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Design and simulation of a power gateway controller for connecting small scale electricity production units to the distribution network

Doctoral thesis for the degree of
philosophiae doctor

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Summary

Electricity markets have been opening up for more local production units, due to large transportation costs and large daily and seasonal load fluctuations. Even small scale producers are gradually getting permission to deliver to the power markets. In some countries, there are electricity consumers who have the possibility for small industrial purposes. Such customers could install electricity production units on their premises, and they could produce excess electricity to sell if they were given the opportunity to do that. In a few countries, plans are underway to fully open up the electricity market to enable these small scale electricity producers to participate.

Integrating the customer units with the utility may on one hand, maximise the use of other available energy resources, whilst on the other hand, significantly reduce the power demand on the network. In addition, utilities desire to provide their customers with necessary information on electricity prices, payments and need for energy by frequent messages throughout the day. In view of the above, there is an interesting aspect to design a unit that monitors market prices, and controls local production and consumption, to optimize the economy of a small scale producer. Such a unit is described as a power gateway controller.

The thesis outlines an experiment of such a system, and simulates different typical load and price situations, to evaluate if such a unit could be beneficial from the point of view of the small scale producer. The thesis is not about analysing investment and infrastructure costs of setting up small scale electricity production units. It is mainly about the technicality of designing a power gateway controller, minimization of operational costs of electricity, and simulation of a plant for testing the functionality of the algorithm.

This thesis presents a designed and simulated power gateway controller (PGC) which can be used at a customer premises. This PGC has the capability to optimize electricity costs at a customer premises, where there is potential to produce electricity locally, and sell excess electricity to the distribution spot market. Also presented is a simulated model of a plant where the PGC may be used and an experimental set-up which can be used for developmental work and extended study of customer-utility interaction.

Contents

Preface

This thesis is a result of a doctoral study carried out in the Department of Engineering Cybernetics at the Norwegian University of Science and Technology (NTNU). Two research visits were made in 2000 and 2004 to the University of Zimbabwe and the Zimbabwe Electricity Supply Authority to collect information for the thesis.

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0.1 Abbreviations

CAPC Central African Power Corporation

CH4 Methane

CHP Combined Heat and Power

CO_2 Carbon Dioxide

DG Dispersed Generation

DistCo Distribution Company

DRC Democratic Republic of Congo

ESI Electricity Supply Industry

EU European Union

FERC Federal Energy Regulatory Commission

GENCO's Generating Companies

HFC Hydro Fluoro Carbons

HV High Voltage

IEA International Energy Agency

IPP Independent Power Producer

KT Kuhn Tucker

LP Linear Programming

NETA New Electricity Trading Arrangements

NGC National Grid Company

NO_x Nitrogen Oxide

NVE Norwergian Water Resources and Energy Directorate

PoolCo Pool Company

PURPA Public Utility Reform Policy Act

PX Power Exchange

SAPP Southern African Power Pool

SF_6 Suphur Hexafluoride

SO System Operator

SO_x Suphur Oxide

SRC Short Rotation Coppice

STEM Short Term Energy Market

ZESA Zimbabwe Electricity Supply Authority

0.2 List of Symbols

$F(x)$ objective function

$Gi(x)$ constraint function

s_p selling price of electricity

bp_e utility price for energy consumption

bp_t utility price for electricity transmission

mp measurement point

C_{Ai} averaged costs for operation, maintenance and fuel for each of the various installed production units

P_{cg} current output of the local generators

P_{gi} output of the local generator *i*

P_{cl} current load consumption at the dairy farm

Σp_l the total instantaneous load which we shall also denote as P_{cl}

P_i imported power

C_e instantaneous operational costs of electricity

C_i import costs

C_{sg} self generation costs

$Cum\ R_e$ Cumulative revenue

R_e export revenue

P_{l1} total maximum power that priority one loads

P_{l2} total maximum power that priority two loads

P_{l3} total maximum power that priority three loads

% bmxg percentage benefit at maximum generation

% bmxi percentage benefit at maximum import

Chapter 1

Introduction

1.1 Rationale

The lack of adequate electricity supply in most countries, and especially during various consumption periods of the day and year, has led to interconnection of national grids to international grids covering large parts of continents. The opening up of national electricity markets, and the trading of electricity between countries have become continuous operations. Due to large transportation costs and large load fluctuations, markets have opened up for more local production units, and even small scale producers are gradually getting permission to deliver to the market.

In some countries, there are electricity consumers who have the possibility for small industrial purposes. Such customers could install electricity production units on their premises, and they could produce excess electricity to sell if they were given the opportunity to do that. In a few countries, plans are underway to fully open up the electricity market to enable small scale electricity producers to participate. These consumers can generate electricity on their premises to meet some of their energy needs, and they can sell their excess electricity to the local utility.

Integrating the customer units with the utility may on one hand, maximise the use of other available energy resources, whilst on the other hand, significantly reduce the power demand on the network. In addition, utilities desire to provide their customers with necessary information on electricity prices, payments and need for energy by frequent messages throughout the day.

In view of the above, there is an interesting aspect to design a unit that monitors market prices, and controls local production and consumption, to optimize the economy of a small scale producer. Such a unit is described as a power gateway controller.

The thesis outlines an experiment of such a system, and simulates different typical load and price situations, to evaluate if such a unit could be beneficial from the point of view of the small scale producer. The thesis is not about analysing investment and infrastructure costs of setting up small scale electricity production units. It is mainly about the technicality of designing a power gateway controller, minimization of operational costs of electricity, and simulation of a plant for testing the functionality of the algorithm.

1.2 Contributions of the Thesis

The main contribution from this study is

- a designed and simulated gateway, which has the capability to optimize electricity costs at a customer premises, where there is potential to produce electricity locally and sell excess electricity to the distribution spot market.
- a simulated model of the plant.
- an experimental set-up which can be used for developmental work and extended study of customer-utility interaction.

1.3 Thesis Outline

This chapter one gives an introduction to the work, whilst **chapter two** gives a background of the developments taking place in electricity markets. **Chapter three** enhances the argument for this work, which is small scale electricity production units. In **chapter four**, the research problem is outlined based on the findings from the literature review. In **chapter five** the theory and design are outlined. **Chapter six** explains the implementation of the experiment whilst **chapter seven** shows some of the results and analysis carried out from the work. The conclusion and discussions are given in **chapter eight** and opportunities for further work are outlined in **chapter nine**.

Chapter 2

Introduction to Electricity Markets

An understanding of the electricity markets and the dynamics of market models forms the backbone of this work. In this chapter, the on-going deregulation and privatisation of the Electricity Supply Industry are described. Possible electricity market models and energy policies are reviewed.

2.1 Deregulation of the Electricity Markets

2.1.1 Arguments for Deregulation

Over the past sixteen years, there has been privatisation and deregulation of electricity supply in most developed countries. This means that there is now competition in producing and supplying electricity to consumers in many countries. There have been different driving forces to restructure the Electricity Supply Industries in different countries. For example on one hand, Livik and Fretheim (1997) in Norway, presented that some of the arguments for change of structure were:

To avoid excessive investment

> Generally the pricing policy of the electric utility industry was based on cost recovery. In a monopoly environment, utility companies could develop more capacity than consumers were willing to pay for. The cost of expensive new development projects were being mixed with cheap existing plants, so that prices to customers did not reflect marginal costs.

To improve selection of investment projects

> New supply resource capacity was being developed in a sense that was not optimal for society. Expensive and unprofitable projects were being developed, while less expensive projects were neglected.

To create incentives for cost reduction

> In a system where prices were based on cost recovery, the monopoly utilities had no basic incentive for cost savings. Excessive costs could be passed on to the consumer. In a competitive system, where the price is settled by the market, cost saving incentives would be created.

Equity among customers

> When prices to customers were being decided in political forum sometimes there was extensive cross-subsidising. For example some customers paid more for their electricity than other customer groups. Differential prices for large, medium and small customers was the norm in vertically integrated utility businesses. Prices were not always reflecting the real costs of the system and from an economic perspective, such cross subsidising between customer categories was unfair and sometimes resulted in losses.

Reasonable geographical variations

> Very different prices between neighbouring utilities gave unclear and inconsistent signals to consumers about the value of energy service provided by electric utilities.

On the other hand Huneault, Galiana and Gross (1999) report that in the United States of America, the main driving force behind electricity deregulation was to introduce competition and to impose electricity prices, which reflected real costs according to use. According to them, the central theme of restructuring was the combined expectation of

higher profits

> Corporate reorganization and downsizing would lead to improved efficiency with little political meddling in utility businesses, which would result in higher profits for the new utility businesses.

influx of private capital

> The government could free up public funds and collect cash from the sale of industry assets to private investors. There would be an influx of private capital resulting from the opening of competitive wholesale energy markets.

lower energy prices

> The expectation of higher profits from the business enterprises and competition from the open market would lead to lower electricity prices to the public.

In several other countries, the public sector could no longer meet the investment needs of the electricity industry. The national debt stifled growth and it was necessary that governments remove themselves from the energy business.

Although this looked like an attractive solution to the immediate problems it also had long term impacts on the economy as a whole, because the long term income from these assets was lost.

The deregulation of the electricity supply business involves replacing non-profit making and inefficient market structures, by market structures, which reward efficiency with profit.

A discussion on the evolution of deregulated markets and the outcome of some of these arguments is given later in this chapter.

2.1.2 Characteristics of the Electricity Business

There are three main characteristics of the electricity business that have a profound effect on trading:

Storage

> Electricity, unlike gas and water, cannot be stored in bulk and the supplier has small control over the load demand at any time. It is necessary to have reliable regulators to keep the output from the generators equal to the connected load at the specified voltage and frequency.

Demand

> There is a continuous increase in the demand for power as the years go by, especially in developing countries.

Location of the basic energy source

The location and nature of the fuel, e.g. coal and uranium, are mined in areas that are not necessarily the main load centres; hydroelectric power stations are usually remote from the large load centres. Transmission losses can lead to increased system costs.

2.1.3 Countries with Open Electricity Markets

Some of the first countries that enacted legislation to open their electricity markets before 2002 are listed in Table 2.1 below.

Table 2.1: Some countries which opened their electricity markets before 2002

place	year	place	year
Norway	1990	Mexico	1999
UK (England and Wales)	1990	Canada	1999
Chile	1990	Portugal	1999
UK (Scotland and N. Ireland)	1990-92	Austria	1999
Argentina	1992	Denmark	1999
South American countries	1993-95	The Netherlands	1999
New Zealand	1995	Switzerland	1999
Sweden	1995	Belgium	2000
Central American countries	1997	France	2000
Spain	1997	Japan	2000
Brazil	1998	Canada	2001
Australia	1998	Greece	2001
USA (California)	1998		

Of these countries, full opening of the retail markets had taken place in Norway (1991), New Zealand (1994), Finland (1997), Sweden (1996) and Germany (1998), United Kingdom (2000), according to the IEA fact sheet (2001). Competition was still limited in many countries. As of today, more than 50 countries have deregulated their electricity markets.

2.1.4 Market Roles in a Deregulated Electricity Market

Generally, a deregulated electricity market consists of the following actors who interact and share information as shown in Figure 2.1.

The arrows show the flow of information for market operation and accounting:

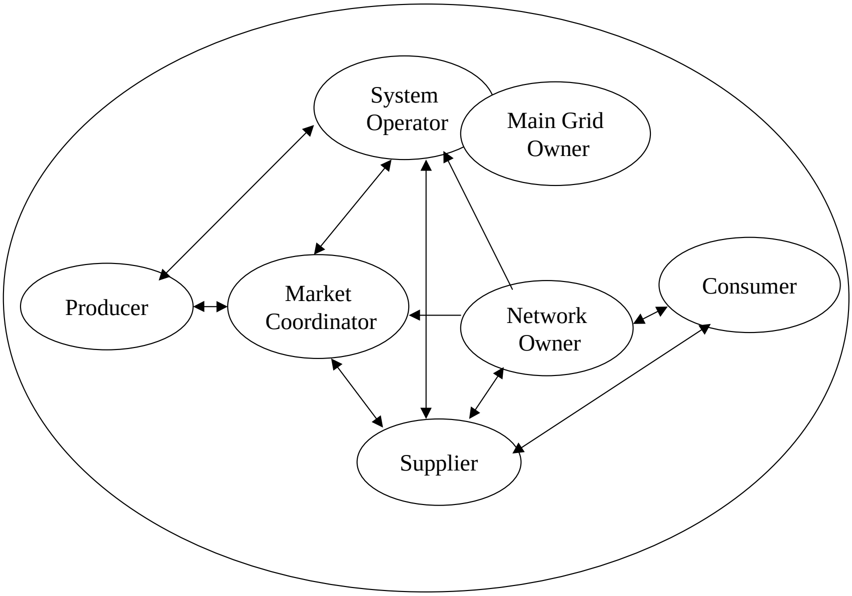

Figure 2.1: Market roles, (adjusted) Livik, Grønli and Fretheim (1997)

System operator

> The system operator maintains the momentary balance, between total production and total consumption of power in addition to managing the ancillary services and system reserves. Under the changing market environment the challenges are great for the system operator.

Producer

> The producer converts different sources of energy into electricity. This electricity is then sold either to the supplier of the electricity distribution system or to the market. The producer may submit bids to the market coordinator. When there is a need to ask the producer to alter their production in order to balance the network, the system operator will communicate this information to the producer.

Supplier

> The supplier sells electricity to the final consumers for example households, industry and many others. The supplier may also be the producer or the electricity may be bought from the open market from other producers. Each supplier is responsible for reporting to the market operator the expected power needed in each geographical price-area in which the supplier has sales.

Market coordinator

> The market coordinator is responsible for organising the electricity market in both short and long-terms. The power exchange (pool) is organised by the market operator.

The network owner /Main grid owner

> The distribution network belongs to the network owner. Power is delivered to the customers, and third party access is made possible for other suppliers, rather than the local, by the network owner. The network owner needs metering data in order to invoice the customer for the power distributed. The network owner has the legal responsibility to secure the quality of data management of customer information. Sometimes the main grid owner of the transmission network is also the owner of some distribution networks.

Consumer

> The consumer buys electricity and transport services from the supplier and the network owner respectively. Meter readings must be taken at the consumer premises and passed on to the supplier and network owner periodically.

An illustration of the system operator’s responsibility is given in Figure 2.2. The system operator SO has responsibility for imports and exports and administers transmission tariffs. In addition to this, maintenance scheduling needs coordination, the system security needs to be maintained, long term planning needs to be coordinated and the SO carries this responsibility. There should be nondiscriminatory open access to all transmission system users. The SO maintains an acceptable system frequency and controls voltage and reactive power. The SO also has authority to commit and dispatch the system resources and in emergency cases, to curtail loads and administer the switching procedures.

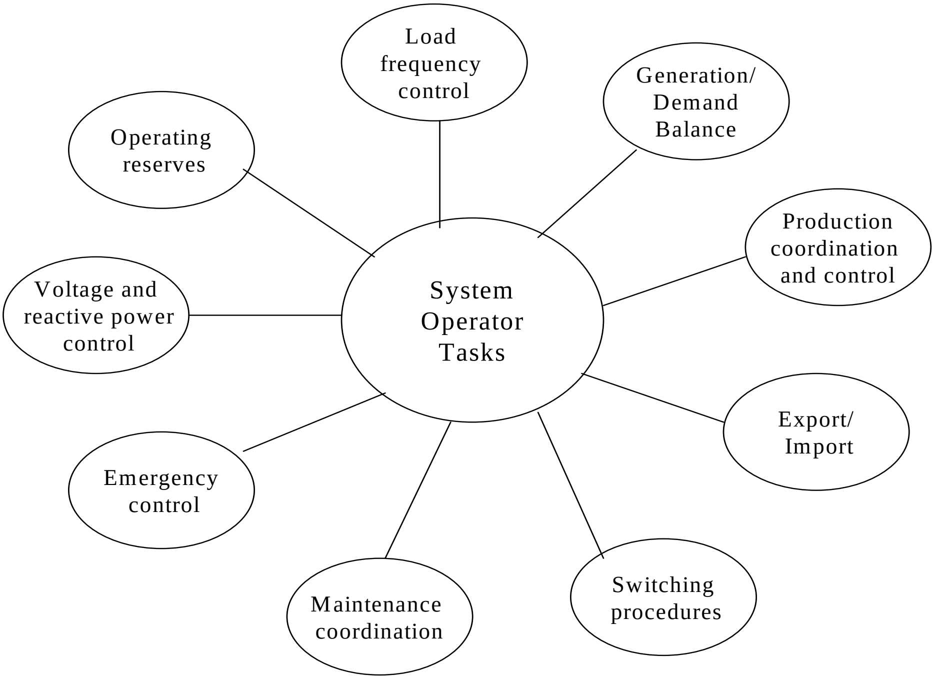

Figure 2.2: System operator's responsibility (Gjerde, Fismen, Sletten (1997))

2.1.5 The Deregulation Models

Most countries that have deregulated their electricity supply business have been doing so in stages. The major first stage has been to introduce competition at wholesale level i.e. in generation and supply of electricity. This has then been extended to retail level by formally separating the monopoly distribution business from the competitive supply.

Varying degrees of monopoly and competition exist in the electricity industry and countries can organize their industries in different structures. Weedy and Cory (1999) presents one way of looking at the structures based on postulations of four deregulation models by Hunt and Shuttleworth (1996). Their first model i.e. the Monopoly model in Figure 2.3.

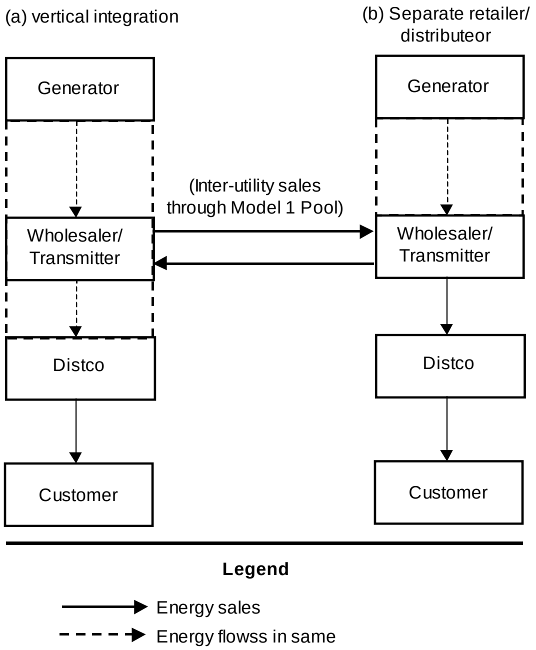

Figure 2.3: Monopoly model (Source: Hunt and Shuttleworth, Competition and Choice in Electricity, Wiley, 1996) Distco means distribution company.

Monopoly model

Under the monopoly model, the old vertically integrated monopoly utilities directly controlled the electricity supply business. Generation, transmission, distribution and supply to the customer (retailing) were all done by one company or one utility. There was no choice for the customers. The government or a regulator was required to control the prices and ensure fairness in pricing. Many utilities have considered different deregulation models in the process of change from this monopoly model.

Purchasing Agency model

In the second model which is the Purchasing Agency model, a single buyer is allowed to purchase energy from competing electricity generators or independent power producers (IPP's). The buyer arranges for delivery over monopoly, transmission and distribution systems and sells at advertised tariffs to all consumers (large and small). The purchasing agency would purchase by tender or bidding system from the IPP's to ensure the best price is obtained throughout the day and year.

Wholesale Competition model

In the third model, which is the Wholesale Competition model, the distribution companies can buy directly from the producers and deliver to their own supply points over the transmission networks. These networks will allow any distribution company to sign a contract for their use, thereby allowing "open access". The distribution company however, has a monopoly over supplying the consumers.

Retail Competition model

The fourth model which is shown in Figure 2.4 is a Retail Competition model where there is competitive energy trading in a completely open structure. Here all the consumers can choose their supplier and pay for delivery over the transmission and distribution networks which are on open access. In the new environment, the generators and suppliers can enter into a series of short-term contracts for the energy required through simple contracts.

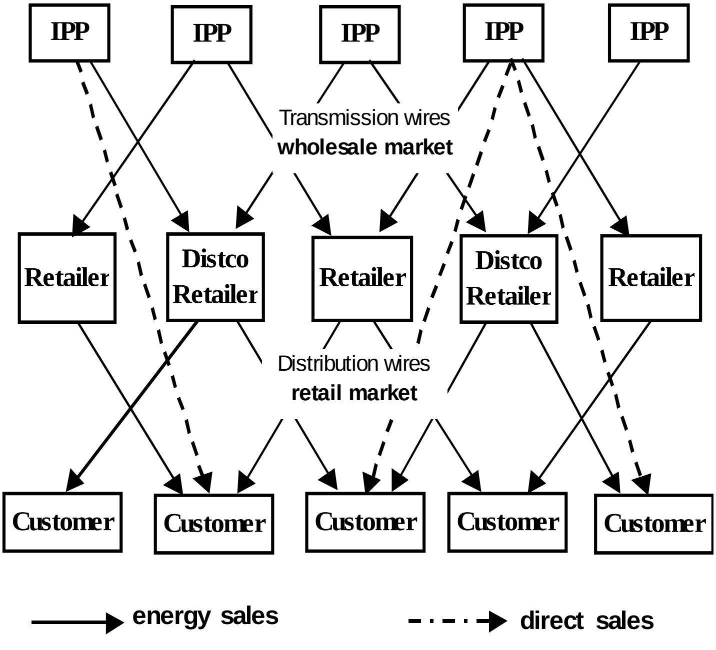

Figure 2.4: Retail competition model: An Open Structure (IPP is Independent Power Producer and Distco is Distribution Company)(Source: Hunt and Shuttleworth, Competition and Choice in Electricity, Wiley, 1996)

In this fourth model competition is at retail level whilst in the third model which was previously discussed, the competition is at wholesale level. There are many problems and difficulties in transferring from one model to another. There is a need to set up an appropriate infrastructure including the necessary control, metering and information technology to achieve a free market at reasonable cost.

A regulator is still required to authorize the monopoly transmission and distribution charges unless alternative delivery networks are built. The regulator is also required to maintain a fair and equitable market structure for consumers to exercise their choice of supplier. This fourth model is of more interest to this work.

Table 2.2 summarizes the four models by Hunt and Shuttleworth (1996).

Table 2.2: Deregulation models

Characteristic	**Model 1-Monopoly**	**Model 2-Purchasing agency**	**Model 3-Wholesale competition**	**Model 4-Retail competition**
Definition	Monopoly at all levels	Competition in generation -single buyer	Competition in generation and choice for Distcos[1]	Competition in generation and choice for final consumers
Competing generators	no	yes	yes	yes
Choice for retailers?	no	no	yes	yes
Choice for final consumers?	no	no	no	yes

[1] Distcos, distribution companies

[1] (Source;Hunt Shuttleworth (1996). Reproduced by kind permission of the authors of the National Economics Research Association {New York & London})

According to the table, there is no freedom at all for the consumers in the monopoly model. There is one player in the market who has no competition and can set the prices to suit self interests, which may not necessarily be for the common good. The regulatory bodies have to be biased towards consumers in order to bring fairness to the power supply business. The degree of freedom for the consumers increases in the second and third models. The fourth model releases total freedom to the consumers to choose their supplier of electricity and also to participate in the energy markets.

There has been evidence that market liberisation leads to reduction in operating costs of generating plants by improving labour productivity, reducing maintanance costs and improving fuel purchasing strategies. The productive efficiency is improved and prices are aligned with costs to improve allocative efficiency.

2.1.6 Electricity Market Models

The basic elements of the restructuring principles are the opening up of the energy market, unbundling of electricity services, and open access to the electricity networks. Huse (1998) presents three different market models which show a different way of looking at the market scenario’s.

Centralized Scheduling model

> In this first model a centralized market place sometimes called a PoolCo, clears the market for buyers and sellers. Electric power sellers compete for the right to supply energy to the grid by submitting bids to the pool for the amount of power they are willing to trade on the market. Buyers also submit their purchase bids and the market dynamics determines the spot price. The system operator within the PoolCo implements the economic dispatch, produces the price and gives participants a clear signal for consumption and investment decisions. Winning bidders are paid the spot price that is equal to the highest bid of the winners. The spot price is likely to be equal to the marginal cost of the most efficient bidder.

Bilateral Contracts model

> In the second model traders negotiate and agree to trade electrical power with each other. They write and sign a contract setting out the terms and conditions of agreements. An independent system operator simply verifies that there is sufficient transmission capacity.

Hybrid model

> The third model combines features from both the PoolCo model and the Bilateral contract model. Any customer has the option either to negotiate a power supply agreement directly with the suppliers or accept power at the spot market price. An independent system operator administers transmission tariffs, maintains the system security, co-ordinates maintenance scheduling and has a role in co-ordinating long-term planning.

The hybrid model gives the customer a higher degree of freedom. This model however presents a greater challenge to the system operator especially when the market is opened up to all consumer categories. These challenges are certainly exciting for engineers who have to plan, co-ordinate and maintain the transmission and distribution systems under the new scenarios. Strategies have to be developed to cope with the dynamics of a changing market.

2.2 Typical Examples of Electricity markets

The following few examples outline information which was collected during the literature review of this work.

2.2.1 The Norwergian Electricity Markets

Norway deregulated its power market in 1990 (Pentzen, 1996). According to Knivsflå and Rud (1995), Norway initially had three organised markets i.e., the spot market (Elspot), the futures market (Eltermin) and the regulating market. These markets were opened in the presence of surplus generating capacity.

Spot market

Tangen, Graabak, Myrvang and Lie (1999) report that on the spot market, energy contracts for delivery of electric energy in the next 24 hours are traded daily. The spot market accepts bids for all 24 hours of each day until 12 o’clock noon before the electricity is traded. The market is settled for each day by 15.00 o’clock on the preceeding day. According to Huse (1998) bids are accepted by FAX, or electronically. The supply bids are aggregated into a supply curve and the demand bids are also aggregated into a demand curve. The intersection point of the supply and demand curves gives the system price for clearing the market. Spot market participation is not mandatory. About 32% of energy in the Nord Pool market area is traded on the spot market.

Regulating market

The regulating market is a tool for maintaining the physical (frequency) balance of the power system i.e. between the total generation and consumption of power in real time. According to Nord Pool (2006) the Nordic TSO's (transmission system operators) are

Statnett SF in Norway

Svenska Kraftnät in Sweden

Suomen Kataverkko Oyj (Fingrid) in Finland

Elkraft System AS in Zealand, Eastern Denmark

Eltra in Jutland/Funen, Western Denmark

> While the spot market balances the predictable deviation between sales and purchases, the regulating market balances the actual system imbalance. This market accepts bids from participants to raise or lower energy generation from scheduled values. Bids are accepted everyday between 15.00 and 19.30 on the preceeding day. Participants must be able to respond within about 15 minutes. When the system operator decides that regulation is necessary, it buys the cheapest block of regulating power. The telephone is used for dispatch. All network users are charged for regulation based on deviation from scheduled hourly energy values.

Futures market

> The futures market is a financial market for risk management and hedging. Hedging is on future buying or selling. Bilateral contracts, which specify the trade of some amount of energy at a given price are made. Trading can be in week contracts, months (a block of four weeks) or seasons. On this market there is continuous trading between 12.30 p.m. and 15.00 p.m. Daily, there is calculation of profit and loss against the 24 hourly price changes and daily financial clearing against the system price in the delivery week.

The total energy traded on the Nordpool in 2004 was 1964 TWh corresponding to an equivalent sum of 389 billion Norwergian Kroner. In March 2004 a new market was introduced on the Nord Pool exchange, called the Electrification market/ TGC market ,Vogstad K-O.(2005). For each MWh of electricity generated from certified renewable sources such as wind, small scale hydro or bio energy, a certificate is issued. These tradable green certificates can be traded as financial assets.

The power exchange NordPool operates the spot market and the futures market. Statnett as shown in Figure 2.5, is the national system operator in Norway and it is responsible for the system coordination and operates the regulating market. The Norwergian Water Resources and Energy Directorate (NVE) is the regulatory authority for the transmission system in Norway. NVE is subordinated to the Ministry of Petroleum and Energy and is responsible for administering the nation's water and energy resources.

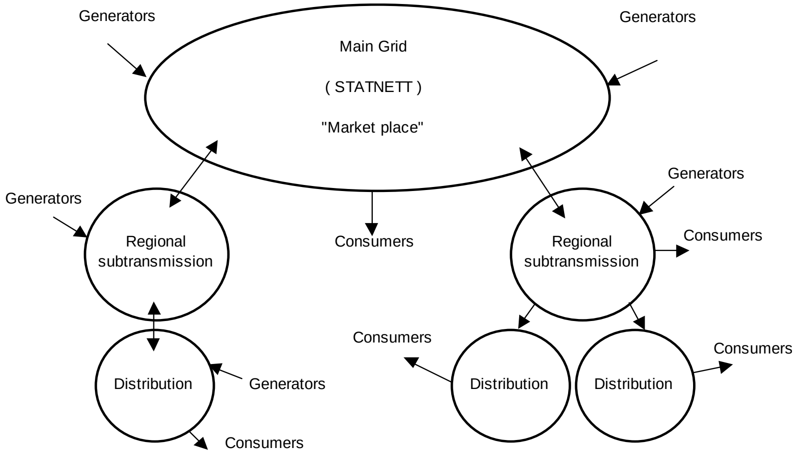

Figure 2.5: Network levels in Norway (Glende (1997)).

As of 1998, about 99.41% of the electric power production in Norway was from hydro plants, 0.59% from fossil fired units and 0.01% was from wind power. There were almost 230 distribution companies in Norway, 90 producers of electricity and about 60 utilities attended both roles.

In 2002 Norway had a total installed capacity of 27 596 MW at 740 hydro power plants larger than 1 MW as reported by Steensnæs and Paaske (2002). However about 23 000 MW was actually available because of maintenance and repairs. Thermal power plants provided an additional capacity of 271 MW. The installed capacity of wind power plants is 13 MW. The largest electricity producer in Norway is Statkraft SF and accounts for 30% of the total production capacity.

According to Hofstad K., Mølmann K., Tallhaug T. (2005) the Norwegian Government has increased its focus on wind power plant installations and set a goal to increase the yearly production from windpower to 3TWh by the year 2010. Five wind power projects were licensed with the expectation of producing about 725 GWh/year. Havøygavlen wind park which consists of 16 wind mills was opened in Norway in June 2003 and produces around 120 GWh of energy each year. The Norwegian Water Resources and Energy Directorate (NVE) (2005) estimated that it is possible for Norway to realise about 5 TWh of small scale hydropower production within a ten year period. The potential for small scale power production under 10 MW with investment costs less than 3 kr/kWh is about 25 TWh.

A process of restructuring and liberalising the electricity supply industry is often combined with a privatisation. Gjerde (1997) reports that in Norway, there was not much privatisation in the electricity supply industry initially. The state and public ownership of most of the industry was maintained even if the companies became exposed to considerable financial risks in the new competitive environment. Gradual changes in privatisation have taken place over the years. The Norwegian Water Resources and Energy Directorate (NVE) (2003) report that the Nordic Power Market has been recorded a success since its early start in 1991.

Norwegian International Energy Interaction

Norway is connected to an international grid which covers several countries. There are crossborder lines and subsea cables for electricity transmission to neighbouring countries. According to the webpage of Statnett (2005), Norway and Denmark are connected by three subsea cables (transmission capacity 1000 MW), whilst areal power lines connect Norway to Sweden (2800 MW), Finland (700 MW), and Russia (50 MW). New subsea cables will connect Norway to England and to the Netherlands (700 MW). Figure 2.6 shows the grid system in the Nordic countries.

These power lines and stations are of major importance to one or more regions or the whole of Norway. Charges for using these transmission facilities are jointly borne by all users.

Sweden and Norway established a common power market in 1996. Later, in 1999, the Scandanavian countries agreed to share a common market for their electricity supplies although the electricity networks were physically connected many years before then. Regulation has played an important role in this development. The advantages of this common power market is that electricity can be imported from neighbouring countries when there is a shortage in Norway or when it is more economical to import than to generate locally. Norway can also sell electricity to its neighbours. The main disadvantage however is that prices on the spot market vary each hour depending on the market conditions, making it difficult for investors to accurately forecast the profit from their investments

Norway participates in the International Energy Agency in implementing an international energy programme. Among other objectives, this programme includes the development of alternative energy sources, rational management and use of world energy resources and the development of a stable international energy trade. A lot can be learned from the Norwergian energy experiences.

The Norwegian electricity grid is split into three levels: main grid, regional grid and distribution grid. The bulk of the transmission grid at the highest voltages: 420, 300 and 132 kV, constitute the main grid. .

Figure 2.6: The Grid System in the Nordic Countries (Stattnett 2005)

2.2.2 The Zimbabwean Electricity Markets

The generation, transmission and distribution of electricity in Zimbabwe was mandated to the Zimbabwe Electricity Supply Authority (ZESA), in 1986. ZESA had a vertically integrated monopoly model as a parastatal organisation, and it was supervised by the Ministry of Transport and Energy.

As of 2003, Zesa's installed capacity was 1961 MW of which about 33% (i.e. 666 MW) were from hydro plants in Kariba and about 66% (i.e.1295 MW) were from coal fired thermal units in Hwange, Harare, Bulawayo and Munyati. However the actual sent out capacity was around 1620 MW because of repair and maintenance routines. There were some small privately owned generators which were not selling to the network at the sugar estates in Triangle (45 MW), Hippo Valley Estates (23 MW) and a 750 kW mini-hydro plant at Rusitu. More than 750 kW photovoltaic cells are installed and many private solar water heaters exist countrywide. The country's maximum demand is about 2007 MW.

Parliamentary discussions on deregulation and privatization started in 1998. The long awaited privatization took off the ground in 2003 according to Chamunorwa 's national report (2003). The Zimbabwe Electricity Amendment Bill was passed in parliarment in March 2003 and the new Electricity Act became law with effect from August 2003. The buying and selling of fuel was also deregulated in the same month removing the monopoly of the National Oil Company of Zimbabwe.

According to All Africa.com (2003) the Electricity Act established ZESA Holdings, a holding company that holds State shares in companies that took over from the privatisation of ZESA.

The companies that took over ZESA are:

- the Zimbabwe Power Company (ZPC), responsible for the generation of electricity
- the Zimbabwe Electricity Transmission Company (ZETCO) responsible for national electricity transmission
- and the Zimbabwe Electricity Distribution Company (ZEDCO) responsible for the distribution and supply of electricity.
- Powertel Communications, a subsidiary which provides data and telecommunication services to ZESA Holdings, the South African Power Pool and the public
- ZESA Enterprises, a subsidiary which comprises four business units namely ZESA Technology centre, Production and Services, Transport and Logistics and Projects

All these companies are owned by ZESA Holdings (Pvt) Ltd the holding company which was created from the unbundling process on behalf of the government. The Zimbabwe Power Company was formed in 1996 and began operating in 1999. It functioned as a shelf company, for the formation of joint venture companies, for the privatisation of Hwange Power Station and Gokwe North Power Station. ZETCO has the mandate to procure bulk electricity from both domestic generating plants (Hwange, Kariba, Harare, Munyati and Bulawayo) and external supplies in the Southern African Power Pool. The purchase of electricity is through commercial contracts (Power Purchase Agreements) with generating companies, regional utilities and Independent Power Producers. The procurred electricity is sold through contracts to the sole distributor ZEDCO, and to regional utilities. The model adopted is like the Purchasing Agency model discussed earlier on in which a single buyer is allowed to purchase energy from competing electricity generators or independent power producers (IPP’s).

In order to meet its growth in demand and ensure security and reliability of supply, Zimbabwe imports more than 30% of its power needs from neighbouring countries. The electricity network is interconnected to the Southern African Power Pool (SAPP). Figure 2.7 from SAPP (2005) shows the SAPP’s existing and proposed interconnectors between the countries Zambia, South Africa, Namibia, Botswana, Mozambique and the Democratic Republic of Congo and Zimbabwe. The Inter-Governmental Agreement of August 1995 created the Southern African Power Pool (SAPP) whose headquarters was in Harare in Zimbabwe. It confirmed the region's commitment to expand electricity trade, reduce energy costs and provide greater supply stability for the region.

The SAPP's original primary objective was to provide reliable and economic electricity supply to the consumers of each member. The SAPP is now evolving from a cooperative to a competitive pool. Power trade continues to increase steadily annually at an average of 20%. The value of the electricity traded in 1999 was over US$150 million. As of 2004 the average energy price was 0.74USc/kWh. A short-term energy market (STEM), which started live trading in April 2001, utilizes the Internet to conduct trade. The STEM is a spot market of non-firm electricity contracts. Independent power producers Hidroelectrica de Cabora Bassa, Kariba North Bank Company, and Zimbabwe Power Company will participate in the STEM, subject to clarification of their status.

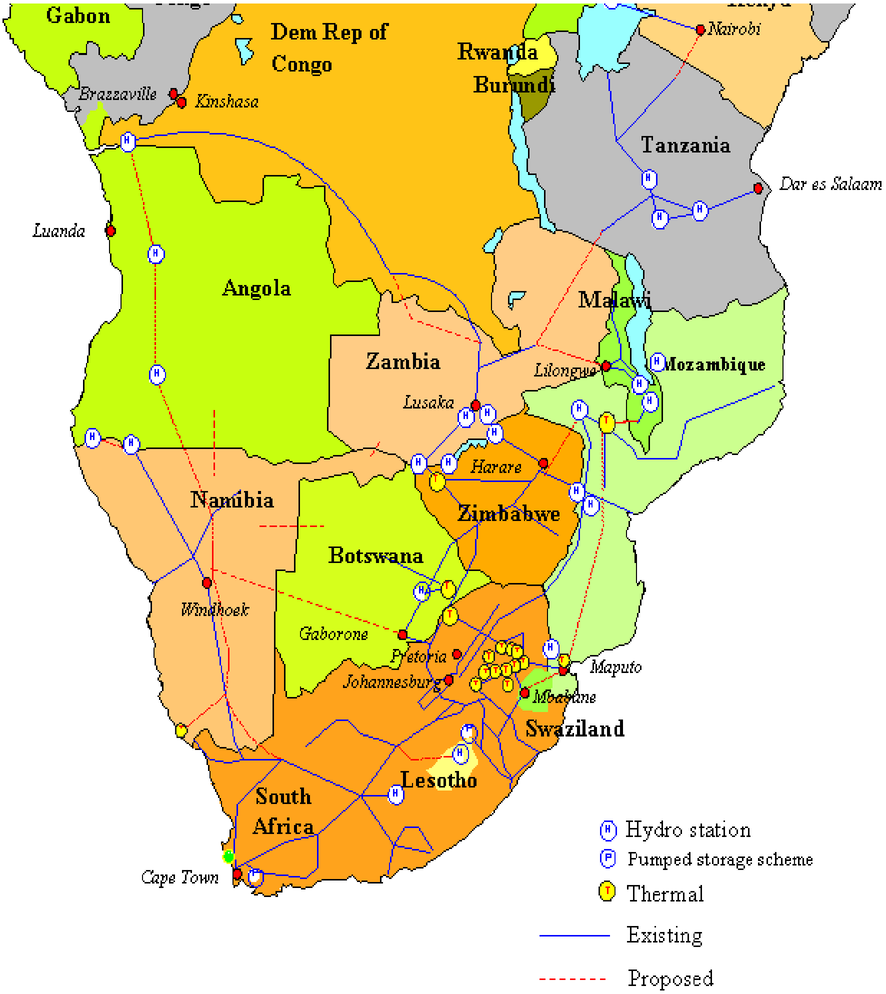

Figure 2.7: The Southern African Power Pool: Existing and proposed SAPP Interconnectors

A significant SAPP accomplishment was the completion of the Matimba-Insukamini interconnector linking South Africa’s Eskom and ZESA in October 1995. This interconnection initiated the first linkage of system operations between the northern and southern electrical systems in the Southern African region. Plans to connect the power grids of Angola, Malawi, and Tanzania with other SAPP member grids are in varying stages of development. According to Musaba L., Naidoo, P., Balet W, Chikova A. (2004), Zambia and the DRC are to upgrade their current 220 kV regional interconnection to a much higher transmission level to allow other SADC countries to tap Inga's energy supplies. More information on the SAPP is given in Appendix A.

Despite the developments in the region's networking projects, it is still necessary for governments to ensure that there is adequate local security of electricity supply. Focussing on small scale renewable energy projects will help Zimbabwe see a more secure and stable electricity supply system in the future, although short term problems can be solved by increasing the electricity imports.

A programme was initiated in the 1980s as a strategy to bring a more sustainable and environmentally friendly alternative renewable energy. The programme was funded from the Rural Electrification Fund Levy, which accounts for 6 percent of electricity bills. There is great potential for renewable energy technologies since this is part of the national energy policy. Mawire (1998) reports that Zimbabwe has a very good solar regime with an annual insolation over 2 MWh/m^2 per year and the potential for solar technologies is quite high. There are a few mini-hydro sites scattered around the country. There is also potential for biomass technologies because the economy is agro-based. The waste from farmlands, forests and seaweeds can be used to generate electricity. The country's rich deposits of methane gas and the recent discovery of natural gas in neighbouring country Mozambique, also brings closer, new opportunities for combined heat and power gas technologies.

Zimbabwe's national energy policy is

- to ensure accelerated economic development
- to facilitate rural development
- to ensure environmentally friendly energy development
- to ensure efficient utilization of energy resources
- to promote small to medium scale enterprises.

Many development projects are expected to take off the ground when the economic climate is conducive, and there will be an influx of private capital.

2.2.3 The British Electricity Markets

In 1990 the British Electricity Supply Industry (ESI) was privatised and separate companies were formed in England and Wales. These companies provided competition in power generation (with the prospect of further independent generators entering the market). The National Grid Company (NGC) in England and Wales, was set up to transmit electrical energy at high voltage (HV), and 12 Regional Electricity Companies (RECs) were formed to distribute and supply energy to consumers.

There were three separate electricity systems in the United Kingdom: England and Wales, Scotland and Northern Ireland. The English and Scottish systems were interconnected with 1600 MW transmission capacity and there was also a 2 GW direct current link between England and France. In 1996 the total electricity production was 347 TWh. The contributions of the largest power production companies were:

- National Power (fossil-fired), about 31%
- Powergen (fossil-fired), about 23%
- Nuclear Electric (nuclear), about 22%

Competition was introduced in generation and retail sales. The market had the centralised scheduling model. The spot market was mandatory and did not allow physical bilateral trades between generators and their customers.

The NGC provided transmission services from generators to RECs, coordinated transmission and dispatch of electricity generators and ran the electricity spot market. It ran both the financial and physical side of the electricity market. It determined the half-hourly market clearing prices and also made generator dispatch decisions in real time to manage congestion on the grid and provided ancillary services necessary to guarantee reliable power to all final customers. Unless a generating facility was dispatched by NGC as part of the day-ahead spot market clearing process, that plant could not produce electricity.

According to Elston (2002) there has been an enormous influx of private capital in Britain, into the power generating industry from investors, lenders and entrepreneurs over the past twelve years. Combined heat and power (CHP) industrial gas turbines developed rapidly because of higher efficiencies and economic operation. There are now more than 5000 MW of CHP plant installed in the UK. This new technology has resulted in dramatic reductions in environmental emissions.

Electricity trading has undergone a further transformation with the Pool system being replaced by the New Electricity Trading Arrangements (NETA). There seems to be a cyclical change in the industry as there appears to be a consolidation of four or five large vertically integrated multi-utility businesses. Helm (2003) presents an argument for the establishment of new structures and bodies to address the twin challenges of reducing carbon dioxide emissions and maintaining security of supply. In February 2003, the UK Government published its energy white paper, spelling out how it planned to cut the pollution blamed for climate change. By 2010, the UK government aims to increase its renewables from the current 3% to beyond 10%. By 2020, it said, Britain should be producing 20% of its electricity from renewables. Gas could account for 55 to 65% of electricity production.

On the 14th of July 2003 the BBC reported that the UK Government announced a big expansion in the amount of electricity generated from offshore wind power. Licences are being issued for thousands of turbines to be built off the British coast to generate as much energy as around six nuclear power stations. Up to 5% of British power needs could be provided by these turbines. According to the BBC news on the 1st of July 2003, Solar Century, a UK company which provides solar photovoltaic installations, made a claim that: “Solar PV-generated power could provide 10,000 times more energy than the world currently uses. Britain also signed an agreement with Russia to import large quantities of natural gas.

The distribution business is still a monopoly although electrical engineers are currently facing the challenges of accommodating distributed generation such as wind and CHP into the distribution network.

The winter load produces the highest peak because of heating appliances although the summer load is also growing due to increasing use of air conditioning in commercial and industrial premises.

2.2.4 The Californian Electricity Markets

The Public Utility Reform Policy Act (PURPA) of 1978 initiated the deregulation process of the US electricity industry when it was passed. Mohammad (2002) reports that the Federal Energy Regulatory Commission (FERC) Order No. 888 mandated the establishment of unbundled electricity markets in the newly restructured electricity industry. Energy and ancillary services were offered as unbundled services. Generating companies (GENCOs) could compete for selling energy to customers by submitting competitive bids to the electricity market.

Although market operations started in March 1998 there have been major problems of blackouts and restructuring of the structured markets to ensure not only economic operation but also secure operation. IEA factsheet (2001) report that Carlifonia went for full market opening, but maintained retail price controls that muffled market signals. The licensing procedures were lengthy and there was a sharp, unexpected growth in demand which resulted in inadequate investment. When wholesale prices soared, some utilities found themselves in an unsustainable position. Whilst some key market participants faced a financial crisis, customers lost supply in a series of rolling blackouts. There was no adequate investment in generation and transmission capacity.

The Carlifornian Power Exchange (PX) is a non-profit cooperation whose purpose is to provide efficient, competitive energy auction at market prices. Two main markets exist i.e. a day-ahead market and an hour ahead market. The market price on the day ahead market is determined by matching the supply to the demand bids for a 24 hour scheduling day. Supply and demand are adjusted to account for congestion and ancillary services. The PX finalizes the schedules. The hour ahead market is similar to the day ahead except that trades are for one hour and the available transmission capacity is reduced by day ahead trades. Market participants can adjust their day-ahead commitments based on information closer to the transaction hour.

Pacific Gas and Electric Company (PG&E), a California based energy transmission and distribution company, have introduced a self-generating incentive program, as one way of combating the energy crisis. The program offers financial incentives to customers who install self-generating technologies. The scale of the incentives varies according to fuel type, air emissions, costs and scale of the technology applied.

One such technology eligible for financial incentive is the fuel cell. ‘Fuel cells using non-renewable fuel, such as natural gas are eligible for $2.50 per watt of installed generation’ state PG&E. It is thought possible to recuperate up to 40 per cent of the project costs in this way. If the program is a success, PG&E may relieve up to 45 MW of demand from the electric grid.

Indeed, fuel cell technology may provide a longer-term solution to California’s energy problems. Fuel cells offer a source of environmentally friendly, clean power.

2.3 Comments and Observations on Electricity Markets

Although it is believed that competition in electricity markets will result in cheaper electricity to all customers, studies carried out by Huber, Auer, Haas and Orasch (1998) indicate that this is not necessarily true. They reveal that if there is no strong regulation protecting small customers like households, electricity prices in the long-term may be at the same high level as under the past regimes of monopolies with franchised service areas. Larger customers are likely to be the main beneficiaries of these new scenarios.

Baldwin (2002) reports that the result of deregulation has been a market of privately-owned companies that are no longer concerned with the engineering challenge of keeping the lights on, but have acquired new commercially-focused skills to attract customers. Livik, K., Grønli, H. and Fretheim, S. (1997) mention the experience from Norway that in the deregulated market, there was no incentive to invest in more capacity. New capacity should result from long term price incentives rather than the understanding that the power system should have a capacity to cover for ordinary situations. It is difficult for the government to give any directives about obligations for supply. One major problem of letting the electricity supply business operate entirely as separate private companies is that nobody takes full responsibility for investing in new generation, transmission or distribution capacity. The result is that the system may lack power capacity, local capacity for transport and be more dependent on imported electricity.

The largest blackout in the United States of America, which took place on the 14th of August 2003 resulted in loss of power to major cities which included New York, Detroit, Cleveland, New Jersey, Connecticut, Vermont, Michigan, Toronto, Ottawa and parts of Ohio. Almost fifty million people suffered massive blackouts. According to CNN (2003), this incident was believed to have been caused partly by failures of a coal-fired generator and partly by insufficient transmission capacity as seen in failure of three transmission lines in Ohio.

The changes in the electricity markets have resulted in a shortage of power supply. Many of the electricity lines are running very close to their limits especially when extreme weather sets as Griffin (2003) reports. In general, governments still have to somehow ensure that mechanisms are put in place to encourage companies to invest in new capacity. There needs to be a shift of paradigm in the point of view of long term planning of the supply side of electricity. Total system planning should integrate the customer in network planning, market planning, and system operator planning.

Botterud (2003) outlines that investors in new power generation capacity face the challenge of maximising their profit in a risky environment where prices are volatile, the market environment is changing and the future is less predictable. There is also increased environmental concern to curb polluting emissions from power generation.

A need has been created for self-generating technologies to be integrated into the existing networks. In this thesis, the connection of local generation to the distribution network is defined as **distributed generation**. Some authors refer to this as embedded generation or dispersed generation. There are many advantages of distributed generation, some of which are outlined in chapter three of the thesis.

2.4 Conclusion

In spite of the positive moves to deregulate the electricity supply market, many countries experience shortages of adequate power supply during peak consumption periods and the cost of electricity is very high. In addition, other countries have very high environmental pollution levels. Some of these problems are being solved by opening up the electricity markets and diversifying the supply of electricity.

Electrical customers who have the possibility to produce excess electricity to sell, hope to be given the opportunity to do that in the near future. In most countries, plans are underway to fully open up the electricity market to enable small-scale energy producers to participate as shown in the literature review in this chapter.

Inter connectivity will enable electricity consumers to participate actively in energy markets. These consumers can buy electricity from the grid when they have a shortage. There is a need to critically review the area of interconnection technologies to expedite the buying and selling of electricity from small-scale producers.

Good results could be achieved if there is two way interconnection between small-scale electricity producers and the existing distribution networks, except in very remote rural areas where this would not be economically viable and the units are left to run in island operation. Some rural areas are already connected to the grid and two way interconnection could easily be achieved to improve the benefits of investing in small scale electricity generation units.

In view of the above, integrating the customer with the distribution network may maximise the use of other available energy resources on the one hand, and significantly reduce the energy demand on the network on the other hand. In addition to this, some customers like farmers, who may not have a stable income throughout the year, will immensely benefit.

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Chapter 3

Renewable Energy Contribution, Production and Utilization

The connection of local generation to the distribution network is defined as **distributed generation or** embedded generation or dispersed generation. A variety of small modular power generating technologies, can be combined with energy management and storage systems, to meet energy needs and improve the operation of the electricity delivery system.

Understanding the interaction of distributed generation with the electricity distribution system requires an understanding of the technology of the production units, the characteristics of the energy sources and also the conditions under which the distributed generation plant is operated. Distributed generation offers a solution to pressing energy issues like energy security, price spikes, tighter emission standards and power cuts.

Renewable energy technologies are an essential part of distributed generation because of their less stress on the environment. Flows of energy that are regenerative or virtually inexhaustible from natural ecological cycles are classified as renewable energy. This most commonly includes solar (electric and thermal), biomass, geothermal, wind, tidal, wave, and hydro power sources. Knowledge of the motivation behind renewable energy technologies, fuels the search for more cost effective, sustainable solutions.

3.1 Motivation for Renewable Energy Technologies

It is important to appreciate why there is a need to continue with the work in renewable energy technologies even if the contribution is considered as small scale towards meeting the world's energy needs. In many countries the need for secure energy supply and environmental concerns provide the main motivation whilst other relevant policy drivers increase the argument in favour of renewable energy technologies.

3.1.1 Need for Energy

Development relies on energy. Technology is necessary to make electrical energy available in acceptable form and suitable quantities. The availability of electricity transforms living standards in society as can be seen in industrialized, developed countries. Of the almost six billion people on earth, two billion still live without electricity. The earth's energy resources need to be exploited to provide electricity to those who donot have it.

According to the European Commission (2000), the EU depends on 40% oil imports from OPEC countries and this could reach 70% by 2030. 41% of natural gas is imported from Russia whilst 30% is imported from Algeria.

In developing countries like Zimbabwe, only 35% of the households have electricity and the country imports more than 30% of its energy needs from neighbouring countries. Renewable energy sources have considerable potential for increasing security of supply.

3.1.2 Environmental Concerns

Reducing gaseous emissions is a major policy driver encouraging connection of renewable generators into the power distribution networks. The use of renewable energy sources is desirable as a way of reducing gaseous emissions of carbon dioxide. The global meeting held in December 1997 in Kyoto, Japan by the United Nations introduced a set of legally binding limitations on emissions from the world's 39 industrialized countries. This protocol was ratified by 171 participating countries. These countries agreed to an average reduction of more than 5% of the total greenhouse gas emissions by the year 2012 as compared to the 1990 emission levels. Although USA has been backtracking on this agreement, it however expressed commitment to finance any projects that have a drive to reduce greenhouse gas emissions. Norway has no problems of gaseous emissions from its electricity production units since 99.3 % of them are hydro powered.

The main drivers of the European Union's energy policy are climate change and sustainable development, security of supply, and competitiveness. There is a move to establish a progressively integrated energy market. A progressive policy of controlling the growth in demand will result in climate change and reduced dependency on external energy sources.

Whenever a power station is to be built, its impact on the environment is usually a major factor in the consideration. There is a generally accepted concern over gaseous emissions from fossil-fuelled plants. In Europe, electricity generation and heating of water are responsible for 37% of CO_2 emissions, transport for 28%, households, people and animals for 14%, industry for 16%, and the services sector for 5%. Some 90% of the projected growth in CO_2 emission will be in the form of the transport sector. Fossil fuels include coal, oil and natural gas. These find application in power generation, heating, chemical manufacture and transportation.

By-products of fossil fuel combustion include carbon dioxide (CO_2) sulphur oxide (SO_x) and nitrogen oxide (NO_x). Other greenhouse gases generated by human activity include hydrofluorocarbons (HFC's), perfluorocarbons (PFC), methane (CH_4), and sulphur hexafluoride (SF_6). Emissions of NO_x and SO_x cause acid rain which causes damage to buildings and vegetation. Sulphate concentrations of 9-10 microgram per cubic metre of air aggravate asthma, lung and heart diseases. Emissions of CFC's cause depletion of the stratospheric ozone whilst emissions of CO_2 cause man-made greenhouse effect. There is a worldwide move towards reducing CO_2 emissions to help counter climate change. Global co-operation and a common effort is required to solve the global problem created by greenhouse gas emissions. In the future development of energy technologies, preference is likely to be given to technologies that emit less greenhouse gases, like carbon dioxide or nitrous oxide and those that use fuels which can be replenished.

Some ways of combatting CO_2 emissions include use of CO_2 sequestration units, imposing taxes on CO_2 emissions and pumping CO_2 into oil wells to make them more productive and worth exploiting. Other ways include sowing more plants and trees which use CO_2 , putting CO_2 into under-sea acquifers and pumping CO_2 deep into the ocean, far out of reach of animals or plant life. Sulphur oxide emissions can be controlled by using fuel with very low sulphur content e.g. less than 1% or removing the sulphur from the coal by gasification or flotation processes, limestone scrubbers or fluidized bed combustion.

3.1.3 Other Policy Drivers

There are other policy drivers which are relevant which include :

- energy efficiency or rational use of energy
- deregulation or competition policy
- diversification of energy sources and economic diversification for rural communities and businesses.
- national power requirement e.g. to meet the maximum demand requirements
- availability of modular generating plant

- ease of finding sites for smaller generators
- short construction times and lower capital costs of smaller plant
- generation may be sited closer to load, which may reduce transmission costs

According to Kennedy, M. (2003) the correct financial incentives for renewable generation must be put in place for example the introduction of Renewable Obligation Certificates can be an effective financial driver. There has to be a bias towards this technology at governmental level in order to promote its expansion. Distributed generation converts the distribution network from a passive network into an active network. Improvements in reactive power and system voltage control are anticipated. Losses and transmission charges are expected to be avoided whilst blackstart capability and the prospect of system islanding is expected to be provided.

3.2 Sources of Energy on the Earth

The major sources of energy on the earth include petroleum oil, coal, natural gas, combustible renewables and waste, nuclear elements and hydro. Other sources of energy are geothermal, tidal, wind and solar power. The major producers and exporters of crude oil are Saudi Arabia (11.5%), Russia (10.7%) and the United States of America (9.9%). Norway is also a major player on the energy markets with a contribution of 4.4%.

3.2.1 Fuel Shares with Respect to Electricity

Most of the electricity in the world is still being produced from coal (38.7%). However, natural gas (18%) and nuclear (17.1%) also play a major role as sources of fuel for electricity production.

According to the International Energy Agency (2003) Figure 3.1 shows the figures for the World’s Fuel shares of electricity generation.

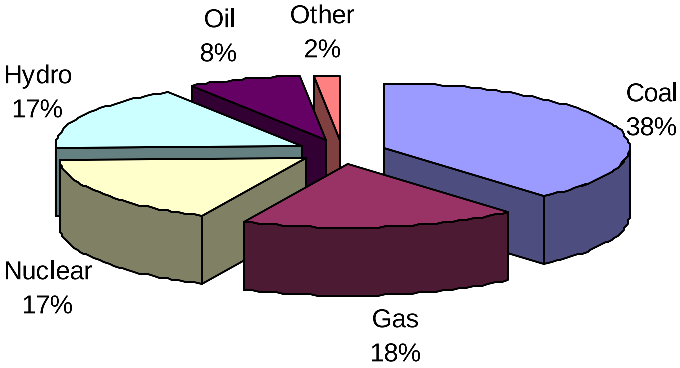

Figure 3.1: World's 2001 Fuel shares of Electricity generation

Large hydro plants account for approximately 16.6% of installed capacity and they are the largest renewable producers. Norway leads the world in hydro power utilization with almost 99.3% of the electricity production coming from hydro power. In Norway, a new company Småkraft AS, plans to expand the small scale hydro production equivalent to 2.5 TWh in the following years until 2012, which is power supply to over 125.000 households.

The other countries which have developed extensive hydro power plants include Brazil (81.7%), Canada (56.7%), and Sweden (49%).

3.2.2 Renewable Contribution

The new renewable energies (i.e. excluding large hydro plants) only account for about 2% of the world's total electric generating capacity which is approximately 15 476 TWh. Apart from small scale hydro plants, the other renewable energy resources include wind power, solar radiation, biomass and municipal waste plants. Solar radiation can be used in photovoltaic cells and solar thermal units.

3.3 Energy and Costs

In deciding on which type of equipment to invest in, energy consumers start with a need for useful energy and consider alternative options taking into account their complete system costs. The system costs include investment costs, fixed and variable operation and maintenance costs. Fixed operation and maintenance costs include all costs borne by producers that do not fall within investment and fuel costs. These could be costs of consumable materials and products, or cost related to treatment, storage, conditioning and waste disposal as explained by the Nuclear Energy Agency, International Energy Agency, OECD (1998).

Usually, fuel costs form a large part of variable operating costs and taxation can substantially affect them. The cost of some renewable energies has prohibited them from playing a significant role in power generation except for hydro power plants and wind power plants.

According to Nasar, A.S. (1996), the relative costs of electricity from some of these different sources are compared in Table 3.1 below :

Table 3.1: Cost of electricity from different energy sources

Energy Source	**US Cents / kWh**
Coal	5.2 to 6
Gas-CCGT (Combined cycle gas turbine)	3.4 - 4.2
Nuclear	7.4 - 6.7
Wind	4.3 - 7.7

Although biomass waste technologies are not included in this table, according to the European Commission (2000) their production costs are very comparable to the costs of coal. Biomass gasification based systems generate power at a cost that is very comparable with a combined cycle power plant that uses natural gas. Cofiring inexpensive biomass fuels with coal can reduce the operational costs by 0.5 cents / kWh in addition to reduced overall emissions. The most economical conditions exist when the energy use is located at the site where the biomass residue is generated.

Hydro power production is much cheaper for large scale projects although the capital costs are very high. The low capital costs of combined cycle gas turbine renders this option very attractive.

Although the costs of solar technologies are ten times higher than conventional energy sources, active research work in this area seem to be producing promising results. Alto, P. (2004) reports that nanosolar scientists are designing low-cost solar electricity cells that will make solar power competitive with conventional energy sources. Roscheisen, the chief executive officer of Nanosolar Inc., demonstrated a nano-engineered material, that "self-assembles" into tiny solar cells that convert sunlight into electricity. He reported that this technology is at the threshold of making solar electricity profitable.

3.4 Distributed Generation in other Countries

Many countries have significant distributed generation. Typical percentage figures of distributed generation to total installed capacity are as high as 28% for Denmark and the Netherlands, 15% for Poland , close to 13% for Belgium and Australia. Refer to Table 3.2 which contains figures from [Jenkins, N., Allan, R., Crossley, P., Kirschen, D., Strbac, G. (2000)]. The major contribution comes from cogeneration plants which are not despatched and small scale hydro units whilst wind is a significant contributor in Denmark and the Netherlands. Other countries which use renewables to a significant extend but are not listed in the table include Norway (99%), Sweden (28,5%), Finland (21,8%), and Portugal (15,7%). Wood, J. (2003) mentions that the UK targets to introduce 10 GW of combined heat and power plants by the year 2010.

Table 3.2: Extent of distributed generation

country	total of dispersed generation	system installed capacity	system maximum demand	% dispersed generation/ installed capacity
Australia	5224	42 437	29841	12.3
Belgium	1938	14893	11972	13.2
Denmark	3450	12150	6400	28
France	1753	114 500	68 900	2.5
Greece	43	9 859	6 705	0.4
Italy	3 708	70 641	43 774	5.2
Netherlands	5 280	18 981	12 000	28
Poland	500	33 400	23 500	15
Spain	4 000	50 311	27 251	8
UK	5977	68 340	56 965	8.7

The type and extend of distributed generation differs very significantly from country to country. Some countries have particular renewable energy resources in abundance e.g. wind power in Denmark whilst others have large chemical complexes with CHP schemes. The differences also arise due to the very different policy and administrative approaches adopted which then strongly influence if a particular technology becomes commercially attractive. In some countries, the distributed generation plant is under control and dispatched whilst in others it is not but the plants may be oblidged to inform the utility of their generation schedule a week in advance.

3.5 Direct Energy Converters

Direct energy converters convert solar, thermal, chemical, and nuclear energy into electrical energy without involving rotary or reciprocating mechanical prime movers. Some of the direct energy converters are not developed to a stage where they could be used for bulk power generation. Existing direct energy conversion systems which are finding application in distributed generation include:

- Fuel cells and batteries
- Photovoltaic cells and batteries

The most common way of generating bulk power is to use electromechanical energy converters.

3.6 Electromechanical Energy Producers

Electromechanical energy converters convert energy from mechanical into electrical energy using rotating prime movers. They come in two forms i.e. generators and motors. Generators convert energy from mechanical form into electrical form and modulates in response to an electrical signal whilst a motor performs the opposite. Electric machines in general are reversible and are capable of operating as generators as well as motors. There are three major classes of rotating electric machines: dc commutator, induction and synchronous machines.

The source of the mechanical energy is the prime mover which is directly coupled to a generator. Among the broad class of prime movers are thermal-, hydro-, wind and tidal driven prime movers. Thermal prime movers include steam turbines, gas turbines, gasoline engines and diesel engines. Hydraulic prime movers are used in hydro-electric and tidal power stations. There are three types of hydraulic turbines suitable for three different heads: Kaplan turbines are suitable for water heads up to 60 m; Francis turbines , for heads from 30 to 300 m, and Pelton wheels for heads between 90 m and 900 m. Kaplan and Francis turbines are reaction turbines whose blades travel at about the same velocity as the water flow whilst Pelton wheels are impulse turbines and the turbine blades reverse the direction of the water flow. Wind turbines can be horizontal-axis or vertical- axis turbines.

3.7 Various Technologies

3.7.1 Combined Heat and Power Technologies

Combined heat and power (CHP) is a very significant type of generation that can be connected to the distribution system. A CHP system supplies both heat and electrical power from the same fuel source. According to Jenkins N.(2000), industrial CHP schemes typically achieve a 35% reduction in primary energy use compared with electrical generation from central power stations and heat only boilers. Small CHP units can be used in remote, rural and farm areas either using back-pressure steam turbines fed from biomass in some cases or reciprocating engines powered by gas. The efficiency can be almost 70 %. Many of the CHP schemes installed in buildings in the leisure, hotel and health sectors have installed electrical capacities below 1MW and can be connected to the 11 kV distribution network.

Irish CHP Association (2006) report that,” Small Scale CHP schemes have tended to have a reciprocating engine as prime mover whereas the large schemes tend to be turbine-based. Recent developments in turbine technology have led to the introduction of ‘microturbines’ for small scale CHP systems.” A gas reciprocating engine is used as a prime mover to drive a generator to produce electricity. Heat energy is recovered from the exhaust stack and cooling jacket of the engine and the cooling jacket of the generator and through a series of heat exchangers, this heat is supplied to the consumer as either hot air or hot water. Some of this wasted heat may be used to supply an absorption refridgeration system thus producing a combined cooling, heat and power system.

Micro CHP systems on farms can operate on a variety of fuels including biogas or liquid biofuels. Most of the micro CHP systems require to be grid-connected in order to function properly. Micro CHP (mCHP) is a mass produced small scale CHP unit that is suitable for domestic and small business applications. mCHP units vary in size up to 100kWe and use a number of different technologies: internal combustion engines; external combustion engines; micro-turbines; and fuel cells (although these are still at the development and demonstration stage). The intermittent renewables like wind, or solar PV may be used together with micro CHP systems. Two good CHP technologies are stirling engines and fuel cells.

3.7.2 Fuel Cells

A fuel cell consists of two electrodes sandwiched around an electrolyte. Oxygen or air passes over one electrode and hydrogen over the other, generating electricity, water and heat. According to www.che.sc.edu (2006), the reactions at the electrodes of a Proton Exchange Membrane Fuel Cell (PEMFC) are as follows:

$$\text{Anode : } 2H_2 \rightarrow 4H^+ + 4e^- \tag{3.1}$$

$$\text{Cathode : } O_2 + 4H^+ + 4e^- \rightarrow 2H_2O \tag{3.2}$$

$$\text{Overall : } 2H_2 \rightarrow 2H_2O + energy \tag{3.3}$$

In the presence of a catalyst, hyrogen splits into a proton and an electron, which take different paths to the cathode. Power is produced electrochemically by passing a hydrogen-rich fuel over the anode. Fuel cells produce DC current.

Hydrogen fuel can come from many different hydrocarbon sources including methanol, ethanol, natural gas and even gasoline or diesel fuel. The breakdown of water molecules also produce hydrogen. Methane gas from landfills and wastewater treatment plants can also be used.

Fuel cell cogeneration units (200kW in size) have ben in use at utility power plants, hospitals, schools, office buildings, and even an airport terminal since the last decade. Fuel cells operate silently, reducing noise pollution as well as air pollution. Their ability to stand alone also makes fuel cells a wise choice for rural power, in places where there are no established power grids and in areas that are inaccessible by power lines. Currently, there is research and testing being done on a variety of sizes and types of fuel cells for power generation. A fuel cell unit could either be connected to an electric grid to provide supplementary power and backup assurance for critical areas, or installed as a grid-independent generator for on-site premium service. The waste heat from a fuel cell typically is used to provide hot water for heating purposes.” There are different types of fuel cells which include:

Phosphoric acid

Phosphoric acid fuel cells are now commercially available and are being installed in hospitals, office buildings, utility power plants and many others. Generally methane is used as the input fuel. They operate at about 200-300 degrees Celsius to produce 200 kW of electrical power plus 200kW of heat energy sometimes with overall efficiency as high as 80 %. Most of the steam generated is used for cogeneration. The investment costs are still very high for example, the stationary 200 kW PC25 phosphoric acid fuel cell system made by UTC costs $4,300 per kW. (Cameron, D.S. (2006))

Proton Exchange Membrane (PEM)

The proton exchange membrane is a thin plastic sheet that allows hydrogen ions to pass through it. The membrane is coated on both sides with highly distributed metal alloy particles (mostly platinum) that are catalysts. Proton exchange membranes operate at relatively low temperatures, have high densitiy and can vary their output quickly to meet shifts in power demand. They are suited for applications where quick start up is required such as in automobiles.

According to Cameron, D.S. (2006), the Japanese developed proton exchange membrane fuel cell systems for residential applications. One was installed in the Japanese Prime Minister's official residence in April 2005. The units, built by Matsushita Electric Industrial Co. Ltd. and Ebara Ballard Corporation, consist of a 1 kW reformer/fuel cell unit and a hot water unit. The device is grid connected, with an inverter to provide AC mains power for the consumer. A 200 litre storage tank provides hot water for domestic use. Over 400 units have been built this year; 175 were installed in the first 6 months. It is planned to build up to 10,000 units by 2008, and tens of thousands of units after 2010. Ultimately, the Japanese market is seen as up to 1.5 million units per year at prices of less than $10,000 each.

According to Adamson K., Crawley G., Jollie D.,(2006), the fuel cell market in general is dominated by these PEM fuel cells.

Molten Carbonate

Molten carbonate fuel cells operate at very high temperatures and use either hydrogen, carbon monoxide, natural gas, propane, landfill gas, marine diesel and simulated coal gasification products.

Solid Oxide

Solid oxide fuel cells have found application in big, high-powered applications such as industrial and large-scale central electricity generating stations.

Alkaline

Alkaline potassium hydroxide is used as the electrolyte. Efficiencies up to 70 percent have been achieved though the costs are prohibitive for commercial applications. The main application has been in space missions.

Direct Methanol Fuel Cells

A polymer membrane is used as the electrolyte and the anode catalyst draws the hydrogen from the liquid methanol, eliminating the need for a fuel reformer. At temperatures between 120-190 degrees F efficiencies around 40 % are achieved.

Regenerative Fuel cells

This fuel cell is still under research. Water is separated into hydrogen and oxygen by a solar-powered electrolyser. The hydrogen and oxygen are fed into the fuel cell which generates electricity, heat and water. The water is then recirculated back to the solar-powered electrolyser and the process begins again.

In conclusion, Cameron D.S., (2006) reports that fuel cell costs need to be reduced to a target of around US $30 per kW, compared to a current estimated cost of US$110 per kW, when a production rate of 500,000 units per year is assumed. The barriers to achieving wide scale deployment of fuel cells are not necessarily technical hurdles but could be codes and standards, the investment required for a hydrogen generation and distribution network, and educating the public.

With regard to efficiency, small fuel cells can be up to 50% efficient. In comparison, present microturbines in the 30 kw range are only about 25% efficient. When heat exchanging is employed, future ceramic microturbines in this size may achieve 35% efficiency.

3.7.3 Solar Photovoltaic and Solar Thermal Cells

Solar energy systems have found application in heating, cooling, ventilation and daylighting of buildings. Savings in energy and power (thermal and electric), as well as maintanance of good indoor comfort levels has been achieved. Warmth within a building is normally lost through ventilation, transmission and infiltration through the building envelope. These losses are partly offset by solar gains through glazing and by usable internal gains from occupants, lights and appliances. To reduce the total energy consumption of buildings, designers of the future need to look at a wide range of solar technologies.

Current solar energy system types can be structured in groups according to their use and technical characteristics.Solar energy technologies for building integration can be electrical, thermal or daylight. Solar cells produce DC current.

Photovoltaics integrated into the fabric of houses are expected to become economically attractive in the future. Thin films are emerging as the future choice for solar cells because the manufacturers can use very thin layers of near-optimum materials. Elliot, T.C., Chen, K., Swanekamp, R.C. (1998) report that although silicon is currently the most popular choice for solar cell materials, this indirect-gap material does not have an optimum bandgap. However, Fell, N. (2003) state that polycrystalline silicon is likely to dominate the solar cell market for at least the next decade because the other technologies in the pipeline have not yet reached the 15% conversion efficiencies of polycrystalline cells. An important parameter for PV cells, modules and systems is efficiency which is the ratio of the output power to the input power. Typical PV cells produce 1000 W/m^2. Thin film solar cells require a silicon layer of only 2 microns which is far less compared to 250 microns or more which is used in conventional cells. Thin film cells can be made from other materials such as cadmium telluride or indium diselenide. However, these compounds have environmental impacts whereas silicon is benign. A big advantage of solar cells is that there are no moving parts , therefore the need for maintenance is minimal during their guaranteed life span of about 25 years.

The quality of power provided by the PV system for on-site ac loads and for delivery to the interconnected utility is governed by practices and standards addressing voltage , flicker, frequency and distortion. IEEE STD 929 (2000) gives guidance regarding equipment and functions necessary to ensure compatible operation of photovoltaic (PV) systems that are connected in parallel with the electric utility. The factors given relate to personnel safety, equipment protection, power quality and utility system operation.

James A.(2004) mentions a project which the Woking Borough Council implemented of installing 14 off grid photovoltaic pay and display machines in Woking Town centre in 1997. This project demonstrated that off-grid photovoltaics was more economical both in capital and running cost terms than conventional grid connected machines because of the high cost of grid connection and the tender for supply and installation. He argues for a mixed technology local private wire distribution system that is backed up by other local larger scale energy systems instead of connecting to a grid where there is centralised power generation. The current regulatory regime for exempt generators and supplies should be changed to allow more customers to benefit from private wire systems.

Solar thermal

Solar thermal technologies use the sun's heat to create steam to drive an electric generator. The parabolic trough, parabolic dish and central receiver systems are three main types of solar thermal systems. Parabolic trough systems concentrate the sun's energy through long rectangular, mirrors which are curved like a U-shape. A pipe which contains flowing oil runs down the center of the trough. The mirrors are tilted toward the sun and they focus sunlight onto the pipe in the center. The focussed sunlight then heats the oil in the pipe which in turn boils water in a conventional steam generator to produce electricity. A parabolic dish system uses a mirrored dish similar to a very large satellite dish. The surface of this dish collects and concentrates the sun's heat onto a receiver. Heat is then absorbed and transferred by the receiver to a fluid within the engine. The fluid then expands against a piston or turbine to produce mechanical power which in turn, is used to run a generator or alternator to produce electricity.

A central receiver or power tower system uses a large field of mirrors to concentrate sunlight onto the top of a tower, where a receiver sits. Salt flowing through the receiver is then heated and its heat is used to generate electricity through a conventional steam generator. Molten salt retains heat efficiently, so it can be stored for days. That means electricity can be produced on cloudy days or even several hours after sunset.

3.7.4 Biomass

Biomass is a widespread and versatile renewable energy resource, that can be used just as easily for heating as for electricity. It can also be used to produce liquid fuels, gaseous fuels and a variety of useful chemicals.

Source of biomass

It comprises of organic matter from wood, agricultural residues and dedicated energy crops like switchgrass, willow, poplar and eucalyptus trees. Forest management and wood producing industries like paper mills, sawmills and furniture manufacturers generate large volumes of wood residues. Some wood waste also comes from tree trimmings, wood packing, construction and demolition.

Biomass can be converted biologically or thermochemically. Biological processes are bacterial activities at lower temperatures e.g biogas production from agricultural wastes, landfill gas from municipality sewage waste and fermentation to ethanol. Methane(CH_4) and carbon dioxide (CO_2) are produced in the process depending on the conditions. Biofuels emit between 40 and 80 % less greenhouse gases than other fossil fuels. They also give less particulate and less carbon monoxide and hydride. However, the energy in biomass is less concentrated than the energy in fossil fuels. Biofuels can be divided into biodiesels (mainly from organic oils and sunflower, e.t.c.) and alcohols coming from beetroot, wheat, sorghum e.t.c.

Biomass technologies

The most commonly used thermochemical processes are pyrolysis, gasification and combustion. In a pyrolysis process, the biomass is heated in inert conditions. Through gasification processes biomass can be used in gas turbines and consequently in combined cycle (gas and steam) plants and stirling engines.

There are four primary classes of BioPower systems:

a) Direct fired

The biomass fuel is burned in a boiler to produce high pressure steam. The steam will flow over a series of aerodynamic turbine blades causing a steam turbine to rotate. The turbine is connected to an electric generator which turns to produce electricity. These plants are less efficient than coal-fired plants because of their smaller capacity.

b) Co-firing

When biomass is mixed with a portion of coal, there are less gaseous and air emissions. The energy in biomass will be converted to electricity with the higher efficiency (33 - 37%) range of a modern coal-fired power plant.

c) Biomass gasifiers

Biomass is heated in an environment where the solid biomass breaks down to form a flammable gas. This offers advantages over directly burning the biomass. The biogas can be cleaned up and filtered to remove problem chemical compounds.

Gasification systems will be coupled with fuel cell systems for future applications. The gas can be used in more efficient power generation systems called combined-cycles, which combine gas turbines and steam turbines to produce electricity. The efficiency of these systems can reach 60%.

d) Modular Systems

These systems employ the same technologies mentioned above but on a smaller scale that is more applicable to villages, farms and small industry.

Burr R.(2004) highlights how energy crops like Short Rotation Coppice (SRC) and Miscanthus offer farmers a means of improving their current income and diversifying their production base in order to sustain their businesses. He mentions a Roves Energy project called the Green Energy Centre in Swindon Wiltshire where 5000 hectares of SRC will be required to produce 2 MW of renewable electricity and 4MW of renewable heat (as steam). The remainder of the wood will be dried and sold for other industrial, commercial and domestic applications.

3.7.5 Wind Power

Kinetic energy of blowing air (wind) is converted to electrical energy by turning a turbine which is connected to a rotor. The power developed by a wind turbine depends on the air velocity and density and also on the area swept by the turbine blades.

The rate of operation of a wind turbine depends upon the wind speed. When the wind speed doubles, the power delivered is eight times as great. Most wind generators are designed to deliver maximum power at a wind speed of 48 km/h. At

24 km/h, they will deliver about 1/8 their rated power. A wind generator should be mounted at least 6 meters higher than any obstruction within 90 meters to avoid turbulence. Wind is an intermittent and variable source of energy. Wind speed varies with many factors and is random in magnitude and direction.

Two major class of wind turbines are the horizontal-axis and the vertical axis turbine. The vertical axis turbine is a high speed machine. In a horizontal-axis turbine, each blade section experiences a constant angle of attack during one revolution , under steady-state conditions.On the other hand, in a vertical-axis turbine, the angle of attack experienced by each blade section varies continously through one revolution.

Power is transmitted from the wind turbines to the generators by gearboxes, belts and pulleys, roller chains, or by hydraulic transmissions. Differences designs include (i) fixed-or variable speed operation, (ii) direct drive generators or the use of a gear box and (iii) stall or pitch regulation. Direct drives are used on very small machines. Figure 3.2 below gives a schematic diagram of a wind conversion system.

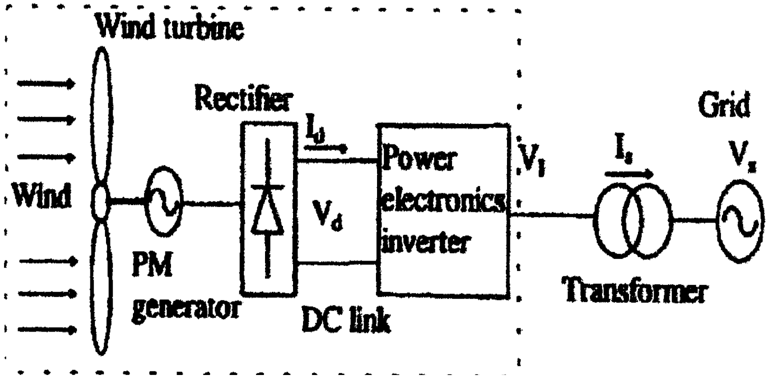

Figure 3.2: Wind conversion system

Fixed-speed wind turbines using induction generators are simpler and usually more robust. It is not usual to use synchronous generators on network-connected fixed-speed wind turbines as it is not practicable to include adequate damping in a synchronous generator rotor to control the periodic torque fluctuations of the aerodynamic rotor.

3.7.6 Small -Scale Hydro-generation

Micro-hydroelectric projects are those that generate less than one megawatt of power. Hydro-electric power stations capture the energy in flowing water to produce electricity. A hydraulic turbine is a rotating machine driven by water under pressure from a penstock or forebay. The energy in the flowing water is converted to mechanical energy by a revolving wheel fitted with blades, buckets, or vanes. The flow is directed at the wheel by a nozzle or an injector allowing the flow to be adapted to the mechanical power required by the electrical equipment being driven. Electric generators are more efficient when they run at high speeds. If a turbine rotates at a low speed, "step-up" gearing can be installed between the turbine and the power generator to increase the rotation speed.

Many developing countries are actively pursuing some form of small or micro hydropower development. Micro hydro plants find application in agricultural processing machinery, small workshops, and the supply of power for essential public services.

The amount of power available depends on the dynamic head, the amount of water flow and the efficiency of the turbine/generator combination. The combined efficiency of the turbine and generator ranges from 40% to 80%, with higher efficiency at higher heads and for larger generators. Small scale hydro-schemes may use induction or synchronous generators. According to NVE (2005) small scale hydropower production units can be divided into the following categories:

Micropower installation, less than 100 kW

Minipower installation, 100 kW - 1000 kW

Smallpower installation, 1000 kW - 10 000 kW

3.7.7 Geothermal Energy

Geothermal heat pumps use energy of rocks deep in the earth’s crust at a depth of around 50m. The geothermal heat pump accomplishes its heating and cooling tasks by obtaining heat through a connection to the earth known as an earth loop or ground loop. The ground loop consists of a piping system circulating a water/ antifreeze mixture from the earth to the geothermal heat pump and back. Most loops for residential geoexchange systems are installed either horizontally or vertically in the ground as shown on Figure 3.3, or submerged in water in a pond or lake. It is a good source of providing heating and cooling for both domestic and commercial buildings.

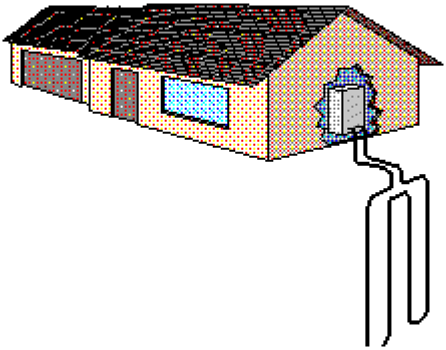

Figure 3.3: Vertical ground closed loop (Geoexchange (2003))

Ground source heat pumps provide a new and clean way of heating buildings. They make use of renewable energy stored in the ground, providing one of the most energy-efficient ways of heating buildings. According to National Energy Foundation (2006), they do not require hot rocks (geothermal energy) and can be installed using a borehole or shallow trenches or, less commonly, by extracting heat from a pond or lake. Heat collecting pipes in a closed loop, containing water (with a little antifreeze) are used to extract this stored energy, which can then be used to provide space heating and domestic hot water. In some applications, the pump can be reversed in summer to provide an element of cooling. Ground source heat pump (GSHP) systems use a heat pump to exchange heat with the earth which remains at a relatively constant temperature and are a very practical way to employ geothermal energy. Several versions of Ground Source Heat Pumps have evolved for both residential and commercial applications. According to Polson Enterprises (2006). Ground Source Heat Pump (GSHP) systems were/are sometimes referred to as Earth-Coupled Heat Pumps, Earth-Coupled Water Source Heat Pumps, Geothermal Heat Pumps, Earth Exchange Systems (EES) or Geo-Exchange systems

According to CADDET (2004), the potential of geothermal energy from suitable European sites is estimated to be about 110 000 MW of electricity-similar to the total electrical capacity currently installed in France. A 6MW pilot project is under construction in France to demonstrate the viability and cost effectiveness of this technology.

3.7.8 Tidal Energy

There is abundant power in the sea, both in deep water and on the coastline which remains untapped. The energy content is very variable in quantity, quality and with time of year, month and day. Tidal energy technology is based on a combination of established wind turbine, off-shore and water power technologies. In

Norway a prototype at Kvalsundet in Hammerfest, weighs 187 tonnes and is located 50 metres (m) below the surface. The prototype was successfully installed in 2003 and connected to the grid and produces 240 kW power output.

The tidal water plant has a 10 m nacelle with turbine blades that have a wingspan of 20 m. The whole unit projects 31 m above the sea bed. The turbine that transforms ocean energy to electricity has an installed capacity of 300 kW, but the system has not yet exceeded 240 kW. Electricity production is around 0.7 GWh/ year. The Hammerfest municipality has 1,088 inhabitants, who use around 21 GWh of electricity/year.

3.8 Challenges of Distributed Generation

Innovation is needed in using distributed generation to raise the quality of supply, to increase and not constrain network flexibility, to incentivise distribution network operators to see distributed generation as an opportunity, to achieve network investment, recognize and reward distributed generation network services and to avoid regulatory micro-level intervention.

Seven issues which Wood, J.(2003) highlights which must be addressed in setting new technical standards for distributed generation include:

- Network management and monitoring
- Power quality- maintaining voltage and frequency at acceptable standards
- Fault levels
- Protection- both of the network and the generator.
- Synchronisation-systems are required to connect small power systems in phase with the network. They must be low cost while meeting systems standards.
- Safety-if current is flowing both ways engineers working on the network must be protected, and circuit isolation must be addressed.
- Installation and commissioning- installing microgeneration is more complex than domestic heating. A new qualification will be required to ensure the installer is competent in the technology not just an ordinary engineer or qualified technician.

Prabhu E. and Michel D. (2005) explain how California is improving the interconnection of distributed generation systems by simplifying the approval of applications to interconnect and their field studies show that on the sites with DG units that were monitored, there was no adverse impact on the distribution systems to which these units were connected.

In their report to the European Commission, Skytte K.and Ropenus S.(2005) identified two solutions to the barriers in distributed generation as : firstly, the move from deep connection charges to shallow charging policies and secondly, the reformulation of the Distribution Use of System pricing methodology to allow the financial recognition of DG contribution on the network costs. They mention that the lack of incentives for the distribution system operator, connection charges and access to balancing are the main barriers to distributed generation. These coupled with the new risk uncertainty regarding system reliability, security and network planning means that explicit incentive mechanisms to integrate DG in distributed networks should be designed.

3.8.1 Microgrids

A new type of power system that has emerged in the last few years is the Microgrid. In a microgrid, small modular generation is interconnected to low voltage distribution systems. According to Hatziargyriou N., Strbac G. (2004), microgrids can be connected to the main power network or be operated autonomously, similar to power systems of physical islands.

The power gateway controller designed in this thesis shares some functionalities with the Microgrid Central Controller that is being developed at NTUA in Greece. The MGCC controls the market operation and system operation in order to keep the overhead cost of operating the microgrids low. The common functionalities are energy management with controllable generators as well as controllable loads. According to Arulampalam, A., Barnes M, Fitzer C, Wu X, and Jenkins N (2005), a working unified complete microgrid control had not been demonstrated. The main difference is that the the MGCC is installed at a MV/LV substation, whilst the power gateway controller in this thesis is a customer interface unit that is located at a customer site in a network where there is decentralised control.

Siddiqui S. A, Marnay C., Bailey O., LaCommare H. K. (2005) describe another relevant work that has been carried out in an optimisation model, the Distributed Energy Resources Customer Adoption Model (DER-CAM), developed at Berkely Laboratory. This identifies the energy bill minimising combination of on-site generation and heat recovery equipment for a naval base building given its electricity and heat requirements, the tariffs they face, and a menu of available equipment.

Bendel C., Nestle D. (2005) also describe another relevant work, which is a bidirectional energy management interface as a point of common coupling between a grid operator and an operator of a generator. Other interesting relevant works have been carried out and described by Hatziargyriou N., Dimeas A., Tsikalakis A. (2005) and Lopes P. J. A., Moreira C.L., Resende F.O.(2005). Kanellos F.D. et al (2005), mentions that technical challenges associated with the operation and control of microgrids are immense. Ensuring stable operation during network disturbances, maintaining stability and power quality in the islanding mode of operation requires the development of sophisticated control strategies for microgrid's inverters in order to provide stable frequency and voltage in the presence of arbitrarily varying loads.

3.9 Comments on various technologies

Wind , water and sunshine are intermittent energy sources. The electricity produced from these sources very much depends on the weather. There is a need to store energy from these sources so that the excess power generated in good weather conditions is not wasted.

Most of the very small generators, which are sometimes referred to as microsources, are not suitable for a direct connection to the distribution network because of the characteristics of the electric power produced in such units. Usually, a DC/AC or an AC/DC/AC power electronic interface would be required with the ability to control the output frequency and voltage. Solar cells and fuel cells need a DC/AC converter in order to supply on-site AC loads and also in order to sell power to the distribution network.

3.10 Energy Storage

Fluctuations in the supply and demand of electricity can be balanced using energy storage. An energy storage device can have a number of applications on a power network. The applications include load levelling, peak generation, ramping or load following, frequency control, e.t.c. Power generating systems use various facilities for storing energy which include storage batteries, pumped storage, superconducting coils, hydrogen gas, compressed air, heat and inertial storage e.g. flywheels.

Superconducting coils are too expensive for large-scale use. There are a number of flywheel systems in commercial development but their use is mainly small scale for power quality and uninterruptible power supplies. Pumped hydro and compressed air are usually geographically constrained. Batteries have a number of advantages in terms of their response time, ramp rate and ease of siting. However, at the larger utility scale, high power output and long discharge time is necessary if it to be useful on a power network. Flow batteries also known as regenerative fuel cells are an ideal candidate technology.

Most secondary (or reversible) batteries use electrodes both as part of the electron transfer process and to store the products of reactants via electrode solid state reactions. The shape and size of the electrodes fix both the energy storage capacity and the power rating. The lead acid battery is the most well known example of this type. Flow cells such as those based on zinc bromine, avoid restrictions in energy capacity by storing electrolyte in separate tanks outside the cell. However, the energy capacity is still limited by the mass of zinc that can physically be plated onto a carbon electrode.

A regenerative fuel cell plant stores or releases electrical energy by means of a reversible electrochemical reaction between two salt solutions (the electrolytes)

Pumped storage consists of an upper and lower reservoir and turbine generators which can be used as motor-pumps. The upper resevoir has sufficient storage usually for 4-6 hours of full load generation, with a reserve of 1-2 hours. During times of peak load on the network, the turbines are driven by water from the upper reservoir. The generators then change to synchronous motor action and, being supplied from the general power network, drive the turbine which is now acting as a pump. During the night, when only base load stations are in operation and electricity is being produced at its cheapest, the water in the reservoir is pumped back into the higher one ready for the next day's peak load. The average efficiency is 67 percent. Synchronous machines can be used as synchronous compensators.

According to Korpås (2004) the efficiencies of some of the energy storage options are:

Pumped hydro65-75%

Compressed air65-75%

Secondary batteries70-90%

Redox flow cells65-75%

Hydrogen 30-70%

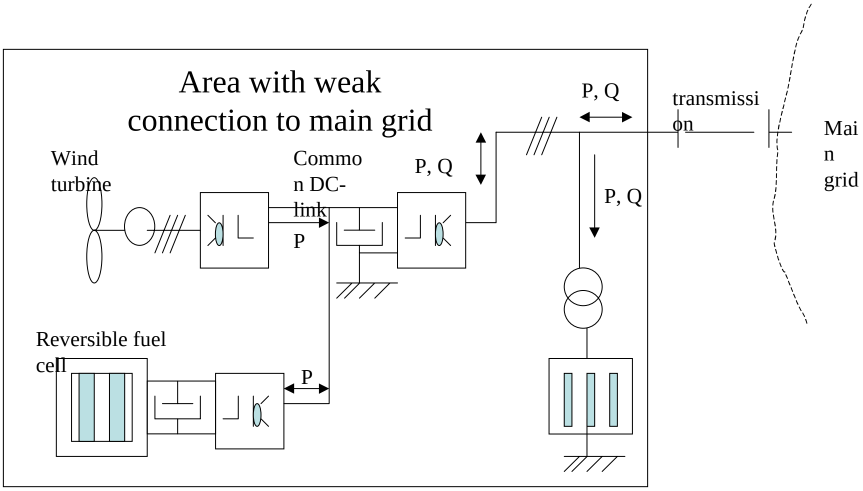

Figure 3.4: Wind-hydrogen system with integration through a common DC-link. P is active power whilst Q is reactive power. Korpås(2004).

Korpås, M.(2004) presents a simulation model of a general wind hydrogen energy system. This model can be used to evaluate how hydrogen storage can increase the penetration of wind power in areas with limited or no transmission capacity to the main grid.

3.11 Summary

Apart from power generation, alternative fuels and technologies are also examined in other sectors which include: steam generation by industrial boilers and CHP plants, space heating in households and in private cars. For renewable sources of energy to take off, financial or fiscal incentives are needed. Attention needs to be focussed on generating financial aid for renewable sources of energy because in the long run, very positive results will be achieved in terms of diversification of energy supplies.

The new renewable energy technology is still in its infancy. However, public support for research has led to significant progress over the last few years. Wind energy is now widely recognised as a viable option. Photovoltaic energy is quite promising although it is still far from being economically competitive. Household waste is constantly growing and provides a significant energy opportunity as well as by products from timber and agri-foods industries. Hydrogen is a very promising energy carrier for the future and it can derive its energy from renewable fuels such as biomass, biogas, solar, wind and hydro(via elctrolysers). Fuel cells and-hydrogen can go a long way to meet electricity needs, thermal needs and transport needs of local communities.

The opening up of electricity markets has led to reduced investments in large expensive elecrticity generating units thereby resulting in net importation of electricity in some areas. Because the prices are sensitive to the demand for electricity, the result has been very high prices during the peak periods of peak seasons to the extend that some private companies are affected drastically in their business operations. This instability of the electricity prices, coupled with the world drive to conserve the environment has resulted in increased interests in private ownership of small scale renewable energy technologies. The shortages in electricity supply also leads to the opening up of the markets at retail level to allow small producers to enter the market and also sell to the network.

Implementation of renewable energy technologies on farms and rural areas will help these communities to become less dependent on energy imports yielding commercial returns in terms of growth of small and medium scale enterprises. Jobs will be created and people can be retained as the new businesses generate more income for these communities.

In this work we envisage a situation where a power producer is also a consumer so that when the market prices are high the customer can produce electricity locally and sell to the network. When the local energy needs are high, the customer can buy electricity from the network.

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Chapter 4

Background of the Power Gateway Controller

An outline of the background of the work carried out and motivation for the study is introduced in this chapter. The evolution in electricity distribution networks has led to problems which need to be addressed. New opportunities emerge as solutions to these problems are sought.

4.1 Electricity Production Systems in Norway and Zimbabwe

According to Nesheim, S.J., (2005), electricity was introduced in Norway in 1880, initially in factories and later for lighting of public and private buildings. When electricity first came to Norway, it was mainly private companies that built their own production facilities and the grids were developed locally. In 1891, the first municipally-owned electricity plant started operating in Hammerfest, in the northern part of Norway and its capacity was 50kW. In Bergen electricity production started in 1900 based on steam, with a production capacity of 725 kW and in Haugesand there was a two-unit waterfall-driven plant with a total capacity of 400 kW from 1909.

Generation and distribution was a monopoly business in various communities. As the market for electricity increased, these private companies expanded their electricity production to sell to nearby communities. The need for safety , reliability and security of energy supply also became driving forces to join the separate entities into larger networks. If a failure occured in one unit, it became easier to isolate the fault and supply the area using other feeders from neighbouring production units. A move from separation to cooperation evolved. As the years progressed the networks continued expanding to allow export and import of electricity even between neighbouring countries, when conditions allowed. In hydrobased electricity production, export and import in a region was based on bilateral agreements, and used only during the periods when there was lack of water, in certain areas covered by the grid.

The production units and the local networks were managed within a community. This means that all over the country there were several hundred participants. Some of them were very large companies with a lot of small contributors. Due to the fact that Norway had a widely distributed population, a lot of local producers and networks evolved. For example, a single farm with its own waterfall could produce enough elecricity for its own consumption and even develop a local industry like a sawmill. As time went on, the large network owners increased their network and the authorities demanded that the very small contributors stop their production. Average sized producers were expanded into city or country based companies, and all new developments needed a concession from the governmental authorities.

The after effects of the deregulation of the electricity market, and the continuous growth of demand, have resulted in net importation of electricity and instability in electricity prices especially during peak seasons. The sensitivity of the electricity prices to the market demand, coupled with the world drive to conserve the environment has resulted in increased interests in private ownership of small scale renewable energy technologies. The shortages in power supply has now led to the opening up of the markets at retail level to allow small producers again to enter the market and also sell to the network.

In comparison, the trend observed in the evolution of electricity markets in Zimbabwe is not too different. Initially local municipalities operated the local distribution networks together with water and waste removal services. These municipalities had electricity departments which were independent power generators.

In 1986 an amalgamation of the municipal electricity departments of the cities Harare, Bulawayo, Gweru and Mutare, and the Electricity Supply Commission (ESC) as well as the Central African Power Corporation (CAPC), took place and a new parastatal ZESA was formed. The network then became bigger and control was centralized.

The annual electricity consumption in Zimbabwe is around 10 000 GWh. Only 35% of the two million households are electrified. Most of the households in rural areas are not connected to the electricity network. Following the completion of the land reform programme, farming areas are likely to demand and consume more power in future since some people will move from rural areas to the subdivided farms. As at the end of April 2003, the demand for power had shot up from 4 900 to 10 000 applicants.

The recent difficulties of failure to pay back loans for large projects, has led to the privatization of ZESA so that future generation projects will be run by smaller independent power producers. It is hoped that the smaller private owners will be better placed to manage the properties more efficiently and pay back the loans.

4.1.1 Challenges in Distribution Networks

Problems in distribution networks can be the same although the causes are different. For example, on one hand, the economy in Norway has generally been improving since the 1970's and people in the major cities have been building bigger houses. The residential energy demand has greatly increased mainly because of the increased space heating. The rapid growth in disposable income also allowed many Norwergians to improve their standard of living by buying more electrical appliances. These appliances demand electrical power. As a result two problems emerge on the distribution network, i.e. a much higher peak demand on the domestic load profile and an increased burden on the already installed equipment like cables, circuit-breakers, transformers, etc.

According to Ettestøl (2003), in 1973 only 42% of the homes in Norway were heated with electricity and this percentage had grown to 65% by 1998. On average 80% of residential energy use in Norway is accounted to electrical space heating. Many families use at least 15 000 kWh of electricity per year to heat their homes. However, because there has been intense utilisation of the installed capacity and the reserve margin has greatly declined, energy efficiency programmes have been introduced.

On the other hand, the electricity consumption in Zimbabwe has been greatly affected by the migration of people from rural areas to cities like Harare and nearby farming areas. Although others have migrated abroad or returned to the rural areas, the growth trend remains upwards in the urban areas, where there is electricity. Accordingly, more domestic appliances are continuously added to the distribution network in the cities.

In the light of the above, the utility has to invest in new cables and other distribution equipment, in addition to demands for increased generation. However, Mangwengwende (2003) reports that the country's reduced capacity to generate foreign currency, has led to the utility's initiation of energy saving programs to address some of the problems discussed above. Load shedding and tariff-based energy rationing programmes were introduced.

Efficient load management tools are necessary in competitive electricity markets. It can be very expensive for a utility to always meet the demand at peak load. Utilities who employ tools to reduce the demand during peak hours are able to offer more competitive prices to the customers than those who do not. Orasch, Auer, Haas and Huber (1998) present two possible dynamic tariffs that could be employed to manage their loads. These are *time of use tariffs* and *real time pric-*

ing. These pricing schemes are also attractive to customers because flexible electricity rates offer them an opportunity to reduce their electricity bill. These tariffs necessitate use of electronic meters and gateways instead of the conventional Ferrari's meters. Scweppe C. (2000) explains how a spot price based energy marketplace has many benefits, both for the electric utility, and its customers. These benefits include improvements in operating efficiency, reductions in needed capital investments, and customer options on the type (reliability) of electricity to be bought. The existence of spot price based energy marketplace stimulates the development of new microelectronic revolution in communication and computation.

4.2 Statement of the Research Problem

4.2.1 Objectives and Scope of the Work

The aim of this study was to design and simulate a power gateway controller which optimises electricity costs at a customers site, where there is a possibility to generate electricity locally and sell to the distribution network.

One major factor that affects the design of a power gateway controller is the market structure in which the power gateway controller will be used. The dynamics of market structures were discussed in the second chapter. The changes in electricity market structures affect the power gateway controller design process. Regulating bodies, e.g. relevant government ministries and standards bodies usually produce guidelines on how to calculate and design network tariffs and technical devices as Livik K. and Knain M. (1996) report. The regulations in the electricity act, the systems in place for information dissemination and data collection aggregation mechanisms also influence the functionalities that can be built into the power gateway controller.

This work focuses on the design and simulation of a power gateway controller for interconnecting small-scale energy producers to the distribution network. The design of a customer power gateway controller involves many stages. The initial stages involve feasibility studies and drawing of specifications. An investigation of the available possibilities and constraints is also necessary.

This chapter gives definition, justification, scope and limitation of the research work in addition to an outline of important interconnection aspects.

Figure 4.1 shows an example of a typical scenario where a customer can be enabled to produce electricity locally by getting two way connection in power flow and communication to the distribution network.

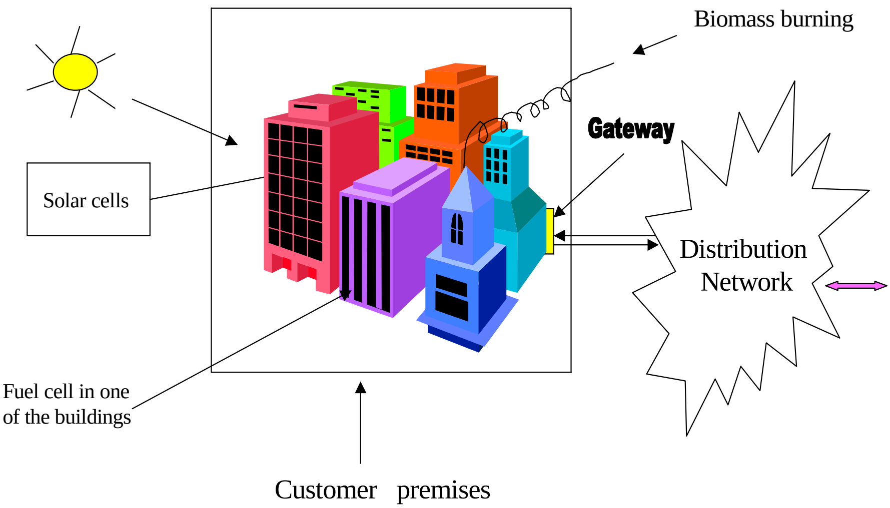

Figure 4.1: Customer scenario

4.2.2 Justification and Validity of the Work

Such a power gateway controller can be used to handle the following scenario problems which include but is not limited to:

a) A customer who is connected to the distribution network, who has the capability to produce electricity locally and is interested in selling any excess to the network.

b) A distribution network that has congestion problems and the utility wants to manage the electricity demand of the connected customers.

c) A government that is concerned about the environment and is interested in keeping the pollution levels low by encouraging the use of renewable energy technologies.

Installing a power gateway controller at a customer site also enables the customer to automate his or her building.

4.2.3 Limitations

This study has been limited to those connected consumers who have their own private electricity production units (less than 10 MW in size), and would be interested to generate more and sell to the distribution network when it is economical to do so. Such systems would not be centrally planned or dispatched by the utility.

4.3 Producer-Consumer Scenarios

From the perspective that in future, both the societies in Norway and Zimbabwe will have increased demand for energy whilst different factors prevent large scale production projects to evolve, three producer-consumer scenarios can be envisioned.

4.3.1 Scenario 1: Buyer Only

In this scenario, the consumer will always buy from the network to cover his electrical loads. This customer might not have any local generation of electricity or the locally installed unit might be so small that it is not worthwhile connecting it to the network or the mechanism to connect and sell any excess generation might not be in place for this customer. This situation can be described by the inequality:

$$P_i \gg P_g, \quad \forall t$$

where P_i is the imported power from the network, P_g is the power that is generated locally which is most probably zero in this scenario and $\forall t$ is all the time. Currently, most residential customers fall into this category.

4.3.2 Scenario 2: Seller Only

This customer will always sell to the network because the locally installed unit is much larger than the customer's power requirements. The locally generated units are connected to the network and the mechanism to sell is in place. This customer acts as an independent power producer who always has excess electricity to sell.

$$P_l \ll P_g, \quad \forall t$$

where P_l is the customer load requirement, while P_g and $\forall t$ are as previously defined.

4.3.3 Scenario 3: Buyer and Seller

This scenario covers the customer who sometimes buys from the network and at other times sells to the network. This type of customer has the opportunity to optimize their operations depending on the price signals. This is the scenario that is of interest in this work. Sometimes $P_l < P_g$ when the load is less than the generation and there is excess locally generated electricity to sell to the market. If the market prices are attractive, it may also be economical to generate more electricity locally and sell to the market. At other times $P_l > P_g$ for example when it is peak period and the customer needs a lot of power then the customer has to buy from the network in order to satisfy the local load requirements. When the selling prices on the market are not so attractive and the network is offering very low electricity prices then it is better to buy more power from the network to cover most of the local load requirements than to generate at a higher cost.

The three possible scenario's described above are summarized in Figure 4.2.

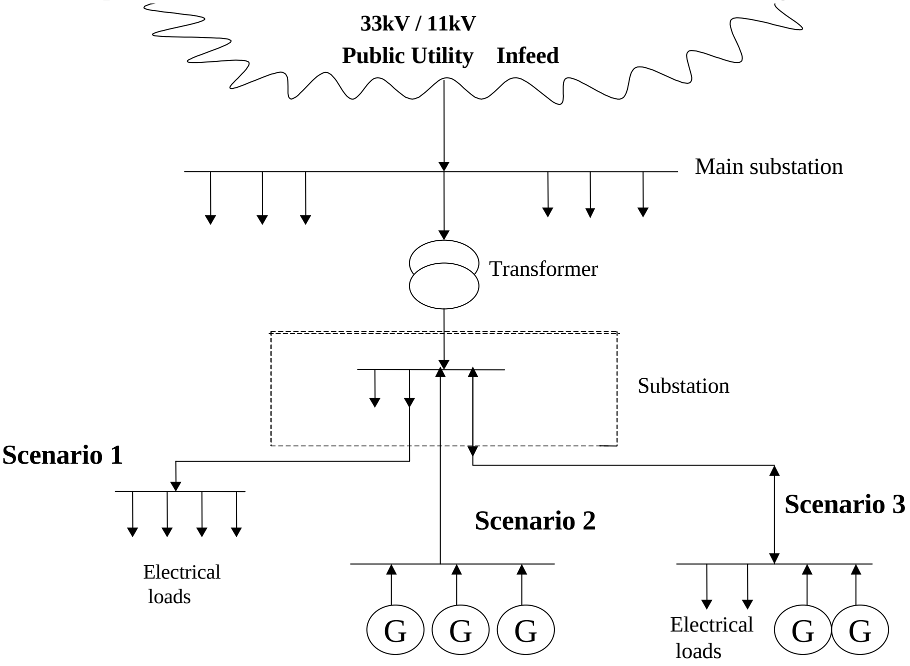

Figure 4.2: Three scenarios

4.3.4 Discussion

Most consumers are not able to invest in large production units that completely meet their power requirements, it is generally desirable to remain connected to the network and only use the local production units when it is optimal to do so. It is also desirable that they remain connected to the network in order to obtain reliability of supply and stability in local operation.

If scenario three is an economical and profitable solution for the future consumer, it can be a positive element in the total society's power production system. For a customer to actively participate in the market, they need to know the market prices of the electricity well in advance. This creates a need for regular communication between the utility and the customer. When the customer receives this information they also need to optimize their operations. A lot of time would be wasted and the costs would not be optimized if the customer was to manually control the locally installed unit. It would be a big advantage to introduce **a smart interface** between the network and the combined installation at the customer site of scenario 3. We choose to call this interface a **power gateway controller**. It would basically connect a customer to some existing networks and enable the customer to optimize the local electricity production.

4.4 Consumers in the Distribution Network

The traditional power system has large central generators feeding electrical power to a high voltage interconnected transmission network through step-up transformers. The transmission system then transports power over variable distances and the power is extracted through a series of step-down distribution transformers and delivered to consumers via the distribution network.

Some electricity consumers on the distribution network can have total loads which draw as much as 630 A at 400 V. Examples of such customers are farmers, residential complexes, commercial consumers, small scale miners and industries.

Table 4.1 categorizes voltage levels of a power system into three groups. The actual values of these levels vary from one country to another e.g. the high voltage network in Norway can be 300 kV or even 420 kV in some places (Stattnett 2005). The electricity consumers which are of interest in this study are those in Group 1 and 2 in Table 4.1. (partly from Jenkins, N. et al (2000).

Table 4.1: Voltage levels in power systems

Group		Definition	Typical voltages
1	Low voltage (LV)	Less than 1 kV	230/400 V
2	Medium voltage (MV)	1kV up to 50 kV	33 kV, 11 kV
3	High voltage (HV)	50 kV up to 420 kV	132 kV

Electricity can provide various end use services. Customers are usually put into categories depending on the nature of their business or day to day operations.

Residential tariffs are applied to customers who live either in individual houses, block apartments or high rise buildings. Commercial tariffs are charged to shopping malls, hotels and accomodation services and various office blocks. Industrial customers fall into two classes i.e. light and heavy industries.

4.4.1 Electricity Costs

Electricity consumption varies from customer to customer depending on the nature of the customer’s activities. For each customer the consumption also fluctuates in the various time zones e.g. in a day, a year or in a business cycle.

Important components of the electricity costs incurred by the customer are energy and transportation and for bigger customers, their maximum demand also. The transportation includes transmission, distribution and system operation costs. End-user services like metering and billing are also part of the electricity price. Many pricing methods have been developed:

- to enable sunk investment costs to be recovered,
- to provide efficient management of network congestion and operation,
- to provide adequate incentives for long-term investment i.e. long term efficiency and
- to promote fairness, simplicity and transparency.

Sometimes prices are charged through a multi-part tariff structure that may include fixed connection charges, demand and energy charges that depend on the time of use. Each part of the tariff can be determined separately for each consumer group of individual locations.

Electricity can also be traded as a commodity on the market where the utility determine the buying prices and the selling prices and customers respond to the changes in the price signals. For a customer to make the most of the market scenario's it is necessary to make a cost benefit analysis before installation of the plant. The plant here refers to the loads and locally installed generators. Efficiency, ease of use, operation and maintance characteristics need to be taken into account. Normally customers have to think about the capital costs, fuel costs, availability of fuel, life span of the production unit, noise generated and interference with their environment. Lootsma, F.A. (1999) outline some useful Multi-Criteria Decision Analysis methods that could be useful in helping customers refine their selection of which local production unit to install.

During the daytime and early evening, the total load on an electric power system is high because the industrial loads are high and people are awake and many lights and domestic loads are on. The loads get lower again later in the night and during early morning hours when most of the population is asleep. It is very expensive to leave production units running at full capacity all day long and all night long since the load is very variable during the day and night and throughout the week. It is necessary to run only enough units to cover the load. The operation costs of electricity production units can be large and it is attractive to apply mathematical programming to the production of electricity when there are more than one units running. In addition to this, the market prices also vary during the day and night.

In this study, we assume that our customers have already installed their loads and they have already carefully selected their generation units. After installation, some customers are concerned about optimizing their day to day operations in order to minimize the electricity expenses. If a power gateway controller that has some commmunication and energy management functions is installed at the customer site, significant savings on the electricity bill could be made.

4.5 Automated Information Exchange of Prices and Meter Readings

It is desirable to provide customers with necessary pricing information from the utility in good time. Such pricing information from the utility can be used to control the loads at the customer premises. The display of prices and time to tariff e.g. market prices or day and night rates or seasonal rates or any other accumulated tariff information is of great interest to customers who participate in the electricity markets.

The customers also need to submit their meter readings regularly. Two way communication between the customers and the utility is necessary and could lead to reduction in overall electricity costs in the long run. Dynamic pricing, meter rate switching and day/night or seasonal rate tariffing becomes possible and easier to implement. Remote meter reading and quick detection of electricity failure or meter tampering also becomes possible.

4.5.1 Flow of Information around the Power Gateway Controller

Figure 4.3 outlines possibilities for flow of information in and around the customer power gateway controller.

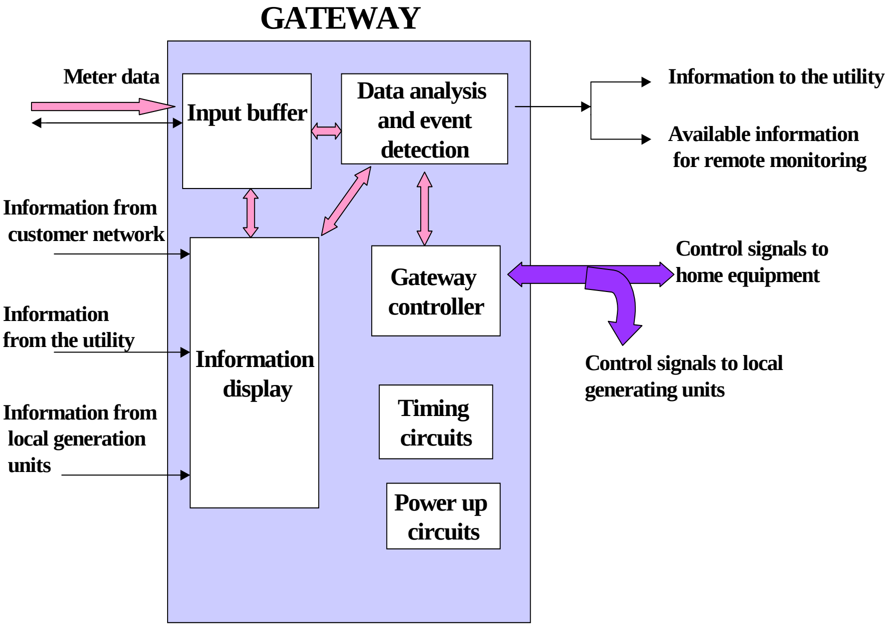

Figure 4.3: Power gateway controller connection

There must be communication between the power gateway controller and the local power meters. The data which is read from the power meters is used to make decisions in the power gateway controller. This data can be stored locally and periodically passed on to the utility for mass storage of data. The power gateway controller could be used to remotely monitor generation and load activities at the customer premises. Information can be received from the local utility and displayed at the customer site.

The output from the local generation units can be measured and the readings can be passed onto the local information display. A control algorithm within the power gateway controller can be used to calculate the control signals necessary to regulate the electrical loads and the generating units. During peak periods, loads can either be switched off or shifted to off-peak periods or generators can be switched. Lighting , cooking, garden irrigation water valves control and other process controls can be implemented locally by the customer depending on the pricing information.

4.5.2 Customer Services

Utilities can communicate more frequently with their customers using a customer network. Automated (remote) payment of bills becomes easier. Sometimes it is necessary for the utility to send short messages to the customers or to provide remote authorisation to pay the electricity bill. Quality of supply could be monitored and maximum demand limits can be set.

The utilities have the possibility to offer to their customers, extra services like safety and security systems, building or home energy management, home shopping, cable TV, other information and telecommunication services. Extra services that could be catered for include remote supply disconnection for nonpayment, itemised load monitoring, and account status monitoring. Fire alarms, water leakage detection, security VCR recording and intrusion detectors are specific examples of safety and security systems.

Remotely controlled thermostats or heating systems can be very convenient for setting the comfort levels in a building before occupying the building or if the control buttons are at a distance within the building. Appendix B gives an outline of communication technologies that could be used to connect customers on the distribution network to the utility.

4.6 Summary

In this chapter, the evolution of electricity distribution systems in Norway and Zimbabwe were discussed. The growth in electricity demand in Norwergian cities is caused by the booming economy whilst that of the Zimbabwean cities is mainly caused by the deteriorating economy. The deteriorating economy has resulted in some people moving from rural areas to the cities, thereby increasing the electricity consumption in the cities. This growth creates the same need, which is to increase and control the electricity supply. Both countries have experienced increases in electricity imports and instability in electricity prices especially during the peak periods. Energy saving programs have been started in both countries whilst the interest in small scale electricity production units has been revived.

This discussion led to the need to design a power gateway controller which enables customers who have small scale electricity production units to interconnect their units to the distribution network and participate in energy markets. Local production is coming back into the existing distribution systems. The main challenge is how to integrate these small scale producers into a system that was designed to function without them.

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Chapter 5

Power Gateway Controller Algorithm Development

The following factors that affect the optimization of electricity costs at the customer's site have been reviewed in the previous chapters: electricity markets and the dynamics of electricity prices and electrical loads, the potential of local power generation and the possible role of two-way communication between the customer and the local power distribution company. Now it is time to develop an appropriate algorithm that will be used in the optimization process.

The problem considered in this study has got constraints. For example the production units have minimum and maximum output production values and the available power supply must meet the load requirements. Various options for constrained minimization exist for example minimax, goal attainment, semi-infinite optimization and Sequential Quadratic Programming.

A case study is chosen as an example of the problem under study. Thereafter, a brief review of some of the available optimization methods is given to place the adopted optimization method in context.

5.1 Physical Definition of the Problem Under Study

The study considered the viability of connecting electricity production units on a farm to the distribution network in such a way that these criteria are satisfied:

(a) Optimise the electricity costs on the farm

(b) Make the investment of local installation of electricity generation units more worthwhile

(c) Assess the benefit to the grid, of making such a connection.

In order to place the solution in context, a dairy farm scenario from Zimbabwe was considered as a possible customer site. A typical farm would have about 500 cows on 10 hectares of land.

5.1.1 Electrical Loads and Generators on a Dairy Farm

The potential for local electricity generation and the use of electricity on a dairy farm was considered in the study. Electricity is important on a dairy farm because dairy products need to be taken care of.

Possible generators on a farm

Figure 5.1outlines possibilities for local electricity generation on a farm.

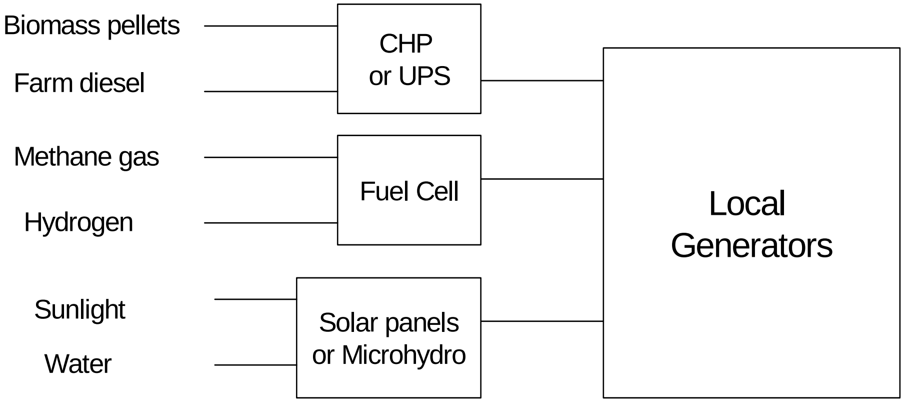

Figure 5.1: Possible production units

A farm has potential for various renewable energy resources that can be used to generate electricity. General possibilities considered include a combined heat and power unit, a fuel cell, and solar panels or a micro hydropower unit.

The combined heat and power unit (CHP) can be used as an uninterruptible power supply unit (UPS) for the farm and it can use farm diesel as a fuel. Normally on a farm where there are critical electricity needs, a UPS unit would have been installed, to supply the critical loads with electricity in case of a power cut. Such UPS units can provide for the power needs of the farm for periods ranging from one to three days. It however, has not normally been the case, to use such units to produce electricity to sell to the utility. The opening up of electricity markets creates this possibility. The CHP unit can alternatively be fired from biomass pellets if some of the timber grown on the farm is cut up. On a farm, waste wood and plant refuse is also fuel that is sometimes readily available. The cost of this fuel can be very low since the farmer does not always have to buy this. The delivery costs of such fuel is minimal. Therefore, the main operational expenses would be labour, plant maintenance and fuel-burning equipment. The hot water produced can be used for some of the heating requirements on the farm.

A fuel cell can be an alternative generation unit on a farm where there is possibility to produce methane gas locally. In general, the operational costs of fuel cells are very much a function of the cost of the energy source. If some of the hydrogen or methane gas is produced locally, fuel costs are reduced. Hydrogen can be produced from the sunlight if a regenerative fuel cell is used. However, supplementary gas may be purchased from the market to make sure that there are always adequate supplies of fuel on the farm.

In sunny places, solar cells can be used. Operational costs for solar cells are low because the fuel, sunlight, is free. The cost of running a solar photovoltaic system is also much lower when the system is connected to the distribution network because the expensive battery is not needed.

Some farms are situated near lakes or dams where livestock drink. Electricity can be generated where there are waterfalls or where the dam was constructed in such a way that electricity can be produced from harnessed water using a microhydropower unit.

Although there exists many alternative energy sources on a farm, it is not necessary that a farmer invest in more than three different units for economic reasons. In the simulation, three units were selected for closer study and these were a CHP unit fired from farm biomass, a fuel cell running on methane gas and solar photovoltaics. Two of the units need fuel which has variable costs i.e. biomass and methane gas whilst the third uses fuel which does not have variable costs. The maximum output from the CHP unit was chosen to be 200 kW whilst that of the fuel cell was set at 600 kW. The solar system was given a maximum output rating of 50 kW. This selection was made in order to make an interesting test case in the simulations and application of theory. In reality, an ordinary farmer would probably invest in only one or two different production units. Although the investment costs of solar cells and fuel cells are still very high, there is a lot of research work going on in these areas leading to new innovations with lower and lower investment costs. In the future, commercial farmers could easily afford to buy several generation units once they are convinced that the investments will be profitable.

Possible loads on a farm

Electricity is consumed at various places on a farm. For example, in buildings, electricity is mainly used for heating, cooling, lighting and other household or office appliances.

On a large dairy farm, electricity might also be used for milking and feeding the cows, processing and storage of milk products. Milk is stored in refridgeration tanks whilst the dairy products are stored in refridgerators. Figure 5.2 shows some milking and washing up machinery on a dairy farm.

Figure 5.2: Milking and washing up equipment

Figure 5.3 illustrates possible electrical loads on a farm.

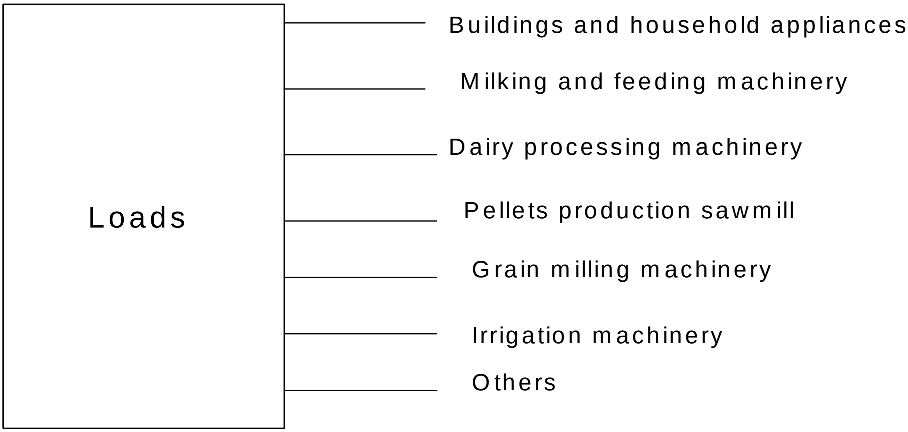

Figure 5.3: Electrical loads on a farm

Electricity is also used for milling of grain which is also necessary on a large farm. After harvest, some of the grain from the farm is prepared into animal food.

The trees grown on the farm can also be chopped down into smaller pieces of wood using a saw mill. This wood can be used as fuel to generate electricity. Some of this electricity can be used for milling of wood and production of the pellets.

An irrigation plant can be installed on farms for use as necessary, especially during dry seasons. Water can be drawn from a nearby dam or river to help provide water throughout the year. Some of this water can be useful for irrigation of crops using electricity.

The switching setup for the electrical loads and generators on the farm can be drawn as shown in Figure 5.4. The farm has a connection to the distribution network and has the possibility to sell its excess electricity to the network. Electricity can be purchased from the network when it is cheaper to do that. The main switch is therefore bidirectional allowing electricity to flow to and from the distribution network. Measurements are taken at the points marked **mp**.

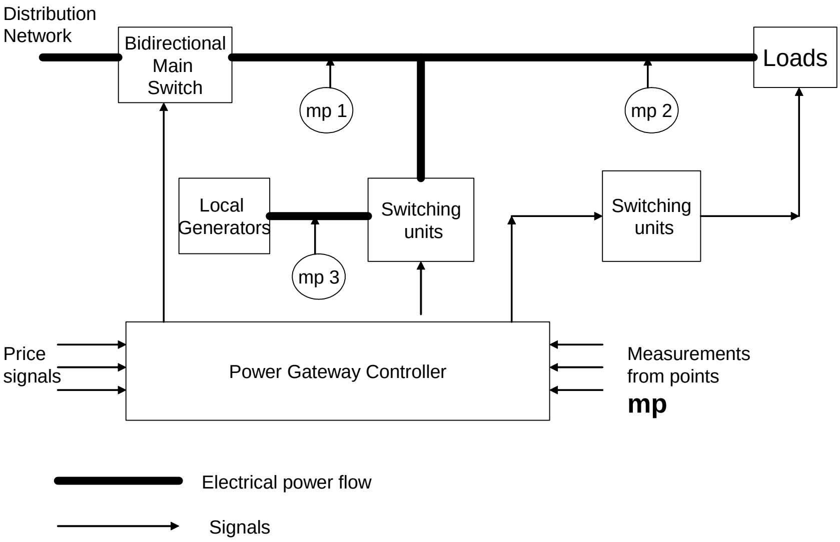

Figure 5.4: Switching setup

The power gateway controller will receive price signals from the market electronically. The other input signals will come from the farmer and from the measurement points.

Based upon the input data, decisions are made to control the switching on and off of generators and loads depending on the output of the power gateway controller. Each of the generators will have its own local controller for frequency, voltage and current, fuel and vibration respectively.

Load priority groups

The loads on this farm can be placed in three groups, which lend themselves to load priority groups.

First. The loads within the refridgeration and production units need to be given a high priority. The financial loss would be high if the milk or dairy products were to go bad because of loss of electricity supply. One part of the farm is allocated to the cows and within this area, there is a milking place where machines are installed to milk the cows. These milking machines need to be placed into priority one group to make sure that the cows are milked without fail within the specified period. The milking plant is also given a high priority. The lights and machines in critical areas on the farm, should also remain connected to the electricity supply as much as possible to avoid loss of man-hours. A few selected domestic appliances also need to be given first priority. The total maximum power that priority one loads (P_{l1}) take was set at 400 kW.

Second. Some of the domestic loads can be placed in priority two. The use of loads like washing and drying machines, cleaning equipment and other farm machinery can be rescheduled without causing much damage to people or the economy of the farm. The maximum power that priority two loads (P_{l2}) take was set at 300 kW.

Third. The milling plant and the irrigation plants were given a much lower priority. They are used only during certain periods of the year and they can be switched on when electricity prices are very low for example at night. The maximum power that priority three loads (P_{l3}) require was set at 200 kW.

The theory behind electrical load measurements and metering of electrical loads is given in Appendix C. The loads on the farm can therefore be divided into three priority groups as shown in Table 5.1.

Table 5.1: Load Priority groups

Rating	Loads	Power rating
Priority 1 load	PL1 Refridgerators Milking and production plant Some residential loads	400 kW
Priority 2 load	PL2 Washing and Drying equipment Other residential loads Other farm machines	300 kW
Priority 3 load	PL3 Milling plant Irrigation plant	200 kW

5.2 Problem Formulation

The main challenge in the problem under study was to minimize electricity costs with respect to the available supply options i.e. the installed production units and power from the distribution network, subject to the load constraints and maximum and minimum limits of the generators.

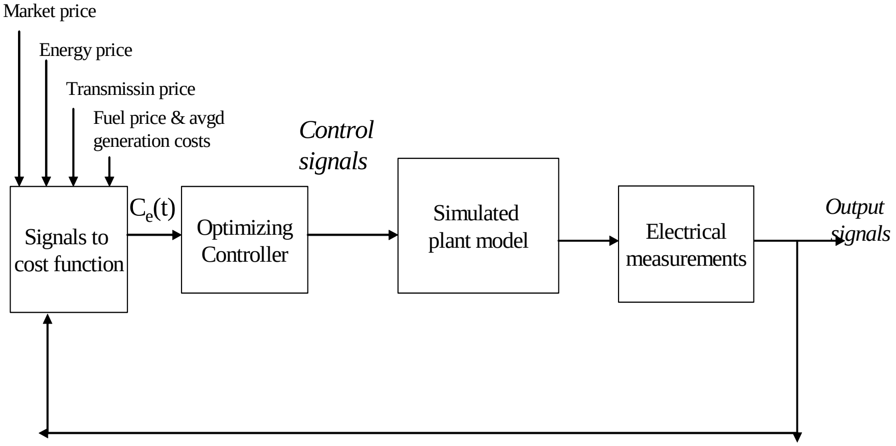

Figure 5.5: Control loop

Figure 5.5 shows a control loop that was used as a basis for the design. The gateway comprised of the optimizing controller and the signals to cost function converter. A calculation of the operations cost function and the optimization took place in the gateway, whilst the control signals from the gateway controlled the simulated plant model which consisted of the generators and loads. A decision on how much of which local generator to engage or disengage and how much to buy from the network was to be made everytime the algorithm was run. In addition to this, was the decision to switch on and off electrical loads in an optimal way depending on the electricity operations cost function. The idea was to maximize the benefit of installing local generators, especially those with very low operating costs.

There are various optimization methods that can be used depending on the problem e.g linear or nonlinear programming, quadratic programming, stochastic programming e.t.c. The techniques employed depend on whether a problem under study has constraints or not. Greig, D.M. (1980) gives examples of line search methods, gradient search methods and Newton and Quasi Newton methods that can be used for unconstrained optimisation. More information on these optimization methods is given in Appendix D.

The Economic Dispatch Problem. The purpose of the economic dispatch problem is to find the optimum operating policy for units which are connected to some system. The economic dispatch problem is usually a subproblem of the unit commitment problem It assumes that there are units available and that a forecast of the demand to be served is also available and the challenge would be to match the subsets of the generating units in order to provide the minimum operating cost. The unit commitment problem may be extended over some period of time.

Constraints in the Unit commitment problem

- Energy balance: There must be enough generating units committed to supply the load. The total amount of generation available should be able to keep the system running at any one time.

- Adequate reserve: If one of the units is lost, there must be ample reserve on the other units to make up for the loss in a specified time period.

- Thermal unit constraints: If any of the generating units are thermal, adequate manpower is necessary to operate the system and since the temperature changes only occur gradually adequate allowance should be provided when bringing the system on-line.

- Certain units require allowances of minimum up time and minimum down time.

Unit commitment solution methods

The most talked about techniques for the solution of the unit commitment problem are

- priority list methods
- Dynamic programming
- Lagrange relaxation

5.2.1 General Optimization Theory

The general form of a constrained optimization problem may be expressed in mathematical terms as

$$\text{minimize } F(x) \tag{5.1}$$

$$x \in \Re \text{ subject to } Gi(x) = 0 \text{ , } i\text{=1,2,......m;} \tag{5.2}$$

$$Gi(x) \geq 0 \text{ , } i\text{=m+1,...........m} \tag{5.3}$$

where $F(x)$ is the objective function

and $Gi(x)$ is the constraint function

The constraints can either be equality constraints or inequality constraints. If both $F(x)$ and $Gi(x)$ are linear functions of x ; then we have a linear programming problem. The number of independent equality constraints $Gi(x)$ should be less than the number of variables n, otherwise the problem is overspecified.

In this problem, an iterative algorithm was developed to optimize the electricity costs with respect to hourly prices of electricity and operational costs of the generators. A priority listing of the loads was considered in controlling the loads.

5.2.2 Constraints Considered

The limitations that affect the optimization process are the maximum and minimum values of the generators and the energy balance in the system. These constraints can be linearized as a first approximation, without a negative effect on the overall results and hence objective of the study. The solar cells chosen were given a maximum rated output of 50 kW. The minimum output for each generator was 0 kW. The maximum output from the fuel cell was set at 600 kW whilst that of the CHP unit was chosen to be 200 kW. The minimum stop and restart times for these two production units was set at 5 minutes. For fuel cells, the real start up times can vary from a few seconds to half an hour depending on the type of fuel cell used according to (www.millenniumcell.com(2006)) and General motors (2006). Since some fuel cells being used in vehicles have very short start up times, it was justifiable to be on the safe side to use 5 minutes for a stationary fuel cell in the simulations.

This customer is assumed to be having contract which allows buying and selling of electricity on the spot market of the power distribution system. This situation is conducive to the installation of a power gateway controller with an optimization algorithm.

5.2.3 Variables in the Algorithm

There are various input and output variables to the algorithm which can be connected in a control loop as was shown in Figure 5.5.

Input variables

The input variables to the proposed algorithm include:

- The selling price of electricity for the 24 hours of the next day, s_p
- Utility prices for electrical energy supply, bp_e and transmission,bp_t.
- The averaged costs for operation, maintenance and fuel for each of the various installed production units,C_{Ai}.
- The current output of the local generators, P_{cg} and
- the current load consumption at the dairy farm, P_{cl}.

Output variables

The output variables of the system are:

- Instantaneous operational costs of electricity, C_e, which is an operations cost function.
- Decision on which generation unit to connect or disconnect and how much capacity of each unit to engage, or how much to import from the distribution network.
- Decision on which loads to cut off or allow to run.

Figure 5.6 shows the schematic diagram of the local generators and loads for the proposed system. The settings of the production units are adjusted based on the decision made in the power gateway controller by the optimizing program.

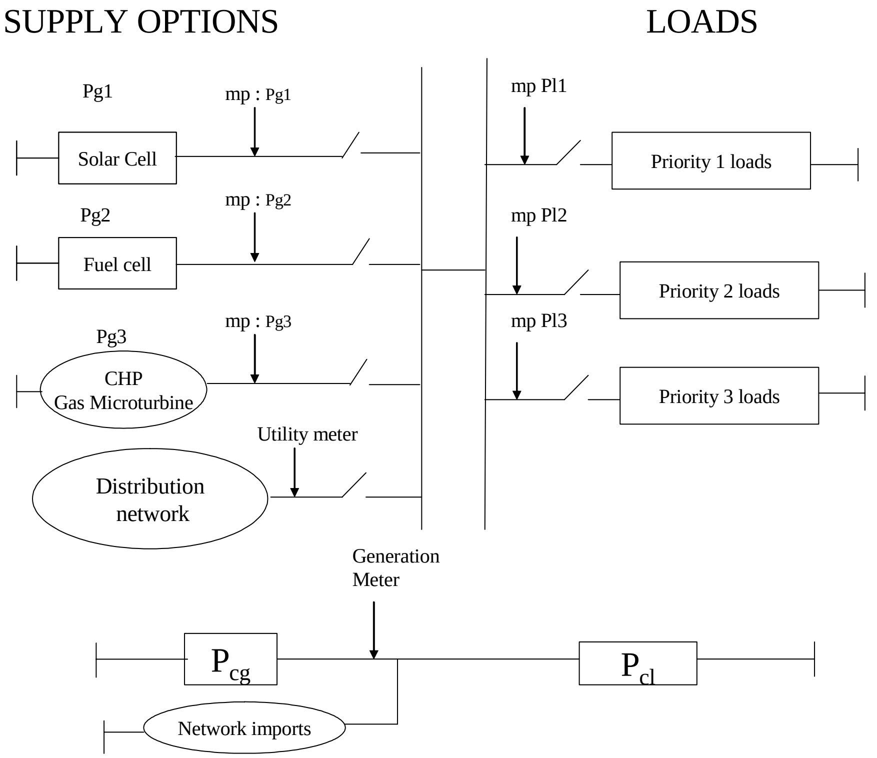

Figure 5.6: Schematic Diagram of loads and generators

5.2.4 Objective Function

The objective function for the electricity costs can be written as

$$C_e = C_i + C_{sg} - R_e \tag{5.4}$$

where

C_e is the operations cost function for electricity

C_i is a function for import costs

C_{sg} is a function for self generation costs i.e. generating the electricity locally

R_e is a function for export revenue (income obtained from selling electricity to the network)

The system can be connected in such a way that it is either in the buying mode or in the selling mode. This means that power can be made to flow in one direction at a time. When the customer is buying electricity from the market, the electricity costs would then be:

$$C_{eb} = C_i + C_{sg} \tag{5.5}$$

where

C_{eb} is the function for electricity costs when the customer is in the buying mode

When the customer is selling electricity to the network the function for electricity costs would then be:

$$C_{es} = C_{sg} - R_e \tag{5.6}$$

C_{es} is the function for electricity costs when the customer is in the selling mode

When the export revenue R_e is much larger than the self generation expenses then the value of the function for electricity costs will be negative meaning that there will be profit for the customer.

5.2.5 The Cost of Buying from the Network C_i

The import costs are a function of the tariff charges and the shortfall in local generation. In general, tariff structures differ from country to country and from network to network. There exists many different combinations of average price levels, charges by location and charges by user. In this case we assume a tariff for buying electricity from the distribution network which consists of two parts i.e.

$$bp = bp_e + bp_t \tag{5.7}$$

where bp is the buying price per kWh

bp_e is the energy tariff for each kWh

bp_t is the transmission tariff for each kWh

We assume that the fixed costs and all other utility overheads are already built into these two figures when the utility gives out the prices on the spot market. The hourly prices are of course a function of the demand and supply of bids on the market. The power imported from the network is given by

$$P_i = \Sigma p_l - \Sigma p_g \tag{5.8}$$

where P_i is the imported power

Σp_l is the total instantaneous load which we shall also denote as P_{cl}

Σp_g is the total instantaneous power generated locally and we also call it P_{cg}

Shortfall in local generation = Power demanded - power generated

Import costs are therefore given by

$$C_i = \int_0^t ((P_{cl} - P_{cg}) \cdot (bp_e + bp_t))dt \tag{5.9}$$

5.2.6 Income from Selling to the Network R_e

We define export revenue as the income that is obtained from selling the locally generated electricity to the distribution network. This is given by

$$R_e = \int_0^t ((P_{cg} - P_{cl}) \cdot s_p)dt \tag{5.10}$$

where R_e is the export revenue and s_p is the selling price

5.2.7 Cost of Local Generation C_{sg}

The cost of generating the electricity locally is given by summing the cost of the individual units´ contributions

$$C_{sg} = \sum_{i=1}^{n} \int_0^t (P_{gi} \cdot C_{ai})dt \tag{5.11}$$

C_{ai} is the averaged cost of operating generator *i* which includes the fuel costs, the maintenance and other relevant running costs. Included in this cost is the monthly payback of loan and interests for installing the unit at the customer premises. Although the investment costs and interest rates vary as new low cost technologies are developed each year, and interest rates vary as well it was however, assumed that the payback of loans could be taken as a constant value that is spread throughout the expexted lifetime of the generation unit. All these costs were assumed to be averaged over each kiloWatt output of the generation unit, into the value, C_{ai}.

Measurements are taken at points marked mp in Figure 5.3. In this case,

$$P_{cl} = P_{l1} + P_{l2} + P_{l3} \tag{5.12}$$

$$\text{and } P_{cg} = P_{g1} + P_{g2} + P_{g3} \tag{5.13}$$

In this scenario the electricity costs during the buying mode is:

Electricity costs = Import costs + Self-generation costs

$$C_{eb} = \int_0^t (P_{cl} - P_{cg}) \cdot (bp_e + bp_t)dt + \sum_{i=1}^{n} \int_0^t (P_{gi} \cdot C_{ai})dt \tag{5.14}$$

The electricity costs when in the selling mode is given by

Electricity costs = Self-generation costs - Export revenue

$$C_{es} = \left(\sum_{i=1}^{n} \int_0^t (P_{gi} \cdot C_{ai})dt \right) - \left(\int_0^t ((P_{cg} - P_{cl}) \cdot (s_p)dt \right) \tag{5.15}$$

The power balance equation is

$$P_{g1} + P_{g2} + P_{g3} + P_i = (P_{cl} + P_e) \tag{5.16}$$

where P_i is the imported power from the network and P_e is the exported power. When the system is in the import mode, then P_e will be equal to zero since the connection at the customer premises is such that the power flows either from the distribution network to the customer or vice-versa. When the customer is selling to the network then P_i will be zero because there will be no imports.

5.2.8 Optimization Period

The optimization period depends on the rate of change of market prices and the minimum start and stop periods for the production units. In this case the market prices change only once each hour and the minimum start and stop times for the production units were chosen to be 5 minutes. Therefore, the timing for running the optimization algorithm was chosen to be every 30 minutes. This was deemed satisfactory as it would ensure steady state operation.

Data was collected continously while the program was running, and at the end of the day, the data was passed onto a file where it was stored locally.

5.2.9 Flow Charts

The above scenario is summarised in the following flow charts. At the beginning of each day the electricity price information for the following day is available for the customer. There are a lot of sources that this information may come through. We assume that our customer will use information that is posted daily on the utility's web page. The hourly prices are extracted from the information that appears on the web page. The flow chart in Figure 5.7 summarizes the procedures for extracting the relevant prices from the utility web page.

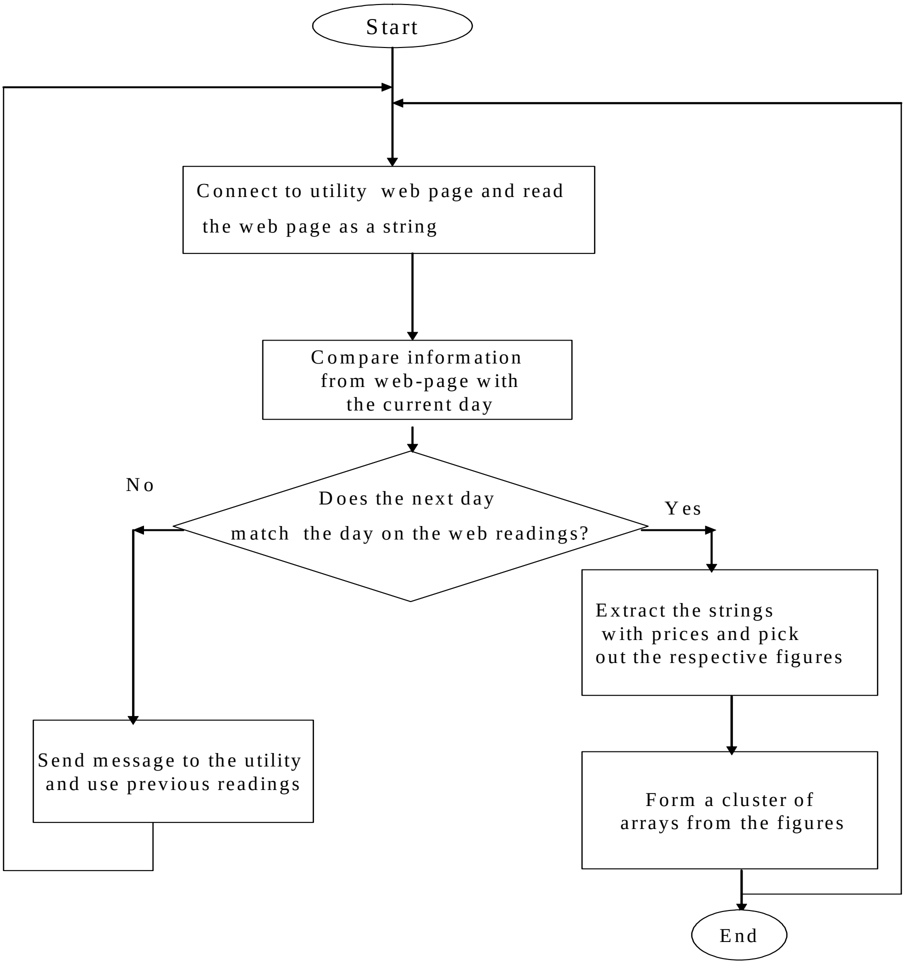

Figure 5.7: Reading the prices from the web page

Firstly the power gateway controller compares the day of the week displayed on the web page with its local date and time information. It is necessary to check that the information on the web page has been updated before it is used. If there are any inconsistencies, an automatic message will be sent from the power gateway controller to the utility. Previously recorded data will be used if the utility completely fails to supply the updated price information in good time to run the following day's routine. When the prices are extracted, they are grouped into a cluster for easy handling.

Information from the web page is extracted only once a day. This information is then sent to the main program which carries out calculations and perfoms the necessary optimization as shown in Figure 5.8.

In the main routine, the price information on the web page, is read at the beginning of each day and stored in the power gateway controller. After this all the other input variables are declared and read into the algorithm. The prices are then indexed from the cluster periodically. Each time a new set of readings is fetched, essential calculations are carried out , after which the optimization process begins.

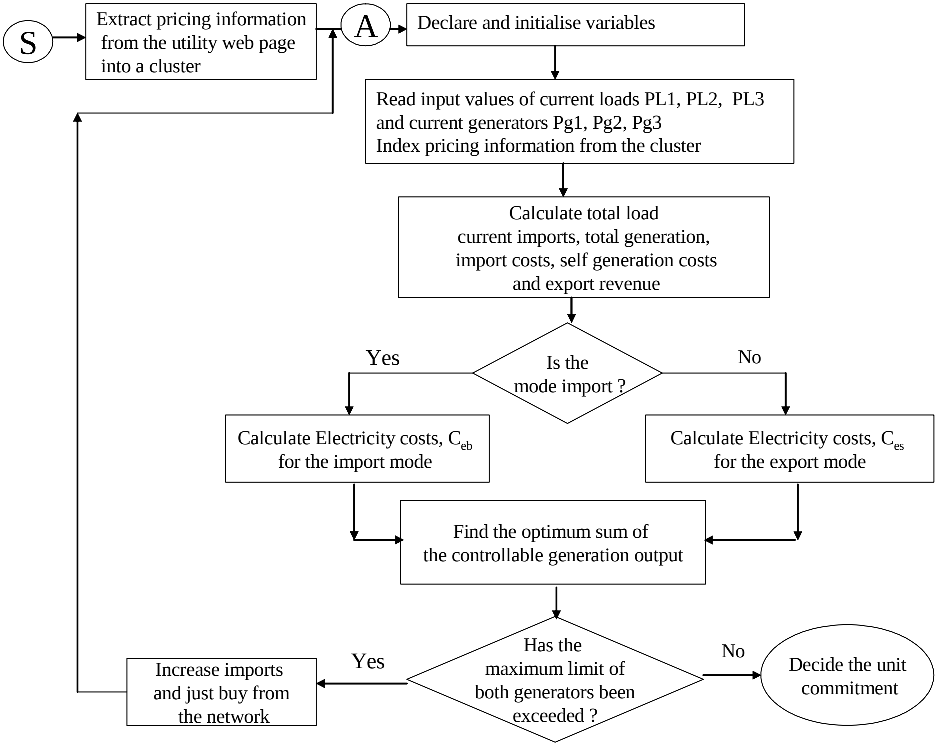

Figure 5.8: Reading inputs and minimising the electricity costs

The optimum settings of the controllable units is calculated using the outline given in Figure 5.9. Before the units are dispatched, a check is made to make sure that the constraints of the maximum values of the production units used in this example are observed.

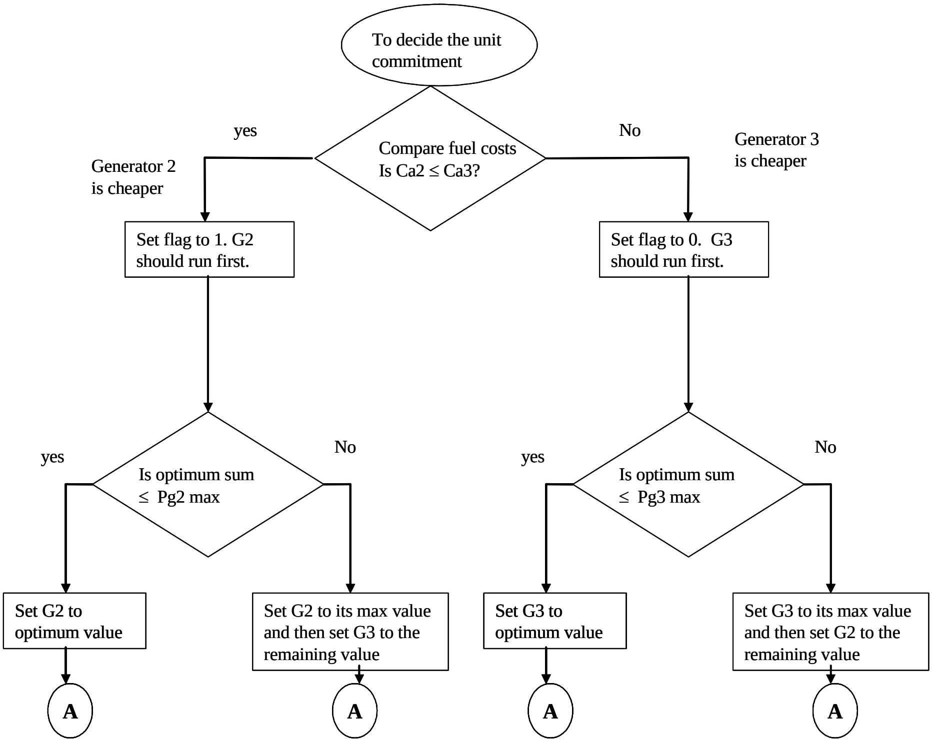

Figure 5.9: Allocation of the production units

Fuel costs of the production units are compared before the allocation takes place. The first production unit is the set of solar panels which will produce electricity depending on the sunshine levels. The output from the solar cells is included in the algorithm, however, the customer does not need to switch off this output. The other two production units can be controlled by the customer depending on their fuel costs. A customer has got the responsibility to change the input values of the averaged costs for the production units whenever the fuel costs change significantly. The accuracy of the decisions will therefore be a function of the customer’s diligence as well.

The unit with lower averaged costs will be commissioned first before the more expensive unit is switched on. The optimum settings of the production units are automatically calculated by the algorithm in the power gateway controller and the information is transmitted to the respective units. The algorithm will repeat itself from point A in Figure 5.8 throughout the day.

A criteria for load shedding was specified. This was based on the hourly cost of the current load. This was a limit on how expensive the operational costs should be before cutting off of any loads started. This criteria was tested to determine if it was necessary to shed any loads in order to reduce the expenses. The loads in priority three are shed off first since they are not very critical, followed by the loads in priority two. At each stage a warning is given to alert the customer. An alarm bell is set to start ringing when the situation gets critical after all the loads in priority two have been shed off. After this, the decision is left to the customer either to

- run only the loads in priority one or
- adjust the test criteria for load shedding and increase the houly costs or
- override the alarms and continue running any urgent loads

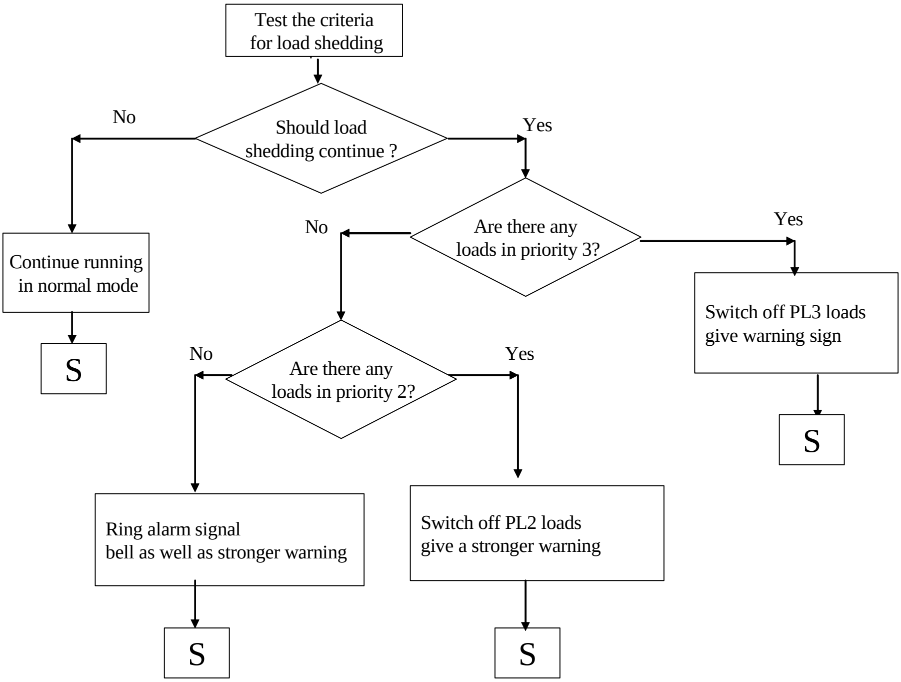

Figure 5.10: Load shedding

The point marked **S** in the flowchart in Figure 10 is the start of the repeated loop in the algorithm which is also shown in Figure 5.8. After the design, the flowcharts, were implemented using a combination of graphical programming and text based programming as explained in the next chapter.

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Chapter 6

Implementation and Experimental Set-up

The problem under study was physically defined and presented in Chapter 5, together with the mathematical formulation of the solution. This chapter brings together the different elements that were necessary to set up the experiment.

These elements are presented in two related parts, which make up the model. The first part, was the programming of the optimisation algorithm developed in chapter five. The algorithm was developed into a program that was implemented in LabView, NI (2005). The significant aspects of the programming are outlined. LabView is a graphical development environment for building data acquisition, instrumentation and control systems. It is based on virtual instruments (VI's). The communication capabilities of Labview's programming environment were useful in implementing the whole experimental set-up.

The second part involved designing of a laboratory experimental set up that modelled the problem under study. One feature of the model is the use of internet technology as a mode of communication. The merits of the simulations are also considered. The results of the tests and optimization are presented and discussed in chapter seven.

6.1 Setting Up the Laboratory Experiment

In order to simulate the exchange of information between the power gateway controller and the utility on the one hand, and between the power gateway controller and the local plant on the other, two computers were used. The first computer (A) modelled the utility web-server which is the data source for electricity buying and selling prices. Computer (B) housed the optimization algorithm, which modelled the power gateway controller. The plant simulation, which consisted of the local production units and electric loads that consume the electricity, was also housed on computer (B). The set up of this experiment is shown in Figure 6.1. The nature of the simulations of the sites is discussed in the next section.

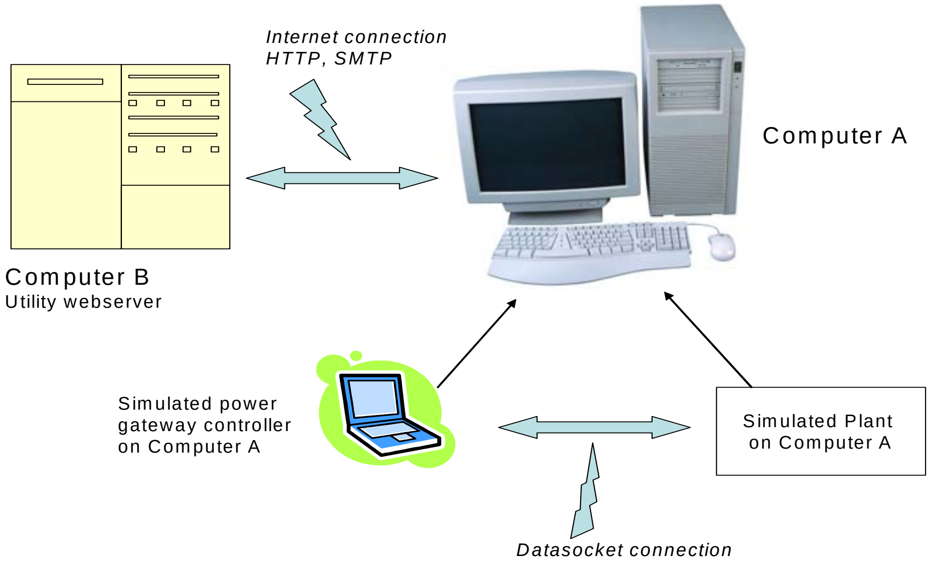

Figure 6.1: Laboratory set up that defined the problem

6.1.1 Simulation of the PGC - Computer A

The major features of the simulation of the power gateway controller is the optimization of electricity costs and communication between the power gateway controller, customer plant and utility webserver.

Flexibility was introduced to the simulation in two ways. Firstly, the programme was designed such that the output of the loads and the production units are displayed on the power gateway controller's graphical user interface as shown in Appendix E.

On the front panel was also displayed the the pricing information and the status. Secondly, there was provision for the consumer to input changes to the averaged costs of the production units depending on the changes in fuel prices. The customer also had the possibility to set the acceptable hourly operations cost which would be used as basis for cutting off of loads.

6.1.2 Simulation of the Source Data - Computer B

The traditional methods of communicating information on daily electricity prices to customers by the local electricity distribution company (utility) is mass broadcasting like daily newspapers, radio or teletext on television channels. These are effective and some customers may want to continue using them. However, the advent and rapid advancement of modern technology offers faster and more efficient communication. Such technologies include the internet, SMS messages, e-mails, e.t.c. Consequently, it was considered pragmatic to simulate the source data using a webserver. In the laboratory set up the utility Webserver was modelled on computer B.

The design. A web page for the utility was designed. The HTTP server in the Internet Toolkit in Labview contains a large collection of *HTML VI's* that can be programmed to create HTML documents. One of these VI's was used to create the web page. The web page contained the following information: A spreadsheet file with electricity prices in the Norwergian currency (kroner) was used as source data to create the web page. The *HTML + Numeric array to Table VI* was used to construct HTML code to describe this table.

Application. The daily market prices and buying prices are posted to this web page. The web page can contain information about the prices for the previous six days for the benefit of the customers. Customers who have access to the internet can view and read the utility prices and adjust their electricity consumption to match their budgeted expenses, as necessary. The assumption is that there exists a daily market for electricity distribution where major customers submit their daily bids to this distribution market. At the end of each day the electricity prices for the following day are determined by the market forces. The distribution company then works out the following day's prices depending on the bids and operations of the current day.

6.1.3 Simulation of the Plant - Computer A

The customer‘s plant was taken to have three generation units and was run from personal computer A. These could be switched on and off to test the optimization algorithm. Normally each of the production units and some of the loads have their own local inbuilt controllers.

Solar cells The first generation unit is taken as solar cells. The operational costs of solar cells are comparatively small. Consequently, there is no need to switch off the solar panel's output at any time once it has been installed. Accordingly, the output from the solar cells does not need to be switched off by the optimization algorithm although the output from the solar cells is taken into consideration in the running of the algorithm. The photovoltaic system also has its own controller. All the electricity generated by the panels should be utilized or sold to the market as necessary.

Fuels cells The other two generation units depend on fuel. This type of generation unit was chosen because a farm has a possibility to produce methane gas in a cost effective way. In general, the operational costs of fuel cells are very much a function of the cost of the energy source; in this case hydrogen or methane gas.

Combined heat and power unit On a farm, waste wood and plant refuse is a fuel that is readily available. The cost of this fuel is therefore very low since the farmer does not necessarily have to buy this. The delivery costs of such fuel is minimal. Therefore, the main operational expenses would be labour, plant services and fuel-burning equipment. A biomass gasifier CHP unit was chosen.

The output of these two units can therefore be regulated depending on the output of the power gateway controller. The readings of the production unit output were communicated to the power gateway controller using datasocket connection.

The loads A simplified representation of the load was simulated. The loads were placed in three main load priority groups as discussed in chapter five. Readings of these load groups are taken and sent to the optimization algorithm every thirty minutes. The output from the locally installed generators is also monitored and readings are also taken and sent to the algorithm. Only three readings of the load demand needed to be periodically communicated to the power gateway controller. Steady state conditions were a necessity for the smooth running of the controller. It was therefore assumed that the system variables could be held constant with respect to time for the purpose of testing the system, whilst static optimization was used in the optimization algorithm. This simplified approach was considered a necessary first step in developing a sound model that could be improved later. The plant simulation was set up as shown in Appendix F.

6.2 The Connections

Internet technology was chosen for communication between the power gateway controller (Personal computer A) and the electricity distribution company's webserver (Personal computer B) (Figure 6.1). Labview, as modelled in the power gateway controller can communicate with other applications over a network using different internet technologies as shown in Figure 6.2. The web page was read using the HTML VIs in the [Internet toolkit] in Labview.

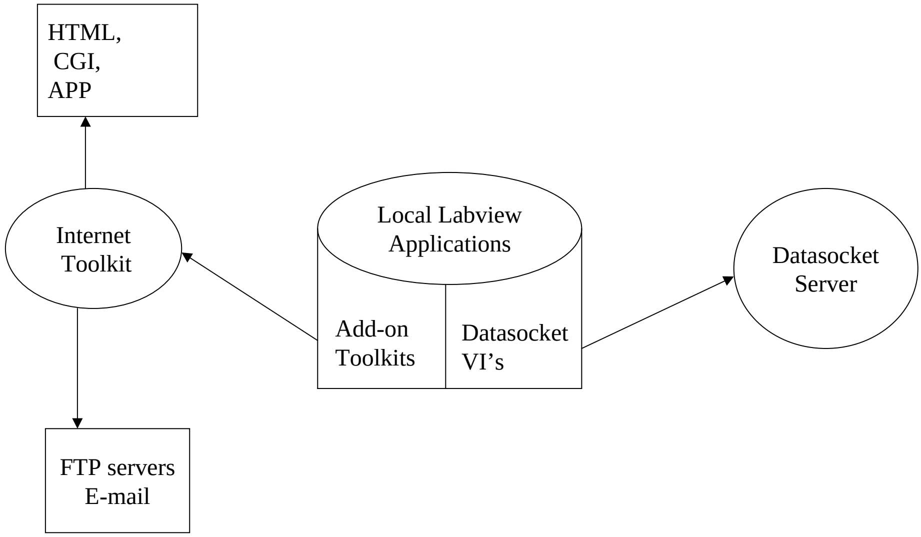

Figure 6.2: Network technologies used in the experiment

6.2.1 Power Gateway Controller-Plant Connection (Datasocket)

Datasocket is a single, unified, end-user Application Programming Interface based on Universal resource locators. It can connect to measurement and automation data located anywhere. It has the advantage that it is independent of the protocol or language or operating system and it is designed to simplify binary data publishing. It is a technology that allows one to send and receive data over a network from a variety of software platforms without worrying about the low-level implementation details. Datasocket technology can be used to easily publish data on the internet. It can be used with Labview (on Windows), Visual Basic, Visual C++ and other applications that can use ActiveX controls.

Datasocket has two main parts that work together i.e. the datasocket server and the datasocket API (Application Programming Interface) for clients. The datasocket server is a standalone application that runs on a computer and handles client connections. The client connections may write data to the server or read data from any one of the publishers. The server is known as a datasocket publisher whilst the client who read data is a datasocket subscriber. Labview VI's and ActiveX control support datasocket transfer protocol. In the experiments the power gateway controller was both a subscriber to the plant and a publisher to the plant to complete the control loop.

A Datasocket server is automatically installed with Labview for windows. However, it is necessary to configure the access information in the Datasocket Server Manager. The one way of writing data to a Datasocket connection used is as follows. The second method is to simply set the control and indicator icons on the Labview Front panel to publish data or subcribe to data depending on their functionalities. See Appendix H for more details.

6.2.2 Power Gateway Controller-Webserver Interaction

The interaction between the power gateway controller and the webserver was via internet communication. This was essentially used to read the web page. Many functionalities were used , in the form of Labview’s VI’s to implement this interaction as shown in appendix G.

6.3 Test Run

The testing phase involved fixing all the bugs in the code. Test plans were developed to verify and validate the code’s conformance to the requirements. The next chapter describes the testing procedures carried out and analysis of the results.

6.4 Bibliography

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Chapter 7

Laboratory Testing of the Model, Results and Analysis

This chapter outlines the procedures adopted in testing the algorithms in the model and the total model as a whole. For each test carried out, the rationale, theory and test method are briefly outlined, as an introduction to the presentation and analysis of the results. The chapter concludes by summarising the pertinent conclusions.

7.1 Laboratory Tests

A test program was designed to provide sufficient information on the functionality and versatility of the algorithm, and on the set up of the experiment adopted in simulating the power gateway controller. Different scenarios were simulated and test results collected for analysis. Finally a cost benefit analysis was done on the power gateway controller.

7.1.1 Test Program

Cost remains a major factor in the buying and selling of electricity. This was considered from the points of view of market prices, buying prices and averaged operational costs. Tests were designed to cover three areas:

- Firstly, appropriate responses, to changes in the variables formed a reasonable basis, to demonstrate that the algorithm worked.

- Secondly, separate tests were run to verify the communication and automation aspects of the set up.

- Thirdly, a test program was aimed at simulating realistic scenarios that could be encountered in the case under investigation.

The monetary figures used were originally in Norwergian currency, and quite close to real figures used by Nord Pool and Trondheim Energiverk.(Nord Pool (2003), Trondheim Energiverk (2006)) Some of the figures used were original and solely for the purpose of making experimental simulation studies. To make the results readable for an international audience the currency was normalized to a unitless currency. This provides flexibility in relating the findings to any currency. The final results can be converted to any equivalent currency by multiplying by a factor, at the time of reading the thesis. The monetary unit can be assumed to be approximately equal to 1 NOK. At the time of writing the thesis, 1 NOK was equivalent to about 0.14 USD. Table 7.1 gives a summary of the tests. The tests were carried out more than once to check repeatability.

Assumptions made in the experiments

Assumptions were made in simulating the power gateway controller which was designed in chapter five. Some of these assumptions were explained as part of constraints in the algorithms, but they are repeated here to give a holistic view of the experiments.

(i) The customer has already selected and installed local production units which are functioning well. The payback of loans and interests are included in the hourly operational costs of running each generation unit, C_{ai}. This value also includes the fuel costs, the maintenance and other relevant running costs. These are averaged out per each kW output considering the expected lifetime of the generation unit.

(ii) All excess electricity generated is sold to the network.

(iii) In this case we assume that prices are posted onto the utility’s web page daily. Hourly market prices for the following day, are given to the customer the day before the electricity is traded.

(iv) Aging of equipment was not taken into consideration.

(v) A linear relationship was assumed between the fuel input and the power output from the production units.

(vi) This small scale electricity producer has a basic negotiated contract with the utility which allows the customer continuous access to the distribution network. The contract gives permission to sell their excess electricity at the daily selling prices. The nature of the trade is such that the customer will respond to the daily market’s buying and selling prices offered by the utility. (vii) The fixed tariffs and all other utility overheads and taxes are built into the energy price and transmission prices, bp_e and bp_t when the utility works out the energy prices and transmission prices.

Table 7.1: Summary of the test program

Test series	**Main goal**	**Description of test**	**Purpose**
1	To study the response of the operations cost function to variations in local generation costs.	vary operational costs of one of the generators, whilst all the other parameters are kept constant	to test the functionality and versatility of the algorithm
	To study the response of the operations cost function to variations in market price	vary market price, whilst all the other parameters are kept constant.	
	To study the response of the operations cost function to variations in buying price.	vary the buying price, whilst all the other parameters are kept constant	
2	Is the power gateway controller able to read data from the utility web?	Input data from the web page and monitor the operations cost function, whilst generators & loads are kept constant	to confirm communication between the stations in the experiment
	Is the power gateway controller able to communicate with the plant ?	Send data to and from the plant and the utility webserver whilst observing the power gateway controller's user interface.	
3	The response of the power gateway controller to load variations and tariffs	Observe and analyse the gateway's response to load shedding.	to simulate realistic scenarios on a farm
		Observe and analyse the response to variations in price profiles on a weekday in summer and on a weekend day.	
		Observe and analyse the response to variations in price profiles on a weekday in winter and on a weekend day in winter	

7.2 Test Series 1:
Functionality and Versatility of the Algorithm

7.2.1 Cost of Electricity versus Averaged Generation Costs

Aim

To study the effect of varying the averaged operational costs of the local generators, on the operational cost of electricity consumed at the farm.

Method

Reference is made to Section 5.2 where the theory and design which form the basis for the experiments carried out in this chapter, were outlined. The average operational cost of generator 2, (C_{a2}), was increased from 0.15 mu/kWh to around 0.52 mu/kWh (mu = monetary unit) in a series of steps, over a period of 40 minutes. C_{ai} is the averaged cost of operating generator *i* which includes fuel costs, operation and maintenance costs and payback on investments as a constant. The optimum sum of the two generator outputs to be controlled from the algorithm is PcgOpt. Observations were done on the electricity operations cost function (C_e) and on the optimum value, PcgOpt.

For this part of the experiment the maximum value of Pg2 was set at 60 kW whilst the maximum value of Pg3 was set at 20 kW.

Theory

According to Equations 5.4 and 5.11 the electricity operations cost function C_e at any one time, depends on the cost of locally generated electricity, C_{sg}, which in turn depends on the averaged operational costs of the production units,C_{ai}.

$$C_e = C_i + C_{sg} - R_e \tag{7.1}$$

where

$$C_{sg} = \sum_{1}^{n} \int_{0}^{t} (P_{gi} \cdot C_{ai}) dt \tag{7.2}$$

If we keep the import costs, C_i , and the earned revenue, R_e ,constant and we vary the averaged operational costs for one production unit at a time, then we can investigate how the operations cost function responds to changes in C_{ai} .

Observation

Figure 7.1 is a plot of the power gateway controller's response to the changes in C_{a2}. The data generated was stored as a spreadsheet file in Labview and the results were plotted as shown below. In this experiment, generator 2 was initially running at an arbitrary value of 16.7 kW whilst generator 3 was running at 20kW, and the total output of local generation was 36.7 kW.

From the plotted graph we observe that the operations cost function C_e (in red) increases with increase in C_{a2}, up to point A. At point A, the optimum sum of the generator outputs, PcgOpt (in green) suddenly decreases to 20kW.

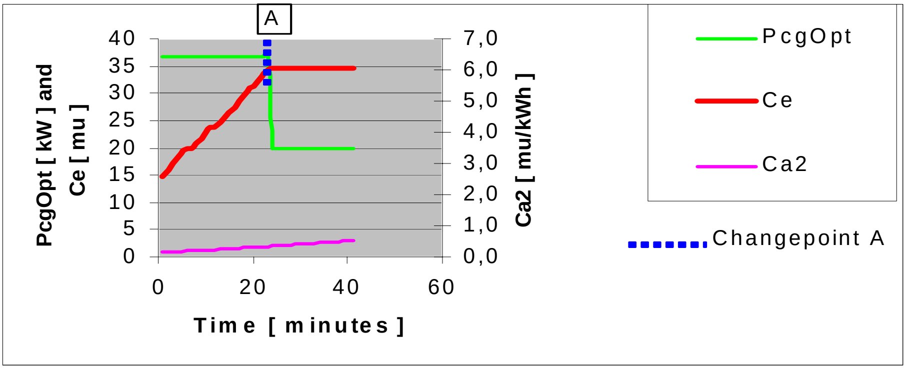


Figure 7.1: Electricity operations cost function vs Averaged operational costs of generator 2.

Anaysis

The power gateway controller detects at point A, that generator 2 is becoming too expensive and it sends a message to the plant to switch generator 2 off. At this point A only the 20kW from generator 3 continues to be produced locally since it is no longer optimal to produce from generator 2. Therefore any further increases in the averaged cost of operating generator 2, C_{a2}, do not affect the overall electricity operations cost function since generator 2 has now been switched off. C_e therefore remains constant at 35 mu. This behaviour confirms that the algorithm detects that there is an optimal point in the system beyond which it becomes uneconomical to continue running generator 2. The electricity operations cost function increased with the integral of the averaged operational costs of generator 2. A similar pattern was also observed when the experiment was repeated for the third generator.

Conclusion

The algorithm responded well to variations in averaged costs of the production units. The results obtained were consistent with what was expected of the power gateway controller.

7.2.2 Cost of Electricity versus Selling Price

Aim

To study the effect of variations in selling price on the instantaneous cost of electricity consumed at the farm.

Method

The selling price was gradually increased from 0 mu/kWh to 0.33 mu/kWh whilst observations were made on the operations cost function C_e and the optimum sum of generators 2 and 3 PcgOpt, over a period of time.

Theory

According to Equations 5.4 and 5.10 the total electricity costs for operating at the customer site, C_e, is also a function of the export revenue which depends on the selling price to the network, s_p.

$$C_e = C_i + C_{sg} - R_e \tag{7.3}$$

$$R_e = \int_0^t ((P_{cg} - P_{cl}) \cdot s_p) dt \tag{7.4}$$

If the import costs C_i , the self generation costs C_{sg}, the current output of the local generators P_{cg} and the current load consumption at the dairy farm P_{cl} are kept constant and the selling price is varied, the response of the algorithm to variations in selling price can be tested.

Observation

In Figure 7.2 , which is a plot of the results obtained, it is observed that initially, C_e is not affected by changes in selling price, until point A. This is because initially, the system is in the buying mode and there is no excess electricity being sold to the network. The loads are consuming all the locally generated electricity and partial imports are made from the network to fully cover the load. However, at point A, the selling price has now reached a level where it is economically viable to increase the local production and sell the excess power to the network. The system therefore switches to the selling mode and PcgOpt goes up to 60kW which, for this experiment, is the maximum set output for generator 2. Now because there is excess generation, revenue is earned from the electricity sold to the network. The earned revenue means that overall, less money will be spent on electricity. We therefore notice a decrease in the electricity operations cost function (in red) as the selling price (in brown) continues to increase.

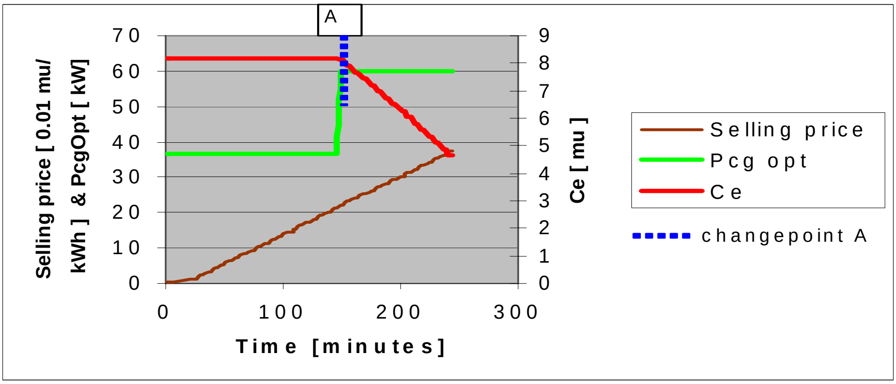


Figure 7.2: Electricity operations cost function vs selling price

Anaysis

The power gateway controller detects that at point A, it is more economical to produce as much as possible locally. After that further increases in market price just lead to more revenue for the farmer. This leads to a decrease in the operations cost function since the relatioship between the operations cost function C_e and the earned revenue, R_e is: $C_e = C_i + C_{sg} - R_e$. This behaviour confirms that the algorithm detects that there is an optimal point in the system where it is better to generate more electricity locally and sell the excess to the network, than to continue buying from the network.

Conclusion

The decrease in the electricity costs confirms the theoretical negative relationship between C_e and s_p. This is also consistent with the expected response of the power gateway controller.

7.2.3 Cost of Electricity versus Buying Price

Aim

To test the response of the electricity operations cost function C_e in the algorithm to variations in buying price.

Method

The buying price was increased steadily from 0.1 mu/kWh to 0.33 mu/kWh whilst observations were made on C_e and PcgOpt, over a period of 50 minutes. The load was kept constant and all the other prices and variables were also kept constant.

Theory

The theory given in chapter five formed the basis for this experimental work. For this part, equations 5.4 and 5.9 show that there is a relationship between the electricity costs at the farm and the buying price.

$$C_e = C_i + C_{sg} - R_e \tag{7.5}$$

$$C_i = \int_0^t ((P_{cl} - P_{cg}) \cdot (bp_e + bp_t))dt \tag{7.6}$$

If we keep the earned revenue, R_e , the costs of local generation, C_{sg}, the local load, P_{cl} and all the other prices constant, and vary only the buying price over a period of one minute, then we can test the algorithm’s response.

Observation

The results obtained are presented in Figure 7.3. The graphs show that at first the electricity operations cost function Ce (in red) increases with increase in the buying price (in orange) up to point A. At point A PcgOpt suddenly jumps from 0 kW to 36 kW showing that there is a sudden increase in local generation. After this point any further increase in the buying price do not affect C_e. Accordingly, C_e is constant.

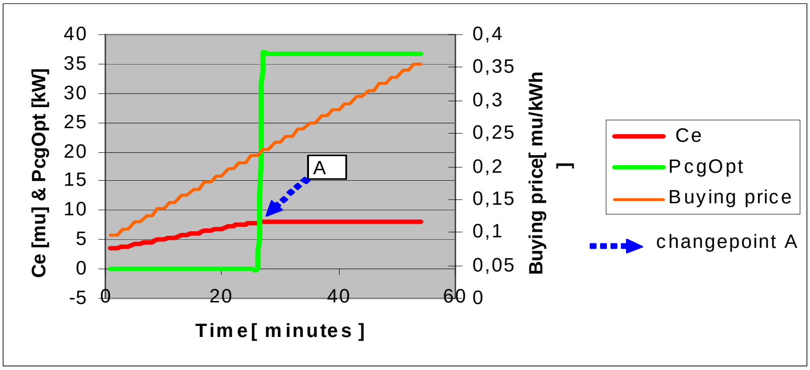


Figure 7.3: Electricity operations cost function vs buying price

Anaysis

These results show that the algorithm detected the point at which it became very expensive to buy from the network. At this point the system switched to local generation. When the local generator starts running, the imports from the network were suddenly stopped and any further changes to the buying price did not affect the electricity costs.

Conclusion

As the buying price increased, there was a corresponding in the operations cost function confirming the theoretical relationship between C_e and bp. The algorithm was also able to detect the optimal point. The results obtained were consistent with what was expected.

7.3 Test series 2: Communication with the Power Gateway Controller

7.3.1 Interaction between the PGC, Utility Web Server and Plant

Aim

To verify that the power gateway controller is able to correctly read the buying and selling prices from the utility web page. Communication between the power gateway controller and the plant using datasocket was also tested.

Method

The web page was stored in the web server directory of Labview on the second computer which simulated the utility interaction. The web server was started using the web publishing tool in Labview. The subVI for reading the web-page was automatically called from the main VI to retrieve the utility web page file at the location specified by the URL using HTTP. The contents were passed onto the subVI as a string for further analysis. The price information was extracted by this VI and passed onto the main algorithm.

The average operational costs of all the generators was kept constant and the solar cells and all the loads were disconnected from the power gateway controller in order to monitor the response of the operations cost function to the utility prices.

After this the connection between the plant and power gateway controller was established and tested. The data flow between the two units was monitored whilst the response of the plant was captured.

Observation

Communication with the utility web page was tested and data was succesfully read and used in the algorithm. Measurements were also successfully taken from the plant, and information was communicated from the plant to the gateway and from the gateway to the plant using datasocket. The output from the power gateway controller was then captured and plotted as shown in Figure 7.4.

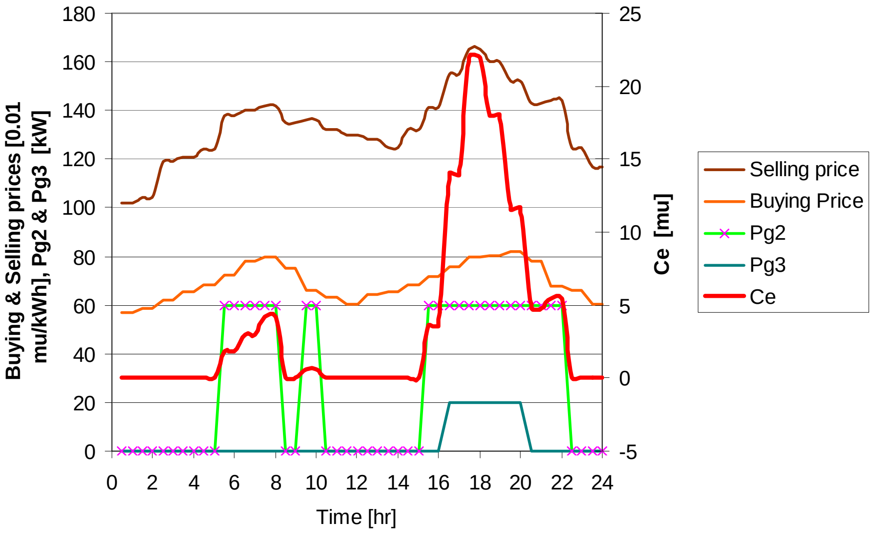


Figure 7.4: Reading price information from the utility web page over a 24 hour period and the algorithm’s response

The buying prices (in orange) and the selling prices (in brown) were succesfully retrieved from the utility webserver without any significant time delay. The response of the operations cost function is shown in red whilst the response of the controlled generators Pg2 and Pg3 is shown in the two different shades of green.

Anaysis

The plots presented in Figure 7.4 show that the selling price was higher than the buying price. In this case the utility was encouraging customers to generate locally and sell to the network on that day. The prices from the utility on that day showed that there were two peak periods. The price of buying electricity in peak period 1 which stretches from 6.00 a.m. to 10.00 a.m. ranges from about

0.70 mu /kWh to 0.80 mu /kWh. In peak period 2 which starts around 16.00 to 21.00 the prices were even higher. During the first peak period, generator 2 is automatically switched on when the buying price becomes higher than the average operational cost of generator 2.

The operations cost function C_e , which is calculated by the power gateway controller, responds to the changes in the prices in a corresponding way. This response shows that all the loads and generators were initially switched off because the initial output of C_e was zero until the generator Pg2 was switched on. After this the value of C_e mainly increased because of the operational cost of having Pg2 on. After the first peak period, Pg2 switches off automatically and the operational costs decreases. Pg2 switches on again during the second peak period. As the selling price escalates, generator Pg3 is switched on when it is economically viable to generate more. However, the switching on of Pg3 increases the operational costs to some extend. When the selling prices start falling, Pg3 switches off first and later on Pg2 also switch off.

Conclusion

The power gateway controller was able to correctly read the price information from the utility web page. The datasocket connection between the plant and the power gateway controller also worked well, as was noticed when the generators on the simulated plant responded to the control signals that came from the power gateway controller.

7.4 Test Series 3: Response of the PGC to Load and Tariff Variations

Test series 1 and 2 were made mainly to test the functionality and versatility of the power gateway controller and to check also the functionality of the experimental setup. After this test series 3 was run on more realistic scenarios in order to assess the response of the gateway to variations in the loads and assess the value of installing such a power gateway controller.

7.4.1 Response of the PGC to Changes in Load Shedding Setpoints

Aim

The aim was to test the loadshedding (cutting off loads) algorithm and study the effect of changing the setpoints for load shedding, on the economic benefit of the power gateway controller.

Method

Reference is made to Figure 5.10 which outlines the loadshedding algorithm. The customer specifies the acceptable hourly electricity costs as a criteria for loadshedding. When the electricity operations cost function (C_e) exceeds the specified value, the loadshedding algorithm is activated.

At each testpoint, data was captured and analysed. In this set of tests the following data was common

- variable loads PL1 (0-400 kW), PL2 (0-300 kW), (0-200 kW)
- variable buying price, bp (0.24-0.45 mu /kWh)
- variable selling price, mp (0.17-0.36 mu/kWh)
- constant Pg1 (50kW)
- constant averaged operational costs for the generators (Ca1 = 0.20 mu/ kWh, Ca2=0.30 mu /kWh and Ca3 = 0.35 mu /kWh)
- maximum value of Pg2 was set at 600 kW whilst the maximum value of Pg3 was set at 200 kW

The hourly cost of the current load was used as a test criteria for cutting off loads. A set criteria was specified, of how expensive the operational costs should be before load shedding started. This criteria was tested to determine if it was necessary to cut off any loads in order to reduce the expenses. The algorithm was scheduled to cut off all second priority loads PL2 and third priority loads PL3 when the hourly cost of the load exceeded the setpoint. The second priority loads like washing and drying equipment can easily be interrupted and restarted without significant inconvinience to the customer or damage to the equipment. The same thing applies to the third priority loads like the milling plant or irrigation plant which are rarely used as explained in section 5.1.

The setpoints for load shedding were adjusted in a series of steps as follows: 40 mu, 80 mu, 120 mu, 140 mu, 180 mu, 220 mu and 260 mu. These seven different set values were tested. The analysis of all the results obtained is given in Table 7.2, towards the end of this section. Figures 7.5 and 7.6 show some of the observations that were made. For test purposes, the loads PL2 and PL3 were switched on simultaneously at the beginning of each test cycle.

Observation

The lowest setpoint for loadshedding that produced noticeable responses was 40 mu. Below this value, the lower priority loads PL2 and PL3 were hardly given an opportunity to run and remained switched off most of the time. Figure 7.5 shows that initially the loads PL1(in pink) and PL2 (in orange) were on, and the operations cost function C_e (in red) in Figure 7.6 was higher than 40 mu. C_e is on the secondary Y-axis. PL2 was then switched off after the algorithm started running. During this time PL3 (in blue) was switched on but it was switched off after half an hour. Around 01.30 the loads PL2 and PL3 were allowed to run and PL3 only ran for another thirty minutes whilst PL2 could run for one hour before they were switched off again. PL2 was allowed to run a little longer because it had a higher priority.

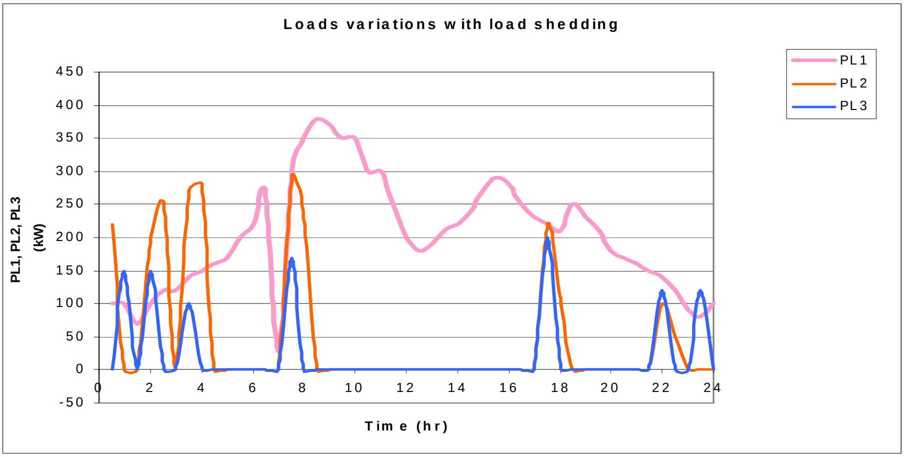


Figure 7.5: Load variations in response to the algorithm at set value 40 mu

These loads were allowed to run again around 03.00 but were also cut off, after a short run around 03.30 because their switching on also increased the electricity costs significantly. This also happened around 07.00, 17.00 and also at 22.00. In Figure 7.5 PL2 and PL3 were observed to run for short periods because the hourly electricity operations cost function C_e was higher than 40 mu most of the time. When C_e went below 40 mu, all the loads were allowed to run. The electricity costs were mainly a function of the loads and, when the loads PL2 and PL3 are off, C_e mainly followed the variations in PL1. The loads PL1 had the highest priority and they were allowed to run any time without being cut off.

The function Pcg (in green), which is a sum of the contributions of the local generators, shows that according to this simulation, the local generation was high.

Figure 7.7 shows how the individual generators contributed to the generation costs C_{sg}. The second generator Pg2 was switched on first at 03.00 because it had a lower averaged operational cost of 0.30 mu/kWh. When Pg2 switched on, the value of C_{sg} also went up significantly as shown by the results in Figure 7.7. It is also interesting to note how the switching on of the third generator at 07.00 also led to a further increase in the cost of generating locally, C_{sg}.

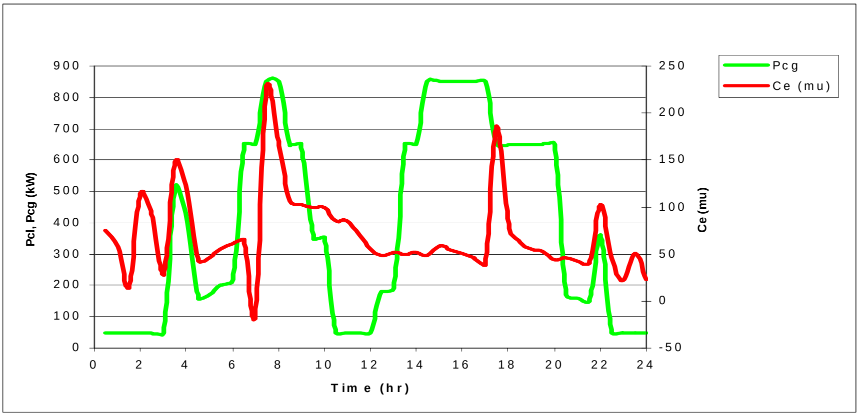


Figure 7.6: Corresponding generation output and operations cost function at 40 mu.

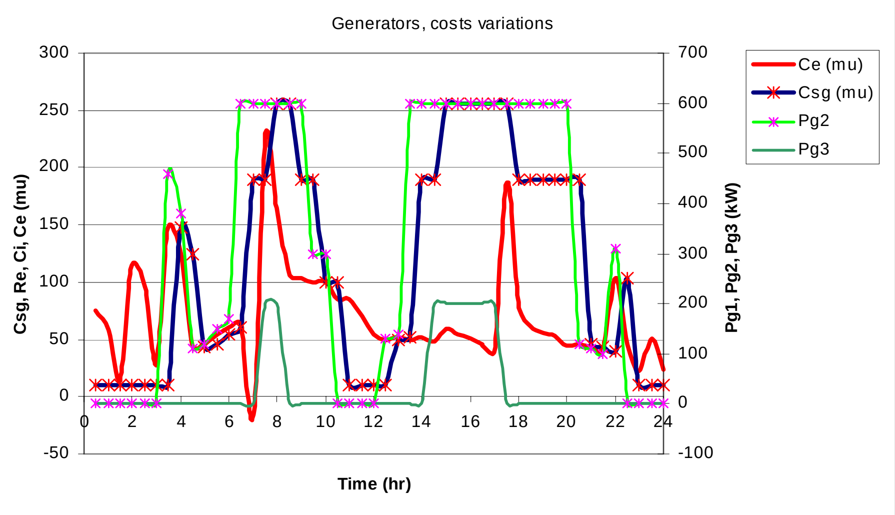


Figure 7.7: Costs and local generation.

Figure 7.8 helps us to take a closer look at the variations in the total load Pcl and total generation Pcg.

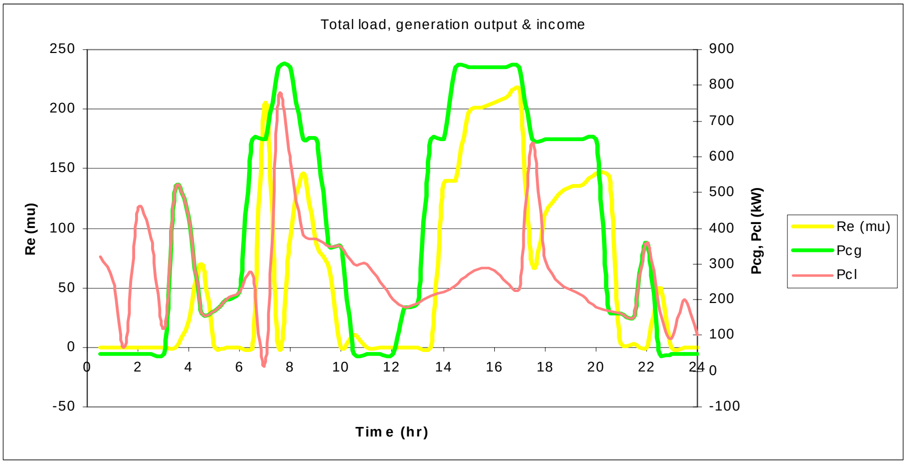


Figure 7.8: Total load, generation, costs and income

The total output of the local generators Pcg (in green) shows that most of the load was covered by local generation and there was significant excess power from the local generators. This excess power was sold to the network and the income obtained R_e is shown in yellow. The income generated when there is excess generation helps to keep the total costs of electricity relatively low. If there was no sale of this excess electricity, the electricity costs would have been very high.

The operation of the local generators is mainly infuenced by the prices. The following Figure 7.9 shows how the variations in spot selling prices affect the total output from the local generators. When the buying price exceeded 0.30 mu/kWh, the second local generator was switched on. The second generator Pg2's averaged operational cost was 0.30 mu/kWh. When the buying price became much more than 0.33 mu/kWh the third generator switched on causing a further sharp peak in the total output Pcg.

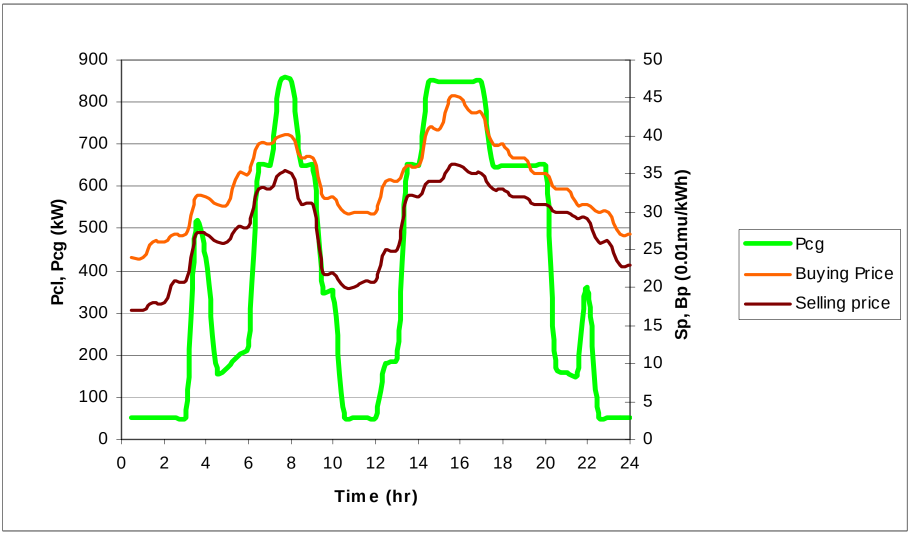


Figure 7.9: Variations in spot selling prices

The cumulative costs and income from the set of data used in this experiment are plotted in Figure 7.10.

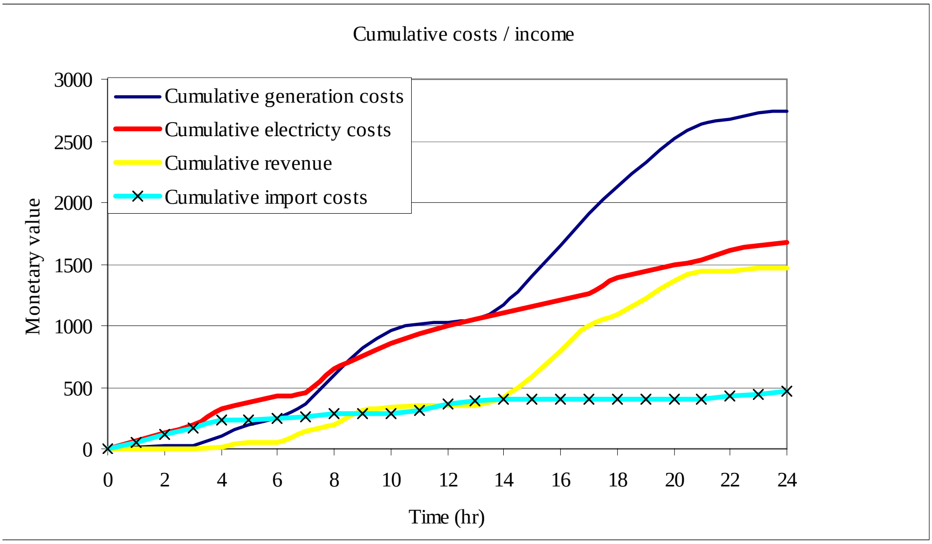


Figure 7.10: Cumulative costs and revenue at set value 40 mu

On this day, the cumulative electricity costs (in red) was found to be 1681 mu. The corresponding buying price on the spot market, was higher than the selling price as shown before in Figure 7.9. This meant that it was more expensive to buy electricity from the market on this day, making it economically viable to generate locally. Most of the loads on this day, were covered by local generation hence the cumulative cost of local generation was high 2739 mu, compared to the cumulative cost of imports which was 462 mu.

Comment

As the setpoint level increased the loads were allowed to run more often. This showed that the loadshedding algorithm was working and also that the setpoint level for load shedding is an important factor.

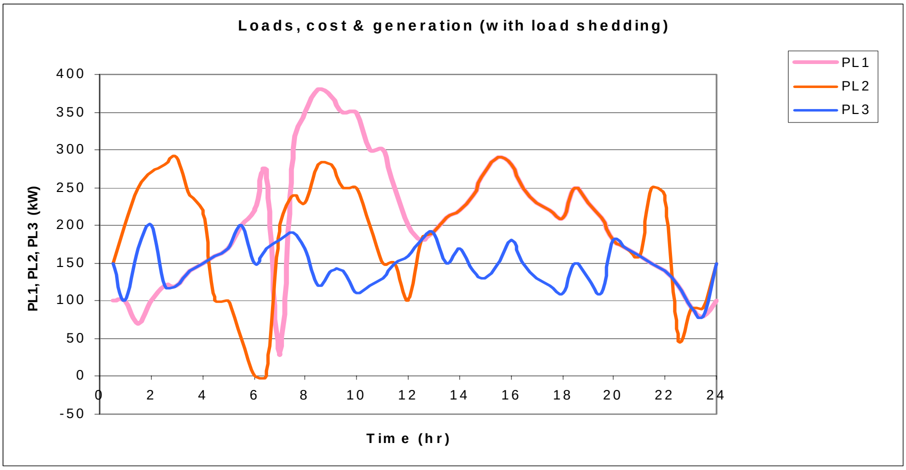


Figure 7.11: Load variations in response to the algorithm at set value 260 mu

At set value 260 mu, the results in Figure 7.11 show that the loads were almost always running. This is because the setpoint was then too high that it was out of range for there to be any meaningful shedding of the loads.

A summary of the analysis carried out for each of the selected setpoints is presented in Table 7.2.

Analysis of load shedding

The analysis on cumulative values obtained is as follows:

$$\text{The total energy expended over the time interval } t_1 \leq t \leq t_2 \qquad (7.7)$$

$$\text{is } \int_{t_1}^{t_2} P(t)dt \text{ for a continuous time power signal.} \qquad (7.8)$$

Firstly, half hourly sampled power signals were averaged out and integrated over one hour to find the hourly energy values. These were then multiplied by the hourly cost values to get the integrated energy costs per hour. These costs were summed over a over a period of 24 hours to get the cumulative energy costs for the day in mu. The cumulative generation costs were calculated as:

$$CumC_{sg} = \sum_{0}^{24}\sum_{1}^{n}\int_{0}^{t}(P_{gi}\cdot C_{ai})dt \qquad (7.9)$$

where n was the number of generation units

units that were running.

Cumulative revenue was expressed as:

$$CumR_{e} = \sum_{0}^{24}\int_{0}^{t}((P_{cg}-P_{cl})\cdot m_{p})dt \qquad (7.10)$$

Cumulative import costs as:

$$CumC_{i}= \sum_{0}^{24}\int_{0}^{t}((P_{cl}-P_{cg})\cdot(bp_{e}+bp_{t}))dt \qquad (7.11)$$

The cumulative electricity costs in the buying mode were

$$CumC_{eb} = \sum_{0}^{24}\left(\int_{0}^{t}(P_{cl}-P_{cg})\cdot(bp_{e}+bp_{t})dt + \sum_{i=1}^{n}\int_{0}^{t}(P_{gi}\cdot C_{ai})dt\right) \qquad (7.12)$$

whilst the cumulative electricity costs in the selling mode were

$$CumC_{es}= \sum_{0}^{24}\left(\sum_{1}^{n}\int_{0}^{t}(P_{gi}\cdot C_{ai})dt - \int_{0}^{t}((P_{cg}-P_{cl})\cdot(s_{p})dt\right) \qquad (7.13)$$

Table 7.2 contains the synthesized results from the seven tests of the setpoints for loadshedding. The set values of the acceptable hourly costs were in mu /hr whilst the cumulative electricity costs, cumulative costs of local generation C_{sg}, cumulative costs of imports C_i and the cumulative export revenue R_e ,were all in mu.

Table 7.2: Analysis of load shedding

Set value	Cum. Ce	Cum. Csg	Cum. Ci	Cum. Re
40	1681	2739	462	1465
80	2366	2948	725	1240
120	3083	3139	942	914
140	3256	3139	986	819
180	3528	3147	914	535
220	3688	3202	919	462
260	3724	3282	880	438

These results show that generally the electricity costs, import costs and the costs of local generation increase with increase in the setpoint level but the increase begins to slow down after 180 mu. This is as expected because when more and more loads are allowed to run, the electricity costs also go up and some local generators will also switch on to help supply the loads i.e. when their fuels costs become lower than the cost of importing. The revenue from local generation decreased with increase in the level of setpoint.

In order to assess the prospective benefit of having a gateway two scenarios were considered:

(*i)* when all the loads are covered by local generation, and the local generators are running at maximum capacity.

$$Benefit\ at\ Max\ Gen = \ (Full\ Generation\ costs - CumC_e) \tag{7.14}$$

This can be expressed as a percentage of the cumulative operations cost function C_e.

$$\%\ bmxg = \left(\frac{Benefit\ at\ Max\ Gen}{CumC_e} \cdot 100\%\right) \tag{7.15}$$

(ii) when all the loads are covered by imports (i.e. all the loads are supplied from electricity bought from the distribution network).

$$Benefit\ at\ Max\ Import = \sum_{0}^{24}\left(\int_0^t (Pcl \cdot bp)dt\right) - (CumC_e) \qquad (7.16)$$

This was also expressed as a percentage of the cumulative of the operations cost function $CumC_e$

$$\%\ bmxi = \left(\frac{Benefit\ at\ Max\ Import}{CumC_e} \cdot 100\%\right) \qquad (7.17)$$

The results obtained from the calculations are presented in Table 7.3.

Table 7.3: Analysis of load shedding (cont'd)

	Benefit of having a gateway as compared to not having one			
Set value	**Benefit at Max Gen.**	**% bmxg**	**Benefit at Max Import**	**% bmxi**
40	4463	266	-901	-54
80	3778	160	-588	-25
120	3060	99	-237	-8
140	2888	89	-95	-3
180	2615	74	242	7

Of interest are the two columns that give the % benefit of the gateway at maximum generation and at maximum imports. These results were plotted in Figure 7.12 and further analysis was carried out.

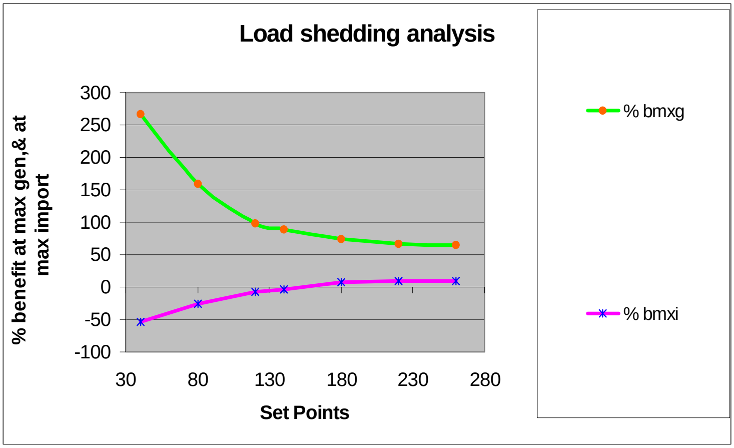


Figure 7.12: Cumulative Load shedding results

With reference to Figure 7.12, the setpoint-region between 80 mu and 180 mu is unstable. In this region, the % benefit of the gateway at maximum import changes from a negative value to a positive value. Within this region a slow down trend is observed on most of the other graphs. Generally beyond this region , the gradients of the curves of the curves are much less. If the gateway is set to operate below 80 mu the benefit would only be realised when there is local generation using this data set. The most preferable setpoint region would be between 180 mu and 230 mu when there is greater stability and the benefit is positive for both local generation and importing. Beyond this region, hardly any loadshedding would take place and this would result in high electricity costs.

Conclusion

The results show two interesting points:

- the setpoint level for loadshedding is an important criteria in the smooth running of the plant.
- The benefit of the gateway to the customer varies quite significantly with the setpoint level for the loadshedding.

According to the comparison at maximum generation, in this data set, this benefit varies between 266% for a low loadshedding level and 74% for a high load shedding level. However, the story is different when importing, because the gateway only becomes beneficial at much higher levels of loadshedding setpoints. This seems to indicate that given the prices in this data set, it is more beneficial to have as little loadshedding as possible. It is also interesting to note that it is possible to set the levels in such a way that the gateway is profitable for both local generation and import situations. The effect of frequent switching of the loads is another point to consider. It is important that the levels be set such that the switching is optimal in order to avoid damages to the equipment as mentioned on page 110.

One alternative method would be scheduling of the loads instead of cost controlled switching. Time controlled load shedding involves a fixed weekly schedule of the loads using timers in order to obtain beneficial results. Time scheduled load control has always worked well for situations where there are established set tariffs. However, cost controlled switching involves the use of real time data which is provided daily. The stochasticity of the spot market means that price profiles are variable on a daily basis and throughout the seasons. Fixing the load schedules would not produce optimal results if the electricity is being traded on the spot market.

7.4.2 Response of the PGC to Variations in Price Profiles

Aim

To investigate if there would be any benefit of having a power gateway controller when variations in the price profiles are taken into consideration.

Method

Tests were made for a weekday in summer and a weekend day in summer, a weekday in winter and a weekend day in winter. Different values were used for transmission tariffs and energy tariffs based on load profiles. Generally the profiles on a weekday is different from that of a day during the weekend and this also depends on the time of the year. These variations were necessary in order to assess the benefit of the gateway on different days in different seasons.

In this set of tests the following data was common

- variable loads PL1 (0-400 kW), PL2 (0-300 kW), (0-200 kW)
- constant Pg1 (50kW)
- constant averaged operational costs for the generators (C_{a1} = 0.20 mu/kWh, C_{a2}=0.35 mu /kWh and C_{a3} = 0.25 mu /kWh)
- maximum value of Pg2 was set at 600 kW whilst the maximum value of Pg3 was set at 200 kW

a) Price profiles on a summer day during the week.

The price profiles in Figure 7.13 were used for a typical day in summer during the week. There were two peak demand periods for electricity around 8.00 and 17.00. These peak periods coincide with the times when people use more electricity preparing meals and heating water or homes. The price for buying electricity on the spot market also followed the same pattern, but was much higher. Generally the utility sells electricity at a much higher price because of the transmission costs over long distances. However, the spot price for selling tends to be much lower because of the competitive bids to the spot market, in addition to the need for distribution costs.

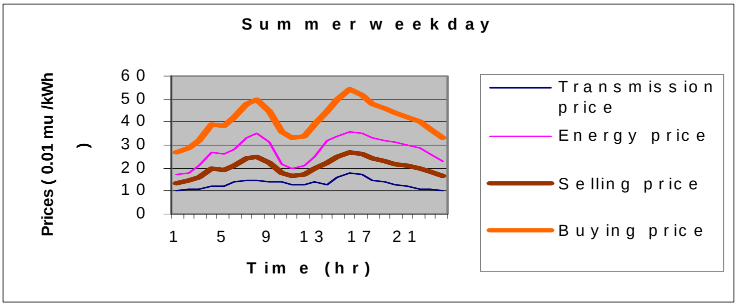


Figure 7.13: Price profiles on a summer day during the week

The buying price is the sum of the transmission price and the energy price as described in section 5.2.5 in equation 5.7 $bp = bp_e + bp_t$.

The profiles used in the algorithm had the following ranges respectively:

- variable buying price, bp (0.27-0.54 mu /kWh)
- variable selling price, s_p (0.14-0.27 mu/kWh)

Observation a)

The output in Figure 7.14 was observed. It shows how the variations in spot selling prices affected the operation of the generators.

Figure 7.14: Electricity operations cost function's response to summer price profiles during the week

In the following discussion, reference is made to both Figure 7.14 and Figure 7.15 when it comes to reading the buying prices and selling prices. Generator 3, Pg3 (in dark green), was switched on early, around 01.00 and it continued running throughout the day. Its averaged operational costs was 0.25 mu/kWh which became much lower than the buying price (in orange) from around 01.00. From Figure 7.14, it is clearly noticeable that the buying price is higher than 0.25 mu/kWh for the rest of the day and that is why generator 3 was allowed to run for the rest of the day.

The averaged operational costs for generator 2 was 0.35 mu/kWh. This only became lower than the buying price (in orange) between 06.00 and 10.00 and also between 13.00 and around 20.00. During these periods, Pg2 (in light green with pink stars), was allowed to run. The overall operations cost function (in red) closely follows the load pattern (in pink).

Figure 7.15 shows how the generation costs (in dark blue with red stars), the import costs (in light blue with black stars) and the revenue (in yellow) contribute to the cost benefit function (in red). The cumulative costs in Figure 7.15 show that the costs of local generation were much higher than the import costs on that day. The total cumulative costs in mu on this day are shown in Table 7.4.

Table 7.4: Cumulative costs for a summer day during the week

Cumulative generation costs (mu)	2675
Cumulative electricity costs (mu)	3762
Cumulative revenue (mu)	105
Cumulative import costs (mu)	1247

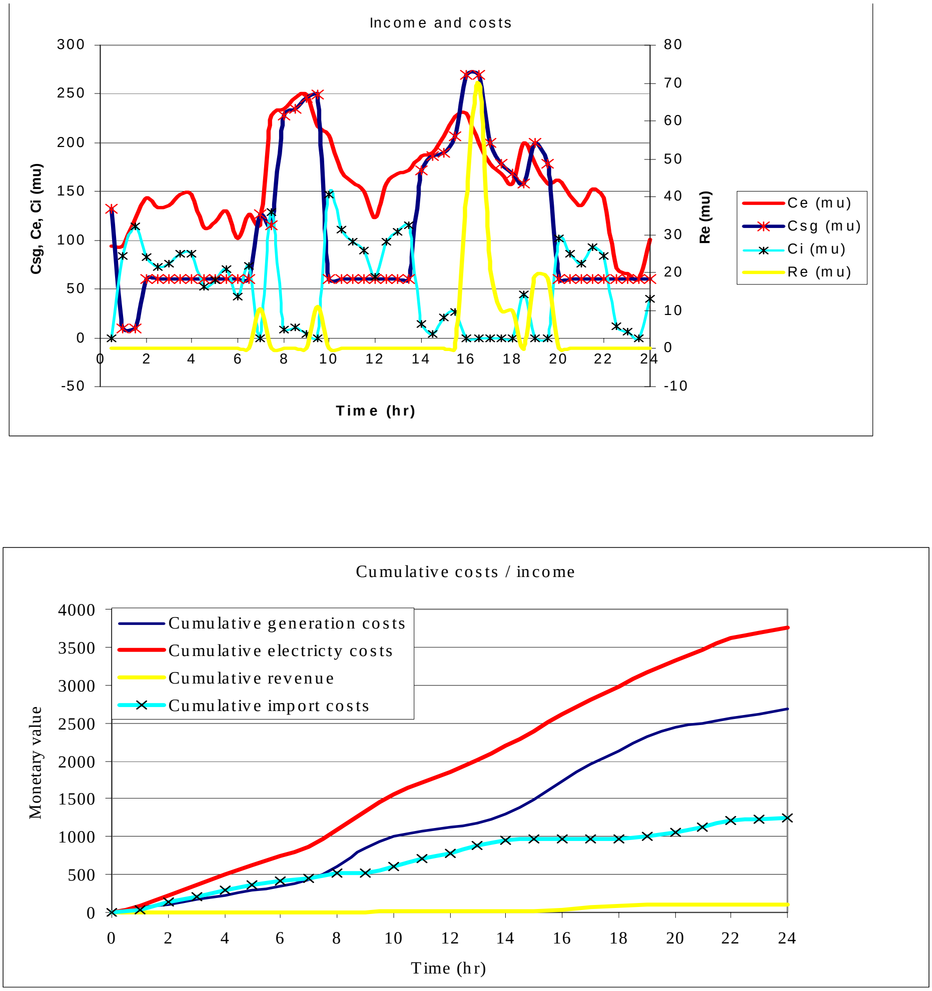


Figure 7.15: Income and costs, Cumulative costs and revenue for a summer weekday

When the expected operations cost function was calculated from the theoretical equation $C_e = C_i + C_{sg} - R_e$, a difference of 105 mu was found compared to the measured value of C_e. This amounts to 2.79 % deviation.

The benefit of the power gateway controller was also calculated using the equations outlined on page 117 and 118. It was found to be 72 % beneficial to have a gateway as compared to maximum local generation without having a gateway, and 18 % beneficial when compared to maximum import without having a gateway.

b) Price profiles on a summer day in the weekend.

There is a general difference in how consumers use electricity during the weekend from during the week. The shape of the profiles for a weekend day was therefore slightly different from those of a weekday. In the weekends, most people start their day late and people tend to cook food and take their baths at different times from the weekday. Fewer people also work during the weekends. Therefore the demand for electricity is generally much lower and spread out more evenly during the weekend than during the week. This means that electricity prices are generally lower during the weekends, and there are no significant peaks in the weekend profiles. The price profiles in Figure 7.16 were used for a typical weekend day.

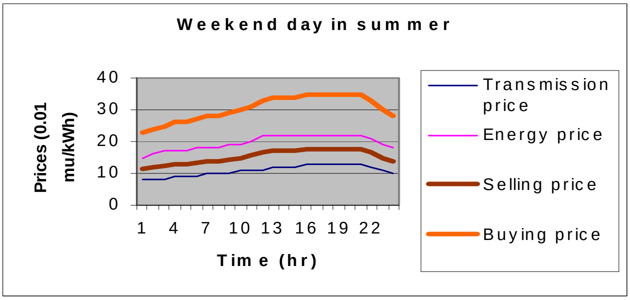


Figure 7.16: Price profiles on a summer day during the weekend

The profiles used in the algorithm had the following respective ranges:

- variable buying price, bp (0.23-0.35 mu /kWh)
- variable selling price, s_p (0.12-0.18 mu/kWh)

Figure 7.17 shows how the variations in spot selling prices affect the operation of the generators. This time generator 3, Pg3 (in dark green), was switched on around 3.00 a.m. which is two hours later than the case of a weekday. The generator remained on throughout the day. Pg2(in light green) did not switch on the whole day because its averaged operational costs of 0.35 mu/kWh was higher than the buying price (in orange) throughout the day. As before, the overall operations cost function (in red) again, closely follows the load pattern (in pink).

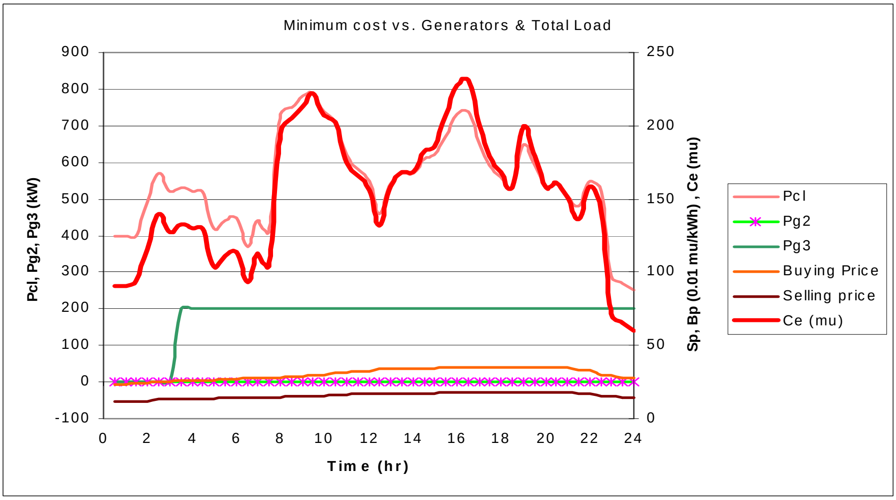


Figure 7.17: Electricity operations cost function's response to summer price profiles on a weekend day

Figure 7.18 shows how the generation costs C_{sg}(in dark blue with red stars), the import costs Ci (in light blue with black stars) and the revenue(in yellow) contribute to the operations cost function (in red). There were very little variations in the generation costs C_{sg} since only one generator was switched on once and it remained on throughout the day. The selling prices were not conducive to sell. All the locally generated electricity was used to supply the loads and there were no sales to the market on this day. This is confirmed by the high imports Ci.

The cumulative costs in Figure 7.19 show that most of the loads were supplied by imported electricity on that day.

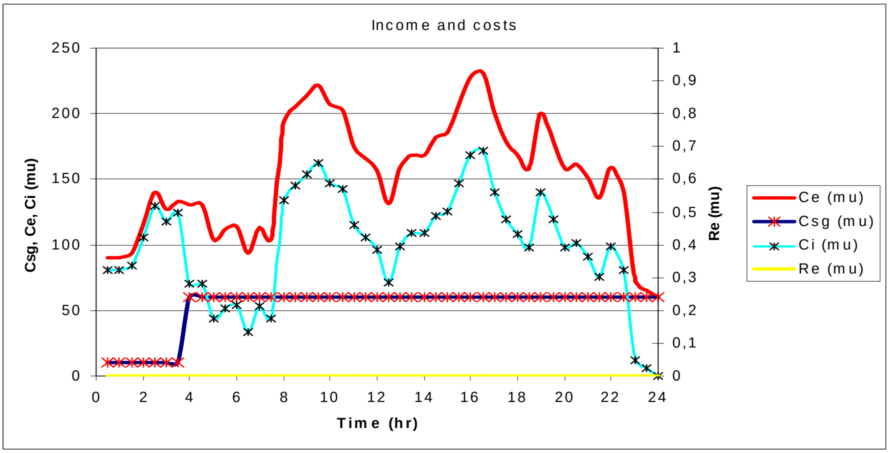


Figure 7.18: Income and costs on a summer day during the weekend

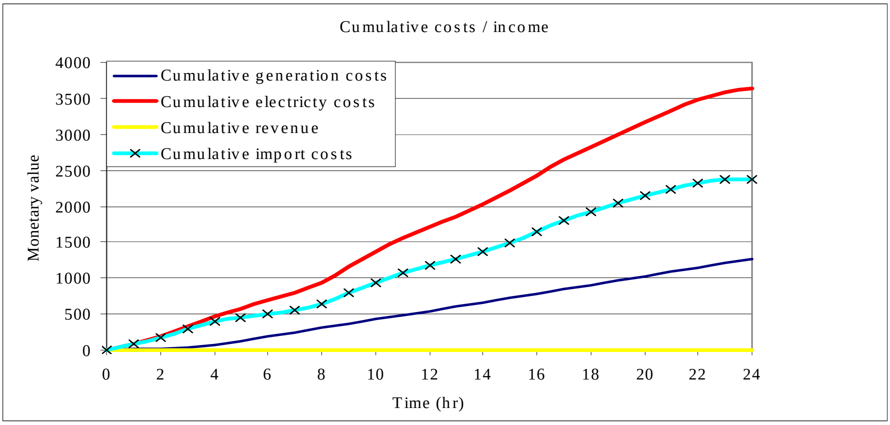


Figure 7.19: Cumulative costs and revenue on a summer day during the weekend

The total cumulative costs on this day were:

Cumulative generation costs (mu)	1265
Cumulative electricity costs (mu)	3642
Cumulative revenue (mu)	0
Cumulative import costs (mu)	2378

When the expected operations cost function was calculated from the theoretical equation $C_e = C_i + C_{sg} - R_e$, a difference of 105 mu was found compared to the simulated value of C_e. This amounted to 0.03 % deviation. From further calculations on the benefit of a power gateway controller, it was found to be 78 %

beneficial to have a gateway as compared to maximum local generation without using a gateway, and 11 % beneficial when compared to maximum import without a gateway.

c) Price profiles on a winter day during the week

Figure 7.20 shows the price profiles used to depict a typical day in winter. The winter prices are much higher than the summer prices. There are two peaks around 8.00 a.m. and 5.00 p.m. when most people cook their food and take their baths.

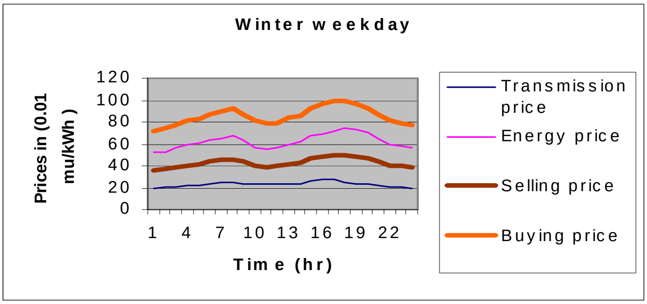


Figure 7.20: Price profiles on a winter day during the week

The profiles used in the algorithm had the following range:

- variable buying price, bp (0.72-1.00 mu /kWh)
- variable selling price, s_p (0.36-0.50 mu/kWh)

The response of the power gateway controller is plotted together with the load profiles in Figure 7.21.

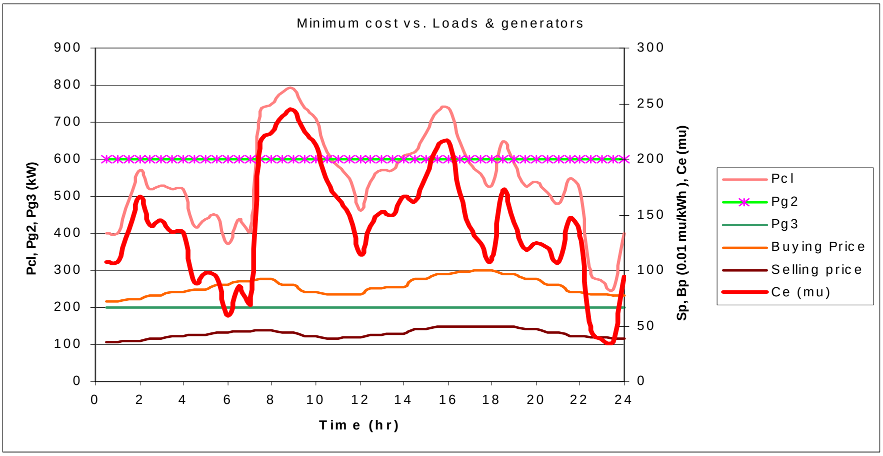


Figure 7.21: Electricity operations cost function's response to winter price profiles during the week

From the response of the power gateway controller, both generators Pg2(in light green with pink stars) and Pg3(in dark green) are on the whole day. This is because the winter prices for buying are much higher than the averaged operational costs of 0.35 mu/kWh and 0.25 mu/kWh throughout the day. Accordingly the cumulative costs in Figure 7.22 show that significant sales were made to the market since the generators were running at full capacity. All the loads were covered by local generation on that day, and there were no imports. This led to an overall reduction in the operations cost function C_e (in red).

Figure 7.22: Income and costs on a winterday during the week

Figure 7.23 helps to show the variations in the cumulative costs during the day.

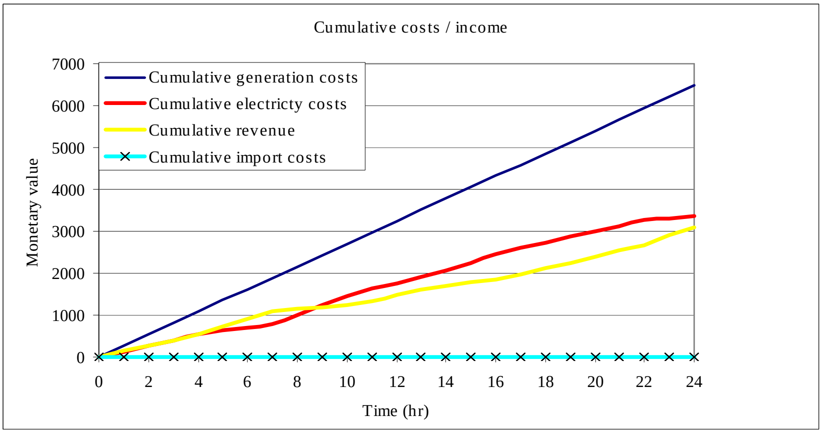


Figure 7.23: Cumulative costs and revenue on a winterday during the week

At the end of the day, the cumulative costs were:

Cumulative generation costs (mu)	6480
Cumulative electricity costs (mu)	3375
Cumulative revenue (mu)	3105
Cumulative import costs (mu)	0

If we calculate the expected electricity costs from the theoretical equation $C_e = C_i + C_{sg} - R_e$, an deviation of 100 mu was found in the simulated value of C_e and this amounts to 2.96 % of C_e. From further calculations on the benefit of a power gateway controller, it was found to be 77% beneficial to have a gateway as compared to maximum local generation without having a gateway, and 121 % beneficial when compared to maximum import without using a gateway.

d) Price profiles on a winter day in the weekend.

The shape of these profiles in Figure 7.24 are almost similar to those of a weekend day in summer except that the prices in winter are much higher than the summer prices.

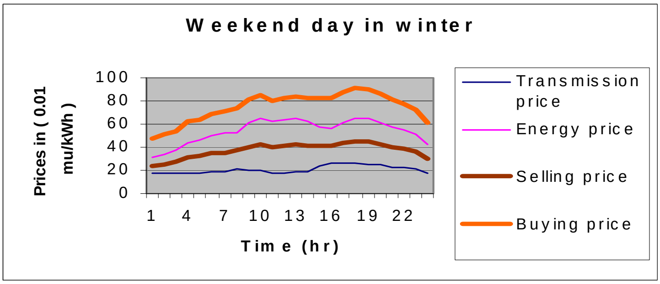


Figure 7.24: Price profiles on a winter day in the weekend

The profiles used in the algorithm had the following range:

- variable buying price, bp (0.48-0.91 mu /kWh)
- variable selling price, s_p (0.24-0.46 mu/kWh)

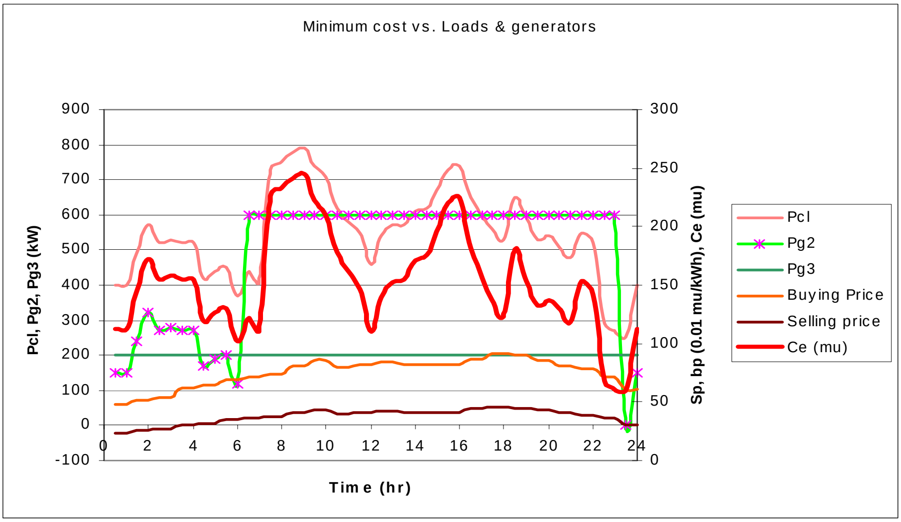


Figure 7.25: Electricity operations cost function's response to winter price profiles on a day during the weekend

Figure 7.26 show that Pg2 and Pg3 were on all day long however, with output from Pg2 being more variable. The cumulative costs in Figure 7.27 show that there were very little imports. Significant income was earned from the local sales.

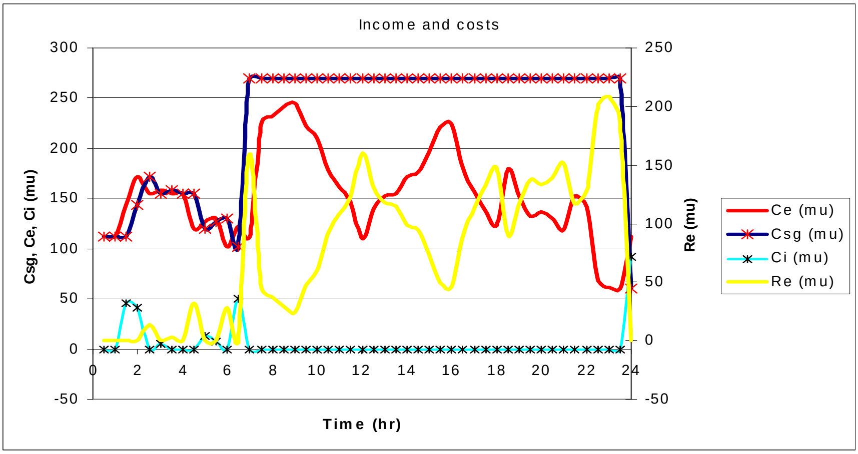


Figure 7.26: Income and costs on a winter day in the weekend

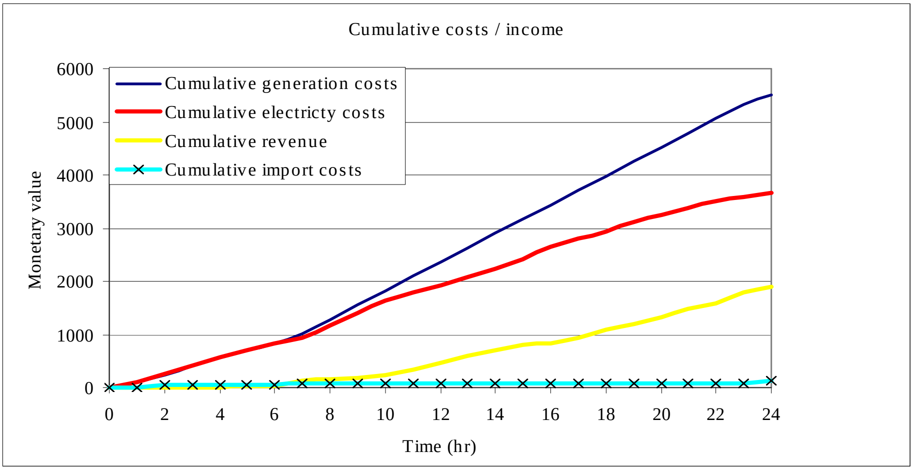


Figure 7.27: Cumulative costs and revenue on a winterday in the weekend

The cumulative costs at the end of the day were:

Cumulative generation costs (mu)	5496
Cumulative electricity costs (mu)	3665
Cumulative revenue (mu)	1889
Cumulative import costs (mu)	127

If we calculate the expected electricity costs from the theoretical equation $C_e = C_i + C_{sg} - R_e$, an deviation of 69 mu was found in the measured value of C_e and this amounts to 1.88 % of C_e. From further calculations on the benefit of a power gateway controller, it was found to be 92 % beneficial to have a gateway as compared to maximum local generation without using a gateway, and 143 % beneficial when compared to maximum import without using a gateway.

Analysis

The results of the responses of the PGC to price profile variations are summarised in the Table 7.5 and analysed.

Table 7.5: Summary of response to load profiles

Day	**Benefit at maximum generation**			**Benefit at maximum import**	
	mu	**%**		**mu**	**%**
Summer weekend day	2838	78		396	11
Winter weekend day	3105	92		4812	143
Winter weekday	2815	77		4420	121
Summer weekday	2717	72		660	18

The results in Table 7.5 show that the percentage benefit of the power gateway controller varies with variations in load profiles. All the figures obtained in this experiment were positive, indicating that it is beneficial to have the gateway whether it is a summer day or a winter day. The benefit is however variable, depending on the day of the week and also on the time of the year. It is also interesting to note that the percentage benefit of the gateway is much higher in winter than in summer. This should be expected since the higher electricity demand in winter leads to a corresponding higher benefit. The percentage benefit of the gateway was generally also higher during the weekends than during the week showing that control of generators and loads during the weekends yields more benefit than during the week.

If we take the theoretically calculated values as standard, the range of the deviations obtained from the measured values lies between 0 - 3%. This was most probably caused by delays in dataflow between the datasocket server and the utility server. The effect of the assumptions made in the design do not constitute any major significant changes to the results.

Variable solar

There were other experiments which were also carried out with all the generators varying. For example, the one illustrated in Figure 7.28 in which a summer weekday was simulated. The variable output from the solar cells (yellow with blue stars) is shown on the secondary axis.The averaged operational costs used for the generators were (Ca1 = 0.30 mu/kWh, Ca2=0.40 mu /kWh and Ca3 = 0.30 mu / kWh

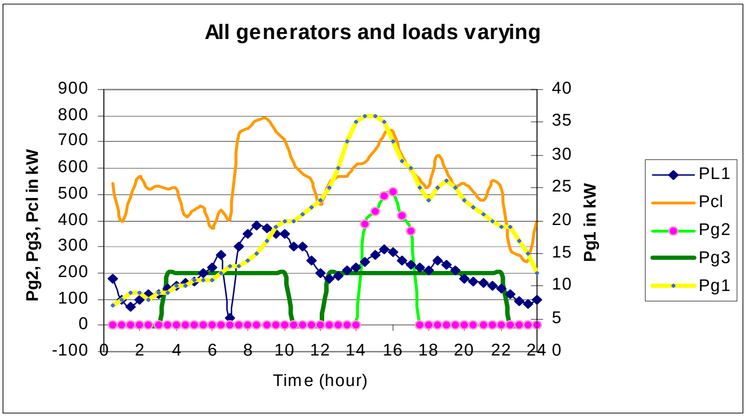


Figure 7.28: All generators varying

The graphs for the cumulative costs and revenue for this scenario is given in Figure 7.29.

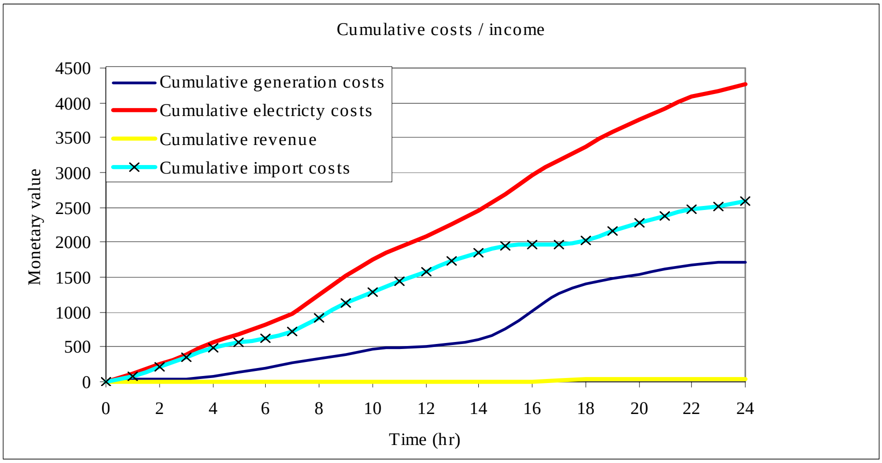


Figure 7.29: Cumulative costs and revenue on a summerday

In this case the benefit of the power gateway controller was also calculated. For this experiment it was found to be 78 % beneficial to have a gateway as compared to maximum local generation without having a gateway, and 6 % beneficial when compared to maximum import without having a gateway.

7.5 General Discussion

The algorithm correctly detected when it was time to make changes in the settings of the local generation units and settings of imports from or exports to the network. In all the cases investigated, the cheaper of the two generators was always switched on first and as the need arose the third generator came on later.

When the operations cost function went down, it meant that the market price was good for selling the locally generated electricity to the network. The customer then generated revenue from the local sales. This income significantly reduced the electricity costs at the customer premises. The gateway helped to make these sales in a more optimal way and also to shed off loads in an optimal way, thereby increasing the overall income of the customer.

The utility prices are very variable and the situation during the weekend is likely to be quite different from that during the week. This variation also differs with the time of year. However, the results obtained show that it is more economical to have a gateway than not to have one despite the variations in the utility prices that were used in the experiments. The benefit increases even further as the utility buys from local producers at more favourable prices. There were other experiments that were carried out in the testing of the gateway which have not been included in this report because of time and cost constraints. There were also ideas which could have been pursued further which are outlined in the following chapters.

According to the market models which were discussed in section 2.1.5, consumers have total freedom to participate in the energy markets at distribution level, in the fourth model which is the retail competition model. In the other three models this customer power gateway controller will not be very relevant. In a market model where there is monopoly, a small scale customer would not be allowed to sell any power to the network. In a model where there is a purchasing agency, or wholesale competition model only independent power producers who sell bulk power would enjoy the market.

A farmer in the retail competition model has total freedom to choose their supplier of electricity and can even have contracts to supply other customers. This means that this flexible gateway would also help the farmer to compare the various prices that other suppliers are offering and easily make changes to increase the profits.

7.6 References

- Nord Pool (2003) http://www.nordpool.com/nordpool/spot/index.html
- Trondheim Energiverk (2006). http://www.tev.no/tev/privatkunder/kraftpriser.asp#variabelkraftpris
- http://www.tev.no/tev/om_energi/kraftborsen.asp

Chapter 8

Conclusions and Discussion

This chapter concludes the investigations by summarizing the results and contributions of the study. The opportunities in electricity markets and challenges in distributed generation are discussed.

8.1 Summary of Results and Contributions

The main contribution from this study is:

- a designed and simulated power gateway controller which was proven to be beneficial through simulations. It has capability to optimize electricity costs at a customer premises, where there is potential to produce electricity locally and sell the excess electricity to the distribution spot market. The power gateway controller also has capability to communicate with the utility webserver and customer plant.

- a simulated model of the plant

- an experimental set-up which can be used for further developmental work and extended study of customer-utility interaction.

8.2 Opportunities

Presently gateways are being designed for home and building automation, as discussed in Appendix B, but very few include the possibilities of connecting electricity production units to the distribution network.

Deregulation and privatisation of the electricity supply industry has created new opportunities for research work. The opening up of electricity markets even at distribution level is motivating customers who have possibilities to participate in these markets to install electricity production units at their premises.

Once such investments are made, it is necessary to optimize electricity costs at the customer premises so that the benefit of investing in a local production unit is maximized. Customers who participate on the spot market need to receive the daily market prices in good time to plan and optimise their electricity costs. This creates the need to include communication and automation capabilities in the power gateway controller as a way of relieving the customer.

In order to make an in-depth study of the possibility to implement such a power gateway controller, a framework for it was designed and simulated.

The distribution network owners also benefit from these energy sales because they can extend their services to other needy customers. The results obtained from the last experiment show that in winter, the customer will run the local generators almost at maximum output. This will greatly relieve the utility because the demand for electricity is usually higher then. There will probably be no need for the utility to cut out electricity supply to other customers if there is significant local generation. The situation only becomes negative when the level of embedded local generation has become too high to affect the sales of the local utility. However, the utility will always have an upper hand because of its ability to influence the tariffs and supply regulations.

8.3 Challenges

In Zimbabwe, farmers tend to have one common major challenge, which might not be the case in Norway. Their annual income is generally a function of the seasons and weather patterns. The availability of electricity on a farm removes this limitation to a much greater extend. Farmers can have other income generating projects such as food processing and timber processing. The availability of electricity in remote areas gives better opportunities for projects of dairy products, meat and fruit products in addition to milk production.

The way in which distributed generation will be handled in the future will vary from country to country depending on each country’s future energy and food policies. This work has been based on speculative future policies which could be implemented in some countries.

Chapter 9

Further Work

In conclusion, directions to continue this research work are outlined. This work could be developed in many ways. Three suggestions of particular interest are outlined below:

9.1 Development of the PGC as a Hardware Unit

The power gateway controller could be realized as a separate hardware unit where the software could be downloaded or as a CPU based unit connected to an I/O system. In the future, the static optimization algorithm will be an integrated part of the software package. This prototype unit can be installed at a customer premises and further tests can be made to investigate how such a unit would benefit the customer and also how it would interfere with the daily routines of the customer.

The cost and life span of the power gateway controller and installation of connection equipment needs to be weighed against the savings made from selling and optimizing electricity costs at the customer premises. When the actual cost benefit analysis is confirmed in a real life set up, recommendations can be made for implementation of such gateways on a bigger scale.

9.2 Expansion of the PGC to a Substation Unit

The power gateway controller could be expanded to cater for many customers in a community. This unit could be housed in a local substation where the load profiles for a bigger area can be monitored and controlled like a mini SCADA (Supervisory Control and Data Acquisition) unit. Direct model based optimization e.g. using the Nealder-Mead method could be incorporated in such a unit. The dynamics of the local loads could be incorporated since the cost of such a unit would be big enough to justify more complexity and accuracy in tracking the load variations. Statistics of the load variations in the area would provide useful information for planning purposes. Another interesting scenario that could be studied is one where different owners co-operate using a common controller. Here different market models could be tested where customers sell power not only to the utility but also to each other in an open access market like the retail market model discussed in section 2.1.5.

An example in Norway could be an installation project in a region like Fosen or Åfjord where there are farmers with small scale hydropower installations distributed around the area. Water boilers can be remotely switched on and off using the intelligent controller in order to save energy and reduce electricity costs.

9.3 Other Functionalities in the PGC

The technical functionality of a single customer power gateway controller can be expanded to include functionalities like power quality measurements and control, two way protection, and advanced customer services.

Various effects may be considered to originate in the transmission and distribution networks and can affect the voltage or frequency of the signals to which the loads and generators are connected. It is important to monitor and control the power quality of output waveforms from distributed generators to ensure that they operate within acceptable limits. When an embedded generator is connected to a distribution network the voltage quality of the network could be affected. This would inconvenience other customers. The steady state voltage, voltage fluctuations during continuous operation and during switching operation should conform to the local utility's standards. Transient voltage variations and harmonic distortion of the network are significant aspects of power quality.

Protection at the interface of generator and distribution network is for the safety and integrity of the systems and equipment of both the utility and the generator. The principal protection requirements are for overcurrent, earth faults, discrimination and islanding i.e. preventing continued generation with a trapped load.

Utilities would have the possibility to offer to their customers, extra services like security / alarms, building or home energy management, home shopping, cable TV, information services and telecommunication services through installation of gateways at the customer site.

9.4 Farm wide optimisation

The research work could be extended to optimize the use of all the resources on the farm, like energy, water, animals, people and consumables. The production on the farm could be maximized and costs could be minimized without violating the process, financial or equipment constraints. Optimizing the use of all other resources on the farm, would help to improve the farmer's profits.

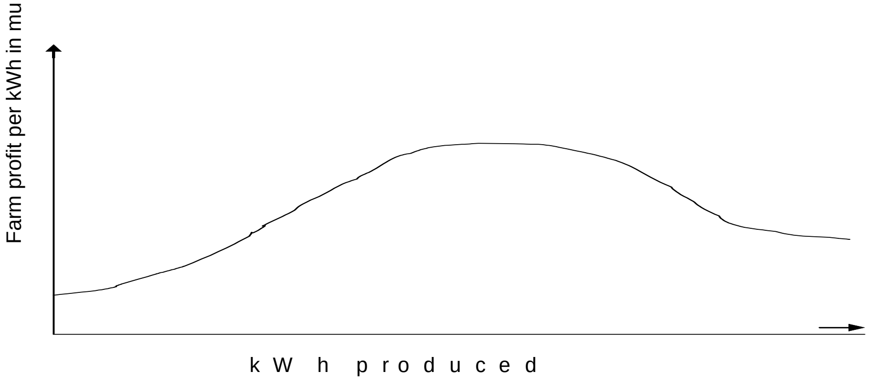


Figure 9.1: Variation of farm profit with KWh produced

If an assessment of how much total profit is earned from each kWh produced is carried out, as shown in Figure 9.1, the optimal production levels can be set for profitable operations at the farm.

9.5 Final Conclusion

When a customer has access to internet technology and participates on the electricity spot market, it is possible to increase the benefit of installing small scale electricity production units by installing a power gateway controller which has communication and optimization capabilities. Both the distribution utilities and customers are likely to benefit from widespread distributed generation and use of internet technology. This work shows that it can be beneficial to encourage electricity consumers to invest in local electricity production units that would be connected to the distribution network.

Appendix A

Southern African Power Pool

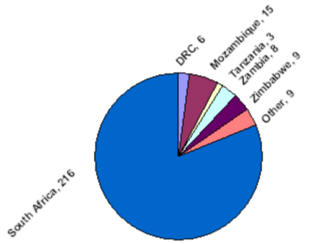
The Southern African Power Pool was created in 1995 when member governments of SADC signed an Inter-Governmental Agreement. The agreement confirmed the region's commitment to expand electricity trade, reduce energy costs and provide greater supply stability for the region's national utilities.:

- Botswana Power Corporation (BPC);
- Electricidade de Mocambique (EDM);
- Angola's Empresa Nacional de Electricidade (ESCOM);
- Electricity Supply Commission of Malawi (ENE);
- South Africa's Electricity Supply Commission (Eskom);
- Lesotho Electricity Corporation; Namibia's NamPower (LEC);
- Swaziland Electricity Board (SEB);
- the Democratic Republic of Congo's Societe Nationale d'Electricite (SNEL);
- Tanzania Electric Supply Company (TANESCO);
- Zimbabwe Electricity Supply Authority (ZESA) and
- Zambia Electricity Supply Corporation (ZESCO).

Southern African Region :Electricity and General Information

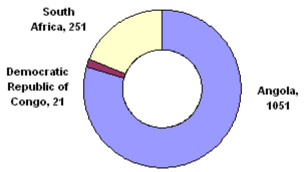
Country	Utility	No. Of Customers	Generation Sent Out in GWh	Installed Capacity in MW	Max Demand in MW	Expected MD in 2010 (MW)
Angola	ENE	119 392	1 993	624	317	952
Botswana	BPC	108 985	2 282	132	393	562
Lesotho	LEC	42 390	429	72	90	142
Malawi	ESCOM	135 000	1 177	285	227	394
Mozambique	EDM	245 859	1 392	177	273	410
Namibia	NamPower	3 265	1 421	393	371	713
South Africa	ESKOM	3 505 039	217 286	42 011	31 928	40 057
Swaziland	SEB	45 300	991	51	171,5	208
Tanzania	TANESCO	485 661	3 052	591	506	873
DRC	SNEL	301 478	6 084	2 442	991	1 207
Zambia	ZESCO	310 000	8 466	1642	1 255	1 529
Zimbabwe	ZESA	540 738	8 799	1961	2 007	2 624

Country	Population in millions	% of Traditional Fuel Consumption	GDP per capita ppp US$	HDI in 2002	Electricity Consumption per capita
Angola	13,2	79,2	2130	0,381	125
Botswana	1,8	N/A	8170	0,589	N/A
Lesotho	1,8	N/A	2420	0,493	N/A
Malawi	11,9	86.6	580	0,388	76
Mozambique	18,5	90,5	1050	0,354	70
Namibia	2	N/A	6210	0,607	N/A
South Africa	44,8	12,9	10 070	1	4 313
Swaziland	1,1	N/A	4550	0,519	N/A
Tanzania	36,3	92,8	580	0,407	85
DRC	51,2	94,6	650	0,365	93
Zambia	10,7	87,1	840	0,389	598
Zimbabwe	12,8	68,6	2400	0,491	950

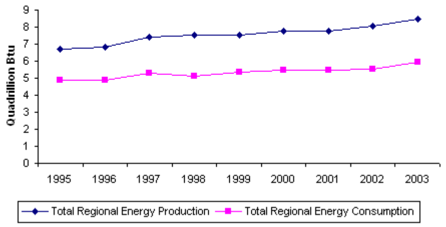


Southern Africa Electricity Generation, by Country, 2003 (Billion Kilowatthours)

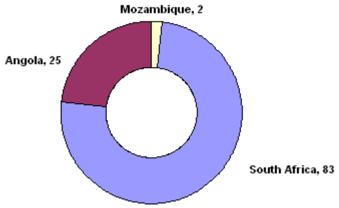
Southern Africa Petroleum Production, by Country, 2004 (Thousand Barrels per Day)



Southern Africa Energy Production and Consumption



Southern Africa Natural Gas Production, by Country, 2003 (Billion Cubic Feet)



During the last quarter of 2004, about 260MW of hydropower was commissioned in Angola, 80 MW at Ubongo in Tanzania, 2 x 150 MW generators at Kafue Gorge in Zambia was rehabilitated giving an additional 30 MW capacity. At Kariba North the first generator was upgraded from 150 to 180 MW and 4 x 10 MW machines were re-commissioned at Victoria Falls Power Station and 190 MW was expected to be commissioned at Campden in South Africa. That increased the regional generation capacity by 620 MW. Tanzania discovered gas deposits and is in the process of constructing CCGT power stations.

According to the SAPP's 2005 annual report, expected new projects in Zimbabwe are given in Table 0.1. These would amount to new commissioning of 2300 MW by 2010.

Table 0.1: Expected projects in Zimbabwe

Project	**Capacity [MW]**	**Type**	**Expected Commissioning Year**
1. Kariba South	300	Hydro	2007
2. Hwange 7 & 8	600	Thermal	2008
3. Lupani	300	Gas	2009
4.Western Power Station	1200	Coal	2008
Total	**2300**		

Other new transmission lines

A 400 kV line was completed in 2000, which links Swaziland and Maputo. The Zambia-Tanzania Interconnection Project involves construction of 700 km of 330-KV transmission line, and is expected to supply up to 200 MW of power. There is a proposed 220 kV line to link Livingstone in Zambia and Katima Mulilo in Namibia for the transfer of 200 MW. A combination of AC and HVDC light technology is being studied.

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Appendix B

Information and Communication Aspects

B.1 Communication Technologies

Tremendous improvements have taken place since people started using telephones in the late 1880’s. At that time the outside plant was nothing more than a wire and a fence post where voice and telegraph signals were shared. The plant design has progressed from bare iron wires to copper wires, coaxial cables and fibre optic cables and now to wireless networks.

Multiplexing technology has also improved from Frequency division multiplexing (FDM) to time division multiplexing (TDM). Although the copper wire is still being used as a medium in some areas, TDM allows the local phone line to handle internet access, alarm systems and control systems in addition to phone calls. If coaxial cable or fiber optic cable is used as the facility to the central exchange, it is also possible to carry television signals on the TDM system.

Switching systems have improved from step by step Strowger systems to computerised switching systems. Today the only major difference between a stored program control switching system for a private switching system (PBX) and an SPC for a public switch is the speed of the central processor, the amount of memory, the size of secondary storage devices and the number of peripheral devices attached to the system.

B.1.1 Telecommunication networks

A telecommunication network contains a large number of transmission links connecting different locations(also known as nodes) as shown in Figure 0.1.

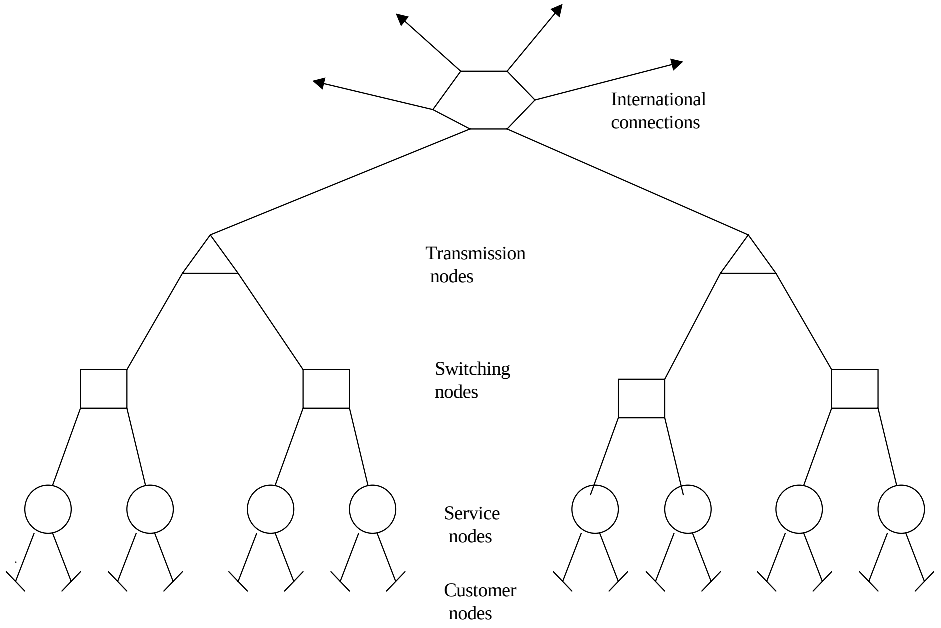

Figure 0.1: Telecomminucation network

In practice there are several networks providing different services but they use common transmission bearers for example:

Public Switched Telephone Network (PSTN)

The customer access network or local distribution network normally provides a pair of twisted wires from each customer premises to the local exchange. The PSTN was developed to transmit analog electrical signals from one phone to another. Voice signals are in the range 300 Hz to 3300 Hz. The twisted pair local loop has a narrow bandwidth and therefore is not able to handle high-frequency signals.

The PSTN has gradually evolved into a digital circuit network where analog voice signals are converted into digital signals by a codec on the line card and carried by the digital PSTN. When it comes to data communication, these circuit switching networks are suitable for real time applications and high speed communication services.

Circuits can be leased from the public telecommunications operator as private networks. Leased lines can cover a wide range of bandwidths with limitations on the number of speed classes. It is however expensive for low density communication.

Packet Switched networks

Packet switching networks are suitable for long distance, low density, middle-speed ranges. Data is broken into packets which are numbered and host and destination addresses are attached to the packets. At the destination nodes, the packets are error checked and retransmitted if necessary, using the X25 protocol to ensure perfect data delivery. Packet switching leads to the future broad-band Integrated Services Digital networks (B-ISDN). ISDN is a set of standards for a digital network carrying both voice and data communications. It includes many different sizes of digital transmission paths.

Special Service Networks

Asynchronous Transfer Mode (ATM) networks can cover the widest transfer speed range. ATM is a universal, service independent switching and multiplexing technique which does not require any fixed channel rate or speed. According to Beyda, W.J. (2000) the basic building block of an ATM link is a 53 byte cell which is made up of a 5 bytes header and a 48 bytes payload. Routing decisions are made before the cells are transmitted and switches are preprogrammed with tabled instructions for handling cells on arrival. The bits are transmitted synchronously but they arrive at an unpredictable rate. ATM offers various service classes. However, it is expensive over long distances. The number of bits transmitted, quality of service and time of day usage are some of the factors considered in working out ATM rates.

Wireless and Mobile Multimedia Networks

Wireless transmission does not use any conductors or optical cables to transmit and receive information. Microwave, radio, infrared light, and lasers are forms of wireless communication. Microwave transmission can be terrestrial or satellite sytems and electromagnetic waves between 2 GHz and 40 GHz are used. Table 8.2 summarizes the electromagnetic spectrum and its applications.(Elahi, A. (2001)

Tatipamula, M., Khasnabish, B. (1998) report that wireless local area networks have supported the Internet protocol suite for quite sometime although the networks are slower than commonly deployed wired networking alternatives like 10- and 100 BASE-T Ethernets.

Frequency range	Name	Application
3-30 kHz	Very Low Frequency (VLF)	Telephone
30-300 kHz	Long Waves (LW)	Radio Frequency for Navigation
300-3000 kHz	Medium Waves (MW)	CB Radio Frequency
3-30 MHz	Short waves (SW)	TV and FM radio
30-300 MHz	Very High Frequency (VHF)	AM Radio Frequency
300-3000 MHz	Ultra High Frequency (UHF)	TV
3-30 GHz	Super High Frequency (SHF)	Terrestrial and satellite Microwave
30-300 GHz	Extreme High Frequency	Experimental
>300 GHz	Infrared Light	TV Remote Control

Figure 0.2: Electromagnetic Frequency Spectrum

There are various methods of communication that one could utilize in gateways. The choice of the communication route depends on the quantity and frequency of data input. Examples of possible available communication technologies include twisted pair metallic cables, coaxial metallic cables, fibre optic cables, distribution power line carrier, internet, VHF radio, satellite, leased service, point-to point UHF radio, multiple access radio system, trunked mobile UHF radio, spread spectrum radio microwave radio e.t.c.

B.2 Internet Access

Internet access from the home and many businesses presently take place at the speeds of 28.8 Kbps or 56 Kbps using relatively cheap and reliable modems. These modems operate over existing voice grade copper pairs. Such speeds are adequate for e-mail and small file transfers. Effective use of the web especially where graphics are involved, require more bandwidth than is achievable over voice grade lines. New technology now being deployed is increasing this bandwidth. the ISDN (Integrated services Digital Network) can provide access up to 128 Kbps. this is fast enough for low quality video such as desk-top video conferencing, but is still slow for video even at VCR quality levels. The Asymmetric digital subscriber line (ADSL) is another option being offered. It operates over the existing copper pairs at downstream data rates between 1.5 up to 9Mbps. The upstream data rate is from 16Kbps to 640 Kbps. ADSL does not affect the current telephone voice channel. It uses Discrete Multi-Tone (DMT) encoding methods, which use QAM to divide the bandwidth of the channel into multiple subchannels.

The cable television operators are using their wide bandwidth coaxial cable and fiber-optic cable to provide high speed internet access using cable modems. These modems operate at a higher speed of the order of 10 Mbps and in some cases 27 Mbps. The bandwidth is shared and not all of the 10 to 27 Mbps is available all the time. The current coax system architecture was not designed for two way communication and tends to be noisy in the upstream direction.

Internet access is now also being offered by Direct brodcast satellite (DBS) operators. Users can download files and view web pages at speeds up to 12 Mbps although the upstream traffic must talke a different route.

Common internet hardware devices and the corresponding maximum theoretical bandwidth are given in Table 0.2:.

Table 0.2: Physical layer network technologies

Physical layer Hardware	**Speed (in bytes/second)**
Cellular modem (wireless)	19K
Serial modem (analog phone line)	56K
ISDN modem	128K
T1	1.544M
ADSL modem	9M
Cable modem	30M
T3	44.736M
OC-12	622.08M
10-BaseT Ethernet (LAN technology)	10M
100-BaseT Ethernet (LAN technology)	100M
Gigabit Ethernet (LAN technology)	1000M

(K=Kilobyte=1024 bits; M=Megabyte=1024K)

Important measures for transport capacity in communication networks include bandwidth, transmission delay and quality of service. Bandwidth availability is one of the biggest limitations in building internet enabled systems. The units for bandwith increase from bits per second (bps) to kilo bits per second (Kbps), mega bits per second (Mbps), gigabits per second (Gbps) e.t.c. The available bandwith is mostly a function of the physical layer. In the 21st century, telecommunications and data communications are converging. The demand for multimedia business communications including voice, image and high speed data is gradually expanding.

Wireless Local Area Network or IEEE 802.11 is a new LAN technology that uses radio frequency or infrared waves as transmission signals and free air as the transmission medium. Users can access the organization’s network from any location inside the organization.

B.3 Data Integrity and Security

Data communication networks have important concerns like data integrity and security. Errors can be reduced by detecting and flagging them or by requesting retransmission when they are detected. Error checking, parity checking, cyclical parity, the Hamming code, various checksums and cyclical redudancy are some of the methods for implementing error control.

The use of passwords, historical and statistical logs, closed user groups, firewalls and encryption help to secure data transmission. Messages can be sealed, sequenced, signed and stamped. secret keys and algorithms can be used for data confidentiality. Data encryption can be performed using hardware, software or firmware methods. New algorithms are constantly being developed to ensure data security.

B.4 The TCP/IP Protocol

The customer who has access to the internet can get access to the daily electricity prices that are posted on the webpage of the utility. This customer can also enable the plant (i.e. loads and generators in this case) so that he can monitor or control the plant remotely. The plant can be viewed from another location on the network. The observation can be done with a client while the process runs on a server. In a remote control application, the customer can send some data, messages or inputs back to the server process if he needs to.

The Transmission Control Protocol over Internet Protocol (TCP/IP) is a network technology for inter-device communication. It has almost become universally implemented as a standard. The TCP/IP specifies how the Network layer and the Transport layers of the OSI model should work.

TCP/IP communication can take place over a variety of communication media like Ethernet, wireless radio or modem. It is platform independent and is supported by different operating systems like Windows, MacOS, Unix e.t.c. It is a connection based protocol where the connection between the origin and destination computers is maintained during data transfer and it is closed after the transfer.

Application level communication protocols include

. HTTP (-defines how web browsers and servers work and relies on TCP/IP)

. FTP (handles the transfer of files between devices)

. E-mail (e.g. SMTP, POP3 protocols)

. Client-server applications

B.5 Web technologies

A URL (Uniform Resource Locator) basically allows us to specify where a document is on the web by providing the Internet address and path of the document.

The generalized syntax for URLs is:

scheme://host[:port]/path[/extra-path-info][?query-info]

`Scheme` is the protocol used to connect to the host. `Host` is the Internet address of the host. `Port` is the optional port number for the requested service e.g. Web servers are usually run on port 80. `Path` is the path to the document or data source. extra-path-info is optional information sometimes used by CGI programs. The character “?” always comes before `query-info` which can contain optional parameters used by CGI programs.

An example of a basic syntax for URL’s is

`http://host/path` where `http` specifies that we are using the Hypertext Transfer Protocol, `host` is the internet address of the website and `path` points to the document requested on the server.The URL

`http://fireworks.com/info/` tells a Web browser to use the hypertext transfer protocol to fetch the hypertext document “info” at the Webserver on fireworks.com. The URL :

`ftp://fireworks.com/documents/manual.pdf`

tells an Ftp application to use File Transfer Protocol to fetch the pdf document called `manual` from the directory “documents” on the ftp server at fireworks.com.

There are other schemes that can be used for accessing data over the Web. Table 0.3 gives examples of some protocols that are used to transfer information.

Table 0.3: Protocols for transferring information

Scheme	**Meaning**
http://	HyperText Transfer Protocol ; for Web sites
ftp://	File Transfer Protocol; for uploading and downloading files at FTP sites
Gopher://	Goper sites. An older, less used type of server that indexes documents.
News://	News servers.
File://	A scheme that does not use TCP/IP but points to a document through your local file system.
telnet://	Not really a URL (since it doesn't point to a document), but can be used to initiate a telnet session with the specified host.
dstp://	Datasocket transfer Protocol; a proprietary protocol from National Instruments for sending instrumentation data over a network.

Grinden, B., Sæle, H. (1998) summarized the driving forces for remote metering in Norway and the need to have two way connection between electricity consumers and the distribution network. They also give important specifications for a residential customer gateway. Zahariadis, Th., Pramataris, K.and Zervos, N. (2002) discuss a residential gateway initiative which provides a single point of convergence between the in-home and the access networks. In their paper, they review some available home-networking technologies and provide a comparison of the competing broadband in-home technologies. They report that more than 50 candidate technologies, working groups and standard specifications exist.

Figure 0.3 gives an idea of a few of the various possible choices for communication inside the building and outside the building.

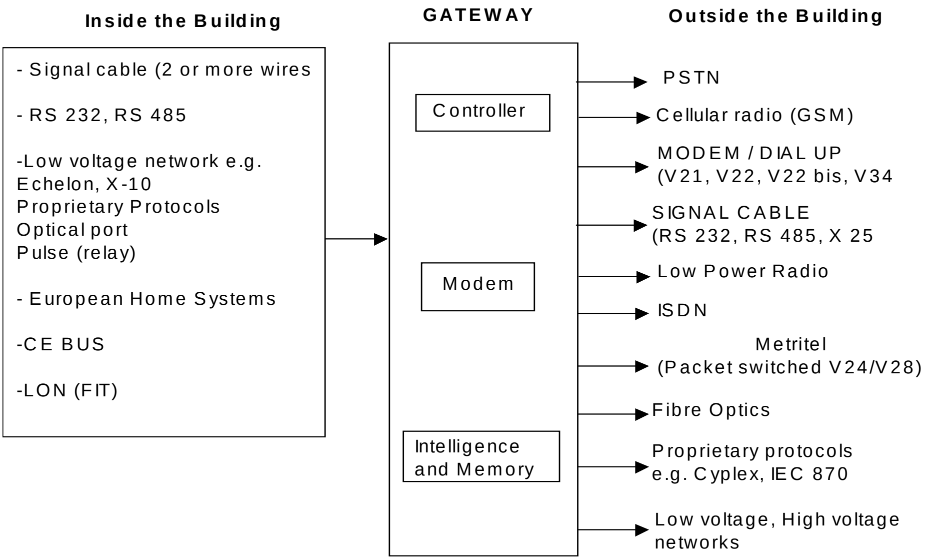

Figure 0.3: Gateway outline

Various functionalities can be included in the gateway design e.g. two way metering, two way communication, energy management functions, power quality monitoring, two way protection and remote monitoring and control functionalities.

Readings of daily (half) hourly consumption can be taken and temporarily stored in the gateway's memory store. Periodically these stored readings can be transferred to the utility's database for billing and archiving. Customers can get access to this information when they want to do their energy audits. Forecasting of utility revenue is another added advantage. The utility may also be able to detect failures in the meters or tampering much earlier. According to Singhal, S. (1999) and Szilvagyi, M.J. (1999) utilities in many countries like India, UK and South Africa could save significant revenue by incorporating communication functionalities.

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Appendix C

Electrical Load Measurements

C.1 Characteristics of electrical loads

Electrical loads absorb power. The instantaneous power in watts absorbed by an electric load, is a product of the instantaneous voltage across the load in volts and the instantaneous current into the loads in amperes.

The average power absorbed by purely inductive loads and purely capacitive loads is zero i.e. they do not dissipate any energy.

General RLC load.

Consider general load composed of RLC elements under sinusoidal-steady-state excitation, where the load current is of the form

$$i(t) = I_{max}\cos(\omega t + \beta) \quad Amps \tag{0.1}$$

and the voltage is:

$$v(t) = V_{max}\cos(\omega t + \delta) \quad Volts \tag{0.2}$$

The instantaneous power by the load will be

$$p(t) = V(t)i(t) = V_{max}I_{max}\cos(\omega t + \delta)\cos(\omega t + \beta) \tag{0.3}$$

$$= \frac{1}{2}V_{max}I_{max}\{\cos(\delta - \beta) + \cos[2(\omega t + \delta) - (\delta - \beta)]\} \tag{0.4}$$

$$= VI\cos(\delta - \beta) + VI\cos(\delta - \beta)\cos[2(\omega t + \delta) - (\delta - \beta)] \quad (0.5)$$

$$p(t) = VI\cos(\delta - \beta)\{1 + \cos[2(\omega t + \delta)]\} \quad (0.6)$$

$$+ VI\sin(\delta - \beta)\sin[2(\omega t + \delta)] \quad (0.7)$$

Letting $I\cos(\delta - \beta) = I_R$ and $I\sin(\delta - \beta) = I_x$, the above equation reduces to

$$p(t) = VI_R\{1 + \cos[2(\omega t + \delta)]\} + VI_x\sin[2(\omega t + \delta)] \quad (0.8)$$

$$= p_R(t) \qquad + \qquad p_x(t) \quad (0.9)$$

$$\text{where,} \quad p_R(t) = VI_R\{1 + \cos[2(\omega t + \delta)]\} \quad (0.10)$$

$$\text{and} \quad p_x(t) = VI_x\sin[2(\omega t + \delta)] \quad (0.11)$$

$p_R(t)$ is the component that is absorbed by the resistive component of the load.

$I_R = I\cos(\delta - \beta)$ is the component of the load current in phase with the load voltage. The phase angle $(\delta - \beta)$ represents the angle between the voltage and current. The component $I_x = I\sin(\delta - \beta)$ is the load current which is 90 degrees out of phase with voltage.

The instantaneous power absorbed by the resistive component of the load, has a double frequncy sinusoid with average value P, given by the expression

$$P = VI_R = VI\cos(\delta - \beta)W \; . \quad (0.12)$$

For circuits operating in the sinusodal steady state, real and reactive power are conveniently calculated from complex power. Let the voltage across a circuit element be $V = V\angle\delta$ and the current into the element be $I = I\angle\beta$. Then the complex power, S is the product of voltage and the conjugate of the current:

$$S = VI^* = [V\angle\delta][I\angle\beta]^* = VI\angle(\delta - \beta) \quad (0.13)$$

$$= VI\cos(\delta - \beta) + jVI\sin(\delta - \beta) \quad (0.14)$$

where $(\delta - \beta)$ is the angle between the voltage and the current.

So we can write $S = p + jQ$, where the magnitude of the complex power, $S = VI$ is the apparent power, whose units are defined as voltamperes (VA).

The real power P is obtained by multiplying the apparent power $S = VI$ by the power factor, $\cos(\delta - \beta)$.

A (positive valued) resistor absorbs (positive) real power $P_R = \frac{V^2}{R}$ and zero reactive power $Q_R = 0$ .An inductor absorbs zero real power $P_L = 0$ and positive reactive power, (0.2)

$$Q_L = \frac{V^2}{X_L} \; var \tag{0.15}$$

$$S_L = +j\frac{V^2}{X_L} \tag{0.16}$$

A capacitor absorbs zero real power $P_C = 0$ and negative reactive power, $Q_C = \frac{V^2}{X_C} \; var$

Alternatively, a capacitor delivers positive reactive power, $+\frac{V^2}{X_C}$

For a good general load composed of RLC elements, the real power $P = R_e(S)$ absorbed by passive load is always positive. The reactive power $Q = Im$ absorbed by a load may be either positive or negative.

$$Power\ factor = \cos(\delta - \beta) = \frac{P}{S} \tag{0.17}$$

C.2 Metering of electrical loads

Power is also the rate of change of enegy with respect to time. The unit of power is a watt, which is a joule per second

$$.P = \frac{dE}{dt} \quad Watts \quad = Joules\ per\ second \tag{0.18}$$

Most residential customers are connected to a single phase power supply. The consumption of the total loads is measured by an electrical meter. Figure 0.1 below is an example of a digital meter which could be connected to the power gateway controller to supply it with information of how much electricity the customer is using.

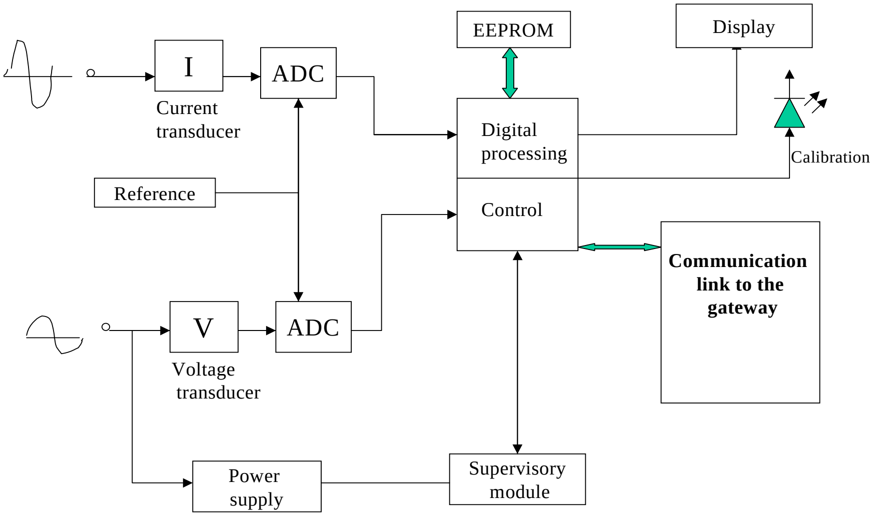


Figure 0.1: Typical residential meter

In a real situation, the power gateway controller designed in this thesis would need information from the loads. This information is obtained from measurements taken by meters. The meters measure how much power each load priority group is using up at any one time.

An alternative to individual meters would be to use a personal computer with labview running on it, connected to an input/output module that is connected to the power distribution box.

Appendix D

Optimization methods

0.2.1 Review of Optimization Methods

Linear Programming. Linear programming (LP) seeks to find the optimum value of a linear objective function, while meeting a set of linear constraints. More information about linear programming can be found in the book written by Glashoff, K., Gustafson, S.(1983).

Quadratic Programming. Quadratic programming concerns the minimization or maximization of a quadratic objective function that is linearly constrained. The problem is described as a quadratic function hence the name.

Nonlinear programming. The objective function and the constraints may be nonlinear functions of the variables. A solution of the nonlinear programming (NP) problem generally requires an iterative procedure to establish a direction of search at each major iteration. Examples are nonlinear least squares and nonlinear curve fitting.

Methods that focus on the solution of the Kuhn-Tucker (KT) equations form the basis to many nonlinear programming algorithms. The KT equations are necesary conditions for optimality.

Lagrangian relaxation is one technique that can be used for optimization. According to Wood, A.J., Wollenberg B.F. (1996), this optimization problem may be solved using calculus methods that involve the Lagrange function. Sequential quadratic programming is a recent nonlinear programming method. At each major iteration an approximation is made of a Lagrangian function.

D.1 Linear Programming

Linear programming (LP) seeks to find the optimum value of a linear objective function, while meeting a set of linear constraints i.e. we wish to find the optimum set of x values that minimize the following objective function:

$$F(x) = p_1x_1 + p_2x_2 + p_3x_3 \ldots\ldots\ldots p_nx_n \qquad (0.3)$$

subject to a set of linear constraints:

$$a_{11}x_1 + a_{12}x_2 + \ldots\ldots + a_{1n}x_n \le b_1 \qquad (0.4)$$

$$a_{21}x_1 + a_{22}x_2 + \ldots\ldots + a_{2n}x_n \le b_2 \qquad (0.5)$$

in other words, $Ax \le b$ where A is a matrix, x is a vector of variables, and b is a set of constants.

In addition, the variables themselves may have specified upper and lower limits.

$$x_i^{min} \le x_i \le x_i^{max} \qquad (0.6)$$

More information about linear programming can be found in the book written by Glashoff, K., Gustafson, S.(1983).

D.2 Quadratic Programming

Quadratic programming concerns the minimization or maximization of a quadratic objective function that is linearly constrained.

This problem can be described as

$$min\frac{1}{2}x^THx + c^Tx \qquad (0.7)$$

where $x \in \Re$ such that $Ax \le b$

where A is a matrix, x is a vector, H is a positive definite symmetric matrix known as the Hessian matrix , c is a constant vector and b is a constant.

D.3 Nonlinear Programming

The objective function and the constraints may be nonlinear functions of the variables. A solution of the nonlinear programming (NP) problem generally requires an iterative procedure to establish a direction of search at each major iteration. In constrained optimization the general aim is to transform the problem into an earlier subproblem that can be solved and used as the basis of an iterative process.

Examples are nonlinear least squares problem given by

$$min\frac{1}{2}\|F(x)\|\Big|_2^2 = \sum_i F_i(x)^2 \qquad (0.8)$$

or nonlinear curve fitting

$$min\frac{1}{2}\|F(x, xdata) - ydata\|\Big|_2^2 \qquad (0.9)$$

where given the input data $xdata$, the observed output data $ydata$ we want to find coefficients that best-fit the equation $F(x, xdata)$.

Methods that focus on the solution of the Kuhn-Tucker (KT) equations form the basis to many nonlinear programming algorithms. The KT equations are necesarry conditions for optimality. If $K_i(x)$, $i = 1, \ldots, m$, are convex functions, then the KT equations are both necessary and sufficient for a global solution point. The Kuhn-Tucker eqautions can be stated as

$$f(x^*) + \sum_{i=1}^{m} \lambda_i^* \cdot \nabla K_i(x^*) = 0 \qquad (0.10)$$

$$\nabla K_i(x^*) = 0 \quad i = 1, \ldots m_e \qquad (0.11)$$

$$\lambda_i \geq 0 \quad i = m_e + 1, \ldots, m \qquad (0.12)$$

At the solution point of the first equation, the gradients between the objective function and the active constraints are cancelled. According to Branch, M.A., Grace, A. (1996), for the gradients to be cancelled, Lagrange multipliers (λ_i,

$i = 1, \ldots m$) are necessary to balance the deviations in magnitude of the objective function and constraint gradients.

Lagrangian relaxation

Consider a system with N production units connected to a single busbar, serving an electrical load of P_{cl}. We suppose that the units in this system were consuming fuel at a specific rate which can be denoted as F_i for each unit. Each unit produces an output P_{gi}. The total cost rate of this system is the sum of the costs of each of the individual units. An essential constraint on the operation of this system is that the sum of the available power outputs must equal the load demand. in addition the power output of each unit must also be less than or equal to the maximum power permitted on that unit. The objective function F_T, is equal to the total cost for supplying the indicated load.

$$F_T = F_1 + F_2 + F_3 \ldots + F_N \text{ that is minimize} \tag{0.13}$$

$$F_T = \sum_{i=1}^{N} F_i(P_{gi}) \text{ subject to the following constraints} \tag{0.14}$$

$$\phi = 0 = \sum_{i=1}^{N} P_{gi} - P_{cl} \tag{0.15}$$

$$P_{gi,\,min} \le P_{gi} \le P_{gi,\,max} \tag{0.16}$$

According to Wood, A.J., Wollenberg B.F. (1996), this optimization problem may be solved using calculus methods that involve the Lagrange function. In order to establish the necessary conditions for an extreme value of the objective function, we add the constraint function to an objective function after the constraint function has been multiplied by a multiplier λ.

The new function called the Lagrange function is given by

$$L = F_T + \lambda\phi \text{ where } \phi \text{ is the constraint function.} \tag{0.17}$$

The necessary condition for an extreme value of the objective function result when we take the first derivative of the Lagrange function with respect to each of the independent variables and set the derivatives equal to zero.

$$\frac{dL}{dP_{gi}} = \frac{d}{dP_{gi}} F(P_{gi}) - \lambda = 0 \tag{0.18}$$

$$\frac{dF_i}{dP_{gi}} - \lambda = 0 \tag{0.19}$$

In other words, the necessary condition for the existence of a minimum cost operating condition for the system is that the incremental cost rates of all the units must be equal to some undetermined value λ. This can be expanded to include the limits of the units i.e.

$$\frac{dF_i}{dP_{gi}} \le \lambda \text{ for } P_i = P_{i,\,max} \tag{0.20}$$

$$\frac{dF_i}{dP_{gi}} \ge \lambda \text{ for } P_i = P_{i,\,min} \tag{0.21}$$

Sequential quadratic programming

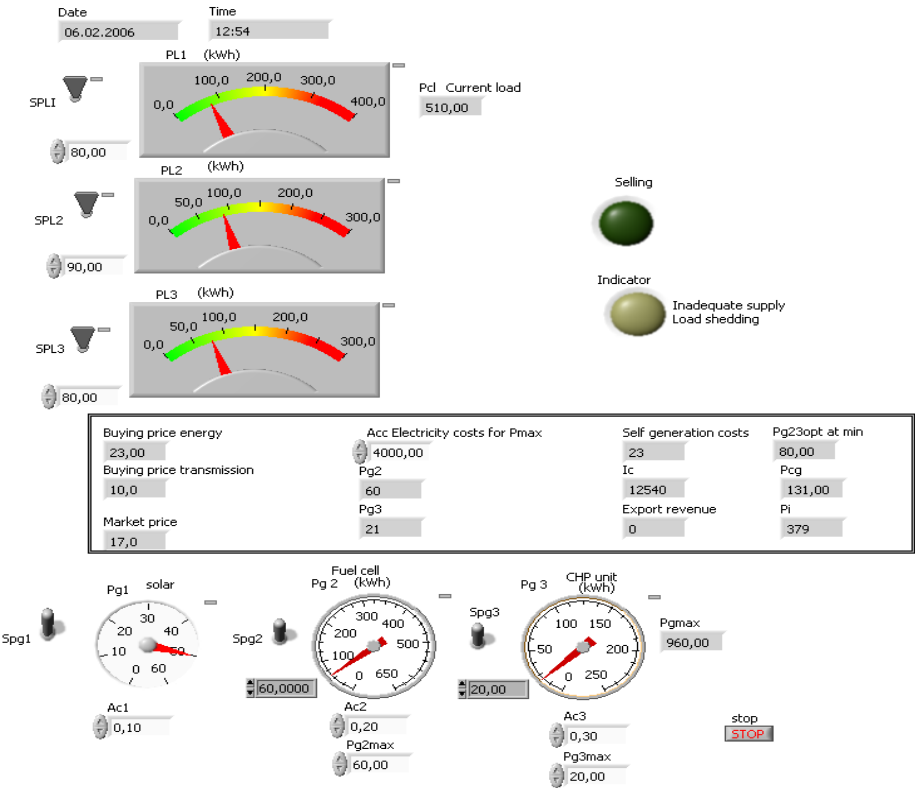
Sequential quadratic programming is a recent nonlinear programming method. At each major iteration an approximation is made of the Lagrangian function

$$L(x, \lambda) = f(x) + \sum_{i=1}^{m} \lambda_i \cdot c_i(x) \tag{0.22}$$

using a quasi-Newton updating method. This is then used to generate a QP subproblem whose solution is used to form a search direction for a line search procedure.

Appendix E

Power Gateway Controller Simulation



Date
06.02.2006

Time
12:54

SPLI
80,00

Pcl Current load
510,00

SPL2
90,00

SPL3
80,00

Buying price energy
23,00

Buying price transmission
10,0

Market price
17,0

Acc Electricity costs for Pmax
4000,00

Pg2
60

Pg3
21

Self generation costs
23

Ic
12540

Export revenue
0

Pg23opt at min
80,00

Pcg
131,00

Pi
379

Spg2
60,0000

Spg3
20,00

Pgmax
960,00

Ac1
0,10

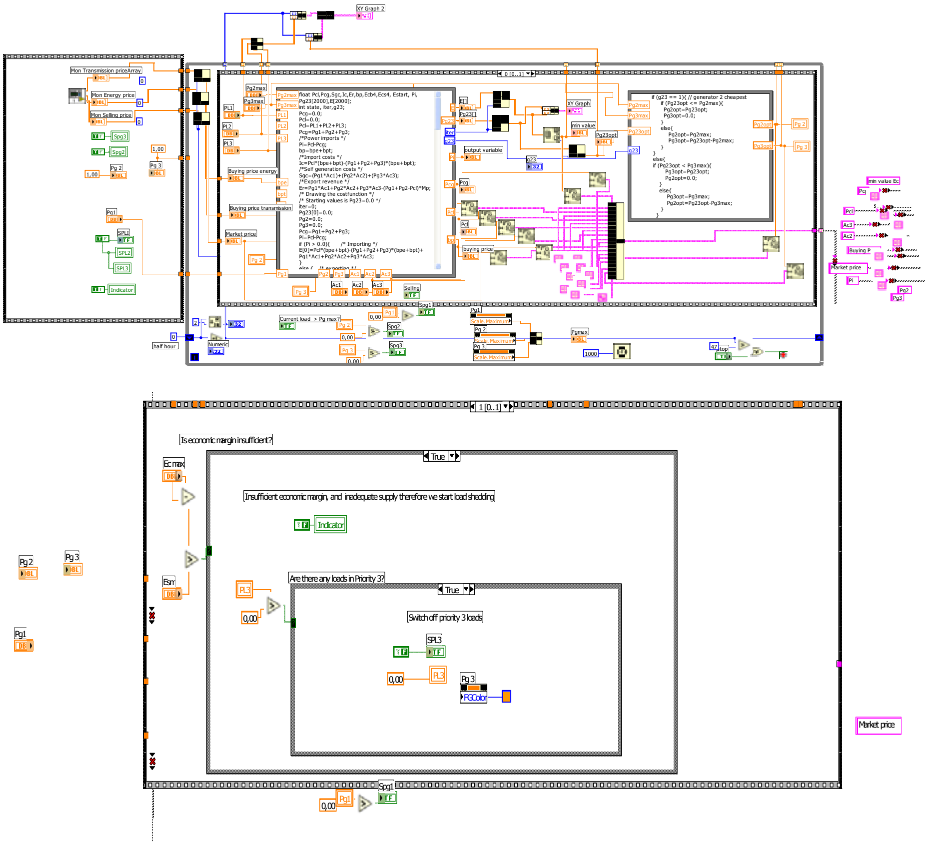
Ac2
0,20

Pg2max
60,00

Ac3
0,30

Pg3max
20,00

Figure 0.1: PGC Front panel



```
float Pcl,Pcg,Sgc,Ic,Er,bp,Ecb4,Ecs4, Estart, Pi,
Pg23[2000],E[2000];
int state, iter,g23;
Pcg=0.0;
Pcl=0.0;
Pcl=PL1+PL2+PL3;
Pcg=Pg1+Pg2+Pg3;
/*Power imports */
Pi=Pcl-Pcg;
bp=bpe+bpt;
/*Import costs */
Ic=Pcl*(bpe+bpt)-(Pg1+Pg2+Pg3)*(bpe+bpt);
/*Self generation costs */
Sgc=(Pg1*Ac1)+(Pg2*Ac2)+(Pg3*Ac3);
/*Export revenue */
Er=Pg1*Ac1+Pg2*Ac2+Pg3*Ac3-(Pg1+Pg2-Pcl)*Mp;
/* Drawing the costfunction */
/* Starting values is Pg23=0.0 */
iter=0;
Pg23[0]=0.0;
Pg2=0.0;
Pg3=0.0;
Pcg=Pg1+Pg2+Pg3;
Pi=Pcl-Pcg;
if (Pi > 0.0){       /* Importing */
E[0]=Pcl*(bpe+bpt)-(Pg1+Pg2+Pg3)*(bpe+bpt)+
Pg1*Ac1+Pg2*Ac2+Pg3*Ac3;
}
else {     /* exporting */
```

```
if (g23 == 1){ // generator 2 cheapest
     if (Pg23opt <= Pg2max){
       Pg2opt=Pg23opt;
       Pg3opt=0.0;
     }
     else{
          Pg2opt=Pg2max;
          Pg3opt=Pg23opt-Pg2max;
     }
 }
 else{
 if (Pg23opt < Pg3max){
        Pg3opt=Pg23opt;
        Pg2opt=0.0;
    }
    else{
        Pg3opt=Pg3max;
        Pg2opt=Pg23opt-Pg3max;
     }
  }
```

Figure 0.2: PGC model

On the front panel of the gateway in Figure 01, is the display of date and time, information from the plant of the loads and generator outputs and their status whether they are on or off and the staus of the gateway. The price information from the web page is displayed as well as the hourly calculation results of the operations cost function, earned revenue and import costs. There is provision for the customer to adjust the averaged operations costs and the setpoint for cutting off of the loads.

Appendix F

Plant Simulation

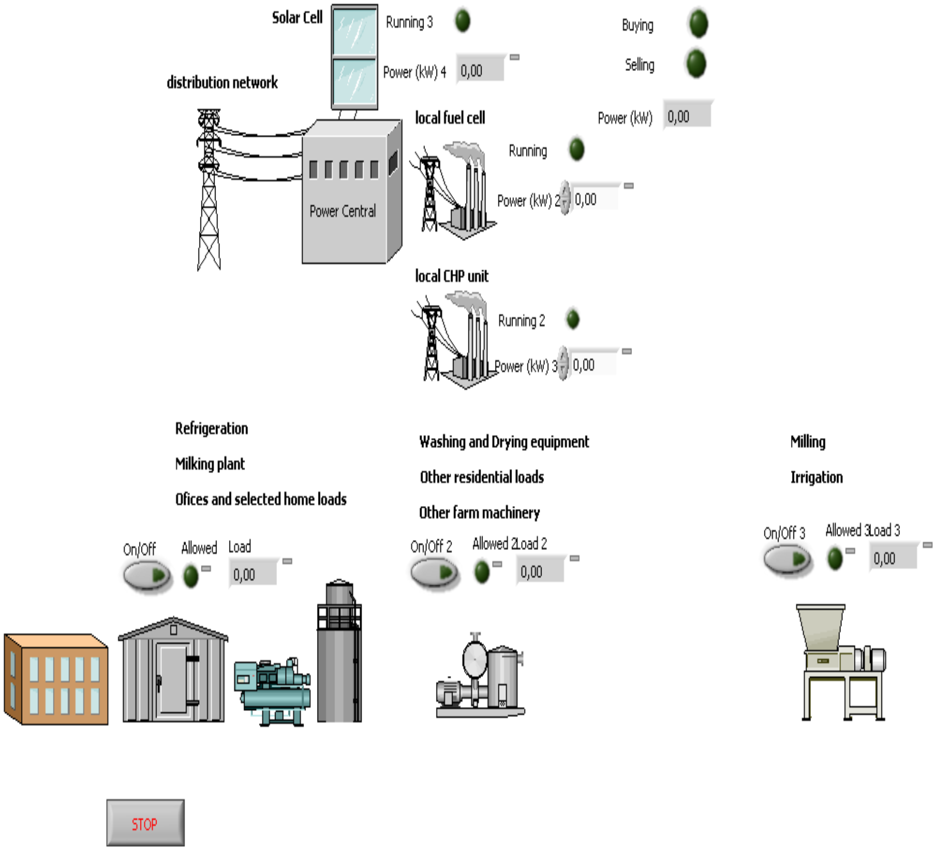
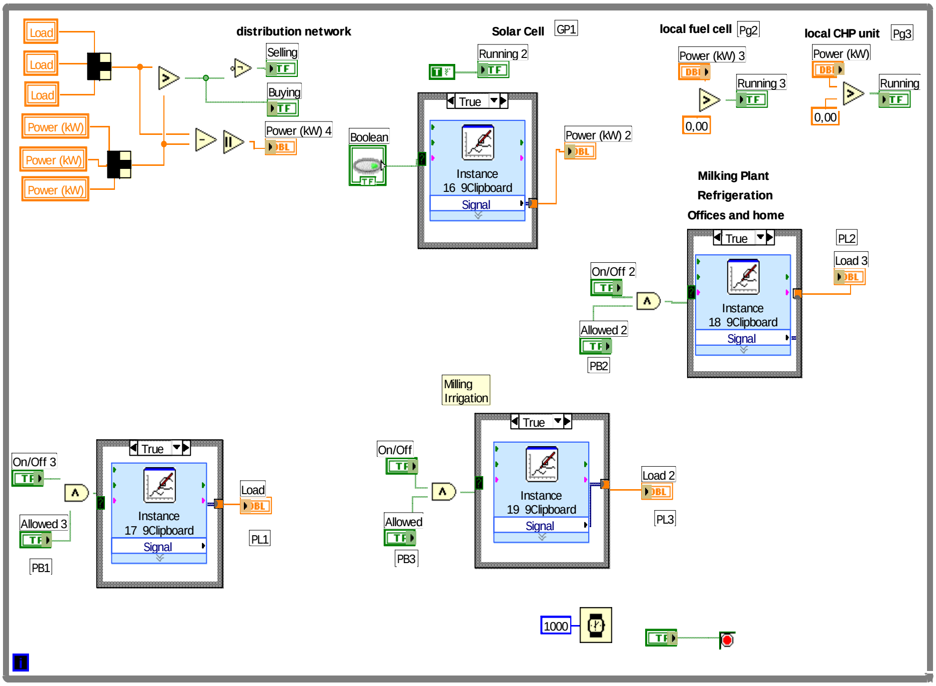


Figure 0.3: Plant simulation


Load
Load
Load
Power (kW)
Power (kW)
Power (kW)
distribution network
Selling
Buying
Power (kW) 4
Solar Cell
GP1
Running 2
Boolean
True
Instance
16 9Clipboard
Signal
Power (kW) 2
local fuel cell
Pg2
Power (kW) 3
Running 3
0,00
local CHP unit
Pg3
Power (kW)
Running
0,00
Milking Plant
Refrigeration
Offices and home
PL2
Load 3
On/Off 2
Allowed 2
PB2
Instance
18 9Clipboard
Signal
Milling
Irrigation
On/Off 3
Allowed 3
PB1
Instance
17 9Clipboard
Signal
Load
PL1
On/Off
Allowed
PB3
Instance
19 9Clipboard
Signal
Load 2
PL3
1000

Appendix G

Utility Web page Reading

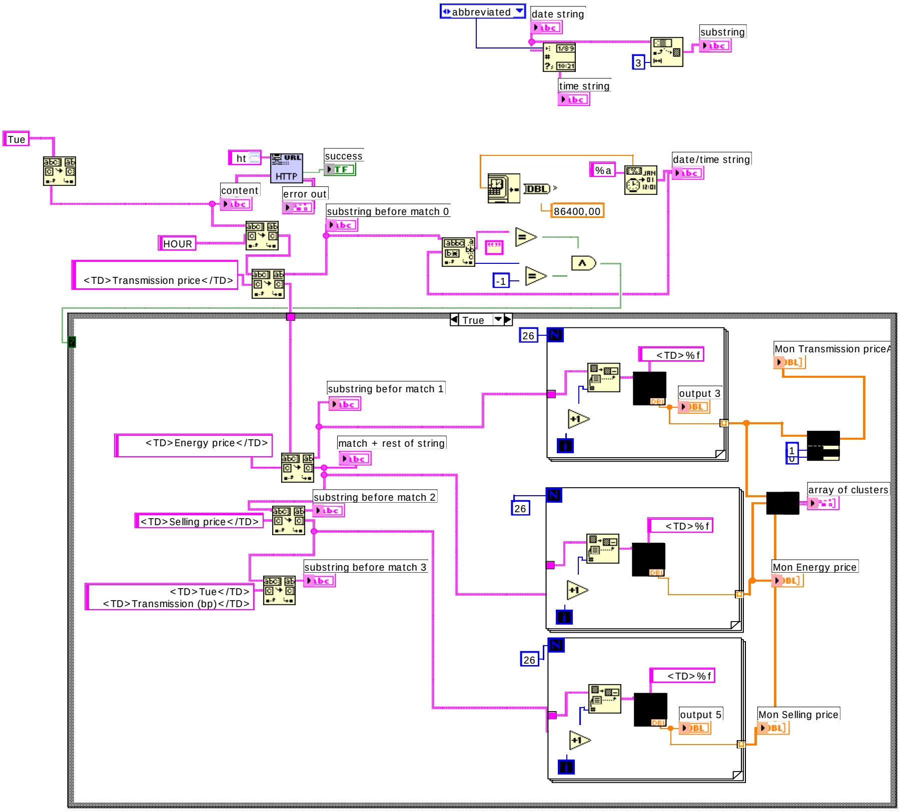
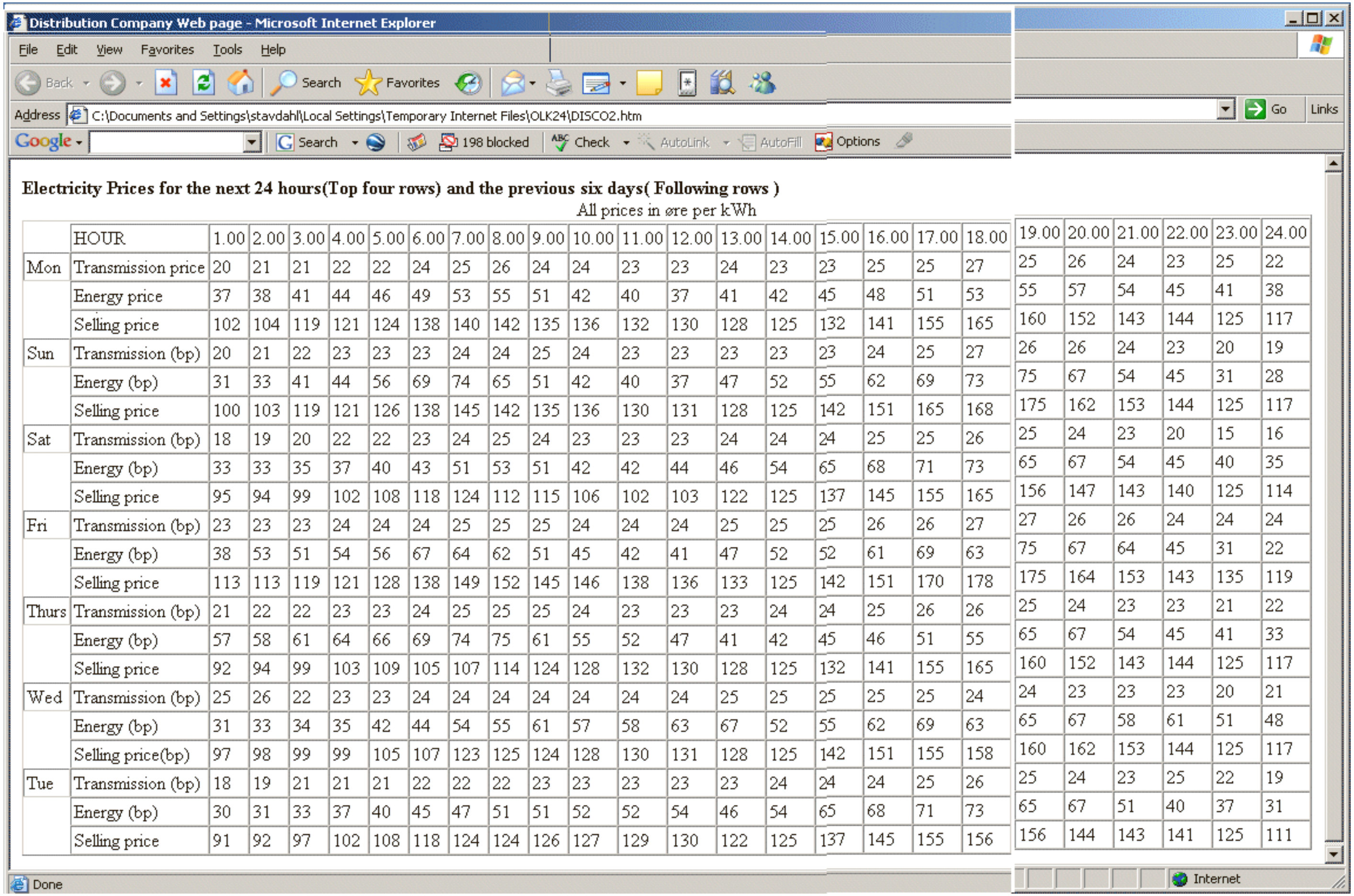


Figure 0.4: Code for reading the web page

A virtual instrument for reading the web page was created and the code is as shown in Figure 0.4. A copy of the Distribution Company’s web page that was created and used is shown in Figure 0.5. Different prices were used for each of the experiments.



Electricity Prices for the next 24 hours(Top four rows) and the previous six days(Following rows)

All prices in øre per kWh

	HOUR	1.00	2.00	3.00	4.00	5.00	6.00	7.00	8.00	9.00	10.00	11.00	12.00	13.00	14.00	15.00	16.00	17.00	18.00	19.00	20.00	21.00	22.00	23.00	24.00
Mon	Transmission price	20	21	21	22	22	24	25	26	24	24	23	23	24	23	23	25	25	27	25	26	24	23	25	22
	Energy price	37	38	41	44	46	49	53	55	51	42	40	37	41	42	45	48	51	53	55	57	54	45	41	38
	Selling price	102	104	119	121	124	138	140	142	135	136	132	130	128	125	132	141	155	165	160	152	143	144	125	117
Sun	Transmission (bp)	20	21	22	23	23	23	24	24	25	24	23	23	23	23	23	24	25	27	26	26	24	23	20	19
	Energy (bp)	31	33	41	44	56	69	74	65	51	42	40	37	47	52	55	62	69	73	75	67	54	45	31	28
	Selling price	100	103	119	121	126	138	145	142	135	136	130	131	128	125	142	151	165	168	175	162	153	144	125	117
Sat	Transmission (bp)	18	19	20	22	22	23	24	25	24	23	23	23	24	24	24	25	25	26	25	24	23	20	15	16
	Energy (bp)	33	33	35	37	40	43	51	53	51	42	42	44	46	54	65	68	71	73	65	67	54	45	40	35
	Selling price	95	94	99	102	108	118	124	112	115	106	102	103	122	125	137	145	155	165	156	147	143	140	125	114
Fri	Transmission (bp)	23	23	23	24	24	24	25	25	25	24	24	24	25	25	25	26	26	27	27	26	26	24	24	24
	Energy (bp)	38	53	51	54	56	67	64	62	51	45	42	41	47	52	52	61	69	63	75	67	64	45	31	22
	Selling price	113	113	119	121	128	138	149	152	145	146	138	136	133	125	142	151	170	178	175	164	153	143	135	119
Thurs	Transmission (bp)	21	22	22	23	23	24	25	25	25	24	23	23	23	24	24	25	26	26	25	24	23	23	21	22
	Energy (bp)	57	58	61	64	66	69	74	75	61	55	52	47	41	42	45	46	51	55	65	67	54	45	41	33
	Selling price	92	94	99	103	109	105	107	114	124	128	132	130	128	125	132	141	155	165	160	152	143	144	125	117
Wed	Transmission (bp)	25	26	22	23	23	24	24	24	24	24	24	24	25	25	25	25	25	24	24	23	23	23	20	21
	Energy (bp)	31	33	34	35	42	44	54	55	61	57	58	63	67	52	55	62	69	63	65	67	58	61	51	48
	Selling price(bp)	97	98	99	99	105	107	123	125	124	128	130	131	128	125	142	151	155	158	160	162	153	144	125	117
Tue	Transmission (bp)	18	19	21	21	21	22	22	22	23	23	23	23	23	24	24	24	25	26	25	24	23	25	22	19
	Energy (bp)	30	31	33	37	40	45	47	51	51	52	52	54	46	54	65	68	71	73	65	67	51	40	37	31
	Selling price	91	92	97	102	108	118	124	124	126	127	129	130	122	125	137	145	155	156	156	144	143	141	125	111

Figure 0.5: Distribution Company Webpage

Appendix H

Coding the Algorithm

The Read from Spreadsheet VI was used to read rows from a numeric textfile beginning at the specified character offset and converted the data to a 2D, single-precision array of numbers. The array could be optionally transposed. The VI in Figure 0.6 opens the file before reading from it and closes it afterwards. You can use this VI to read a spreadsheet file saved in text format

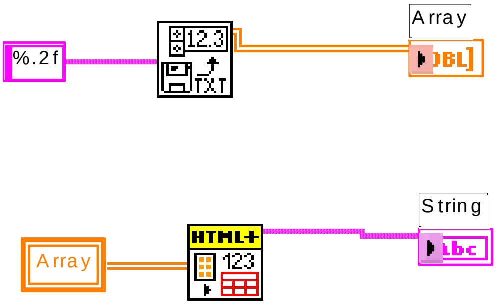


Figure 0.6: Reading from Spreadsheet

H.1 Datasocket

The Datasocket transfer protocol (DSTP) can be used in a URL in much the same way as we use http for hypertext documents. A Datasocket URL like:

`dstp :// fireworks.com / variable1`

will tell the application to fetch data called “`variable1`” from the DSTP server on fireworks.com. The difference is that most dstp URL’s do not point to the documents as with http or ftp, but point to data sources instead. The Datasocket applications programming interface allows one to also read data items on:

. http servers

. ftp servers

. OLE for Process Control (OPC) servers

. DSTP servers

. local files (file://URL)

One can also read text, spreadsheet files and sound files in WAV format.

Datasocket is built on top of TCP/IP and its perfomance varies largely with network bandwidth, network traffic e.t.c. data transfer rates can be as fast as 320kB/ sec between machines connected by the 10 BaseT Ethernet. It can be used with data up to 1MB in size. It uses TCP/IP port 3015 which has been registered with the IANA (Internet Assigned Numbers Authority) as the National Instruments Datasocket Transfer Protocol (dstp) port. It does not provide support for encryption but the user can encrypt the data when sending it.

A Datasocket server is automatically installed with Labview for windows. To start the server we go to

Start >> Program Files >> National Instruments >> datasocket server

We configure the access information in the Datasocket Server Manager.

Basic reading and writing to datasocket servers

There are two ways of writing data to a Datasocket connection. The first way involves:

a). Opening a Datasocket connection using a dstp URL

b). Writing data to that item using a datasocket icon.

c). Closing the datasocket connection when done.

The Figure 0.7 below shows the icon for a datasocket write.

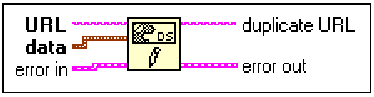


Figure 0.7: Datasocket Write

In this VI **URL** identifies the data source to read. URLs begin with the name of the protocol you want to use to read the data, such as dstp, opc, logos, ftp, and file.

data is the data written to the DataSocket connection. **data** can be in any format or LabVIEW data type.

error out contains error information. If **error in** indicates that an error occurred before this VI or function ran, **error out** contains the same error information. Otherwise, it describes the error status that this VI or function produces.

The second method is to simply set the control and indicator icons on the Labview Front panel to publish data or subcribe to data depending on their functionalities. If a right click on the indicator is made and data operations >> datasocket connection is selected the URL path and the respective operations can be specified.

Reading of data involves the datasocket read icon shown in Figure 0.8.

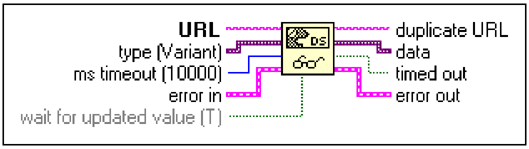


Figure 0.8: Datasocket Read

In this VI **type (Variant)** specifies the type of data to be read and defines the type of the data output terminal. The default type is a Variant, which can be any type.

ms timeout specifies how long to wait for a value update. This time is ignored if **wait for updated value** is false and an initial value has arrived. The default is 10 seconds.

wait for updated value waits for an updated value when true. If the value has been updated since the last read, the function returns immediately. Otherwise, the function waits **ms timeout** milliseconds for an update. If an update does not occur in the timeout period, the current value is returned and the **timed out** result is true. When false, the function returns the current value of the data. The timeout is only used if no value has yet arrived.

Datasocket Virtual Instruments can handle several native Labview data types without a need to typecast the data to a string. The read and write icons for datasocket are found in Functions>>Communication>>Datasocket.

H.2 Reading the Webpage

A number of different virtual instruments were used to read and process the price information from the web page.

H.2.1 URL Get http document VI

The URL Get http document VI which is shown in Figure 0.9 below was used to connect the power gateway controller to the Utility webpage. Http URL is the location of the document and this can be specified in full or partial format. A user name and password can be used for authentication. The URL for the Utility webpage with the price information was specified.

File path specifies where the document is to be saved. In our case the document was returned in content as a string. Content-type is the MIME type of the retrieved document.

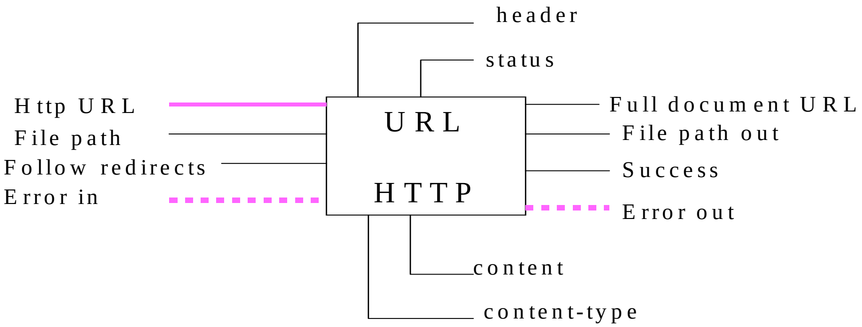


Figure 0.9: URL Get http document

If the VI follows HTTP redirection replies, this will be indicated by follow redirects. The HTTP header from the server will be returned in header and the status from the header will also be returned.

If an error occured before the VI started executing, the error will be passed on to the error output. The default is "no error". When an error occurs, the status flag will indicate True and the warning code is the error code number that identifies the name of the VI that produced the error. The error can be identified through the source string.

H.2.2 Get Date/Time string

This VI in Figure 0.10 gets a date string and a time string from configured time zone of the local computer. If the flag "want seconds ?" is set to T (true) then the time string will also include the display of seconds.

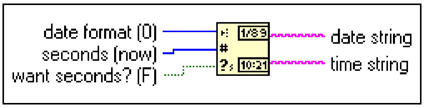


Figure 0.10: Get date/Time strinng

The computer counts the Universal time from 12:00 a.m., Friday, January 1, 1904 in seconds and returns this as a time zone independent number in seconds(now). The current date and time is taken as the default.

H.2.3 Search / Split String

This function in Figure 0.11 divides a single string into two substrings. A character or a substring is specified for this function to search for in the input string. The input string is then divided into the substring before the match and the match and rest of the split string. It will also mark the position of the search string in the main string.

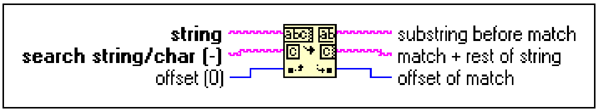


Figure 0.11: Search/Split String

H.2.4 Pick line

A line is chosen from a multi-line string and is presented to the output as a string. Line index acts as a pointer to indicate which line to be picked. This function in Figure 0.12 is useful in filtering out the lines which contain price information.

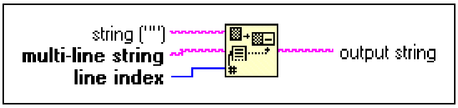


Figure 0.12: Pick line

H.2.5 Scan from String

Figure 0.13 shows the inputs and outputs to the scan from string VI. This function scans the input string and converts the string according to the specified format. If there is no format specification then the default format for the data types of the outputs will be adopted.

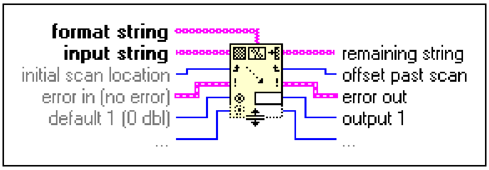


Figure 0.13: Scan from String

H.2.6 SMTP send message

This VI was used to send a message to the utility to request price information for the following day. If the utility fails to post the market, transmission and selling prices of electricity for the following day, then a request message is automatically sent by the algorithm to the utility.

The Simple Mail Transfer Protocol (SMTP) is a fairly simple TCP/IP protocol used in sending and receiving e-mail. An alternative to SMTP that is used in Europe is X.400. SMTP allows our gateway to specify our host on the internet (i.e. the utility mail server) and to send text-based data or messages. The SMTP server usually runs on port 25.

The Internet Toolkit e-mail VI’s in Labview all use MIME (Multipurpose Internet Mail Extensions) encoding. It defines character sets to allow for more than the 7 bit ASCII text characters. It enables multiple attachments to be sent in one e-mail message including binary executables, HTML, images, video e.t.c, and it defines different ways to encode attachments so that they can be compatible with the 7 bit ASCII limitation of SMTP servers and it encodes messages with the MIME standard. The internet Toolkit uses the internet.ini. configuration file in the internet directory to keep track of the HTTP, SMTP and FTP default settings. By clicking Tools > Internet Toolkit >> Internet Toolkit Configuration and choosing SMTP (e-mail) , the mail settings can be configured. The TCP connection is opened and estableshed with the specified address and port. The address can be in internet dot notation or it can be a hostname. If the connection is not established within the set time, the VI completes and returns an error. The default set timeout is 60 000 ms (1 minute).

The inputs and outputs of the SMTP send message VI are shown in Figure 0.14.

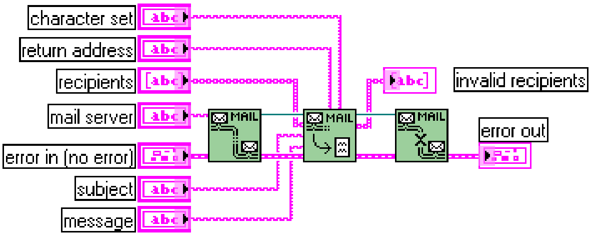


Figure 0.14: SMTP send message

The character set is normally ASCII which is used in the message. The return address is the e-mail address of the sender whilst the recipeints are the list of receivers. Mail server is the name or IP address of an SMTP server.

H.2.7 Handling Errors

The SMTP send message VI functions normally if no error occured before the VI started executing. One can wire an error handler VI to the VI to return a description of any errors that occur. The error handler VI can display a dialog box with an error code description and buttons that can stop or continue execution.

Errors can be caused by various reasons like :

- failed transactions
- mailbox not available or server unavailable
- local error in processing the message
- insufficient system storage
- syntax error due to unrecognised command or in parameters or arguments
- command line is too long or if there was a bad sequence in the commands

Each of these error descriptions will have an associated error code.

H.2.8 The For loop

In order to read all the 24 houly values from the columns in the tables, it was necessary to repeat the picking of lines and scan of string operations at least 24 times. The For loop structure shown in Figure 0.15 was used for this purpose and the output was indexed into an array.

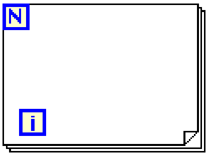


Figure 0.15: The For Loop

H.3 The Main Program

Labview is user-friendly in building, simulating and running scientific experiments. The flow charts given in chapter five were used to code the algorithm.

A number of functions and structures were used in the main program which include:

H.3.1 Sequence Structures

A sequence structure similar to Figure 0.16 was used at the beginning to ensure that initialisation of variables and reading of the web page would be done at the beginning of the day before the routine for that day is carried out. The VI for reading the webpage was placed inside this initial sequence structure.

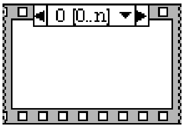


Figure 0.16: Sequence structure

H.3.2 The While Loop

The main program was placed inside a while loop similar to Figure 0.17 which would run continously until the stop button is pressed or the program is interrupted.

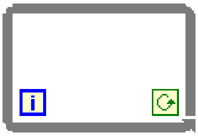


Figure 0.17: The while loop

Two formula nodes were used to execute the mathematical and optimization operations. According to Bitter (2001) et al, a formula node evaluates mathematical formulae and expressions similar to C on the block diagram. Multiple formulas can be enclosed in a single node, and each formula ends with a semicolon. Most of the outputs were converted into string values and stored in a format that would be easier for spreadsheet analysis. The number to fractional string function shown in Figure 0.18 was used.

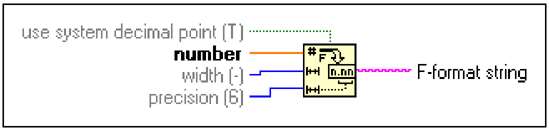


Figure 0.18: Number to fractional string

H.3.3 Concatenate Strings

This function in Figure 0.19 was used to concatenate the output strings from the formula nodes and 1D arrays of strings into a single string. For array inputs, this function concatenates each element of the array.

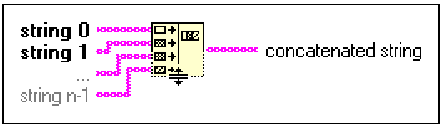


Figure 0.19: Concatenate strings

H.3.4 Write Characters to File

This VI shown in Figure 0.20 has the ability to open a file before writing to it and close the file afterwards. It writes string data to a new byte stream file or if there is an existing file already it appends the string to an existing file.

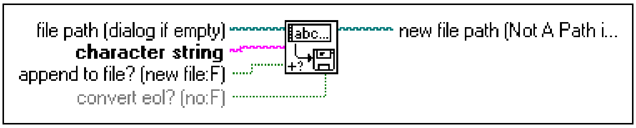


Figure 0.20: Write characters to file

H.3.5 Case Structure

The case structure was used many times in the program as an if-then -else block. Most of the case structrures used in this program used Boolean data type to drive the structures. A Boolean was wired to the selector terminal represented by the question mark (?) on Figure 0.21 resulting in either a true case or a false case depending on the test results.

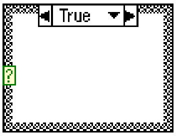


Figure 0.21: Case structure

Appendix I

Paper 1

This paper was presented at the “ Industrial and Commercial use of Energy Conference” in Cape Town , South africa in May 2005

Industrial and Commercial Use of Energy Conference 2005

A COMPARISON OF ELECTRICITY MARKETS IN ZIMBABWE AND NORWAY WITH THE VIEW OF SELF AND CO-GENERATION OPPORTUNITIES

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ABSTRACT

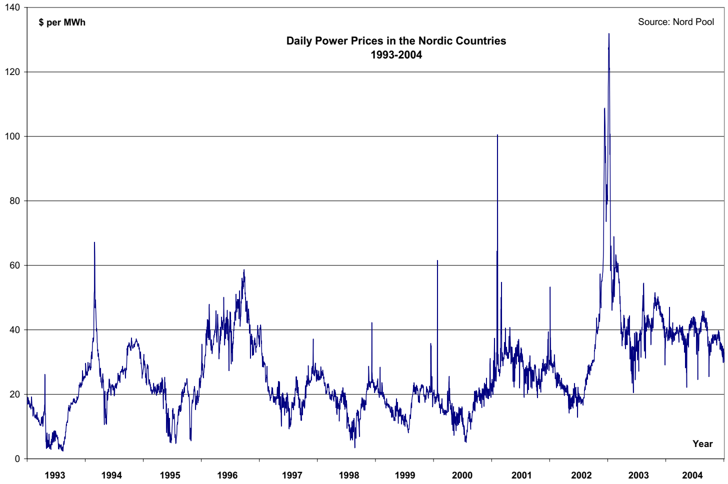
This paper reviews the electricity markets in Norway and Zimbabwe and outlines the need for self and co-generation as a way of solving common problems.

1. BACKGROUND

The extended installation of local power production units depends on the existence of an encouraging environment in the political, economical and technical framework of any nation [1.] The shift towards liberalised and competitive power markets has led to a major change in how electrical power systems are being operated and organized. The focus of the participants in a competitive regime change from cost minimisation to profit maximisation since they are exposed to competitive prices with increased volatility as shown in Figure 1.

Future decisions concerning investments in the power system are less predictable in a system with decentralised decision making [2]. Generally the deregulation of the electricity supply industry has resulted in lack of willingness by the utilities to invest in generation because of the high risk of volatile market conditions. New opportunities have been created for private companies and individuals to install their own power production units in order to hedge against high market prices during the peak periods. Norway deregulated its power market in 1990 [3]. There is a high interest in developing distributed generation, particularly small and medium scale hydro power, and especially after two winters with drought (1996/1997 and 2002/2003) and high power prices as shown in Figure 1.

In Norway, the opening up of the electricity market at retail level, involved the establishment of legal and regulatory provisions which established the general rules of the game for competitive reform of the


Daily Power Prices in the Nordic Countries
1993-2004

Source: Nord Pool

Figure 1: Volatility of spot prices in the Nordic Countries

electricity industry. This was followed by the development of technical and commercial infrastructures which created the operational means. Norway's energy imports have been gradually increasing in percentage over the past few years. There is a need to build more power production units particularly those that are environmentally friendly. Research results [4] have shown that technologies like small-scale wind and hydropower are the technologies which in the short term are best for Norway, whilst in the far fetched future other technologies like fuel cells and biomass might become of greater potential as improvements in these technologies continue. Micro gas turbines and combustion engines can be competitive technologies if a distribution network for natural gas exists.

On the other hand, the generation, transmission and distribution of electricity in Zimbabwe were mandated to the Zimbabwe Electricity Supply Authority (ZESA), in 1986. A new Electricity Act was passed in March 2002 and it became operational in August 2003 [5]. The Electricity Act established ZESA Holdings, a holding company that is holding State shares in companies to take over from the privatisation of ZESA. The Authority was then restructured into several successor companies. [6].

The country has high energy imports and there is a need to increase the security of energy supply. Solar and biomass technologies have greater potential in Zimbabwe than wind or micro hydro. If the excess heat generated in solar and biomass technologies is used to heat up water, the efficiency will almost double whilst the operational costs would be halved. Although the country has great reserves of coal supply, environmental concerns makes it difficult to focus on the development of large scale thermal power production units.

2. CAPACITIES

As of 1998, about 99.41% of the electric power production in Norway was from hydro plants, 0.59% from fossil fired units and 0.01% was from wind power. There were almost 230 distribution companies in Norway, 90 producers of electricity and about 60 utilities attended both roles.

In 2002 Norway had a total installed capacity of 27 596 MW at 740 hydro power plants larger than 1 MW. [7]. However about 23 000 MW was actually available because of maintenance and repairs. Thermal power plants provided an additional capacity of 271 MW. The installed capacity of wind power plants is 13 MW. The largest electricity producer in Norway is Statkraft SF and accounts for 30% of the total production capacity. Five wind power projects have been licensed and when they come into operation they will produce about 725 GWh / year.

In Zimbabwe, as of 2003, Zesa's installed capacity was 1961 MW of which about 33% (i.e. 666 MW) were from hydro plants in Kariba and about 66% (i.e.1295 MW) were from coal fired thermal units in Hwange, Harare, Bulawayo and Munyati. However the actual sent out capacity was around 1620 MW because of repair and maintenance routines. See Table 1. There were some small privately owned generators which were not selling to the network at the sugar estates in Triangle (45 MW), Hippo Valley Estates (23 MW) and a 750 kW mini-hydro plant at Rusitu. More than 750 kW photovoltaic cells are installed and many private solar water heaters exist countrywide.

Table 1 Comparison of installed capacity in Zimbabwe and Norway (around year 2002)

Electricity Production and Demand	Zimbabwe	Norway
Installed capacity (MW)	1961	27 596
Available capacity (MW)	1620	23 000
Max Demand (MW)	2028	23 700
% Imports	32	7
Hydro (MW)	666MW (33.9%)	27 430MW (99.4%)
Thermal (MW)	1295MW (66%)	62MW (0.59%)
Total Energy from local electricity production	8 587	107 273
Total Energy Consumption	12 597 GWh	115 158

3. MARKETS

3.1 ORGANISATION OF THE NORWEGIAN MARKET

Norway had three organised markets i.e., the spot market (Elspot), the futures market (Eltermin) and the regulating market.[8]

3.1.1 Spot market

On the spot market, energy contracts for delivery of electric energy in the next 24 hours are traded daily [9]. The supply bids are aggregated into a supply curve and the demand bids are also aggregated into a demand curve. The intersection point of the supply and demand curves gives the system price for clearing the market [10]. Spot market participation is not mandatory. About 16% of energy in the Nord Pool market area is traded on the spot market.

3.1.2 Regulating market

The regulating market is a tool for maintaining the physical (frequency) balance of the power system. While the spot market balances the predictable deviation between sales and purchases, the regulating market balances the actual system imbalance. This market accepts bids from participants to raise or lower energy generation from scheduled values. When the system operator decides that regulation is necessary, it buys the cheapest block of regulating power. All network users are charged for regulation based on deviation from scheduled hourly energy values.

3.1.3 Futures market

The futures market is a financial market for risk management and hedging. Hedging is on future buying or selling. Bilateral contracts, which specify the trade of some amount of energy at a given price, are made. Trading can be in week contracts, month (a block of four weeks) or season. On this market there is calculation of profit and loss against the 24 hourly price changes and daily financial clearing against the system price in the delivery week.

3.1.4 Electrification market/TGC market

The elcertificate market was introduced on the Nord Pool exchange in March 2004 [11]. For each MWh of electricity generated from certified renewable sources such as wind, small scale hydro or bio energy, a certificate is issued. These tradable green certificates can be traded as financial assets.

3.1.5 Bilateral contracts

About two thirds of wholesale trading takes place with bilateral contracts. These contracts can be over the counter and may have a flat profile over the contract period or they may be tailor made according to the agreement between the buyer and the seller.[12].

3.1.6 Some Participants

The power exchange NordPool operates the spot market and the futures market. Statnett is the national system operator in Norway and it is responsible for the system coordination and operates the regulating market. The Norwegian Water Resources and Energy Directorate (NVE) is the regulatory authority for the transmission system in Norway and is subordinated to the Ministry of Petroleum and Energy.

Gradual changes in privatisation have taken place over the years as the market became more open. By 1998 all end users in Norway could change supplier on a weekly basis. [13]. Figure 2 below shows a model where both the customers and the independent power producers (IPP's) are free to choose retailers. These retailers may be distribution companies (Distco's) who own a network or they may be companies who do not own any wires but offer services.

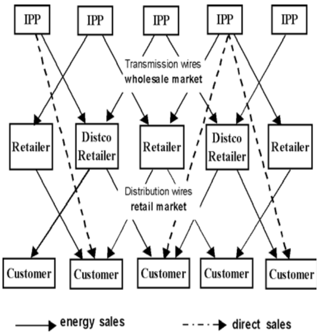


Figure 2 The Retail Competition Model [14]

The Nordic Power Market has been recorded a success since the early start in 1991 [15]. Sweden and Norway established a common power market in 1996. Later, in 1999, the Scandinavian countries agreed to share a common market for their electricity supplies although the electricity networks were physically connected many years before then. There is now exchange with different European markets. Norway participates in the International Energy Agency in implementing an international energy programme. Among other objectives, this programme includes the development of alternative energy sources, rational management and use of world energy resources and the development of a stable international energy trade.

3.2 ORGANISATION OF THE ZIMBABWEAN MARKET

Zimbabwe has adopted a single buyer model e.g. Figure 2 whereby a single buyer is allowed to purchase energy from competing electricity generators or independent power producers (IPP's). The buyer arranges for delivery over monopoly, transmission and distribution systems and sells at advertised tariffs to all consumers (large and small). The purchasing agency would purchase by tender or bidding system from the IPP's to ensure the best price is obtained throughout the day and year.

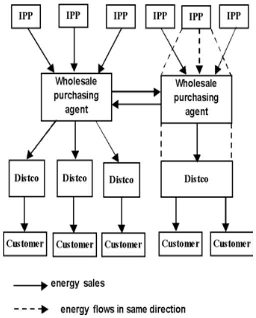


Figure 2 The Single buyer Model [15]

The new companies from ZESA include the Zimbabwe Power Company responsible for generation, the Zimbabwe Electricity Transmission Company responsible for the transmission network and the major wholesale purchasing, Zimbabwe Electricity Distribution Company, ZESA enterprises, Powertelecommunications, ZESA Holdings (Pvt) Limited and the Rural Electrification Agency.

In order to meet its growth in demand and ensure security and reliability of supply, Zimbabwe imports about 32% of its power needs from neighbouring countries. The electricity network is interconnected to the Southern African Power Pool (SAPP) which was created in 1995 with its headquarters based in Harare in Zimbabwe.[16]. The region's commitment is to expand electricity trade, reduce energy costs and provide greater supply stability for the region's 12 national utilities.

The SAPP is now evolving from a cooperative to a competitive pool. Power trade continues to increase steadily annually at an average of 20%. The value of the electricity traded in 1999 was over US $150 million. A short-term energy market (STEM), which started live trading in April 2001, utilizes the Internet to conduct trades. The STEM is a spot market of non-firm electricity contracts. Independent power producers Hidroelectrica de Cabora Bassa, Kariba North Bank Company, and Zimbabwe Power Company will participate in the STEM, subject to clarification of their status. The SAPP managed to secure financial support from NORAD to develop a competitive electricity market for the SADC region and to update its cross-border transmission lines. [17]

Despite the developments in the region's networking projects, it is still necessary for governments to ensure that there is adequate local security of electricity supply. Focussing on small scale renewable energy projects will help Zimbabwe see a more secure and stable electricity supply system in the future, although short term problems can be solved by increasing the electricity imports. It is obvious that the neighbouring countries will soon need more electricity and a saturation of the SADCC market in 2007 has already been forecasted if new production installations are not commissioned by then.

3.3 THE GROWING NEED FOR ELECTRICITY

The annual electricity consumption in Zimbabwe is more than 10 000 GWh and only 35% of the two million households are electrified. Following the completion of the land reform programme, farming areas are likely to demand and consume more power in future since some people will move from rural areas to the subdivided farms. As at the end of April 2003, the demand for power had shot up from 4 900 to 10 000 applicants. A Rural Electrification Act was also passed in the same year that the new Electricity act [18] was passed. The objectives of the electricity reform programme was to rapidly increase the penetration of the electricity grid into the rural areas and to make use of off grid options for remote areas.

In Norway, the after effects of the deregulation of the electricity market, and the continuous growth of demand, have resulted in net importation of electricity and instability in electricity prices especially during peak seasons. The sensitivity of the electricity prices to the market demand, coupled with the world drive to conserve the environment has resulted in increased interests in private ownership of small scale renewable energy technologies. [19] The shortages in electricity supply have now led to the opening up of the markets at retail level to allow small producers again to enter the market and also sell power to the network.

In 1973 only 42% of the homes in Norway were heated with electricity and this percentage had grown to 65% by 1998 [13]. On average 80% of residential energy use in Norway is accounted to electricity space heating. Many families use 15 000 kWh's or more electricity per year to heat their homes. However, because there has been intense utilisation of the installed capacity and the reserve margin has greatly declined, energy efficiency programmes have been introduced [20].

This growing need is not only in Norway but in other countries and currently there is a high interest in distributed generation in the European Union and the United States of America, leading to development of new and/or better and cheaper technologies.

3.4 CHALLENGES IN DISTRIBUTION NETWORKS AND THE NEED FOR INVESTMENTS

Problems in distribution networks can be the same although the causes are different. For example, on one hand, the economy in Norway has generally been improving since the 1970's and people in the major cities have been building bigger houses. The residential energy demand has greatly increased mainly because of the increased space heating. The rapid growth in disposable income also allowed many Norwegians to improve their standard of living by buying more electrical appliances. These appliances demand electrical power. As a result two problems emerge on the distribution network, i.e. a much higher peak demand on the domestic load profile and an increased burden on the already installed equipment like cables, circuit-breakers, transformers, etc.

On the other hand, the economy in Zimbabwe has deteriorated and many people have migrated from rural areas to cities like Harare and to nearby farming areas. Accordingly, more domestic appliances were added to the distribution networks in the cities. The country's reduced capacity to generate foreign currency has led to the utility's initiation of energy saving programs to address some of the problems discussed above. Load shedding and tariff-based energy rationing programmes were introduced.[21]

The above problems necessitate utilities to invest in new cables and distribution equipment, in addition to new generation units. Self and co-generation will help the utilities to delay the need to make such investments especially during the reform period when the risk is very high.

4. SUMMARY

In this paper the electricity markets in Norway and Zimbabwe have been reviewed. The need for investment in new electricity production units is common to both countries although the causes of this need are different. We discuss self generation and co-generation as a way of solving these common problems.

5. ACKNOWLEDGEMENTS

The funding from the Norwegian government through NUFU, the University of Zimbabwe, the Norwegian University of Science and Technology and the support from SINTEF is sincerely appreciated.

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This paper will be presented by Margrate Mawire.

Paper 2

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Use of an interface unit at a customer premises could increase the daily profit

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INTRODUCTION

This paper shows how a customer who has locally installed electricity production units could increase the daily profit of local electricity production by using a smart interface unit.

The opening up of electricity markets has led to reduced investments in large energy generating units thereby resulting in net importation of electricity in some areas [1]. Because the prices are sensitive to the demand for electricity, the result has been very high prices during the peak periods of peak seasons to the extent that some private companies are affected negatively in their business operations. This instability of the electricity prices, coupled with the world drive to conserve the environment has resulted in increased interests in private ownership of distributed energy technologies. The shortage in electricity supply is also leading to the opening up of the markets at retail level to allow small scale producers to enter the market and sell electricity to the network.

Some of the distributed energy technologies are still in infancy. However, public support for research has led to significant progress over the last few years. Wind energy is now widely recognised as a viable option. Solar photovoltaic energy is quite promising and is slowly becoming economically competitive. Household waste is constantly growing and provides a significant energy opportunity as well as by products from timber and agri-foods industries. Hydrogen is a very promising energy carrier for the future. Fuel cells can go some way, to meet electricity needs, thermal needs and transport needs of local communities. Many countries are actively pursuing some form of small or micro hydropower development.

Implementation of distributed energy technologies on farms and rural areas will help these communities to become less dependent on energy imports yielding commercial returns in terms of growth of small and medium scale enterprises. Jobs will be created and people can be retained as the new businesses generate more income for these communities.

The viability of selling possibilities can be an important encouraging factor for many people who would like to invest in local generation. Factors to consider include connection fees, fuel prices, market prices, availability of connection and control technologies.

There are many technical and commercial issues that need to be addressed in order to connect small to medium scale energy producers to the distribution network as highlighted by [2]. In this paper we present a possible solution to the problem of profitability of small scale production units. Customers are likely to invest in technologies that will bring benefit to themselves or to their communities.

Farm Scenario

We envision a farmer who has installed a combined heat and power (CHP) unit, some solar cells and a fuel cell. This farmer has a possibility to generate electricity and meet the farm's energy needs from renewable energy resources like animal waste, biomass and sunshine. The use of a combustion unit which produces and utilizes both heat and power results in a higher efficiency. An example of the potential that a farming project can have in generating electricity is given in [3]. Figure 1 shows the scenario on the farm with respect to local electricity generation, utilization and energy transfer.

Response to Prices

The scenario presented in this paper covers a customer who sometimes buys from the network and at other times sells to the network. When the load is less than the local generation then there is excess electricity to sell to the market. If the market prices are attractive, it may be economical to generate more electricity locally and sell to the market. At other times for example when it is peak period at the customer premises and the customer needs to use a lot of electricity, then the customer has to buy from the network in order to satisfy the local load requirements. When the selling prices on the market are not so attractive and the network is offering very low electricity prices then it is better to buy more power from the network to cover most of the local load requirements than to generate at a higher cost.

The running costs of each of the generation units are different. The cost of fuel, which sometimes varies throughout the year, can be a major part of the operational costs of the fuel cell or the CHP unit. By using an interface unit with switching capability one can automatically control the generation of electricity of the production units and significant savings for the customer could be realized. This interface unit can easily access pricing information from the local electricity supply company on a regular basis. Based on load conditions, cost of own production and market prices an optimization for best profit could be done.

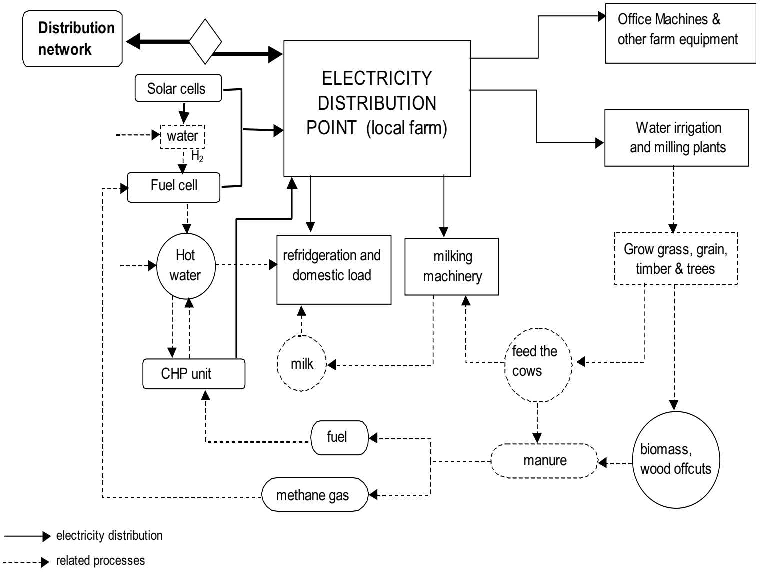

Figure 1: Farm Scenario

General Optimisation Theory

The general form of a constrained optimization problem may be expressed in mathematical terms as

$$\text{minimize } F(x)$$

$$x \in \Re \text{ subject to } Gi(x) = 0 \text{ , } i\text{=1,2,......m;}$$

$$Gi(x) \geq 0 \text{, } i\text{=m+1,...........m}$$

where $F(x)$ is the objective function

and $Gi(x)$ is the constraint function

The constraints can either be equality or inequality constraints. [4]

Minimisation Problem

In this problem, the general function for the electricity costs is written as

$$C_e = C_i + C_{sg} - R_e \qquad (1)$$

Where

C_e is the function for operational electricity costs

C_i is the function for import costs

C_{sg} is the function for cost of generating the electricity locally

R_e is the function for Export revenue (income obtained from selling electricity to the network)

The function C_e is optimized subject to the constraints of maximum and minimum (kW) output values of the generators and the power balance in the system.

$$0 \leq P_{g1} \leq 10 \qquad (2)$$

$$0 \leq P_{g2} \leq 20 \qquad (3)$$

$$0 \leq P_{g3} \leq 60 \qquad (4)$$

$$P_{g1} + P_{g2} + P_{g3} + P_i = (P_{cl} + P_e) \qquad (5)$$

where P_{gi} is the power output from generator *i.* When the system is in the import mode, then P_e will be equal to zero. The connection at the customer premises is such that power flows either from the distribution network to the customer or vice-versa. When the customer is selling to the network then P_i will be zero because there will be no imports. When the export revenue R_e is much larger than the self generation expenses, the customer will be making a profit.

Implementation

The graphical programming environment of LabView was chosen as the implementation tool for the interface unit which we chose to call a gateway. The communication capabilities of this programming environment were useful in implementing the experimental set-up.

Internet technology was chosen for communication between the electricity distribution company's web server (Personal computer A) and the gateway (Personal computer B) as shown in Figure 2. The webpage was read using the HTML VIs in the Internet toolkit in LabView, whilst data socket was used for communicating with the plant which was simulated on Personal computer C.

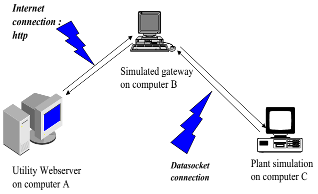

Figure 2 Experimental set up

Readings from the loads and generators as well as price information were displayed on the front-panel of the simulated gateway. The output of the Fuel cell and CHP unit could be switched on and off in an optimal way using the algorithm developed.

The output from the locally installed generators was monitored and readings were taken and sent to the algorithm. Steady state conditions were a necessity for the smooth running of the controller.

Communication

It is desirable to provide customers with necessary pricing information from the utility in good time. Such pricing information from the utility can be used to control the loads at the customer premises. The display of prices and time to tariff e.g. market prices or day and night rates or seasonal rates or any other accumulated tariff information is of great interest to customers who participate in electricity markets.

The customers also need to submit their meter readings regularly. Two way communications between the customers and the utility is necessary and could lead to reduction in overall electricity costs in the long run. In addition remote meter reading and quick detection of electricity failure also becomes possible.

It is envisioned that the utility posts the buying prices and selling prices for the next twenty- four hours of the following day, onto a web page. These prices are also very variable depending on the seasons of the year and they depend also on the availability of generation units which participate on the spot market. Using Internet technology the dairy farmer can readily access this data and manage the local generators automatically. Measurement data can also be sent periodically from the farm to the utility.

Experimental data

Different data sets were considered in analysing the functionality of the gateway. The maximum power ratings of the loads and generation units that were used in the simulation are given in Table 1.

Table 1 Power ratings of loads and production units.

Generation Unit	Maximum kW rating
Solar Panels	10 kW
Fuel Cell	20 kW
CHP unit	60kW
Loads	Maximum kW ratings
Refridgeration and domestic loads	40kW
Milking loads	20 kW
Milling and other equipment	30 kW

Variable price profiles were used to test the gateway and assess the profitability. Half hourly periods were used during the optimization and the profiles used resembled a pattern that could be found on a spot market. Output from the solar panels was not controlled by this algorithm because the operational costs of solar panels are low and once a customer installs solar cells, it is logical to just utilize all or store the generated energy in batteries.

Results

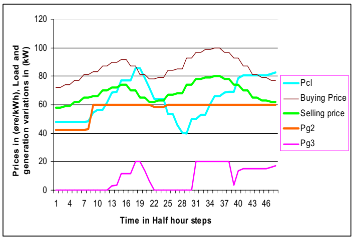

Figure 3 Generation units responding to the algorithm

Figure 3 illustrates how the generators respond to price and load variations. For example, when the load, Pcl, starts increasing in time step 7, the algorithm detects that it is becoming too expensive to continue importing from the network in order to meet the increasing load demand. It then automatically switches on generator 2, Pg2. As the load continues to increase generator 3 Pg3,also comes on. Later on, the load starts decreasing and, generator 3, is decreased first until it switches off. Generator 2 remains on because its set averaged costs of 65 øre/kWh are lower than the buying price on the market. In this case we assume that the utility will allow the customer to sell power at a price that is at least 80% of the buying price.

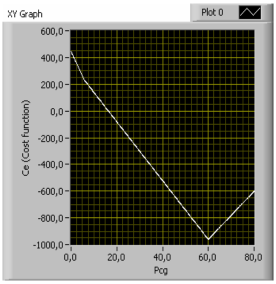

Figure 4 Observations on the cost function minimization

The minimum of the cost function could be observed on the front panel. Data was captured for analysis whilst the experiments were running. Figure 4 was a snapshot of an instance when the customer was generating at least 60 kW and selling some of its power to the network. The cost function shows that the cost to the customer at this moment is below zero. When the cost function is negative, it means that the market price is good for selling the locally generated electricity. The customer will earn an income from the local sales such that the generation expenses become much less that the revenue earned. This is a desirable situation for the customer because returns on investment start coming in.

The results obtained from sensitivity analysis on different data sets showed that significant revenue can be generated when the fuel cell (Pg2) and the CHP unit (Pg3) are switched on and off in an optimal way. Figure 5 is an example of the cumulative revenue that can be collected on a day in winter when the prices are very high.

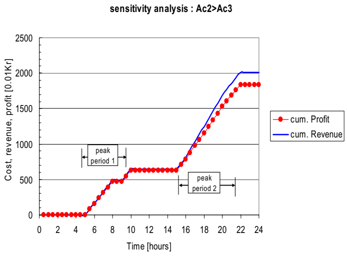

Figure 5 Results from sensitivity analysis

Conclusion

From the data sets that were used in this example, we see that the use of a gateway could lead to a significant economic benefit. Farmers could improve their income by selling electricity to the local utility in an optimal way using an interface unit with communication and automatic switching capability.

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