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Investigation of the Doubly Fed Permanent Magnet Synchronous Machine

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Problem Description

In renewable energy the Permanent Magnet Synchronous Machine (PMSM) is suggested for usage in a range of applications. The compactness and efficiency of the PMSM is the main motivation for introduction in this marked sector. The main drawback for the PMSM is that it usually need a full rated converter in order to interface to the grid. A novel system named Doubly Fed PMSM (DF-PMSM) has been introduced from the company SmartMotor AS. This concept reduces the need for full size converters as only a part of the windings are connected via the converter while the rest of the windings are directly coupled to the grid.

The master thesis involves patent search, state of the art section, simulations and conceptual validation by laboratory work. As this is a novel concept the student will have to develop new models to be able to simulate. Also a laboratory setup must be established to do the validation.

Assignment given: 25. January 2009
Supervisor: Tore Marvin Undeland, ELKRAFT

1 Table of contents

2 Preface

This is a master thesis at the Norwegian University of Science and Technology in Trondheim, NTNU. This follows the work from the specializing project, autumn 2008. The master thesis is prepared for the title Master of Technology.

The project treats the patenting and testing process of a novel "generator with converter concept". This technology is named "Doubly-Fed Permanent Magnet Synchronous Machine", DF-PMSM, and is based on connecting two sets of three phases from one generator to increase controllability of the Permanent Magnet Synchronous Generator.

The first winding set is named "control winding" and is routed through a converter with active-front-end rectifier. It will be used to control the power factor of the output from the machine. The other winding set is named "power winding" and will carry most of the generated power, directly coupled and in sync with the voltages of the connected grid.

Prior to the master thesis there was a specializing project during autumn 2008 that started on developing this doubly fed generator with converter topology. In the specializing project the emphasis was research into similar technology that could conflict with patent interests and give a hint to what path to choose and what problematic areas to expect when working with doubly fed and multiphase machines. The patent of the design was filed as a result of work in the specializing project and is under the process of becoming accepted during the master thesis period spring/summer 2009.

Following up the specializing project, the master thesis is to include a case where the concept is compared to the alternatives of today, a machine simulation and a lab to provide an insight to what can be expected of this design. The case will compare this design to a regular generator configuration and compare price and other technical aspects like size and efficiency.

The DF-PMSM is developed with help from SmartMotor in Trondheim, Norway, which owns the patent of this machine.

I would like to use this opportunity to thank the following people for helping me in the project period:

Prof. Tore Undeland at NTNU

Dr. Ing Sigurd Øvrebø, Dr. Ing. Richard Lund, Dr. Ing Tore Skjellnes, Eirik Elvestad, Svein Erik Evju and the rest of the employees of SmartMotor for tips and help during the project period.

3 Summary

This master thesis treats the research of a novel “generator with converter” design called “Doubly Fed Permanent Magnet Synchronous Machine”, DF-PMSM, patented by SmartMotor. The thesis includes an introduction to the machine, a state-of-the-art survey, a hydro power case, simulations and a laboratory experiment. The DF-PMSM concept adds an important feature to fixed speed PMSM systems; the reactive power can be regulated. Compared to a direct coupled PMSM the DF-PMSM concept can add voltage control (by controlling the reactive power) in addition to active power control.

The concept is based on a 6-phase Permanent Magnet Synchronous Machine where the windings are grouped into two sets of 3-phase, both situated in the stator. These winding sets are named “control” and “power” winding, named after their purpose in the design. The “control winding” is routed through a converter with active-front-end rectifier. It will be used to control the reactive power and the active power from the control winding. The “power winding” will carry most of the generated power, directly coupled and in sync with the voltages of the connected grid.

The state-of-the-art survey includes constant speed and variable speed generators utilized in hydro power generation today. It also includes some general info about doubly fed and multiphase machines. The grid regulations for Norway are also investigated to give a pointer to what requirements that the DF-PMSM needs to fulfill to be connected to the grid.

The machine simulations are done in LTspice where machine simulation models are developed for this purpose. Simulation of machine startup and changes is load is done. The simulation models are developed as hierarchical sub blocks that can be re used in later simulation cases.

The laboratory is done with two machines in back-to-back configuration with industry standard converters. The DF-PMSM is made from a 3-phase permanent magnet machine that is rewired to a 6-phase configuration. The laboratory exercise includes start up, synchronization of the power winding to the grid, machine loading and reactive power compensation by the active front end converter.

The DF-PMSM is confirmed working and design considerations are given based experience gained from working with this design. All of this information is included in this report and the further work needed before this machine is constructed and sold is sketched in the conclusion.

4 Introduction

4.1 Status

The world needs more energy to be able to satisfy the power demands of an ever expanding global wealth. At the same time global heating makes it important to shift from power production by burning fossil fuels to clean renewable alternatives. This increases the importance of researching new energy alternatives and optimizing already well known designs to raise the efficiency overall and increase the world's electric power supply.

Research into novel methods of taming nature, like the utilization of offshore windmills, wave or tidal power, etc. can be one method of attacking this problem. All of these are new and interesting ways of producing electrical power and has great potential if they are economically and technological feasible to develop and operate. There is always the danger of not knowing if it is going to work in a big scale and this kind of research is often projects with a long development period where it is planned to profit from the work when the design is found viable.

Instead of developing new concepts it can be advantageous considering optimizing already well known designs, which often can be achieved in a shorter development period. The design presented in this report, the "Doubly Fed Permanent Magnet Synchronous Machine"[1] is one of those concepts, bringing a cheaper and controllable alternative to the hydro power generation industry. This report aims to increase the knowledge around this design and include important aspects when designing the optimal DF-PMSM generator and to show that the concept works.

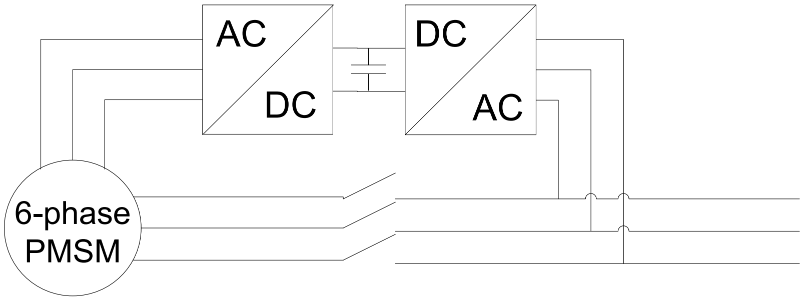

FIGURE 1: DOUBLY FED PERMANENT MAGNET SYNCHRONOUS GENERATOR

The concept is based on a 6-phase or higher Permanent Magnet Synchronous Machine[2] where the windings are grouped into two sets of 3-phase, both situated in the stator, as seen in Figure 1. These winding sets are named "control" and "power" winding, named after their purpose in the design. These names are used to describe the same windings in the Brushless Doubly Fed Induction Machine (see chapter 7.2.3) and transferred to this type of design to keep consistency.

The power winding is going to be directly coupled to the grid, carrying most of the power generated. The control winding will run through a converter with active front end rectifier to be able to manipulate the reactive power from the machine, and therefore changing the voltage

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[1] Known as DF-PMSM from here on out

[2] Known as PMSM from here on out

amplitude[3]. This way it is possible to have one of the most effective generator alternatives with the possibility to control the power factor in a limited range[4] and possibly have the ability to counteract fast transient voltage disturbances on the grid, in a cheap and good manner depending on the converter and controller.

This design aims to compete in the hydro power generation market against the synchronous and asynchronous generator alternatives. This is because the generator is operated synchronously with the connected grid frequency when the power winding is connected, and turns at a constant mechanical speed.

To know this designs viability it is necessary to do some searches into previously research technology in this field to see if there is some valuable information that can be taken into account when planning the design of this generator. This work was started in the specializing project autumn 2008 and has been refined in the master thesis.

To investigate the machines capability a machine lab as well as computer simulations is important. The simulations will be done in a Spice [1] based simulation tool where as the machine models and needed tools must be developed prior to starting the simulations. They will give a general impression of the machine and how it should be controlled and designed.

The laboratory work is done at SmartMotor, Trondheim and is based on two machines in a back-to-back configuration where one of the machines will serve as a “turbine” running the generator machine at different loads etc.

The predictions for this machine are based on previous experience working with these kinds of machines at SmartMotor. The idea behind this design origins from SmartMotor, and has been patented during the specializing project period.

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[3] The concept of being dependent of having both converter and machine to function will be addressed as one machine or generator from here on and out.

[4] The voltage range is limited by the size and configuration of both converter and machine.

4.2 Outline of work

This chapter will serve as an overview to what work has been done during the project period including the specializing project period starting autumn 2008. The work includes:

- Patenting the DF-PMSM machine including search for prior patents as well as papers on the machine and similar designs.
- State-of-the-art study that includes doubly fed machines and regular fed machines to build knowledge about multiphase and especially doubly fed machines and the other alternatives in hydro power generation today.
- Investigate the grid regulations in Norway
- Propose a machine/converter setup based on the grid regulations in Norway today
- Case study comparing this generator to the already existing alternatives.
- Development of machine models and tools for machine simulation in LTspice[2].
- Simulations of the DF-PMSM in different operations.
- Development of a lab with SmartMotor machines and industry standard converters.
- Laboratory exercise with the DF-PMSM in a back-to-back configuration.

4.3 Chapter overview

Chapter 4 introduces the reader to the DF-PMSM concept and the layout of this report and what is done during the project period.

Chapter 5 and 6 discusses the DF-PMSM and what is hoped by introducing it as a new generator to the hydro power generation market.

Chapter 7 shows the existing generators available today that can be used in a hydro power plant

Chapter 8 deals with the grid regulations in Norway that the DF-PMSM must fulfill to be allowed to be connected to the grid and put into operation.

Chapter 9 compares the DF-PMSM to the alternatives mentioned in Chapter 7 and defines the simulation and lab experiments

Chapter 10 and 11 treats the planning and construction of the simulation and lab experiments

Chapter 12 and 13 displays and discusses the results from the simulation and lab

Chapter 14 concludes the project

5 DF-PMSM

This chapter explains the DF-PMSM in detail so it is possible to follow the report without previous knowledge about doubly fed and multiphase machines. This chapter will discuss the technical solutions and some considerations taken when designing the machine. Chapter 6 will deal with the motivational aspects of what can be expected when researching the DF-PMSM.

The proposed design is based on a 6-phase permanent magnet synchronous machine with two sets of 3-phases named control and power winding, ref Figure 1. The windings are situated in the machine stator and the rotor consists of permanent magnets like in the traditional PMSM. When both the control and power winding is situated in the machine stator it is called doubly fed.

The power winding is directly coupled to the grid with the purpose to carry most of the generated power, and is also the reason why it is necessary to run the machine at constant speed. The control winding is routed through a converter with an active-front-end rectifier to be utilized as control power to alter the voltage amplitude at the machine terminals by altering the power factor of the total produced power of both sets of windings.

The operation of the DF-PMSM is not similar to the "Brushless Doubly Fed Induction Machine"[5] that runs asynchronously and has a much wider application area but not that great efficiency as the DF-PMSM. The fact that the DF-PMSM is synchronous and directly connected to the grid trough the power winding makes it impossible to operate at variable speed. The machine will run in synchronism with the grid when the power winding is connected, but it is possible to operate the machine using only the control winding allowing variable speed, typically used when starting and synchronizing the power winding to the grid.

The synchronization to the grid is proposed as starting the machine only on the control windings, running the machine on the converter up to the correct frequency (50 Hz in Norway). Then it is important that the machine runs at the same speed and that the phases that are connected to the grid are in phase with the machine windings back emf voltages. This is checked using a "synchroscope" sensing the voltages in all three phases in both machine and grid. When they are in phase the machines power windings can be connected.

The "control winding" can have smaller size than the "power winding" because it is supposed to carry less power. The size the control windings compared to the power winding are depending on how much controllability that is wanted and what is feasible considering problems with lower machine efficiency.

The rating of the control winding and converter is depending on how much controllability that is necessary to satisfy the grid demands, and will be based on the grid connection guidelines [3] published by the Distribution System Operator (DSO) in Norway.

The converter/winding rating is much larger than needed, to be able to complete the research even if it appears problems considering the size during the project period. As learned from the state of the art study in the specializing project, multiphase machines have problems with over harmonic content compared to regular 3 phase machines. This difference might give problems to

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[5] Read more about the BDFIM in chapter 7.2.3

the machine efficiency as well as other unforeseen problems that might appear during the testing process.

The machine design referred to in this report is based on the machine used in the laboratory exercise. This machine has a 60 degree angle between all the phases in the 6-phase configuration as seen in Figure 2. Here –C means control winding and –P means power winding.

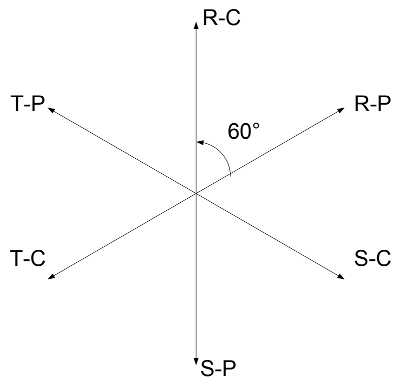

FIGURE 2: MACHINE PHASE LAYOUT

Even though this report is discussing the concept of a generator, the DF-PMSM can be used for several other applications. For example it can be used as a motor for ship propulsion. It can be installed on ships having pitch-able propellers. The machine can be started with pitched out propeller on the power of the control winding up to synchronous speed. When the machine has reached synchronous speed the power winding is engaged giving the motor max torque capabilities. Then the vessel speed can be controlled by alternating the pitch of the propeller. A possible problem area is that the power winding needs AC-currents to operate because of the lack of a converter. This can of course be circumvented using a DF-PMSM as the generator.

This way it is possible to achieve a motor with high efficiency and small size for small and big vessels. The gains from doing it this way is that the converter can be much smaller and the machine efficiency higher. The reduction in converter size makes the converter take less space onboard the vessel.

As previously shown there can be many other good uses of this machine layout, and the one proposed in this report, a generator, is one. How much interest that should be put into this machine will rely heavily on what results that this report finds about how the machine handles the tasks it is put trough.

6 Motivation

This chapter will discuss the features of the "Doubly Fed Permanent Magnet Synchronous Machine" and serves as a motivation for why this work is important and what is hoped by introducing it as an alternative to today's generators. It is written based on the knowledge gained in the specializing project and will therefore assume some machine characteristics. When more of the machine is exposed, the road will be shorter to expanding this technology further.

Since the DF-PMSM is based on a PMSM, the machine itself will be small and efficient. The permanent magnets in the rotor ensure this since there are no magnetizing currents in the rotor that generates losses and no brushes/slip rings to feed these currents. The size of a regular synchronous machine rotor is larger than the usual permanent magnet rotor and that will have an effect on the whole machine size.

If the converter connected to the control winding can be reduced, the cost and losses with converter will be reduced in comparison to a full converter. The reduction in cost can make this machine a cheap controllable alternative. The generator can be competitive to the voltage regulation capabilities of regular magnetization equipment both in transient as well as stationary voltage deviations. The converter will only supply the extra needed reactive power to get the correct power angle output from the machine but can also supply extra active power.

The losses that appear because of the complex layout of the machine phases and the losses in the converter can compete against the losses of the magnetization equipment of the synchronous machine. In case of the asynchronous machine it will compete against the lower efficiency of the generator and losses in the compensational equipment.

The DF-PMSM has the possibility to be sold as a kit machine where the converter is a part of the machine design and therefore being more streamlined to install and operate. There is one problematic area considering kit-machine design that this machine is operated synchronous and therefore must run at the machines specified speed. The machine mechanical speed is changed through altering the pole count in the machine making it necessary to offer more than one generator. Hydro turbines operate at different speeds depending on the turbine type utilized or other location specific issues.

If this concept is economically and technically feasible it can have an impact on which machines will be used in smaller hydro power plants if it is put into production. In addition to get a reduction in price it will contribute to keep high voltage quality. This really important in small hydro power stations that are often connected in the low-voltage parts of the grid (distribution grid) that is more vulnerable to poor voltage quality because of the long transmission lines between the small power plant and the higher voltage regional or central grid. The voltage quality is also more critical nearer the end consumer.

Other opportunities considering motoring disciplines for example ship propulsion as mentioned in chapter 6 makes it interesting to see this machines capabilities in an even broader perspective.

To summarize are the foreseen features of this machine:

- High efficiency because of less current trough converter and efficient permanent magnet machine.
- Smaller size due to smaller converter and small size of permanent magnet machine compared to regular synchronous machines.
- Low price because of smaller rated converter makes it affordable even though the Permanent Magnet Machine costs more than a regular synchronous machine.
- Can be manufactured as one unit with the converter already assembled to the machine to streamline operation and installation of hydro power plant generators.
- Possible to connect anywhere in the grid because of good compensational abilities.
- Competitive pricing will make this the best alternative for hydro power generation.
- Transient voltage deviation correction.

7 State-of-the-art

To support the case study it is important to know what competing technology exist today and what positive aspects as well as problematic areas these technologies represent. This chapter is written to summarize the available technologies, lesser or well known. This chapter will also show what research considering doubly fed machines that has been done prior to the case study in chapter 9.

The DF-PMSM is a constant speed machine and it has to operate at a speed proportional to the frequency of the grid it is connected. Because of this the chapter starts with constant speed generator alternatives, but also discuss variable speed generators that in the later years have been examined more closely as an alternative in hydro generation [4].

Much of the material found in this chapter is based on the findings in the specializing project but it has been cut down from covering different applications of electrical power generation to only include hydro power applications. This is because the DF-PMSM is a constant speed generator and will therefore be mostly suited for this purpose.

7.1 Constant-speed Generators

As mentioned in the introduction The Doubly Fed Permanent Magnet Synchronous Machine is operated at a proportional speed to the network frequency. This is because its rotor is turning at the same speed as the voltage frequency with the pole count as the only “divider”, see Equation 1 for calculation of speed based on the network frequency. Generators in this category are the preferred solution to hydro power generation today.

$$n_s = \frac{120 * f}{p}$$

EQUATION 1: CALCULATION OF SPEED BASED ON NETWORK FREQUENCY

7.1.1 Synchronous Generator

The field exited Synchronous Generator is the one of the most used generators in the world today. It has the ability to alter the voltage output trough altering the field excitation. The field windings are for the most times situated in the machines rotor and are injected with DC current through either slip-rings/brushes or by an auxiliary magnetizing machine.[5] The magnetization of the machine is controlled by altering the field current. By changing the magnetization current there will be changes in the power factor (cos phi) resulting in changes in the voltage amplitude.

Often in the older and smaller synchronous machines the excitation is taken care of by the auxiliary magnetizing machine on the same shaft as the rotor. Here the currents are going through the magnetic field of the auxiliary machine eliminating the need for brushes/slip rings. This solution has the downside of having bigger time constants and has no ability to counteract small transient voltage fluctuations.

In newer and refurbished synchronous generators the excitation is controlled trough static excitation solutions using thyristors to manipulate the current and brushes to feed the rotor winding. This is a more effective solution than the auxiliary machine even though it depends on having slip-rings/brushes and has the ability to counteract small transient voltage fluctuations [5]. The downsides are losses in the brushes and brush-wear.

The regulation of the synchronous generator depends on if it is connected to an isolated or a stiff power grid. When the machine is connected to the stiff power grid, it for the most part controls the active/reactive power balance trough changing the magnetization of the rotor. Depending on the stiffness of the grid and the size of the machine is the voltage altered by changing the power balance. The machine is controlled with a run-diagram that shows the relation between apparent power (S) and active power (P) output when operating the machine as over- or under magnetized, see Figure 3. Also printed in the figure are the operating borders of the stator-current limiter and under magnetization preventer in red. If the machine is set to run outside these borders it will lose synchronism.

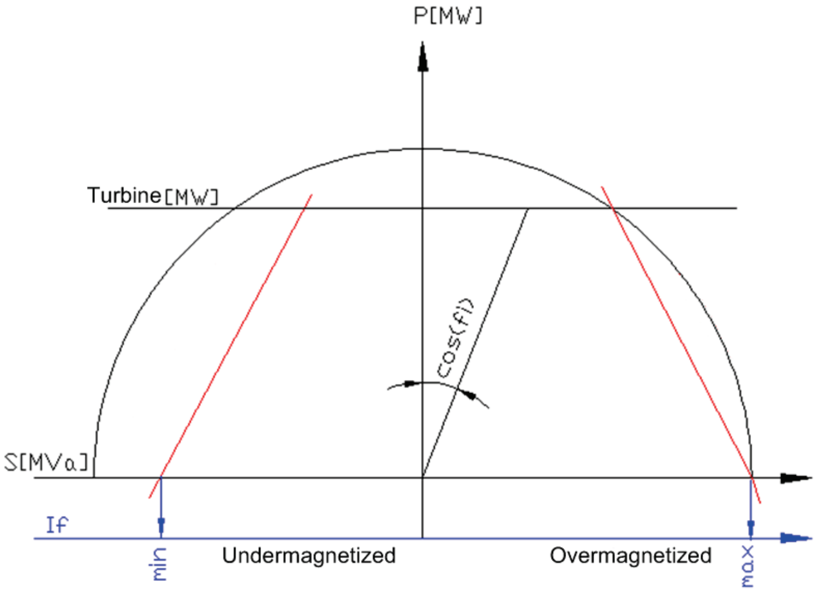

FIGURE 3: RUNNING-DIAGRAM FOR A FIELD-EXITED SYNCHRONOUS GENERATOR

7.1.2 PMSM Direct coupled

The permanent magnet machines are constructed with electrical windings in the stator armature and permanent magnets in the rotor. This removes the need for slip-rings or brushes to magnetize the rotor with DC-current like in the regular field exited synchronous machines. Because of this the size of the machine is considerably smaller compared to regular synchronous machines, and there isn't any need for maintenance of brushes. The losses in the machine are also reduced as a result of no currents in the rotor making the efficiency of the machine greater. Considering both size and efficiency makes the permanent magnet machine preferred to the classical synchronous machine.

The issue of these machines is that the magnetization is locked by machine design choices. This makes this machine more expensive to install since it has to be customized to each application, to ensure no changes in the voltage at the connected spot in the grid outside the boundaries of grid restrictions. This can be fixed with external compensational equipment like a Statcom[6] or a full converter in front of the generator.

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[6] See chapter 7.3.2 for more information about the Stacom

7.2 Variable-speed generators

The DF-PMSM is operated at constant speed and will therefore have a different operating characteristic compared to generators in this category. One of the generators used in many small hydro power plants today, the induction machine is the basis for most of the machines in this category.

There has been done research utilizing variable speed instead of constant speed generators to widen the operational area of the machine [6]. The claimed benefits using a variable speed generator are increased efficiency because a wider operation are of the turbine, as well as increased lifetime of the turbine hydraulics because of possibilities to counteract cavitations and draft tube oscillations.

Variable speed generation is mostly used where the speed of the machine has great impact on the power produced from the generator. One of the applications benefiting much from using variable speed generators are windmills that has a variable power-curve depending on what shaft speed the generator is operated as seen in Figure 4. The four different generator characteristics shows variation in the power as the shaft speed varies. The difference is inclining as the machine rating gets larger.

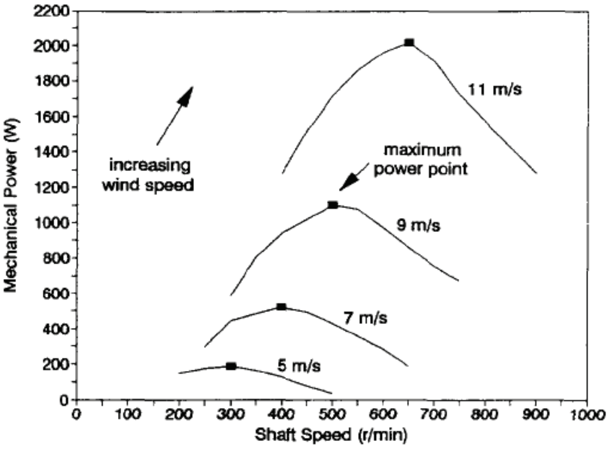

FIGURE 4: WIND TURBINE POWER CHARACTERISTICS, FROM [7]

7.2.1 Self-exited Induction generator

Most of all designed for motor applications, these types of generators are best suited in locations where the voltage is stiff. The reason for this is that the machine consumes reactive power to magnetize itself and therefore can be seen as an inductive load on the grid, pulling down the voltage. This limits its use to small generators sizes that does not influence the voltage noticeably or installations in more stiff parts of the grid closer to the big regulating generators.

The asynchronous generator was often used in the first electric windmills, in later years also as doubly fed in the rotor to get a wide speed range and better fault ride trough capabilities.

This machine has traditionally been the first choice in many small/micro hydro power stations in Norway, and in some cases still is the preferred solution because of the low price and easy technical installation.

When a new plant is commissioned today, simulations are performed to see if the grid is capable of keeping the voltage quality with the new gear. Based on these load simulations the grid operator can demand that a controllable generator is installed instead.

When the induction machine is overloaded the voltage will collapse. This can cause bad situations when the surrounding grid is disconnected, leaving the asynchronous generator as the only production source [8]. Local grid owners often have requirements to decoupling of the asynchronous generator in grid-island situations. This is a problem that has received more attention in the later years as the problem has become more evident because of higher usage of voltage/frequency sensitive equipment by the end consumer. It is one of the incentives to the development of grid regulations for generators in the distribution grid [9].

More problems appear when the surrounding grid is so weak that it has problems delivering all the reactive power needed to magnetize the induction machine therefore pulling down the voltage. In such cases there is a need for reactive power compensation by installing capacitor banks. It is possible either installing an actively controlled capacitor bank in parallel with the machine or it can be realized using a full AC to AC converter on all of the stator windings.

It is also possible to connect direct coupled static capacitor banks, ref Figure 5. Often designed with a configuration that covers the reactive load at no-load, making the $\cos\varphi$ about 0.95 when the machine is running at max production. Machines coupled this way must have a separate circuit-breaker on the static-capacitor bank because of possible self magnetization if the machine is separated from the stiff grid.

The semiconductors and capacitors are expensive equipment that will contribute much to the overall cost of the installation. The machines efficiency will also be reduced because of losses in the switchgear and capacitors.

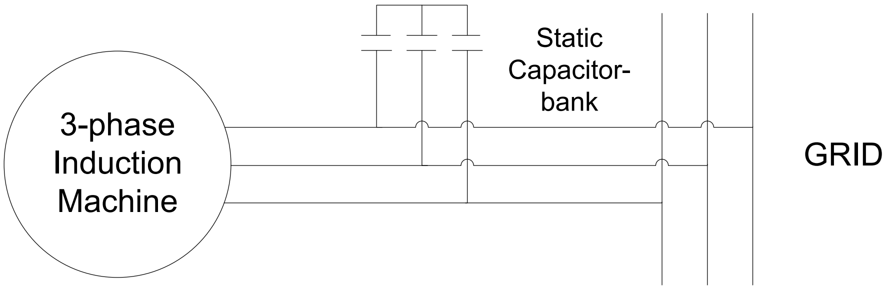

FIGURE 5: TRADITIONAL SETUP OF SELF-EXITED INDUCTION GENERATOR

In Norway today the power grid owners are not charging for consumed reactive effect in small hydro power stations even though there is set a tariff. I evaluated if the local grid owner in Northern Trøndelag in Norway, NTE[10] was to reevaluate their policies for small/midi/micro power-stations in my bachelor project [11], which will generate an extra expense for the power station owner. This can encourage installing more advanced solutions like the DF-PMSM.

7.2.2 Doubly-Fed induction generator

In the doubly fed induction machine is the squirrel cage rotor are exchanged with a wound rotor with slip rings or brushes so that the field currents in the rotor can be manipulated. The current in the rotor is generated using a converter. The converter injects slip power to the rotor to be able to operate in a wide speed range.

The machine slip gives the difference in the speed of the field in the stator compared to the rotor speed, ref Equation 2. The operation of this machine is similar to the Brushless doubly-fed discussed in chapter 7.2.3, but is less complex because of the second stator winding set and current loading in the stator [12].

$$s = \frac{n_s - n_r}{n_s}$$

EQUATION 2: CALCULATION OF SLIP ON ASYNCHRONOUS GENERATOR

7.2.3 Brushless Doubly-Fed induction generator

The "Brushless Doubly-fed Machine"[7] design appeared in the 90'es as an up and coming design for controlled induction generation. This design is much like the DF-PMSM, but is based on the induction machine instead of the PMSM. One of the first papers [7] considering this design was using a 1.5kW experimental machine to check the predictions in steady-state. They concluded with three claims of 25% converter size, good speed control as well as excellent waveforms on the output voltages.

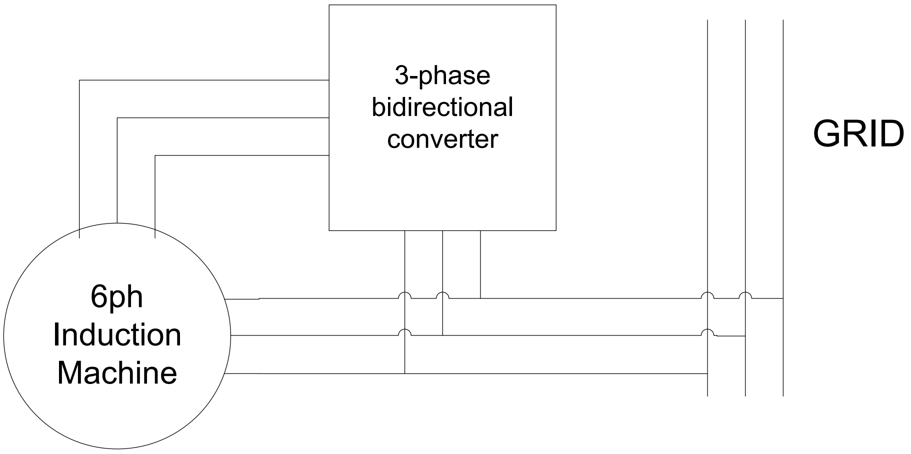

FIGURE 6: BRUSHLESS DOUBLY-FED DESIGN

Calculating the optimal converter size, which in this case is the smallest possible, is dealt with in one of the papers [13]. Having the possibility to regulate the output from the machine is of course the most important issue to consider. Prior to this paper these machines was designed to match the ratio of control winding compared to power winding using Equation 3. In this

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[7] Known as BDFM from here on out

equation grid frequency is f_1 and f_2 is the frequency supplied to the control winding. It's found that this equation does not satisfy the grid constraints if the control winding voltage is going to be varied to avoid machine saturation.

$$S_2 = S_m \cdot \frac{|f_2|}{|f_2| + |f_1|}$$

EQUATION 3: OPTIMAL CONVERTER SIZE CONSIDERING WINDING RATIO

The normal operating modes of the BDFM induction machine is also covered in the above mentioned paper. If the machine is running at nominal speed, and DC is injected trough the control winding, the power winding will generate more VArs like the field winding in a traditional synchronous machine design. At all other speeds will VArs flow in the control winding as a result from magnetizing VArs and VArs transferred across the air gap from the rotor. For an ideal BDFM it is possible to calculate the VArs generated by using Equation 4.

$$Q_2 = Q_1\left(\frac{N_r}{N_n} - 1\right)$$

EQUATION 4: VARS PRODUCED IN THE CONTROL WINDING RELATED TO THE POWER WINDING VARS

The result from the optimizing process is a way of determining the smallest possible inverter rating taking the power factor constraints into consideration and also varying the control-winding voltage to avoid saturation.

An equivalent circuit method was later developed to calculate the performance of the brushless doubly-fed design as generator as well as motor [14]. Using this they could calculate the power flow in a lossless machine, see Table 1. Here the power output of the machine was compared to a standard induction machine as well as two wound-rotor machines in cascade. All three machines are of same physical size, has the same electrical and magnetical loading and the power-factor output from the power windings is equal. The results show a 25% less output from the BDFM compared to the other solutions with the same frame size.

TABLE 1: POWER FLOW IN LOSSLESS BDFM

	Below ω_n		**Above ω_n**	
Operational modus	Power Winding	Control Winding	Power Winding	Control Winding
Generation	OUT	IN	OUT	OUT
Motoring	IN	OUT	IN	IN

In addition to these general papers there is also one wind application specific paper [15] , as well as one investigating the correct pole number combination in a BDFM[16].

7.2.4 Dual Stator-winding induction generator

This design is similar to the BFDM, but the control-windings are coupled to a capacitor or a battery-bank it is called “Dual Stator”. In this configuration the reason for doing so is to counter-effect the resulting change in the power factor caused by the load variations of the machine. This keeps the voltage output of the machine constant trough load variations on the turbine [17].

The paper above has also been looked further into and has been modeled with a fuzzy logic system [18].

The control-winding is going to supply the machine with power in a specific manner to compensate for low or high voltage, the converter can be considerably smaller than the case where as all the machines windings are coupled trough the converter. Also the amount of windings used as control-winding can be far smaller than the amount of power-windings carrying the most of the load of the machine.

There has been a lot of research done on a 12+3 phase machine for high-speed configurations [19],[20],[21],[22]. The layout of the testing process can be seen in Figure 7.

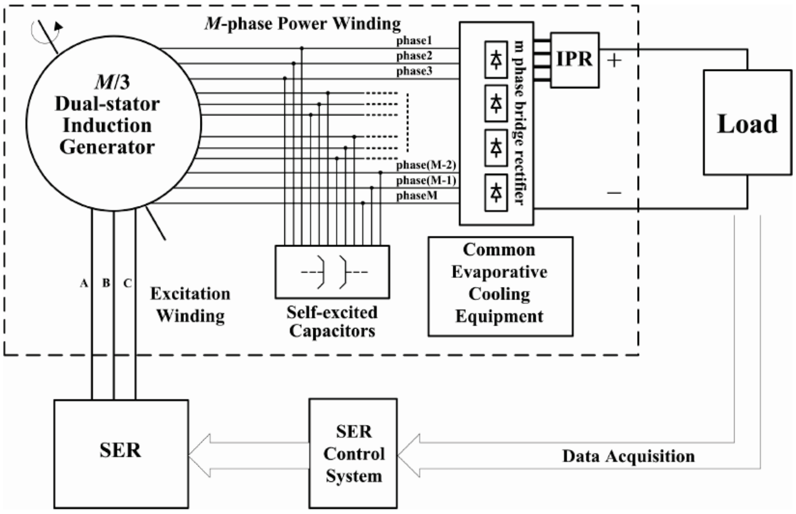

FIGURE 7: HIGH-SPEED DUAL-STATOR INDUCTION MACHINE WITH 12+3 PHASES

Issues that have been addressed are stator/rotor layout, cooling, THD reduction in excitation current, size, FEM modeling as well as a DC-bus voltage issue. The general conclusion is that this is a good machine for high-speed applications with good static and dynamic performance.

7.3 Compensational equipment

7.3.1 Generator behind full AC-AC converter

Machines behind full AC/AC converters will always be able to have satisfactory voltages at the grid frequency and is therefore able to be installed in front of any type of generator. Since the converter converts the generated voltages to grid acceptable content the machine will get a much wider speed-range. This makes the choice of generator into a selection between the one with the most efficiency versus the cost.

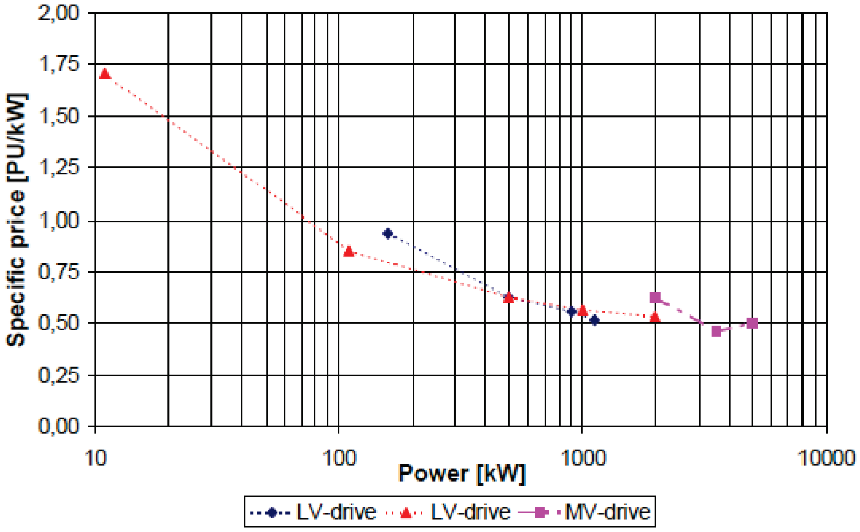

FIGURE 8: SPESIFIC PRICE OF CONVERTER BASED ON ACTIVE POWER RATING, [23]

As seen in Figure 8 is the price in per unit based on the generator price that varies with the power rating of the generator [23]. As seen is the price crossing 1p.u. at 70kW, but does not fall far below 0.5p.u. of the machine cost. These converters are standard ABB/Siemens converters.

7.3.2 Statcom

The Statcom is used to give a controlled regulation of the reactive effect in the surrounding grid. It consists of a capacitor bank behind an AC-DC converter. The converter rebuilds the voltage waveform like the control-winding converter of the DF-PMSM and therefore acts as a source or sink of reactive power[23].

Statcom is used as voltage/power factor regulation in week parts of the grid. The Statcom can also be used for harmonic filtering. The reactive power output is not affected by the voltage magnitude and is therefore better than the alternative Static VAR Compensator which reduces the reactive output by square of the voltage magnitude.

The DF-PMSM can have a smaller capacitor bank, a variable speed control winding and possibly lower price and higher efficiency than the Statcom.

8 Grid regulations

This chapter provides the specifications needed of generators in the Norwegian grid set by the network operator. These specifications must be considered when designing a machine to be able to connect it to the grid. These values are taken into consideration when the DF-PMSM design is further evaluated.

To evaluate the concept correctly is it important to know what the demands of regulation for hydro power generation the power plant owner have to follow to be allowed to connect the generator to the grid. In Norway is this reference is called "Functional requirement in the power grid" that goes into detail about how the machine must be controlled [24]. Since this machine firstly is a Norwegian patent only these requirements are taken into consideration in this report, but similar restrictions will exist in other countries.

8.1 Generators connected to the regional or central grid.

These regulations are valid for all generators in the regional or central grid.

The machine must be able to operate inside a specific frequency/voltage specter as seen in Table 2, split into blocks of for how long duration the machine must be able to operate in that specific area, as seen in Figure 9.

Frequency [Hz]	Voltage [pu]	Duration
45,0-47,5	0,90-1,05	>20 s
47,5-49,0	0,90-1,05	>30 min
49,0-52,0	0,90-1,05	Continuous
52,0-53,0	0,90-1,05	>30 min
53,0-55,0	0,90-1,05	>20 s
55,0-57,0	0,90-1,05	>10 s

TABLE 2: FUNCTION AREA TABLE

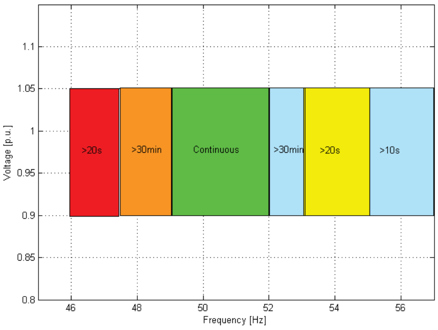

FIGURE 9: FUNCTION AREA GRAPH

There are specific standards required for hydro power plants with rating above 10 MVA that requires them to have turbine regulators described in [24]. If the size is below 10 MVA there is less demand to the regulator specification. Further there are many general considerations to regulators mentioned that is not considered important in this context.

Generators rated higher than 1 MVA must be equipped with voltage regulators that actively compensates for low or high voltage on the grid. Since this is the whole purpose of the control winding will this be one of the good benefits of choosing the DF-PMSM.

If the machine is rated above 25 MVA is static magnetization and damper windings a requirement.

The requirement for reactive capacity is possibly the most important aspect to fulfill for this generator. The regulator must be able to control the cos phi of the machine between 0.91 inductive and 0.91 capacitive, as seen in Figure 10. Wind mills have their own requirements for reactive capacity that is a cos phi of 0.95.

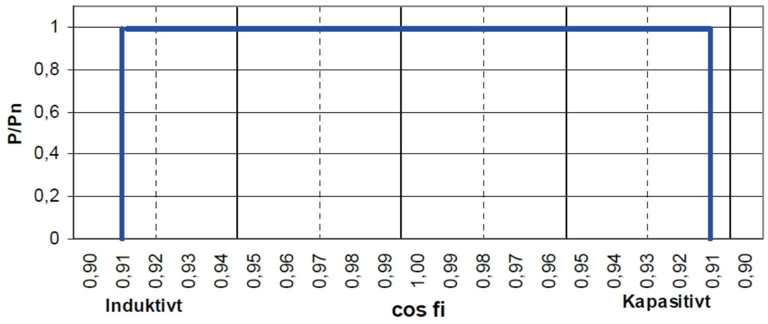

FIGURE 10: REACTIVE POWER REGULATION BOUNDARIES

The generators connected to the regional or central grid must fulfill fault ride trough demands[8]. The demands are different based on the voltage level the generator is connected to, above and below 200kV. This is to ensure secure fault clearing and maintaining delivery after fault clearing.

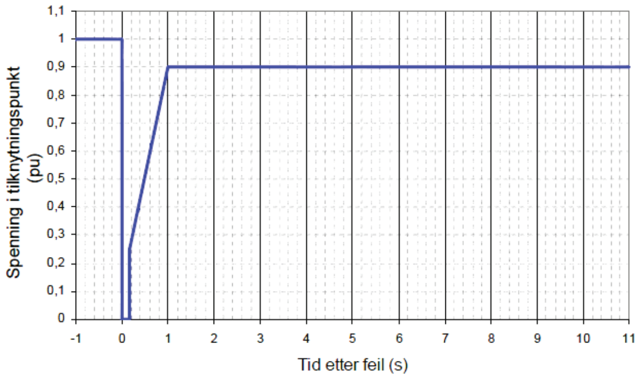

FIGURE 11: FAULT RIDE TROUGH FOR GENERATORS CONNECTED TO >200KV

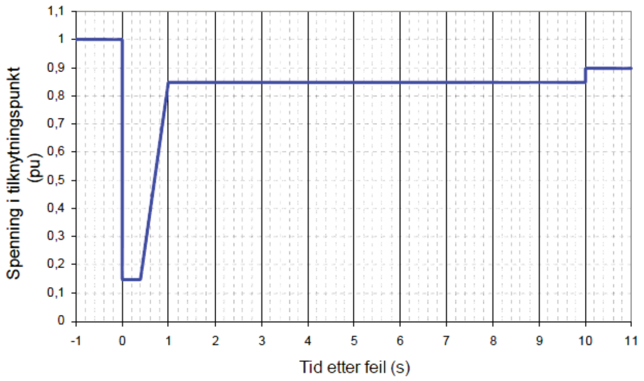

FIGURE 12: FAULT RIDE TROUGH FOR GENERATORS CONNECTED TO <200KV

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[8] Known as FRT from here on out

8.2 Generators coupled to the distribution grid.

Generators in the distribution grid with ratings between 1MVA and 10MVA and voltage levels beneath 22kV have their own set of grid guidelines [9]. These guidelines are developed at Sintef Energy Research [25] in partnership with several large grid owners in Norway. The guidelines are developed to keep the grid a safe work place and keeping the voltage quality acceptable in a social-economical manner.

The reason for having own regulations for machines in the distribution grid is to ensure that the voltage quality is kept in the most sensitive part of the grid. Since the distribution grid is to supply power to consumers, not feeding power into the grid there is problems when power starts flowing in the other direction. It is no longer given that the voltage is the highest at the station and at the line-end the lowest. Components are exerted to higher current stress than they are not designed for and there will be higher short-circuiting currents. All this requires the grid owner to rethinking their layout and protection setup.

Much of the data are based on simulation results at that particular placement in the grid and is therefore given on a pr. generator basis.

Machines rated higher than 250 kW must not have voltage peaks higher than described in Table 3. The grid owner can set stricter demands if needed.

TABLE 3: MAXIMUM BORDER FOR VOLTAGE PEAKS IN NORMAL OPERATION

Frequency of voltage peaks in connection point	Voltage peak [%]	
	0.23 kV < Un < 1 kV	Un >1 kV
Until 24 peaks pr. day	4	4
More than 24 peaks pr. day	3	3

Border values for over harmonic currents can be read in Table 4.

TABLE 4: MAX OVERHARMONIC CURRENTS

Overharmonic order h:	5	7	11	13	sqrt(sum ih2)
Overharmonic current ih=Ihi/Ii [%]:	5 - 6	3 - 4	1.5 – 3	1 - 2,5	6 – 8

Synchronous generators and doubly fed asynchronous machines must be dimensioned for a power factor in between 0.95 – 1.0 when the generator pulls reactive effect and a factor of 0.9 – 1.0 when the machine produces reactive effect. The DF-PMSM being a controllable machine will most probably fall into this category as well.

Asynchronous machines that are self-exited must be phase compensated using a capacitor bank so that the power factor of the installation is in the area of 0.9-1 during full load operation. For most asynchronous generators will an installation that covers the idle load give a power factor of 0.95.

Synchronous machines with lower rating than 1 MW can have arbitrary magnetization system but must be transient stable from 500 kW and up. Over 1 MW there are demands to the magnetization system being able to damp voltage oscillations. Generators with ratings above 1 MW can be allowed to actively regulate the reactive effect production if found necessary during simulations. Machines with 1 MW or lower rating are often set to regulate only on the voltage.

To ensure that the generators are not connected when the grid falls and the machine is not capable to supply the load increase there are regulations on how fast the machine must disconnect from the grid if the voltage or frequency peaks/drops as seen in Table 5 and Table 6. The generator must be disconnected if there is an internal error in the power station.

TABLE 5: DEMANDS FOR BREAKER RESPONSE DURING OVER/UNDER-VOLTAGE

Voltagearea in % of nominal voltage	Max. Duration before disconnection
U > 115	0,2
U > 110	1,5
U < 85	1,5
U < Ulower*	0,2

TABLE 6: DEMANDS FOR BREAKER RESPONCE DURING FREQUENCY VARIATION

Frequencyarea [Hz]	Max duration before disconnection
f > 51	0,2
f < 48	0,2

The grid operator must also be able to monitor selected parameters from the power station. This is often to ensure that the generator is operating normally and that work on the distribution grid is carried out without the generator producing power in cases of service grid. The parameters are:

- Current in 1 or 3 phases
- Phase-voltages in 1 or 3 phases
- Active power
- Reactive power
- Circuit-breaker status

And they must be able to operate the circuit breaker remotely and the reference voltage and power factor where needed.

9 Hydro Power Generator Case

This chapter is written to discuss the important factors where the DF-PMSM has to be proven against the synchronous and asynchronous generator. The simulation and laboratory tasks are discussed and decided in this chapter. It uses the chapters prior as a basis for discussion. This chapter is divided into three sub chapters: Grid regulation, prize/size and a lab-simulation chapter.

The DF-PMSM is an alternative to an already mature market with many generator alternatives and it is therefore crucial that the DF-PMSM is a good alternative in issues like price, size and technical capabilities. The generator is designed for constant speed hydro power generation, making this machine compete against separately exited synchronous generators, asynchronous generators, mostly self-exited and machines behind full converters.

DF-PMSM is firstly designed with small/midi/micro power plants in mind, meaning machines with a maximal power rating of 10MVA. These generators are often connected to the distribution grid and must follow a stricter set of regulations, as seen in chapter 8.

9.1 Grid regulations

The grid regulations case intends to show what rules and regulations the machine must follow to be producing power to the grid considering voltage quality. These rules are based on the guidelines set by the TSO[9] in Norway, Statnett. These regulations are shown and discussed in chapter 8 and can be used as a requirement to connect the generator to the grid in Norway today. The guidelines can be ignored in less extent by the grid owner, but they can also be stricter in less stiff parts of the grid. If the DF-PMSM is designed to satisfy these guideline regulations with ease it will be possible to place it nearly anywhere in the grid.

There have recently been published new guidelines for generators in the distribution grid where the demands to voltage quality are higher because it is close to the end consumer, ref chapter 8.2. Since the voltage level is lower and the load usually flows from station to the end consumer an introduction of new power is of great influence. The guidelines introduce incentives made to avoid islanding-situations. Islanding happens when the generator is operating and gets disconnected from the rest of the grid and must carry all the load of the end consumers in that grid radial. If the power plant is not able to deliver all the active power drawn by the consumers the result will be fluctuating voltage and frequency if the generator does not stop.

The biggest difference between generators connected to the distribution grid compared to the regional or central grid is that the rules for fault ride trough are different. In the distribution grid there are rules to disconnection of the generators if there is a voltage or frequency fluctuation over a certain limit, and in the regional/central grid there are fault ride trough rules where the machine must be attached trough the entire fault and be ready to produce its power when the fault clears again. This is important when the grid returns to normal operation so that the load covered by the disconnected generator does not have to be covered by another machine. This is not that crucial on smaller generators in the distribution grid.

It is important that the DF-PMSM is equipped with gear that disconnects the machine in these cases and powers down the generator in a protective manner so that generator does not get damaged. The Vacon NXP converter used in the experiment can be utilized as a trigger for

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[9] Transmission System Operator

fluctuating voltages and control a circuit breaker. The asynchronous generators do not have their own regulator reading the voltage/current values, since it is not needed, and must therefore be equipped with an especially programmed circuit breaker.

Machines behind active front end converters have much over harmonic content. This makes the need for a LCL (sinus filter) filters to get sinusoidal waveforms. This is necessary in the DF-PMSM control winding to follow the regulations.

The machines must be able to work in the power angle range of 0.95 inductive to 0.9 reactive in the distribution grid and 0.91-0.91 in the regional grid. If the converter is designed so that a range of 0.91-0.9 is achieved it will cover all kinds of locations and a wider application area. If the machine is operated with a back emf that equals the grid voltage it will have a cos phi of 1.

A power factor of 0.91 on a 10 MVA rated machine/turbine gives a needed production of 9.1 MW and 4.15 MVAr as calculated, ref Equation 5 and Equation 6. This means the converter rating must be approx 40 % of the machine size before the Norwegian grid regulations are covered.

$$\mathrm{P=S*cos}\ \varphi\mathrm{=10\ MVA*0.91 = 0.91\ MW}$$

EQUATION 5: ACTIVE POWER

$$S = S * Sin\varphi = 10\ MVA * \sin\left(cos^{-1}(0.91)\right) = 4.15\ MVAr$$

EQUATION 6: REACTIVE POWER

9.2 Price and size comparison

The DF-PMSM will consist of the converter and the permanent magnet machine itself. The permanent magnet machines are known to be smaller than the field exited synchronous machine and can therefore be viewed upon as a smaller design. The permanent magnet machine consists of the same stator as the synchronous machine but has permanent magnets in the rotor that has no current carrying capability and will therefore be smaller in size than the regular rotors.

The synchronous machine will also often on the smallest machines have a auxiliary magnetizing machine on the same shaft as the rotor to magnetize that takes up a lot of space. The static magnetizing alternative as well as the aux machine needs a converter to get the right dc-current output.

Even though the size of this machine will be based on assumptions will the size of the DF-PMSM be small or in the worst case of the same size and will therefore have no problem being installed as a new generator in old plant buildings or in applications where space is of concern.

To be able to compare the DF-PMSM machine it is important to have general knowledge of what other generator alternatives costs and compare it to the price of the DF-PMSM price. It was proven really difficult to get any price suggestions from entrepreneurs, often explained by the variable price in the total solution considering the layout of the penstock, construction of the generator housing and alike. Also issues like the speed of the machine and what classification needed in that environment is of concern. There are also many entrepreneurs considering this information as company confidential.

The price of the DF-PMSM is not at this time known and will therefore be based on speculations. The price of the unit as a whole consists of the filter, converter and the generator house itself as well as manufacturing costs. Since the design is new and not optimized there will also be some development costs involved in the price.

Figure 8 shows the relation between the costs of the converters versus the cost of the generator. This gives an indication of the potential cost benefits for the DF-PMSM concept.

When a new machine is to be connected to the grid is it the grid operator that has the final word in what generator that can be placed at that particular place in the grid. The demand is set by running a grid analysis to see if the network is able to cope. When building small scale hydro power plants is always money an issue and therefore will often the cheapest possible solution like an induction machine that is directly coupled be chosen over the more expensive regular synchronous generator if the grid owner gives the plant owner permission. The asynchronous machines are often viewed as the toughest machine to install because it does not contribute to the grid quality[10]. To increase the quality of the technical installations in new power plants it is necessary to make that technology cheaper, and by doing that it will become the obvious choice for new power plants.

In an ever expanding grid there is always new generators seeking permission to get connected that will affect the grid. In Norway there are rules that if new generators are to be installed in the grid does all the existing plant owners in that part of the grid have to take some of the cost of assuring that the voltage quality demands are followed. From this social economical viewpoint there are possibilities that an old plant owner have to refurbish their plant and install a controllable generator.

There can also be incentives from the grid owner that a fully controllable generator is wanted in any location in there grid. In this case are social economical issues considered, but the issue getting more power can suffer in this case because of higher costs results in fewer investments in the area.

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[10] When the machine is not behind a converter will it be seen as an inductive load.

9.3 Simulation/Lab-work

This sub chapter will serve as a work list for the simulations and lab work. The simulations will be a preparation to the lab. After the machine is synchronized and running against the grid it can be put through a different set of tests. The Lab-chapter will discuss more in detail how the generator is controlled and synchronized to the grid.

The simulations will give an overview on how to start this machine and what kind of regulation that is smartest in the startup of this machine. After this is done it will be easier to do the lab exercises based on this knowledge.

The proposed list of simulations is the following:

1. Evaluation of start methods
2. Using different regulation parameters determine how the machine will react to changes in load etc.

The operational range of this machine can be changed by using different rated machine and converter design and size. The machine utilized in the lab in this by no means designed to this specific task and the converter are not designed to a specific percentage of the machine output, but is chosen out of availability and convenience issues.

The lab work in this report does therefore serve as a "proof of concept" and the machine will therefore need more work before it can be put to production.

The proposed work list of the laboratory exercise is therefore the following:

1. It is important to see the machine operation in different turbine "gate opening". During different loading of the machine the power output will be recorded to see the machine efficiency. These tests will show what can be expected of performance from the machine and that the machine works.
2. The active-front-end converter is able to control its power angle by altering its switching frequency. The reactive power reference is input to the converter either by programming it into memory or by analog input to the converter during operation. In this configuration it is possible to play with the reactive power reference and see what the limits of power angle control are in this configuration. This must be controlled automatically in the commercial DF-PMSM by an external sensor alternating the reactive reference based on the measured values.
3. In the latest task the focus is shifted over to determine if the control winding can counteract different sizes of voltage alternations. The input voltage is changed using a variac on the input from the grid. Then the converter will try to alter the power angle of the control winding so that the voltage either increases or decreases to counteract the disturbance on the grid.

10 Simulations

The simulations done in this thesis project build on machine models of the permanent magnet machine developed in the specializing project period. During this period there was done a test simulation that was compared to results from simulations done earlier in Simulink[26], a toolbox graphical simulation toolbox in Matlab.

The results from the simulations in this project will provide useful information to the real lab exercise as well as provide general impression about how the machine will operate.

The program selected to do these simulations is LTspice developed by Linear Technologies. More information about why this program was chosen can be read in the sub chapter below.

During the project period is the foundations for a toolbox for streamlined machine simulations developed so future simulations can be done without learning all the tricks using LTspice to model machines and therefore done more rapidly.

10.1 General info about LTSpice

LTspice or "Linear Technology Simulation Program with Integrated Circuit Emphasis" is the name of the chosen simulation program. LTspice is based on Spice 3[1]. Linear Technology is a company developing and selling electronic components and LTspice is developed to assist engineers developing electronic circuits so they can plan, develop and rapidly prototype new components. LTspice has a big component library so the engineers using Linear Technology components easily can design their electronics in that environment.

LTspice is free to use software and can be downloaded from Linear Technology's homepage [2]. End users can refer to LTspice group [27] at yahoo for help on modeling circuits and tutorials on how to use the SWCad program to design their circuits. LTspice is under constant development where as the last addition is a multiprocessor-algorithm to enhance the simulation speed on capable processors. LTspice is developed for Microsoft Windows, but operates just as fast in Wine[28] framework on Linux.

10.2 Planning of simulation

The simulations done are based on the case that also the lab will be based on. This is to have a consistency of the results as well as the simulations will probably enlighten problematic areas of the design that can be good to know in the laboratory. Please refer to chapter 9.3 for more information about what is to be simulated.

The simulations was originally planned to be the machine with converter and a grid, but it became too much to keep track of during the development of the simulation model so it was cut down to a d-q controlled version of the 6-phased machine. The 6-phased machine consists of two machines with separate d-q systems for each machine as if the machine was consisting of two separate machines on the same shaft.

The simulations were therefore cut down to include of the machines starting and how to do this most efficiently so it could be used in the laboratory exercise.

10.3 Development of simulation models

Being able to model the machine sufficiently exact is important to ensure good results of the simulations. This chapter discusses the methods used and what has been done to preserve the readability of the simulation models so it is possible to see what considerations was taken when the model was developed.

As mentioned in chapter 10.2, the complexity of the machine simulations was reduced to only the machine during the process of constructing the models. Even though, there was also a full AC–DC–AC converter with active rectifier and inverter constructed during this process. There were also developed circuits to ensure correct switching of the transistors. The only thing missing was the d-q controller circuits for both rectifier as well as inverter.

The simulation model is developed with hierarchical sub-blocks to preserve the readability of the schema. Since the calculated values is based on behavioral sources that can output currents and voltages must an only one of them be chosen to represent the calculated "signal" value between the blocks. Here are voltages chosen because of the reduction of components needed to transfer the voltage-values between blocks that reduce the chances of doing mistakes when developing new models. Therefore must the signals between the hierarchical sub-blocks not always be treated as voltage and current values, but the possibility that they are either.

In Table 7 I have listed the developed blocks available for easy and fast simulations of 3-phase machines in the future. I will go through the process of making these blocks later in this chapter.

TABLE 7: THE SUB-BLOCKS DEVELOPED FOR SIMULATING MACHINES IN LTSPICE

Developed Sub-Blocks	Operation
abc-dq	Converting a 3-phase system to the dq system
dq-abc	Converting from a dq-system to a 3-phase system
3phpm	3ph Permanent Magnet Synchronous Machine
pos_calc	Calculating the rotor position from the given speed
a_sw	two-way switch
pi_reg	PI regulator
6phpm	6ph Permanent Magnet Synchronous Machine
pi_current_reg	Pi current regulator

Since this software is made with electrical circuit simulations in mind it is necessary to substitute mechanical properties like torque and speed with electrical properties. For convenience are the flux-linkages of the machine are kept constant.

The model is developed to give the transient and steady state simulation results, and is a p.u. model

10.3.1 The 3ph permanent magnet machine

To gain knowledge of the general machine modeling there was first developed a 3-phase permanent magnet machine model. This is to get used with simulating in the LTspice framework and being able to compare the results from the simulation with a previously simulated machine that was done in the Simulink framework. This simulation was done as a part of the specializing project autumn 2008.

The 3 phase machine is based on inputting the machine voltages in the d-q system and getting out the machine speed, torque and currents in the d-q system as well. This is done using behavioral sources with machine equations as input.

This way we more easily can control the machine regulating only on the wanted d-q currents or speed.

The machine parameters for the 3-ph machine can be seen in Table 11 in Chapter 11.1.

The machine model is a d-q model of the permanent magnet machine. It is based on the following equations taken from [29]. The first equations are based on the machines voltages.

$$u_d = r_s i_d + \frac{1}{\omega_n}\frac{d\psi_d}{dt} - n\psi_q$$

$$u_q = r_s i_q + \frac{1}{\omega_n}\frac{d\psi_q}{dt} - n\psi_d$$

$$\frac{dn}{dt} = \frac{1}{T_m}(\psi_m i_q - (x_q - x_d) i_d i_q - m_L)$$

$$\frac{d\theta}{dt} = \omega_n n$$

EQUATION 7: EQUATIONS FOR D-Q TRANSFERRED PERMANENT MAGNET MACHINE BASED ON VOLTAGES

Where rearranging so they are based on the currents gives:

$$\frac{di_d}{dt} = -\frac{\omega_n r_s}{x_d} i_d + n\frac{\omega_n x_q}{x_d} i_d + \frac{\omega_n}{x_d} u_d$$

$$\frac{di_q}{dt} = -\frac{\omega_n r_s}{x_q} i_q - n\frac{\omega_n x_d}{x_q} i_d - n\frac{\omega_n}{x_q}\psi_m + \frac{\omega_n}{x_q} u_q$$

$$\frac{dn}{dt} = \frac{1}{T_m}(\psi_m i_q - (x_q - x_d) i_d i_q - m_L)$$

$$\frac{d\theta}{dt} = \omega_n n$$

EQUATION 8: EQUATIONS FOR D-Q TRANSFERRED PERMANENT MAGNET MACHINE BASED ON CURRENTS

The parameters above are explained in Table 8

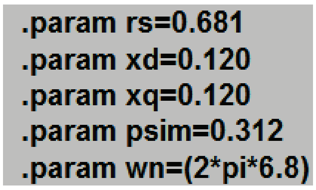
TABLE 8: LEGEND FOR MOTOR P.U. MODEL

Parameter	Symbol
d-axis voltage	u_d
q-axis voltage	u_q
d-axis current	i_d
q-axis current	i_q
d-axis flux	ψ_d

q-axis flux	ψ_q
Mutual flux	ψ_m
Electrical rotor speed	n
Electrical rotor angle	θ
Motor torque	m_e
Load torque	m_L

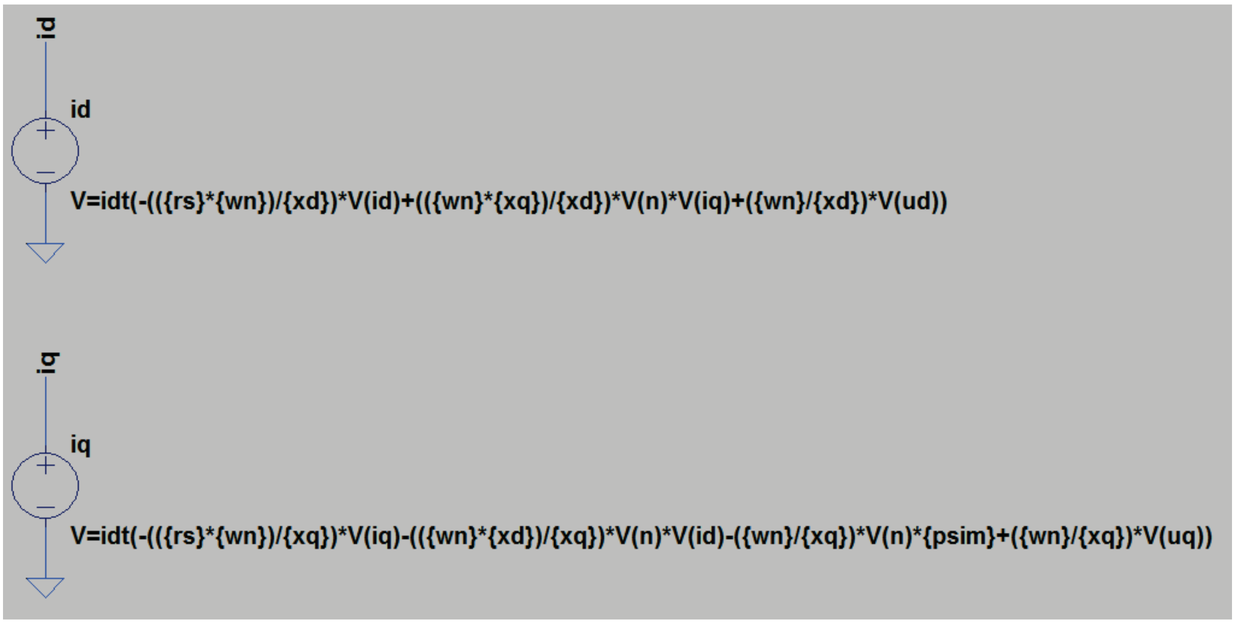
In the machine is behavioral current sources exchanged with behavioral voltage sources used for simplicity. As a general note all circuits must be grounded to be able to simulate to give a common reference for the simulation.

First of all it is good to start out defining the static parameters of the machine. This is done by inserting a SPICE Directive into the circuit scheme. Here the statement begins with ".param" followed by the name and value of the parameter. The parameters as entered for this d-q machine model can be seen in Figure 13.



```
.param rs=0.681
.param xd=0.120
.param xq=0.120
.param psim=0.312
.param wn=(2*pi*6.8)
```

FIGURE 13: MACHINE PARAMETERS IN LTSPICE. PSIM IS THE FLUX LINKAGE IN THE MACHINE (ψ_m).



```
V=idt(-((({rs}*{wn})/{xd})*V(id)+((({wn}*{xq})/{xd})*V(n)*V(iq)+({wn}/{xd})*V(ud))
```

```
V=idt(-((({rs}*{wn})/{xq})*V(iq)-((({wn}*{xd})/{xq})*V(n)*V(id)-({wn}/{xq})*V(n)*{psim}+({wn}/{xq})*V(uq))
```

FIGURE 14: D AND Q-AXIS CURRENTS IN LTSPICE

In Figure 14, the currents i_d and i_q are calculated and given out as voltages from the behavioral sources of convenience. The voltages u_d and u_q are applied behavioral current source so no circuit is therefore modeled here. They are only input to the model trough nodes so that the values are available for the behavioral models.

The speed and torque of the machine are modeled using the behavioral sources seen in Figure 15.

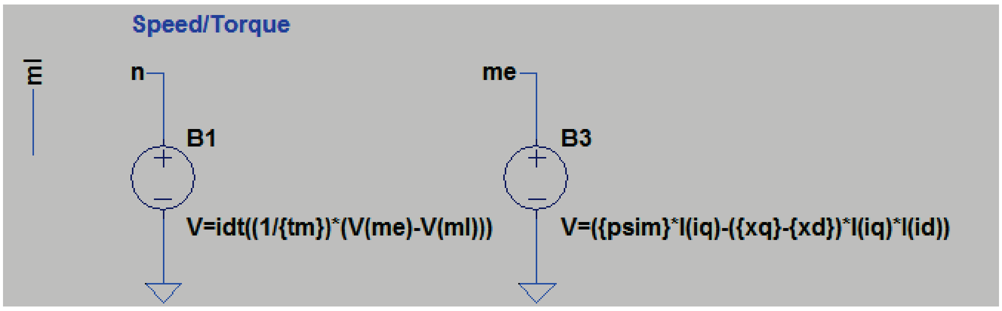


FIGURE 15: SPEED AND TORQUE SUB CIRCUITS

The two sub circuits above calculate the machine speed and produced electrical torque. The node m_L is an input from the outside of the hierarchical block.

10.3.2 The 6ph Permanent Magnet Machine Model

The 6ph machine model is based on the 3-phase machine model. It has two sets of d and q windings and the electrical torque is calculated for each machine and summarized. How this was realized can be seen in Figure 16.

When two machines are connected to the same shaft the machine speed will deviate some from 1p.u. because of numerical inaccuracy.

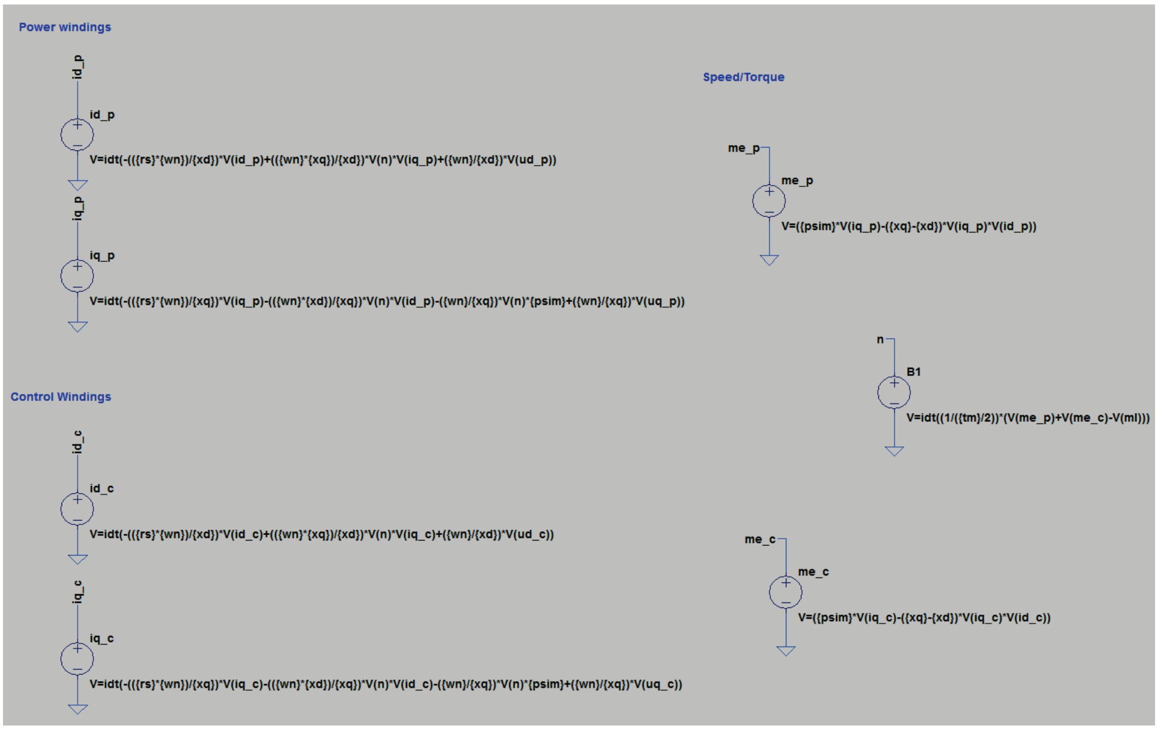


FIGURE 16: 6-PHASE PMSM

10.3.3 ABC to dq and inverse transform blocks.

The machine is modeled in the dq system and therefore the applied voltages/currents must be converted from the 3-phase abc-system to the dq-system.

This is done by first converting the signals from the abc system to the αβ-system using the Clarke transform. The αβ-system is a two phase system separated by 90°. Then by applying the Park transform introducing rotation to the αβ-system. This conversion changes the signals from sinusoidal to constant values [30].

$$x^{dq} = \begin{bmatrix} \frac{2}{3}\cos\omega t & \frac{2}{3}\cos(\omega t - 120°) & \frac{2}{3}\cos(\omega t - 240°) \\ -\frac{2}{3}\sin\omega t & -\frac{2}{3}\sin(\omega t - 120°) & -\frac{2}{3}\sin(\omega t - 240°) \end{bmatrix} \cdot x^{abc}$$

EQUATION 9: ABC TO DQ CONVERSION

$$x^{abc} = \begin{bmatrix} \cos\omega t & \sin\omega t \\ \cos(\omega t - 120°) & \sin(\omega t - 120°) \\ \cos(\omega t - 240°) & \sin(\omega t - 240°) \end{bmatrix} \cdot x^{dq}$$

EQUATION 10: DQ TO ABC CONVERSION

Using Equation 9 and Equation 10 this is realized mathematically using behavioral sources.

10.3.4 Regulators

The PI regulator in Figure 17 is here to control the machine speed in single 3-phase configuration. The feedback to this regulator is the machine speed, and it calculates q and d currents based on the output from the speed loop. The regulator is realized like the machine, using behavioral voltage sources.

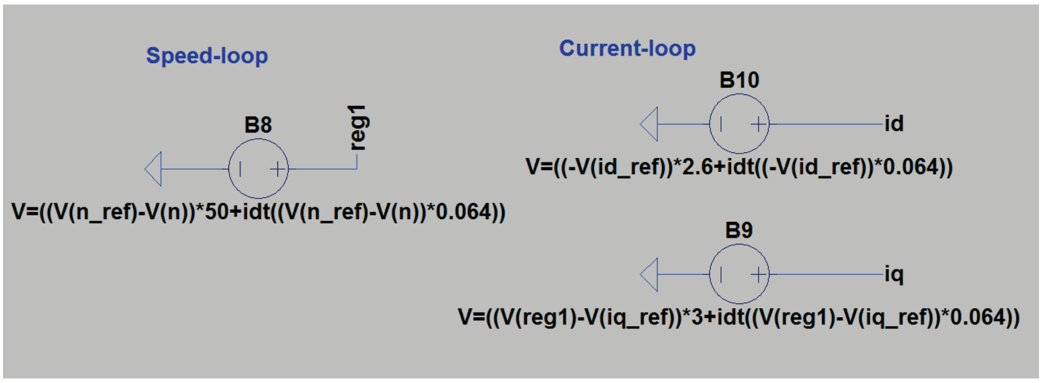


FIGURE 17: PI-REGULATOR BLOCK

10.3.5 Converter model

Even though the converter was not used in the simulations the description on how it was made is included in this chapter. By documenting the idea behind the construction of the model it can more easily be used in later simulations with some extra work on the regulators controlling the machine. The general layout of the converter can be seen in Figure 18.

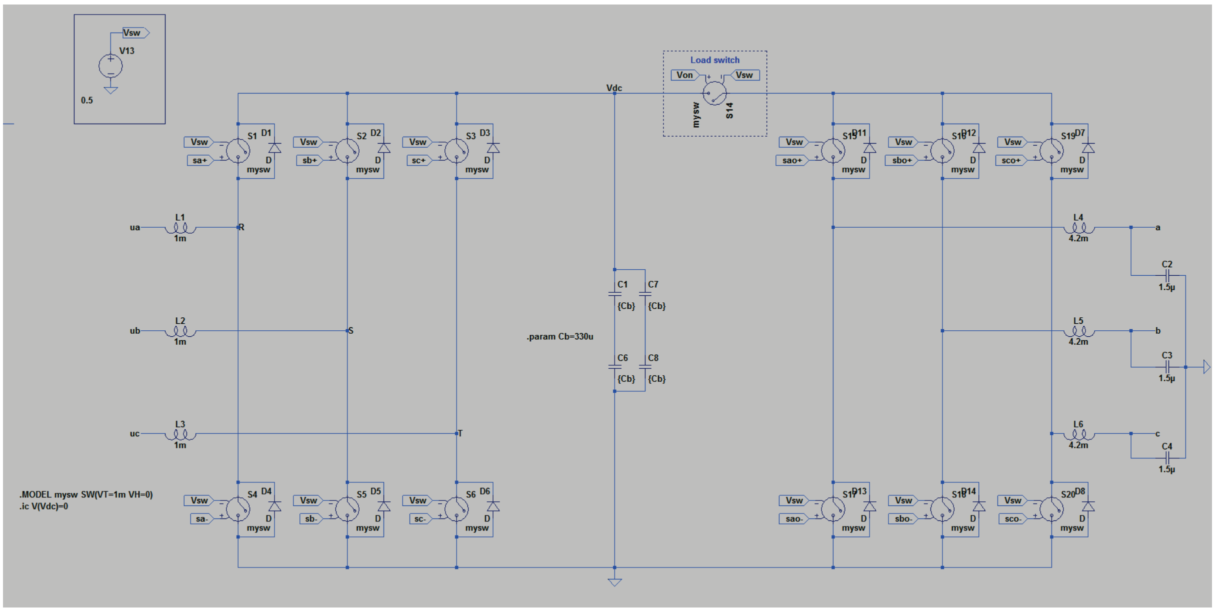


FIGURE 18: CONVERTER LAYOUT

The rectifier is on the left side, the inverter on the right and the dc-link with a capacitor bank links them together. In the development the parameters was taken from the Vacon NXP converter used in the lab exercise. The switches are operated using an external driver circuit that is seen in Figure 19. The triangular waveform with the correct switching frequency goes in on the input named Vcr and is compared to the reference signal going in on either ref_a, ref_b or ref_c. Then the duty cycle is calculated and the switches are operated accordingly.

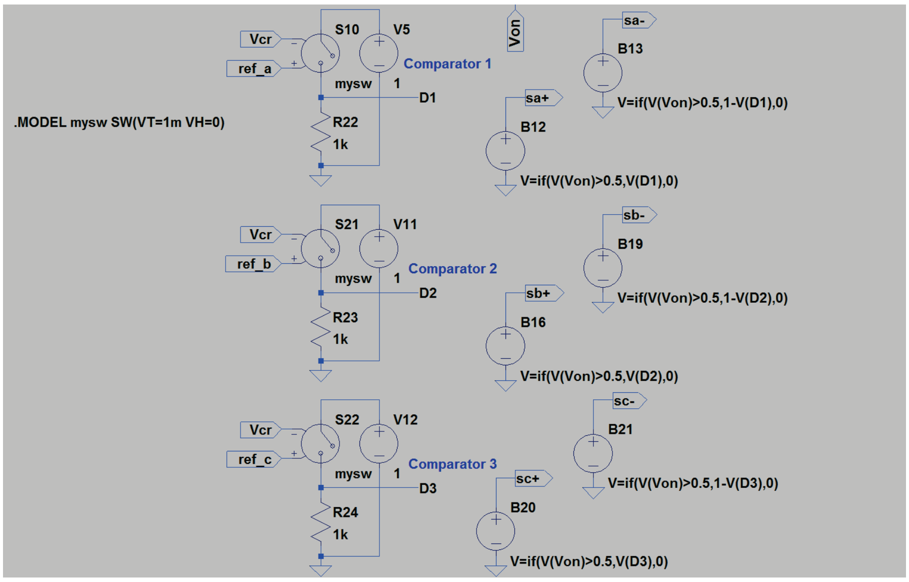


FIGURE 19: CONVERTER DRIVER CIRCUIT

11 Lab

This chapter describes the lab setup, with explanations in detail about every vital component in this lab. The lab is based on two machines coupled in a back-to-back configuration with two converters, one to drive the “turbine”-machine, the other converter consists of an active-front-end converter and a converter running the machine application coupled together in the dc-link. The active-front-end application has the ability to reverse the power flow of the converter and is therefore used to control the output from the generator machine. The two converters connected to the generator are both Vacon NXP-converters at 230 V 4.8 A max rating, as well as the turbine machine converter.

The lab was done at SmartMotor facilities in Trondheim.

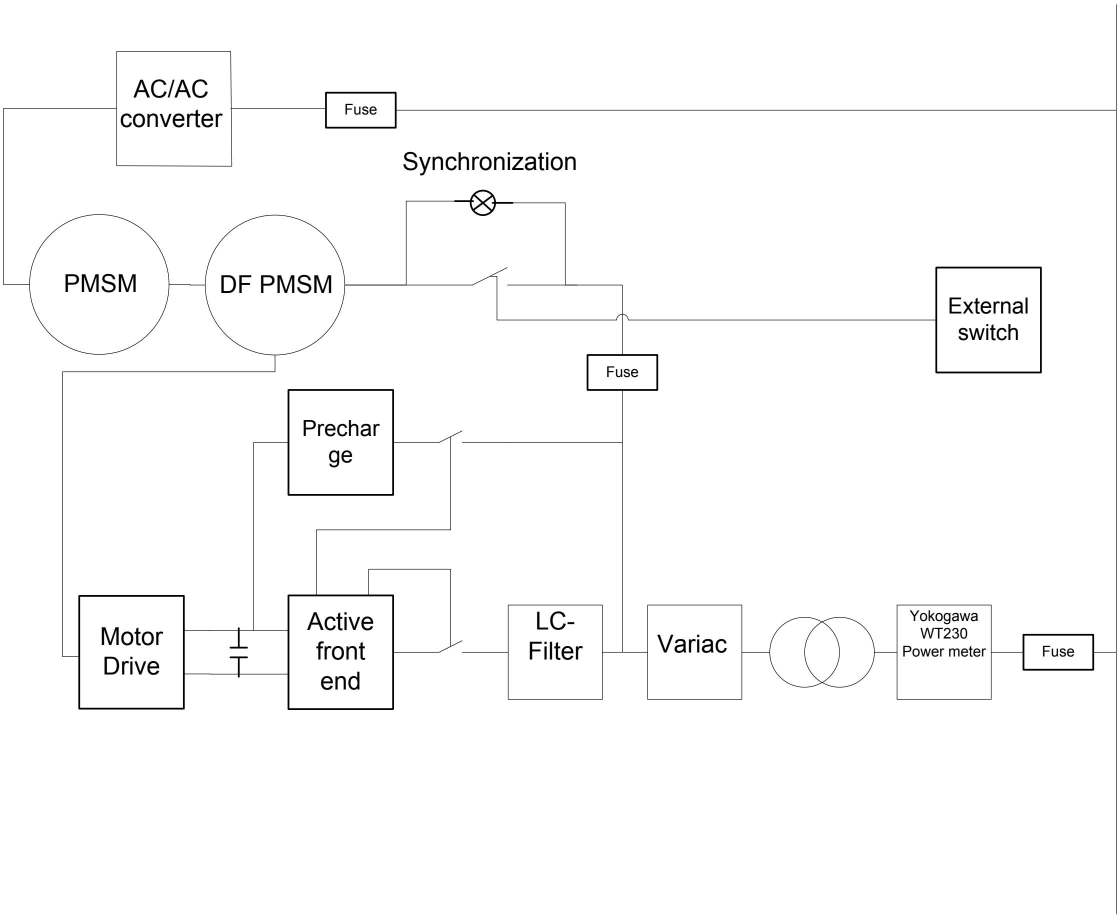


FIGURE 20: LAB SETUP

As seen in Figure 20 is the final lab setup. It includes two similar machines in back to back configuration. The 3-phase machine marked as PMSM will serve the purpose as a turbine and will “drive” the 6-phase generator marked DF-PMSM. As the PMSM machine uses power from the grid the DF-PMSM feeds it back. This way we are delivering all the power back to the grid minus the losses in both converters and machines.

The machines will be discussed more in detail in the parts sub-chapter. The 3-phase machine is driven by a standard AC/AC converter with diode-rectifier and will only have a power flow to the machine.

TABLE 9: LIST OF EQUIPMENT

List of equipment			
Number	Type	Manufacturer	Model
3	Converter	Vacon	NXP00042A2H1SSSA1A2000000
3	Contactor	Siemens	16A
3	Breakers	ABB	C10
2	Machines	Smartmotor	RF600
1	Variac	N/A	N/A
1	Isolation transformer	N/A	N/A
1	Sinusfilter	Schaffner	FN5010-10-99
3	RS-323 Cable	Profilic	N/A
3	Bulb sockets	N/A	N/A
3	Bulbs	Osram	60 W / 25 W
1	Power meter	Yokogawa	WT230

11.1 Machines

The machines used in this lab are permanent magnet synchronous machines developed by SmartMotor, which will be used as both generator as well as turbine, coupled back-to-back. They are previously sold as actuator machines with their own integrated position regulator, but in this project the regulator is removed. The machine casings was also discarded and new casings in aluminum was made for this purpose.

The machine parameters in unaltered three phase configuration can be seen in Table 10

TABLE 10: MACHINE PARAMETERS

Parameter	
Rs	34Ohm
Lf_d/q	140mH
Back emf	17,9V
Pole count	17
Nominal frequency	6,8Hz
Nominal speed	24rpm

The DF-PMSM machine is cut from the actuators 3-phase to a 6-phase configuration. Each phase of the actuator machine consisted of two sets of three wound coils placed opposed to each other in the machine stator. To get six phases the two sets are cut and the negative polarity end is coupled together in the machines common neutral point for both 3-phase systems. The positive polarity end is taken outside the machine casing for connection to the converter/grid. The stator during rewiring can be seen in Figure 21.

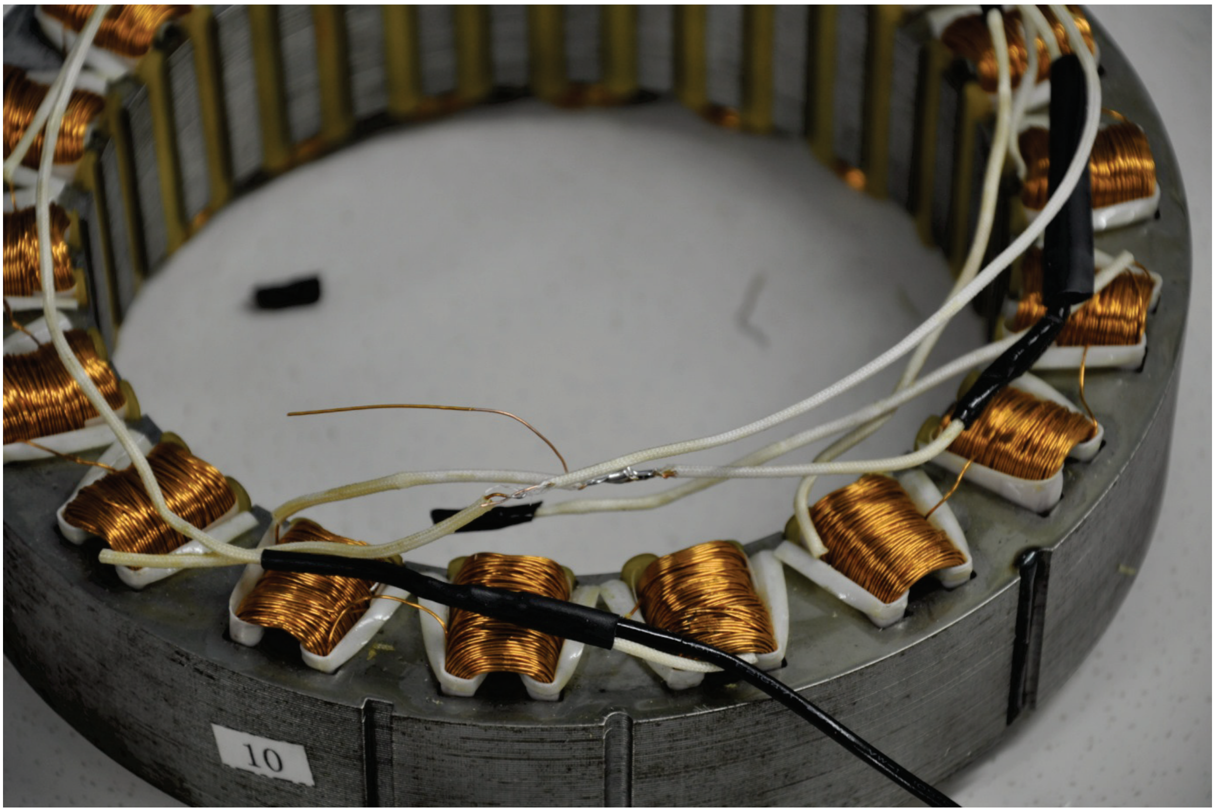


FIGURE 21: THE EXPERIMENTAL DF-PMSM STATOR

Since the machines where modified the parameters was altered. The machine parameters are scaled to 50Hz operation prior to inputting them into the controller software from Vacon because of limitation in the motor nominal voltage drive-application from Vacon. The back emf increases linearly with the speed the machine is operated and is therefore 131.2V in 50Hz operation in the original series layout, ref Equation 11.

$$back\ emf_{50Hz} = 17.9V * \frac{50\ Hz}{6.8\ Hz} = 131.2V$$

EQUATION 11: BACK EMF AT 50HZ OPERATION

This gives a line back emf of 227.25V, ref

$$back\ \mathrm{emf}_{50\mathrm{Hz}}\mathrm{line} = 131.2\ V * \sqrt{3} = 227.25V$$

EQUATION 12: BACK EMF LINE VOLTAGE AT 50HZ

The actuator machine is originally a 3-phase machine so it was no point in altering the stator at first, but the back emf line voltage at 50Hz operation was too high to be able to cope without field weakening the machine at 50Hz operation. The back-emf can be as high as 0.95*dc-link voltage before field weakening is needed. The field weakening controller in the Vacon converter was tried, but it was problematic to get the machine stable so the machine configuration had to be altered. Each of the three phase phases was consisting of two series of three coils coupled in series and was changed to parallel instead that reduced the back emf to half of the original value.

The back emf was reduced to half of this value in both machines after rewiring. The parameters for the DF-PMSM can be read in Table 11. The Lf and Rs was measured using a Fluke RLC-meter.

TABLE 11: MACHINE PARAMETERS FOR DF-PMSM

DF-PMSM		Turbine Machine	
emf	65,81 V	emf	65,81 V
Rf	16,3 Ohm	Rf	8,2 Ohm
Lf_d	33 mH	Lf_d	43 mH
Lf_q	33 mH	Lf_q	43 mH
Nominal data		**Nominal data**	
Frequency	50,0 Hz	Frequency	50,0 Hz
In	4,27 A	In	3,80 A
Un	180,00 V	Un	180,00 V
Psi_m	0,296 Wb	Psi_m	0,296 Wb
Polepair	17	Polepair	17
Tn	45,618 Nm	Tn	40,596 Nm
Pn	843,0 W	Pn	750,2 W
Pu-modell, basis values		**Pu-modell, basis values**	
I_unit	6,04 A^	I_unit	5,37 A^
U_unit	146,97 V^	U_unit	146,97 V^
Z_unit	24,34 Ohm	Z_unit	27,35 Ohm
Psi_unit	0,47 Wb^	Psi_unit	0,47 Wb^
pu-modell		**pu-modell**	
rs	0,668	rs	0,301
xd	0,421	xd	0,494
xq	0,421	xq	0,494
psi_m	0,312	psi_m	0,312

The DF-PMSM had to be opened to separate the common neutral point coupling into one per three phase winding. This was because when the switched control winding was started the zero point voltage often deviates from zero called common mode voltage. This was the same for the other end of the machines that triggered the earth fault protection. It was removed by having an isolation transformer between the lab-equipment and the grid.

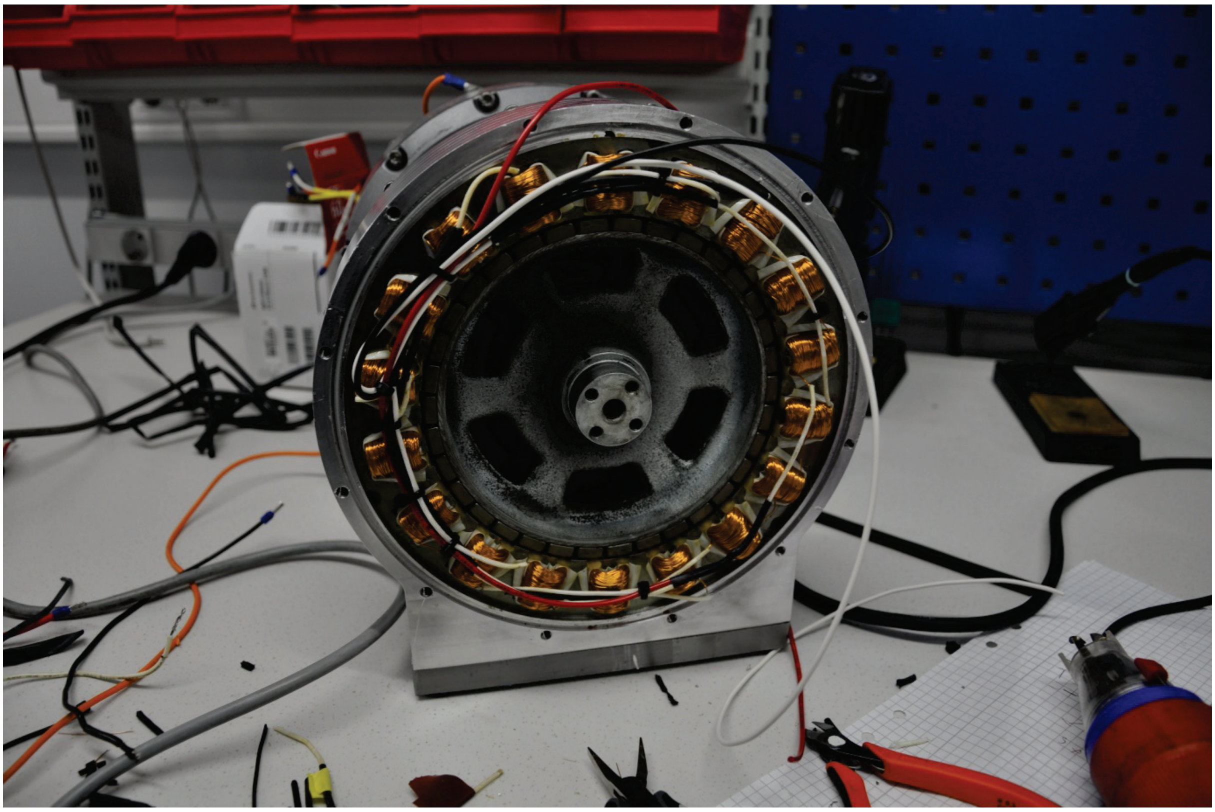


FIGURE 22: CHANGING POLARITY IN THE TURBINE MACHINE

11.2 Active front end converter

The second most important part of the lab is the converter that is based on two “off the shelf” Vacon NXP converters. These converters are AC-AC converters but feature a diode rectifier instead of having a switched rectifier. In this configuration there is not possible to reverse the power flow in the converter (operation in four quadrants). Therefore it is necessary to utilize two converters coupled together trough in the DC-link to be able to control the power flow in both directions. One of the converters will then run as an active-front end rectifier with an analog input to how much reactive power that is wanted based on a percentage of the active current output from the converter.

The active-front-end converter has a two-step start up process. First the diode-rectifier in one of the converters are connected to supply a dc current to the capacitors trough a resistor to make sure that the current transient is not to big. The resistors are disconnected before normal operation. If the relay does not couple out the resistor the currents will burn of the resistor after a short while when the converters are operated at normal rating.

When the dc-link voltage is >0.8*1.35*Un the control logic of the converters starts. This can be heard when the fans of the converter is starting. This procedure is called a pre charge and when the pre charge is finished the converter will switch a relay connecting the inverter, now used as rectifier, to the grid and disconnecting the diode rectifier.

Often a separate pre charger is used to supply a slow current not to overload the capacitors and destroy them or the converter during charging. In this case this was evaluated before the choice of using the converters rectifier bridges was chosen. They had a built in soft-charge mechanism with a relay that disconnects the resistances before normal operation occurs and Vacon was positive to that both the converters capacitor banks could be charged this way.

Figure 23 shows the filter capacitors and the capacitor bank on the diode rectifier as it is mounted in the converter. The gate operation circuit board is mounted on top of the capacitors.

The active front end works by regulating the dc-link voltage. During normal operation the converter will boost the DC-link voltage to 400 V DC from the 300V gained from the diode rectifier. When power are fed from the machine to the converter during generator operation the dc-link voltage will raise making the active front end switch so that the power flows back to the grid with the wanted power factor.

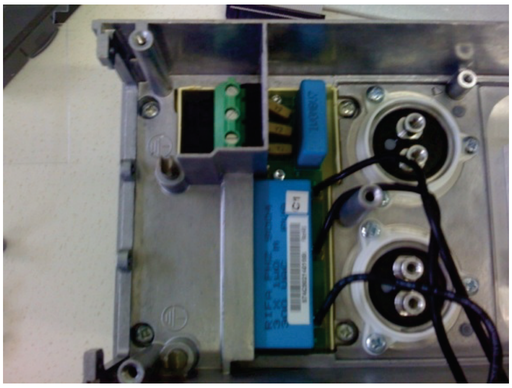


FIGURE 23: THE CAPACITOR BANK AND FILTER CAPACITORS OF THE VACON NXP CONVERTER

The control logic of the Vacon NXP converter can be seen in Figure 24. This is programmed/controlled trough a RS-232 serial cable that can be seen going out to the front panel in the far back of the picture. The main board is the general controller where as the two front mounted ones are extension boards featuring inputs and outputs from/to the internal control logic of the converter and a relay for control of the contactors disconnecting the diode rectifier after pre charge and connecting the IGBT-switches.

The converters are programmed and monitored using Vacons own software, NCDrive. The software is based on having the correct motor/generator application which in this lab was a permanent magnet application and an active front end application.

The active front end application was set up to maintain the dc-link voltage at 400V and left that way.

The machines were to be run “sensorless”, meaning without a speed/position encoder on the machine shaft. The permanent magnet machine application was configured with the machine nominal data and the stator reactance/resistance and back emf. The regulation was chosen to sensorless closed speed loop and the machine was attempted started. This was more problematic than expected and a lot of time was used to tune these regulators to be able to drive the machines. The problem was eventually narrowed down to the “VoltCorr”-regulator that needed much stricter tuning.

FIGURE 24: THE CONTROL LOGIC OF THE VACON NXP CONVERTER WITH EXTENTION BOARDS

As for controlling the machine the converter converts the phase voltages and currents from the abc to the dq system like in the simulations where the q current controls the torque directly and the d current the field. By applying a negative iq-current the machine is field weakened, meaning that the back emf voltage is reduced and the machine can operate at higher speed than nominal if the motor voltage has reached more than 0.955% of the dc-link voltage. This is handled by the flux controller in the Vacon converter but was not used in this lab.

11.3 Other

A synchroscope was designed to ensure a safe synchronization with the grid before connecting the directly coupled power winding. It was chosen done the old way with 3x60 W bulbs coupled over the power contactor, seen in Figure 25. When all the bulbs are out at the same time the machine was in phase and could be connected to the grid.

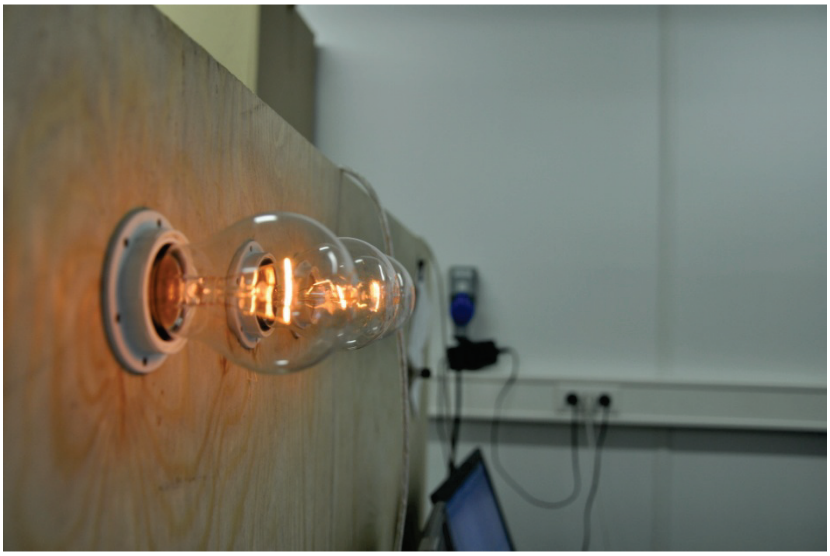


FIGURE 25: SYNCHROSCOPE WITH 60 W BULBS

A Yokogawa W230 power meter was connected in between the variac and isolation transformer. From this meter it is possible to monitor the power flow from the DF-PMSM machine.

On the output from the active front end there was mounted a sinus filter to remove switching noise from the active rectifier. This filter was a standard 10A Schaffner produced filter.

The final lab can be seen in Figure 26 and Figure 27.

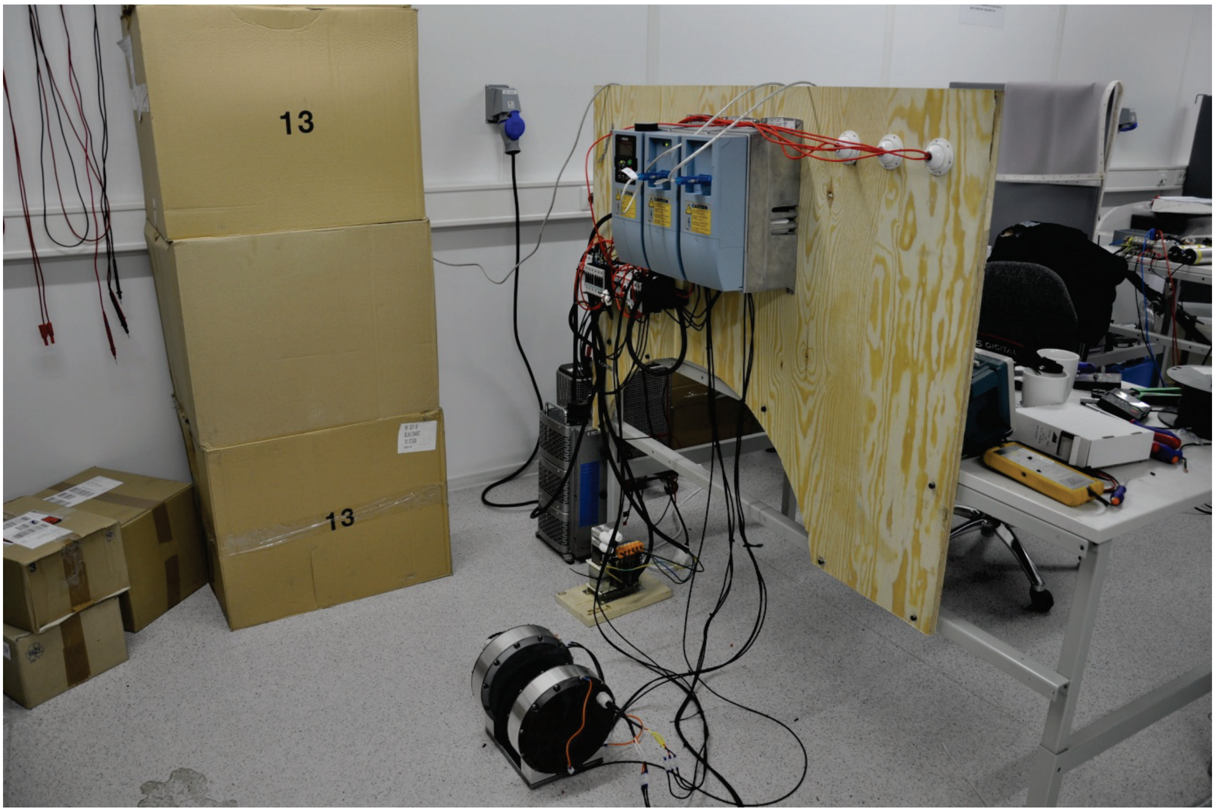


FIGURE 26: MACHINES AND CONVERTER

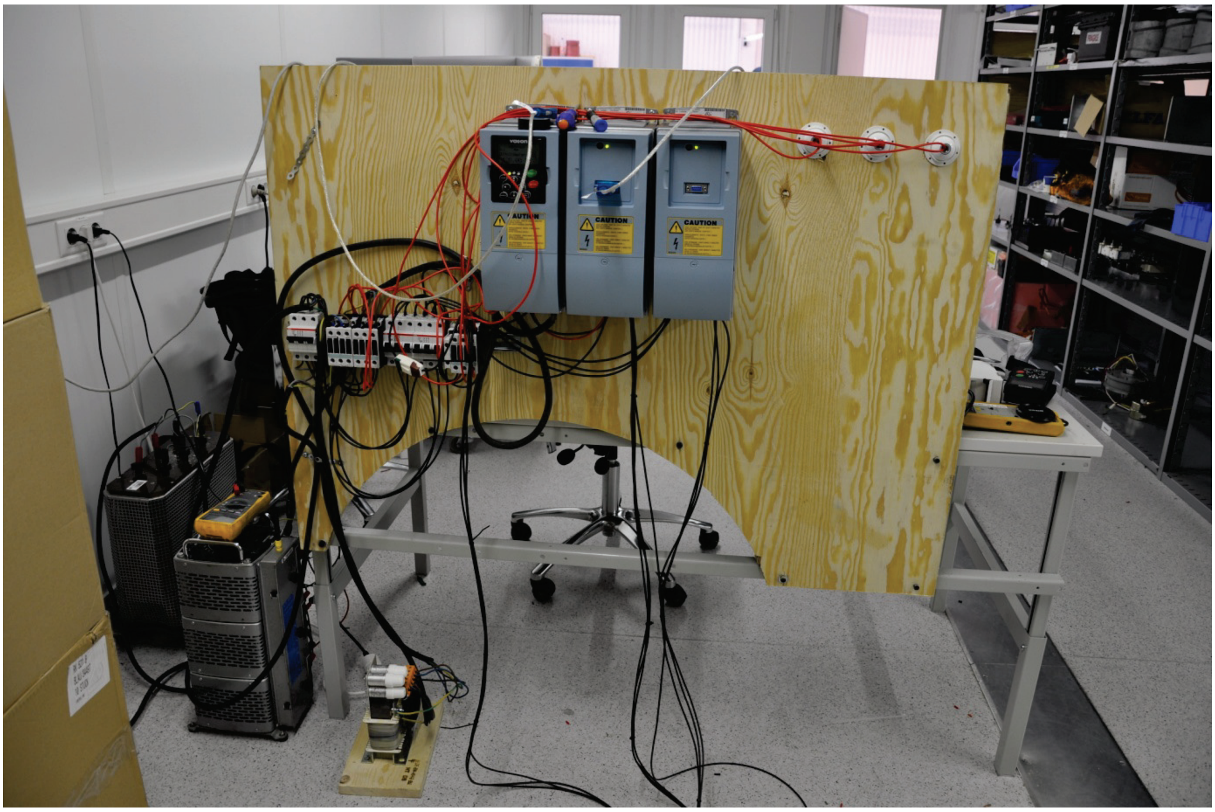


FIGURE 27: THE CONVERTERS, FILTER, VARIAC AND ISOLATION- TRANSFORMATOR.

12 Results

In this chapter the results from both simulations and the lab exercise is presented. The result is discussed in chapter 13.

12.1 Simulation results

Seen in Figure 28 is the simulation schematic with the 6-phase machine, regulators and d-q transform blocks among other. The simulations simulated a startup of the machine with synchronizing the power winding to the grid and switching over to current regulation on the control winding. When that was done the turbine was started with 1p.u. in torque.

It was proven difficult to achieve a total decoupling of the power winding during startup, and some currents was running in the power winding producing some torque because of this. This was because the machine equations does not considered if the d and q currents are able to flow (if the motor phases is open).

To get the d-q system working in both power and control winding the power grid directly connected to the power winding was done by using a closed loop speed regulator.

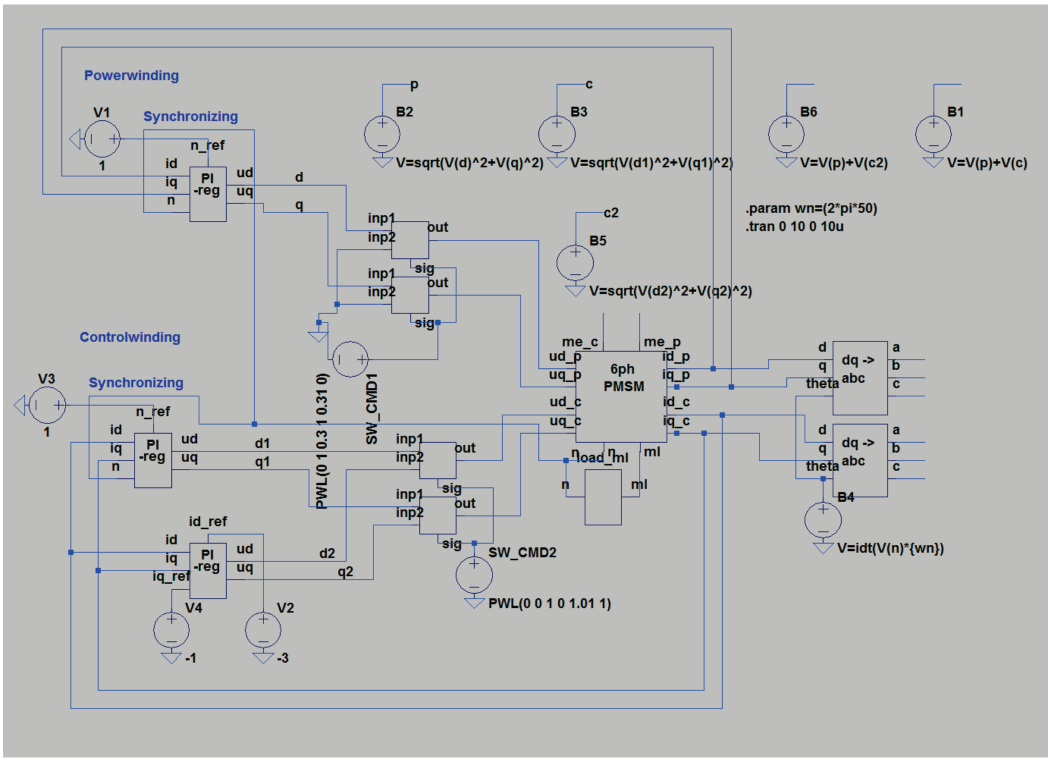


FIGURE 28: SIMULATION SCHEMATIC

In the first simulation the machine startup was simulated by increasing the speed to 1 on the control winding to see how the machine coped.

The second simulation was the machine running with changes in d and q current references on the control winding and the resulting q and d currents in the power winding can be seen.

The first simulation, step-by-step:

1. The machine was started using the control winding. It was done using a closed loop speed regulator that ramped the voltages in both d and q axis to get the machine up to speed.
2. The power winding is attached using also a speed regulator to emulate the stiff power grid the machine is connected to.
3. After this the control winding was switched over to closed loop current regulation only to pretend different amounts of compensational power wanted trough the converter.
4. The turbine of the machine seen as the little box underneath the machine in Figure 28 ramps the load to -1 p.u. at 1.2 s.

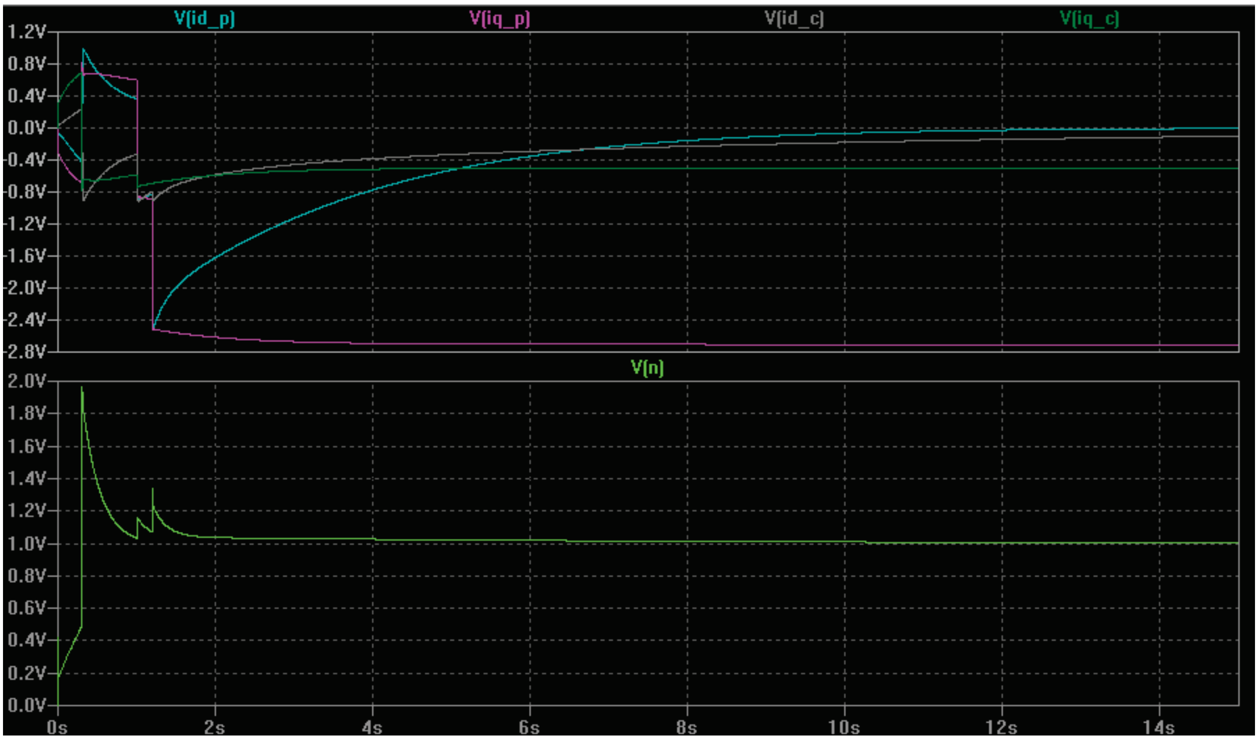


FIGURE 29: FIRST MACHINE SIMULATION RESULTS

Not being able to simulate a totally stiff grid the speed deviated some on the changes of regulators as seen represented by the V (n) in green.

The four curves seen in Figure 29 shows the id and iq currents in p.u. of both power and control winding. Here the control winding iq reference is -0.5 and id is 0. As seen is the resulting iq and id from the power winding a id of 0 and iq of approx -2.7. Here _p means power winding and _c means control winding.

When this was done it was possible to operate the machine at different loading in the control and power winding by changing reference currents of the control winding.

During the next simulation the iq reference of the control winding was changed while the machine was running to see how the machine coped with changes in the load from the control winding. The speed deviated some when the iq-reference of the control winding had the biggest changes, but this would not have happened if it was connected to a stiff power grid.

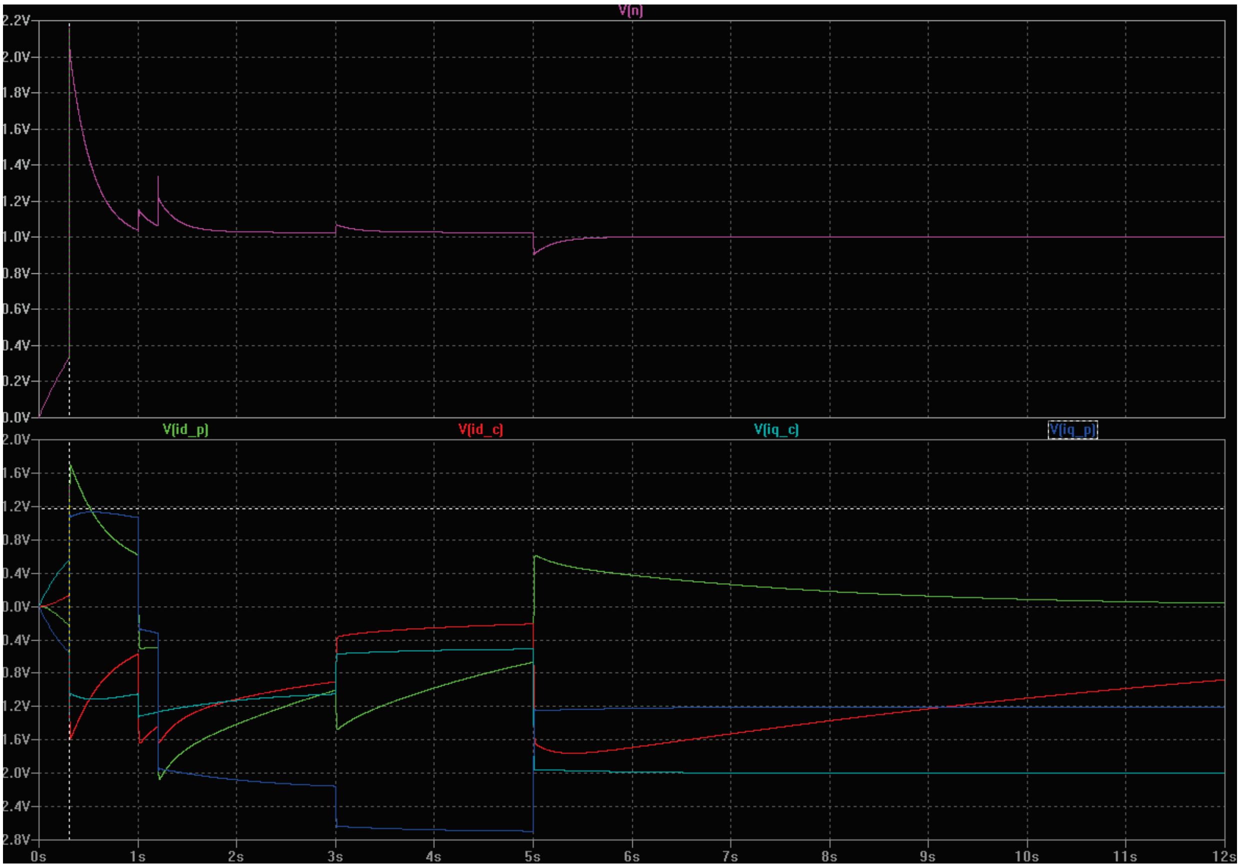


FIGURE 30: SECOND SIMULATION RUN RESULTS

12.2 Lab

The first lab started with just running the machine to show that it actually works like the first task described in chapter 9.3.

The turbine machine was ramped up to 50 Hz operation and the integration part of the speed regulator is disconnected, ref Figure 31. The peak in motor current seen in Figure 31 is a part of the start mechanism when running sensorless. The converter finds the position of the rotor by injecting a DC-current that gives back information about the rotor position.

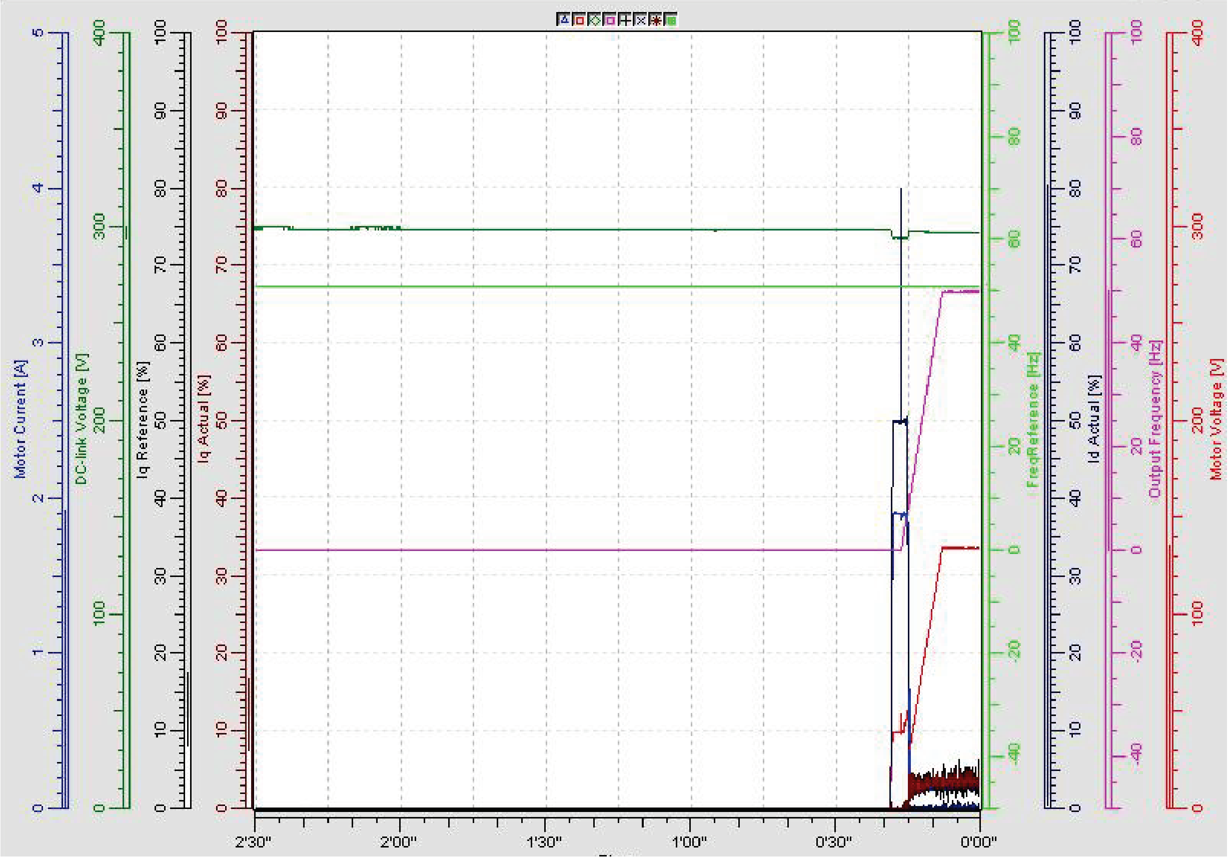


FIGURE 31: TURBINE MAHCINE IS RAMPED TO 50HZ SEEN FROM THE TURBINE MACHINE CONVERTER

Then the power winding are phased into the grid using the synchroscope. At first 60w bulbs where used, causing the machine to lose synchronism because of to high current. The bulbs where changed to 25w to reduce the current later. The power winding are then connected using a contactor.

There was some problems considering switching noise when synchronizing the power winding to the already running turbine machine that caused the turbine machine to stop turning. This was circumvented by running both the turbine machine and control winding when connecting the power winding, so if the turbine machine would stop it could be fly-started on the running DF-PMSM machine.

Then the control winding machine is fly started if not already, ref Figure 32, with nearly no disturbance on the turbine machine. Now both machines are running and contributing to keeping the speed of the machine. The power winding keeps the machine running at exactly the same frequency as the grid.

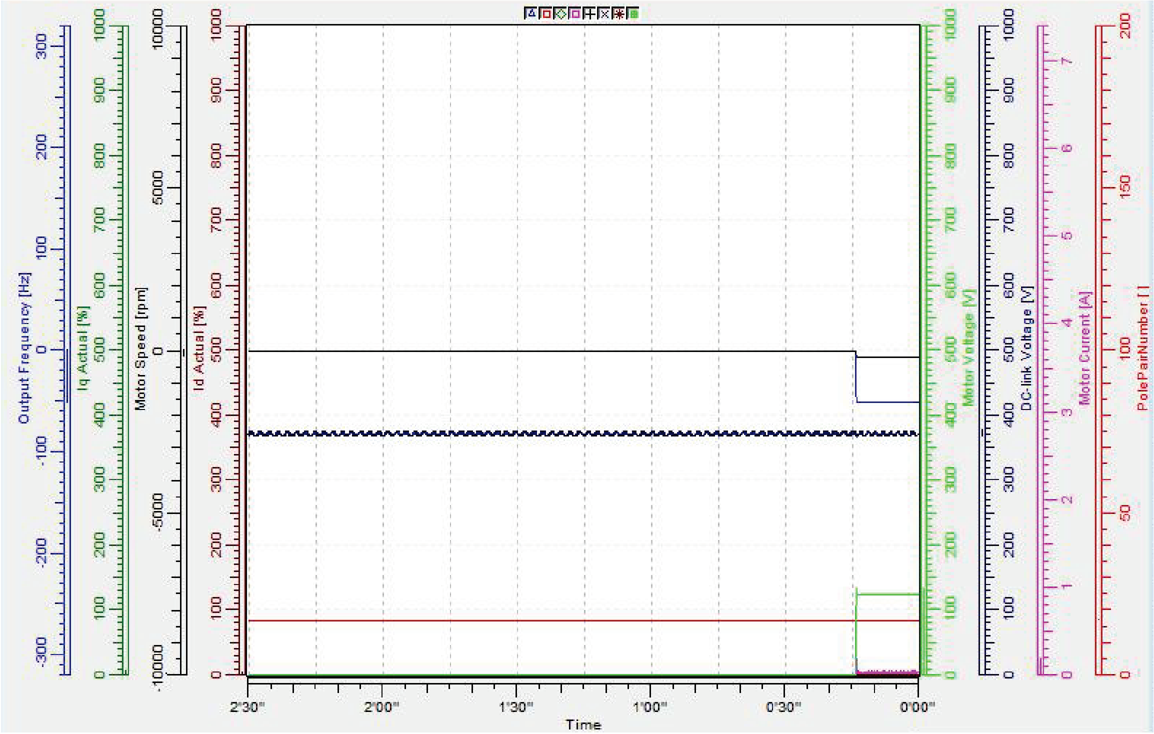


FIGURE 32: THE CONTROL WINDING IS FLY STARTED, SEEN FROM THE CONTROL WINDING CONVERTER

The turbine machine speed reference is increased in steps and since the integrator of the speed regulator is gone the only incline is in the machine iq-current as seen in Figure 33.

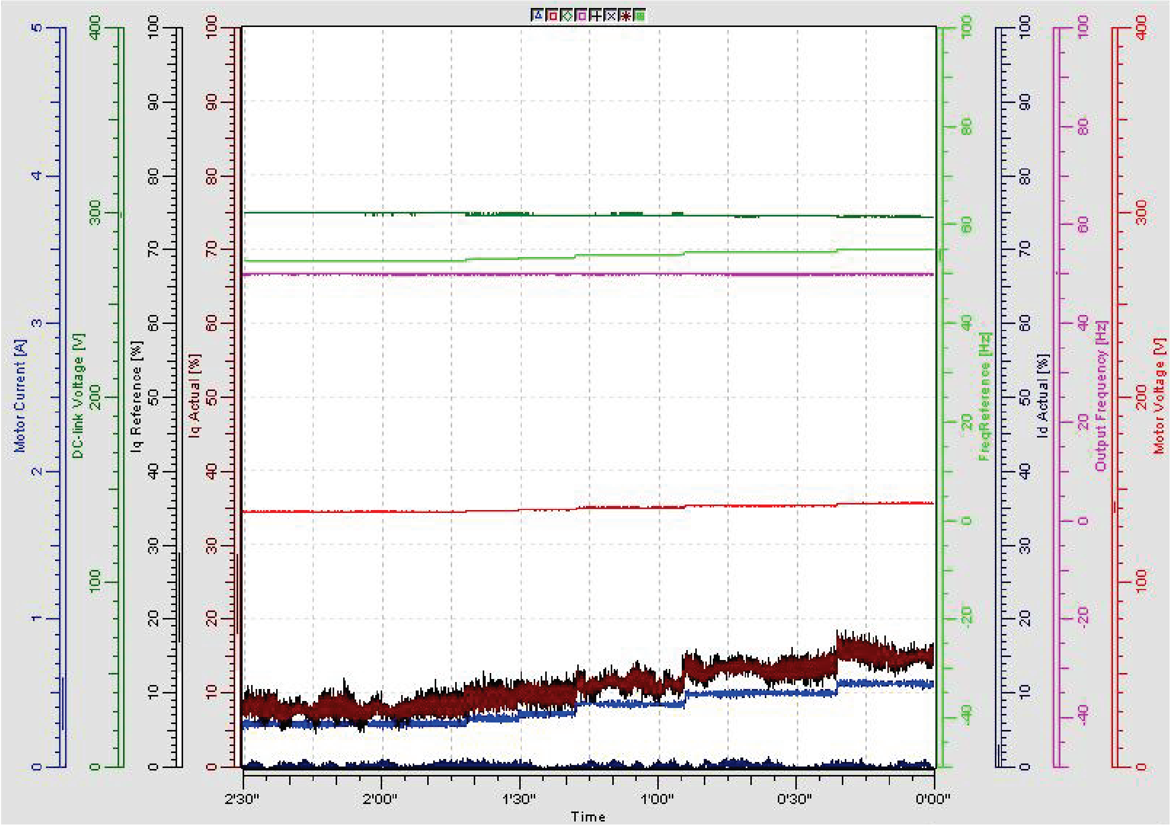


FIGURE 33: THE CURRENT REFERENCE IS INCREASED ON THE TURBINE MACHINE SEEN FROM THE TURBINE MACHINE CONVERTER.

This was done until the machine started making less noise when the speed reference at the turbine machine was 94%.

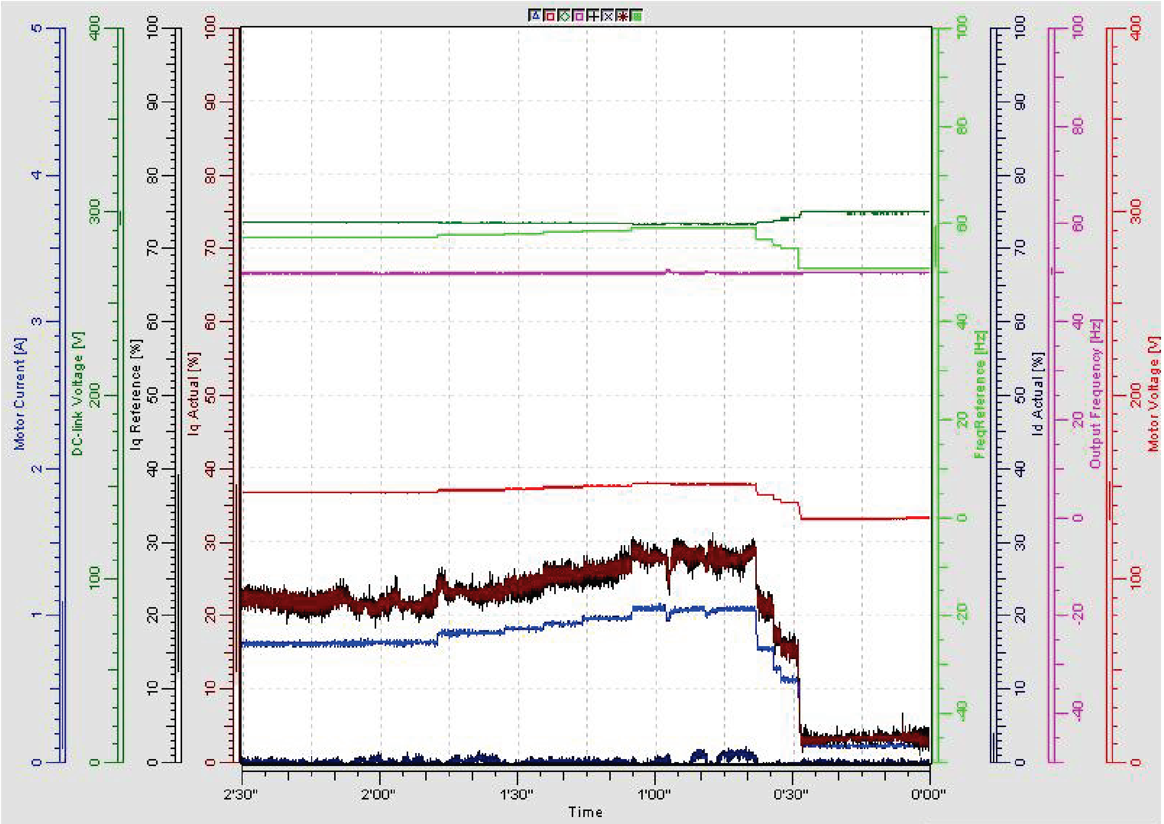


FIGURE 34: THE MACHINE WAS RUN UP TO 94% SPEED REFERENCE

The machine reference was operated up to 100% speed reference which equals to 60Hz in speed reference on the speed regulator

In Figure 35 the power flow to the DF-PMSM can be seen, including both control and power winding. Figure 36 shows the power factor. The power factor is bad because the active-front-end is not compensating with reactive effect.

The turbine machine was audible during the first experiment, but the noise disappeared as soon as the machine was producing active power to the grid. The noise was first presumed to be because of cogging because of the coil layout changed from being in series to parallel to reduce the back emf voltage. Later it was found that it was because of the rotor not being in center of the stator and therefore touching the stator during operation. When the load became large enough the rotor got back in place and the noise disappeared.

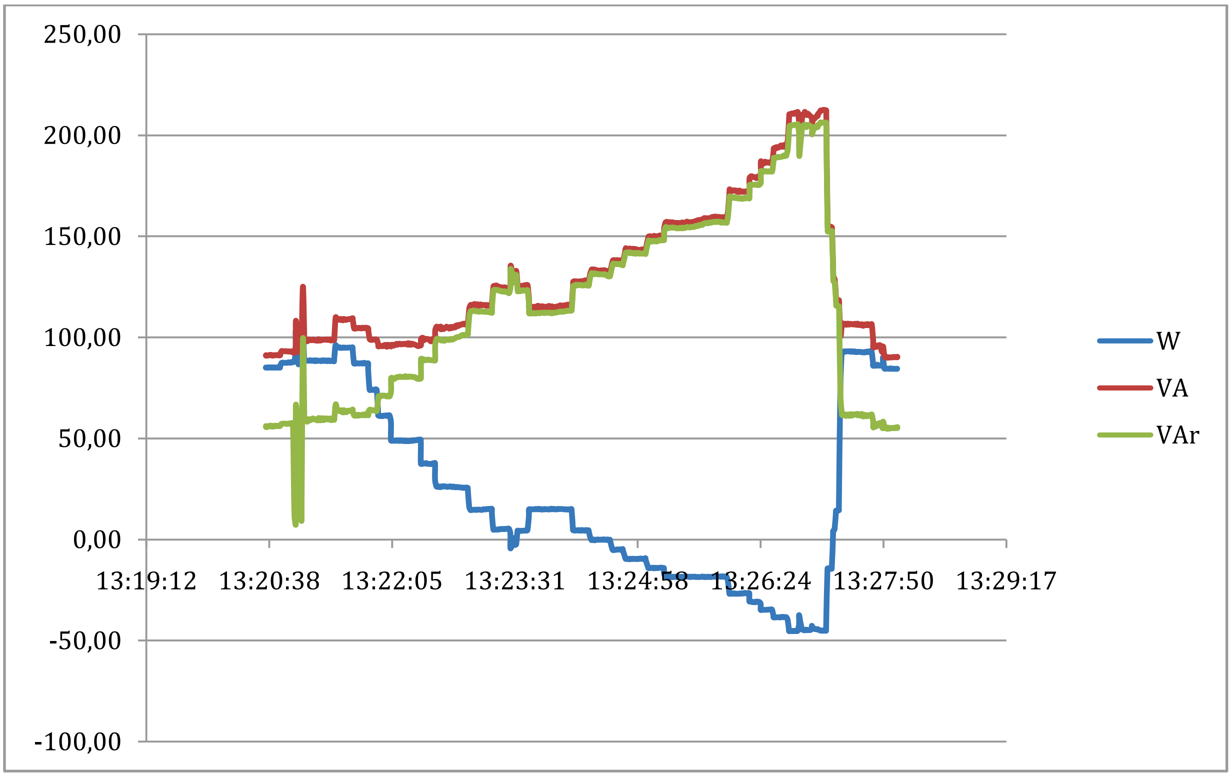


FIGURE 35: POWER FLOW IN DF-PMSM DURING GENERATION

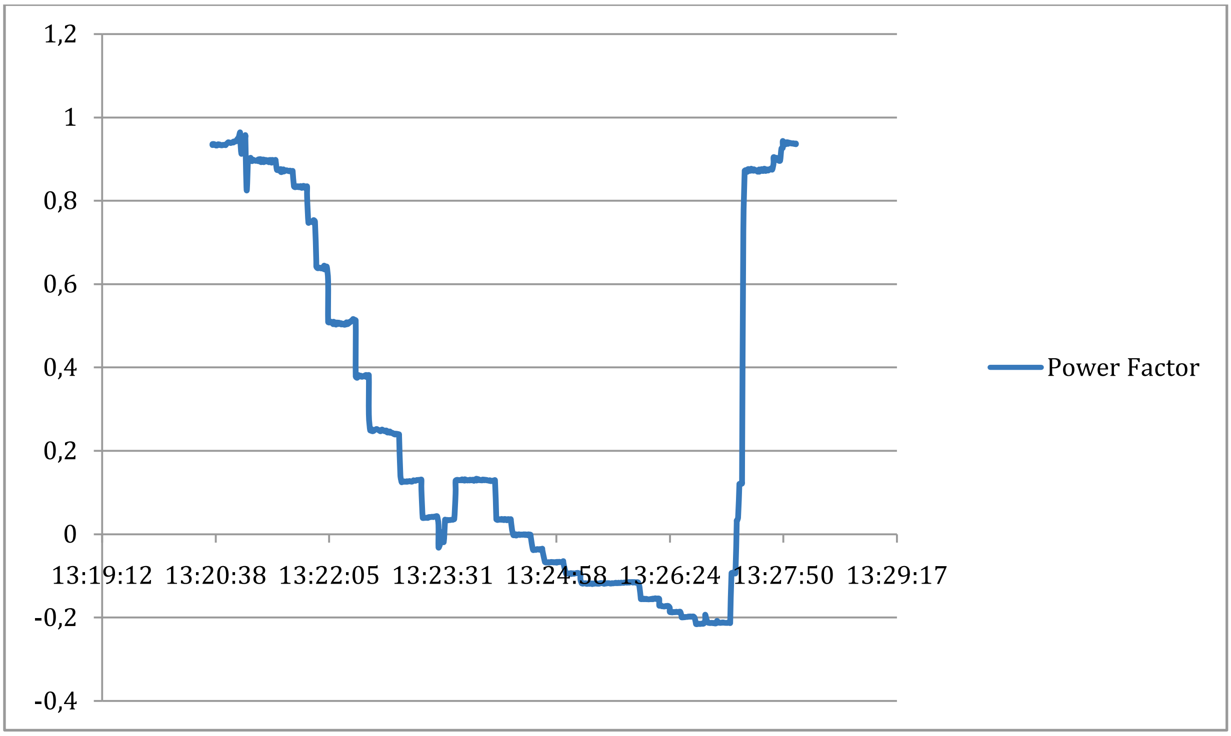


FIGURE 36: POWER FACTOR OF DF-PMSM DURING GENERATION

Under the second lab run the machine was driven up to speed like in the first run until the motor current was 1.5A, and the reactive current reference was changed so that the active front end consumed and produced reactive power. It gave the results seen in Figure 37 and Figure 38. The changes in reactive power produced a local voltage deviation of 3V at maximum during the experiment.

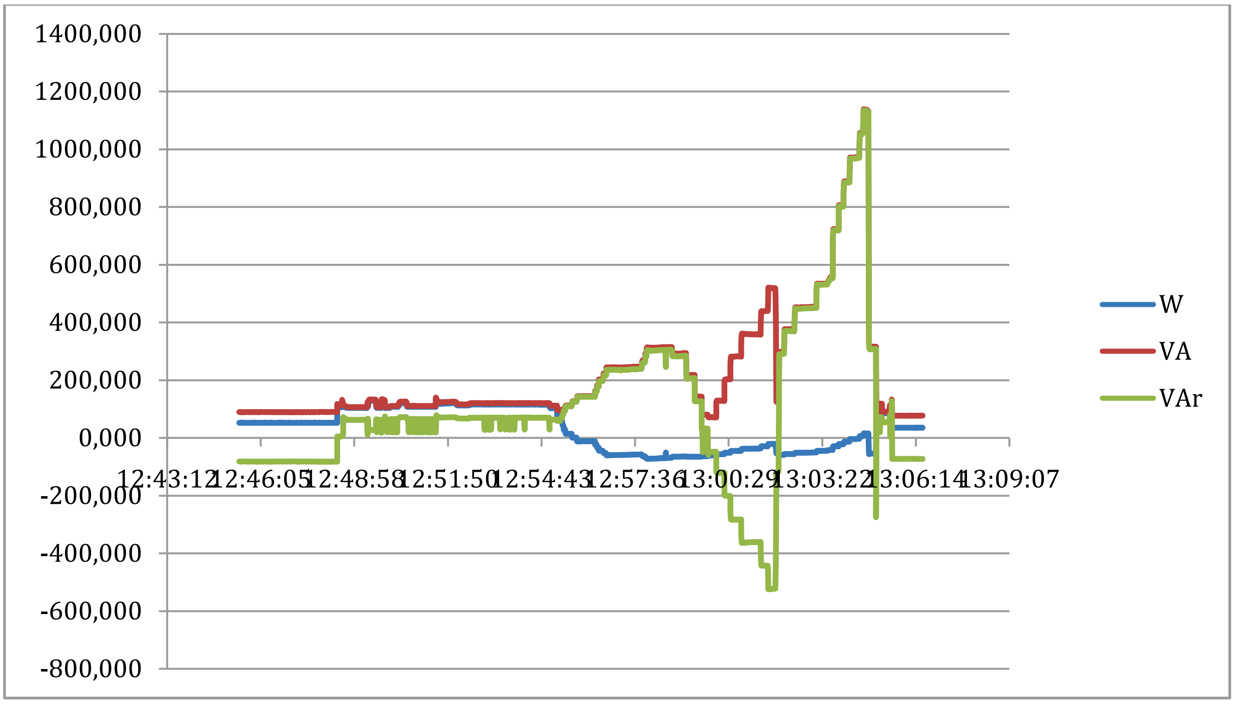


FIGURE 37: POWER FLOW IN LAB2 WITH COMPENSATION USING ACTIVE FRONT END

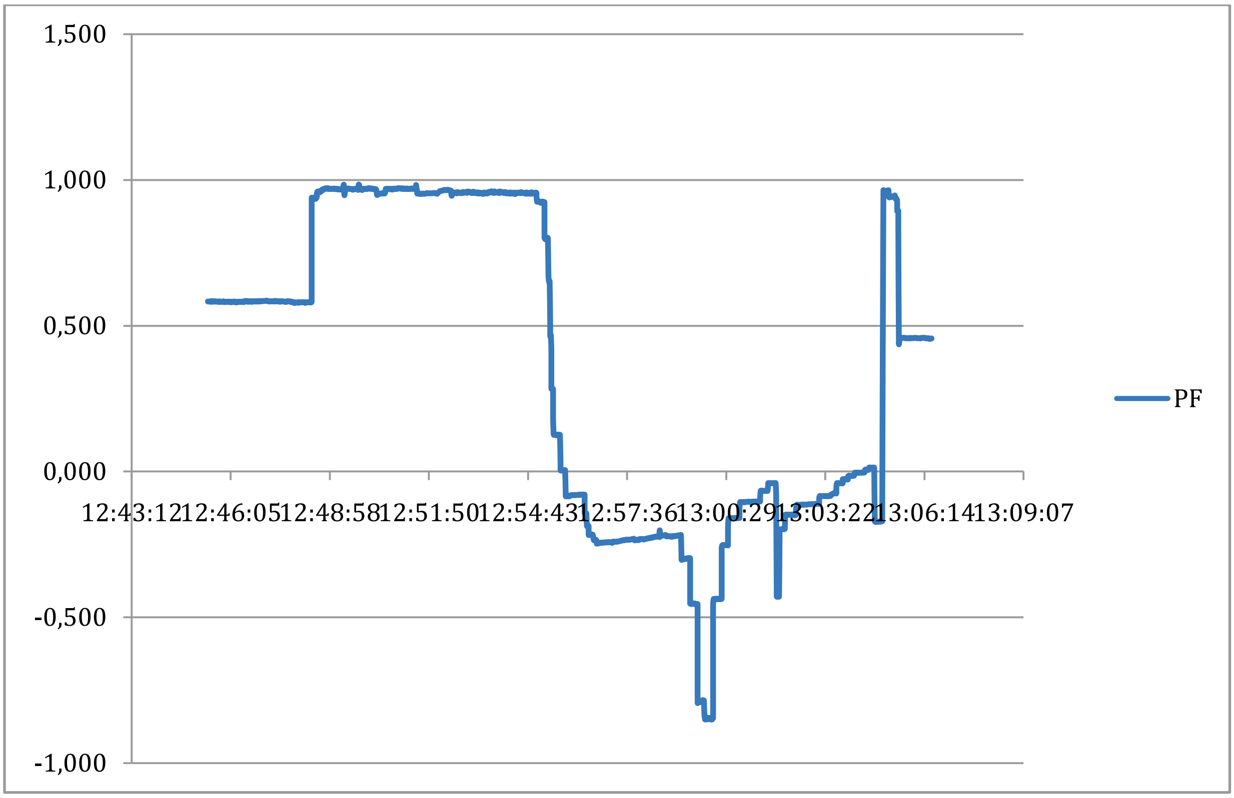


FIGURE 38: POWER FACTOR DURING LAB2

13 Discussion

In this chapter the results from the laboratory and simulations will be discussed.

13.1 Simulations

There were some shortages to the machine model considering that the 6-phase machine consisted of two separate 3-phase machines modeled on the same shaft that shared the equal load. This meaning it was impossible to simulate the effects of only operating half of the machine was working. There is also not possible to simulate interference between the winding sets with this model, therefore simulation of field weakening across the 3-phase sets is impossible.

The simulation firstly showed that the machine design works. As seen when the two machines shared the torque produced by the “turbine”. The regulators would need some tighter parameters to ensure less deviation from the speed and faster regulation, but the steady state values showed was stabile.

It showed how connecting the machines by first running the turbine up to speed, and then connect the power and control winding of the DF-PMSM would work. This of course is maybe not the wisest method in a small hydro power plant, and can be redone by staring the machine on the control winding of the DF-PMSM, then connecting the power winding and starting the turbine. The turbine and control winding can even start in parallel if the turbine is easier to control this way. The power winding must only be connected when the machine is operated at correct speed.

The last simulation shows that the machine copes with changes in demand of compensation power when connected to the stiff grid. The deviations in speed are because of the “simulated grid” using a closed loop regulator with not so strict parameters.

13.2 Lab

The converter setup was not straight forward for the lab exercise. This was a result of an early decision that the machines should be operated sensorless and therefore only closed loop speed regulation was possible in the machine application in the Vacon converter. This was circumvented on the turbine machine as the integrator part of the speed regulator was removed resulting in a current controlled machine with “unknown” current reference (The reference would be the speed deviation multiplied with the Kp of the speed controller).

The control winding on the other hand had problems when working together with the power winding to keep the speed. The integrator part had to be removed here as well not to give too much gain when the control winding frequency reference deviated from the grids frequency. This resulted in the control winding exerted nearly no opposing torque, leaving that job to the power winding, resulting in no active power flow from the control winding.

If the converters had a sensorless current control application or had a position encoder on the shaft this would have been no problem.

Even though this meant that the control winding nearly just lay unused the lab still showed that the machine worked according to theory. This was because the active front end was rated much higher than the machine and worked as a Statcom which compensated for the reactive power drawn as seen illustrated in Figure 39.

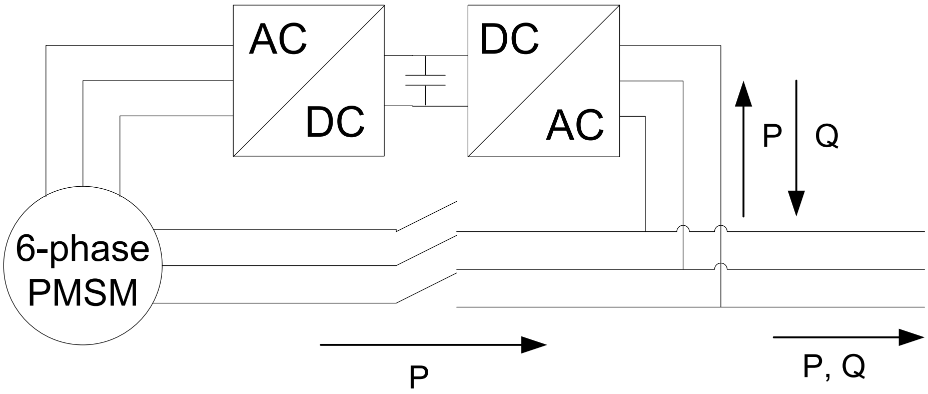


FIGURE 39: POWER FLOW DURING SECOND LAB EXPERIMENT

In the second lab run when the turbine machine was operated at maximum and the reactive power reference was changed there was one moment when the net flow of both active and reactive power was out from the generator in to the grid from the machine. The best power factor achieved then was 0.86 which could have been better if there was a regulator giving the reactive power reference which was in the lab changed in 10%-steps without knowing the result before after the experiment.

As long as the power factor was negative the active power flow was from the machine to the grid as seen in Figure 36 and Figure 38.

If the two converters used in this laboratory exercise are to be used in the DF-PMSM they would have to get data from an external controller with a power meter at the grid connection because of:

- The Active front end must get feedback about the power factor at the grid connection calculating the correct reactive power reference. The reactive reference in the Vacon converters is based on the amount of active power drawn by the active front end so the total power drawn by the active front end would also have to be outputted from the Vacon converter to the external controller.
- The converter on the control winding would have to be current-regulated getting feedback about how much q and d current to produce to the DC-link based on how much compensational power the active front end needs.

14 Conclusion

The concept is functionally proven by simulations and lab exercises. It shows that the machine is capable of working with two sets of three phases in the same generator both equal in size which must be the absolute maximum size of the control winding. The machine can operate on one or two of the windings without problems, though it was more audible.

The active front end capabilities where shown as it compensated for all the reactive power drawn and was found able to produce substantially more reactive power than the machine produced of active power resulting in a wide power factor range. This will in the final design be reduced because of a lower and optimal rated converter to suite the grid regulation demands to reduce the cost and losses.

As for the machine simulations missing a converter model and a more detailed machine model for even more exact simulations the results where good and showed how the machine would cope with changes in load and during starting/stopping. The machine simulation fundament developed in LTspice will ensure faster development of motor simulation in the future.

The optimal configuration for a permanent magnet generator in a hydro power plant in the doubly fed configuration can be to have a back emf voltage that equals the voltage of the power grid it is connected to. When operated at nominal voltage the machine will have a power factor of 1 and then the reactive power control is up to the active front end converter. The active front end must then supply reactive power making it possible to vary the power factor in a 0.9-0.91 range.

In normal operation of the DF-PMSM the control winding can be idle or produce active power to assist the power winding and supply reactive power when needed. But most of the time the machine will be set to produce at a fixed cos phi.

Most of the grid regulations based on fault scenarios and voltage peaks and dips can be fulfilled by a intelligent control system controlling the reactive power production and machine breakers and control these based on voltage/current/frequency measurements at the grid connection of the machine.

The most important aspects for further development of this machine are found to be the following:

- A market survey on how much interest there is for this type of machine prior to further development.
- The optimal converter size must be found based on the generator rating.
- The machine design must be optimized to match the converter rating.
- Investigation into field weakening of the power winding by using the control winding can be evaluated in a specially designed machine.
- A control system for remote control of the power plant and reactive power compensation must be developed with rules for what errors the generator must be disconnected according to the placement in the grid.

If this concept is developed further it would have potential to be sold as a cheap controllable alternative that makes it the first choice in new and old power plants. This will gain new and old power plant owners, the grid owners and the company producing and selling the DF-PMSM.

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