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Testing av regulator for små turbiner

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MASTEROPPGAVE

for

Stud.techn. Øystein Hveem

Våren 2013

Testing av regulator for små turbiner

Testing of governor for small turbines

Bakgrunn og målsetting

I mange land i den tredje verden er det stort behov for elektrisk kraft, samtidig som vannkraftpotensialet er stort. Vanskeligheten med å bygge ut er dels knyttet til investeringer, men også mangelen på elektrisk nett. Lokalt nett er en utforming mhp å regulere frekvens ved varierende last. Frekvensregulering som benyttes i store kraftverk er for dyrt og komplisert. Et alternativ er å sørge for konstant moment på turbinakslingen ved å dumpe overskudd av effekt til for eksempel å varme vann.

Et slikt system kan også gi mulighet for å kombinere flere el-produserende enheter, for eksempel PV sol og vindkraft til samme nett.

Masteroppgaven er en fortsettelse av prosjektoppgaven. Den beste løsningen er å benytte en såkalt dump-last-regulator, det vil si at regulatoren sørger for å holde konstant moment på turbinakslingen ved å regulere effekt slik at ubenyttet elektrisk effekt brukes til for eksempel å koke vann. En slik regulator er utviklet av Remote Hydro Light, kalt ELC. En regulator er blitt gjort tilgjengelig for uttesting.

Oppgaven bearbeides ut fra følgende punkter

1. Designe system for uttesting av ELC regulatoren
2. Bygge og instrumentere testfasiliteten i tilknytning til tverrstrømsturbinen i Vannkraftlaboratoriet
3. Kartellegge regulatorens egenskaper med hensyn på kvalitet på frekvensreguleringen
4. Designe system hvor forskjellige andre energisystemer kan påkobles
5. Om mulig, teste ut systemet hvor PV-sol vekselrettes og tilkobles som ekstra energikilde

" - "

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☒ Arbeid i laboratorium (vannkraftlaboratoriet, strømningsteknisk, varmeteknisk)
☐ Feltarbeid

NTNU, Institutt for energi- og prosessteknikk, 24. april 2013

Olav Bolland
Instituttleder

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Faglig ansvarlig/veileder

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Øystein Sveinsgjerd Hveem
Trondheim, September 26, 2013

Samandrag

Denne masteroppgåva beskriv installasjon og testing av ein vasskraftmodell tilkopla eit frittstående kraftsystem. Modellen vart installert i Vannkraftlaboratoriet ved NTNU og bestod av ein tverrstrømturbin, ein synkrongenerator og ei enkel last-kontroll-reguleringseining (ELC) produsert av Remote HydroLight i Afghanistan. Målsetjinga med forsøka var å evaluera eigenskapane til kontrollsystemet mtp sprangrespons i frekvens og generatorspenning. Kontrolleininga nytta fasevinkelregulering og fleire halvleiarar (triacar) for å leia overskuddseffekt frå generatoren til dumplastar. Dumplastane var varmekolbar som var montert og senka ned i det nedre reservoaret i laboratoriet. Ei tilsvarande konfigurasjon med varmekolbar vart nytta for å simulera variabel forbrukslast i energisystemet. Fleire testar vart utført for å evaluera eigenskapane til kontrollsystemet. Det svake leddet i testriggen var utvekslinga med beltedrift, som under testinga byrja å slure. Dette førte til ei auke i turtalet på turbinen og reduserte kvaliteten på resultata. Under brå tilkopling og fråkopling av full last vart det oppdaga eit enkelt kraftig sprang både i frekvens og generatorspenning. Dette signalet kan forstyrra og skada sensitive elektriske apparat. Trass dette, var responsen til kontrollsystemet god under dei ulike testane med stabil regulering i både spenning og frekvens.

I oppgåva blir det foreslått å implementere pulsbredde-modulasjon for å eliminere den ugunstige påverknaden frå halvleiarane i generatorspenningssignalet. Denne modifikasjonen gjev auka fleksibilitet i energisystemet ved å opna for bruk av induktive eller konduktive lastar som til dømes ein batteribank.

I oppgåva er det skildra eit frittståande hybridenergisystem der eksisterande testrigg er kopla til eit solcellepanel, medan eit meir sofistikert oppsett er skildra for meir komplekse energisystem. Begge systema er basert på ein felles likestraumskrins og lading av ein batteribank. Dette fører til eit meir fleksibelt, påliteleg og stabilt energisystem.

Abstract

In this master thesis, an experimental setup for a stand-alone power system has been installed and tested in the Waterpower Laboratory at NTNU. The experimental test rig consisted of a cross-flow turbine, a synchronous generator and an electronic load controller (ELC) manufactured by Remote HydroLight in Afghanistan. The objective of the experiments was to evaluate the performance of the ELC regarding step response in frequency and generator voltage. The controller used phase angle regulation and triacs to divert excess energy to dump loads. The dump loads were heating elements installed and submerged in the lower reservoir in the laboratory. A similar configuration was installed for varying the user load in the energy system. Several tests were performed to evaluate the performance of the ELC. A weak component in the test rig was the transmission system that started to slip. This resulted in an increase in turbine speed during the experiment and reduced the quality of the results. However, the tests indicated that a rapid single peak appears during abrupt disconnection and connection of loads. This may disturb and damage sensitive electronic equipment. Despite this, the ELC performed well during the diffent tests with stable regulation in voltage and frequency.

Introducing pulse width modulation would eliminate the unfavorable influence of the triacs in the generator voltage signal. With this modification it is possible to increase the flexibility in the energy system by introducing inductive or conductive loads like a battery bank.

A hybrid stand alone energy system connecting existing test rig with a photovoltaic-module has been developed. For a larger and more complex energy system, a more sophisticated system has been designed. Both systems are based on a common DC-grid and charging of a battery bank. This results in a more flexible, reliable and a more stable energy system.

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Nomenclature

η	hydraulic efficiency, $-$
ω	angular velocity, s^{-1}
ρ	density, kg/m^3
σ_m	mean standard deviation
f_{mains}	mains frequency, Hz
H_n	net head, mWc
n_{ED}	reduced rotational speed
P_h	hydraulic power, W
P_m	mechanical power, W
Q_{ED}	reduced discharge
A	area, m^2
D	diameter, m
e	error
F	force, N
g	acceleration of gravity, m/s^2
I	current, A
n	rotational speed, RPM
P	real power, W
p	pressure, Pa
Q	reactive power, VAr
Q	volume flow (discharge), m^3/s

R resistance, Ω

S apparent power, VA

s sample standard deviation

V voltage, V

v water velocity, m/s

Abbreviation

AC Alternating current

BEP Best efficiency point

BL Binary loads

DAQ Data acquisition

DC Direct current

ELC Electronic load controller

EMS Energy management system

HSE Health, safe and environmental

IAM International Assistance Mission

IGBT Insulated-gate bipolar transistor

MOSFET Metal oxide semiconductor field effect transistor

MPPT Maximum power point tracking

NTNU Norwegian University of Science and Technology

PV Photovoltaic

PWM Pulse width modulation

RAPS Remote area power supply

RHL Remote HydroLight

RMS Root-mean-square

RSS Root-sum-square

SAPS Stand-alone power system

TMT Traditional Mill Turbine

TRIAC Triode for Alternating Current

Chapter 1

Introduction

Access to electricity leads to increased welfare and development. [18] When looking on Earth from the outer space at night, it is easy to see the big global differences in electricity access. Comparing with the level of prosperity in the similiar countries, it is easy to see a connection. Level of prosperity increases with access to electricity. Knowledge and education is crucial when working with electricity. In many developing countries, education is expensive and available only for the upper-class in the society. Thus, many remote areas still have no electricity. The most common way of introducing electricity is by use of fossil fuel like a diesel generator. This is a cheap way to obtain electricity, but a costly way in long term, since fuel is expensive. Fossil fuel is also a limited resource and should in a global perspective be avoided. Many articles are written about this topic the last decades, and the common thread is that the global community has to tend towards a more sustainable way of managing the limited resources.

Using renewable energy sources instead of fossil fuel is an important step towards this goal. Energy sources like photovoltaic(PV)-, wind- and hydro power are all renewable and with free supply of fuel. PV-energy is a much used energy source in many remote areas. One of the reason is that the purchasing- and maintenance-costs are small. The charging- and control systems with batteries have become quite advanced compared to the cost. The last few years, small cheap wind turbines have been introduced to the global market. Compared with PV-energy, wind energy has higher efficiency, but larger mechanical forces and stress are introduced. Thus, wear and maintenance costs increases. Hydro-energy is a stable energy source with high efficiency. It is depending on location and access to water. Building small reservoirs increase the flexibility of this energy source.

Remote HydroLight is a full-range supplier of micro hydro power plants in Afghanistan. The company has been involved in training of personnell, manufacturing of components and installation of hydro power plants. Finding cheap, simple and robust solutions for power plants in remote areas has been an objective for the company.

One of the tasks has been to develop an easy and cheap governing system with low maintenance costs. Using equipment locally produced in Afghanistan has reduced the costs in the production a lot.

In this master thesis, a governing system (electronic load controller) produced by Remote HydroLight has been tested and connected to a cross flow turbine manufactured by the same company. In addition, a proposal for connection between several energy sources in a stand-alone power system has been described.

The thesis is structured in chapters and headings in order to make it surveyable and easy-to-follow. It starts with a general introduction about the turbine, generator and governing system. In the next chapter, the controller and the relation between the most important parameters used in the experiments are presented. In *Instrumentation* the equipment used in the experiments are described. The procedures for the tests are explained in *Method.* The most important results from the work are prestened in *Results*, and these are discussed in the *Discussion* chapter .In *Further work* several recommendations for further investigations are explained. A summary of the results and discussion is presented in *Conclusion.* In appendix, calibration data, data sheets from equipments used in the experiment, software used for logging of data and a HSE-repport for the work in laboratory are attached.

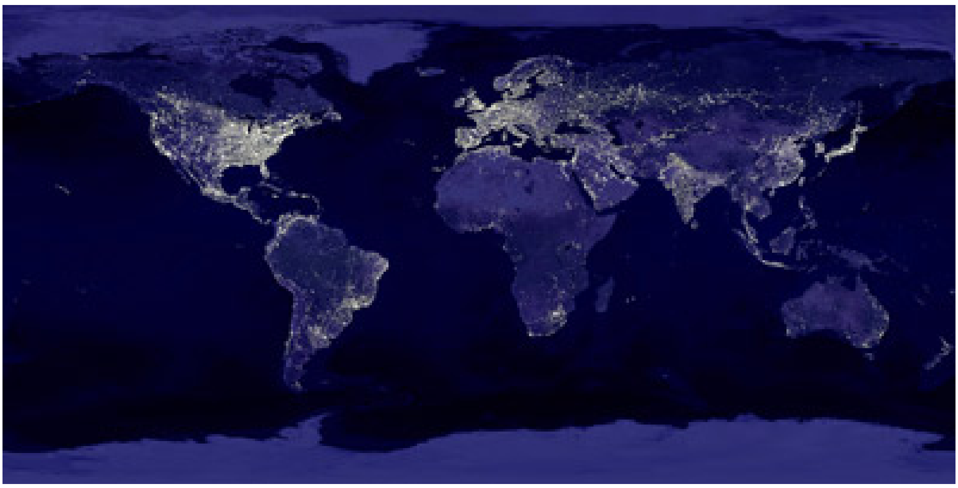


Figure 1.0.1: View of Earth from outer space at night

Chapter 2

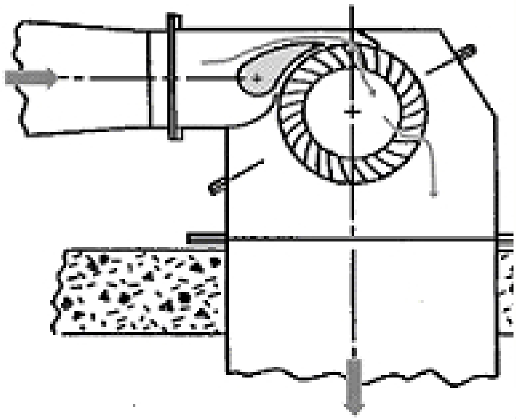
Background

2.1 Cross-flow turbine (Ossberger turbine)

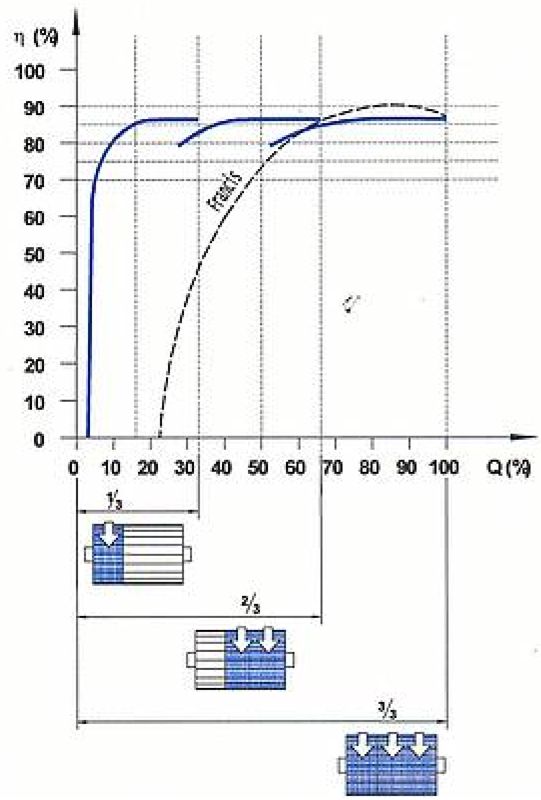
The Cross-flow turbine is an impulse turbine where all pressure energy is converted into kinetic energy when entering the runner (ideal case). At the inlet of the turbine a large guide vane is located controlling the volume flow into the turbine. The runner consists of a large number of vanes (up to 37) located symmetrically around the runner. The water enters and flows through the turbine before exiting through the runner vanes on the other side of the turbine. The turbine can be splitted up in several chambers with runner vanes. This multi-cell turbine is better adapted to varying volume flows, since the area of the inlet is adjusted in two directions by valves. (see figure 2.1.1b) It is operating with a range in head of 2,5-200m and discharge range of 0,04-13m^3/s. The turbine is provided with a power range of 15-3000kW by the manufacturer. A mean efficiency of 80% is expected for small power outputs and higher efficiency (up to 86%) could be obtained for larger units. Since most micro hydro plants in developing countries have no reservoirs, the volume flow during the year is changing. For these run-off plants, the multi-cell cross-flow turbine is a good choice. [9]

2.2 Generator

In the generator, the mechanical energy from the runner is transformed into electric energy. Generators in small stand-alone powerplants generally belong to one of the following categories: induction generator with a capacitor bank (IG) or permanent magnet synchronous generator (PMSG). The simplest and also cheapest generator is the IG. It is easy to control the voltage, but has limitations in speed variation and efficiency. The PMSG has better efficiency, but large cost and limited variation in speed are the major drawbacks. [7]



(a) Principle of a cross-flow turbine



(b) Stable efficiency curve when using a multi-cell turbine

Figure 2.1.1: Cross-flow turbine

For micro hydrosystems below 30 kW, IG is the recommended solution. The IG is cheap and robust. To run it with overspeed does not damage it, and maintenance costs are small. It is also possible to run it on lower nominal speed, and then get a lower transmission ratio. For systems with a capacity >30 kW, the synchronous generator is a better solution, and this is also the solution used in Remote HydroLight's projects in Afghanistan.[7]

2.3 Electronic load controller (ELC)

A well-developed power grid is in many countries non-existent. In many remote areas, a stand-alone power system (SAPS) is the only feasible choice. The ELC is a much used governing system for these power systems. The controller keeps the torque constant by connecting and disconnecting dump loads frequently as the consumption loads change. Thus, it works like an electronic brake on the generator. The dump load energy is in most projects used for heating water. It is a small and cheap solution for controlling the power output. For small run-off-river systems it is a very preferable system, since the alternative is that the dump load energy would dissipate anyway.

The ELC that is tested in lab has a capacity of 6 kW and is manufactured by Remote HydroLight in Afghanistan. By the end of september 2012, 1750 ELC's have been installed in Afghanistan by Remote HydroLight. The motivation for the company has been to develop a simple but robust controller with a quality that is appropriate. The ELC is only possible to connect to a synchronous generator. Producing an ELC for connection with induction generator is planned in the future.

2.4 Earlier work

In 2008 a cross-flow turbine manufactured by Remote HydroLight (RHL) was installed in the Waterpower Laboratory at NTNU. The turbine, also known as the IAM-turbine had a diameter of 270mm, width of 335mm and a power output within 1-22 kW.

In 2008, an efficiency test was performed on the IAM-turbine in the Waterpower laboratory at NTNU by two master students: Eve Kathrin Walseth and Sven Olaf Danielsen. The laboratory is IEC approved and the IAM-turbine perfomed max efficiency of 78.6 $\pm$ 0.9 % with 5m head and 80% nozzle opening. An CFD-simulation was performed to locate the losses in the inlet and through the runner. The simulation showed a great potential in design of both the inlet and runner. [21]

In 2009, Eve Cathrin Walseth continued working with the IAM-turbine. Further investigation of the flow through the runner was done. A visualisation of the flow by use of a single-lens camera and stroboscopes was carried out showing how the direction of the flow changed by changing the nozzle opening. The torque transfer was also investigated by use of strain gages. The results showed that the turbine works well for large nozzle openings. The flow enters the runner close to the nozzle that results in an inlet angle that corresponds well with the angle of the blade. The investigation of the torque showed that 53,7 % of the torque was transferred through the second stage. [20]

In 2013 masterstudents Oblique Shrestha and Supriya Koirala continued working with the IAM-turbine. The efficiency was investigated and a rig with high speed camera, lightning and mirrors was installed. This resulted in better visualisation of the flow through the runner. [12]

Chapter 3

Theory

3.0.1 Direct Current (DC) and Alternating Current (AC)

In a DC-circuit the direction of current is constant. A standard nominal voltage for DC-circuit is $12V$. This is the same voltage-level as used in standard automotive batteries (lead acid batteries). For high power electric equipment using AC, an inverter is used to convert from DC to AC.

In an AC-circuit, the direction of current is constantly changing. The number of oscillations per second is set by mains frequency (explained in the next section). Unlike DC, AC is well suited for transforming up to high voltage. For transport over large distances high voltage AC is the best solution to avoid large losses in the grid. The national grid is a three phase AC-system. The electricity is then distributed in three different phases and transported in four separate lines where one is connected to ground. In Norway, the nominal voltage on the grid is $220V$ into the households.

3.0.2 Mains frequency

Frequency is defined as the number of cycles per unit time. The SI-unit for frequency is Hertz (Hz=$\frac{1}{s}$). Thus, 1 Hz is equal to 60 cycles per minute. Mains frequency (utility frequency) is defined as the frequency of oscillations from a sine-wave-formed AC-curve. From eq.3.0.1, the coherence with generator speed and number of pairs of poles is established. It is important that the frequency is constant. If there is a marked drop in frequency, sensitive electronic equipment may be damaged. In Norway and in many western countries, $50Hz$ is the standard mains frequency. This is different from Canada and USA where $60Hz$ is standard. For Norway, a variation of $\pm$ $0.1Hz$ is set as limit.

The connection between rotational speed,n, pairs of poles P, and mains frequency, f_{mains} can be expressed:

$$f_{mains} = \frac{n \cdot P}{60} \tag{3.0.1}$$

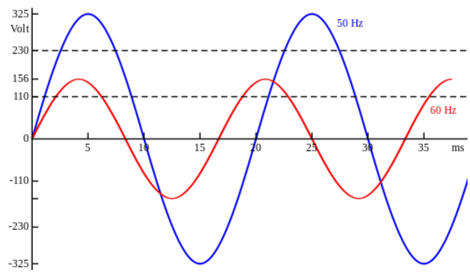


Figure 3.0.1: Principle of mains frequency

3.0.3 Electric Power

Electric power can generally be described as work done per unit time. Watt $[W]$is unit, defined as J/s. Power is depending on current I,voltage U and phase angle θ. θ is defined as the angle between the current- and voltage-sine wave. The general relation in an AC circuit is:

$$P = \frac{1}{2} U \cdot I \cdot cos\theta = U_{RMS} \cdot I_{RMS} \cdot cos\theta \tag{3.0.2}$$

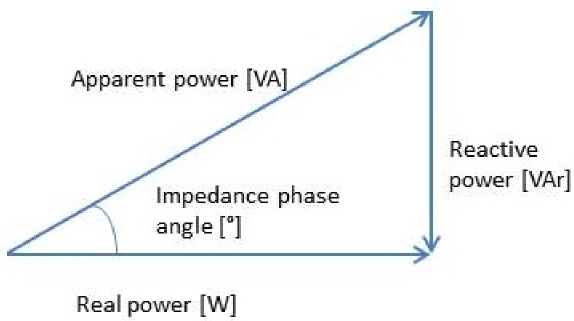


Figure 3.0.2: Power triangle

The power triangle displayed in figure 3.0.2 describes the relation between real-, reactive- and apparant power. When equipment with capacitors or coils are introduced in a circuit, a reactive contribution in power appears. For a pure resistive circuit, reactive power is 0. Thus:

$$P = U \cdot I = I^2 \cdot R \tag{3.0.3}$$

Since only resistive loads are connected in the experimental setup, the reactive contribution is 0 and will not be considered further.

3.0.4 RMS-value

The root-mean-square-value (RMS-value) is a statistical parameter that is used to find the magnitude of a signal. It is very useful when a signal is both positive and negative, like the AC sine wave. The RMS-value for a continous function $f(t)$ over a time interval $T_1 \leq t \leq T_2$ can generally be expressed:

$$f_{RMS} = \sqrt{\frac{1}{T_2 - T_1} \int_{T_1}^{T_2} [f(t)]^2 \, \mathrm{d}t} \tag{3.0.4}$$

An AC voltage sine wave can be expressed:

$$V(t) = V_p sin(\omega t) \qquad \text{where } V_p = \text{peak voltage} \tag{3.0.5}$$

Using this equation, the RMS-value for the AC-voltage signal can be expressed:

$$\begin{aligned} V_{RMS} &= \sqrt{\frac{1}{T_2 - T_1} \int_{T_1}^{T_2} [V_p sin(\omega t)]^2 \, \mathrm{d}t} \\ &= V_p \sqrt{\frac{1}{T_2 - T_1} \int_{T_1}^{T_2} [sin^2(\omega t)] \, \mathrm{d}t} \\ &= V_p \sqrt{\frac{1}{T_2 - T_1} \int_{T_1}^{T_2} \frac{1 - cos(2\omega t)}{2} \, \mathrm{d}t} \\ &= V_p \sqrt{\frac{1}{T_2 - T_1} \left[\frac{t}{2} - \frac{sin 2\omega t}{4\omega} \right]_{T_1}^{T_2}} \end{aligned}$$

Since it is a periodic signal the sine-part removes. Thus:

$$V_{RMS} = \frac{V_P}{\sqrt{2}} \tag{3.0.6}$$

The RMS-value of an AC voltage signal can be described as the equivalent DC voltage that would dissipate equal amount of heat. Similar analysis is used for finding I_{RMS}.

$$I_{RMS} = \frac{I_P}{\sqrt{2}} \tag{3.0.7}$$

3.1 Test rig

3.1.1 Necessary parameters

In order to define an operating point for the cross flow turbine, it was necessary to measure the following parameters: discharge, pressure, rotational speed and water temperature. This was done in order to make it easier to repeat the tests and validate the results. To control the electric power to the ELC, current and voltage was measured.

3.1.2 Hydraulic power

Hydraulic power is defined as power derived from motion and pressure in a certain liquid. Hydraulic power in a hydro system is given by eq.3.1.8. This is not used in the experiments, but explains the correlation between density, discharge and net head.

$$P_h = \rho \cdot g \cdot Q \cdot H_n \cdot \eta_h \tag{3.1.8}$$

Here the density is determined by measuring atmospheric pressure and water temperature [8]:

$$\frac{1}{\rho} = V_0 \left[(1 - A \cdot p) + 8 \cdot 10^{-6} \cdot (\theta - B + C \cdot p)^2 - 6 \cdot 10^-8 \cdot (\theta - B + C \cdot p)^3 \right] \tag{3.1.9}$$

$$\begin{aligned} V_0 &= 1 \cdot 10^-3 m^3/kg \\ A &= 4,6699 \cdot 10^{-10} \\ B &= 4,0 \\ C &= 2,1318913 \cdot 10^{-7} \end{aligned}$$

Note: $p = p_{abs}$ [Pa] and θ=temperature [$^\circ C$]

Acceleration of gravity

Norwegian Metrology Service (Justervesenet) has measured the acceleration of gravity in the Waterpower laboratory:

$$g = 9.821465 m/s^2 \tag{3.1.10}$$

Net head-H_n

The specific hydraulic energy (Net head H_n), was determined by using Bernoulli's equation from inlet of the turbine to center of the turbine. The level difference was measured between center of the pipe and center of the runner. The velocity at the inlet was set by measuring the discharge and using the diameter of the pipeline.

$$H_n = \frac{P_i}{\rho g} + Z + \frac{v_i^2}{2g} \tag{3.1.11}$$

Converted into pressure:

$$m = \rho \cdot V \tag{3.1.12}$$

$$F = m \cdot g \tag{3.1.13}$$

$$p = F/A \tag{3.1.14}$$

$$1 bar = 1 \cdot 10^5 Pa = 100 kPa \tag{3.1.15}$$

$$1 Pa = 1 \cdot 10^{-5} bar \tag{3.1.16}$$

Example: $5 mWC$ at $20\ ^\circ\ C$ converted to bar:

$$m = 998,2071 kg/m^3 \cdot 5 m^3 = 4991,0355 kg$$

$$F = 4991,0355 kg \cdot 9.821465 m/s^2 \approx 49019 N$$

$$p = \frac{49019 N}{1 m^2} = 49019 Pa = 0,49019 bar$$

Velocity at the inlet:

$$Q = A_i \cdot V_i \tag{3.1.17}$$

$$V_i = \frac{Q}{A_i} = \frac{Q}{\pi \cdot (\frac{D_i}{2})^2} \tag{3.1.18}$$

Hydraulic efficiency

Hydraulic efficiency, η_h, is defined as the ratio between output mechanical power and input hydraulic power. η_h is between 0 and 1 and is expressing the hydraulic losses through the turbine. Mechanical power was not measured, but use of electrical power instead gives almost similiar results.

$$\eta_h = \frac{P_m}{P_h} \tag{3.1.19}$$

3.2 Uncertainty analysis

Error is by the International Electrotechnical Commision (IEC) defined as the difference between a measurement and the true value of the quantity. Uncertainty is defined as the range of values likely to enclose the true value. A 95% confidence interval is a standard requirement, meaning the true value is expected with 95% probability to lie within this range. This is important information about the measurements and should always be included. Errors in experiment can be categorised as spurious-, random- and systematic errors. [8]

3.2.1 Spurious errors

Errors detected from human failure or instrumental malfunction are examples of spurious errors. If spurious errors are detected during the experiments, the results are not valid and should be discarded. Better preparations and clear procedures are strategies for reducing these errors.

3.2.2 Random errors and related uncertainty

Random errors occur as small fluctuating differences in measurements. They are deviating from the true mean value, according to the laws of chance. The random uncertainty is depending on number of samples and operating conditions. When the number of samples increases, the random uncertainty decreases. Keeping the operating conditions constant is reducing the deviation from the mean value, leading to a reduction in random uncertainty. To determine the random uncertainty in the measurements, sample standard deviation s first needs to be calculated: [14]

$$s = \sqrt{\frac{\sum_{i=1}^{N} (x_i - \overline{x})^2}{N-1}} \tag{3.2.20}$$

x_i= independent measurement
$\overline{x}$=arithmetic mean value
N= number of samples

The mean standard deviation of the mean value for a set of measurements is then defined:

$$\sigma_m = \frac{s}{\sqrt{N}} \tag{3.2.21}$$

Student's t-factor is used to correct the random uncertainty for small number of samples. When a measurement has a large number of samples, a Gaussian (normal) distribution is assumed to give an applicable representation. Absolute error e is then determined:

$$e = \frac{t \cdot s}{\sqrt{n}} = \frac{1.96s}{\sqrt{N}} \tag{3.2.22}$$

For the experiment,t-distrubution was used due to a relative small number of measured values. The relative random error f_r (in %) can be calculated:

$$f_r = \frac{e}{\overline{x}} \cdot 100 \tag{3.2.23}$$

Systematic errors and related uncertainty

Systematic errors are expected in all measurements and are independent of number of samples. They are internal errors that are constant, predictable and occuring during the entire experiment if operating conditions remain constant. If the assumptions or operating conditions change during the experiment, it is likely to expect that also the systematic error will change. To determine the systematic error, two different measuring system have to be used, and the deviation in each measurement has to be evaluated. It is also possible to evaluate the error by using experience and obtain a subjective estimate. Precise measuring equipment and good accuracy in calibration of measuring equipment are important factors for reducing the systematic errors.

It is important to identify all contributors of systematic errors when evaluating systematic uncertainty. The total systematic uncertainty, $f_{s,t}$, is defined by the Root-Sum-Square (RSS)-equation consisting of all systematic uncertainties from the measured variables:

$$f_{s,t} = \sqrt{\sum {f_{s,i}}^2} \tag{3.2.24}$$

Total uncertainty

The total uncertainty,f_t, in a measurement is evaluated by using the RSS-relation. The total uncertainty includes contribution from both random and systematic uncertainty and is expressed in equation 3.2.25.

$$f_t = \sqrt{{f_{s,t}}^2 + {f_r}^2} \tag{3.2.25}$$

3.2.3 Uncertainty analysis of experiments

During the experiments both generator- and dump load voltage were measured frequently with a data aquistion-module. The module was not calibrated before the experiment started, resulting in an accuracy in voltage signals of $\pm 0.4\%$ given by the manufacturer. [10] Current and power were measured by a power analysing instrument Voltech PM3000A, with an accuracy of $\pm 0.5\%$. [11] There are not identified other significant systematic contributors in the experiment.

Before and after every test was performed, random uncertainty in the measured parameters was calculated. This was done to verify that the values and the performance were stable and did not affect the logging of dynamics when testing started.

3.3 Governing system - Electronic load controller

The Afghan company Remote HydroLight (RHL) has developed an electronic load controller (ELC) for micro hydro power plants located in remote areas. The controller is a simplified version of Jan Portegijs' ELC, the Humming Bird [15], modified by Anders Austegard. The cost is important, and one of the main goals for the company has been to develop a simple and understandable ELC that can be produced in Afghanistan by the Afghan people. Even if it is simple, it has been important to develop a robust controller with a quality that is appropriate. Remote HydroLight's ELC is tested for micro hydro power plants with capacities up to 45 kW. It has also been installed on hydro power plants with larger capacities, but then with several ELC's connected in series. By the end of september 2012, 1750 ELCs have been installed in Afghanistan. To decrease the cost and make it easy to handle, many simplifications have been implemented compared to the original Humming bird. [5] A cost estimate for a $6kW$ three-phase controller with digital card is set up in appendix $B.2.1$.

The controller is developed for connection with a synchronous generator in a stand alone power plant. It is connected to one or several dump loads that are triggered by triacs in order to brake and regulate the turbine. Heating elements are used as dump loads and are either installed in a water-filled tank or in the river downstream. Often, more than half of the energy produced is consumed in dump loads. This sounds quite ineffective, but for most of these micro hydro power systems storing water in reservoirs is not an option. The intake is usually located in a river and the water that is not used, is lost energy anyway. The cost of a speed control governor like an oilhydraulic mechanical system is so high that in many cases it is more economical to use an ELC with dump loads instead. In RHL's projects, a water tank with several heating elements connected is used as dump load system. The principle of the system is shown in figure 3.3.3.

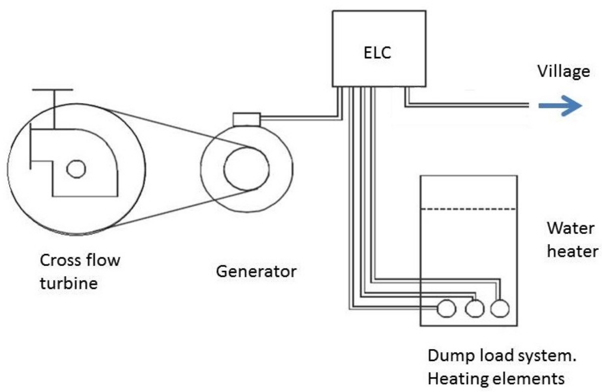


Figure 3.3.3: Principle of electronic load controller

Phase angle regulation

The controller uses phase angle regulation to divert the power to the dump loads. The dump loads are triggered by triacs at a certain phase angle between 0° and 180°. This is referred to as the trigger angle. When the dump loads are triggered, they start conducting until the generator voltage crosses the $0V$-line. This response is continous and appears twice for each AC-period. (see figure 3.3.4).

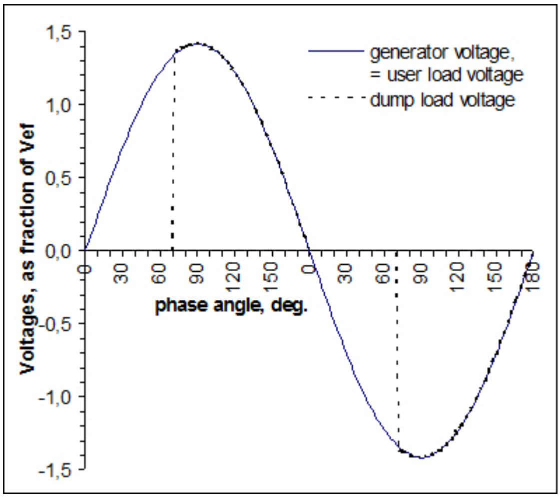


Figure 3.3.4: Generator voltage with dump loads triggered at 70°

Digital/Analog control systems

The control system of the ELC is located on the printed circuit board (PCB). RHL produces both digital and analog PCBs to their control systems. The analog card (PCB) uses frequency as input for regulation. Analog cards are mainly recommended in projects where two generators are operating synchronously. Compared with a digital card it has a larger range in voltage, and may be used in systems where extra high or low voltage is required. One example is projects with large transmission losses. Analog cards are frequently used in older versions of ELC, but are generally more complicated and more expensive to produce.

The digital card is controlling voltage. It is the most used solution for new ELCs, and is cheaper and easier to produce. [5] In the experiments, a digital three-phase card is used. In the next sections only the digital version is described.

Response of a small reduction in consumption load

In most projects the consumption loads (village) are connected in parallel. From eq.3.3.26, a reduction in consumption load results in an increase of total resistance, R_{Tot}. Thus, from equation 3.3.27 and 3.3.28, a reduction in load leads to a reduction in current and torque. Since power P is constant, angular velocity, ω, mains frequency n_0 and the generator voltage, U_{gen} will increase. The load controller triggers several dump loads simultaneously, in order to keep the torque and voltage constant. A reduction in consumption load will lead to a smaller trigger angle and thus dump load voltage (RMS) will increase.

Response of a small increase in consumption load

In the opposite situation, a small increase in consumption load will lead to a decrease in the total resistance. This results in an increase in torque and current. Power P is still constant and angular velocity, ω, mains frequency n_0 and the generator voltage, U_{gen} will decrease. The controller responds by varying the trigger angle of the dump loads in order to keep torque and power constant. An increase in the consumption load will result in a larger trigger angle and thus dump load voltage (RMS) will be reduced.

For a parallel connected consumption load:

$$\frac{1}{R_{Tot}} = \frac{1}{R_1} + \frac{1}{R_2} \cdots \tag{3.3.26}$$

$$P = U \cdot I = R \cdot I^2 = \frac{U^2}{R} \tag{3.3.27}$$

$$P_{Mechanical} = T \cdot \omega \tag{3.3.28}$$

$$n_0 = \frac{60 \cdot n_g}{p} \tag{3.3.29}$$

where: n_0=mains frequency [Hz], n_g=rotational speed generator [RPM] , p= number of pairs of poles [-]

3.3.1 Critical situations

Overload situation

Generally, when several user loads are connected, current and torque increases. This leads to a drop in generator voltage. To counteract this, the trigger angle of the dump loads increases until torque and voltage is back to the set points. When consumption load is equal to the capacity of the power plant, no load is diverted into the dump loads. If more user loads are connected, an overload situation will occur. The generator speed will decrease resulting in a new operational point for the turbine and generator. Since best efficiency point (BEP) normally is set for the turbine, this results in a reduction of power output. The response depends on the connected components. Generally, generator voltage will drop until a new stable operational point is reached. For an electrical fan this will reduce the speed of the fan. For a bulb this may result in flashing. Since the consumption load normally consists of several different components it is hard to predict the response directly. In RHL's projects, fuses are installed in each family house to reduce overload situations and to detect where the overload occured. To reset the fuses the family must contact an operator and this reduces later overvoltage situations.

Rapid off-load situation

If an error occurs on the transmission lines, the generator suddenly looses the consumption load. This results in a reduction in current and torque. Thus, the generator voltage will increase. To withstand this, more power is diverted to the dump loads and the trigger angle is decreased. If some of the dump loads are damaged or disconnected, the generator speed and the generator voltage will increase until a new stable operational point is obtained. If all dump loads are disconnected, a run-away situation occur. This is a critical situation where the turbine will spin up to run-away speed (where efficiency is 0) and equipment may be damaged.

3.3.2 Front panel of the ELC

A $6kW$ ELC, similar to the one used in the experiments, is shown in figure 3.3.5.

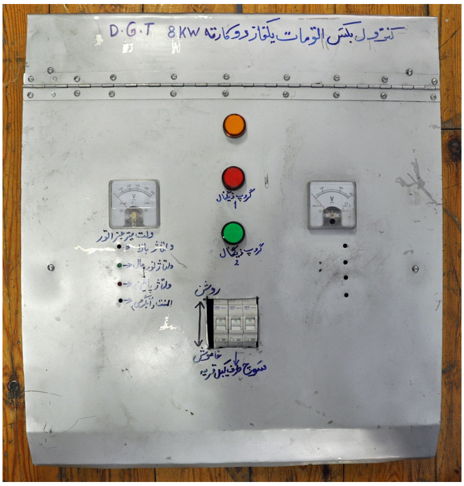


Figure 3.3.5: Electronic load controller developed and manufactured by Remote HydroLight

Diodes

Four small light emitter diodes (LEDs) are installed on the left side of the front panel of the ELC. Their objective is to display the status of the ELC:

Red LED:	Overvoltage situation, meaning that all power is directed to the dump loads.
Green LED:	Voltage level in the village is normal and no power is diverted in the dump loads,
Red LED:	Undervoltage situation. In this situation no power is directed to the dump loads and the frequency of the generator may be reduced.
Green LED:	Voltage level in the village is normal and the dump load is partly triggered.This means some of the power is directed to the dump loads.The brightness increases when trigger angle decreases.

Three larger LEDs (orange, red and green) are installed in the center of the front panel. When they light, they indicate that voltage is connected on each of the three phases from the generator.

Meters

Two voltage meters are installed on the ELC that was evaluated. The first meter displays the generator voltage (RMS), and the other displays the voltage of the dump loads (RMS). It is also possible to install one or several amp-meters by measuring the current through the coil.

Fuses

Three fuses are installed between the ELC and the consumption load. They protects the village from overvoltage and damage on electrical equipment. When the fuses blow, all energy is diverted in the dump loads.

Cabinet

The cabinet is protecting the different modules against overheating, water leakage and moisture. RHL suggests two different boxes: one low-cost and one more robust. The low-cost cabinet contains of a steel cover with openings on the sidewalls and at the bottom. The more robust alternative uses a larger cabinet with a door and opening on bottom. On top of the cabinet it is a small gap for ventilation.

Dump load system

The dump load system consists of several resistive heating elements where excess energy from the village is used to heat water. In RHL's projects, a steel tank is used with heating elements installed at the bottom of the tank. Installing the elements at the bottom is done to avoid dry-out and give better circulation since hot water will rise. This kind of solution is shown in figure 3.3.6

Figure 3.3.6: Water heater used in RHL's projects

3.3.3 Inside the ELC

In figure 3.3.7 the components inside the ELC is displayed. In the next sections the different components are described briefly. The circuit diagram for the ELC used in the experiments is given in appendix B.2.

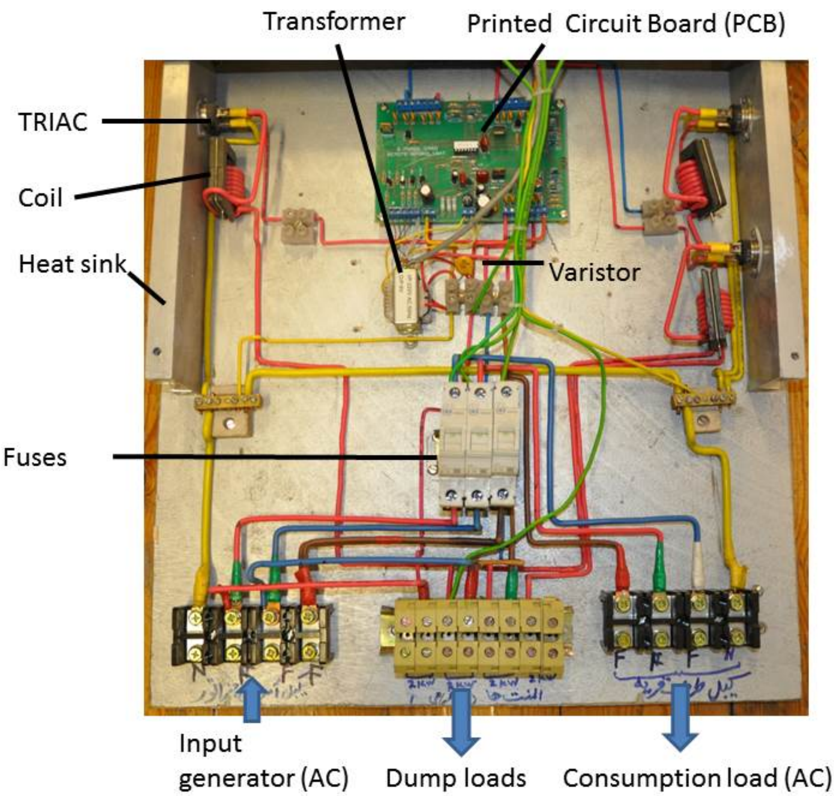


Figure 3.3.7: Inside the electronic load controller

3.3.4 Signal distribution

Generator voltage (220V AC) is used as input to the ELC. The signal is connected to the village only separated by fuses. The signal is also directed to the varistor and transformer that makes the entrance of the ELC.

Varistor and transformer

A 220V/6V transformer is used before the signal enters the card. This is because the components on the card are not able to handle such high voltage. To avoid high peaks in the voltage signal, a varistor is installed in front of the transformer. The varistor works like a simple overvoltage protection by avoiding damage on the card and the transformer.

Digital card

The digital card (PCB) used in the tests is shown in figure 3.3.8. Centrally located on the PCB is the microcontroller. RHL uses a Texas Instrument MSP430F2012 microcontroller in their design. The controller has an A/D converter with a sampling rate of 12600 samples per second for each phase. It has 14 terminals, 128 byte RAM memory and 2kB flash memory.[5]. Since both input and output of the card is connected to phases (see circuit diagram in appendix B.2), thermistors are used on the output to the triacs to prevent high voltage to enter the PCB.

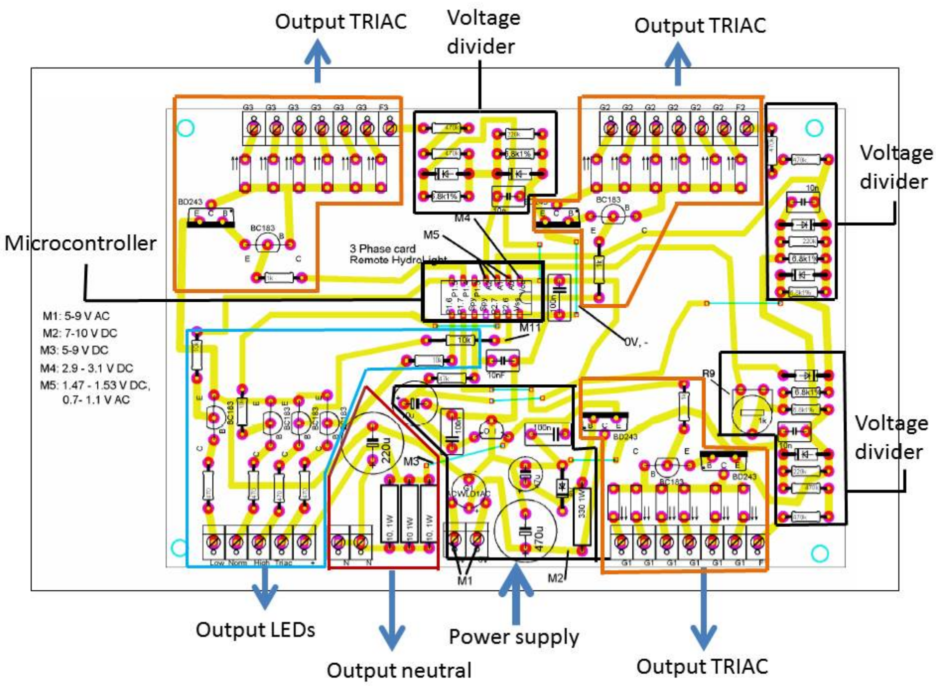


Figure 3.3.8: Digital 3-phase PCB used in the experiment

Governing parameters

The accumulated mean value of the generator is used as input signal for the governing parameters. This value is used instead of the RMS-value, due to stability. To govern the system, the controller uses a Propotional-Integal-regulator (PI-regulator).The proportional part is based on frequency and the integrator-part is based on voltage. The governing parameters have been tuned by Remote Hydro-Light. They are conservative chosen to avoid unstable situations and equal for all of the ELCs that RHL has installed in Afghanistan. The generator voltage level (RMS) is set to $230V \pm 5V$. For small corrections in setpoint of voltage, a varistor located on the PCB is utilised.

Triac and coil

The triacs are used to trigger and divert power to the dump loads. The triacs conduct in both directions and each dump load is connected to one triac. RHL uses original triacs from ST Microelectronics (BTA40-600B). These components have capacity up to 40A and 600V. This results in less problems with overload and makes the ELC more robust.To protect the triacs, ferrite coils are used and connected in series with the triacs.

The triacs are triggered in a single step process, meaning that all the triacs trigger in the same moment. This results in a rapid response in the generator voltage and may lead to noise and vibration.

Heat sink

During operation the ELC produces a lot of heat. To avoid damage on sensitive electronic components, it is necessary to cool down the controller with air. The controller uses heat sinks of aluminum with several fins to increase the surface area. Each heat sink can be connected with two triacs. The heat sinks are located on the outside of the ELC in order to get proper ventilation.

3.3.5 Experience from RHL's projects

Anders Austegard and Remote HydroLight started with production of analog ELCs in 2006. In 2009 the digital ELC was released. Compared with the analog version it was a much more reliable solution and easier to construct. Poor component quality has been a common thread on the problems that has occured since the beginning of production.[5] [3]

One of the major problems has been brakedown of heating elements. Poor quality heating elements from China has led to fatigue and failure on several elements. High quality heating elements are much more expensive than elements from China, but in many projects the people in the village do not want to spend extra money on this. Finding high quality original parts has generally been a challenge. In some cases, non-original triacs and transformer have been installed by other companies and this has resulted in failure. In most of RHL's projects the generators are manufactured in China. To increase the durability, many of the electronic components are changed with higher quality parts before installation on the plant.

There have been some problems with water leakage and moisture on the connections between the heating elements and the wire. Condensation has resulted in moisture on the connections between the terminal on the heating element and the wire. Thus, short circuit and failure has occured.

In RHLs first projects, the triacs were connected in parallel. This led to a more harmonic generator voltage curve, due to less influence of the triacs. However, the circuit also became more complicated and in later projects the triacs have been connected in series instead.

In general, the digital ELCs seem to work much better than the analog ELCs. The use of thermistors at the outlet of the PCBs have been an important factor, but also improved simplicity and robustness of the system.

3.4 Improvements of the ELC

Phase angle regulation with triacs is a simple way of controlling an energy system. It is a cheap and robust solution, but with limited range of application, since only resistive dump loads can be connected. The quality of the signal is poor. Each time the triacs trigger, a rapid peak in the generator voltage occur. This disturbance may create problems when connecting and synchronising with other energy sources. Jan Portegijs mentions two different alternatives to phase angle regulation: Pulse Width Modulation (PWM) and Binary Loads (BL). [15]

3.4.1 Pulse width modulation

Pulse width modulation (PWM) is a commonly used technique for modulating a voltage signal. PWM uses modern transistors like IGBT or MOSFET to set up a pulse signal. In general the signal in PWM is either on or off. The method uses the width of the pulse signal to determine the average voltage signal (see figure 3.4.9). The time the signal is on (the width) is defined as the duty cycle. By varying the duty cycle, the output voltage signal is changed. Since the voltage level is proportional to the power, it will in an ELC-circuit be controlling the power to the dump loads.

Example: When the consumption load decreases, the generator voltage level increases. In order to keep a constant voltage level, power has to be diverted to the dump loads. This is achieved by increasing the duty cycle of the signal. Thus the average voltage signal increases and the power diverted to the dump loads increases. The frequency of the PWM-signal has to be set larger than the change of the system to provide stability. It is also important to make it different from the audible frequency range to evade noise.

In general, PWM has an advantage with a simple electronic circuit to control modern power transistors like IGBT and MOSFET. Disadvantages include high price, poor availability and sensitivity of the power transistors. [15]

3.4.2 Binary loads

The second alternative, binary loads (BL), uses a set of dump loads where the capacity of the second load is half of the first load. This gives 2^n combinations for the dump load system. To trigger these loads, Solid State relays are used. By use of BL there is no problem with electric noise due to triggering only at the beginning of each half period, or no triggering at all. However, there are also some disadvantages; The costs of the relays are rather high compared with triacs, and a large number of dump loads are required. [15]

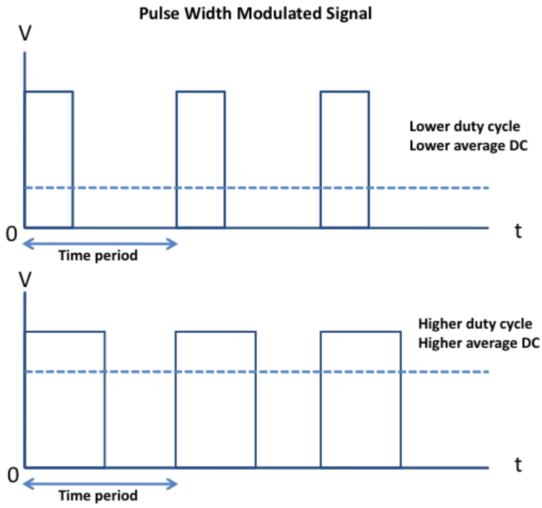


Figure 3.4.9: Principle of PWM [13]

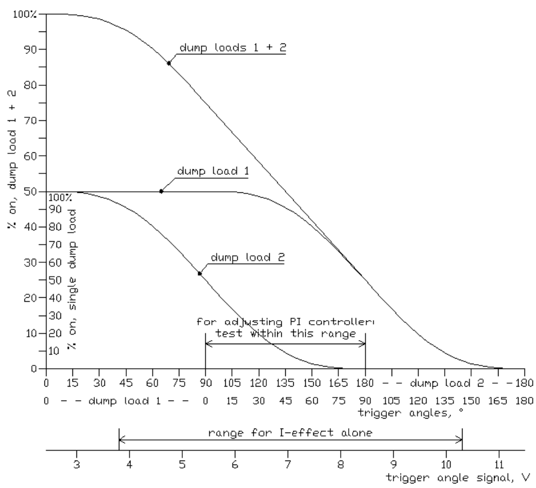


Figure 3.4.10: Principle of binary loads [15]

3.5 Hybrid energy systems

Since the energy demand and energy availability is changing through the year, it is often necessary to introduce several energy sources. A hybrid energy system consists of two or more energy sources resulting in increased power supply and power balance. In the next sections wind energy, photovoltaic energy and energy from fossil fuel are explained.

3.5.1 Photovoltaic energy

Photovoltaic (PV) energy is a widely used source for energy production. Photovoltaic-cells are used to convert the energy from the radiation of the sun to electric energy. PV-energy generates DC-voltage, and to store the energy, several lithium-batteries are connected in parallel. PV-cells have quite low efficiency compared with other energy sources. The efficiency for simple PV-cells is about 4-8 % (a-Si cells), but a bit higher for more sophisticated cells (10-17%) [6] Because of mass production and low prices, it is often the definite best and cheapest solution for bringing electricity to isolated households and villages.

3.5.2 Wind energy

Wind energy is a renewable energy source where kinetic energy in wind is converted into mechanical energy through a turbine. The turbine is connected to a generator. The last few years, small, cheap wind turbine systems have been introduced on the global market. Compared with PV-energy, wind energy has higher efficiency and generates both day and night. Major drawbacks are introduction of large mechanical forces and stress. Thus, wear and maintenance costs increases.

3.5.3 Energy from fossil fuel

Fossil fuel generators are much used in countries and areas with shortage of electricity and energy resources. It consists of a diesel/gasoline engine and an electric generator. The advantages with fossil fuel generators are the flexibility and the security of supply. The major disadvantages are large emissions, not renewable fuel and high cost. Since fossil fuel is not a renewable energy source, it should in a climate perspective be avoided. High prices of fuel will in the long term result in a very expensive solution. Thus, the suggestion is to minimize the consumption of energy from fossil fuel.

3.5.4 Maximum power point tracking

Maximum power point tracking (MPPT) is a commonly used electronic system for obtaining maximum power in a variable energy source like a PV-module or a wind turbine. During the day, the irradiation and wind intensity change. As a result of this, the maximum power output changes. In order to achieve maximum power from a PV-module, the best combination of current and voltage has to be chosen. For a wind turbine it is important to find the optimum rotational speed of the turbine (see figure 3.5.12 and 3.5.11). There are different versions of MPPT, from simple to more sophisticated methods. There are generally two main methods that are used: Perturbation and Observation ($P\&O$) and Model based control. The first method uses input data to investigate if there is a positive or negative slope in the power output. If the slope is positive, power output is increased and opposite if slope is negative. Model based control, on the other hand, uses predetermined equations for power output curves to quickly determine the optimal conditions. [16]

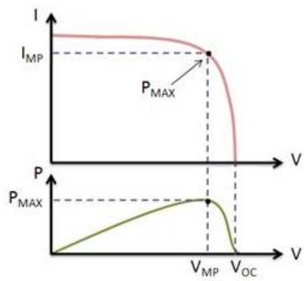


Figure 3.5.11: MPPT

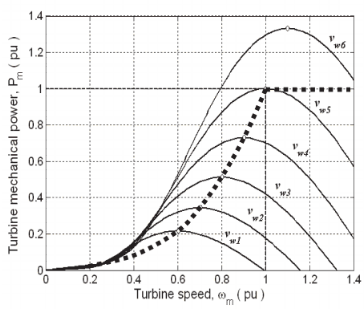


Figure 3.5.12: Wind power plot

3.5.5 Inverter, rectifier and DC/DC-converter

Inverters and rectifiers are power electronic converters that convert between direct current (DC) and alternating current (AC). In order to vary the amplitude of a DC-signal, a DC/DC-converter is used. Pulse width modulation (PWM) can be utilised for this purpose. [2]

3.5.6 Energy management system

Connecting several energy sources results in a more complex energy system. To achieve optimum performance of the system, a well functioning energy management system (EMS) is required. The EMS has the overall control of the different energy sources, and can change the performance of the separate modules directly. The system may also control the energy access for the different user loads. A ranking system can be established to ensure reliability of supply for important loads. A few examples may explain this better: If the battery is fully charged, the EMS must reduce the energy production. If the energy demand is larger than the energy availability, it is necessary to stop energy access to lower ranked loads like heating of water and ensure energy to higher ranked loads, like a ward or a hospital. [2]

3.6 Hybrid energy system for remote areas

In many projects it is convenient to connect several energy sources together in order to obtain a reliable and stable energy system. A hybrid energy system has many advantages. If one energy source fails, there is always a backup-system. In figure 3.6.13, a hybrid energy system with a hydro power plant, a wind turbine and a PV-module charging a battery bank is displayed. In this system, a parallel DC-grid with a voltage-level of 300-400V is used. The hydro power plant is directly connected with a rectifier. For the wind turbine, a rectifier and a DC/DC-converter with MPPT are used to achieve the optimum rotational speed of the turbine. The PV-module is connected to a DC/DC-converter with MPPT to attain maximum power output.

A charging control system is connected to the battery bank. The control system consists of a two-way DC/DC-converter which makes it possible to both charge and discharge, and for determining the optimum charging voltage. A dump load system is used as backup in case of a failure in the EMS or in the charging system. For emergency situations and to handle top loads, a standby diesel generator is used. By increasing the battery bank and using a sophisticated energy management system, the dependence of the standby generator is reduced.

The distance from the power plant to the village is important when considering using DC or AC. If it is long distance between the connected units and the consumers, it is suggested to transform up to high voltage (to reduce losses), and then

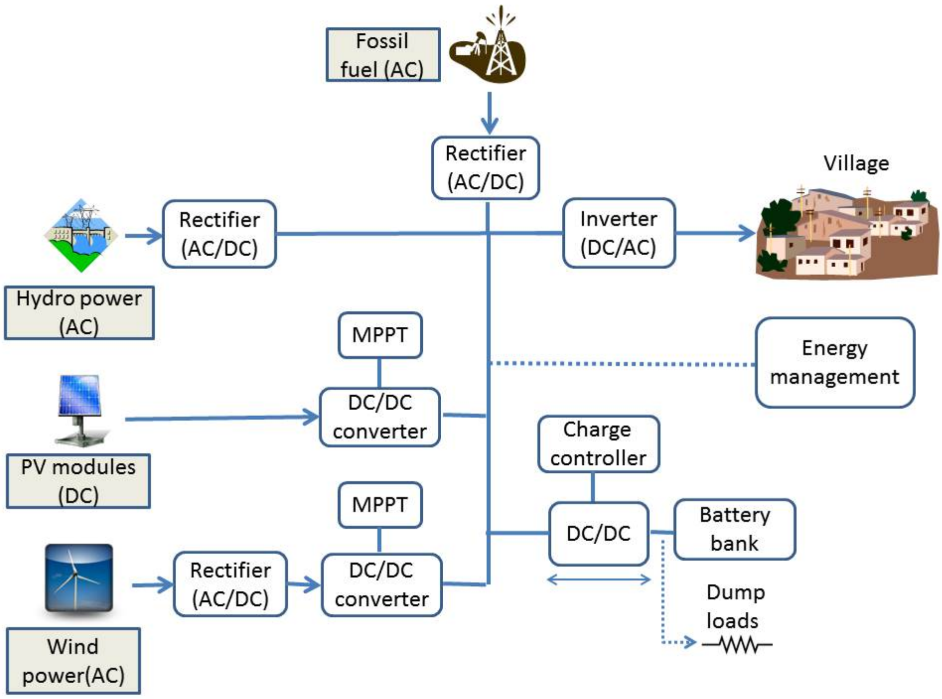


Figure 3.6.13: Hybrid energy system for remote areas

AC is the best choice. If the energy system is located close to the consumers, a DC-grid is a good choice. [2]

3.7 Hybrid energy system with ELC

For connecting a hydropower plant w/ELC to a PV-module, it is possible to use a simple rectifier and connect the two energy sources to a battery bank. This solution is illustrated in figure 3.7.14. The PV-module consists of a MPPT-system and a DC/DC-converter in order to obtain maximum power output and the correct voltage (300-400V). When the battery bank is fully charged, the PV-module is disconnected. With this solution, it is possible to use the existing ELC (with triacs) and only divert energy to the dump loads when the battery bank is fully charged or a failure has occured. An energy management system can be implemented for better control and better utilising the different energy sources. This is not required for the system, but will increase the quality and efficiency of the energy system. This is specially recommended for larger and more complex energy systems where a small increase in efficiency will result in a larger difference.

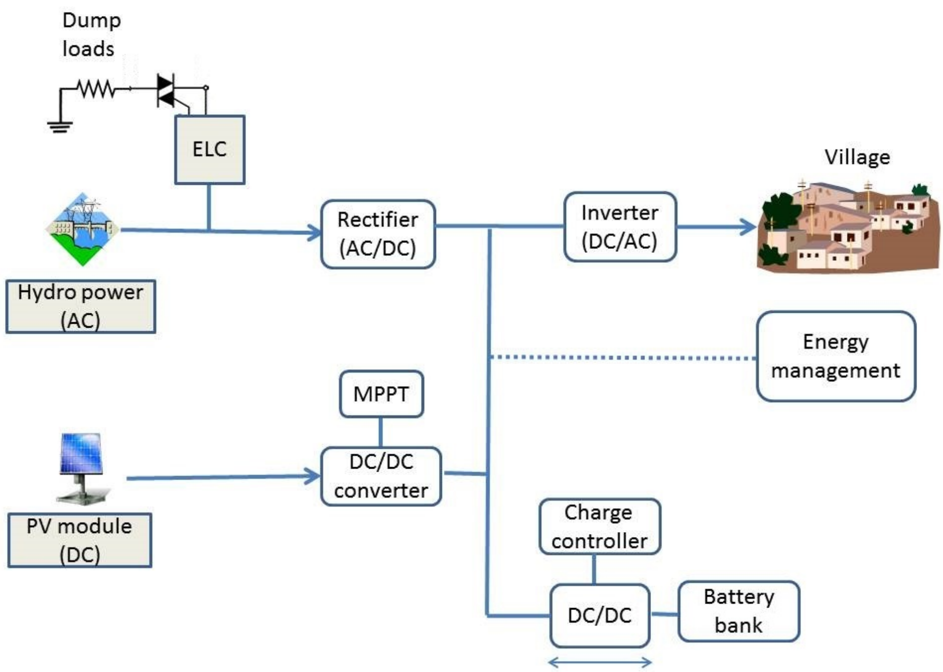


Figure 3.7.14: Stand alone hybrid energy system with ELC

Chapter 4

Instrumentation

4.1 Experimental setup

The piping network used in the experiment is shown in figure 4.1.1. Water was pumped up to the pressure tank where it stabilised and $5mWc$ head was set. Water was then directed into the cross-flow turbine. This setup is different from Walseth/Danielsen and Korala/Shrestra's setup that pumped water to the upper free surface reservoir using a throttling valve to reduce the head. These setups may have introduced some cavitation just after the throttling valve and this may have affected the volume flow measurement. [4] To reduce this disturbance, the pressure tank was used instead and the correct net head, H_n, was obtained by changing the rotational speed of the pump.

In figure 4.1.2, the principles of the governing system is shown. The generator was connected to the turbine via a belt drive. The generator was connected to the ELC and further to the consumption load. The signal from the generator was processed by the ELC and the remaining power was diverted into the dump loads. In this setup, both dump loads and consumption loads were heating elements submerged in the lower reservoir in the laboratory.

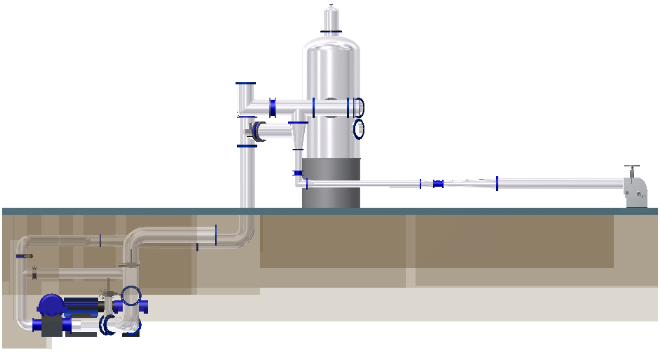


Figure 4.1.1: Piping network for cross-flow turbine

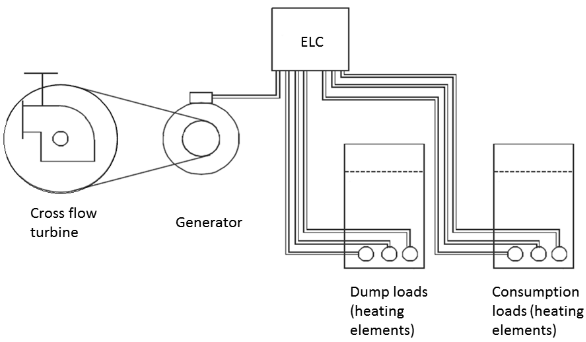


Figure 4.1.2: Principle of experimental setup

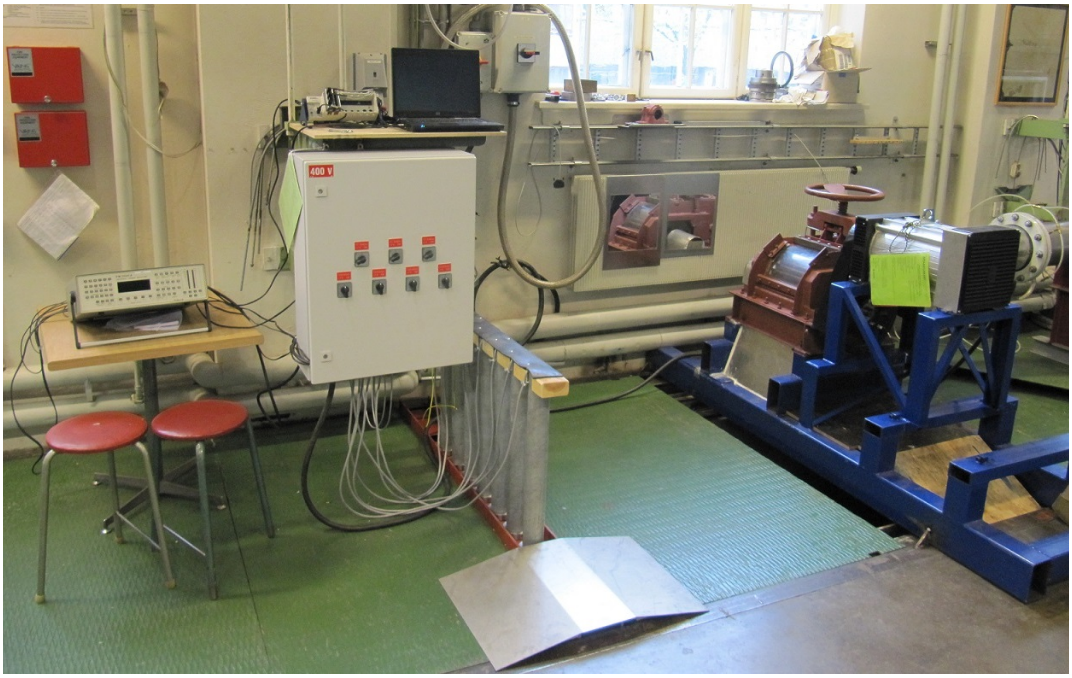


Figure 4.1.3: Overview of the experimental test rig

4.1.1 IAM-turbine

The installed cross flow turbine was manufactured by Remote HydroLight (RHL) in Afghanistan. The turbine was a Traditional Mill Turbine (TMT) and was originally designed by Owen Schumacher (RHL). After installation and testing in 2008 by Danielsen and Walseth, the turbine was referred to as the IAM-turbine. The turbine had a diameter of $270mm$, a rotor width of $335mm$ and a tested power output within 0-$23kW$.[21] It is estimated that more than 4000 turbines has been installed with this design in Afghanistan. [17]

4.1.2 Generator

To convert the mechanical energy to electrical energy, a synchronous generator was used. The generator was a Sincro GS4 LES imported by BEVI Sweden. It was an AC-generator with an apparent power of 25 kVA, a power factor of 0.8 and thus a capacity of $20kW$. It consisted of brushes and had 2 pairs of poles resulting in a nominal rotational speed of 1500 RPM. Datasheet for the generator is attached in appendix B.1.

Since the turbine and generator had different speeds, a belt drive system was installed, connecting the turbine shaft and the generator shaft. Gummi og maskinteknikk AS designed the system resulting in a configuration with two V-belts. The ratio between turbine and generator speed was 1:3.57.

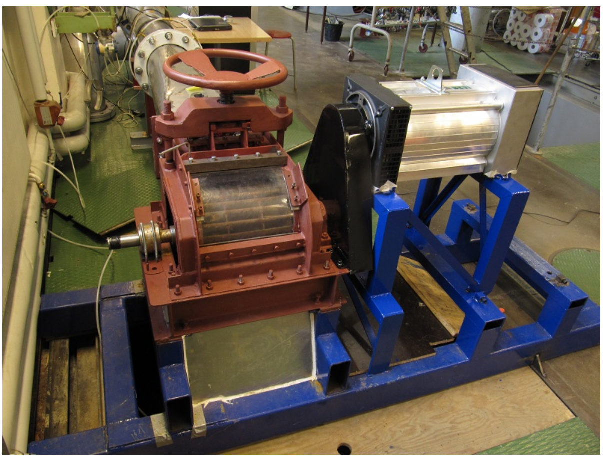


Figure 4.1.4: IAM-turbine and synchronous generator with belt drive (behind black cover)

4.1.3 Electronic load controller

In order to control the power from the generator, an electronic load controller was installed. The ELC was manufactured by RHL and was a simplified version of Jan Portegijs' 'Humming Bird'. [15] The structure of the ELC is described in section 3.3.

The ELC used in the experiments had a capacity of $6kW$. It was a three-phase digital version where voltage from the generator was regulated and controlled. The test object had not been installed in any projects earlier. Three dump loads, each with capacity of $2kW$, were installed. Each dump load was connected to one triac and two heat sinks were used to avoid overheating.

Due to Health, safe and environmental (HSE) requirements from the University (NTNU), all unoriginal non-western components had to be replaced with original parts. Wires were changed, and all components and wiring had to be installed in a new approved terminal box. This was done in order to avoid damage in the lab. The transformer, the PCB-card, the triacs and the two heat sinks were approved and were used in the new setup. The circuit diagram for the ELC is attached in appendix B.2. The HSE-repport is attached in appendix E.

(a) Inside

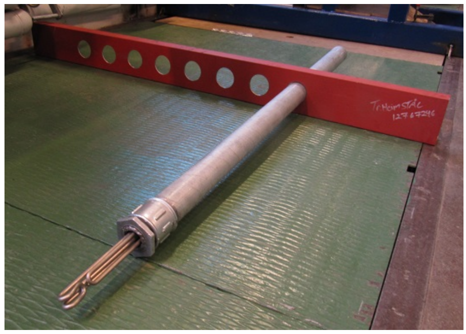
(b) Outside

Figure 4.1.5: Electronic load controller used in experiments

4.1.4 Dump load system

The dump load system consisted of three heating elements with capacity of $2kW$ each. The elements were manufactured by Norske Backer AS. Datasheets for the heating elements are given in appendix B.3. The elements were installed inside pipes in a waterproof environment and submerged into the lower reservoir. The pipes were connected with a beam perpendicular to the channel. The beam was then tightened into two girdeers parallel with the channel. See figure 4.1.6 for details around installation.

(a) Heating element



(b) One of the seven heating elements submerged into the lower reservoir

Figure 4.1.6: Dump load and consumption load system

4.1.5 Consumption load system

In order to set up a variable consumption load, three heating elements with capacity of 2 kW each were used. Each of the heating elements were connected with a switch to one phase. To simulate an overload situation, an extra heating element of $1kW$ was connected. The setup of the heating elements were similiar to the dump load system and the heating elements were submerged on the same beam perpendicular to the channel.

4.2 Measurements

Since the capacity of the ELC was much smaller than the turbine/generator, it was important to control hydraulic and electric power to avoid overload. To determine the hydraulic power, pressure, discharge and water temperature were measured. Electric power was measured with a power analyzing instrument.The instruments used in the experiment are given in table 4.2.1.

Measurement	***Instrument***
Pressure	*Fuji Electric France SAFKKW37V1AKCYYAE*
Discharge	*Krohne Aquaflux F6*
Rotational speed turbine	*Jaquet AG*
Water temperature	*Systemteknikk AB S1220*
Temperature ELC	*PT-100*
Electric power	*Voltech PM3000A*
Data acquisition hydraulic power	*NI PCI-MIO-16XE-10*
Data acquisition ELC	*NI 9225*

Table 4.2.1: Instruments used in the experiments

4.2.1 Logging instrument - IAM-turbine

A data acquisition(DAQ)-unit from National Instruments was used for logging hydraulig performance on the IAM-turbine. The unit had 16 input channels, max sample rate of 1.25 kS/s and a range of -10 – 10V. To analyse and convert rawdata to values with comprehensible units, a program in NI LabVIEW was established. See appendix C.1 and program given in electronic version for details about the program.

4.2.2 Inlet pressure

Four pressure taps were installed at the pipeline and connected to a pressure transducer. The pressure taps were evenly distributed perpendicular to the flow upstream the turbine. The pressure transducer consisted of a high and low pressure side, divided by a membrane. The inlet pressure was connected to the high pressure side and air to the low pressure side. The transducer measured the change in expandation of the membrane as a voltage signal. The pressure transducer was manufactured by Fuji Electric France S.A with a range of -2000kPa - 2000kPa.

4.2.3 Discharge

A Krohne flow rate meter (see figure 4.2.8) was used for measuring discharge. The principle of the flow meter was based on Faraday's law of induction. An electro-

Figure 4.2.7: Pressure transducer

magnetic field was introduced perpendicular to the flow. The flow of water worked like a conductor in this field, resulting in an induced voltage signal. Since the cross-section was constant and the voltage signal was proportional to the velocity, it was possible to determine the discharge.

Figure 4.2.8: Krohne flowmeter

4.2.4 Rotational speed

Rotational speed of the turbine was measured optically using a photoelectric detector and a reflector. The time between each reflection was measured and rotational speed determined.

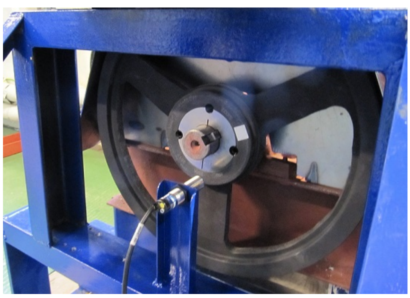


Figure 4.2.9: Optical measurement of rotational speed on turbine

4.2.5 Water temperature

For temperature measurements at the inlet, a sensor manufactured by Systemteknik AB was used. A voltage signal was generated by the temperature difference between the sensor and the water pipe.

Figure 4.2.10: Temperature measurements

4.2.6 Temperature - ELC

During operation the temperature inside the ELC-cabinet was measured with a standard PT100 resistive themometer. This was done to detect and avoid overheating of the electronic components.

4.3 Generator- and dump load system

4.3.1 Logging instruments

A DAQ-module for high voltage signals (NI 9225) was used for logging generator- and dump load voltage. The unit had three input channels, sample rate of 50 kS/s and a range of -300 – 300V. The logging program was established in NI LabVIEW. From the program, the voltage signals were used to determine the respectively RMS-values, the frequency and the trigger angle. The LabVIEW-program is attached in Appendix C.1 and in electronic version.

4.3.2 Measurements

The generator voltage (phase to neutral) was continously measured with the DAQ-module. The signal was displayed in the LabView-program, and from this signal the frequency and the RMS-value was evaluated. Dump load voltage (element to neutral) was also measured and from this signal the trigger angle and the RMS-value was determined.

Power output from generator was measured with a power analyzing instrument (Voltech PM3000A). Voltage and current were used as input parameters. Voltage was directly connected and for current, three amp clamps were connected to the conductors from the generator. From the display of the instrument, power output was registered. The instrument was connected to the LabView-program and power output (real power) and current were logged frequently.

Chapter 5

Method

5.1 Calibration

To obtain reliable results all measuring devices must be calibrated frequently. This reduces the uncertainty and validates the results. All calibrations were done according to the IEC 60193 standard. [8]. Before starting the experiment the volumetric flow meter and the pressure transducer were calibrated. Details from the calibrations can be found in appendix A.

5.1.1 Inlet pressure

The pressure transducer was calibrated with a portable pressure calibration gauge (Druck DPI 601). A static pressure was set up by the calibrator at the high pressure side, and air connected to the low pressure side of the transducer. The pressure difference led to an expansion in the membrane that was measured as a voltage signal. Measuring pressure with pressure transducer is by IEC defined as a secondary measurement method. Calibrating against a portable pressure calibrator is not a primary measuring method, but it is a quick way to reduce the uncertainty into an acceptable level.

5.1.2 Discharge

The electromagnetic flow meter is defined as a secondary measuring instrument. [8] To obtain an approved calibration it was necessary to calibrate it against a primary measuring method. In the Waterpower Laboratory the weighing method is used by measuring weight and time of filling of an approved tank. This is a primary method that is recommended according to IEC 60193.

(a) Pressure taps

(b) Calibrator-Digital pressure indicator

Figure 5.1.1: Equipment for calibrating pressure transducer

The flow meter is calibrated by use of the weighing tank which rests on three weighing sensors. These weighing sensors were calibrated by Andrea Stranna [19] in 2012. To calibrate the flow meter, the piping system had to be rebuilt. A tilting screen was used to direct the water either to the weighing tank or directly to the lower reservoir. The flowmeter was calibrated by leading water into the weighing tank for a certain time interval. The mass of the water and the time interval was then measured and the flow determined. Flow increased by increasing the pump speed and the valve opening. In order to fill the tank with minimum $2000kg$ each interval, the time varied between 30 and 70 seconds,.

Figure 5.1.2: Rebuilding the piping system for calibration of flow meter

5.2 Procedure for experiments

Several stress tests were accomplished to investigate the performance of the governor. Such tests are recommended to do before installing a new ELC in order to verify the quality of the system and avoid damages.[15] Before all tests (except the power test) started, random uncertainty in logged parameters was calculated. This was repeated when the tests finished in order to validate the results in the different tests.

5.2.1 Power test

To test the reliability of the controller and the experimental test rig, the rig was running on different loads and with different inlet pressure. The aim of this was to detect overheating in the components and wirings inside the ELC and to detect weaknesses in the installed equipment. When stable operating conditions was achieved, logging of four different load situations (0-4kW) was performed.

5.2.2 Rapid on-load situation

During startup of the generator, the village is (usually) disconnected the plant in order to prevent failure on electrical equipment. When the village is connecting to the power plant, a rapid on-load situation occur. If the governing parameters are not correctly tuned, an unstable situation may appear. The response in generator voltage (RMS-value), frequency, dump load voltage (RMS-value) and trigger angle was logged during this situation.

5.2.3 Rapid off-load situation

A rapid off-load situation occurs if there is an error in the transmission lines to the village. The consumption loads are then rapidly disconnected and all power is diverted to the dump loads. Generator voltage, dump load voltage (RMS-values), frequency, and trigger angle were registered during the test.

5.2.4 Overload signal/undervoltage

To simulate an overload situation, an extra consumption load was connected. The consumption load was increased gradually until the ELC was overloaded. If this situation occurs in a village, sensitive user loads may be damaged.

5.2.5 Run-away test

If the load on the generator is disconnected rapidly, the generator- and turbine speed increases suddenly. It will increase until a stable speed is obtained. This is known as the run-away speed. The turbine and generator should be designed to withstand the mechanical forces that occur during this situation. Thus, it is a good way of checking the quality of the mechanical components. The load to the generator was disconnected by blowing the three fuses F1 at the input of the ELC. Rotational speed was measured during this test.

Chapter 6

Results

An experimental setup with a cross-flow turbine connected to an electronic load controller (ELC) has been installed and tested in the Waterpower Laboratory at NTNU, September 2013. The intention of the experimental setup has been to simulate a stand alone power system disconnected the national grid. The cross-flow turbine was a TMT-turbine manufactured by Remote HydroLight (RHL). A synchronous generator was connected to the turbine. To obtain a nominal generator speed of $1500 RPM$, a transmission system with belt drive (two belts) was installed. The capacity of the ELC was $6kW$ and it was produced and developed in Afghanistan by RHL. The controller used phase angle regulation, a digital printed circuit board (PCB) and three triacs to govern the power system. Due to HSE-requirements from the university (NTNU), the controller had to be rebuilt before testing could start. Wires, fuses and connectors were replaced, and all components were installed in a new approved cabinet. This increased the quality of the controller and reduced the risk of overheating and failure. Three heating elements with total capacity of $6kW$ were used as dump loads. To simulate a small village, $6kW$ consumption loads were connected. Similar to the dump load system, three $2kW$ heating elements were used in the consumption load system. In addition, a $1kW$ heating element was connected in order to carry out an overload test of the system. The heating elements were installed in a waterproof environment, and submerged in the lower reservoir in the laboratory. The final test rig is shown in figure 6.0.1.

The performance of the controller has been evaluated with respect to step response in generator voltage and frequency. A power analysing instrument, Voltech PM3000A, was used for measuring electric power, and voltage was logged with a data acquisition module, NI 9225. The hydraulic perfomance of the test rig was evaluated by measuring inlet pressure, discharge, water temperature and rotational speed of the turbine. The software for the experiment was programmed in NI LabVIEW, a graphical programming platform. Two separate programs were established, one measuring hydraulic perfomance of the Cross flow turbine and another for logging electric performance of generator and dump loads. Both programs

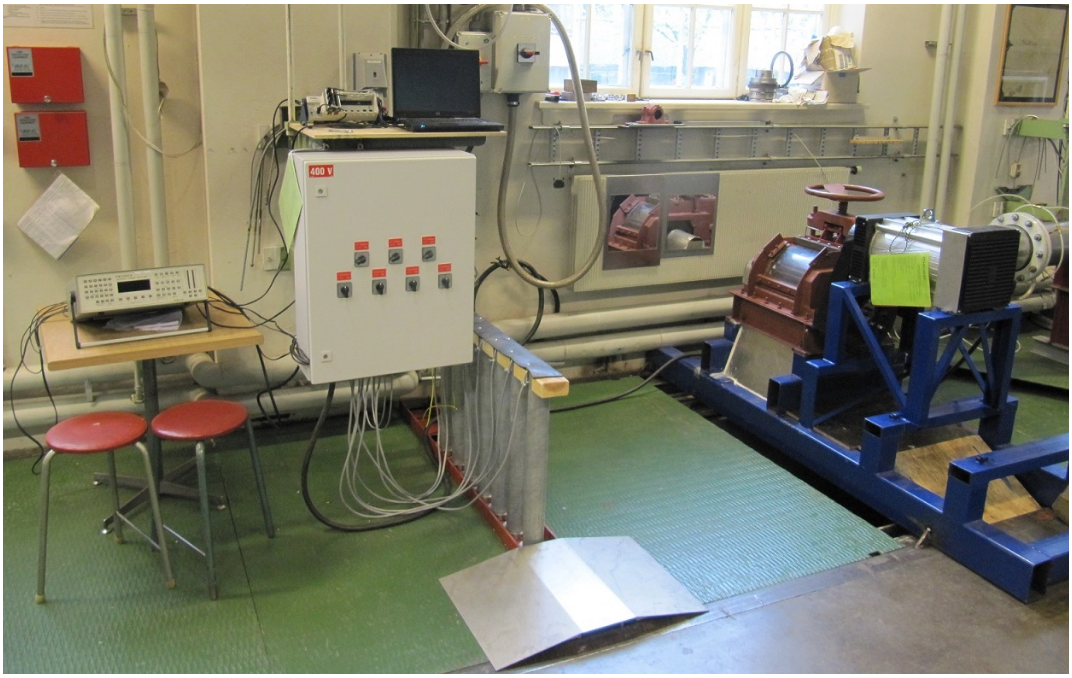


Figure 6.0.1: Final test rig

are attached in appendix C.1. Hydraulic and electric parameters for the different tests are attached in appendix D.

6.1 Performance of the experimental test rig

The cross-flow turbine and the synchronous generator worked well during the experiment. The weak component in the rig was the transmission system. During the power test, the belt drive started to slip, resulting in noise, high temperature and smell of burning rubber. The belt drive was tightened, but the problem was still persistent when increasing the pressure and the generator speed. Due to shortance of time, it was decided to use the existing belt drive system and reduce the power output from the generator from $6kW$ to $4kW$. The dump load capacity was kept at $6kW$ in order to avoid unequal distribution on the three phases.

Before the tests started and when the tests had finished, an operating point with $6kW$ dump loads and $0kW$ consumption load was set and hydraulic parameters registered. During the different tests, the pump speed and nozzle opening were kept constant. Approximately constant hydraulic performance on the test rig was expected, but during the testing the rotational speed of the turbine increased with 2,33%. The parameters used in the operating point are shown in table 6.1.1.

Hydraulic performance		Start of testing			End of testing		
Pump speed	*RPM*	368,0			368,0		
Nozzle opening	%	80			80		
Pressure	*kPa*	49,034	±	0,013	48,859	±	0,013
Turbine speed	*RPM*	474,140	±	0,081	485,20	±	0,11
Discharge	m^3/s	0,152541	±	0,000016	0,1523614	±	0,0000079
Hydraulic power	*W*	8380,4	±	2,5	8342,0	±	1,9
Net head	*mWc*	5,5980	±	0,0014	5,5791	±	0,0013
Temperature	$^\circ C$	14,603066	±	0,000086	14,76722	±	0,00020
Density	kg/m^3	999,237387	±	0,000014	999,212596	±	0,000031

Table 6.1.1: Parameters in operating point

6.2 Performance of the ELC

6.2.1 Power test

During the first start-up tests of the rig, a failure in the connection of the triacs was observed. One of the triacs had been connected wrong and high voltage from the generator had been directed into the PCB from the outlet to one of the triacs. Fortunately the thermistors prevented the PCB from being damaged.

The ELC was tested with different consumption- and dump loads in order to detect weaknesses and limitations in the system. Four small LEDs (red and green) were installed inside the ELC-cabinet to monitor status of the controller. A thermal sensor was installed between the heat sinks and the digital card. The generator voltage signal was measured from one phase to neutral and the dump load voltage signal for one heating element was measured from heating element to phase. A snapshot of the two voltage signals are displayed in figure 6.2.2 where $1kW$ consumption load is connected. The figure illustrates the rapid single-step triggering response from the triacs. The abrupt triggering is affecting the generator voltage signal with rapid peaks each half periode. Logging of the trigger angle was challenging. A peak detector was used for identifying the peaks in the generator and the dump load signal. Challenges regarding logging the first peaks and noise from the triggering of the triacs resulted in many outliers in the measurements. The ELC performed well during the testing. The temperature inside the cabinet increased slightly during the testing, but no overheating or failure occured.

Important electric- and hydraulic parameters for different load situations are given in table 6.2.2.

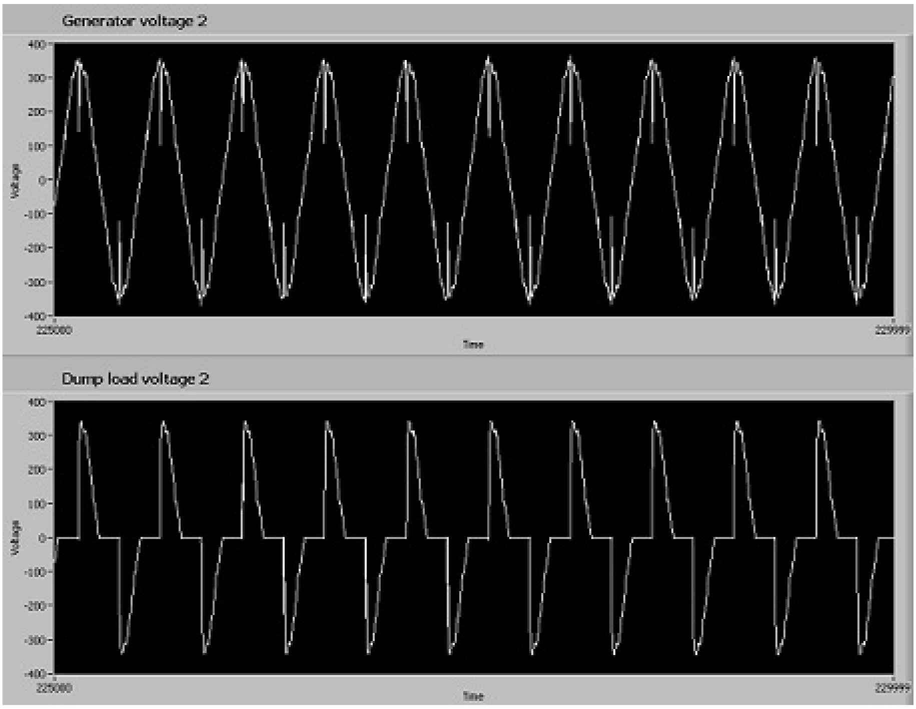


Figure 6.2.2: Generator and dump load voltage. In this situation $6kW$ dump loads and $1kW$ consumption loads are connected. The resulting trigger angle is 113°

.

Generator		**0kW**	**1kW**	**2kW**	**3kW**	**4kW**
Frequency	*Hz*	51,167 ± 0,010	51,149 ± 0,013	51,207 ± 0,016	51,3903 ± 0,0090	51,1139 ± [illegible]
Voltage (RMS)	*V*	230,42 ± 0,24	231,04 ± 0,24	230,33 ± 0,23	229,54 ± 0,23	233,47 ± [illegible]
Current (RMS)	*A*	7,1544 ± 0,0011	7,32100 ± 0,00096	7,22265 ± 0,00083	6,88715 ± 0,00081	6,2100 ± [illegible]
Apparent power (one phase)	*VA*	1648,52 ± 1,79	1691,4 ± 1,8	1663,6 ± 1,7	1580,9 ± 1,6	1449,82 ± [illegible]
Real power (sum)	*W*	4050,0 ± 1,2	4068,78 ± 0,72	4093,297 ± 0,499	4096,95 ± 0,38	4127,17 ± [illegible]
Dump load						
Voltage (RMS)	*V*	193,37 ± 0,33	166,86 ± 0,34	138,62 ± 0,42	104,39 ± 0,31	48,10 ± [illegible]
Trigger angle	*deg*	90,4670 ± 0,0096	112,96 ± 0,20	117,94 ± 0,17	122,38 ± 0,18	141,12 ± [illegible]
Hydraulic performance						
Inlet pressure	*kPa*	49,034 ± 0,013	48,962 ± 0,014	49,013 ± 0,014	48,958 ± 0,016	48,952 ± [illegible]
Turbine speed	*RPM*	474,140 ± 0,081	474,571 ± 0,089	475,910 ± 0,088	478,14 ± 0,11	476,229 ± [illegible]
Discharge	*m3/s*	0,152541 ± 0,000016	0,152490 ± 0,000017	0,152487 ± 0,000011	0,152483 ± 0,000013	0,1524171 ± [illegible]
Hydraulic power	*W*	8380,4 ± 2,5	8366,1 ± 3,0	8373,6 ± 2,4	8365,1 ± 2,8	8359,8 ± [illegible]
Net head	*mWC*	5,5980 ± 0,0014	5,5903 ± 0,0015	5,5954 ± 0,0015	5,5899 ± 0,0017	5,5888 ± [illegible]

Table 6.2.2: Power test - Different load situations

6.2.2 Rapid on-load situation

A rapid-on-load situation was performed with an abrupt connection of $4kW$ consumption load (starting from $0kW$). This resulted in a marked step response in generator voltage (RMS) and frequency, displayed in figure 6.2.3 and 6.2.4. Important electric and hydraulic parameters are given in table 6.2.3.

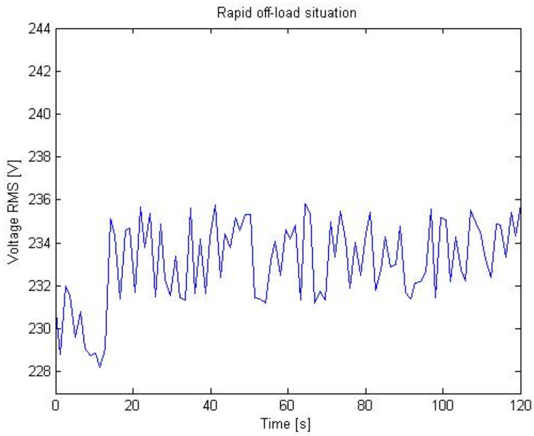


Figure 6.2.3: Step response in generator voltage (RMS)

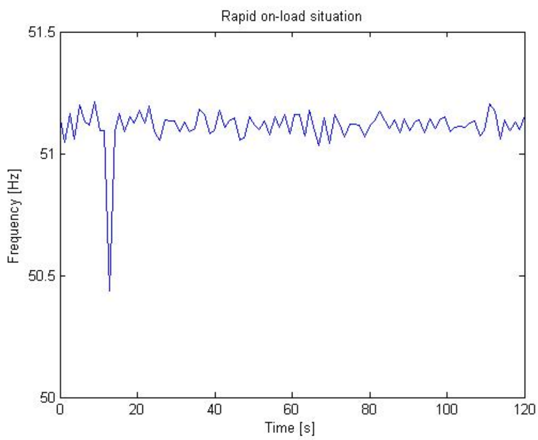


Figure 6.2.4: Step response in frequency

		Stable operating point - 0kW			Stable operating point - 4kW			Stable operating point - 0kW		
Generator										
Frequency	*Hz*	51,145	±	0,010	51,1205	±	0,0058	51,142	±	0,010
Voltage (RMS)	*V*	230,16	±	0,21	233,60	±	0,19	230,15	±	0,18
Current (RMS)	*A*	7,06716	±	0,00074	5,7901	±	0,0054	6,8733	±	0,0023
Apparent power (one phase)	*VA*	1626,6	±	1,5	1352,6	±	1,7	1581,9	±	1,3
Real power (sum)	*W*	3954,20	±	0,60	3943,1	±	2,9	3747,1	±	2,4
Dump load										
Voltage (RMS)	*V*	190,95	±	0,28	34,61	±	0,57	186,01	±	0,26
Trigger angle	*deg*	90,4529	±	0,0077	92,9	±	2,7	91,9	±	3,0
Hydraulic performance										
Inlet Pressure	*kPa*	48,956	±	0,013	48,926	±	0,012	48,962	±	0,015
Turbine speed	*RPM*	478,330	±	0,080	481,43	±	0,17	487,906	±	0,094
Discharge	*m3/s*	0,1524281	±	0,0000090	0,152409	±	0,000012	0,152415	±	0,000014
Hydraulic power	*W*	8361,2	±	2,2	8355,4	±	2,2	8361,214	±	2,9
Net head	*m*	5,5893	±	0,0014	5,5862	±	0,0013	5,590	±	0,0016

Table 6.2.3: Important parameters registered during the rapid on load situation

6.2.3 Rapid off-load situation

To simulate a rapid off-load situation, $4kW$ consumption load was disconnected (starting from $4kW$). The step responses in generator voltage (RMS) and frequency are displayed in figure 6.2.6 and 6.2.5. Important hydraulic and electric parameters were measured before and after the test and are given in table 6.2.4

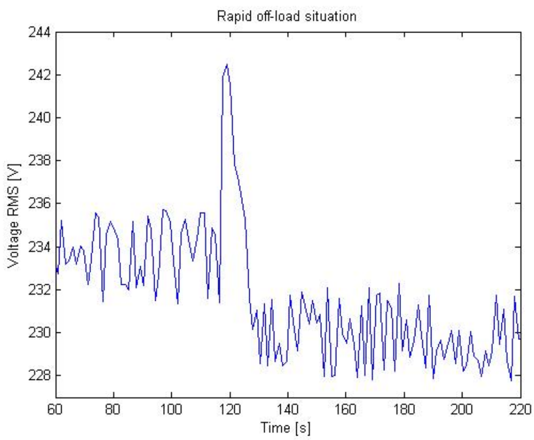


Figure 6.2.5: Step response in generator voltage (RMS)

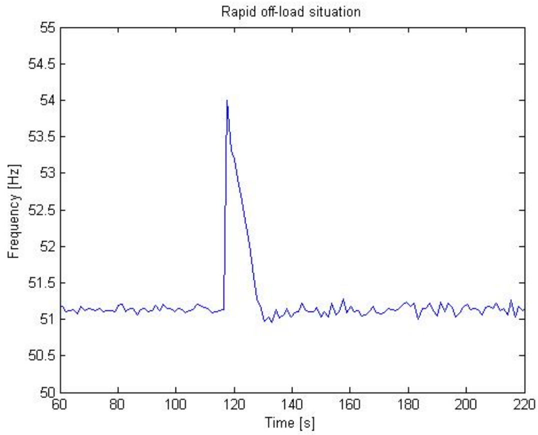


Figure 6.2.6: Step response in frequency

		Stable operating point - 4kW			Stable operating point - 0kW			Stable operating point - 4kW		
Generator										
Frequency	*Hz*	51,1366	±	0,0064	51,1349	±	0,0094	51,1226	±	0,0066
Voltage (RMS)	*V*	233,60	±	0,22	230,00	±	0,19	233,55	±	0,20
Current (RMS)	*A*	5,6681	±	0,0016	6,95726	±	0,00053	5,7772	±	0,0012
Apparent power (one phase)	*VA*	1324,0	±	1,3	1600,2	±	1,3	1349,3	±	1,2
Real power (sum)	*W*	3873,9	±	1,0	3836,23	±	0,21	3936,89	±	0,51
Dump load										
Voltage (RMS)	*V*	24,09	±	0,36	187,86	±	0,25	35,41	±	0,30
Trigger angle	*deg*	92,254	±	0,011	92,0	±	3,0	148,00	±	0,26
Hydraulic performance										
Inlet pressure	*kPa*	48,951	±	0,017	48,934	±	0,010	48,923	±	0,018
Turbine speed	*RPM*	485,32	±	0,11	483,763	±	0,066	481,370	±	0,088
Discharge	*m3/s*	0,152377	±	0,000018	0,1524120	±	0,0000071	0,152412	±	0,000010
Hydraulic power	*W*	8357,0	±	3,2	8356,8	±	1,7	8355,0	±	2,8
Net head	*mWc*	5,5884	±	0,0018	5,5870	±	0,0011	5,5858	±	0,0019

Table 6.2.4: Important parameters registered during the rapid off load situation

6.2.4 Overload signal/undervoltage

To simulate an overload situation, an extra heating element with capacity of $1kW$ was connected. The test started with $4kW$ consumption loads, and when steady state was obtained, the extra heating element was connected. The step responses in frequency and generator voltage (RMS) are shown in figure 6.2.7 and 6.2.8. A $2kW$ heating element was then introduced and a new similar test was accomplished. Connected consumption loads were then 6kW. The responses in frequency and voltage are displayed in figure 6.2.10 and 6.2.9. Important parameters registered during the overload situations are given in table 6.2.5 and 6.2.6.

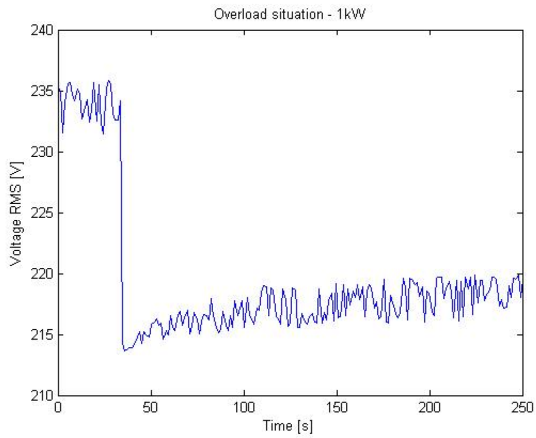


Figure 6.2.7: Step response in generator voltage (RMS)

		Stable operating point - 4kW			Stable operating point - 5kW			Stable operating point - 4kW		
Generator										
Frequency	*Hz*	51,1159	±	0,0066	48,5069	±	0,0076	51,1143	±	0,0061
Voltage (RMS)	*V*	233,71	±	0,19	218,75	±	0,20	233,72	±	0,19
Current (RMS)	*A*	5,7923	±	0,0016	6,5536	±	0,0009	5,7952	±	0,0028
Apparent power (one phase)	*VA*	1353,7	±	1,2	1433,6	±	1,3	1354,5	±	1,3
Real power (sum)	*W*	3944,59	±	0,83	4195,81	±	0,90	3945,9	±	1,4
Dump load										
Voltage (RMS)	*V*	37,01	±	0,35	0,0081	±	0,0040	35,92	±	0,29
Trigger angle	*deg*	146,76	±	0,25	Inf	±	-	147,74	±	0,27
Hydraulic performance										
Inlet pressure	*kPa*	48,972	±	0,021	48,852	±	0,012	48,935	±	0,016
Turbine speed	*RPM*	481,225	±	0,098	460,90	±	0,10	481,32	±	0,12
Discharge	m^3/s	0,152519	±	0,000025	0,1525160	±	0,0000085	0,152449	±	0,000013
Hydraulic power	*W*	8369,5	±	4,5	8351,0	±	2,0	8359,3	±	2,9
Net head	*mWc*	5,5916	±	0,0023	5,5794	±	0,0013	5,5874	±	0,0017

Table 6.2.5: Important parameters registered during overload situation with $1kW$

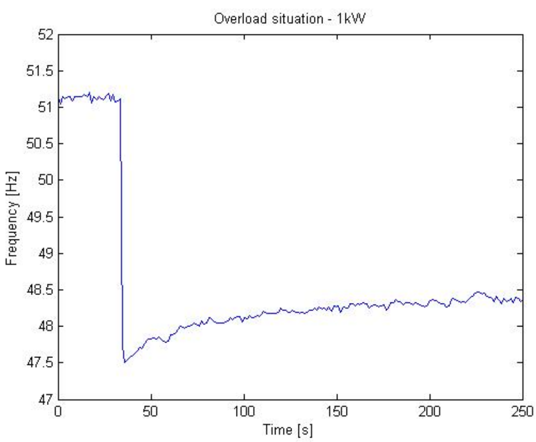


Figure 6.2.8: Step response in frequency

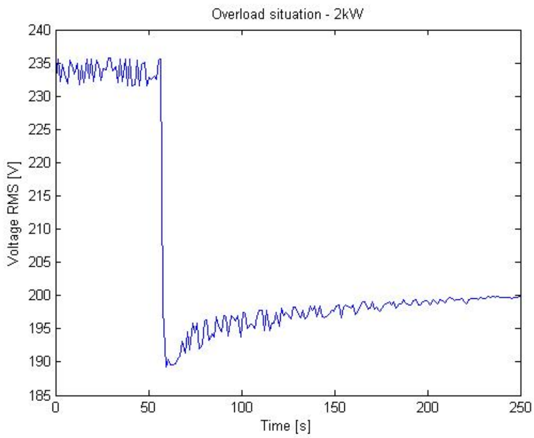


Figure 6.2.9: Step response in generator voltage (RMS)

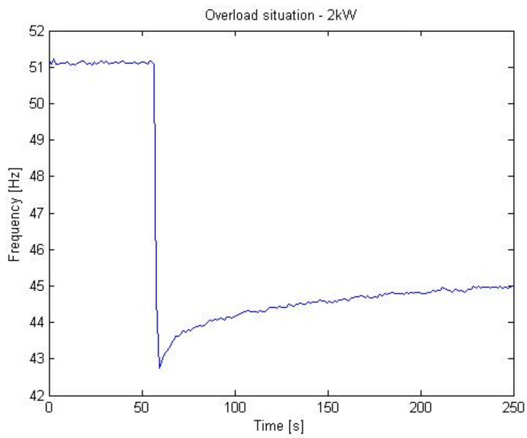


Figure 6.2.10: Step response in frequency

		Stable operating point - 4kW			Stable operating point - 6kW			Stable operating point - 4kW		
Generator										
Frequency	*Hz*	51,1183	±	0,0071	45,1120	±	0,0095	51,3378	±	0,0078
Voltage (RMS)	*V*	233,76	±	0,22	200,456	±	0,056	231,42	±	0,21
Current (RMS)	*A*	5,77608	±	0,00062	7,4048	±	0,0014	5,7734	±	0,0023
Apparent power (one phase)	*VA*	1350,2	±	1,3	1484,33	±	0,57	1336,1	±	1,4
Real power (sum)	*W*	3936,17	±	0,24	4404,2	±	1,5	3972,0	±	1,1
Dump load										
Voltage (RMS)	*V*	34,97	±	0,28	0,0073	±	0,0040	25,90	±	0,31
Trigger angle	*deg*	148,25	±	0,24	inf	±	-	334	±	87
Hydraulic performance										
Inlet pressure	*kPa*	48,908	±	0,012	48,847	±	0,018	48,959	±	0,021
Turbine speed	*RPM*	481,359	±	0,067	435,70	±	0,17	482,74	±	0,18
Discharge	m^3/s	0,152406	±	0,000010	0,152558	±	0,000021	0,152527	±	0,000022
Hydraulic power	*W*	8352,4	±	2,0	8352,9	±	3,3	8368,0	±	3,8
Net head	*mWc*	5,5843	±	0,0012	5,5791	±	0,0019	5,5904	±	0,0022

Table 6.2.6: Important parameters registered during overload situation with $2kW$

6.2.5 Run-away-test

A run-away test was carried out. The test started with $6kW$ dump loads and $4kW$ consumption loads connected. Then, the fuses to the generator were blown. The runner accellerated rapidly from a constant speed of $487RPM$ to a speed of $710RPM$,i.e an increase of 45,8%. Because of weakness in the transmission system, it was decided to reduce the sampling time for the run-away speed to avoid damages. When a relative stable turbine speed was obtained, the pump speed and discharge of water was reduced. The response in the rotational speed of the turbine is shown in figure 6.2.11. Hydraulic parameters before and after the test was performed are given in table 6.2.7.

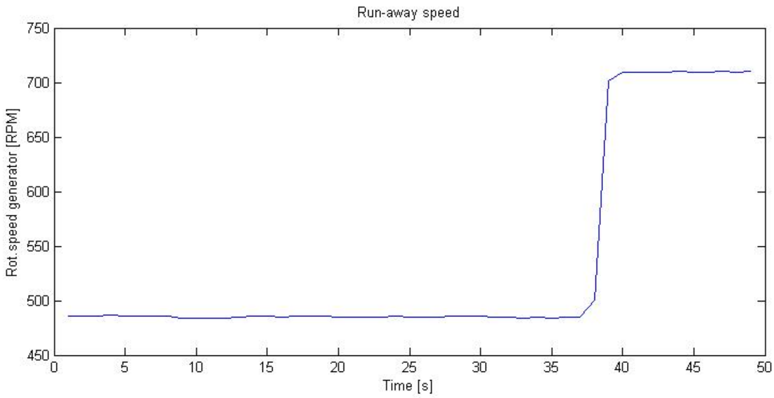


Figure 6.2.11: Run-away speed

Hydraulic performance		**Stable operating point - 4kW**			**Stable operating point - 4kW**		
Inlet pressure	kPa	48,927	±	0,031	48,859	±	0,013
Turbine speed	RPM	486,62	±	0,24	485,20	±	0,11
Discharge	m^3/s	0,152474	±	0,000027	0,1523614	±	0,0000079
Hydraulic power	W	8359,8	±	5,7	8342,0	±	1,9
Net head	mWc	5,5868	±	0,0032	5,5791	±	0,0013

Table 6.2.7: Hydraulic parameters registered before and after the run-away test

6.3 Improvements of the Electronic load controller

There are several ways of improving the ELC. As seen from figure 6.2.2, the generator signal is strongly affected by the triacs. A suggestion is to introduce pulse width modulation (PWM) or binary loads (BL). This will lead to a smoother output signal and will improve the possibilities for using the dump load energy better. When using phase angle regulation, the controller can only use resistive dump loads, due to risk of unstability around $0V$. By using binary loads, a smoother output signal is obtained. Developing a system with PWM will improve the output signal, and make it possible to implement inductive or capacitive dump loads.

6.4 Connection with other energy sources

In this report, two other relevant renewable energy sources are described, namely photovolatic(PV)- and wind-energy. PV-energy is much utilised in remote areas and has technology that is easy to implement in a DC-setup with hydro power. The major drawbacks are low efficiency and no production during the night. Wind energy for small scale projects is not as much utilized as PV-energy. Compared with PV-, wind turbine systems have higher efficiency and produce energy both day and night. Nevertheless, large forces and considerable mechanical stress are introduced. Major drawbacks include wear in mechanical components and higher maintenance costs.

For a stand alone power system it is often essential to introduce several energy sources and connect them in a hybrid energy system. With a hybrid system, the energy production becomes more reliable and stable. If one energy source fails, there is always a backup system. For a hybrid energy system in a remote area, voltage regulation and DC-connection between the different energy sources is preferable. By implementing a battery bank with a charge controller, a more flexible energy system is obtained. To handle top load, it is possible to connect a diesel generator. In figure 3.7.14 a hybrid energy system with a PV-module connected to a hydropower plant is illustrated. An ELC is used for regulating voltage on the hydro power plant. The PV-module is connected to a DC-DC-converter with a MPPT-module to obtain maximum power output. A battery bank with a charge control is implemented to achieve more flexibility. If the energy plant and the village are located far apart, an inverter (DC/AC) is recommended to reduce transmission losses.

A more complex hybrid energy system is given in figure 3.6.13. In this system hydro-, wind- and PV-energy is connected in a DC-grid. The hydropower plant is connected to the DC-grid via a rectifier (AC/DC-converter). For maximum power output, the PV-module and the wind turbine is connected to a DC/DC-converter with a MPPT-system. To handle top load, a diesel generator is connected. A battery bank with charge control and a backup dump load system is implemented.

The dump load system is only used to handle excess energy or in case of a failure in the system. An energy management system is recommended for improved performance of the energy system.

Chapter 7

Discussion

7.1 Performance of the experimental test rig

The cross-flow turbine from RHL and the synchronous generator from Bevi performed according to the spesifications during the experimental tests. This was not surprising, since both generator and turbine were rather overrated with capacities of $20kW$ and $23kW$. (Appendix B.1, [21])

The transmission system was the weak component in the experimental test rig. Due to lack of time, price and availability, a belt drive system was chosen. Belt drive introduces losses and will generally decrease the efficiency of the system. The design and dimensioning of the belt drive was based on experimental data from earlier tests on the turbine. [21] In the earlier tests, an asynchronous generator with capacity of $55kW$ had been installed. Since the only experimental data available was from this configuration, the design was based on these values. The design criteria for the belt drive was power output of $6kW$, torque of 122-147Nm and a turbine speed of 400-450RPM. The generator speed was designed for 1500RPM. Gummi og Maskinteknikk AS designed the transmission system. During the power test, it was observed that the turbine speed was much higher than the design criteria. This resulted in slip in the belt drive. The friction between the belt pulley and the belt was too small, resulting in slip and damage of the belt. By increasing the number of belts, the problem would have been solved, but due to time limitation it was decided to use the existing belt and reduce power output from the generator.

During the testing, rotational speed of the turbine increased from 474 to 485RPM. After discussions with technicians in the Waterpower Laboratory, it was concluded that the characteristic of the belt drive must have changed during the experimental tests. [1] It was discovered that the belt had loosened during the testing. In addition, small amount of rubber dust was found beneath the belt drive. Rapid changes in loads and many hours running the rig may have been factors that have contributed to this.

7.2 Performance of the ELC

7.2.1 Power test

The performance of the ELC was satisfying. However, only 2/3 of the capacity was tested. Due to strict HSE-requirements, the controller had to be rebuilt before the testing could start. This resulted in a more robust and safe solution. For testing of the response in the governing system, the rebuilding was not affecting the results. However, the general performance like overheating and quality of electronic components and wiring, was no longer comparable.

In table 6.2.2 five different load situations have been evaluated. The hydraulic performance was almost constant for the different situations. The deviation in frequency was $0.28Hz$. In Norway the limit for deviation in frequency is $\pm\ 0.1Hz$. Thus, the ELC did not fulfill this requirement. Since the deviation was rather small, it was not expected to influence standard user loads.

The design criteria for the generator voltage (RMS) was $230\pm5V$. In the different load situations, maximum deviation was $3.48V$ and the requirement was fulfilled.

The trigger angle increased with increasing consumption load. The corresponding dump load voltage was then reduced. According to the description given in section 3.3, this verified the purpose and mode of operation for phase angle regulation.

7.2.2 Rapid on-load situation

When testing for a rapid on-load situation, a rapid increase in generator voltage and an abrupt short decrease in frequency was observed. In the frequency-plot, a minimum peak value of $50.4Hz$ was observed. This was a reduction of 1.4% compared with the stable values before starting the test. When comparing stable averaged values before and after the test (0 and $4kW$), a reduction of $0.025Hz$ was calculated. This was a very accurate and quick response and corresponded well with the expected response described in section 3.3.

In generator voltage (RMS), a maximum peak of $235.1V$ was detected. The stable average generator voltage increased with $3.4V$ after connecting the load. This was within the requirement given by RHL of $230\pm5V$. The response in generator voltage was different from what was expected in the analysis before the tests started. During this test a small overload of the system was observed. For an overload situation a reduction in generator voltage similar to a corresponding reduction in frequency was expected. This was discussed with Anders Austegard (the designer of the controller) but no clear reason has been identified.

The logging of trigger angle did not work well and the values are not valid for the test. The problem was related to peak detection in the LabView-program. Several parameters had to be tuned in order to filter out noise in the generator signal. The noise was related to the triggering of the triacs.

During the test, turbine speed changed with 9.58 RPM (2.0%). Since the discharge and inlet pressure (and thus the hydraulic power) was rather constant, it was probably the characteristic of the transmission system that was changed. The increased turbine speed resulted in a reduction in power output, meaning the efficiency was reduced.

7.2.3 Rapid off-load situation

A sharp significant peak was observed in both generator voltage and frequency during the rapid off-load situation. The maximum value in frequency was 54.0Hz deviating with 2.9Hz from the stable value after the test. This was a large and noticeable deviation. However, the average value was reduced with only 0.0017Hz during the test (4kW to 0kW).

When the test started, it was observed that the system was slightly overloaded (similar to the rapid off-load situation). During the test, the average voltage value (RMS) decreased from 233,6V to 230,0V. Even if the mean value was within the voltage range, a single rapid peak of 242,5V, far beyond the maximum limit, was observed. This peak was damped shortly after, and the voltage was quickly stabilised. This kind of peaks can affect sensitive electronic equipments and is not desirable.

The logging of trigger angle was not reliable during this test. The problem appeared when detecting large trigger angles and was similar to the previous test related to noise in the generator voltage. This made it hard to obtain stable values since many outliers appeared.

The response in frequency corresponded well with the expected response described in section 3.3. The response in generator voltage (RMS) was opposite of what was expected. The reason has, like for the previous test, not been detected.

7.2.4 Overload signal/undervoltage

Two overload-tests were performed. In the first test, the load was 125% of expected power output. This resulted in a reduction in frequency of 2,6Hz and a stable average value of 48,50Hz. The detected minimum peak was 47,5Hz. Similar to the rapid on-load- and off-load tests, the system was slightly overloaded when the test started. The average generator voltage decreased from 233,30V to 218,75V during this situation with a minimum peak of 213,6V.

To evaluate the response of a large overload/undervoltage situation, the load was increased to 150% of power output. Similar to the first overload situation, generator voltage and frequency dropped rapidly. The average generator value (RMS) decreased with 33,23V to 200,46V. A reduction from 51,12Hz to 45,11Hz (average values) was observed in frequency. This is rapid changes that may disturb sensitive electronic equipment. However, an unstable situation did not appear. The response in generator voltage and frequency match the expected response from section 3.3.1.

7.2.5 Run-away-test

In the run-away test, a stable turbine speed of approximately 710RPM was observed. This corresponded to 146% of the starting speed. Due to risk of damaging the weak transmission system, this speed was not logged for more than 10s. For a cross-flow turbine, run-away speed was expected to be approximately 200% of nominal speed, but since a residual magnetic field still appeared in the generator, the torque on the generator was not equal to 0. [3] Thus, the run-away speed for the turbine was not detected. The objective of the run-away test was to verify the robustness of the mechanical system. Even if no equipment was damaged, it was evident that the test rig had weak components that needed to be improved before further testing could be conducted.

7.3 Improvements of the electronic load controller

In this report two suggested improvements have been suggested, namely pulse width modulation (PWM) and binary loads (BL). For simple hydropower systems with focus on cost and simpleness, phase angle regulation with triacs is a proper solution. The major disadvantages are the disharmonics in the generator voltage introduced by the triacs, and the simple dump load system where only resistive dump loads can be utilised. By using binary dump loads (BL,) the disharmonic is removed. The major disadvantages with BL are the large number of resistive dump loads that need to be connected, and the inflexible dump load system. By introducing PWM and modern transistors, the problem with trigger response is solved. With this solution it is possible to connect both inductive and conductive loads and thus utilise the dump load energy better. An implementation of PWM will increase the cost of the controller, and may result in more stops in the energy production due to a potentially more complex circuit. Nevertheless, it will improve the performance of the controller, increase the flexibility in the use of excess energy and will for further tests be recommended.

7.4 Connection with other energy sources

Connecting several energy sources is the optimal solution for many energy projects in remote areas. This results in a more flexible energy system and reduces the dependence on only one energy source. Connecting different energy sources with a common DC-grid is the suggested solution. This will reduce costs and complexity of synchronization. Implementing a battery bank in a DC-grid is recommended leading to increased flexibility and energy availability in the grid.

Two different hybrid energy systems are presented in this report. The first solution (see figure 3.7.14) utilises the existing ELC for controlling the output generator voltage in a hydro power plant. With this solution it is easy to obtain the correct DC voltage value by installing a simple rectifier. A PV-module is connected to a DC/DC-converter w/MPPT in order to obtain optimum performance and to set the correct voltage level. A battery bank is connected to the DC-grid via a two-way DC/DC-converter and a charge controller. If a wind turbine is more suitable, the connection is almost similar to the PV-module, but with a rectifier implemented. To handle the top load, it is possible to connect a diesel generator via a rectifier. This is in a climatic perspective not recommended, but is a way of increasing the flexibility of the energy system and to avoid an oversized battery bank.

The hybrid energy system in figure 3.6.13 is a bit more sophisticated and complex. The ELC has been removed, and the generator voltage level in the hydro power plant is controlled by a rectifier. The cost of the ELC compared to the rectifier must be evaluated, but a more appropriate use of energy is introduced since the dump load energy is used for charging a large battery bank. Dump loads are still required as emergency system, but less energy will dissipate this way. In the suggested system, a PV-module and a wind-turbine is connected. This system is rather flexible and reduces the requirement of installing a diesel generator to handle the top load. However, to ensure energy availability a diesel generator may be used as a stand-by generator to ensure energy access to vulnerable consumers like a ward or a hospital if a failure occurs. To ensure optimum performance of the energy system, it is suggested to develop an energy management system (EMS). This is suggested especially for larger energy systems, where the difference in performance is more evident.

Chapter 8

Further work

The governing parameters in RHL's ELCs are set equal in all projects. The parameters are rather conservative chosen in order to prevent unstable situations. Tuning the parameters for better response and to avoid single rapid peaks, as illustrated in the rapid on- and off-load tests, is suggested.

The synchronous generator was more expensive than expected. Using an induction generator will reduce the costs and is a proper alternative. Until now, the ELC is only designed for connection with synchronous generators. Developing a controller for connection with an induction generator is strongly advised.

Phase Angle Regulation with triacs are a rather simple way of governing the power diverted in the dump loads. From figure 6.2.2, it is evident that the harmonics of the triacs influence the generator voltage strongly. By using a more sophisticate method like Pulse Width Modulation (PWM), this problem will be eliminated. Phase angle regulation has limitations in selecting dump loads. To prevent unstable situations around trigger angles of $0°$ and $180°$, only resistive dump loads can be connected. By introducing PWM, other dump loads (capacitive and inductive loads) may be implemented. Designing and developing of an ELC with PWM, plus finding proper solutions for better use of the dump load energy is strongly recommended.

Finding proper, robust, low-cost solutions for connecting several energy sources is a very important task for the future. A suggestion for connecting hydro, wind, PV is set up in figure 3.6.13. It is focused on use of renewable energy sources, but with the possibility of using energy from fossil fuel to cover the top load. Further investigation and evaluation of hybrid energy systems is suggested. In long term, testing the performance of a small scale system in laboratory may be possible.

Connecting a PV-module to the existing test rig is recommended and will be a realistic goal for new master thesis. A proposed setup is given in figure 3.7.14.

Chapter 9

Conclusion

The results from the experimental tests indicate that the electronic load controller from Remote HydroLight performs well with stable regulation under different load conditions. During the power test, several weaknesses in the experimental setup were detected. The transmission system was underdimensioned and slip occured. The slip in the belt drive affected the measurements. During the tests, turbine speed increased with 2.33%. Altered characteristic of the belt drive was expected to be the reason. This resulted in a reduced power output and the tests were thus performed with a slightly overloaded system. However, the general performance of the ELC was good without any overheating, noise or failure in components.

The results from the different load situations verified the principle of phase angle regulation. When consumption loads increased, dump load voltage (RMS) decreased and trigger angle increased. The tests illustrated that the triacs affected the generator voltage signal each time the triacs triggered, i.e twice each periode.

The general response of the controller was good with stable average values and maximum deviation of $0.025Hz$ and $3.6V$ in frequency and generator voltage (RMS) However, during the rapid on- and off-load tests a single short rapid peak was detected in both frequency and in the voltage measurement (RMS). The signal stabilised immediatly, but such large peaks in voltage and frequency might damage sensitive user loads.

To improve the performance of the electronic load controller, it is suggested to introduce pulse width modulation (PWM). This will eliminate the influence from the triggering of the triacs. By using PWM, it will be possible to utilise the dump load energy in a more appropriate manner by connecting inductive and conductive dump loads. With PWM, a battery bank can connected as dump load, resulting in a more flexible and stable energy system.

Two different suggestions for connecting several energy sources have been established. Both systems are based on a common DC-grid with charging of a battery bank. The first system uses existing test rig with ELC in connection with a PV-module and a battery bank. The other system is more complex and is connecting a hydro power plant (without using ELC) directly to a PV-module and a wind turbine. An energy management system (EMS) is suggested to obtain optimum performance of the energy system, and to ensure energy access to vulnerable consumers.

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Appendix A

Calibration

WATERPOWER LABORATORY

Calibration Sheet

Calibration of flow meter

Date: 27.06.2013

Operator: Øystein Sveinsgjerd Hveem and Chiyembekezo Kaunda

Calibrator: Weighing tank system

Unit: Flowmeter, reg nr. 4624-7 (A03 36133)

Calibration constants for weighing tank correction		
	a_1	5,06290E-22
	a_2	-1,13860E-16
	a_3	8,49760E-12
	a_4	-2,49860E-07
	a_5	1,00150E+00

Coments:
The flow rate changes during calibration.
The inlet conditions to the pumps will change due to less water in the reservoir.

Corrected weight is calculated from formula where parameters a,b,c,d and e is achieved through substituion calibration.

$$W = a\cdot\frac{mW^5}{5}+b\cdot\frac{mW^4}{4}+c\cdot\frac{mW^3}{3}+d\cdot\frac{mW^2}{2}+e\cdot mW$$

Density of water is calculated from formula

$$\rho_m = \frac{1000}{(1-4,6699\cdot10^{-10}\cdot p_{abs})+8\cdot10^{-6}\cdot(\theta-4+2,1318913\cdot10^{-7}\cdot p_{abs})^2-6\cdot10^{-8}(\theta-4+2,1318913\cdot10^{-7}\cdot p_{abs})^3}$$

Density of air is calculated from formula

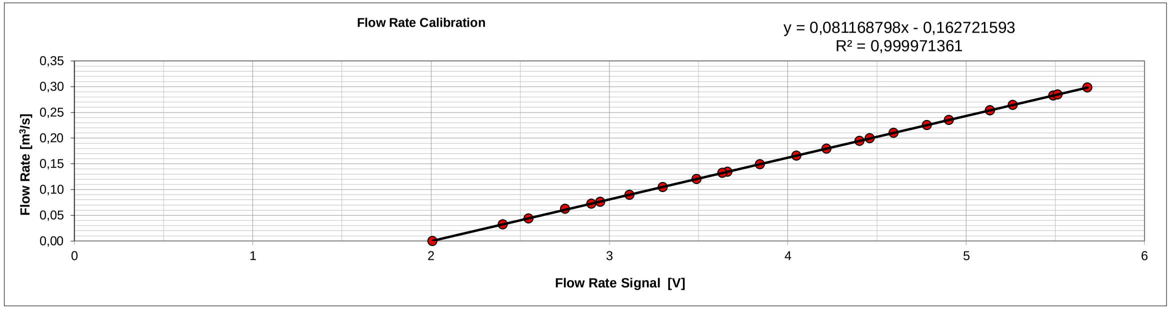
$$\rho_a = \frac{(p_{abs}\cdot 3,4837\cdot10^3)}{(273,15+\theta)}$$

Discharge is found from formula

$$Q = \frac{W_2-W_1}{\rho_m\cdot t\cdot(1-\frac{\rho_a}{\rho_m})}$$

Date	Manual Observation before Weight [kg]	Manual Observation after Weight [kg]	Manual Observation Voltage [V]	Time [s]	Ambient pressure P_{amb} [kPa]	Water temp T_W [°C]	Air temp T_A [°C]	Calculated value before Weight [kg]	Calculated value after Weight [kg]	Differential weight Weight [kg]	Density of water r [kg/m³]	Density of air r [kg/m³]	Differential volume Volume [m³]	Calculated Flow Rate Q [m³/s]	Estimate Q [m³/s]	Deviation [%]
27.06.2013	24524,8	24524,8	2,008283356	1,000												
27.06.2013	24524,8	26926,5	2,402313296	75,101	101,346	16,20	21,12	24518,8	26918,1	2399,3	998,9618	1,2006	2,40463	0,0320187	0,03233	0,95037
27.06.2013	26926,5	29112,2	2,546385289	50,100	101,353	16,20	21,13	26918,1	29101,5	2183,5	998,9618	1,2006	2,18837	0,0436800	0,04402	0,76434
27.06.2013	31233,6	33434,1	2,751881162	35,102	101,357	16,20	21,10	31220,8	33419,1	2198,3	998,9618	1,2008	2,20325	0,0627672	0,06069	-3,42080
27.06.2013	35733,9	38024,8	2,948784831	30,101	101,355	16,22	21,10	35716,7	38005,5	2288,8	998,9585	1,2008	2,29391	0,0762071	0,07667	0,60191
27.06.2013	38024,8	40721,2	3,113250732	30,101	101,357	16,26	21,08	38005,5	40699,5	2694,0	998,9517	1,2009	2,70005	0,0896998	0,09001	0,34899
27.06.2013	40721,2	43869,5	3,299186651	30,101	101,355	16,30	21,03	40699,5	43845,0	3145,6	998,9449	1,2011	3,15270	0,1047374	0,10510	0,34636
27.06.2013	43869,5	47488,8	3,489050993	30,101	101,353	16,30	21,03	43845,0	47461,3	3616,3	998,9449	1,2011	3,62447	0,1204102	0,12051	0,08088
27.06.2013	47488,8	51533,1	3,661704023	30,102	101,349	16,32	21,02	47461,3	51502,3	4041,0	998,9415	1,2010	4,05014	0,1345473	0,13452	-0,02222
27.06.2013	51533,1	56019,9	3,84431413	30,103	101,344	16,31	21,02	51502,3	55985,4	4483,0	998,9432	1,2010	4,49319	0,1492605	0,14934	0,04990
27.06.2013	22915,8	27900,0	4,048366526	30,101	101,314	16,33	21,14	22911,4	27890,6	4979,1	998,9398	1,2001	4,99042	0,1657891	0,16589	0,06236
27.06.2013	27900,0	33300,1	4,218246192	30,101	101,316	16,33	21,15	27890,6	33285,3	5394,7	998,9398	1,2001	5,40689	0,1796250	0,17968	0,02905
27.06.2013	33300,1	39148,6	4,402058953	30,103	101,317	16,33	21,14	33285,3	39128,3	5843,0	998,9398	1,2002	5,85624	0,1945400	0,19459	0,02697
27.06.2013	39148,6	45467,2	4,594412542	30,102	101,317	16,35	21,15	39128,3	45441,4	6313,1	998,9364	1,2001	6,32747	0,2102010	0,21020	-0,00016
27.06.2013	45467,2	52236,7	4,780619943	30,101	101,321	16,35	21,13	45441,4	52205,3	6763,9	998,9364	1,2003	6,77929	0,2252181	0,22531	0,04091
27.06.2013	19502,2	26575,4	4,904540025	30,101	101,287	16,44	21,17	19501,1	26567,3	7066,2	998,9210	1,1997	7,08236	0,2352866	0,23537	0,03356
27.06.2013	26575,4	34209,8	5,134731837	30,102	101,276	16,43	21,18	26567,3	34194,1	7626,7	998,9227	1,1995	7,64413	0,2539411	0,25404	0,04057
27.06.2013	34209,8	42159,6	5,261639913	30,103	101,267	16,42	21,17	34194,1	42136,6	7942,5	998,9245	1,1995	7,96064	0,2644468	0,26434	-0,03968
27.06.2013	42159,6	50661,4	5,489687682	30,102	101,270	16,46	21,15	42136,6	50631,3	8494,7	998,9176	1,1996	8,51417	0,2828438	0,28285	0,00096
27.06.2013	50661,4	59633,5	5,680392424	30,102	101,267	16,49	21,12	50631,3	59595,8	8964,4	998,9125	1,1997	8,98496	0,2984840	0,29832	-0,05462
27.06.2013	29923,6	38488,8	5,513132632	30,102	101,260	16,52	21,16	29912,1	38469,1	8556,9	998,9073	1,1994	8,57659	0,2849175	0,28475	-0,05920
27.06.2013	38488,8	46120,0	5,133900593	30,102	101,252	16,54	21,19	38469,1	46093,7	7624,6	998,9038	1,1992	7,64215	0,2538752	0,25398	0,03997
27.06.2013	46120,0	52116,5	4,459464541	30,103	101,247	16,53	21,12	46093,7	52085,2	5991,6	998,9056	1,1994	6,00536	0,1994937	0,19925	-0,12203
27.06.2013	52116,3	56089,3	3,634209592	30,103	101,235	16,55	21,10	52085,0	56054,7	3969,7	998,9021	1,1994	3,97880	0,1321730	0,13229	0,08570
27.06.2013	56088,7	58269,2	2,899512745	30,102	101,222	16,53	21,07	56054,1	58232,7	2178,6	998,9056	1,1993	2,18359	0,0725398	0,07267	0,17974

Calibration constants, 27.06.2013	
C_0	-0,16260647
C_1	0,081143601



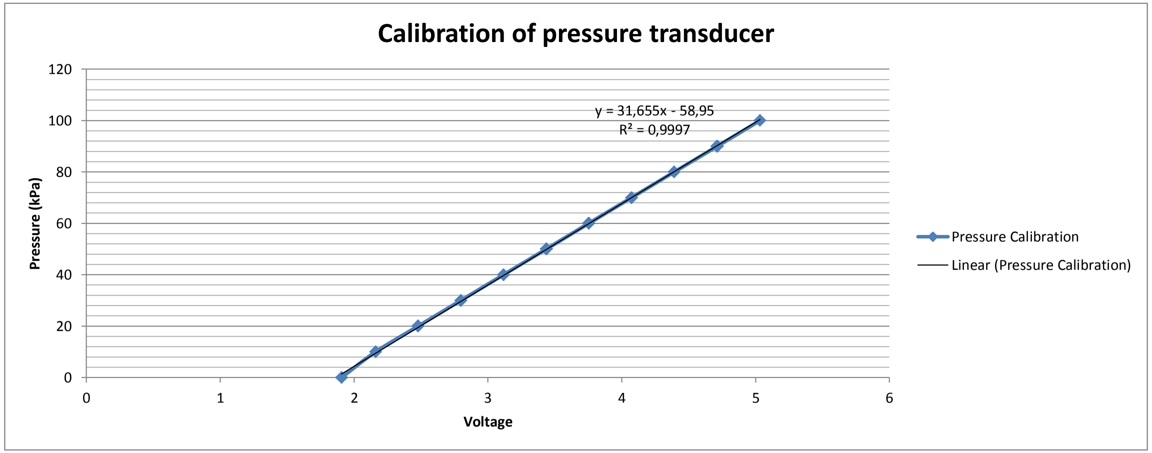
Calibration of pressure transducer

Rig: *Cross flow turbine test rig*

Operators: *Øystein S. Hveem*
Chiyembekezo Kaunda

Date: *09.09.2013*

Pressure (Bar)	Voltage	Pressure (kPa)
0	1,906159575	0
0,1	2,161128619	10
0,2	2,480126232	20
0,3	2,797693241	30
0,4	3,117776471	40
0,5	3,435668945	50
0,6	3,751422036	60
0,7	4,071978219	70
0,8	4,392696857	80
0,9	4,715814905	90
1	5,032886551	100
0,9	4,711379191	90
0,8	4,392161246	80
0,7	4,074526935	70
0,6	3,756374191	60
0,5	3,438559693	50
0,4	3,115887789	40
0,3	2,799692932	30
0,2	2,477609689	20
0,1	2,161682027	10
0	1,906188183	0



Appendix B

Instrumentation

B.1 Generator

KS GS *series*

KS

Alternatori sincroni monofasi a 2 e 4 poli autoregolati senza spazzole
> Protezione: IP 21.
> Tensione standard: 115/230 V - 50 Hz.
> Corrente di cortocircuito superiore a 3 In.
> Forme costruttive: IM B34 - B3/B14, IM B35 B3/B9, IM B35 - J609b, SAE 3, SAE 4, SAE 5.

Single -phase synchronous self-regulated brushless 2 and 4 poles alternators.
> *Protection: IP 21.*
> *Standard voltage: 115/230 V - 50 Hz.*
> *Short circuit current greater than 3 In.*
> *Shape: IM B34 - B3/B14, IM B35 B3/B9, IM B35 - J609b, SAE 3, SAE 4, SAE 5.*

tipo *type*	*potenza rating*	η 4/4 p.f. = 1	*potenza rating*	η 4/4 p.f. = 1	peso weight	peso weight
	kVA	%	kVA	%	Kg	Kg
	50 Hz - 3000 r.p.m.		60 Hz - 3600 r.p.m.		IM B34 • IM B35	SAE 4 • SAE 5 • SAE 3
*KS 2 MAL	15	79	18,5	80	70	86
*KS 2 MBL	17,5	80	22	82	90	106
KS 2 LAL	20	82	25	84	98	114
KS 2 LBL	25	84	31	86	117	133
	50 Hz - 1500 r.p.m.		60 Hz - 1800 r.p.m.		IM B34 • IM B35	SAE 4 • SAE 5
*KS 4 MEL	11	80,8	13,2	81,2	71	87
*KS 4 MFL	13,5	81,5	16,2	83,1	92	105
KS 4 LEL	16	83,1	19,2	84,2	101	117
KS 4 LFL	17,5	85,1	21	86,6	121	137

* solo in SAE 3 • only in SAE 3

GS

Alternatori sincroni trifasi a 2 e 4 poli autoregolati con spazzole
> Protezione: IP 21.
> Tensione standard: 231/400 V - 50 Hz.
> Corrente di cortocircuito superiore a 3,5 In.
> Forme costruttive: IM B34 - B3/B14, IM B35 B3/B9, IM B35 - J609b, SAE 3, SAE 4, SAE 5.

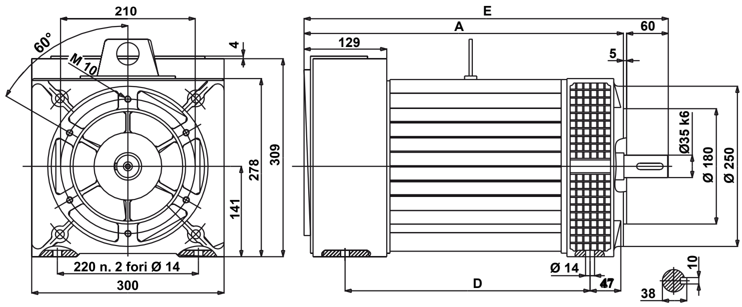
Three -phase synchronous self-regulated brushes 2 and 4 poles alternators.
> *Protection: IP 21.*
> *Standard voltage: 231/400 V - 50 Hz.*
> *Short circuit current greater than 3,5 In.*
> *Shape: IM B34 - B3/B14, IM B35 B3/B9, IM B35 - J609b, SAE 3, SAE 4, SAE 5.*

tipo *type*	*potenza rating*	η 4/4 p.f. = 0,8	*potenza rating*	η 4/4 p.f. = 0,8	peso weight	peso weight
	kVA	%	kVA	%	Kg	Kg
	50 Hz - 3000 r.p.m.		60 Hz - 3600 r.p.m.		IM B34 • IM B35	SAE 4 • SAE 5 • SAE 3
*GS 2 MAS	22	83	27,5	84	76	92
*GS 2 MBS	27	85	34	86	86	102
GS 2 LAS	31,5	86	40	87	101	117
GS 2 LBS	38	88	47,5	89	122	138
	50 Hz - 1500 r.p.m.		60 Hz - 1800 r.p.m.		IM B34 • IM B35	SAE 4 • SAE 5
*GS 4 MES	16,5	84,5	19,8	85,3	78	93
*GS 4 MFS	20	87	24	88,2	92	108
GS 4 LES	25	88	30	89	110	126
GS 4 LFS	30	89,2	36	90,1	131	147

* solo in SAE 3 • only in SAE 3

forma costruttiva / shape IM B34 - B3/B14 cod.E

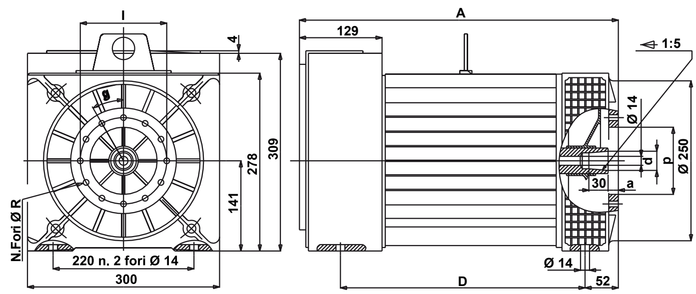
tipo - *type*	dimensioni - *dimensions*		
	A	D	E
	[mm]	[mm]	[mm]
KS - L / GS - L	597	481	662



forma costruttiva / shape IM B35 - B3/B9 cod.B/G

tipo - *type*	dimensioni - *dimensions*	
	A	D
	[mm]	[mm]
KS - L / GS - L	592	481

albero - *shaft*		flangia - *flange*					cod.
d	a	l	p	N. fori	R	g	
30	16	135	105	12	9	30°	B
38	5	150	125	4	12	90°	G

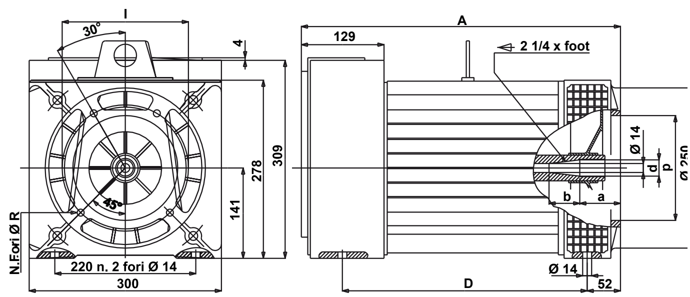


forma costruttiva / shape IM B35 - J609b cod. F

tipo - *type*	dimensioni - *dimensions*	
	A	D
	[mm]	[mm]
KS - L / GS - L	592	481

albero - *shaft*			cod.
d	a	b	
25,4	63,5	45	D
35	12,4	71	F

flangia - *flange*			
l	p	N. fori	R
165	146,1	4	11
197	163,6	4	11
197	177,8	4	11

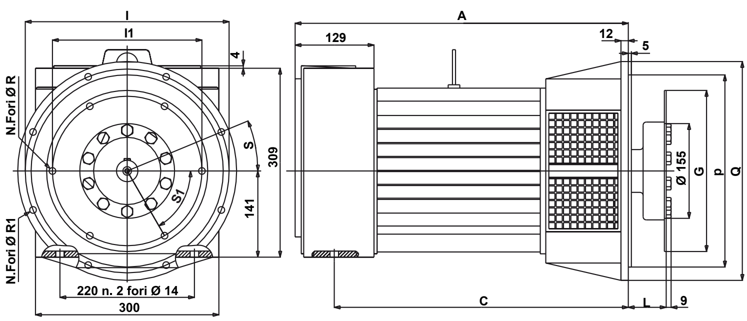


forma costruttiva / shape SAE cod. 4/5

tipo - *type*	dimensioni - *dimensions*	
	A	C
	[mm]	[mm]
KS - M / GS - M	545	481
KS - L / GS - L	644	580

SAE	flangia - *flange*					
	Q	P	I	N. fori	R1	S
3	452	409,6	428,6	12	11	15°
4	405	362	381	12	11	15°
5	358	314,3	333,4	8	11	22° 30°

SAE	giunto a dischi - *disk joint*					
	L	G	I1	N. fori	R	S1
6,5	30,2	215,9	200	6	9	60°
7,5	30,2	241,3	222,2	8	9	45°
8	62	263,5	244,5	6	11	60°
10	53,8	314,3	295,3	8	11	45°
11,5	39,5	352,4	333,4	8	11	45°



series KS / GS - 11/2010

www.sinteticomunicazione.it

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Ph. +39 0445 450500 • Fax +39 0445 446222 • sales.sincro@sogaenergyteam.com

Subsidiary • Soga Electric Group S.L. • Pol. Ind. Casa Grande Apartado 213 • Torrevieja • SPAIN
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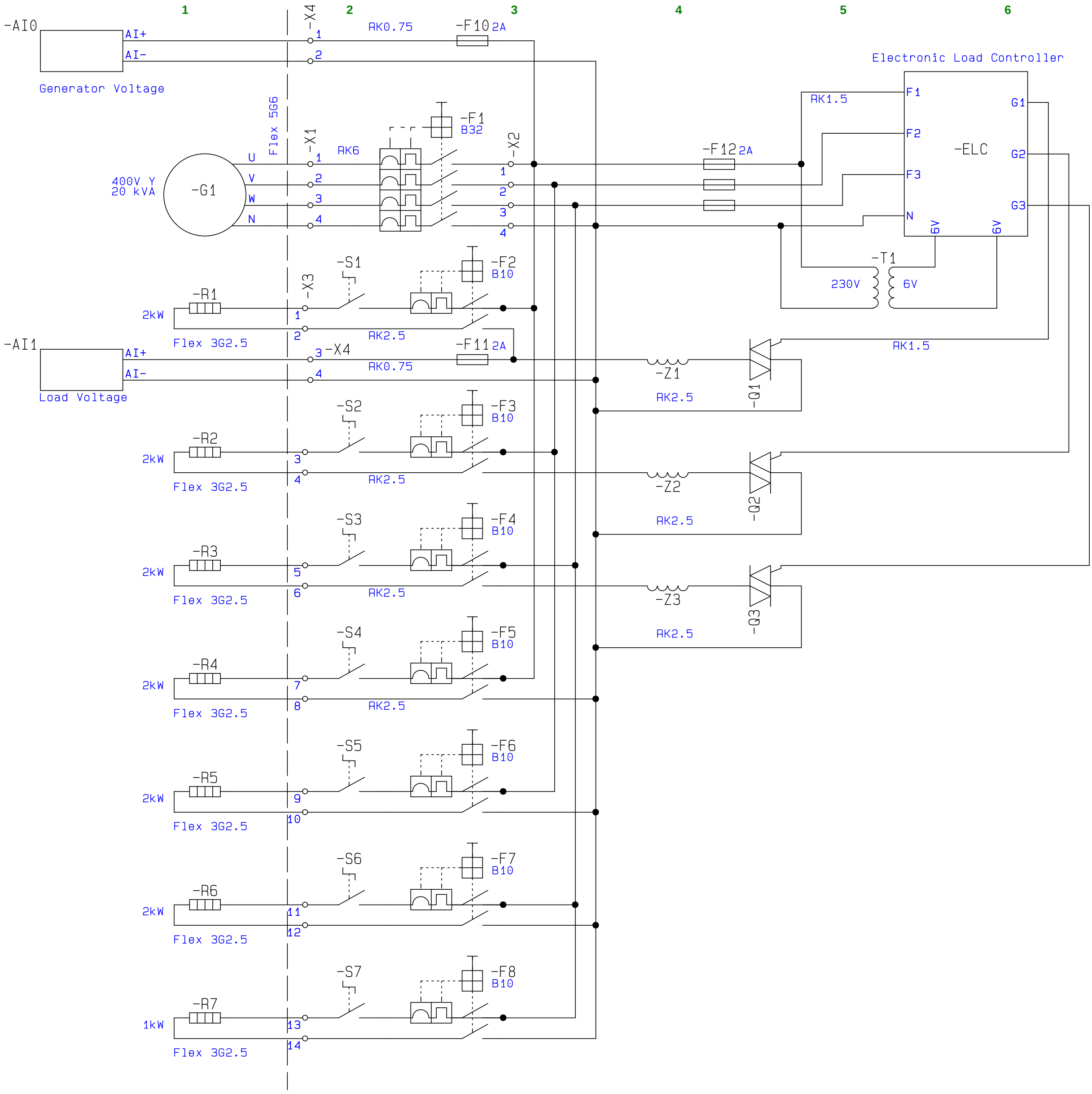
www.sogaenergyteam.com

B.2 ELC


1
2
3
4
5
6
-AI0
AI+
AI-
Generator Voltage
-X4
RK0.75
-F10 2A
Electronic Load Controller
-ELC
F1
F2
F3
N
G1
G2
G3
6V
6V
RK1.5
Flex 5G6
-X1
RK6
-F1
B32
-X2
-F12 2A
400V Y
20 kVA
-G1
U
V
W
N
-T1
230V
6V
-S1
-F2
B10
-X3
-R1
2kW
Flex 3G2.5
RK2.5
-AI1
AI+
AI-
Load Voltage
-X4
-F11 2A
RK0.75
-Z1
-Q1
RK1.5
RK2.5
-S2
-F3
B10
-R2
2kW
Flex 3G2.5
RK2.5
-Z2
-Q2
RK2.5
-S3
-F4
B10
-R3
2kW
Flex 3G2.5
RK2.5
-Z3
-Q3
RK2.5
-S4
-F5
B10
-R4
2kW
Flex 3G2.5
RK2.5
-S5
-F6
B10
-R5
2kW
Flex 3G2.5
-S6
-F7
B10
-R6
2kW
Flex 3G2.5
-S7
-F8
B10
-R7
1kW
Flex 3G2.5

Tilkoblingsliste

Ekstern	Klemme	Beskrivelse	Vern	Lastbryter
G1:U	X1:1	L1 fra generator	F1	
G1:V	X1:2	L2 fra generator		
G1:W	X1:3	L3 fra generator		
G1:N	X1:4	N fra generator		
R1:L	X3:1	Dumplast L1, styrt via ELC/triac, 2kW	F2	S1
R1:N	X3:2			
R2:L	X3:3	Dumplast L2, styrt via ELC/triac, 2kW	F3	S2
R2:N	X3:4			
R3:L	X3:5	Dumplast L3, styrt via ELC/triac, 2kW	F4	S3
R3:N	X3:6			
R4:L	X3:7	Forbrukslast L1, 2kW	F5	S4
R4:N	X3:8			
R5:L	X3:9	Forbrukslast L2, 2kW	F6	S5
R5:N	X3:10			
R6:L	X3:11	Forbrukslast L3, 2kW	F7	S6
R6:N	X3:12			
R7:L	X3:13	Forbrukslast L3, 1kW	F8	S7
R7:N	X3:14			
AI0:L	X4:1	Generatorspenning til DAQ – L	F10	
AI0:N	X4:2	Generatorspenning til DAQ – N		
AI1:L	X4:3	Lastspenning til DAQ – L	F11	
AI1:N	X4:4	Lastspenning til DAQ – N		

B.2.1 Estimated price

Cost estimate of ELC- Remote HydroLight

The following cost calculation is done for a 6 kW ELC with single card:

What	Number	Price each		Tot
		Part	Work + wires	
Heat sink	2	200	250	900
TRIAC	3	300	150	1350
Digital card 3 phase	1	1450	1200	2650
Coil	3	80	90	510
Transformer	1	220	200	420
Varistor	1	35	0	35
Box, wood + front plate	1	1000	0	1000
Fuse	3	310	240	1650
Voltmeter	2	140	100	480
Connector 3 phase	2	700	0	1400
SUM			Afs	10395
			USD	208
			NOK	1248

USD has rate 50 Afs/USD
NOK (Norwegian kroner) has rate 6 NOK/USD

This is the cost in Afghanistan when delivered from the shop making the ELC either bought by me (Anders Austegard) or the village people from the Industry. Bought by other NGOs must assume a higher price.

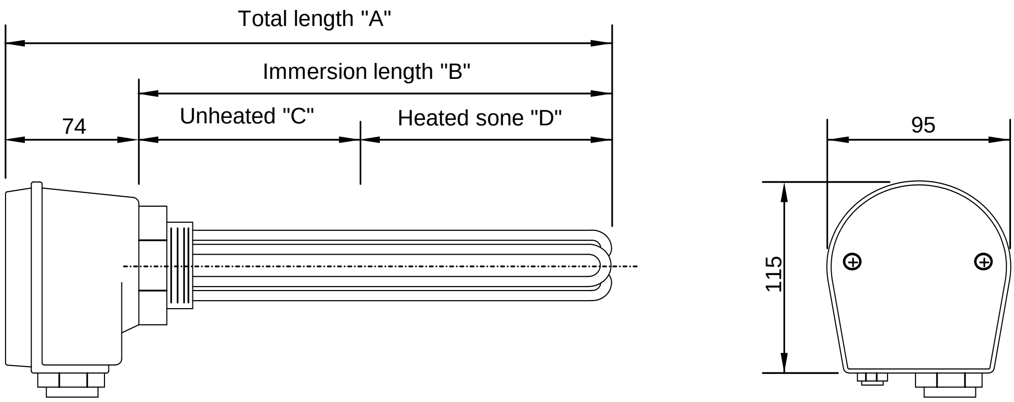
The price for a 3 phase ELC with double cards with capacity P [kW] becomes about:
Price = 10 000 Afs+ P * 600 Afs/kW. Eventually ampere meters increase the price.

In addition comes the water heater with a total price of around 200 USD.

Anders Austegard
Remote HydroLight
www.remotehydrolight.com

B.3 Heating elements

"Datasheet Backer Heater"
Datablad Backer Varmekolbe



Heater
Varmekolbe type: **IU 25**

To heat
For oppvarming av: **Vann**

Power
Total effekt: **1000W**

Voltage
Spenning: **230 V**

Immerson lenght
Instikkkslengde "B": **160mm**

Unheated
Innaktiv sone "C": **20 mm**

Heated
Varm kolbe "D": **140mm**

Flange/Screw plug
Flens/hode: **R 1 1/4" BSP**

Element
Rør type: **9SF7**

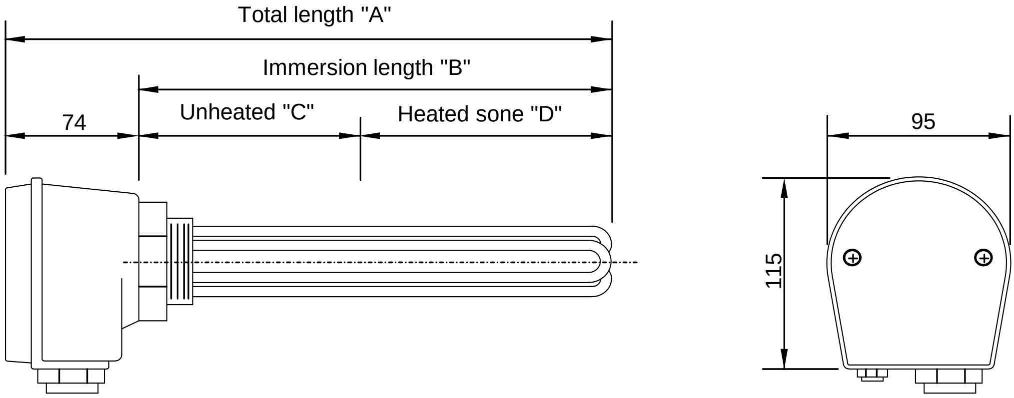
Pcs
Antall: **2**

Surface loading
Overfl.belastning **8,8** W/cm^2

Terminal box
Koblingsboks type: **K7**

Total length incl. terminal box
Total lengde inkl. koblingsboks "A": **234mm**

"Datasheet Backer Heater"
Datablad Backer Varmekolbe



Heater
Varmekolbe type: **IU 27**

To heat
For oppvarming **Vann**

Power
Total effekt: **2000 W**

Voltage
Spenning: **230 V**

Immerson lenght
Instikkkslengde "B": **250 mm**

Unheated
Innaktiv sone "C": **35mm**

Heated
Varm kolbe "D": **215 mm**

Flange/Screw plug
Flens/hode: **R 1 1/4" messing**

Element
Rør type: **8,5 mm SS 2348**

Pcs
Antall: **2**

Surface loading
Overfl.belastning **8,5** W/cm^2

Terminal box
Koblingsboks type: **K 7**

Total length incl. terminal box
Total lengde inkl. koblingsboks "A": **324mm**

Appendix C

Data aquistion-program

C.1 LabVIEW-program

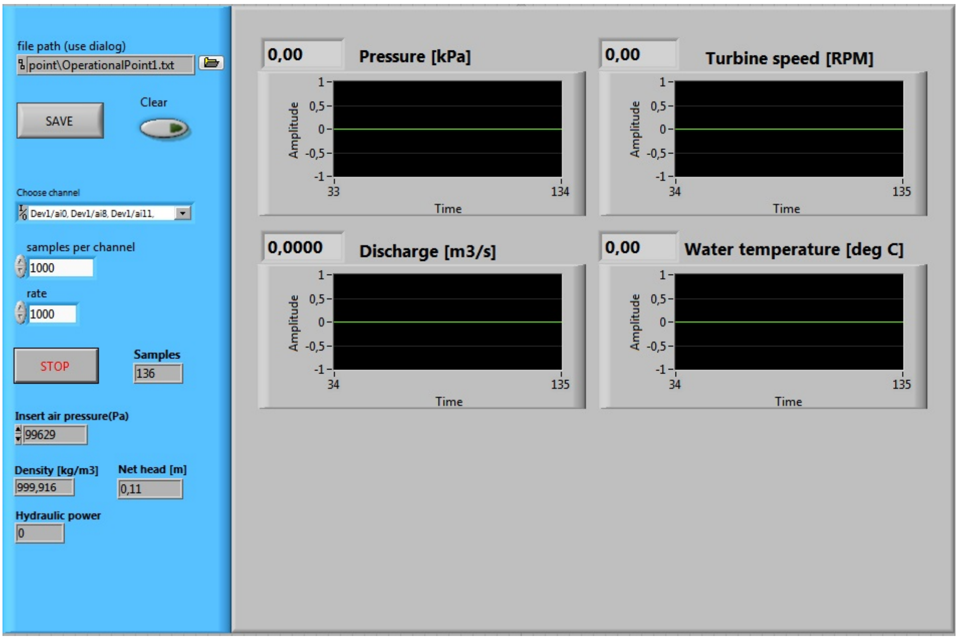


Figure C.1.1: Front panel of LabView program for hydraulic performance. Due to a very large block diagram it was not possible to view the whole program. See

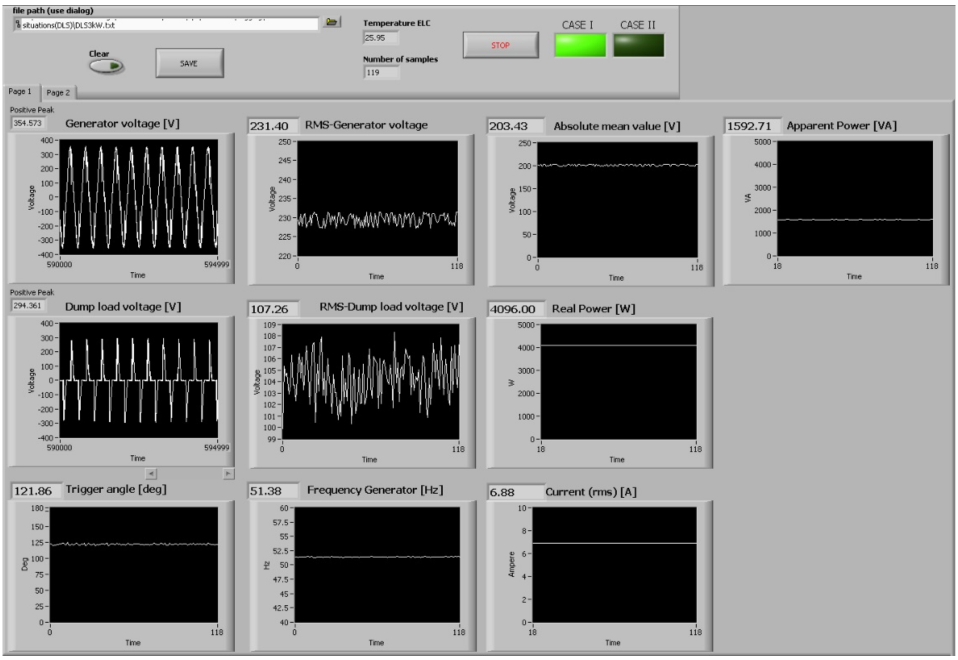


Figure C.1.2: Front panel of LabView program (tab 1) for ELC with processing of dump load- and generator voltage signals. Due to a very large block diagram it was not possible to view the whole program

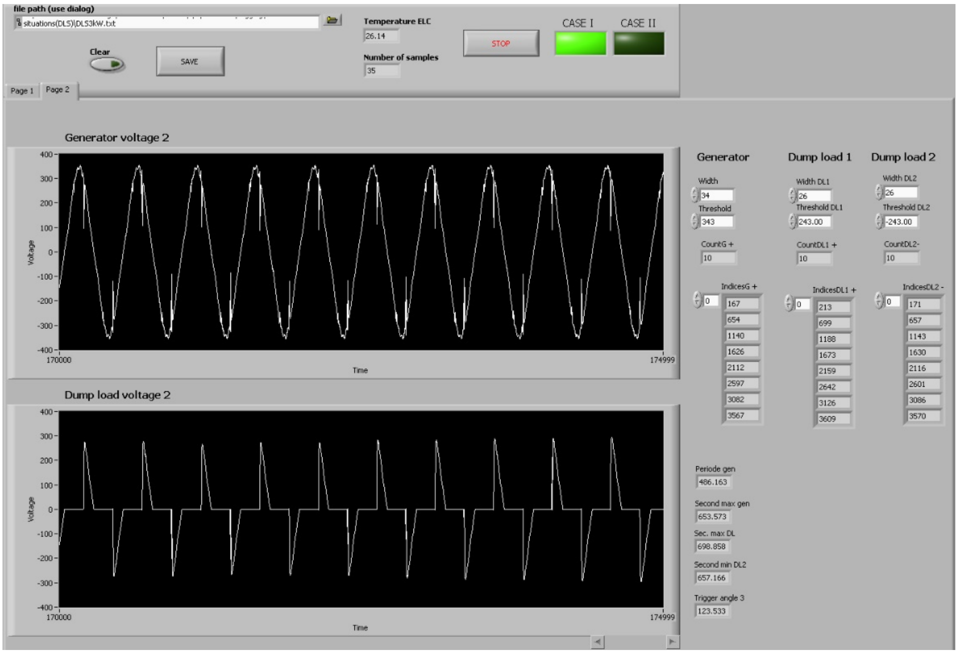


Figure C.1.3: Front panel of LabView program(tab 2) for ELC with only dump load- and generator voltage signals plotted. Due to a very large block diagram it was not possible to view the whole program

Appendix D

Experimental data

Different load situations		0kW	1kW	2kW	3kW	4kW
Frequency Generator	*Hz*	51,167 ± 0,010	51,149 ± 0,013	51,207 ± 0,016	51,3903 ± 0,0090	51,1139 ± 0,0089
Amplitude Generator Voltage	*V*	350,31 ± 0,17	367,30 ± 0,20	378,37 ± 0,49	354,067 ± 0,055	359,768 ± 0,051
Generator RMS-Voltage	*V*	230,42 ± 0,24	231,04 ± 0,24	230,33 ± 0,23	229,54 ± 0,23	233,47 ± 0,27
Absolute mean Generator	*V*	202,29 ± 0,29	202,84 ± 0,29	202,11 ± 0,28	201,21 ± 0,27	203,44 ± 0,31
Amplitude dump load	*V*	348,888 ± 0,070	344,44 ± 0,13	313,39 ± 0,26	288,94 ± 0,43	175,10 ± 0,90
RMS Voltage dump load	*V*	193,37 ± 0,33	166,86 ± 0,34	138,62 ± 0,42	104,39 ± 0,31	48,10 ± 0,32
Trigger angle	*deg*	90,467 ± 0,010	112,96 ± 0,20	117,94 ± 0,17	122,37 ± 0,18	141,12 ± 0,82
Real power	*W*	4050,0 ± 1,2	4068,78 ± 0,72	4093,30 ± 0,50	4096,95 ± 0,38	4127,17 ± 0,43
Current (RMS)	*A*	7,1544 ± 0,0012	7,3210 ± 0,0010	7,22265 ± 0,00083	6,88715 ± 0,00081	6,2100 ± 0,0011
Apparent power	*VA*	1648,5 ± 1,8	1691,4 ± 1,8	1663,6 ± 1,7	1580,9 ± 1,6	1449,8 ± 1,7
Pressure	*kPa*	49,034 ± 0,013	48,962 ± 0,014	49,013 ± 0,014	48,958 ± 0,016	48,952 ± 0,012
Temperature	*deg C*	14,603066 ± 0,000086	14,60520 ± 0,00010	14,60770 ± 0,00011	14,61147 ± 0,00014	14,61606 ± 0,00012
Generator speed	*RPM*	474,140 ± 0,081	474,571 ± 0,089	475,910 ± 0,088	478,14 ± 0,11	476,229 ± 0,088
Discharge	*m3/s*	0,152541 ± 0,000016	0,152490 ± 0,000017	0,152487 ± 0,000011	0,152483 ± 0,000013	0,1524171 ± 0,0000094
Ned	-	17,2651 ± 0,0029	17,2925 ± 0,0027	17,3334 ± 0,0027	17,4232 ± 0,0029	17,3553 ± 0,0029
Qed	-	0,282200 ± 0,000033	0,282298 ± 0,000027	0,282164 ± 0,000036	0,282296 ± 0,000043	0,282201 ± 0,000032
Power_hydr	*W*	8380,4 ± 2,5	8366,1 ± 3,0	8373,6 ± 2,5	8365,1 ± 2,8	8359,8 ± 2,1
Pressure_pa	*Pa*	49034 ± 13	48962 ± 14	49013 ± 14	48958 ± 16	48952 ± 12
Velocity_inlet	*m/s*	3,10755 ± 0,00032	3,10650 ± 0,00035	3,10644 ± 0,00022	3,10636 ± 0,00026	3,10501 ± 0,00019
H_net	*m*	5,5980 ± 0,0014	5,5903 ± 0,0015	5,5954 ± 0,0015	5,5899 ± 0,0017	5,5888 ± 0,0012
Density	*kg/m3*	999,237387 ± 0,000014	999,237038 ± 0,000018	999,236685 ± 0,000017	999,236098 ± 0,000020	999,235407 ± 0,000019

Rapid on load situation

		Stable operating point - 0kW			Stable point after change - 4kW			Stable operating point 2 -0kW		
Frequency Generator	*Hz*	51,145	±	0,010	51,1205	±	0,0058	51,142	±	0,010
Amplitude Generator Voltage	*V*	351,80	±	0,42	358,969	±	0,093	362,20	±	0,54
Generator RMS-Voltage	*V*	230,16	±	0,21	233,60	±	0,19	230,15	±	0,18
Absolute mean Generator	*V*	202,08	±	0,25	203,44	±	0,23	202,16	±	0,21
Amplitude dump load	*V*	348,244	±	0,069	131,8	±	1,9	347,117	±	0,068
RMS Voltage dump load	*V*	190,95	±	0,28	34,61	±	0,57	186,01	±	0,26
Trigger angle	*deg*	90,4529	±	0,0077	92,9	±	2,7	91,9	±	3,0
Real power	*W*	3954,20	±	0,60	3943,1	±	2,9	3747,1	±	2,4
Current (RMS)	*A*	7,06716	±	0,00074	5,790	±	0,005	6,8733	±	0,0023
Apparent power	*VA*	1626,6	±	1,5	1352,6	±	1,7	1581,9	±	1,3
Pressure	*kPa*	48,956	±	0,013	48,926	±	0,012	48,962	±	0,015
Temperature	*deg C*	14,62569	±	0,00014	14,63875	±	0,00016	14,65783	±	0,00018
Generator speed	*RPM*	478,330	±	0,080	481,432	±	0,175	487,906	±	0,094
Discharge	*m3/s*	0,1524281	±	0,0000090	0,152409	±	0,000012	0,152415	±	0,000014
Ned	-	17,4310	±	0,0026	17,5491	±	0,0067	17,7792	±	0,0037
Qed	-	0,282208	±	0,000037	0,282253	±	0,000032	0,282171	±	0,000034
Power_hydr	*W*	8361,2	±	2,2	8355,4	±	2,2	8361,2	±	2,9
Pressure_pa	*Pa*	48956	±	13	48926	±	12	48962	±	15
Velocity_inlet	*m/s*	3,10524	±	0,00018	3,10486	±	0,00024	3,10497	±	0,00029
H_net	*m*	5,5893	±	0,0014	5,5862	±	0,0013	5,5899	±	0,0016
Density	*kg/m3*	999,233968	±	0,000023	999,231996	±	0,000025	999,229146	±	0,000025

Rapid off load situation

		Stable operating point - 4kW			Stable operating point - 0kW			Stable operating point 2 - 4kW		
Frequency Generator	*Hz*	51,1366	±	0,0064	51,1349	±	0,0094	51,1226	±	0,0066
Amplitude Generator Voltage	*V*	357,722	±	0,152	357,753	±	0,569	359,327	±	0,041
Generator RMS-Voltage	*V*	233,60	±	0,22	230,00	±	0,19	233,55	±	0,20
Absolute mean Generator	*V*	203,43	±	0,26	201,95	±	0,23	203,38	±	0,24
Amplitude dump load	*V*	99,34	±	0,98	347,525	±	0,058	134,5	±	1,0
RMS Voltage dump load	*V*	24,09	±	0,36	187,86	±	0,25	35,41	±	0,30
Trigger angle	*deg*	92,254	±	0,011	92,0	±	3,0	148,00	±	0,26
Real power	*W*	3873,9	±	1,0	3836,23	±	0,21	3936,89	±	0,51
Current (RMS)	*A*	5,6681	±	0,0016	6,9573	±	0,0005	5,7772	±	0,0012
Apparent power	*VA*	1324,0	±	1,3	1600,2	±	1,3	1349,3	±	1,2
Pressure	*kPa*	48,951	±	0,017	48,934	±	0,010	48,923	±	0,018
Temperature	*deg C*	14,67053	±	0,00020	14,68580	±	0,00022	14,70723	±	0,00019
Generator speed	*RPM*	485,32	±	0,11	483,763	±	0,066	481,370	±	0,088
Discharge	*m3/s*	0,152377	±	0,000018	0,1524120	±	0,0000071	0,152412	±	0,000010
Ned	-	17,6873	±	0,0035	17,6327	±	0,0022	17,5473	±	0,0026
Qed	-	0,282136	±	0,000042	0,282237	±	0,000026	0,282267	±	0,000053
Power_hydr	*W*	8357,0	±	3,2	8356,8	±	1,7	8355,0	±	2,8
Pressure_pa	*Pa*	48951	±	17	48934	±	10	48923	±	18
Velocity_inlet	*m/s*	3,10419	±	0,00036	3,10491	±	0,00015	3,10491	±	0,00021
H_net	*m*	5,5884	±	0,0018	5,5870	±	0,0011	5,5858	±	0,0019
Density	*kg/m3*	999,227233	±	0,000029	999,224928	±	0,000033	999,221695	±	0,000028

Overload situation- 1kW

		Stable operating point- 4kW			Stable point after change-5kW			Stable operating point 2-4kW		
Frequency Generator	*Hz*	51,1159	±	0,0066	48,5069	±	0,0076	51,1143	±	0,0061
Amplitude Generator Voltage	*V*	359,410	±	0,046	337,230	±	0,053	359,318	±	0,040
Generator RMS-Voltage	*V*	233,71	±	0,19	218,75	±	0,20	233,72	±	0,19
Absolute mean Generator	*V*	203,59	±	0,23	190,46	±	0,24	203,61	±	0,23
Amplitude dump load	*V*	140,4	±	1,2	0,0252	±	0,0040	136,6	±	1,0
RMS Voltage dump load	*V*	37,01	±	0,35	0,0081	±	0,0040	35,92	±	0,29
Trigger angle	*deg*	146,76	±	0,25	Inf	±		147,74	±	0,27
Real power	*W*	3944,59	±	0,83	4195,81	±	0,90	3945,9	±	1,4
Current (RMS)	*A*	5,7923	±	0,0016	6,55356	±	0,00087	5,7952	±	0,0028
Apparent power	*VA*	1353,7	±	1,2	1433,6	±	1,3	1354,5	±	1,3
Pressure	*kPa*	48,972	±	0,021	48,852	±	0,012	48,935	±	0,016
Temperature	*deg C*	14,71519	±	0,00021	14,72397	±	0,00014	14,73272	±	0,00025
Generator speed	*RPM*	481,225	±	0,098	460,90	±	0,10	481,32	±	0,12
Discharge	*m3/s*	0,152519	±	0,000025	0,1525160	±	0,0000085	0,152449	±	0,000013
Ned	-	17,5330	±	0,0026	16,8109	±	0,0030	17,5433	±	0,0041
Qed	-	0,282319	±	0,000041	0,282623	±	0,000033	0,282297	±	0,000039
Power_hydr	*W*	8369,5	±	4,5	8351,0	±	2,0	8359,3	±	2,9
Pressure_pa	*Pa*	48972	±	21	48852	±	12	48935	±	16
Velocity_inlet	*m/s*	3,10709	±	0,00052	3,10703	±	0,00017	3,10567	±	0,00026
H_net	*m*	5,5916	±	0,0023	5,5794	±	0,0013	5,5874	±	0,0017
Density	*kg/m3*	999,220514	±	0,000027	999,219136	±	0,000022	999,217851	±	0,000037

Overload situation- 2kW

		Stable operating point -4kW			Stable point after change - 6kW			Stable operating point 2 -4kW		
Frequency Generator	*Hz*	51,1183	±	0,0071	45,1120	±	0,0095	51,3378	±	0,0078
Amplitude Generator Voltage	*V*	359,234	±	0,046	308,699	±	0,063	352,140	±	0,099
Generator RMS-Voltage	*V*	233,76	±	0,22	200,456	±	0,056	231,42	±	0,21
Absolute mean Generator	*V*	203,64	±	0,26	174,614	±	0,057	201,66	±	0,25
Amplitude dump load	*V*	133,2	±	1,0	0,0202	±	0,0040	99,45	±	0,87
RMS Voltage dump load	*V*	34,97	±	0,28	0,0073	±	0,0040	25,90	±	0,31
Trigger angle	*deg*	148,25	±	0,24	inf	±		334	±	87
Real power	*W*	3936,17	±	0,24	4404,2	±	1,5	3972,0	±	1,1
Current (RMS)	*A*	5,7761	±	0,0006	7,4048	±	0,0014	5,7734	±	0,0023
Apparent power	*VA*	1350,2	±	1,3	1484,33	±	0,57	1336,1	±	1,4
Pressure	*kPa*	48,908	±	0,012	48,847	±	0,018	48,959	±	0,021
Temperature	*deg C*	14,73804	±	0,00014	14,74489	±	0,00019	14,75302	±	0,00020
Generator speed	*RPM*	481,359	±	0,067	435,70	±	0,17	482,74	±	0,18
Discharge	*m3/s*	0,152406	±	0,000010	0,152558	±	0,000021	0,152527	±	0,000022
Ned	-	17,5493	±	0,0027	15,8922	±	0,0050	17,5900	±	0,0052
Qed	-	0,282293	±	0,000032	0,282707	±	0,000055	0,282366	±	0,000057
Power_hydr	*W*	8352,4	±	2,0	8352,9	±	3,3	8368,0	±	3,8
Pressure_pa	*Pa*	48908	±	12	48847	±	18	48959	±	21
Velocity_inlet	*m/s*	3,10479	±	0,00021	3,10789	±	0,00044	3,10725	±	0,00044
H_net	*m*	5,5843	±	0,0012	5,5791	±	0,0019	5,590	±	0,0022
Density	*kg/m3*	999,217034	±	0,000021	999,215973	±	0,000029	999,214791	±	0,000031

Run-away speed

		Stable operating point			Stable operating point 2		
Pressure	*kPa*	48,927	±	0,031	48,859	±	0,013
Temperature	*deg C*	14,76172	±	0,00020	14,76722	±	0,00020
Generator speed	*RPM*	486,62	±	0,24	485,20	±	0,11
Discharge	*m3/s*	0,152474	±	0,000027	0,1523614	±	0,0000079
Ned	-	17,7373	±	0,0055	17,6978	±	0,0036
Qed	-	0,282358	±	0,000070	0,282344	±	0,000037
Power_hydr	*W*	8359,8	±	5,7	8342,0	±	1,9
Pressure_pa	*Pa*	48927	±	31	48859	±	13
Velocity_inlet	*m/s*	3,10618	±	0,00055	3,10388	±	0,00016
H_net	*m*	5,5868	±	0,0032	5,5791	±	0,0013
Density	*kg/m3*	999,213458	±	0,000031	999,212596	±	0,000031

Appendix E

HSE-repport for experiment

Risk Assessment Report

Cross flow turbine connected to ELC

Prosjektnavn	Crossflow Turbine connected to ELC
Apparatur	Crossflow Turbine, Electronic load controller
Enhet	NTNU
Apparaturansvarlig	Bård Brandåstrø
Prosjektleder	Torbjørn Nielsen
HMS-koordinator	Morten Grønli
HMS-ansvarlig (linjeleder)	Olav Bolland
Plassering	Waterpower Laboratory
Romnummer	Room 21
Risikovurdering utført av	Øystein Sveinsgjerd Hveem, Magni Fjørtoft Svarstad, Kristin Gjevik, Chiyembekezo Kaunda, Peter Joachim Gogstad, Bård Brandåstrø

Approval:

	Navn	Dato	Signatur
Prosjektleder	Torbjørn Nielsen		
HMS koordinator	Morten Grønli		
HMS ansvarlig (linjeleder)	Olav Bolland		

TABLE OF CONTENTS

1 INTRODUCTION

The experimental test rig is under construction with a cross flow turbine connected to a synchronous generator where an Electronic Load Controller (ELC) is used as governing system. The motivation of the experiment is to investigate the performance, stability and measure the response time of the ELC manufactured by Remote HydroLight/Anders Austegard. The rig is located in Room 21 of the Waterpower laboratory.

2 CONCLUSION

The experimental setup is approved

Apparaturkort (UNIT CARD) is valid for **12 months**
Forsøk pågår kort (EXPERIMENT IN PROGRESS) is valid for **12 months**

3 ORGANISATION

Rolle	
Prosjektleder	Torbjørn Nielsen
Apparaturansvarlig	Bård Brandåstrø
Romansvarlig	Halvor Haukvik
HMS koordinator	Morten Grønli
HMS ansvarlig (linjeleder):	Olav Bolland

4 RISK MANAGEMENT IN THE PROJECT

Hovedaktiviteter risikostyring	Nødvendige tiltak, dokumentasjon	DATE
Prosjekt initiering	Prosjekt initiering mal	
Veiledningsmøte Guidance Meeting	Skjema for Veiledningsmøte med pre-risikovurdering	
Innledende risikovurdering Initial hazard assessment	Fareidentifikasjon – HAZID Skjema grovanalyse	
Evaluation of technical security	Prosess-HAZOP Tekniske dokumentasjoner	
Evaluation of operational safety	Prosedyre-HAZOP Opplæringsplan for operatører	
Final assessment, quality assurance	Uavhengig kontroll Utstedelse av apparaturkort Utstedelse av forsøk pågår kort	

5 DESCRIPTIONS OF EXPERIMENTAL SETUP

Give a short description of the experimental setup and the purpose of the experiments
The purpose with this experiment is to analyse the performance of an electronic load controller (ELC) manufactured by Remote HydroLight/Anders Austegard. The ELC is connected to a synchronous generator on the Cross flow turbine test rig. The controller uses phase angle regulation to control the power output of the system, by triggering three 2kW heating elements (dump loads). A quantitative analysis will be performed by logging output electrical power + generator voltage and compare it with dump load voltage. Since electrical equipment is sensitive to changes in frequency, the generator frequency is logged. Several stress tests will be performed in order to check the stability and the response time of the system.

The experiment is set up in the Waterpower Laboratory. The setup arrangement is duplex; the cross flow turbine test rig and the ELC-system. The cross flow turbine test rig is composed of piping network to conduct water from the pump, through the pressure tank and into the Cross flow turbine rig.

The installed cross flow turbine is made up of a nozzle, runner, and housing. A screw handle is used to adjust the nozzle opening and to control the flow to the runner. The flow is changed by increasing or decreasing the pump speed. To convert the mechanical energy to electrical energy, a synchronous generator is used. The Cross flow turbine is connected to the generator via a belt drive.

The ELC-system is composed of an ELC-cabinet, a dump load system and a consumption load system. The ELC is connected to the generator (220V AC) and uses generator voltage as input signal. Four heating elements (3x 2kW + 1x 1kW) with switches are used as consumption load. The dump load system consists of three heating elements with capacity of 2kW each. Both dump load- and consumption load-systems are submerged into the lower reservoir. They are installed in a waterproof environment to prevent short circuits. A verified cabinet is used to protect the electrical components in the ELC. The switches are installed on the front panel of the cabinet. To log the generator and dump load voltage, a data aquistion unit from National Instrument (NI9225) is used. The instrument has a range of -300 - +300V.

In order to control the flow and pressure at the inlet of the turbine, an electromagnetic flow meter and a pressure transducer are assembled to the test rig. Power output is determined by measuring voltage and current from the generator. (P=U*I)

The following are added to this report as Attachment A:
- Process and Instrumentation Diagram (PID)
- Drawings and photos describing the setup.

6 EVACUATION FROM THE EXPERIMENTAL AREA

Evacuate at signal from the alarm system or local gas alarms with its own local alert with sound and light outside the room in question, see 6.2

Evacuation from the rigging area takes place through the marked emergency exits to the assembly point, (corner of Old Chemistry Kjelhuset or parking 1a-b.)

Action on rig before evacuation:
Use emergency switch to stop the pump and close windows.

7 WARNING

7.1 Before experiments

Send an e-mail with information about the planned experiment to:
Liste iept-experiments@ivt.ntnu.no

The e-mail should contain the following items:

- Name of responsible person:
- Experimental setup/rig:
- Start Experiments: (date and time)
- Stop Experiments: (date and time)

You must get the approval back from the laboratory management before start up. All running experiments are notified in the activity calendar for the lab to be sure they are coordinated with other activity.

7.2 Non-conformance

FIRE
If you are NOT able to extinguish the fire, activate the nearest fire alarm and evacuate area.
Be then available for fire brigade and building caretaker to detect fire place.
If possible, notify:

NTNU	SINTEF
Morten Grønli, Mob: 918 97 515	Harald Mæhlum, Mob: 930 14 986
Olav Bolland: Mob: 918 97 209	Anne Karin T. Hemmingsen Mob: 930 19 669
NTNU – SINTEF Beredskapstelefon	800 80 388

GAS ALARM
If a gas alarm occurs, close gas bottles immediately and ventilate the area. If the level of the gas concentration does not decrease within a reasonable time, activate the fire alarm and evacuate the lab. Designated personnel or fire department checks the leak to determine whether it is possible to seal the leak and ventilate the area in a responsible manner.

PERSONAL INJURY

- First aid kit in the fire / first aid stations

- Shout for help
- Start life-saving first aid

CALL 113 if there is any doubt whether there is a serious injury

OTHER NON-CONFORMANCE (AVVIK)

NTNU:
You will find the reporting form for non-conformance on:
https://innsida.ntnu.no/wiki/-/wiki/Norsk/Melde+avvik

SINTEF:
Synergi

8 ASSESSMENT OF TECHNICAL SAFETY

8.1 HAZOP

The experiment set up is divided into the following nodes:

Node 1	Pressure tank
Node 2	Cross flow turbine with generator
Node 3	ELC
Node 4	Heating elements

Attachments: Form: HAZOP Template
Conclusion: Safety taken care of

8.2 Flammable, reactive and pressurized substances and gas

Are any flammable, reactive and pressurized substances and gases in use?

YES	Pressurised water

Attachments: None
Conclusion: This experiment will be carried out using low head values (up to 5 mWc). The consequences from pressurised water are therefore small.

8.3 Pressurized equipment

Is any pressurized equipment in use?

YES	Pump, pressure tank and pipes

Attachments: None
Conclusion*:* The pump, pressure tank and the pipeline (except the last pipe from V23 to Crossflow turbine) has been pressure tested. Even though the pipe has not been pressure tested, since the experiment will use low values of head, the stress levels in the pipe will be low.

8.4 Effects on the environment (emissions, noise, temperature, vibration, smell)

Will the experiments generate emission of smoke, gas, odour or unusual waste?
Is there a need for a discharge permit, extraordinary measures?

NO	

8.5 Radiation

NO	

8.6 Chemicals

NO	

8.7 Electricity safety (deviations from the norms/standards)

NO	

9 ASSESSMENT OF OPERATIONAL SAFETY

Ensure that the procedures cover all identified risk factors that must be taken care of. Ensure that the operators and technical performance have sufficient expertise.

9.1 Procedure HAZOP

The method is a procedure to identify causes and sources of danger to operational problems.
Attachments: HAZOP Procedure
Conclusion:

Operation and emergency shutdown procedure
The operating procedure is a checklist that must be filled out for each experiment.
Emergency procedure should attempt to set the experiment setup in a harmless state by unforeseen events.
Attachments: Procedure for running experiments
Emergency shutdown procedure

9.2 Training of operators

A document showing training plan for operators
What are the requirements for the training of operators?
- *What it takes to be an independent operator*
- *Job Description for operators*

Attachments*:* Training program for operators

9.3 Technical modifications

- Technical modifications made by the Operator
  o (for example: Replacement of components, equal to equal)
- • Technical modifications that must be made by Technical staff:
  o (for example, modification of pressure equipment).
- • What technical modifications give a need for a new risk assessment; (by changing the risk picture)?

Conclusion:
If some components fail and need to be changed, experiment will stop and technical staff will be contacted. If larger modifications are necessary, a new risk assessment will be carried out.

9.4 Personal protective equipment

- It is mandatory use of eye protection in the rig zone
- It is mandatory use of protective shoes in the rig zone.
- Use gloves when there is opportunity for contact with hot/cold surfaces.
- Use of respiratory protection apparatus

Conclusion:
Protective eyewear will be used at all times when the experiment is in progress. The goggles are found in two boxes in Laboratory: one box is placed just at the entrance (Entrance Door to Room 21 of the Waterpower Main Laboratory Section) and the other box is placed close to the emergency exit door to the main entrance of the Water power Laboratory. Since water is conductive, it is important to keep hands dry when working in the lab to minimize the risk of electric shock.

9.4.1 General Safety

- The area around the staging attempts shielded.
- Gantry crane and truck driving should not take place close to the experiment.
- Gas cylinders shall be placed in an approved carrier with shut-off valve within easy reach.
- Monitoring, can experiment run unattended, how should monitoring be?

Conclusion:
A barrier will be installed around the ELC, heating elements and generator during testing. The experiment should not be run without being attended by the operators. The operators should monitor the progress of the experiment at all times. The rotating shafts (turbine and generator shafts + belt drive) should not be touched and to avoid this, a cover has been installed. There is a possibility of water spillage on the floor (which is along one of the emergency escape routes in the Laboratory) and should it happen, then operators should mop the water spillage after the experiment. If spillage accumulates during the experiment, then the experiment should be stopped until the water is mopped. Electric operated vacuum water mopper is available in the Laboratory base floor where the experiment test rig is.

Is Operator allowed to leave during the experiment?

The operators cannot leave the test rig while this experiment is in progress. As already stated above, the operator should monitor the progress and pay attention to the quality of the experiment process at all times. If it happens that the experiment is not progressing as envisaged and that danger to the machine units (turbine and generator) and to operators is most likely, then the experiment should be stopped using the emergency shutdown procedure.

9.5 Safety equipment

- Warning signs, see the Regulations on Safety signs and signalling in the workplace

9.6 Special preparations

For example:

- Monitoring.
- Safety preparedness.
- Safe Job Analysis of modifications, (SJA)
- Working at heights
- Flammable / toxic gases or chemicals

10 QUANTIFYING OF RISK - RISK MATRIX

The risk matrix will provide visualization and an overview of activity risks so that management and users get the most complete picture of risk factors.

IDnr	Aktivitet-hendelse	Frekv-Sans	Kons	RV
1	*Rotating shaft and belt drive, danger of contact*	1	C	C1
2	*Much noise, people without protective gear enter the rig site*	1	A	B1
3	*Splashing water*	3	A	A3
4	*Overheating electronic equipment*	2	C	C2
5	Short circuits on electronic components	1	B	C1

Conclusion: The risks associated to this experiment are acceptable. The most risk-associated part of the experiment is the performance of the electronic components in the ELC. In order to reduce the risk according Idnr.4, the temperature inside the cabinet is measured and the operators have to pay attention if temperature changes rapidly. The fire extinguisher is located by the entrance door in the laboratory. To reduce risk according Idnr 1, a cover has been installed to avoid contact. All electronic components in the setup have been controlled by verified personnel. Nevertheless, it will always be a risk according short circuits in components since it is high voltage and components may change behaviour during the experiment.

11 REGULATIONS AND GUIDELINES

Se http://www.arbeidstilsynet.no/regelverk/index.html

- Lov om tilsyn med elektriske anlegg og elektrisk utstyr (1929)
- Arbeidsmiljøloven
- Forskrift om systematisk helse-, miljø- og sikkerhetsarbeid (HMS Internkontrollforskrift)
- Forskrift om sikkerhet ved arbeid og drift av elektriske anlegg (FSE 2006)
- Forskrift om elektriske forsyningsanlegg (FEF 2006)
- Forskrift om utstyr og sikkerhetssystem til bruk i eksplosjonsfarlig område NEK 420
- Forskrift om håndtering av brannfarlig, reaksjonsfarlig og trykksatt stoff samt utstyr og anlegg som benyttes ved håndteringen
- Forskrift om Håndtering av eksplosjonsfarlig stoff
- Forskrift om bruk av arbeidsutstyr.
- Forskrift om Arbeidsplasser og arbeidslokaler
- Forskrift om Bruk av personlig verneutstyr på arbeidsplassen
- Forskrift om Helse og sikkerhet i eksplosjonsfarlige atmosfærer
- Forskrift om Høytrykksspyling
- Forskrift om Maskiner
- Forskrift om Sikkerhetsskilting og signalgivning på arbeidsplassen
- Forskrift om Stillaser, stiger og arbeid på tak m.m.
- Forskrift om Sveising, termisk skjæring, termisk sprøyting, kullbuemeisling, lodding og sliping (varmt arbeid)
- Forskrift om Tekniske innretninger
- Forskrift om Tungt og ensformig arbeid
- Forskrift om Vern mot eksponering for kjemikalier på arbeidsplassen (Kjemikalieforskriften)
- Forskrift om Vern mot kunstig optisk stråling på arbeidsplassen
- Forskrift om Vern mot mekaniske vibrasjoner
- Forskrift om Vern mot støy på arbeidsplassen

Veiledninger fra arbeidstilsynet
se: http://www.arbeidstilsynet.no/regelverk/veiledninger.html

12 DOCUMENTATION

- Tegninger, foto, beskrivelser av forsøksoppsetningen
- Hazop_mal
- Sertifikat for trykkpåkjent utstyr
- Håndtering avfall i NTNU
- Sikker bruk av LASERE, retningslinje
- HAZOP_MAL_Prosedyre
- Forsøksprosedyre
- Opplæringsplan for operatører
- Skjema for sikker jobb analyse, (SJA)
- Apparaturkortet
- Forsøk pågår kort

13 GUIDANCE TO RISK ASSESSMENT TEMPLATE

Chapter 7 Assessment of technical safety.

Ensure that the design of the experiment set up is optimized in terms of technical safety.
Identifying risk factors related to the selected design, and possibly to initiate re-design to ensure that risk is eliminated as much as possible through technical security.
This should describe what the experimental setup actually are able to manage and acceptance for emission.

7.1 HAZOP

The experimental set up is divided into nodes (eg motor unit, pump unit, cooling unit.). By using guidewords to identify causes, consequences and safeguards, recommendations and conclusions are made according to if necessary safety is obtained. When actions are performed the HAZOP is completed.
(e.g. "No flow", cause: the pipe is deformed, consequence: pump runs hot, precaution: measurement of flow with a link to the emergency or if the consequence is not critical used manual monitoring and are written into the operational procedure.)

7.2 Flammable, reactive and pressurized substances and gas.

According to the Regulations for handling of flammable, reactive and pressurized substances and equipment and facilities used for this:

Flammable material: Solid, liquid or gaseous substance, preparation, and substance with occurrence or combination of these conditions, by its flash point, contact with other substances, pressure, temperature or other chemical properties represent a danger of fire.
Reactive substances: Solid, liquid, or gaseous substances, preparations and substances that occur in combinations of these conditions, which on contact with water, by its pressure, temperature or chemical conditions, represents a potentially dangerous reaction, explosion or release of hazardous gas, steam, dust or fog.
Pressurized : Other solid, liquid or gaseous substance or mixes having fire or hazardous material response, when under pressure, and thus may represent a risk of uncontrolled

emissions

Further criteria for the classification of flammable, reactive and pressurized substances are set out in Annex 1 of the Guide to the Regulations "Flammable, reactive and pressurized substances"
http://www.dsb.no/Global/Publikasjoner/2009/Veiledning/Generell%20veiledning.pdf
http://www.dsb.no/Global/Publikasjoner/2010/Tema/Temaveiledning_bruk_av_farlig_stoff_Del_1.pdf

Experiment setup area should be reviewed with respect to the assessment of Ex zone
• Zone 0: Always explosive atmosphere, such as inside the tank with gas, flammable liquid.
• Zone 1: Primary zone, sometimes explosive atmosphere such as a complete drain point
• Zone 2: secondary discharge could cause an explosive atmosphere by accident, such as flanges, valves and connection points

7.4 Effects on the environment

With pollution means: bringing solids, liquid or gas to air, water or ground, noise and vibrations, influence of temperature that may cause damage or inconvenience effect to the environment.
Regulations: http://www.lovdata.no/all/hl-19810313-006.html#6
NTNU guidance to handling of waste:http://www.ntnu.no/hms/retningslinjer/HMSR18B.pdf

7.5 Radiation

Definition of radiation

Ionizing radiation: Electromagnetic radiation (in radiation issues with wavelength <100 nm) or rapid atomic particles (e.g. alpha and beta particles) with the ability to stream ionized atoms or molecules.
Non ionizing radiation: Electromagnetic radiation (wavelength >100 nm), og ultrasound$_1$ with small or no capability to ionize.
Radiation sources: All ionizing and powerful non-ionizing radiation sources.
Ionizing radiation sources: Sources giving ionizing radiation e.g. all types of radiation sources, x-ray, and electron microscopes.
Powerful non ionizing radiation sources: Sources giving powerful non ionizing radiation which can harm health and/or environment, e.g. class 3B and 4. MR$_2$ systems, UVC$_3$ sources, powerful IR sources$_4$.
$_1$Ultrasound is an acoustic radiation ("sound") over the audible frequency range (> 20 kHz). In radiation protection regulations are referred to ultrasound with electromagnetic non-ionizing radiation. $_2$MR (e.g. NMR) - nuclear magnetic resonance method that is used to "depict" inner structures of different materials. $_3$UVC is electromagnetic radiation in the wavelength range 100-280 nm. $_4$IR is electromagnetic radiation in the wavelength range 700 nm - 1 mm.

For each laser there should be an information binder (HMSRV3404B) which shall include:
- General information
- Name of the instrument manager, deputy, and local radiation protection coordinator
- Key data on the apparatus
- Instrument-specific documentation

- References to (or copies of) data sheets, radiation protection regulations, etc.
- Assessments of risk factors
- Instructions for users
- Instructions for practical use, startup, operation, shutdown, safety precautions, logging, locking, or use of radiation sensor, etc.
- Emergency procedures
- See NTNU for laser: http://www.ntnu.no/hms/retningslinjer/HMSR34B.pdf

7.6 The use and handling of chemicals.

In the meaning chemicals, a element that can pose a danger to employee safety and health
See: http://www.lovdata.no/cgi-wift/ldles?doc=/sf/sf/sf-20010430-0443.html
Safety datasheet is to be kept in the HSE binder for the experiment set up and registered in the database for chemicals.

Chapter 8 Assessment of operational procedures.

Ensures that established procedures meet all identified risk factors that must be taken care of through operational barriers and that the operators and technical performance have sufficient expertise.

8.1 Procedure Hazop

Procedural HAZOP is a systematic review of the current procedure, using the fixed HAZOP methodology and defined guidewords. The procedure is broken into individual operations (nodes) and analyzed using guidewords to identify possible nonconformity, confusion or sources of inadequate performance and failure.

8.2 Procedure for running experiments and emergency shutdown.

Have to be prepared for all experiment setups.
The operating procedure has to describe stepwise preparation, startup, during and ending conditions of an experiment. The procedure should describe the assumptions and conditions for starting, operating parameters with the deviation allowed before aborting the experiment and the condition of the rig to be abandoned.
Emergency procedure describes how an emergency shutdown have to be done, (conducted by the uninitiated), what happens when emergency shutdown, is activated. (electricity / gas supply) and which events will activate the emergency shutdown (fire, leakage).

Chapter 9 Quantifying of RISK

Quantifying of the residue hazards, Risk matrix
To illustrate the overall risk, compared to the risk assessment, each activity is plotted with values for the probability and consequence into the matrix. Use task IDnr.
Example: If activity IDnr. 1 has been given a probability 3 and D for consequence the risk value become D3, red. This is done for all activities giving them risk values.
In the matrix are different degrees of risk highlighted in red, yellow or green. When an activity ends up on a red risk (= unacceptable risk), risk reducing action has to be taken

CONSE	QUENC	Svært alvorlig	E1	E2	E3	E4	E5
		Alvorlig	D1	D2	D3	D4	D5

	Moderat	C1	C2	C3	C4	C5
	Liten	B1	B2	B3	B4	B5
	Svært liten	A1	A2	A3	A4	A5
		Svært liten	Liten	Middels	Stor	Svært Stor
		PROBABILITY				

The principle of the acceptance criterion. Explanation of the colors used in the matrix

Colour		Description
Red		Unacceptable risk Action has to be taken to reduce risk
Yellow		Assessment area. Actions has to be considered
Green		Acceptable risk. Action can be taken based on other criteria

Attachment to Risk Assessment report

Cross flow turbine connected to ELC

Prosjektnavn	Crossflow Turbine connected to ELC
Apparatur	Crossflow Turbine and ELC
Enhet	NTNU
Apparaturansvarlig	Bård Brandåstrø
Prosjektleder	Torbjørn Nielsen
HMS-koordinator	Morten Grønli
HMS-ansvarlig (linjeleder)	Olav Bolland
Plassering	Waterpower Laboratory
Romnummer	Room 21
Risikovurdering utført av	Øystein Sveinsgjerd Hveem, Magni Fjørtoft Svarstad, Kristin Gjevik, Chiyembekezo Kaunda, Peter Joachim Gogstad, Bård Brandåstrø

TABLE OF CONTENTS

ATTACHMENT A: PROCESS AND INSTRUMENTATION DIAGRAM

Introduction

The following are listed in Attachment A to further describe experimental setup of the the Crossflow Turbine rig connected to the ELC.

Process and Instrument Diagram (PID)

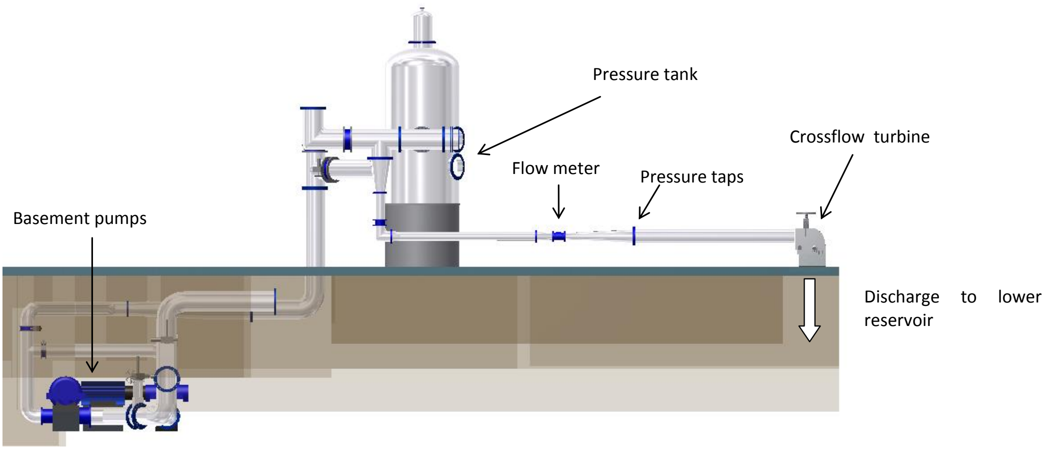


Figure 1: Waterflow system for the experiment showing arrangement and position of Crossflow Turbine rig with respect to pumps, pressurised tank and pipe network.

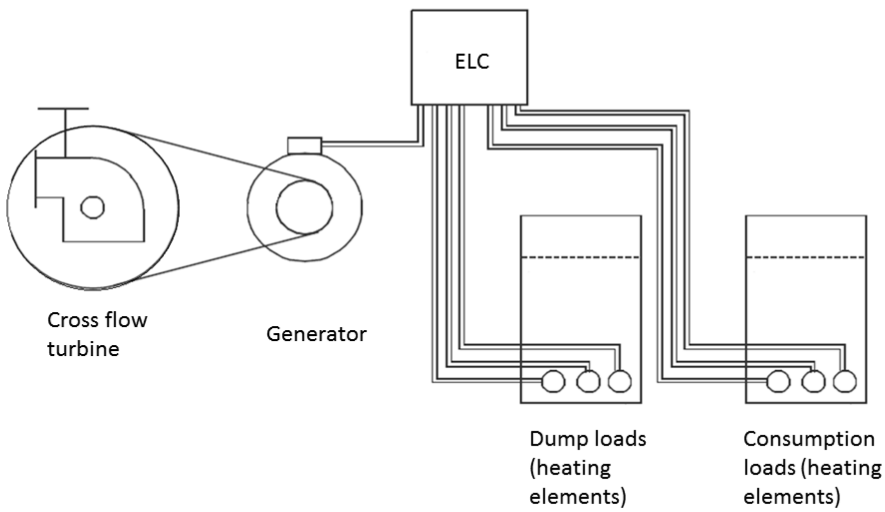


Figure 1: Principle of experimental setup

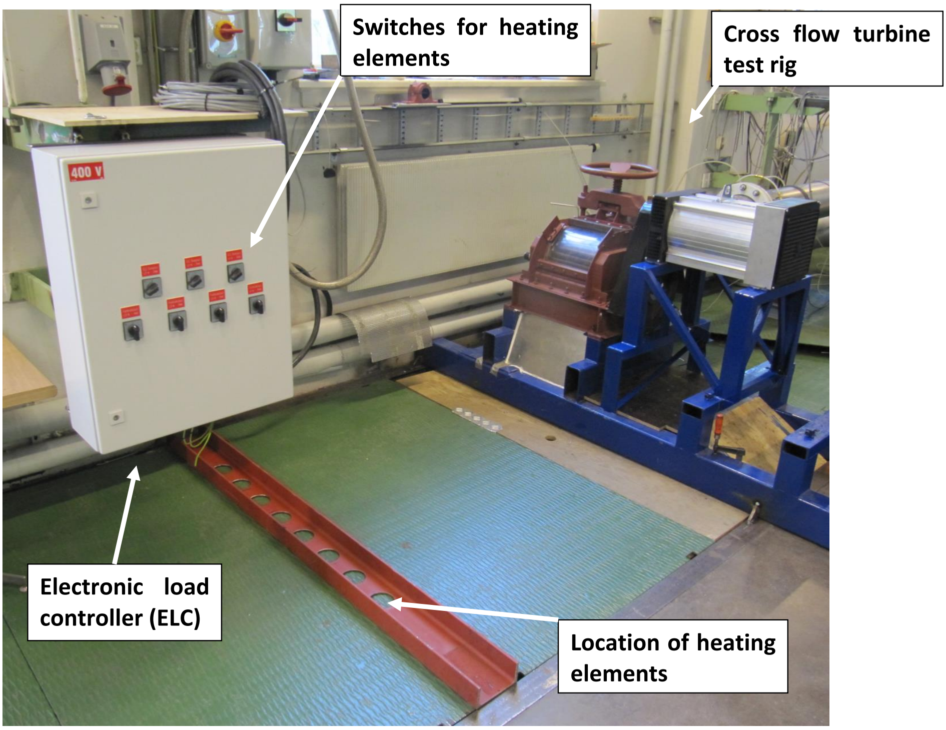


Figure 2: Cross flow turbine connected to ELC with 7 heating elements submerged in lower reservoir.

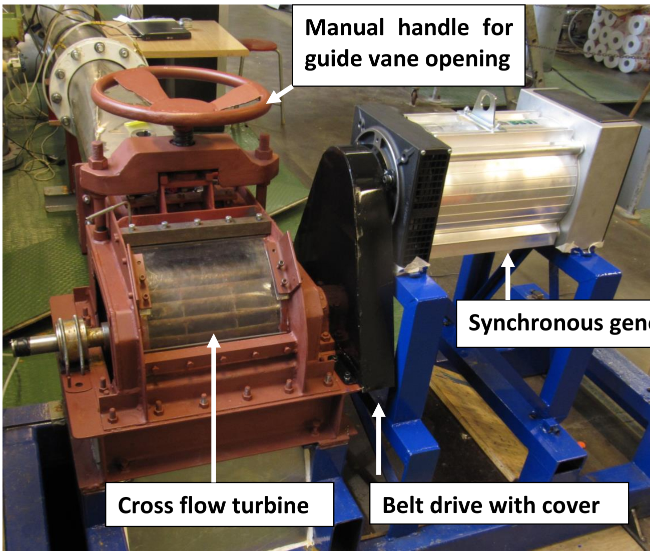


Figure 2: Experimental setup: Cross flow turbine test rig

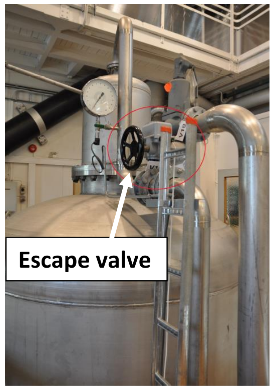


Figure 3: Escape valve on top of pressure tank

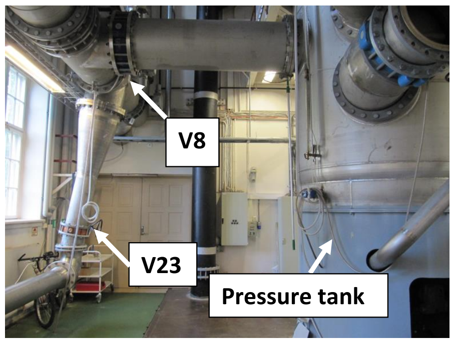


Figure 4: Part of the piping network to the Cross flow Turbine Test Rig showing manual operated valve V23 and valve V8.

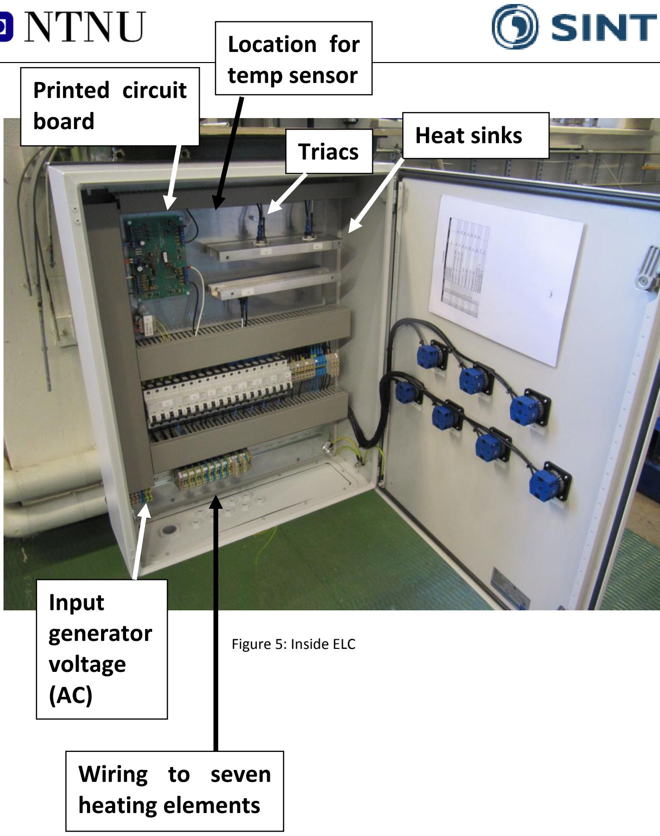


Figure 5: Inside ELC

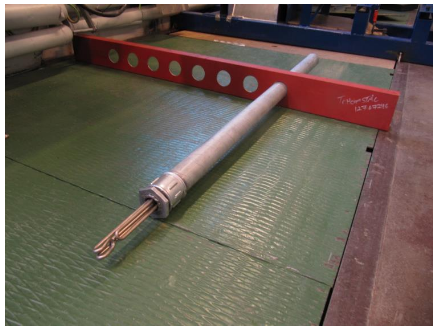


Figure 6: Setup of heating elements

Figure 7: Heating element

Figure 8: Installed electromagnetic flow rate meter.

Figure 9: Temperature measurement for water

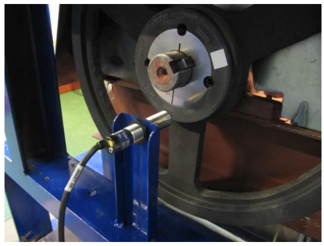


Figure 10: Optical measurement of turbine speed

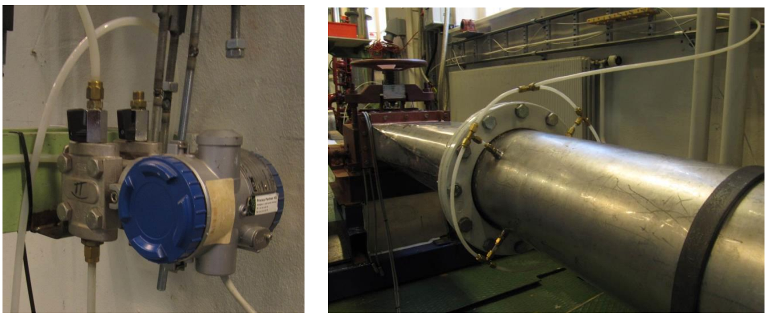


Figure 11: Pressure taps installed perpendicular to the pipe at the entrance of the turbine. Notice the tubes carrying water to the pressure transducer. The when the experiment is running, the tube must be checked of presence of air bubbles. Presence of air bubbles in water in the tube affects the quality of pressure signal from the transducer and gives incorrect differential pressure. The entrained air bubbles are removed from the tubes by bleeding.

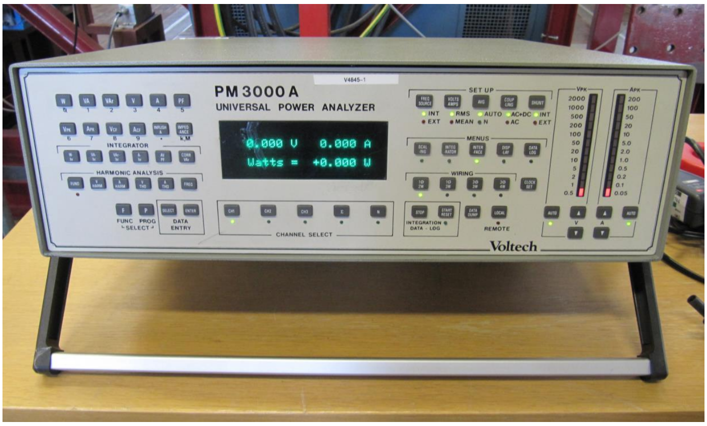


Figure 12: Instrument used for measuring voltage and current. From these values, power output is determined.

Figure 13: Amp clamp meter used together with Voltech PM3000A

Attachment B: HAZOP template

Project: Cross flow turbine connected to ELC **Node: 1 – Pressure tank**						**Page** 1	
Ref	**Guideword**	**Causes**	**Consequences**	**Safeguards**	**Recommendations**	**Action**	**Date/Sign**
	No flow	Closed valve	No consequence		Open valve		
	Reverse flow	High pressure in the tank			Increase pump speed		
	More level	Too high pump speed		Overflow pipe line in the pressure tank is installed			
	Less level	Low pump speed					
	More pressure	Too high pump speed					
	Less pressure	Low pump speed					
	Loss of pump power		No flow				

Project: Cross flow turbine connected to ELC Node: 2 – Crossflow turbine rig with generator						Page 2	
Ref	**Guideword**	**Causes**	**Consequences**	**Safeguards**	**Recommendations**	**Action**	**Date/Sign**
	No flow	Closed valve	No consequence		Open screw valve		
	Reverse flow	Not possible					
	More flow	Too high pump speed	Increased flow leakage to the floor		Reduce pump speed.		
	Less flow	Low pump speed					
	More pressure	Too high pump speed	Increased flow leakage to the floor		Reduce pump speed		
	Less pressure	Low pump speed					
	Loss of pump power		No flow				
	Loss of load	Generator disconnected	Rotational speed of turbine increases	Emergency switch for disconnecting the pump is installed	Reduce pump speed gradually and stop the pump		

Project: Cross flow turbine connected to ELC Node: 3 – ELC						Page 3	
Ref	**Guideword**	**Causes**	**Consequences**	**Safeguards**	**Recommendations**	**Action**	**Date/Sign**
	Temperature in ELC increases rapidly	Short circuit or too bad ventilation	Overheating and damaging electronic components	Fire extinguisher is located close to the test rig	Use emergency shutdown switch if critical	Stop experiment. Open ELC-cabinet and look for damaged components	
	Smell of burning	Overheating or short circuits of electronic components	Damage electronic components	Fire extinguisher is located close to the test rig	Use emergency shutdown switch if critical	Stop experiment. Open ELC-cabinet and look for damaged components	
	Fuses to heating elements brakes	Possibly short circuit on heating element terminal				Stop experiment and control heating element	
	Fuses between generator and ELC brakes	Possibly overvoltage from generator	Load disconnected and turbine speed increases rapidly	Emergency switch for shutdown pump is installed		Stop experiment by reducing pump speed and close valves.	

Project: Cross flow turbine connected to ELC Node: 4 – Heating elements						Page 4	
Ref	**Guideword**	**Causes**	**Consequences**	**Safeguards**	**Recommendations**	**Action**	**Date/Sign**
	Dryheating	Low waterlevel in reservoir	Damage elements		Stop experiment and control level in reservoir.	Submerge element	
	Short circuit on terminal	Moisture/water leakage into terminals	Elements stop heating			Stop experiment	

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ATTACHMENT C: TEST CERTIFICATE FOR LOCAL PRESSURE TESTING

Trykkpåkjent utstyr:	
Benyttes i rigg:	
Design trykk for utstyr (bara):	
Maksimum tillatt trykk (bara): (i.e. burst pressure om kjent)	
Maksimum driftstrykk i denne rigg:	

Prøvetrykket skal fastlegges i følge standarden og med hensyn til maksimum tillatt trykk.

Prøvetrykk (bara):			
X maksimum driftstrykk: I følge standard			
Test medium:			
Temperatur (°C)			
Start tid:		Trykk (bara):	
Slutt tid:		Trykk (bara):	
Maksimum driftstrykk i denne rigg:			

Eventuelle repetisjoner fra atm. trykk til maksimum prøvetrykk:…………….

Test trykket, dato for testing og maksimum tillatt driftstrykk skal markers på (skilt eller innslått)

Sted og dato Signatur

ATTACHMENT D: HAZOP PROCEDURE (TEMPLATE)

Project: **Node: 1**						**Page**	
Ref#	**Guideword**	**Causes**	**Consequences**	**Safeguards**	**Recommendations**	**Action**	**Date/Sign**
	Not clear procedure	Procedure is to ambitious, or confusingly					
	Step in the wrong place	The procedure can lead to actions done in the wrong pattern or sequence					
	Wrong actions	Procedure improperly specified					
	Incorrect information	Information provided in advance of the specified action is wrong					
	Step missing	Missing step, or step requires too much of operator					
	Step unsucessful	Step has a high probability of failure					
	Influence and effects from other	Procedure's performance can be affected by other sources					

ATTACHMENT E: PROCEDURE FOR RUNNING EXPERIMENTS

Prosjekt Crossflow Turbine	**Dato/Signatur**
Apparatur Crossflow Turbine	
Prosjektleder Torbjørn Nielsen	
Operatører: Øystein Sveinsgjerd Hveem	
Magni Fjørtoft Svarstad	
Kristin Gjevik	
Chiyembekezo Kaunda	

	Conditions for the experiment:	**Completed**
	Experiments should be run in normal working hours, 08:00-16:00 during winter time and 08.00-15.00 during summer time. Experiments outside normal working hours shall be approved.	
	One person must always be present while running experiments, and should be approved as an experimental leader.	
	An early warning is given according to the lab rules, and accepted by authorized personnel.	
	Be sure that everyone taking part of the experiment is wearing the necessary protecting equipment and is aware of the shutdown procedure and escape routes.	
	Preparations	**Carried out**
	1. Make a walk-through inspection in the laboratory, paying attention to any hazard. Clear all of the identified hazards before starting the experiment. Close all drain pipes. Check that all instrumentations to the rig are intact. Open the ELC cabinet and look for any changes in components (smell of burning, open wires etc.). Set up barriers around experimental setup. Control the level in the lower reservoir and verify that all heating elements are submerged. In the control room, check that there are no alerts in the lab. 2. If no extraordinary hazards are observed, the experiment is ready to be started. Turn on the frequency converter for the pump located in the pump room in the basement. Turn the switch to **START**. Keep it there for a while (a second or so) and then let it go so that it stops at position marked **1**. 3. On the Cross flow Turbine test rig, post the “Experiment in progress” card.	

Start up procedure

Filling the pressure tank

1. Check that the annular valve is closed at the bottom of the pressure tank. Also check that the manual valve to the Crossflow turbine V23 is closed.
2. **Control room**: use the PLC and identify the loop to use for the Crossflow turbine test rig. Check that valves V9 and V29 are closed.
3. Check the water level in the pressure tank.
4. Open the manual valve on top of the pressure tank
5. Startup pump using the PLC in the control room by gradually increasing the speed to about 325 rpm. Check the water level as the pump is running. When the water the level has stabilized at the set point, then close the manual valve on top of the pressure tank.

Startup Crossflow turbine and ELC

1. Go down to the Cross flow turbine test rig. Launch the LabView Program – "CrossflowTurbine" on the main computer and "ELC_Logging" on the second computer.
2. Switch the dump loads ON
3. Check that the guide vane on the Cross flow turbine is open. Open valve V8 (out from pressure tank) using the PLC. Open the manual valve V23 slowly in order to get a smooth acceleration of the turbine. Bleed the pipes for the pressure transducer while the turbine is running.
4. Start choosing an operational point for the cross flow turbine, by changing (head and cross flow guide vane opening). The ELC has a capacity of 6kW so the two parameters; pump speed and nozzle opening, have to be set rather low to avoid damage on the ELC. An operational point with a net head of 5m, nozzle opening of 80% and a rotational speed on the cross flow turbine of 400-450 RPM is used in order to get a power output of 6kW. Guide vane opening is set by using the manual valve (on top of the cross flow turbine) to the marked opening (percentage value). Rotational speed of the turbine is set with pump speed and flow.
5. The rig is now ready for doing measurements.

	Experiment	
	Controlling LEDS and components 1. Check that all of the three large LED lights. These monitor that the three phases on the generator are connected. 2. Reset the fuses. All energy should then still be diverted into the dump loads. (Since consumption load is 0) 3. Switch on more consumption loads and control that all the four small LEDs are working properly. 4. Run with only dump loads connected for two hours and look for overheating and failure in components. **Rapid off-load-situation** 1. Switch on 6 kW consumption loads. 2. Switch all consumption loads off. Log response in generator voltage. **Rapid on-load-situation** 1. Keep only dump loads connected (6kW). 2. Switch 6 kW consumption loads on. Log response in generator voltage. **Overload situation** 1. Switch on 6kW consumption loads. 2. Switch on the extra 1kW heating element and log response in voltage **Run-away situation** 1. Switch off all consumption loads. 2. Brake fuses from generator and simulate a disconnection of load to generator. 3. When a constant speed is obtained, reduce the pump speed and do the stop procedure.	

	Measurements 1. From the LabView-program "ELC_Logging" , generator voltage, dump load voltage, trigger angle and frequency are measured and logged during the experiments. In "CrossflowTurbine" , hydraulic power is obtained from logged values of discharge, water temperature and pressure.	
	Shutdown procedure	
	1. Reduce the pump speed slowly to 320 RPM by a decrease of 10 rpm 2. Close V8 from pressure tank. 3. When pipes in cross flow loop are empty for water: Close V23 manually 4. Check for over-pressure in the pressure tank 5. Open the manual valve on top of the pressure tank 6. Reduce the pump speed further to 100 rpm by a decrease of 10. 7. Stop the pump 8. Stop the frequency converter by turning the switch to **0**	
	End of experiment	
	1. Tidy and cleanup work areas and equipment. 2. Remove all obstructions/barriers/signs around the experiment. 3. Return equipment and systems back to their normal operation settings	
	Emergency Shutdown procedure	
	If an emergency situation arises, switch off the power to the pump using the emergency switch which is located inside the Control Room or using the emergency switch that is located in the base floor close to the pressure transducer.	
	To reflect on before the next experiment and experience useful for others	
	Was the experiment completed as planned and on scheduled in professional terms?	
	Was the competence which was needed for security and completion of the experiment available to you?	
	Do you have any information/ knowledge from the experiment that you should document and share with fellow colleagues?	

ATTACHMENT F: TRAINING OF OPERATORS

Prosjekt Crossflow Turbine	**Dato/Signatur**
Apparatur Crossflow Turbine and Electronic Load Controller	
Prosjektleder Torbjørn Nielsen	

	Knowledge about EPT LAB in general	
	Lab - Access -routines and rules -working hour	
	Knowledge about the evacuation procedures.	
	Activity calendar for the Lab	
	Early warning, **Liste iept-experiments@ivt.ntnu.no**	
	Knowledge about the experiments	
	Procedures for the experiments	
	Emergency shutdown.	
	Nearest fire and first aid station.	

I hereby declare that I have read and understood the regulatory requirements has received appropriate training to run this experiment and are aware of my personal responsibility by working in EPT laboratories.

Name	Signature
Øystein Sveinsgjerd Hveem	
Magni Fjørtoft Svarstad	
Chiyembekezo Kaunda	

ATTACHMENT G: FORM FOR SAFE JOB ANALYSIS

SJA name:		
Date:		Location:
Mark for completed checklist:		

Participators:		
SJA-responsible:		

Specification of work (What and how?):
Risks associated with the work:
Safeguards: (plan for actions, see next page):
Conclusions/comments:

Recommended/approved	**Date/Signature:**	**Recommended/approved**	**Date/Signature:**
SJA-responsible:		HSE responsible:	
Responsible for work:		Other, (position):	

HSE aspect	Yes	No	NA	Comments / actions	Resp.
Documentation, experience, qualifications					
Known operation or work?					
Knowledge of experiences / incidents from similar operations?					
Necessary personnel?					
Communication and coordinating					
Potential conflicts with other operations?					
Handling of an eventually incident (alarm, evacuation)?					
Need for extra assistance / watch?					
Working area					
Unusual working position					
Work in tanks, manhole?					
Work in ditch, shaft or pit?					
Clean and tidy?					
Protective equipment beyond the personal?					
Weather, wind, visibility, lighting, ventilation?					
Usage of scaffolding/lifts/belts/ straps, anti-falling device?					
Work at hights?					
Ionizing radiation?					
Influence of escape routes?					
Chemical hazards					
Usage of hazardous/toxic/corrosive chemicals?					
Usage of flammable or explosive chemicals?					
Risk assessment of usage?					
Biological materials/substances?					
Dust/asbestos/dust from insulation?					
Mechanical hazards					
Stability/strength/tension?					
Crush/clamp/cut/hit?					
Dust/pressure/temperature?					
Handling of waste disposal?					
Need of special tools?					
Electrical hazards					
Current/Voltage/over 1000V?					
Current surge, short circuit?					
Loss of current supply?					
Area					
Need for inspection?					
Marking/system of signs/rope off?					
Environmental consequences?					
Key physical security systems					
Work on or demounting of safety systems?					
Other					

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APPARATURKORT / UNITCARD

Dette kortet SKAL henges godt synlig på apparaturen!
This card MUST be posted on a visible place on the unit!

Apparatur (Unit) Cross flow turbine connected to ELC	
Prosjektleder (Project Leader) Torbjørn Nielsen	**Telefon mobil/privat** (Phone no. mobile/private) 91897572
Apparaturansvarlig (Unit Responsible) Bård Brandåstrø	**Telefon mobil/privat** (Phone no. mobile/private) 91897257
Sikkerhetsrisikoer (Safety hazards) • Splashing Water • Rotating equipment • Overheating of electronic components • Short circuits on components	
Sikkerhetsregler (Safety rules) • Set up barriers • Wear safety glasses • Do no touch rotating shaft	
Nødstopp prosedyre (Emergency shutdown) Shut down feed pumps. The Emergency switch located in the Main Laboratory Control Room and in the Laboratory First Floor	

Her finner du (Here you will find):

Prosedyrer (Procedures)	In a Laboratory Book
Bruksanvisning (Users manual)	In a Laboratory Book

Nærmeste (Nearest)

Brannslukningsapparat (fire extinguisher)	Near the entrance\exit
Førstehjelpsskap (first aid cabinet)	Near the entrance\exit

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Signert ______________________________

FORSØK PÅGÅR /EXPERIMENT IN PROGRESS

Dette kortet SKAL henges opp før forsøk kan starte!
This card MUST be posted on the unit before the experiment startup!

Apparatur (Unit) Cross flow turbine connected to ELC	
Prosjektleder (Project Leader) Torbjørn Nielsen	**Telefon mobil/privat** (Phone no. mobile/private) 91897572
Apparaturansvarlig (Unit Responsible) Bård Brandåstrø	**Telefon mobil/privat** (Phone no. mobile/private) 91897257
Godkjente operatører (Approved Operators) Øystein Sveinsgjerd Hveem, Magni Fjørtoft Svarstad, Kristin Gjevik, Chiyembekezo Kaunda	**Telefon mobil/privat** (Phone no. mobile/private) 99406075 41641665 98809726 40299725
Prosjekt (Project) Crossflow Turbine connected to ELC	
Forsøkstid / Experimental time (start - stop) 05.09.2013 - 30.09.2013	
Kort beskrivelse av forsøket og relaterte farer (Short description of the experiment and related hazards**)** The experiment is analyzing the performance of an electronic load controller in connection with a cross flow turbine and a generator. The related hazards are: • Water splash • Rotating shaft • Overheating of electronic components • Short circuits on electronic components	

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