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Industrial Electrical Engineering and Automation

Island Operation with Induction Generators

Frequency and Voltage Control

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“Never forget that only dead fish swim with the stream”

Malcolm Muggeridge

Abstract

Our vulnerability to a blackout is increasing as the number of functions in the society depending on electricity is increasing. One way to decrease the outage time and the consequences of outages is to operate small distributed production units in island operation and thus supply a local load.

One of the best distributed generation sources are probably small hydro power stations. These have a high availability of controllable primary energy. Unfortunately these stations are often equipped with induction generators and their capabilities for island operation and black-start are not obvious. However due to the remanence in the generator it is possible to raise the voltage by means of connecting capacitors to the generator terminals and thus achieve black-starting. The voltage may then be controlled by supplying appropriate amounts of reactive power. If a part of the reactive power comes from fixed capacitors and the rest from a STATCOM, the voltage may be continuously controlled.

In this thesis island operation with two parallel induction generators excited by fixed capacitors and STATCOM is investigated in simulations and laboratory experiments. Different loads are used and it is shown that island operation is feasibly from the stability point of view. Further the influence of the voltage regulator is investigated and it is shown that a fast voltage regulator may not be desirable for induction generators in combination with hydro turbines.

To evaluate the possibility to maintain acceptable voltage and frequency quality during island operation a real hydro power station with a 275 kW semi-Kaplan turbine is studied. To assess the turbine behaviour, and the need for extra control equipment for island operation, field tests are performed in the power station. The influence of gate opening and runner blade angle is studied. The power-pressure relationship of the turbine is shown to exhibit behaviour similar to the power-voltage relationship of a power system often called nose curve, with a stable and an unstable operating region. Field test proves that no-load operation implies an unstable operating point. A small dump load is suggested to make sure that the unstable region is never reached during island operation. The power station is then simulated and different loads such as impedance load and

induction motor load are tested. It is shown that with load steps of about 6-10 % of the generator rating it is possible to maintain a voltage within 360-440 V and a frequency within 47.5-52.5 Hz. Further it is shown that damping increases with loading, i.e. the generator is able to handle larger load steps when already loaded.

The induction generator is quite complex, especially when operating with self-excitation. In order to help the understanding of its behaviour a mechanical model for the self-excited induction generator is developed. The model can be used to explain the cross-coupling between voltage and frequency, the self-excitation process and the impact of changes in load and turbine power. This offers a way to intuitively understand the dynamics of the self-excited induction generator.

Acknowledgements

Some years ago I thought I was done with the academic world. However Dr. Olof Samuelsson talked me into being a PhD-student and became an excellent supervisor. I am most grateful for this.

I would also like to thank Professor Sture Lindahl who, as an assistant supervisor, always answered my questions and shared a part of his great knowledge with me.

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Finally I would like to thank my parents, my father for all the discussions about the mystery of electricity and my mother for patiently listening to the frequent discussions about electricity at the dinner table.

Lund, December 2008
Johan Björnstedt

Contents

Chapter 1

Introduction

In this chapter the background to the thesis is initially presented. The objective of the thesis is described followed by its outline. Finally some contributions are stated.

1.1 Motivation

A half century ago, electricity was important but not necessary to maintain important functions in the community. Today on the other hand it is almost impossible to live a civilized life without electricity. The dependency on electricity has increased the consequences of a blackout. When we think of a blackout we immediately realize that space heating, light and communication are lost, but there are many other important problems that occurs. We have no water supply, no alarm functions, traffic problem, no fuel and most shops are closed.

In the early days of electricity, island operation was the general way to operate a distribution system. In rivers power stations were built to supply industries and other local loads effectively forming a small but complete power system. Gradually the electricity system was developed, small systems were interconnected and independent operation of these small systems – island operation – was forgotten. This has lead to many new distributed production units not designed for operation without connection to the grid. At a blackout these small stations cannot energize the local network. Today when we are more dependent on electricity than ever, island operation is again an interesting alternative. It is then possible to decrease the outage time and the consequences of an outage.

Island operation is something most utilities are anxious about. Distributed power sources are equipped with anti-island protection to avoid unintentional island operation. Unintentional island operation occurs if a part of the grid, with a generator and a load, is separated from the rest of the grid and the power supply is maintained. In this case, the power quality to the costumers could not be guaranteed and equipment may be damaged. Another important issue is the risk when personnel are sent out to work assuming a dead network which instead is energized due to island operation. These problems may of course not be neglected but let us not forget that island operation is used in many cases. A hospital having emergency backup power may be considered as a small island grid. Important industries such as paper mills disconnect from the grid and use their own power generation in an island grid during thunderstorms to avoid uncontrolled interruptions in the production.

There are a number of different types of small production units that might be suitable for island operation but one of the best is probably hydro power stations. These have a robust and reliable construction and they have the advantage to have a high availability of primary energy. This may not be the case with for example diesel generators that need a constant supply of fuel.

One way to utilize a small hydro power station is to energize a small medium voltage system and then use this system to start up a larger power plant. Another possible application is to supply important customers such as telephone stations and thus maintain communications.

A challenge with the small hydro power stations is that nowadays they are often equipped with induction generators. It is well known that it is possible to magnetize a stand-alone induction generator by means of capacitors connected to the terminals (Elder et al. 1983), (de Mello et al. 1981). These generators are inexpensive and reliable but need an extra controllable reactive power source to control the voltage. Another challenge is the slow turbine control leading to difficulties in frequency control.

1.2 Objectives

The objective of this thesis is to investigate parallel operated induction generators, driven by hydro turbines, in an island grid. The voltage control is handled by one STATCOM at each hydro power station and the frequency is controlled by a turbine governor at each set. The important question to be answered is whether it is possible to achieve acceptable power quality, i.e. acceptable frequency and voltage, in such system or not.

1.3 Outline of the Thesis

Chapter 2 contains a description of common components in a distributed generation system where island operation is feasible.

In Chapter 3 the self-excitation of the induction generator is described in a simple way and steady state calculations are performed. This chapter is written in collaboration with Francesco Sulla.

In order to help the understanding of the self-excited induction generator a mechanical analogy is presented in Chapter 4.

In Chapter 5 the basics in frequency and voltage control are discussed together with a more specific control strategy for hydro power and island operation of induction generators.

Power quality and other requirements are discussed in Chapter 6. Relevant standards for this thesis are IEC 60034-1 *Rotating electrical machines*, EN 50160 *Voltage characteristics of electricity supplied by public distribution networks*, SvKFS 2005:2 *Security requirements on production units* and SS 437 01 40 *Connection of low-voltage installations to the utility supply network*.

In Chapter 7 a test system with two parallel operated induction generators excited by fixed capacitors and STATCOM is simulated and tested in the laboratory. The chapter starts with a description of the test system, the simulation program and the simulation models. Then different load steps are tested and analysed.

Chapter 8 contains simulations of Forsa power station and some field test results.

Conclusions and some ideas on future work are summarized in Chapter 9

1.4 Contributions

This thesis shows that parallel operation of hydro power stations with self-excited induction generators in an island grid is realistic. Frequency is controlled by a turbine governor and voltage by a STATCOM.

Control performance depends a lot on individual power station properties such as inertia time constant. For a 275 kW hydro power station with semi-Kaplan turbine and induction generator it is shown that with load steps of about 6-10 % of the generator rating it is possible to maintain a frequency within 47.5-52.5 Hz and a voltage within 360-440V. The load has a stabilizing effect, hence the generator is able to handle larger load steps when already loaded.

A mechanical analogy for the self-excited induction generator is presented and used in order to help the understanding of the phenomenon in the self-excited induction generator.

The behaviour of a semi-Kaplan turbine at low load is investigated in a field test. It is shown that the power-pressure relationship is similar to the power-voltage relationship for a transmission line often called a nose curve.

Chapter 2

Distributed Generation System

When talking about island operation it is impossible not to mention something about distributed generation. The fact is that the production units supposed to run in island operation is the one distributed in the power system and connected at the lower voltage levels. Naturally these sources are much smaller than the large ones connected more directly to the transmission system.

2.1 Distributed Generation Sources

There are different definitions of distributed generation. One of them is given in (Ackermann et al. 2001) where many different aspects are taken into account. In general, distributed generation can be defined as electric power generation within distribution networks or on the customer side of the network. In Sweden there are mainly three types of distributed generation sources, combined heat and power, wind power and hydro power.

CHP

Combined heat and power plants are heated by fossil fuel or bio fuel and produce approximately 60 % heat and 30 % electricity. Hence they have the high efficiency of 90 %. One drawback with these power plants when it comes to island operation is that it is not possible to run them without producing heat at the same time as electricity. This could be a problem during the summer. If the power plant is located close to water it is possible to install condensers for cooling in order to produce electricity without producing any heat to the district heating system.

The electricity production from CHP and industrial back-pressure power is about 9 % of the total electricity consumption in Sweden.

Wind Power

Over the last few years the electricity production from wind power has increased and wind power has become an attractive alternative to fossil fuels. In year 2007 the Swedish wind power produced 1.4 TWh electricity, i.e. about 1 % of the total electricity consumption 146 TWh (Svensk Energi 2008). Today the trend is towards large offshore wind farms. However to fulfill the high European goals concerning generated power from wind it is necessary to build wind turbines onshore as well. These turbines are connected to the lower voltage levels and are therefore a part of the distribution system. The early wind turbines are equipped with induction generators that cannot be controlled in island operation. However the requirements on fault ride through capability for distributed generation sources have made solutions with power electronics more common. This result in increased opportunities to utilize wind turbines in island operation but there are still some difficulties due to the uncontrollable nature of wind.

Hydro Power

When talking about hydro power in connection with distributed generation it is the small sized hydro power stations that are concerned. There are several different definitions of small sized hydro power. In Sweden units below 1.5 MW are considered as small while the European Commission has put the limit at 10 MW.

In Sweden there are 1500 hydro power stations below 1.5 MW (year 2004). These stations have a yearly production of 1.7 TWh. If the 10 MW limit is used the number of power stations are 1650 and the production is 4.5 TWh which corresponds to 3 % of the total electricity consumption (Småkraftverkens Riksförening 2005).

In 1950 there were about 4000 hydro power stations smaller than 1.5 MW in Sweden but when the large scale hydro power and nuclear power expanded, many of the smaller stations were shut down. According to the Association for Small Hydropower in Sweden there are about 2000 old stations just waiting for restoration.

2.2 Hydro Power

This thesis is dealing with hydro power and here follows a short description of this area. Hydro power is a well-tried and reliable energy source with a long endurance. Furthermore it is environmentally friendly when it comes to carbon dioxide emission.

Turbines

There are two types of hydro turbines, impulse turbines and reaction turbines. The most common impulse turbine is the Pelton turbine. One or more jets are hitting buckets mounted on the periphery of a wheel. The flow is controlled by a needle in the nozzle. The Pelton turbine is used for high heads, 100 - 1500 m, and has a high efficiency down to 30 % flow. Due to the high heads these turbines are most frequent in larger power stations.

Reaction turbines could be divided into Francis and propeller turbines and are used for lower water heads. The Francis turbine has fixed runner blades and adjustable guide vanes. The turbine has a radial flow and is used for heads from 3–700 m. The highest efficiency, 90 %, is achieved at about 80 % of the maximum flow and decreases fast with decreasing flow. About 80 % of the small sized hydro power stations in Sweden are equipped with Francis turbines. The other 20 % are Kaplan turbines.

Kaplan and propeller turbines have an axial flow and are used on low heads 2–40 m. The Kaplan turbine has adjustable guide vanes and runner blades while the semi-Kaplan has fixed guide vanes and adjustable runner blades. The propeller turbine is unregulated and is used when flow and head is nearly constant. Due to the double control the ordinary Kaplan turbine has a high efficiency, 90 %, over a wide operating range. The peak efficiency for the semi-Kaplan turbine is over 90 % but like the Francis turbine the efficiency decreases fast with the flow. Due to the lack of adjustable guide vanes the propeller and semi-Kaplan turbine is dependent on a gate in order to start and stop the turbine.

Generators

In older power stations the synchronous generator is commonly used due to the fact that these stations were built to supply a local grid in island operation. The synchronous generator needs extra equipment for the excitation and has the additional drawback of mechanical wear of the brushes and slip rings. This could be solved by using brushless excitation but implies a higher cost.

When the power system grew and island operation was no longer necessary it became possible to replace the expensive synchronous generator by the less expensive induction generator. These have their magnetizing current from the grid and the control equipment is therefore minimized. Further, no synchronizing unit is needed when connecting to the grid. When the generator is running at nominal speed a circuit breaker is closed and the generator is magnetized from the grid. Approximately 25 % of the small sized hydro power stations in Sweden have induction generators.

Nowadays when island operation is an attractive alternative for reducing the effects of an outage, it is of interest to study island operation with induction generators.

Semi-Kaplan Turbine with Induction Generator

As an example of a small sized hydro power station an arrangement with an induction generator driven by a semi-Kaplan turbine is chosen. Such a power station is shown in Figure 2.1. The construction is very robust and reliable and requires minimum maintenance.

The turbine has a low speed and in order to reduce the number of poles in the generator, and thus the size, a gearbox is used between the turbine and generator so that the generator has a higher speed than the turbine. The gear ratio is chosen in order to have the highest efficiency of the turbine when the generator is operating at rated power.

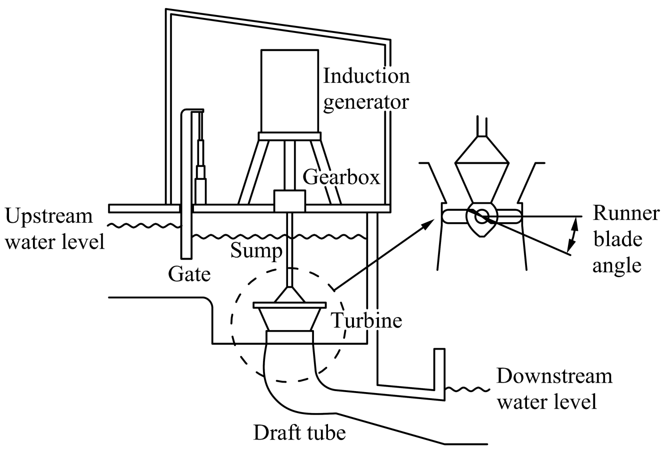

Figure 2.1 Hydro power station with semi-Kaplan turbine and induction generator and gearbox.

The start-up procedure is very straightforward: First the gate is slowly opened and the water accelerates the generator. At nominal speed the generator circuit breaker is closed and the generator is magnetized from the grid. The gate continues to open and when fully open normal operation is reached and the output power is determined by the runner blade angle. This start-up procedure requires a minimum of equipment, but assumes the existence of an energized network. The normal way to control such a turbine is to control the output power in order to keep the upstream water level constant. This control is very slow and requires only a simple regulator.

It is possible to operate the induction generator in island operation by means of connecting capacitors to the generator terminals. At the same time a turbine governor is required in order to keep the frequency at its nominal value. The combination with semi-Kaplan turbine and induction generator is one of the most complicated arrangements to control in island operation but if manageable, it would be possible to run all types of small hydro power stations in a local grid. A more detailed description of the self-excited induction generator is given in the next chapter.

Chapter 3

Self-Excited Induction Generator

Before proceeding to analyzing specific aspects of island operation with induction generators, it is very important to understand self-excitation. It is this physical process that permits the use of the induction generator in island operation. This chapter has the purpose to introduce this process and to explain how the steady-state operating points can be determined. An algorithm for predicting the steady-state operation of the self-excited induction generator, SEIG, feeding an impedance load is proposed. Experience has shown that after short-circuits, self-excitation may not take place because of the low residual flux in the induction generator. To gain a better understanding of how the residual flux varies with the fault resistance, some laboratory measurements on a small induction generator have been performed and are reported in the last section of this chapter.

3.1 Self-Excitation

Unlike the synchronous generator, an induction generator does not have an internal magnetization source. However, a voltage may build up in an induction generator as the result of a physical process known as self-excitation. This permits the utilization of an induction generator as a stand-alone unit operating in island without connection to any other voltage source.

The process of self-excitation is well known and it has been described mathematically in (Elder et al. 1983). It may take place if a sufficient amount of capacitors is connected at the generator terminals. Self-excitation is initiated by the residual flux in the induction generator rotor iron. When the generator is accelerated to a certain speed, the residual flux will induce a voltage in the stator. Under these conditions, the induction generator behaves much like a synchronous generator with permanent magnet rotor.

If capacitors are connected at the generator terminals, the induced stator voltage will cause the flow of a current into the capacitors. Depending on the generator parameters, the value of the capacitors and the generator speed, a transition from the synchronous operating mode to the asynchronous operating mode may take place at some point leading to the self-excitation of the induction generator.

Once the self-excitation process has started, the induction generator voltage builds up. The voltage build up can be understood by considering the phasor diagram shown in Figure 3.1. The induced stator voltage causes a capacitor current that generates a flux into the generator with the same direction as the residual flux. Therefore, the current circulating in the stator reinforces the residual flux. This in turn causes a higher induced stator voltage leading to a successive increase in current and flux.

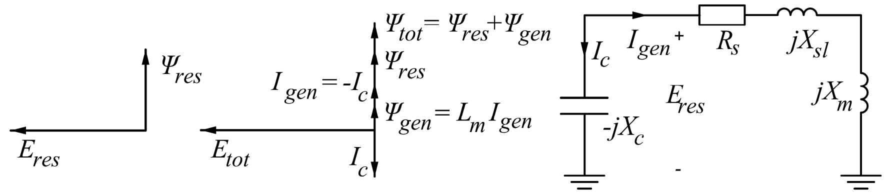

Figure 3.1 Phasor diagrams before and after the capacitor current starts to flow, neglecting stator resistance and leakage reactance. To the right, single line diagram of the induction generator and shunt-connected capacitors.

This voltage build up process comes to a halt when the capacitor voltage curve intersects the no-load curve of the induction generator, see Figure 3.2. This point is a stable operating point and it is the steady-state operating point of the self-excited induction generator running at no-load with the shunt-connected capacitors. At this point, the capacitors supply exactly the reactive power needed by the induction generator at no-load.

The no-load steady-state operating point is determined by the no-load curve of the induction generator, by the value of the capacitors and by the generator speed, as illustrated in Figure 3.2. Increasing the value of the capacitors has the effect of shifting the no-load steady-state point towards higher voltages. Increasing the generator speed, i.e. the frequency of the induced voltage, shifts the no-load curve of the generator upwards, while the slope of the capacitor voltage curve decreases. The net result is still an increase in the no-load steady-state voltage.

In reality, there exists another point of intersection with stable operation at very low voltage and current. The existence of this point has been confirmed during this work by laboratory measurements on a small induction generator. To start the self-excitation process, the generator must be "pushed" beyond this point.

From the above considerations, it is deduced that the connection of capacitors supplying a larger reactive power than needed by the induction generator at no-load may cause overvoltage at the generator terminals.

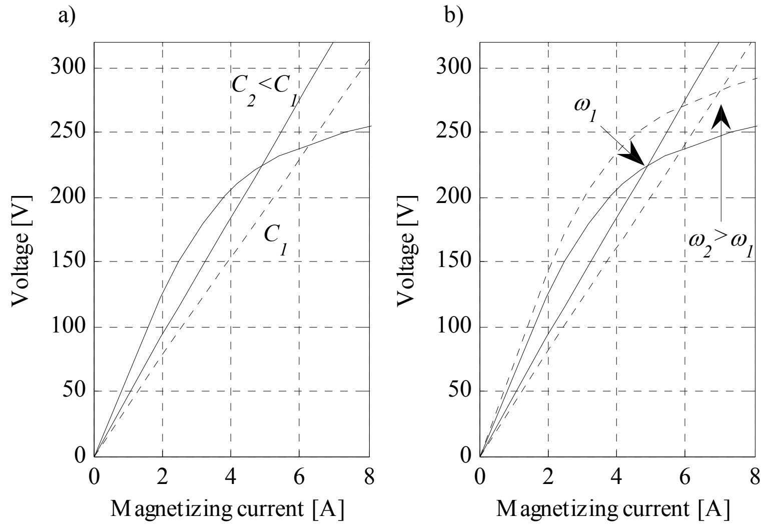

Figure 3.2 Induction generator no-load and capacitor voltage curve. a) Different capacitors. b) Same capacitor, different generator speeds.

3.2 Steady-state Analysis

It is common to plot the induction generator magnetizing curve at no-load as in Figure 3.2 but a similar curve applies for a loaded generator in steady-state as well. To determine steady-state operating points for the self-excited induction generator under different loading conditions, the equivalent circuit in Figure 3.3 is used. The load and capacitors connected to the generator terminals could always be interpreted as one resistive and one capacitive part. If the load has an inductive part it simply means that the resulting capacitor is smaller. If the load resistor and generator are considered together it is clear that the current flowing into the capacitors is 90º ahead of the terminal voltage and the only way to achieve this is to adjust the slip, s, so that the generator and the load together give a corresponding angle of -90º. The slip is the difference between mechanical and electrical speed and in this case the electrical speed is constant and the slip is adjusted by means of varying the mechanical speed. For a given load at a given voltage and frequency it is then possible to calculate this slip, and thus the generator impedance and current.

The advantage of this method is that is uses the same intuitive approach and the same kind of curves as used when determining the no-load steady-state operating point. From the analysis of these curves under loading conditions, it may be easily understood how the various parameters in the analysis will influence the generator steady-state operation.

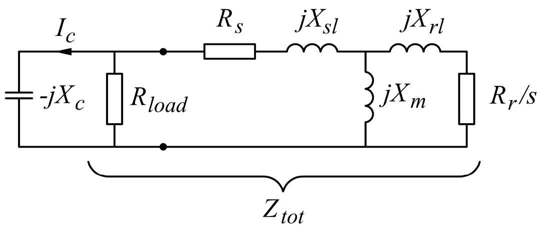

Figure 3.3 Per phase equivalent circuit of self-excited induction generator and resistive load.

Steady-state Laboratory Experiments

The induction generator no-load curve is experimentally determined by connecting the generator to the grid via a variable transformer and reading the current at different voltages. It is then important that the slip is zero when reading the current. The slip is adjusted to zero by means of a DC motor driving the generator.

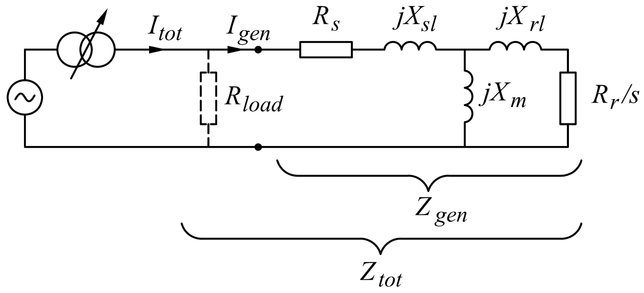

Figure 3.4 Per phase equivalent circuit of grid connected induction generator and resistive load.

The experimentally obtained no-load curve of a 230 V 2.2 kW squirrel cage induction machine with parameters according to Table 3.1 is displayed in Figure 3.5 with a dashed line. It shall be noted that the points at low voltage are very difficult to measure accurately. The induction machine parameters have been measured with standard no-load and blocked-rotor tests. A DC measurement of the stator resistance has also been done.

Table 3.1 Generator parameters.

Nominal power	2.2 kW
Nominal voltage	230 V
Nominal current	9 A
Stator resistance (R_s)	1.0 Ω
Rotor resistance (R_r)	0.7 Ω
Leakage stator inductance (X_{sl})	1.2 Ω
Leakage rotor inductance (X_{rl})	1.2 Ω
Base impedance (Z_{base})	14.8 Ω

A curve similar to the no-load curve could be obtained for the case with a loaded generator. This curve is measured with the 2.2 kW generator, and a parallel load resistor of 25Ω, connected to the grid via a variable transformer. The DC motor driving the generator is now adjusted to achieve a 90º lagging current from the grid meaning that the generator in parallel with the load is purely inductive and may be compensated by a capacitor if operated with self-excitation. The new curve, solid line in Figure 3.5, appears below the no-load curve. The characteristic of 8 steps of a capacitor bank is included in the figure to illustrate the fact that with fixed capacitors the voltage decreases when applying a load. Each capacitor step corresponds to a generated reactive power of 270 var at 230 V.

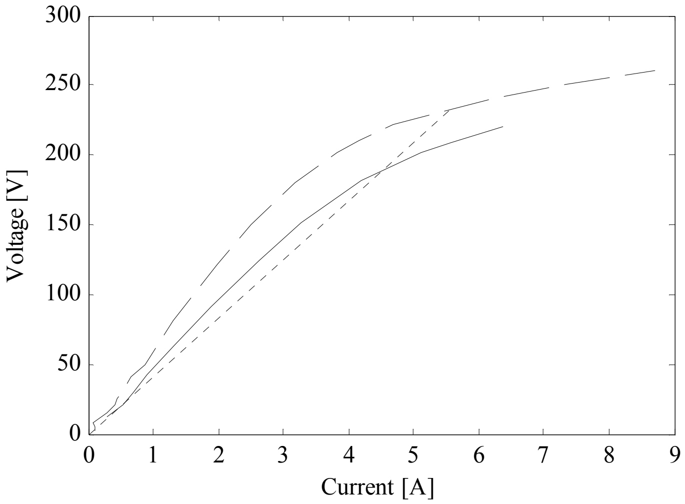

Figure 3.5 No-load curve (dashed), grid connected generator and resistive load (solid) and grid connected capacitors with 8 steps (dotted).

If we now replace the grid by capacitors it is possible to operate the induction generator with self-excitation. If different numbers of capacitor steps are connected, different operating points are obtained. These points form the very same curve as obtained in the grid connected mode. In Figure 3.6 the experimentally determined results with grid connected generator (solid line) and self-excited generator (+) are presented. As expected the new operating points correspond well with the intersection points between the generator and capacitor curves. For the case with 7 steps it is not possible to achieve a stable operating point and the generator demagnetizes. This could also be deduced from Figure 3.6 by observing that the 7 step curve is almost the tangent to the generator plus resistor curve, meaning that instability is reached.

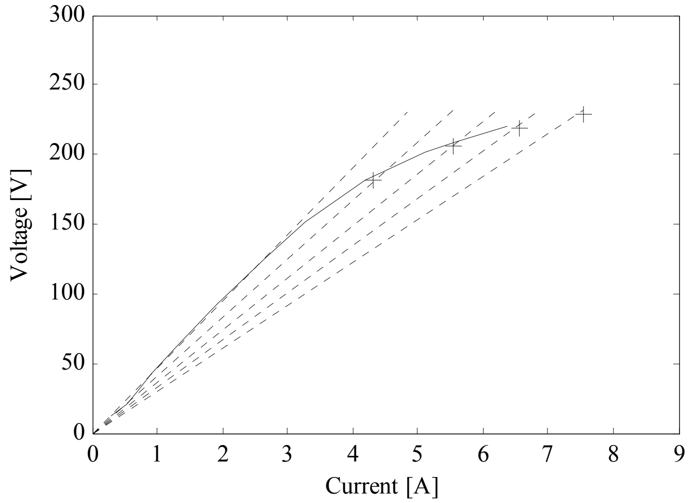

Figure 3.6 Grid connected generator and resistive load (solid), capacitor characteristic with 7-8-9-10-11 steps (dotted) and SEIG with 8-9-10-11 capacitor steps (+).

Algorithm for Steady-state Calculations under Load Conditions

From the previous section it is clear that the induction generator and the load resistor could be considered as one impedance, denoted Z_{tot} in Figure 3.4, when determining steady-state operating points. By means of a simple algorithm it is then possible to calculate all feasible operating points with any loading.

The no-load curve from the laboratory measurements is used and frequency is considered constant when calculating each steady-state point. For different voltages, the generator impedance is calculated by adjusting the slip so that the real part of I_{tot} is zero. A real part of $I_{tot}=0$ implies a possible operating point. The calculations are done under the assumptions that inductive reactances are proportional to the frequency and capacitive reactances are proportional to the inverse of frequency.

```
slip = -0.2
for every voltage V
      while real(Itot)>0.01
            increase slip by 0.00001
            calculate ZIG from Rs, Xsl, Rr/s, Xrl, Xm
            calculate Itot from V, Rload, ZIG
            calculate IIG from V, ZIG
            calculate Xm from no-load curve, V,
                        Rs, Xsl, IIG
      save Itot
```

To verify the calculations the results are compared with a SIMULINK SIMPOWERSYSTEMS simulation of a self-excited induction generator and measurements on the laboratory machine. The results are presented in Figure 3.7. The small deviations between calculated, simulated and measured values are mainly due to how the machine no-load curve is implemented in SIMPOWERSYSTEMS and uncertainties in the measured laboratory machine parameters.

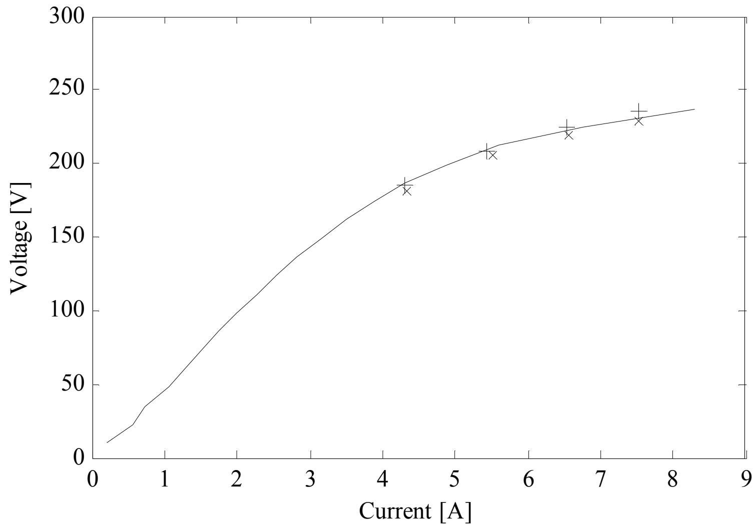

Figure 3.7 SEIG with 25 ohm resistive load. Calculations (solid), simulations (+) and laboratory experiment (x).

The procedure described above could be repeated for different frequencies and result in Figure 3.8. The capacitor characteristic appears as a surface in the figure and the intersection between the capacitor and generator-load surfaces represents all possible operating points with R_{load}=25Ω and 10 capacitor steps.

When the generator is accelerated, with the capacitors connected, self-excitation is not possible in the beginning. Then at about 40 Hz the self-excitation process starts and the voltage increases. If the generator is further accelerated it moves along the curve formed by the intersection between the two surfaces. If the generator speed decreases below a certain frequency self-excitation is not possible and the generator demagnetizes.

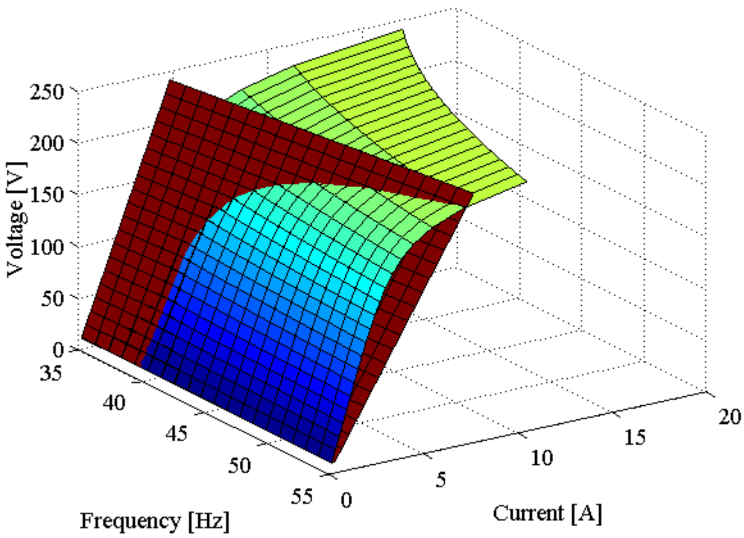

Figure 3.8 Characteristics of a loaded generator (green-blue) and a capacitor (brown). The intersection between the two surfaces represents all possible steady-state operating points at different frequencies.

3.3 Residual Flux Measurements

It is often stated in the literature (Bansal 2005), (Jain et al. 2002) that it may be difficult to self-excite an induction generator after it has been stopped with some load connected or after a short-circuit. The reason is the loss of the residual flux in the rotor iron. More precisely, the residual flux in the rotor iron will decrease to a low value and this value will depend on the way a previously excited generator has been stopped. To get some more insight into the dependence of the residual magnetism on the fault resistance of an applied short-circuit, some measurements have been performed on the small induction generator used above.

The generator has been previously excited and it has been run at nominal speed. Three-phase short-circuits with different fault resistance have been applied at its terminals. The short-circuit causes the demagnetization of the induction generator. After the demagnetization has occurred, the capacitors and the fault resistance have been disconnected while the generator was still running, and the voltage induced by the residual flux has been measured. It is remarked that stopping and reaccelerating the generator proved to have no effects on the reading of the residual voltage. Therefore, during the measurement sequence the generator was never stopped.

The measurements are shown in Figure 3.9. It can be observed that the residual flux magnitude decreases as the fault resistance increases from zero. A further increase in fault resistance does not change much the value of the residual flux. It is interesting to note that above a certain fault resistance, close to twice the generator base impedance, the residual flux increases sharply.

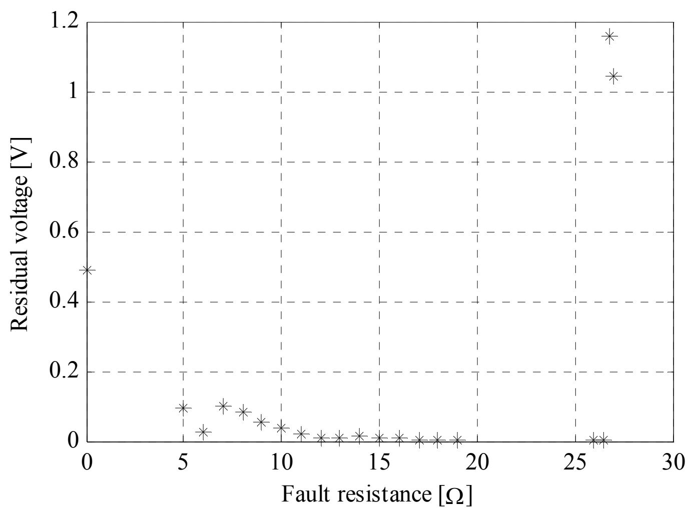

Figure 3.9 Measured residual phase-phase voltage as a function of fault resistance of the applied three-phase short-circuit. The generator base impedance is 15Ω.

The measurements show that a sudden connection of a resistance close to the generator base impedance results in the demagnetization of the generator and a subsequent very low residual flux in the rotor iron. On the other hand, solid short-circuits and connection of a resistance higher than twice the generator base impedance both cause higher residual fluxes.

Different methods can be used whenever the self-excitation of the induction generator becomes difficult due to low residual flux in the rotor iron (Elder et al. 1983). Among these, connecting a dc voltage source, for example a battery, to the stator seems the most practical one. Other methods, such as using high value capacitors or accelerating the generator above nominal speed, may cause dangerous overvoltages once the self-excitation process has started.

3.4 Summary

The self-excitation process has been described together with an explanation of how to determine steady-state operating points. An algorithm for predicting the steady-state operation of the self-excited induction generator feeding an impedance load was proposed. Laboratory measurements on a small induction generator were performed and it was shown that the residual flux after a short-circuit varies with the fault resistance.

Chapter 4

Mechanical Model

The principle of a self-excited induction generator was described in the previous chapter. To help the understanding of the induction generator, and motor as well, a mechanical analogy for the electrical system is useful. Such an analogy is described in this chapter and the behaviour when increasing load, speed and capacitance is studied in the mechanical system. The mechanical analogy of the electrical system together with a representation of the mechanical part of the machine is also very useful when studying oscillations in a system. (Peterson 1993)

4.1 Electrical System

The electrical part of a squirrel cage induction machine may be described by the following equations in the stator reference frame (Kovács 1984)

$$\frac{d\overline{\psi}_s}{dt} = \overline{u}_s - R_s \cdot \overline{i}_s \tag{4.1}$$

$$\frac{d\overline{\psi}_r}{dt} = j\omega\overline{\psi}_r - R_r \cdot \overline{i}_r \tag{4.2}$$

where the fluxes are given by

$$\overline{\psi}_s = \overline{i}_s\left(L_{sl} + L_m\right) + \overline{i}_r \cdot L_m \tag{4.3}$$

$$\overline{\psi}_r = \overline{i}_r\left(L_{rl} + L_m\right) + \overline{i}_s \cdot L_m \tag{4.4}$$

The mechanical motion of the machine is described by

$$J\frac{d\omega}{dt} = \mathrm{Im}\left(\overline{\psi}_s^* \cdot \bar{i}_s\right) - T_m \tag{4.5}$$

Voltage, current and flux phasors for an induction motor and generator are shown in Figure 4.1. If the stator resistance is neglected the stator flux Ψ_s is perpendicular to the stator voltage u_s.

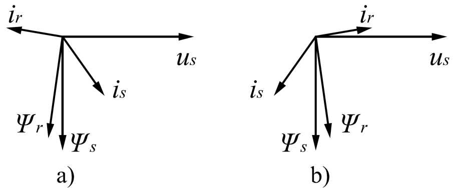

Figure 4.1 Voltages, currents and fluxes for a) induction motor and b) induction generator.

4.2 Mechanical Analogy

Equation 4.1 to 4.5 form the complete description of an induction machine and the phasors are shown in Figure 4.1 but the behaviour of the machine is difficult to see. The equations could be linearized and eigenvalues calculated but the machine may still be a mystery especially when operated with self-excitation. To help the understanding of the generator a mechanical analogy is used. The translation between the electrical and the mechanical system is presented in Table 4.1.

Table 4.1 Translation between electrical and mechanical quantities.

Electrical Quantity	Mechanical Quantity
Power P (W)	Power P (W)
Current i (A)	Force F (N)
Voltage u (V)	Speed v (m/s)
Flux Ψ (Vs)	Distance x (m)
Resistance R (Ω)	Inverse of damping $1/d$ (m/Ns)
Inductance L (H)	Inverse of spring stiffness $1/k$ (m/N)
Capacitance C (F)	Mass m (kg)

The mechanical analogy for an induction motor is described in (Peterson 1993), here the analogy is applied to a self-excited induction generator.

When translating the electrical system to a mechanical system an inductance becomes spring with stiffness k proportional to the inverse of the inductance and the fluxes are phasors with the same length and direction as in the electrical system, see Figure 4.2. Then a force equals current. This force is transferred from the rotor to the stator by means of a viscous damper with the damping d=1/R_r. The rotor resistance may be represented by a drag-pad on an oily rotor surface. The stator voltage equals the velocity of the tip of the stator flux phasor. In order to raise the voltage on the generator a capacitor is required. The capacitor is represented by a mass m attached to the tip of the stator flux. This mass is dragged on an oily stationary surface with the damping representing a load resistor connected in parallel with the capacitor. An increase in damping then implies an increase in load, i.e. decrease in load resistance. In this model the stator resistance is assumed to be small compared the stator leakage impedance and is neglected.

When the rotor is rotated by means of a mechanical torque applied to the shaft, the rotor resistance drag-pad make the fluxes rotate with an angular speed somewhat below the rotor speed. This difference in speed corresponds to the slip. Due to the centrifugal force on the mass and the damping from the load, a force i_s is applied to the tip of the stator flux phasor. This force is a combination of the radial force Im(i_s) from the rotation and Re(i_s) from the damping on the stationary surface. It is then clear that when running at no load the generator current phasor is radial. The generated voltage corresponds to the velocity of the mass and is thus proportional to the rotational speed and the distance form origin, i.e. the stator flux.

$$u = \omega \cdot \psi \Leftrightarrow v = \omega \cdot x \tag{4.6}$$

If the rotor plate has the same inertia as the actual rotor this is a complete model of the machine and any dynamics in the machine may be studied.

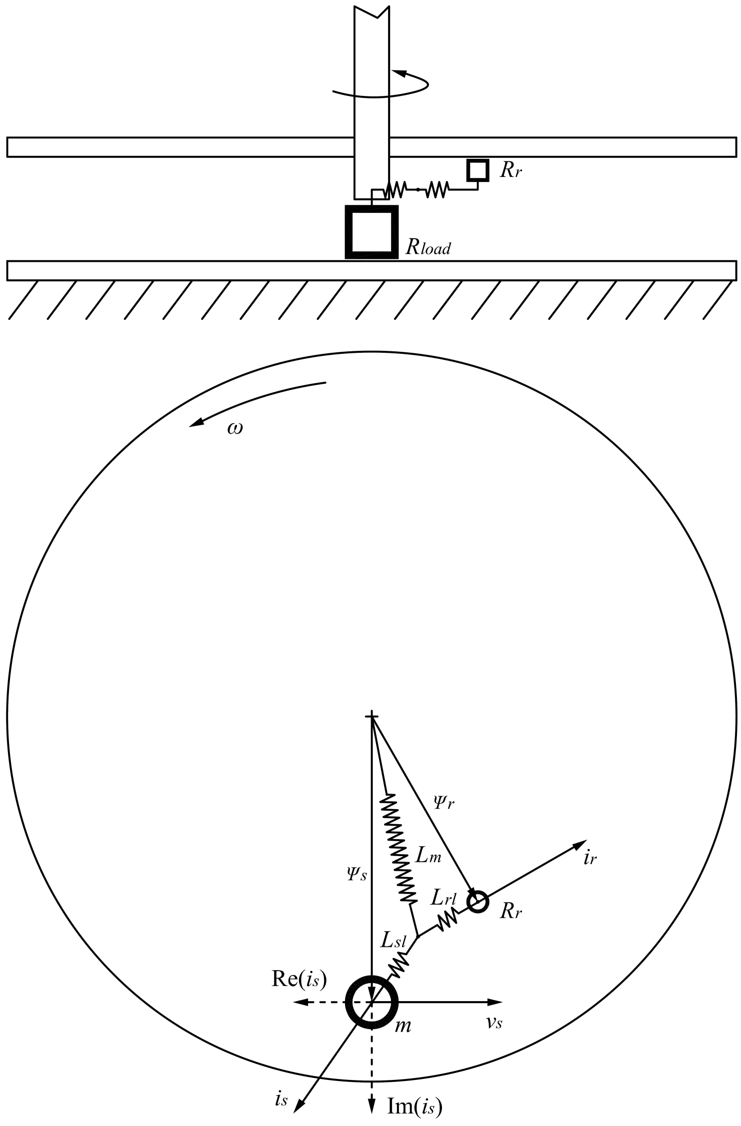

Figure 4.2 Mechanical model of a self-excited induction generator.

4.3 Explaining Dynamic Phenomena

By means of the mechanical model the most important dynamic phenomena in the self-excited induction generator may be described in order to make the understanding easier.

Black-Start

Energizing a power plant after an outage is called black-start. It is a very important way to initiate island operation. The remanence in the rotor causes an initial flux in the rotor and stator. In the mechanical model this equals a small offset of the rotor drag-pad from the origin. When the rotor is accelerated the radial force on the mass increases and the mass is moved outwards from the origin. At the same time the rotor drag-pad moves outwards. Hence the stator and rotor fluxes are increased. The condition for magnetizing the generator is that the centrifugal force on the mass is higher than the force from the spring L_m.

$$m\omega^2 x > kx \tag{4.7}$$

$$m\omega^2 > k \tag{4.8}$$

This may be transferred back to the electrical system

$$C\omega^2 > \frac{1}{L_m} \tag{4.9}$$

and an expression similar to the one for resonance is obtained

$$\omega > \frac{1}{\sqrt{CL_m}} \tag{4.10}$$

From equation 4.8 it is clear that with a spring constant k, once the excitation process has started the mass would move outwards eternally. Fortunately the spring is saturated just like the inductance L_m in the electrical system. When the spring is stretched it becomes more and more a straight string and its stiffness increases. Consequently the force it takes to stretch the spring increases with increasing distance x and a stable operating point is obtained.

Increasing Load

When operating at no load and with losses neglected the stator current is solely imaginary and the stator and rotor fluxes are in phase. When increasing the load, i.e. decreasing the resistance a braking tangential force is applied to the mass. The fluxes then move apart from each other and the slip is increased. If the mechanical input power is constant the braking force from the load then leads to a decrease in rotor speed and consequently the radial force on the mass is decreased. Hence the voltage is decreased both due to the decrease in rotor speed but also due to the decrease in distance from the centre point to the mass. The frequency may be restored to its nominal value by means of increasing the input power. At the same time the voltage increases but due to the braking force on the mass the voltage will be somewhat below the voltage prior to the load step.

Increasing Shunt Capacitance

There are two ways of increasing the voltage, one is to increase the speed and the other one is to increase the amount of capacitors, i.e. the mass. If the mass is increased with a turbine governor keeping the frequency constant the mass will move outwards. Due to the increased distance from origin the braking torque and thus the power to the load will increase.

Demagnetizing

The generator may be demagnetized if the load is increased too much, the capacitance is decreased or the speed is decreased. In all three cases the radial force on the mass will decrease. If the decrease of the radial force is small a new stable operating point will be obtained but if the decrease is big the resulting force on the mass will be inwards. The mass moves towards the center point and the generator is demagnetized.

4.4 Summary

The basics of a mechanical analogy to the self-excited induction generator are described. The model is perfect for interpreting machine behaviour as observed from measurements or simulations.

Chapter 5

Voltage and Frequency Control

In this chapter the voltage and frequency control is described. First a general voltage and frequency control is considered and then the control of an island operated induction generator.

5.1 Voltage and Frequency Control in General

The frequency in a power system is closely related to the generator speed. In synchronous generators the speed is directly tied to the frequency through the number of poles divided by two. In induction generators the frequency also differs from the mechanical speed by the number of poles divided by two, but also by the slip which is in order of a percent. The torque balance in the system given by Equation 5.1 directly affects the system frequency.

$$J\frac{d\omega}{dt} = T_{mec} - T_{el} \tag{5.1}$$

A difference between driving mechanical torque, e.g. water in a turbine, and electrical load torque results in a change in frequency. Equation 5.1 could be expressed with power as well.

$$J\omega\frac{d\omega}{dt} = P_{mec} - P_{el} \tag{5.2}$$

If the input mechanical power is higher than the electrical power consumption the frequency increases and if the consumption is higher than the input power the frequency decreases. The rate of change in frequency is proportional to the inverse of the inertia, *J*. In a big power system *J* is the total inertia of all connected generators and their turbines. With more generators connected a disturbance has less influence on the frequency. It is thus more difficult to regulate frequency in an island grid with only one or a few generators. The same load changes will have greater impact on frequency than at interconnected operation.

The influence between power and frequency is utilized in the turbine control. In Figure 5.1 a load step is applied to a generator with frequency control. The frequency decreases and the frequency error is fed back to the turbine governor which opens the gate. After about 15 s the input power is higher than the consumed power and the frequency increases. At t=110 s the balance between mechanical and electrical power is restored and the frequency is stabilized at a value lower than 50 Hz. The deviation Δf is determined by the gain R in the turbine governor in Figure 5.2.

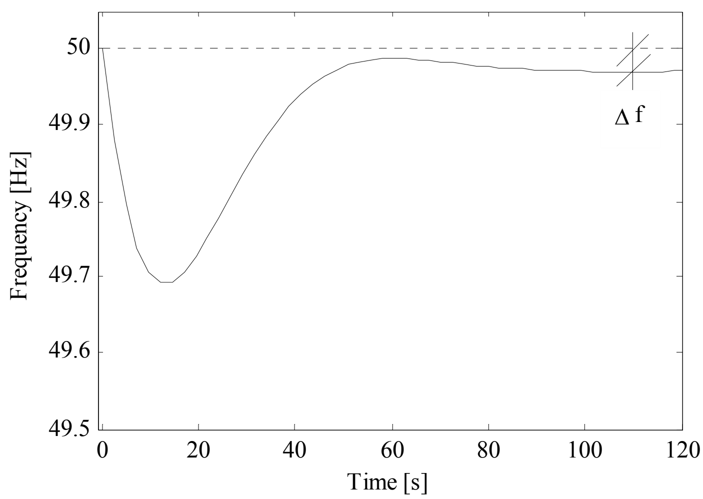

Figure 5.1 Frequency response when applying a load step to a power plant on frequency control.

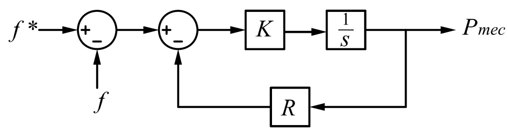

Figure 5.2 Frequency controller.

The gain R is called frequency droop. It is given by

$$R = \frac{\Delta f}{\Delta P} \tag{5.3}$$

and determines the maximum steady-state frequency error when the generator is operating at full load. If R is selected to have the same value in pu for different generators this allows parallel operation with equal sharing of the control effort. A change in frequency then results in the same power change in pu for all the generators. This is illustrated in Figure 5.3 where the right generator is half the size of the left and therefore has half the power. R is the slope of the droop characteristic.

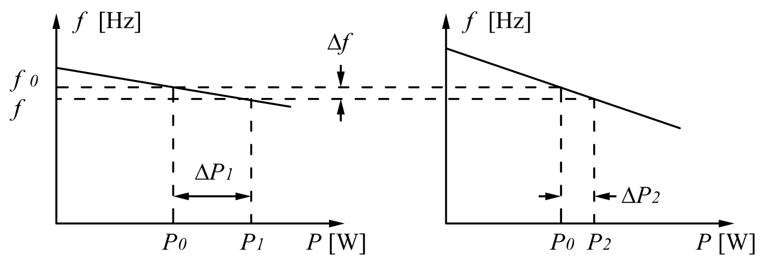

Figure 5.3 Load sharing by parallel units with droop characteristic.

While the frequency is the same in the entire grid the voltage is not. The voltage is controlled by each generator individually. In a synchronous generator this is done by changing the excitation. The reactive power to the grid is then changed and the voltage at the connection point is changed accordingly. Another way to control the voltage in a grid is to change the reactive power balance by means of connecting reactors or capacitors. The local change in voltage may then be approximately calculated from the short circuit capacity of the grid.

$$\Delta V \approx \frac{\Delta Q}{S_{sc}} \tag{5.4}$$

5.2 Hydro Power

When the load in the power system is changed it is important to immediately compensate for this by means of changing the mechanical power input to the generators. If this is not done properly the frequency may deviate too much from 50 Hz and in case of a big change in power, caused by for example disconnection of a large production unit, the power system may go unstable. A fast turbine governor is therefore desirable. However all types of power sources do not permit fast control of mechanical power. Among these are hydro power stations which often have long waterways and hence a large inertia in the water that has to be accelerated when an increase in power is required. An additional problem with hydro power is the non minimum phase characteristic of the system. When opening the gate the power decreases before increasing. This may lead to instability if the electrical power is used as feedback to the governor. Another problem with power feedback is that the voltage control affects the frequency control. Voltage variations may then lead to fluctuations in the water flow which results in torque and power oscillations and further voltage variations. If the gate position is used as feedback signal instead, the system will be more stable. However the relation between gate position and power output is non-linear and thus the feedback is slightly non-linear. In case of an electro-hydraulic turbine governor this may be easily compensated for and causes no problem.

5.3 Hydro Power Station in Island Operation

Small island systems with low inertia tend to lead to higher frequency variations than for large interconnected system. In hydro power plants the water inertia is significant and implies an additional challenge when maintaining as stable frequency as possible.

The frequency control with droop described above is insufficient for hydro turbines in island operation. The total inertia is small, the load steps are big in proportion to the generator rating and the mechanical system is slow due to long water starting time. This together with the non minimum phase characteristic puts great demands on the frequency control. If a fast turbine governor is used this will lead to instability. To maintain stability the governor has to be slowed down in order to give time for the water to accelerate. This is achieved by means of a transient droop compensation in the governor (Kundur 1994). Such a governor where the speed error is fed back in the outer loop and the gate position in the inner loop is shown in Figure 5.4.

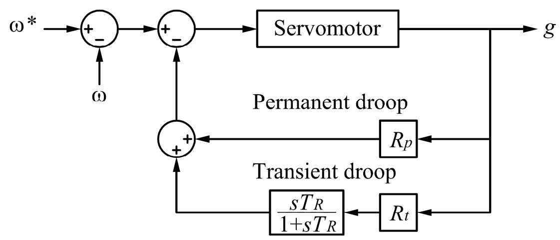

Figure 5.4 Turbine governor with permanent and transient droop compensation.

With this arrangement the governor has a low gain for fast speed deviations and the steady-state behaviour of an ordinary droop controller. The influence of the transient droop is determined by the gain R_t and the reset time T_R. For a hydro power station operating in island operation the transient droop is especially important but also in interconnected systems the transient droop is normally in operation. However during loading and unloading the transient droop may be disconnected in order to have a fast response.

5.4 The Island Operated Induction Generator

As mentioned in Chapter 3 there is a strong connection between frequency and voltage in an induction generator. This does not cause much problem when the generator is connected to a strong grid due to the fixed frequency. In island operation on the other hand there is no fixed frequency, the generator sets both voltage and frequency by itself and the connection between voltage and frequency become obvious. There are two reasons for this connection, one is the dependence between generator speed and voltage, shown in Figure 3.8, and the other is the voltage dependent power to the impedance load connected to the generator.

For an induction generator reactive power absorption is necessary in order to magnetize the generator and thereby generate power. Induction generators are normally grid connected and then absorb the reactive power from the grid. For island operation connecting capacitors to the generator terminals is necessary for the magnetization, see Chapter 3. The reactive power for excitation is then generated by the capacitors. When the generator loading increases the reactive power to the generator has to increase in order to keep the voltage constant. This may be achieved by means of connecting more capacitors or by installing a variable reactive power source. Switched capacitors are the most cost efficient alternative but the drawback is the discrete steps resulting in voltage and frequency fluctuations. Continuous voltage control may be achieved by using an SVC or a STATCOM (de Mello et al. 1981), (Sekhar et al. 2004). Both the SVC and the STATCOM can provide capacitive and inductive current but the STATCOM has the advantage of a wider operating area at lower voltages (Yu et al. 2004).

SVC

There are a number of different SVC (Static Var Compensator) configurations. Among these are thyristor-switched capacitors and thyristor-controlled reactors. The principle of a thyristor-controlled reactor is a reactor in series with a bidirectional thyristor switch with controllable firing angle. The firing angle, measured from the voltage zero crossing, is varied between 90° and 180° to alter the susceptance of the device. Full reactive power is absorbed with a firing angle of 90°. When the firing angle increases the current waveform becomes less sinusoidal and harmonics are generated. The thyristor-switched capacitors have several steps of capacitors that can be switched individually. A capacitor is connected in series with a bidirectional thyristor switch and a small inductance. The firing angle is chosen so that the capacitor is turned on when the grid voltage has its maximum and equals the charge of the capacitor. Switching transients are then minimized. The capacitor is turned off again when reaching a voltage peak and the capacitor remains charged. The small series inductor is limiting the switching transients, and inrush currents. The number of conducting capacitors can be changed every half cycle in order to control the total susceptance. This control does not generate any harmonics.

STATCOM

A STATCOM (STATic synchronous COMpensator) is a voltage source converter with the output stage transistors in series with an inductance. When the converter is operated in current control mode it is possible to control the AC current magnitude and phase relationship to the AC voltage. The control is quick and both leading and lagging current is achievable. Ideally the average power flowing in the converter is zero and there is no need for a DC source. Instead small capacitors are used on the DC side for energy storage. These are charged by real power flowing from the AC side in order to compensate for the converter losses and to maintain a constant DC voltage (Mohan et al. 1995). The current reference value is calculated by the AC and DC voltage regulators, Figure 5.5. The current controller is then calculating the voltage reference values in order to achieve the desired current. These three phase voltage references are used for the pulse width modulation of the converter.

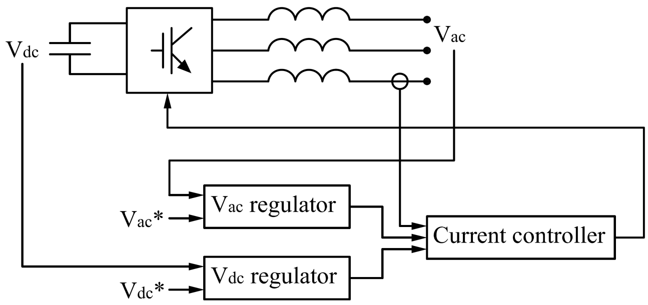

Figure 5.5 Operation principle of a STATCOM.

Island operation with induction generators in combination with small hydro power stations have been reported in several papers (Marinescu et al. 2005), (Marra et al. 1999), (Bonert et al. 1998). In these papers the turbine is uncontrolled, and instead a dump load is used for frequency control. Parallel-operated SEIG have also been investigated (Al-Bahrani et al. 1993) however not in combination with STATCOM and a hydro turbine governor. The control method proposed in this thesis is based on a turbine governor for frequency control and a STATCOM for voltage control. In order to evaluate the control method it is important to first establish an operating range for voltage and frequency. This is done in the next chapter.

Chapter 6

Power Quality and Requirements

Two quantities in the grid are important to look at when deciding whether the power quality is acceptable or not, namely voltage and frequency. To determine an acceptable operating range for the island operated system, several standards and regulations are studied in this chapter. These are, *Rotating electrical machines - rating and performance* (IEC 60034-1, 2004), *Voltage characteristics of electricity supplied by public distribution networks* (EN 50160, 2007), *Security requirements on production units* (SvKFS 2005:2) and *Connection of low-voltage installations to the utility supply network* (SS 437 01 40, 2006).

6.1 Effects of Extreme Voltage and Frequency

Naturally, too high voltage could damage equipment connected to the grid but also a low frequency is devastating to electromagnetic equipment, such as motors. The flux in a motor is given by

$$\phi(t) = \int u - Ri \, dt \tag{6.1}$$

If the resistance, R, is assumed to be small and $u(t) = \hat{u}\sin\omega t$ the flux is approximately

$$\phi(t) \approx -\frac{\hat{u}}{\omega}\cos\omega t \tag{6.2}$$

Equation 6.2 then gives that a decrease in frequency will lead to an increased flux for the same voltage. The increased flux causes saturation in the iron and the flux begins to flow in metal parts not designed to carry flux. This leads to heating of the iron and may damage the motor. At the same time the current is increased due to lower reactance in the machine. This leads to increased resistive power losses and additional heating. To avoid damage a limited V/Hz ratio has to be retained. When the frequency decreases the voltage is decreased and thus a constant flux is achieved. The worst operating condition for a machine is of course a combination of low frequency and high voltage at the same time. What is said above may become further aggravated by the fact that for very low frequencies induction motors may stall and then draw an even higher current.

Another important load is space heating, however due to the construction with resistances these will not be damaged due to voltage and frequency deviations.

Nowadays electronic equipment is often equipped with switched power supply and is designed to operate in a wide voltage and frequency area. Island operation will therefore probably not cause any damage to this kind of equipment.

An often disregarded component sensitive to extended operation on low voltage are contactors. If the voltage is too low to operate the contactor the core will not be closed. Due to the air gap the reluctance in the magnetic circuit is high and the inductance low. The current at half of the rated voltage could therefore become about three times the current at rated voltage. The most likely cause of such a low voltage in the system is if one phase is lost on the high voltage side of a distribution transformer. This is however not considered as a problem that is specific to island operation.

6.2 IEC 60034-1

As mentioned above one component in the grid sensitive to voltage and frequency deviations are motors but of course, the generator in the island system has to be protected as well. The IEC standard concerning rating and performance for rotating electrical machines states what machine performance the manufacturer should guarantee. Generators and motors are considered separately in the standard but due to the fact that induction generators in small power stations are initially constructed as motors this is the only case considered here. In the standard, it is stated that a machine shall be capable of performing its primary functions within zone A, Figure 6.1, but does not need to have the same performance as when operating at rated voltage and frequency. A deviation likely to occur is a temperature rise in the machine. Further it is stated that a machine shall be capable of performing its primary functions within zone B, but may exhibit greater deviations from its performance at rated voltage and frequency than in zone A. Extended operation at the perimeter of zone B is not recommended. It shall be noted that within the given zones the machine shall be capable of performing its primary functions such as rated power and rated torque. This does not necessarily mean that a temporary operation outside zone B is dangerous to the machine. The slope of the limits equals a constant V/Hz ratio.

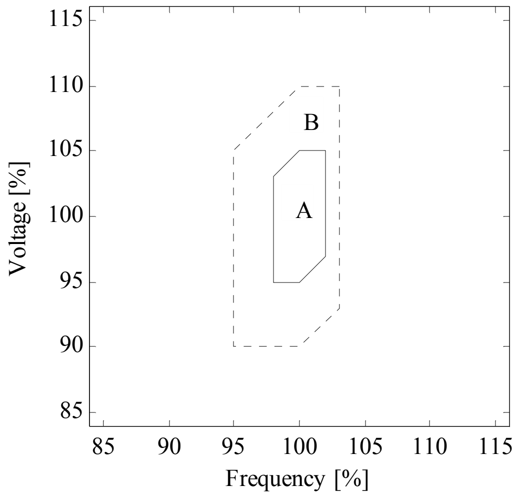

Figure 6.1 Operation area for motors according to IEC 60034-1.

In an island operated grid with induction generators the voltage is strongly dependent on the machine speed, i.e. the frequency. This means that the most severe operation condition with low frequency and high voltage is not likely to occur in such a system. When the frequency is decreased the voltage decreases as well.

It shall also be noted that hydro generators are designed with special bearings in order to withstand the high runaway speed achieved when the load is suddenly disconnected. Thus over speed should not be any problem to the generator and turbine.

6.3 EN 50160

Power quality of voltage supplied by the utility to low- and medium voltage costumers is regulated by the standard EN 50160. According to the standard the voltage may not deviate from its nominal value by more than ±10 %, except when a fault occurs. A test method for this is also given.

The mean value over 10 minutes shall be within ±10 % for 95 % of a week and the mean value shall be within +10 % to –15 % for 100 % of the time. This means that the voltage may temporarily be lower than –15 % or higher than 10 % as well.

For the frequency there is a difference depending on the system type but here the only case considered is the one with a system without connection to the main grid, i.e. an island grid. The mean value of the fundamental frequency over 10 s may not be outside the range 49 – 51 Hz for 95 % of a week and must be within 42.5 – 57.5 Hz for 100 % of the time.

In the standard no method for calculating the 10 s mean value is given. The standard regards operation of a system where the frequency does not change fast. However in a small island system fast frequency variations are present and when the mean value over 10 s is calculated this may result in Figure 6.2. The frequency is below 48 Hz at its minimum but the calculated mean value is newer below 49 Hz. Information about the absolute maximum and minimum frequency together with limits for the 10 s mean value would therefore be desirable.

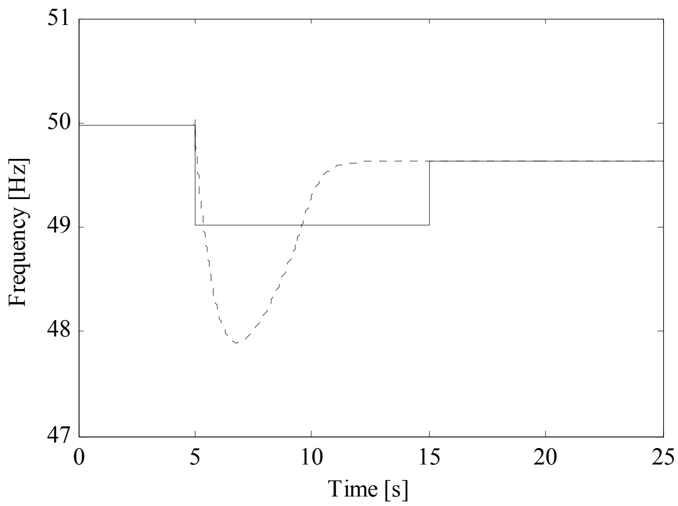

Figure 6.2 Connecting load to an island operated induction generator. Actual frequency (dotted) and mean value over 10 s (solid).

It shall also be noted that this standard is not valid during abnormal operating conditions such as operation after a fault, temporary arrangements at maintenance, or when the utility attempts to minimize a blackout. This actually means that it is very difficult for a costumer to claim that power quality for electricity supplied by the utility is poor.

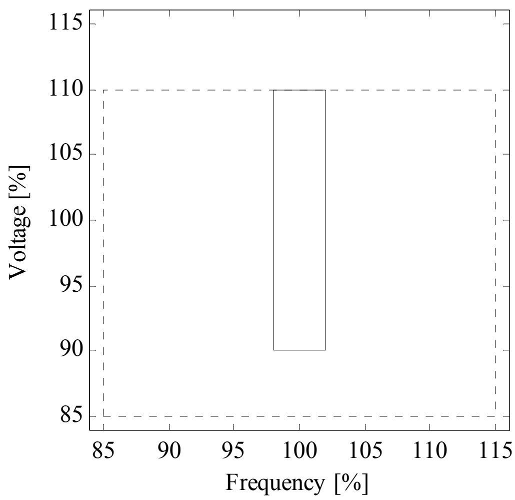

Figure 6.3 Maximum voltage and frequency deviations in power supplied to low- and medium voltage costumers according to EN 50160.

6.4 SvKFS 2005:2

This far the requirements on machine performance and power quality to the customers are studied. To connect a power plant to the grid there are requirements stated by Svenska Kraftnät, the TSO in Sweden. In SvKFS 2005:2 there are different requirements depending of the size and type of power plant, however no plant smaller than 1.5 MW is considered. For the smallest plants in the regulations the operation range is given in Figure 6.4. In zone A the plant must be capable of operating continuously and on rated power. The plant must be capable of operating in zone B at maximum 5 % power reduction for at least 30 minutes and in zone C with reduction for at least 30 minutes. The intention of these requirements is to avoid blackout by means of keeping the production units connected during disturbances but gives an idea of the voltage and frequency deviation a power plant must be capable of handling.

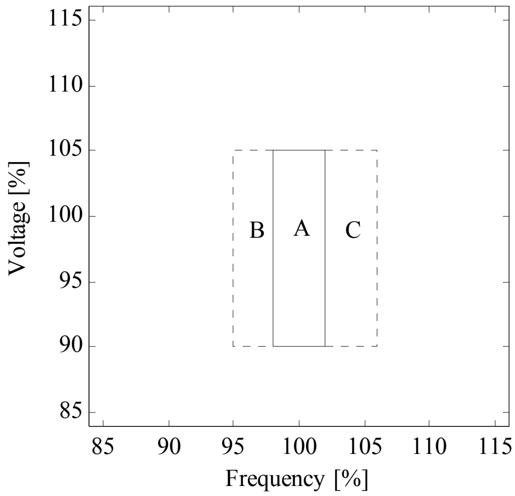

Figure 6.4 The Svenska Kraftnät requirements on small power plants.

6.5 SS 437 01 40

The acceptable operating range for the island grid has now been studied but to determine if island operation is possible according to these restrictions, it is essential to know how big load steps that may occur during island operation. The requirements on installation connected to the low-voltage grid in Sweden are stated in SS 437 01 40, Connection of low-voltage installations to the utility supply network.

Motors

According to SS 437 01 40 a three phase motor may be directly started if the starting current does not exceed 1.5 times the rating of the main fuse. Otherwise some starting device, e.g. Y-D starter or frequency converter has to be used in order to reduce the starting current.

Space Heating

In the 3rd edition of SS 437 01 40 there is a recommendation to use a time delay on space heating when connecting after a power failure. This is good in order to facilitate a black-start. However the recommendation would probably not be observed when carrying out electrical installations.

In the previous 2nd edition of SS 437 01 40 there were absolute limits for the maximum space heating to be connected simultaneously. These restrictions are excluded from the latest edition of the standard but in most distribution systems resistive load steps have little impact on the voltage.

The limits from the 2nd edition are not valid any more but they still give an idea of the expected load step size. In Figure 6.5 the maximum power is presented as function of number of connections per unit of time. From this figure it can be concluded that in a strong distribution system the maximum space heating to be connected in *one* step is approximately 18 kW and in a rural system 12 kW.

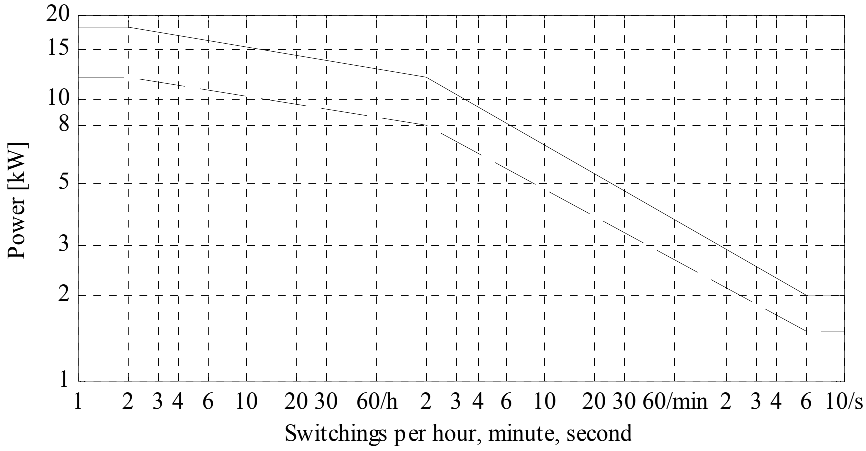

Figure 6.5 Maximum three phase space heating power to be connected simultaneously in a strong distribution system (solid) and weak rural distribution system (dashed).

These load steps are what could be expected when the island system is in operation. Of course when first energizing the system the load steps are far bigger than this but this is only temporary and the power quality is not critical as far as the system is stable. As stated in EN 50160 this is an abnormal operating condition and voltage and frequency limits are therefore not valid.

It is important to be aware of the meaning of the standards and who they concern. IEC 600034-1 states what a costumer buying a machine could expect. It does not say that operation outside this area is dangerous to the machine. EN 50160 states what power quality a costumer buying electricity from the utility could expect and is written so that the utility get through in most possible operating situations. The requirements on the costumer installations stated in SS 437 01 40 are written so that the utility will be able to fulfil the requirements in EN 50160 in most cases.

SvKFS2005:2 states the requirements on a power plant in order to avoid blackouts and concerns plants larger than 1.5 MW. This means that none of these standards and regulations is directly applicable in a small island system with small production units when determining an acceptable operating range.

6.6 Conclusions

A situation where island operation is often used is when emergency power supply is supplying a small load area. The over- and under frequency protection for such a generator is set to ±10 %.

Due to the lack of requirements in this area it is necessary to estimate appropriate limits for the island system. Based on the different requirements and knowledge about the consequences of exceptional voltage and frequency the desirable operating range, when considering maximum load step in the simulations of a real power station, is set to 47.5–52.5 Hz and 360–440 V independently of each other.

Chapter 7

Laboratory Setup

In this chapter island operation with two parallel induction generators and a STATCOM is investigated in simulations and a laboratory setup. First of all the test system is described together with the simulation models. Then the behaviour when loading the system is studied.

7.1 Test System

The same test system is used in both the simulations and the laboratory experiment. The system contains two 230 V, 2.2 kW induction generators driven by hydro turbines, see Figure 7.1. In the laboratory setup the turbines are replaced by DC motors controlled to have the same steady-state and dynamic behaviour as the hydro turbines. Each generator is excited by 1.9 kvar fixed capacitors and a 1.5 kvar STATCOM. The fixed capacitors are selected to generate the no-load reactive power to the generator and the STATCOM is used to compensate for the extra reactive power required when the load is increased and also, if necessary, supply reactive power to the load. The two generator bus bars are connected to each other through a 3 mH inductance. The inductance equals a 2 kVA transformer with 0.04 pu reactance. Each unit has an inertia time constant of 0.17 s, which is much lower than for a real hydro turbine. This should put higher demand on the control equipment and if it is possible to control these machines it would be possible to control a unit with higher inertia as well. The generator is the same as in Chapter 3 with the parameters listed in Table 3.1.

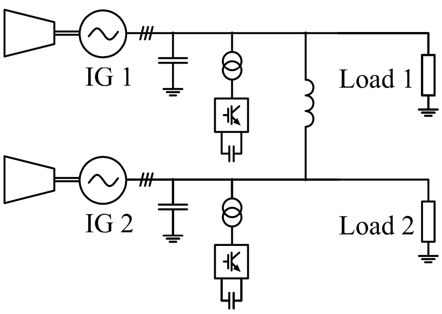

Figure 7.1 Simulation and laboratory model with two parallel induction generators driven by hydro turbines.

7.2 Simulation Program and Models

Most power system simulation programs are dependent on the fact that the mechanical and electrical angular velocity in a synchronous machine are equal in order to calculate the electrical frequency. This means that it is not possible to simulate an island grid with only induction generators, since the program is then unable to determine the frequency. However with MATLAB SIMULINK SIMPOWERSYSTEMS it is possible to simulate with induction generators exclusively and it is possible to simulate the system in both fundamental frequency simulation (phasor simulation) and instantaneous value simulation. The drawback with the fundamental frequency simulation, except for the fact that only the fundamental frequency is studied, is that the reactance values are not frequency dependent. In an island grid the frequency may deviate a lot from its nominal value and a simulation with constant reactance values is therefore not appropriate in this case.

In SIMPOWERSYSTEMS models for the induction machine and the STATCOM are available. In the following simulations the standard induction machine model is used while the STATCOM model is modified in order to be applicable to the instantaneous value simulation. All simulations are made in SIMPOWERSYSTEMS version 4.5 (R2007b) and are instantaneous value simulations.

Induction Generator

The induction generator is electrically represented by a fourth-order system and the mechanical part by a second-order system. In the model there is no saturation in the leakage fluxes. The mutual flux saturation is modelled by a nonlinear function calculated from the no-load curve. The shape of the saturation curve is extremely essential when simulating a self-excited induction generator as outlined in Chapter 3. If the curve is slightly shifted it has great influence on where the stable operating point is located in the I-V plane.

STATCOM

The STATCOM control is implemented according to Figure 5.5. The pulse width modulation of the voltage in the output stage is omitted in the model. Instead the output stage is represented by current sources. A model with the switching implemented has been tested as well but due to long simulation time the simplified model is used. No difference between the results for the two models has been observed and the simple one is sufficient as long as switching harmonics are neglected.

Hydraulic Turbine

Modelling a turbine with its waterways perfectly is difficult and not always necessary. The model may be more or less detailed. If the penstock is long, travelling waves may occur due to the elastic pipe walls and water compressibility. However for smaller stations the penstock is short and this effect is therefore omitted in the model. According to (Kundur 1994) a nonlinear model assuming inelastic water column is adequate for governor tuning studies and for transient stability studies in an isolated system. Such a model with the friction in the penstock neglected is shown in Figure 7.2. G is the ideal gate opening, i.e. when the no-load losses are deducted, H is the water head, i.e. the distance between upper and lower water surface and H_0 is the initial value of H. U is the velocity of the water in the penstock and U_{nl} is the no-load flow. The turbine gain A_t is set to 1.04 and the water starting time T_W=2 s.

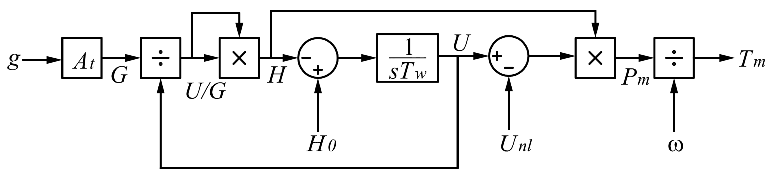

Figure 7.2 Nonlinear turbine model.

Turbine Governor

The turbine governor was briefly described in Chapter 5. Here follows a more detailed description of the model used in the simulations. As described earlier the governor is equipped with one permanent droop and one transient droop compensation, Figure 7.3. This is actually the model for a hydraulic turbine governor but electrical governors are often constructed to have the same behaviour. $R_{max\ open}$ and $R_{max\ close}$ represent the maximum gate opening and closing time, in pu/s, while *Min gate* and *Max gate* indicate the end positions of the gate. The output from the integrator, i.e. the servo motor position is fed back to the droop functions. This kind of governor is described in (Kundur 1994) and (IEEE 1992).

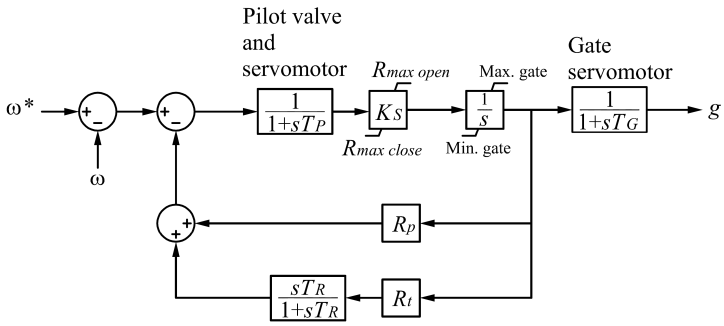

Figure 7.3 Turbine governor model.

Kundur (1994) gives the following equations for calculating R_t and T_R

$$R_t = \left(2.3 - \left(T_W - 1\right) \cdot 0.15\right) \cdot \frac{T_W}{T_M} \tag{7.1}$$

$$T_R = \left(5 - \left(T_W - 1\right) \cdot 0.5\right) \cdot T_W \tag{7.2}$$

which in this case gives R_t=3.45 and T_R=9. However due to the strong connection between frequency and voltage in an island operated induction generator pointed out in Chapter 3, these are not the optimal values for the self-excited induction generator governor in this case. Hence the calculated values are used as initial values and then tuned according to the simulation results. The final governor parameters are listed in Table 7.1.

Table 7.1 Turbine governor parameters.

Governor gain (K_s)	5
Pilot valve time constant (T_P)	0.2 s
Gate servomotor time constant (T_G)	0.2 s
Permanent droop gain (R_p)	0.04
Transient droop gain (R_t)	7
Transient droop reset time (T_R)	2 s
Maximum open and close speed ($R_{max\ open} = R_{max\ close}$)	1/30 pu/s

Voltage Regulator

The STATCOM voltage regulator is a PI-controller with a permanent and a transient droop compensation according to Figure 7.4 where the reactive power reference value is fed back and subtracted from the voltage error. This allows low gain for fast voltage variations and the normal permanent droop behaviour for slow variations. Voltage regulator parameters are listed in Table 7.2.

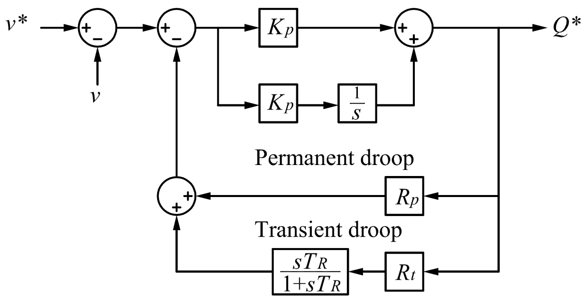

Figure 7.4 Voltage regulator with transient droop compensation.

Table 7.2 Voltage regulator parameters.

Proportional gain (K_p)	1
Integral gain (K_i)	0.5
Permanent droop gain (R_p)	0.04
Transient droop gain (R_t)	0.9
Transient droop reset time (T_R)	12 s

These regulator parameters are determined together with the governor parameters by simulating the system in Figure 7.1 and are tuned to achieve the best combination of voltage and frequency control.

7.3 Simulations

Simulation of the self-excitation process is almost impossible due to difficulties in modelling the generator perfectly at low voltages. Hence the black-start process is tested in the laboratory instead. In the following simulations the system is assumed to be in operation initially. The load given in percent refers to the rated power which is 2 kW for the DC-motor driving the generators in the laboratory. 100 % thus equals 4 kW.

Dynamic Properties of Load Step Changes

The two 2.2 kW generators in Figure 7.1 are operated at 25 % loading with load 1 connected. This is a resistive load of 1000 W at 230 V. Then at t=10 s an additional load, load 2, rated 160 kW is connected. This load corresponds to 4 % of the total rating of the two units. The results from generator 1 and STATCOM 1 are shown in Figure 7.5. Due to the equal machine rating and the permanent droop characteristic the units share the load equally. Hence the results from generator 2 are equal to the ones from generator 1. The transient voltage and frequency droops act to reduce the step response for both active and reactive power and an overshoot and a probable instability are prevented.

The simulation model is adapted to the equipment available in the laboratory. Thus there are high no-load losses and the gate opening is about 50 % instead of the ideal 25 % in the beginning of Figure 7.5.

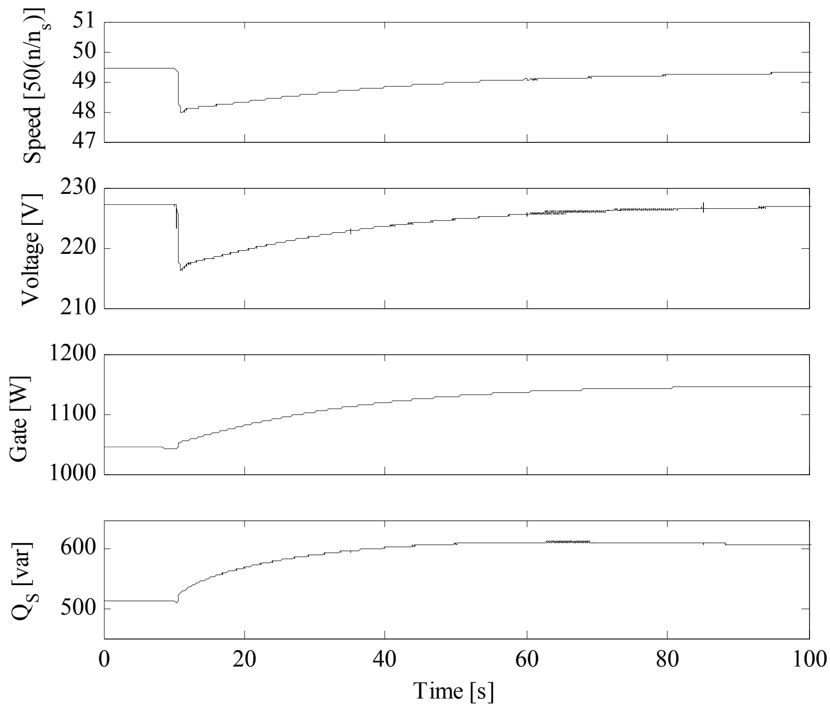

Figure 7.5 Increasing load from 25 % (1000 W) to 29 % (1160 W) in simulation. From top: speed generator 1, terminal voltage generator 1, turbine gate opening generator 1, STATCOM 1 output reactive power.

In all figures the speed is presented instead of the frequency. This is valid under the assumption that the slip is small. Simulations and laboratory experiments are performed with both speed and frequency control and no difference in stability is observed.

The disconnection of load in Figure 7.6 is not exactly the inversion of the curves in Figure 7.5 due to the nonlinear I-V characteristic of the induction generator and due to the frequency dependent reactive power from the fixed capacitors.

The switching of a 4 % load is handled well by the turbine governor and the STATCOM voltage regulator and the voltage and frequency never reach excessive values.

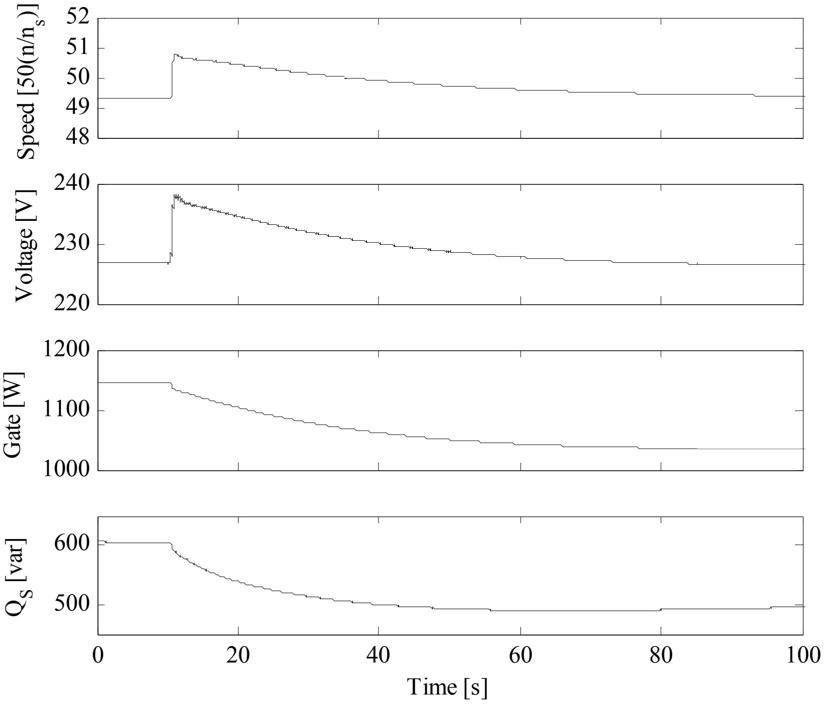

Figure 7.6 Decreasing load from 29 % (1160 W) to 25 % (1000 W) in simulation. From top: speed generator 1, terminal voltage generator 1, turbine gate opening generator 1, STATCOM 1 output reactive power.

Influence of Voltage Regulator

To investigate the influence of the voltage regulator speed, simulations are made with a slow and a fast voltage regulator, i.e with and without transient droop compensation. In Figure 7.7 it is shown that a fast acting voltage regulator is devastating not only to frequency but also to voltage. The voltage control is actually made worse by the fast voltage regulator.

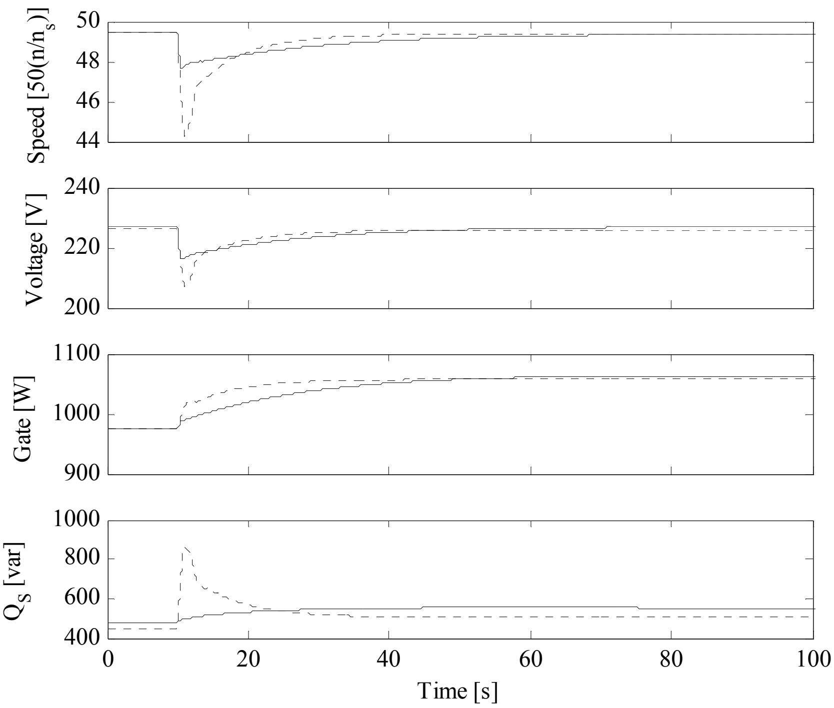

Figure 7.7 Increasing load from 25 % (1000 W) to 29 % (1160 W) in simulation. From top: speed generator 1, terminal voltage generator 1, turbine gate opening generator 1, STATCOM 1 output reactive power. Fast (dotted line) and slow (solid line) voltage regulator.

The behaviour may be described with the mechanical analogy from Chapter 4. At the instant when load is connected the real part of the stator current is increased and consequently the braking torque is increased and the speed decreased. Hence the mass moves inwards and the voltage is decreased both due to the decrease in speed but also due to the decrease in distance to the centre point. If we at the same time increase the reactive power (increase the mass) fast in order to increase the voltage the mass attempt to moves outwards. This is counteracted by the increase in braking torque from the load resistor leading to a further decrease in speed. Hence the voltage is decreased instead of increased. This leads to the conclusion that a slow voltage regulator increasing the reactive power at about the same speed as the active power is increased facilitates both voltage and frequency control.

7.4 Laboratory Experiments

The previously simulated system is tested in a laboratory experiment as well. All parameters are the same as in the simulations. The generators are now driven by DC motors controlled to have the same behaviour as a hydro turbine. The dynamics of the current controller and the DC machine are assumed to be fast and are neglected in comparison with the turbine, governor and generator dynamics.

Black-Start

To perform black-start fixed capacitors are connected to the generator terminals. The two generators are separately accelerated and when they are close to nominal speed the self-excitation process takes place, Figure 7.8. This process is quite fast and to avoid dangerous over voltage it is important not to have excessive capacitors connected or run the generator at over speed.

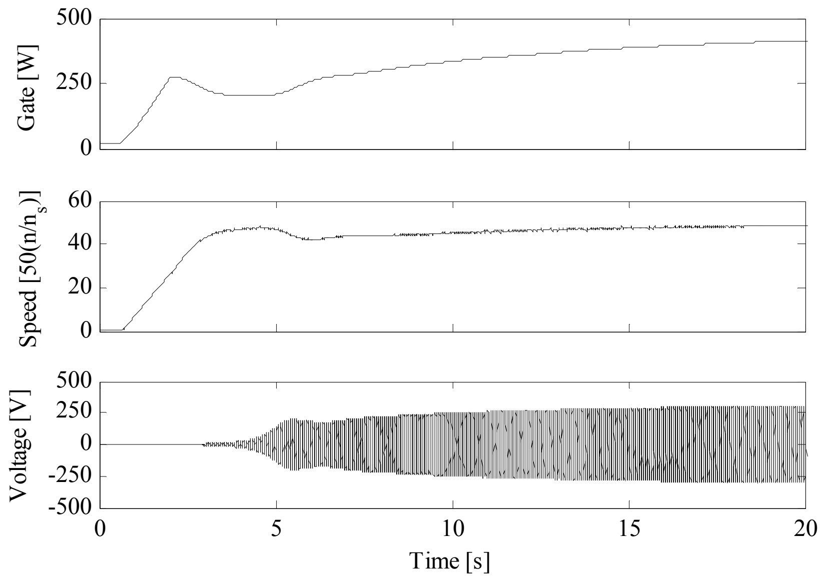

Figure 7.8 Generator voltage build up. From top: turbine gate opening, generator speed, and terminal voltage.

If the remanence in the generator rotor iron is low it might be easier to build up the voltage if the capacitors are disconnected when the generator is accelerated and then connect them all at once.

When the voltage is close to nominal voltage the STATCOM are connected and the voltage regulators are started. When the two units are operating at nominal voltage and frequency they are synchronized. Neither voltage nor frequency regulators have any problem handling the synchronization.

Dynamic Properties of Load Step Changes

The case with connection of 4 % load when running at 25 % loading is tested on the laboratory system. As can be seen, the curves in Figure 7.9 are almost similar to those from the simulations in Figure 7.5.

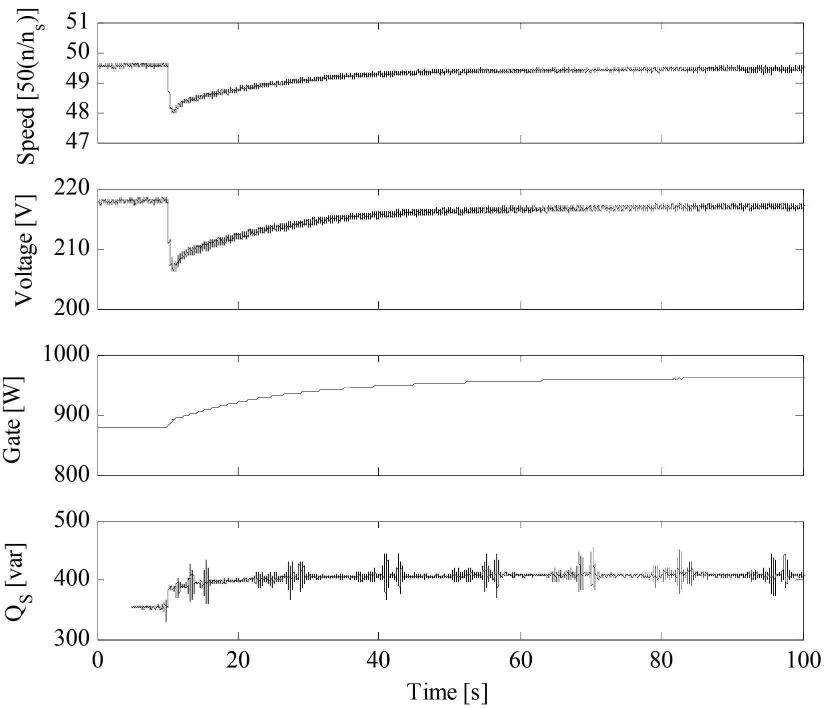

Figure 7.9 Increasing load from 25% (1000 W) to 29 % (1160 W) in laboratory. From top: speed generator 1, terminal voltage generator 1, turbine gate opening generator 1, STATCOM 1 output reactive power.

The only difference is the level of the gate opening and the STATCOM output. The error in gate opening is mainly caused by the fact that the electrical losses in the DC-motor and the mechanical losses in transmission are not perfectly modelled in the simulation. In the simulation all losses are considered as friction losses. The difference in reactive power is most likely due to voltage measurement errors.

The results from the other generator look similar to those in Figure 7.9. Due to the equal nominal power of the generators they share the load equally. Tests have been carried out with unequal permanent droop settings in the turbine governors. Of course they do not share the load equally then, but it does not lead to any stability problems.

Induction Motor Starting

The generator performance during motor starting is investigated with an induction motor, rated 6 % of the total installed power, connected to a fan. The torque for a fan, like for a pump, is proportional to the square of the speed. In Figure 7.10 a constant power load of 250 W is connected at t=10 s. Then at about t=80 s the fan is started and runs until it is stopped at t=170 s. As can be seen from the figure both frequency and voltage are stable during the start up, even though both quantities reach very low values. In this experiment the voltage control is handle by one single STATCOM, while the other converter is used as constant power load.

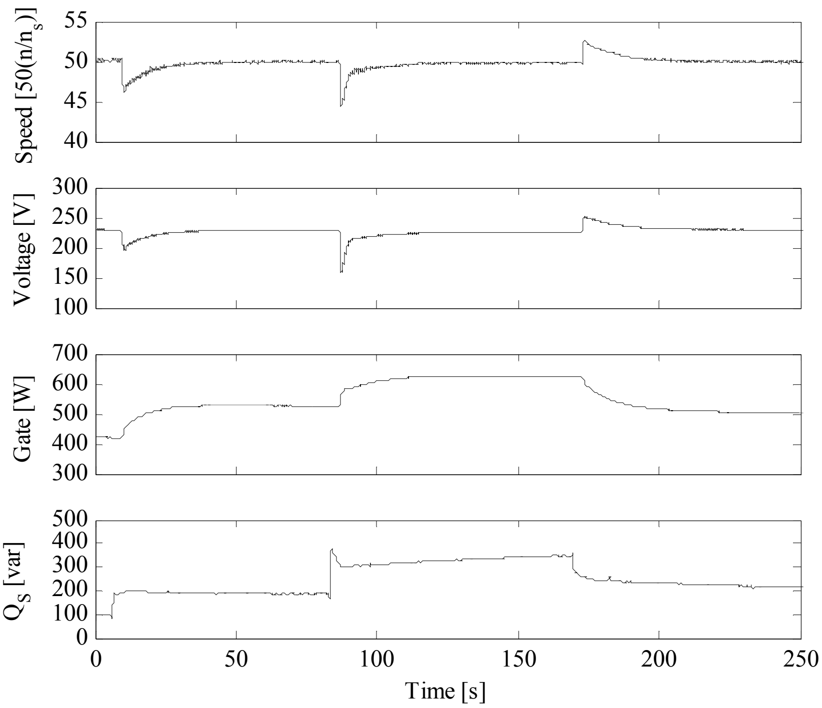

Figure 7.10 First connecting 250W, then starting an induction motor fan of 250W and then stopping the fan. From top: speed generator 1, terminal voltage generator 1, turbine gate opening generator 1, STATCOM 1 output reactive power.

The highest voltage and frequency deviation caused by switching a load is greatly affected by the generator and turbine parameters. The machine in the laboratory setup has at least three times lower inertia time constant than a real machine. Too much attention should therefore not be paid to the absolute values from this experiment. The important result is that a stable control of the two parallel hydro power induction generators with STATCOM is achievable. A more realistic hydro power station is studied in the next chapter.

Chapter 8

Forsa Power Station

The laboratory experiments in the previous chapter have shown that it is possible to operate two parallel hydro turbine driven induction generators with STATCOM units in an island system. In this chapter a real hydro power station is simulated and a field test regarding low-load operation is performed. Due to the more realistic parameters in these simulations the evaluation of the control strategy is more reliable when it comes to absolute values.

8.1 Test System

The station investigated is the Forsa power station located outside Katrineholm in Sweden. This is a typical small sized hydro power station with an induction generator driven by a semi-Kaplan turbine.

Figure 8.1 Forsa hydro power station with semi-Kaplan turbine and induction generator.

Rated power of the unit is 275 kW. The 400 V generator is connected to the turbine through a gearbox and has a nominal speed of 756 rpm at 50 Hz. The generator is connected to the grid with a 500 kVA 0.4/10 kV transformer and is phase compensated with 150 kvar capacitors, switched in three steps. Costumers are connected to the transformer low voltage side.

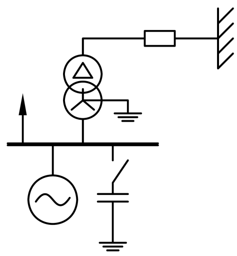

Figure 8.2 Forsa power station today.

Runaway Test

One important parameter in the simulation model is the inertia time constant (*H*) of the unit. To determine *H* a runaway test was performed. The generator was connected to the grid generating 170 kW when the generator circuit breaker was opened. At the same time the gate was closed as fast as possible and the capacitors were disconnected. It is important to disconnect the capacitors in order to avoid self-excitation and overvoltage when the generator is accelerated. The signal from the speed sensor was recorded together with the phase voltages. According to the speed sensor the turbine reaches more than twice the nominal speed. At t=27 s the gate is fully closed and the speed decreases faster.

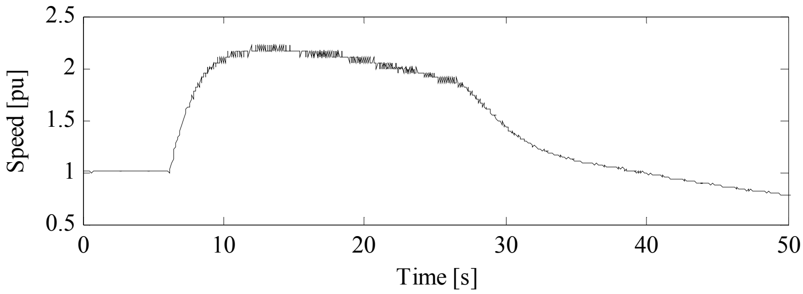

Figure 8.3 Runaway test: speed from speed sensor.

To determine the inertia, the first hundreds of milliseconds after the breaker opening are studied. In Figure 8.4 the measured speed and the speed estimated from the voltage are shown together with the tangent to the speed change directly after breaker opening. There is no difference between the two methods for determining the speed.

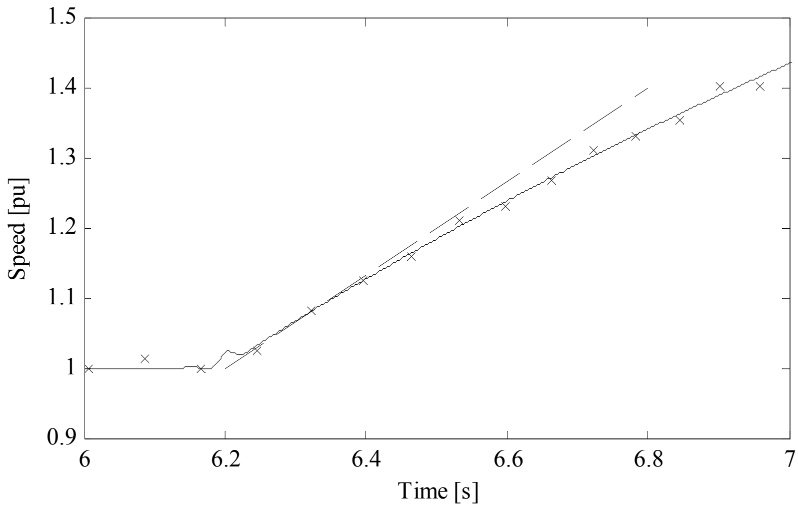

Figure 8.4 Runaway test: speed estimated from the voltage (solid), speed from speed sensor (x) and the tangent to the speed change directly after generator breaker opening (dashed).

The nominal generator speed is 756 rpm=79.2 rad/s and the inertia is given by

$$J = \frac{T}{\frac{d\omega}{dt}} = \frac{\frac{P}{\omega}}{\frac{d\omega}{dt}} = \frac{\frac{170 \cdot 10^3}{79.2}}{\frac{0.4 \cdot 79.2}{0.6}} = 40.7\,\mathrm{kgm}^2 \tag{8.1}$$

and the inertia time constant is

$$H = \frac{J\omega^2}{2S_n} = \frac{40.7 \cdot 79.2^2}{2 \cdot 275 \cdot 10^3} = 0.46\,\mathrm{s} \tag{8.2}$$

The rest of the turbine and generator parameters are listed in Table 8.1. The water starting time is estimated based on the geometry of the waterways and the generator parameters are standard values from (Anderson 1973).

Table 8.1 Turbine and generator parameters.

Turbine nominal power	275 kW
Water starting time (T_w)	1 s
Inertia time constant (H)	0.46 s
Generator nominal power	315 kW
Voltage	400 V
Stator resistance (R_s)	0.009 Ω
Rotor resistance (R_r)	0.006 Ω
Leakage stator inductance (X_{sl})	0.038 Ω
Leakage rotor inductance (X_{rl})	0.038 Ω
Magnetizing inductance (X_m)	1.26 Ω

Black-Start

Black-start of Forsa power station was tested by connecting 165 kvar fixed capacitors to the terminals and then slowly accelerating the generator. When running close to nominal speed the self-excitation process takes place and the voltage rises, Figure 8.5. At t=58 s 50 kvar is disconnected, the reactive power is now insufficient for self-excitation and the demagnetizing process is started. To avoid fully demagnetising the generator, the 50 kvar step is connected at t=65 s and the voltage recovers. During this test the speed was manually controlled by controlling the inlet gate and the runner blade angle was kept at its minimum angle. It is obvious that it is difficult to maintain a constant speed with this control and that the reactive power has high influence on the speed.

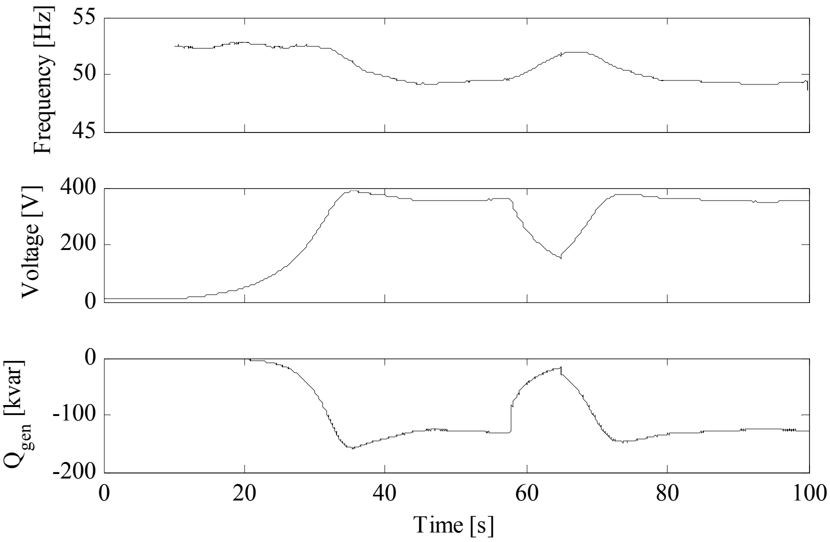

Figure 8.5 Black-start of Forsa power station with fixed capacitors. From top: frequency, generator voltage, generator reactive power.

Available Control Equipment

In normal operation a PI-controller is keeping the upstream water level constant by means of adjusting the runner blade angle. When the gate is fully opened no-load operation is not possible and the minimum output power is 80 kW. An electric motor is controlling the hydraulic runner blade servomotor. Time for full stroke is 54 s. The electric motor is controlled by two signals to increase or decrease runner blade angle. This means that the speed of the servomotor is fixed.

Low-Load Operation

As previously mentioned a semi-Kaplan turbine is not designed for island operation and no-load or even low-load operation is therefore not possible. When operating in normal grid connected mode the gate is always fully opened and the power is determined by the runner blade angle in a limited range from 30 to 100 % of rated output.

When starting up the unit in island operation it is essential to first raise the voltage on the generator and then slowly increase the load. While this is standard procedure for hydro units with a synchronous generator it is not for units with an induction generator. To gain knowledge about this uncommon operating regime of a semi-Kaplan turbine, field tests have been conducted.

One possibility to reduce the minimum power is to throttle the flow by means of controlling the gate as well. In the field tests the influence of gate and runner on the output power is studied. During the tests the generator is connected to the grid. The gate opening is kept constant and the electrical power and the water level in the sump are measured at different runner blade positions. The procedure is repeated at several gate openings. Figure 8.6 shows electrical output power as the runner blade angle is increased for a gate opening of 300 mm. As expected the power output initially increases, but at t=530 s the effect is reversed and an increased angle results in a decrease in power. Furthermore, a variation in the power is observed. As the gate opening is reduced, the reverse action occurs at lower values of the runner blade angle.

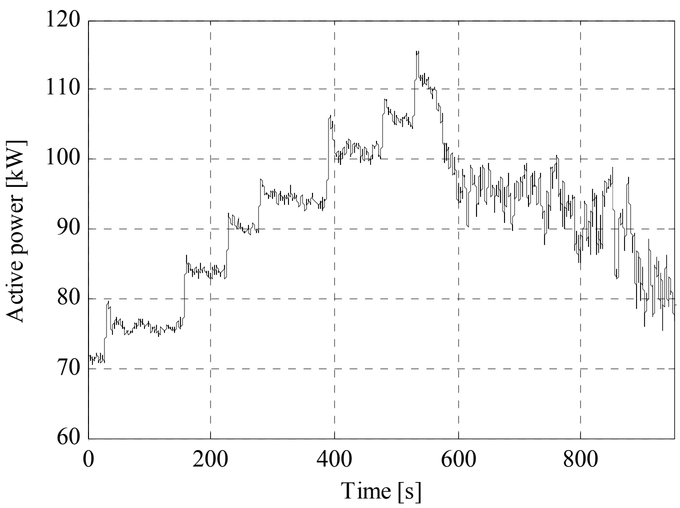

Figure 8.6 Active power at 300 mm gate opening as the runner blade angle increases from 5 to 13 deg. in steps of 1 deg. Reverse action starts at 12 deg.

The turbine output power depends on the runner pressure, which can be derived from the measured water level in the sump. Zero equals the downstream water level and 1 p.u. corresponds to the upstream water level. The graphs in Figure 8.7 show that as the runner blade angle increases, the pressure monotonously decreases while power first increases and then decreases. The dashed lines indicate the limitations in runner blade angle and pressure. Due to turbulence in the sump at lower water levels values at these levels are not reliable and are not shown in the figure.

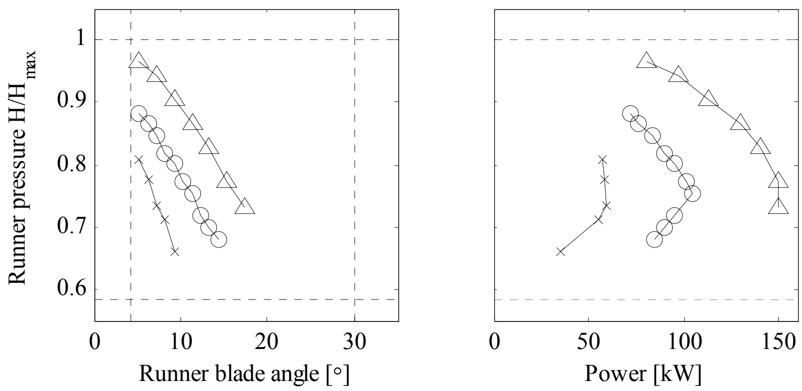

Figure 8.7 Runner blade angle (left) and power (right) versus runner pressure at 200 (x), 300 (o) and 400 (Δ) mm gate openings.

The reverse effect of runner blade angle on output power at a small gate opening can be explained with an analogy to electric power systems. The translations between mechanical and electrical quantities in Table 8.2 give the circuit equivalent in Figure 8.8a of the semi-Kaplan turbine. The very similar circuit in Figure 8.8b describes power transfer through a network impedance to a load in a power system.

Table 8.2 Translation between mechanical and electrical quantities.

Mechanical Quantity	Electrical Quantity
Flow	Current
Pressure	Voltage
Gate	Voltage dependent resistance
Runner	Voltage dependent resistance

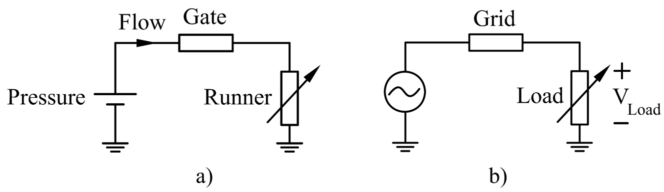

Figure 8.8 Equivalent circuit diagram for a) turbine and b) power system

Plotting the load power and load voltage for the power system as the load resistance is varied gives the well-known PV-curve or “nose curve” (Taylor 1994). Different grid impedances give different nose curves. At the tip of the nose the transmitted power is at its maximum. Lower power values can be obtained at two voltage values: On the upper side of the curve the voltage is high and the current is low. Here a decrease in load resistance increases the load power. Below the critical point in what is often called the unstable region, the situation is reversed and decreased load resistance reduces the power.

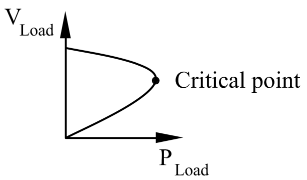

Figure 8.9 Nose curve used for voltage stability analysis.

The plot in Figure 8.7 of output power as a function of runner pressure for the semi-Kaplan turbine can be interpreted in the same way. On the upper side of the curve the pressure across the runner is high and the flow is low. When the runner blade angle is increased, the output power increases until the maximum power is reached. A further increase in angle results in lower power. This means that when the turbine is operated on the lower side of the curve the power control is reversed. For each gate opening a specific curve is obtained. In normal operation, when the gate is fully opened, the water level in the sump is high and almost constant and an operating point below the critical point is not possible.

When throttling the water flow with the gate to reduce output power, an operating point on the lower side of the curve may be obtained. Since a power controller cannot handle the reversal in behaviour in a robust way these operating points are not desirable. Another problem with operating on the lower side is that the output power fluctuates as indicated in Figure 8.6 due to insufficient amount of water in the sump. In normal conditions with large gate opening, the turbine is operated only on the upper left part of the power-pressure curve with practically constant pressure. The critical point of the curve is then far above the operating range of the plant.

For a power station such as the one studied here, no-load or even low load operation is not practically achievable by controlling gate and runner blades. An alternative is to install a local load corresponding to the minimum output power of the turbine. The generator can then run with maximum gate opening and without external load connected. Furthermore the turbine governor is kept simple as only the runner blades are used for control of the frequency.

New Equipment for Island Operation

When operating the Forsa power station in island operation the breaker on the transformer high voltage side is opened and the costumers on the low voltage side are supplied from the generator. The generator is delta connected and the transformer is therefore required in order to ground the system.

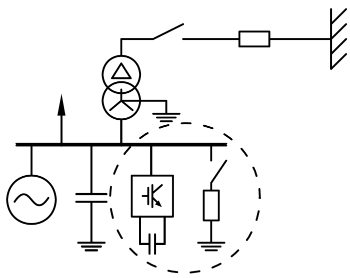

Figure 8.10 Forsa power with equipment for island operation.

According to the previous field tests it is not possible to operate the turbine at no-load, the minimum load is about 80 kW. Thus a dump load has to be installed in order to start the unit in island operation. Energizing the generator with the dump load connected may be difficult (Elder et al. 1983) and a connection procedure with three steps is therefore used instead.

At start-up the generator is accelerated by slowly opening the gate. The fixed capacitors make the voltage rise to nominal voltage at nominal speed. To avoid additional acceleration of the generator when the gate is further opened the dump load is connected as soon as the voltage is around nominal voltage.

The control of the constant speed servomotor implies a challenge compared to a variable speed servo. It is preferable not to have repeated open or close operations. This is important to minimize the wear of the relays and the control motor but also to minimize the voltage and frequency variations. Owing to the fixed speed control motor it is not possible to make the system stabilize exactly at the nominal frequency and deadbands for voltage and frequency are therefore required in order to make the system stable in steady-state. The turbine governor simulation model with relays is shown in Figure 8.11.

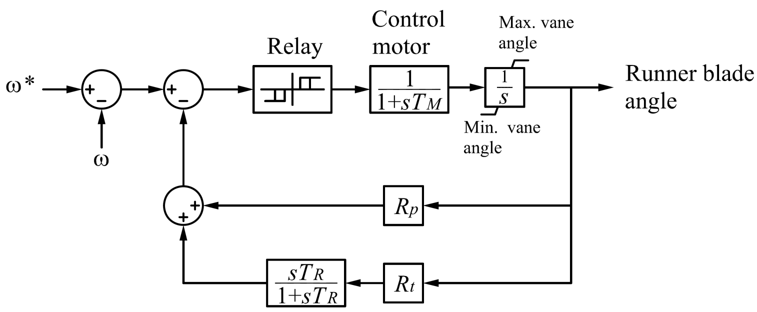

Figure 8.11 Turbine governor with relays.

Table 8.3 Turbine governor parameters.

Control motor time constant (T_M)	0.2 s
Permanent droop gain (R_p)	0.01
Transient droop gain (R_t)	1.5
Transient droop reset time (T_R)	0.8 s
Servomotor speed	1/54 pu/s
Relay on	±0.01 pu (±0.5 Hz)
Relay off	±0.001 pu (±0.05 Hz)

Today the only reactive power control at the power station is 150 kvar switched capacitors. These capacitors almost correspond to the generator reactive power consumption at no-load that is 160 kvar. To be able to control the voltage when the generator is operated in island operation a 100 kvar STATCOM is used just like in the laboratory experiment. In the laboratory a voltage controller with transient droop compensation was used. The purpose of this extra droop compensation is to slow down the controller. However the voltage regulator parameters are determined by the generator parameters and the inertia of the unit and in this case a slow PI controller with the parameters in Table 8.4 is sufficient to control the STATCOM reactive power. No extra transient droop compensation is necessary.

Table 8.4 STATCOM voltage regulator parameters.

Proportional gain (K_p)	1.5
Integral gain (K_i)	0.8
Permanent droop gain (R_p)	0.04
Deadband	±0.0125 pu (±5 V)

8.2 Simulations

The test system with Forsa power station in Figure 8.10 is simulated in an instantaneous value simulation in SIMPOWERSYSTEMS. First of all the start-up procedure is studied, then the behaviour when connecting and disconnecting load. The load is assumed to be located close to the station and the grid is therefore omitted in the model.

Start-up Procedure

To facilitate the energization of the generator it is preferable not to have the fixed capacitors connected when accelerating the induction generator. Hence the start up procedure starts by slowly opening the gate and accelerating the generator. When the generator is running at nominal speed the capacitors are connected and due to the remanence the generator is energized. The gate is further opened and the speed increases together with the voltage, Figure 8.12. When the voltage reaches 440 V the first dump load step, 20 kW, is connected in order to avoid over speed and over voltage. When the voltage reaches 440 V again step number two, 25 kW, is connected and finally step number three, 35 kW, is connected. The generator is now operating with minimum runner blade angle and fully opened gate and is generating approximately 30 % of its rated power. The turbine governor and STATCOM can now be turned on and the station is ready for connecting the costumers. The generator is able to handle larger load steps when already loaded. Hence the dump load steps are of different sizes and selected in order to cause the same voltage and frequency deviation in all three steps.

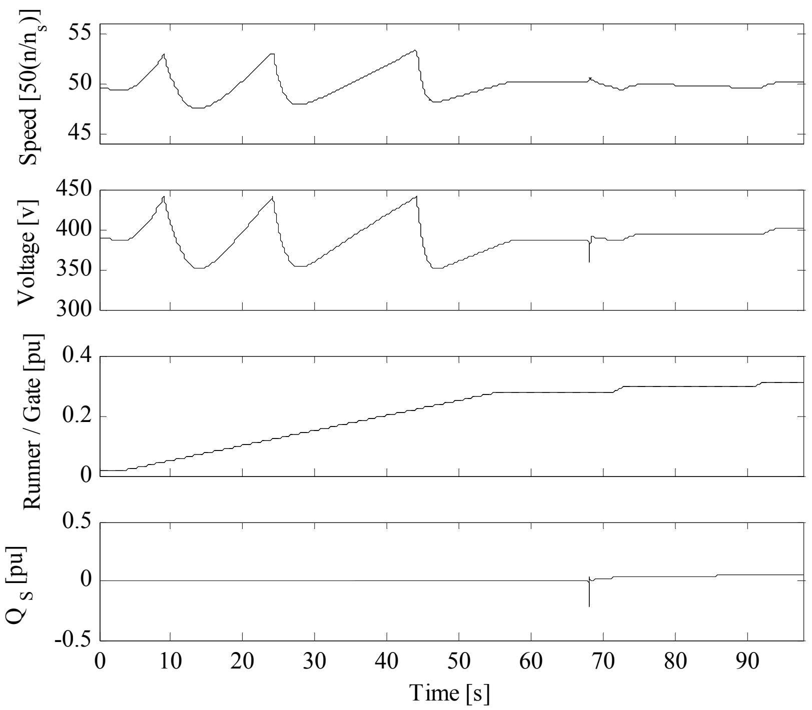

Figure 8.12 Start-up procedure with connection of dump load in steps of 20 kW, 25 kW and 35 kW. From top: generator speed, generator terminal voltage, combination of gate opening and runner blades, STATCOM output reactive power.

Dynamic Properties of Load Step Changes

It has already been shown in simulations and laboratory tests that island operation with induction generators controlled by turbine governor and STATCOM is possible from the stability point of view. However one important issue is weather it is possible to maintain acceptable voltage and frequency levels when applying load steps. The ability to handle load steps is therefore investigated. When evaluating the control performance the limitations from Chapter 6 of 360 – 440 V and 47.5 – 52.5 Hz is used.

In Figure 8.13 resistive load is connected in steps of 7, 14, 21 and 28 kW when the generator is operating at 50 % loading. Per unit refers to the turbine rating 275 kW. Naturally a higher amount of connected load results in a lower voltage and frequency following the connection. When connecting a 10 % load the frequency is slight below the acceptable 47.5 Hz but the voltage is still within the acceptable range. The voltage decreases at about the same rate as the frequency and the STATCOM is controlled in order to slowly increase the reactive power and restore the voltage at about the same rate as the frequency is restored.

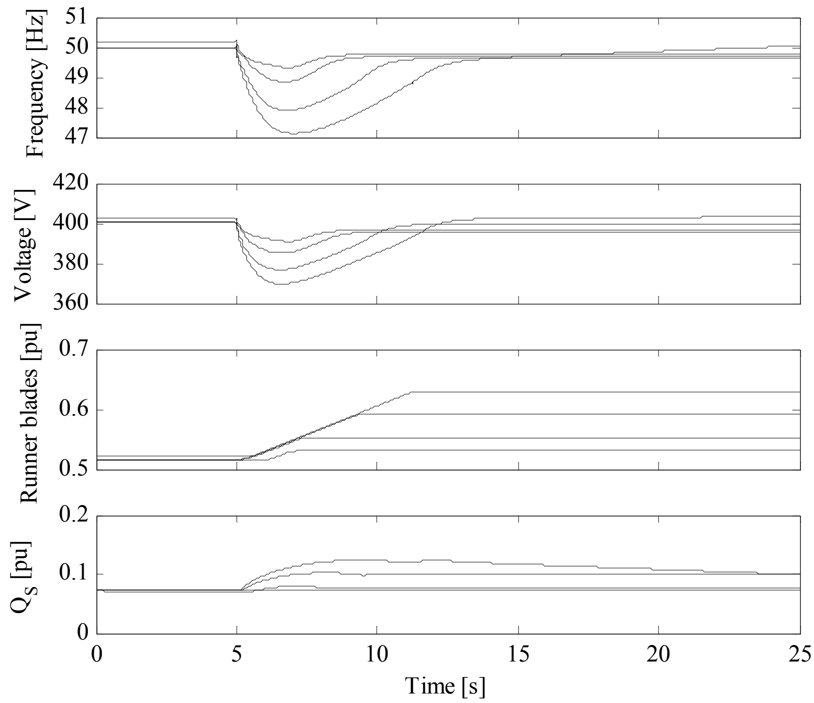

Figure 8.13 Connecting resistive load in steps of 7 kW (2.5 %), 14 kW (5 %), 21 kW (7.5 %) and 28 kW (10 %). From top: frequency, generator voltage, runner blade angle, STATCOM output reactive power.

Important to notice is that one single operation of the servo motor is enough to restore the frequency to its nominal value. Hence the wear of the control equipment is minimized. At the same time repeated frequency variations are avoided.

In Figure 8.14 the same amount of load as previously connected are disconnected. When disconnecting 28 kW from 50 % loading the frequency reaches 54 Hz which is a bit above the desired maximum frequency 52.5 Hz. The STATCOM is producing negative reactive power to avoid an over voltage and the voltage is kept below the 440 V limit.

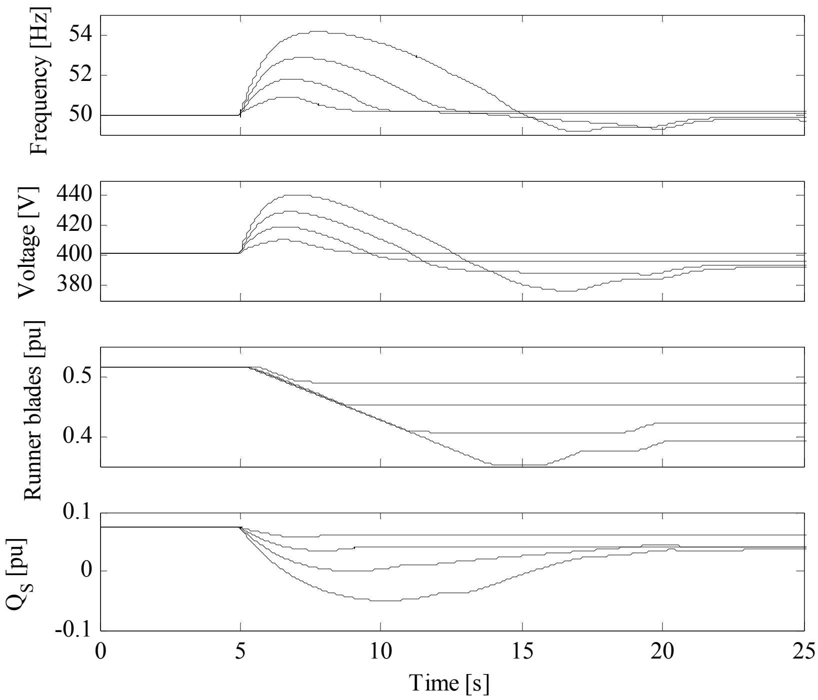

Figure 8.14 Disconnecting resistive load in steps of 7 kW (2.5 %), 14 kW (5 %), 21 kW (7.5 %) and 28 kW (10 %). From top: frequency, generator voltage, runner blade angle, STATCOM output reactive power.

The case with an inductive part in the load is also simulated. The tested power factors tanφ=0, tanφ=0.25 and tanφ=0.5 are based on rates stated by several Swedish utilities where the free reactive loading is 50 % of active power. The active power is held constant while the reactive part is increased.

The reactive part of the load is rapidly decreasing the voltage and thus unloading the generator before the speed has decreased, Figure 8.15. This results in a better frequency control without deteriorating the voltage control. The lowest voltage is not affected at all. Thus one solution to achieve better frequency control without deteriorating the voltage control is to have a temporary rapid decrease in reactive power from the STATCOM when the frequency decreases. However the problem is to make this control fast enough. In order to have the desired effect the reactive power has to be reduced immediately after the load is connected.

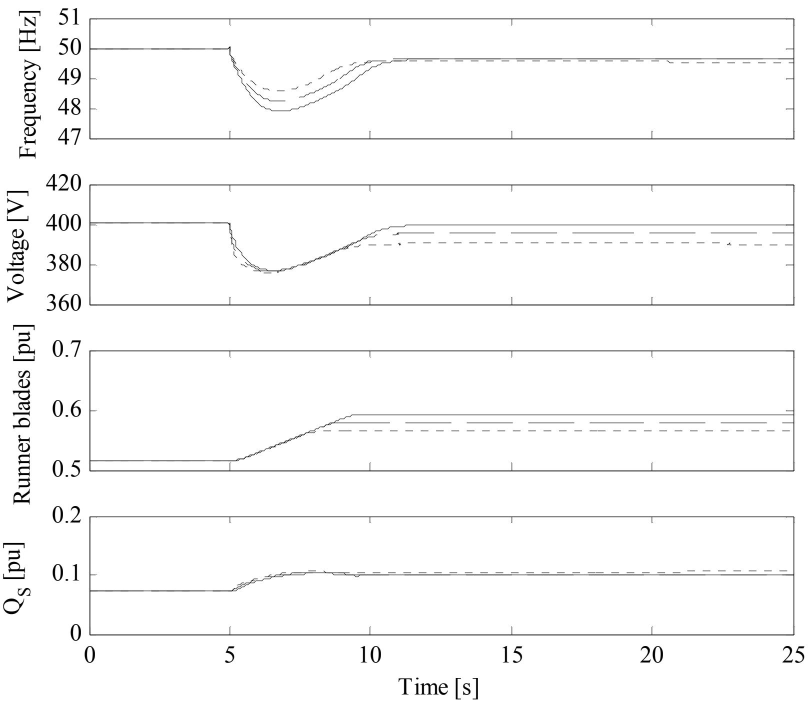

Figure 8.15 Connecting an impedance load of 21 kW with tanφ=0 (solid), tanφ=0.25 (dashed) and tanφ=0.5 (dotted). From top: frequency, generator voltage, runner blade angle, STATCOM output reactive power.

Influence of Reactive Power

In a strong interconnected grid the voltage may be increased by means of increasing the reactive power input. To investigate the influence of a change in reactive power in island operation with an induction generator, a simulation where the reactive power is exclusively increased is carried out. Initially the generator is operating in steady-state, Figure 8.16. In order to increase the voltage the reactive power input is increased. Initially the voltage increases but then the frequency decreases and the voltage decreases instead of increasing. The decrease in frequency and voltage will go on until the frequency is outside its dead band and the active power is increased. The frequency then increases and at the same time the voltage increases. The system is now in steady at a higher voltage.

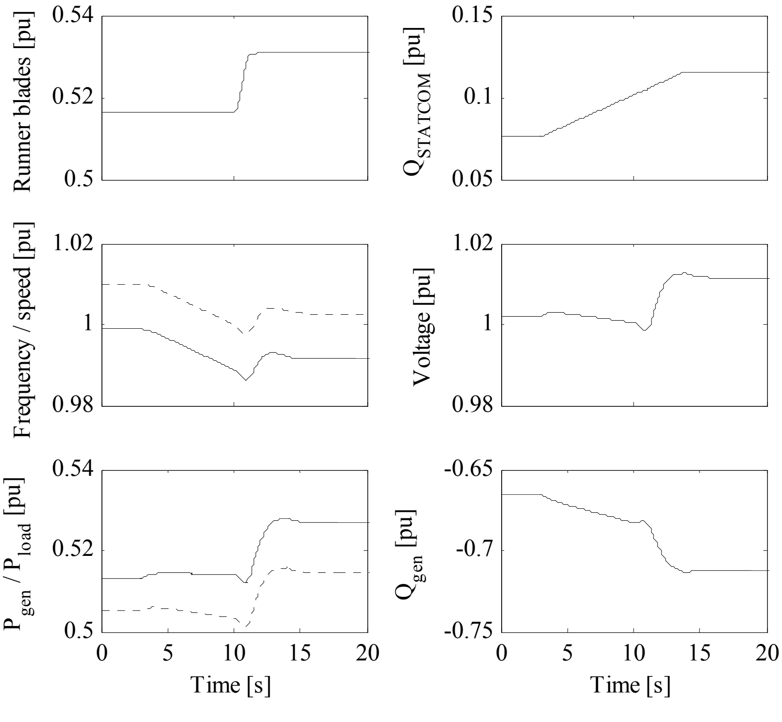

Figure 8.16 Influence of increasing reactive power with a STATCOM. Per unit refers to the base power 275 kW. From top: Runner blade angle, STATCOM reactive power output, frequency (solid), generator speed (dotted), generator voltage, generator active power (solid), load power (dotted), generator reactive power.

As shown in Figure 8.16 there is a difference in active power in the generator and in the load. This difference equals the losses of some kW in the STATCOM. These losses increase when the reactive power from the STATCOM is increased. To avoid this effect on the active power balance and to make the analysis easier, an ideal reactive power source is used instead of the STATCOM, Figure 8.17. The generated active power now equals the power to the load. The slope of the reactive power increase is the same as previously and the reactive power has less, but still some negative influence on the voltage. The actual voltage increase does not occur until the generator speed is increased by increasing the runner blade angle. This means that it is not possible to control the voltage without

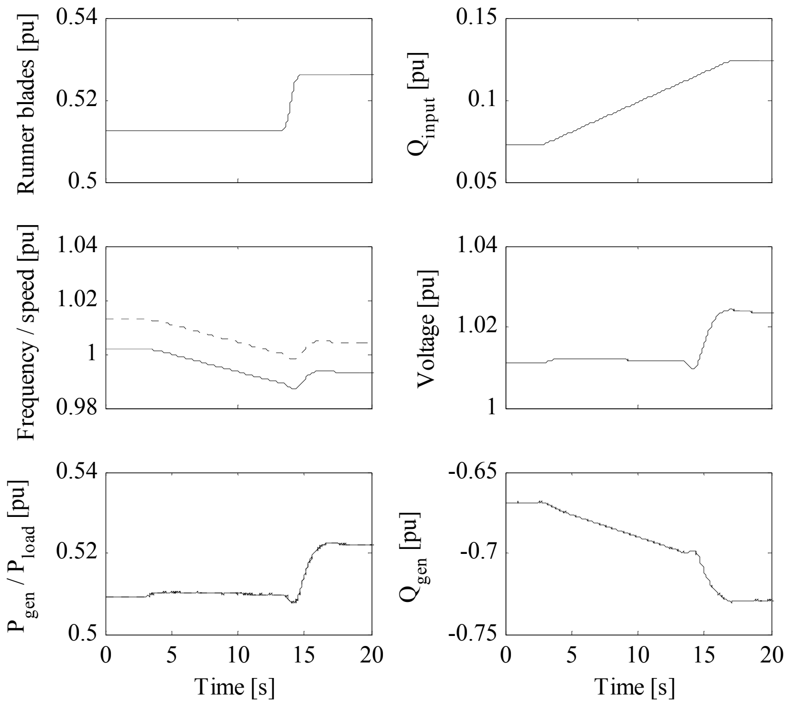

Figure 8.17 Influence of increasing reactive power with an ideal reactive power source. Per unit refers to the base power 275 kW. From top: Runner blade angle, reactive power input, frequency (solid), generator speed (dotted), generator voltage, generator active power (solid), load power (dotted), generator reactive power.

controlling the frequency at the same time and implies a difficulty when a wide frequency deadband is used. A coordination of voltage and frequency control is therefore preferable.

The behaviour described above may be somewhat clearer by studying the mechanical model of the generator described in Chapter 4.

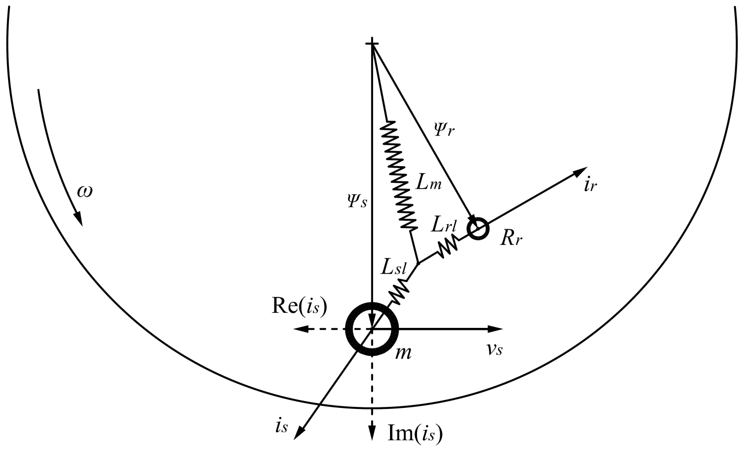

Figure 8.18 Mechanical model of a self-excited induction generator.

An increase in mass attempts to move the mass outwards. When the mass moves outwards the braking torque from the stationary plate increases and attempts to decrease the rotor speed. The decrease in speed counteracts an increase in voltage. When the input power is increased the speed increases and consequently the mass moves outwards and voltage increase. This leads to the conclusion that it is not possible to control the voltage without controlling the mechanical power input.

Induction Motor Starting

This far the only load considered is impedance load. However it is important to study the behaviour when starting a motor as well. In Figure 8.19 a 7.5 kW induction motor connected to a pump is started. The pump has a characteristic with a torque that is proportional to the square of the speed.

Due to the reactive power consumed by the motor at start up the voltage decreases fast. This fast reduction in voltage is favourable to the frequency control. When the voltage decreases the load power decreases temporarily and counteracts the frequency dip. The frequency is above 49 Hz during the start up and the voltage is above 380 V, i.e. both voltage and frequency is well within their limits. According to SS 437 01 40 a motor with a starting current higher than 1.5 times the main fuse rating may not be directly started. The 7.5 kW motor in this case has a starting current of approximately 100 A (Anderson 1973). A costumer with main fuse rated higher than 63 A is not probable in the present grid and a start of a motor in this size is considered sufficient when evaluating the system performance.

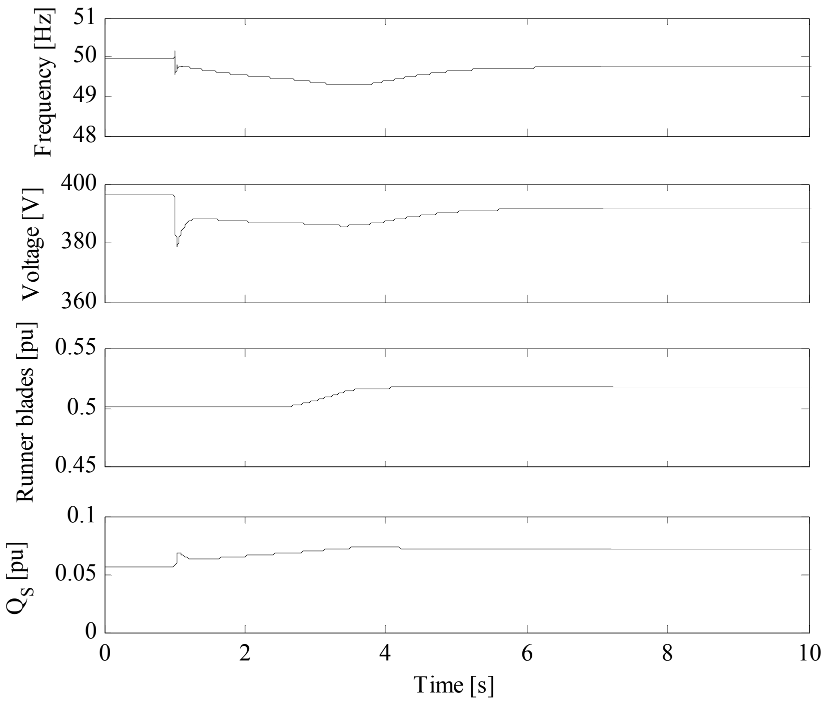

Figure 8.19 Starting a 7.5 kW induction motor connected to a pump. From top: frequency, generator voltage, runner blade angle, STATCOM output reactive power.

Maximum Load Step

It is essential to know how big load steps the generator is able to handle without a frequency and voltage outside the range 47.5–52.5 Hz and 360–440 V respectively. These limits are of course not valid during loading of the generator when first energizing the network. Figure 8.20 shows the maximum acceptable load steps as function of the loading prior to the load step for both connecting and disconnecting load. Due to the semi-Kaplan turbine construction loading less than 0.3 pu is not possible. The load is assumed to be purely resistive.

When the generator loading is increased the maximum permitted load step increases. This behaviour may also be explained with the mechanical model of the generator. When the generator loading increases the damping between the mass and the stationary plate increases. Hence the mass does not move as far as when connecting load under low load condition.

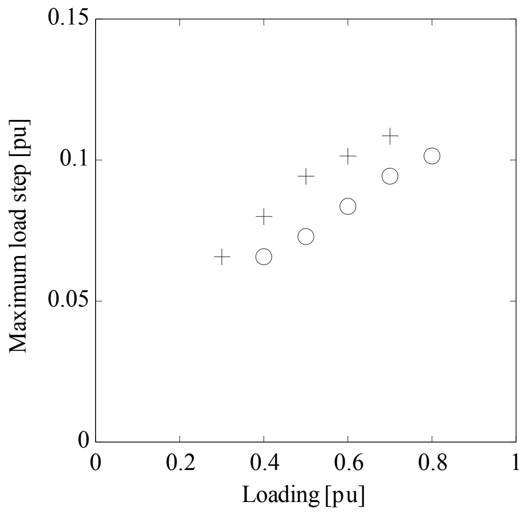

Figure 8.20 Maximum load step as function of loading prior to the step when connecting (+) and disconnecting (o) load, provided that the frequency may not be less than 47.5 Hz or exceed 52.5 Hz.

As Figure 8.20 shows the disconnection sets the limit on maximum load step. For all loadings it is the frequency that is critical, the voltage limit is never reached. At 0.5 pu loading the maximum step is 20 kW. Considering the present distribution system and the requirements in SS 437 01 40 this is a sufficient step size when the system is in stable operation, i.e. not during black-start and loading.

No-Load Operation

The dump load is necessary due to the turbine construction but may also be preferable in order to get a stable control without any external load. From the previous section it is clear that the induction generator has poor damping on low loading. If we look at the mechanical model no-load operation corresponds to solely radial forces on the mass. A change in speed then has high influence on the mass distance to the centre point. At the same time there is no damping from the stationary plate. Hence a small change in speed results in a large and fast change in voltage.

The poor damping on low load in combination with the simple turbine governor and auxiliary equipment may imply difficulties when operating without any load connected. The fact that it is not possible to control the generator below 30 % loading is now omitted. Figure 8.21 show the result from a simulation with the generator operating without any load connected. Without the stabilizing impedance load and with the simple turbine governor it is not possible to reach steady-state. With this turbine control it takes about 15 % resistive load to obtain a stable operation.

With a continuously controllable turbine it would be possible to achieve a stable operation without any load but this is an expensive solution. In this case the dump load is necessary, but also when not necessary, this solution is much more inexpensive than an advanced turbine control.

If the turbine governor is disconnected and the frequency is manually controlled a stable steady-state operating point is obtained. However the control is very sensitive and it is difficult to control the frequency to exactly 50 Hz.

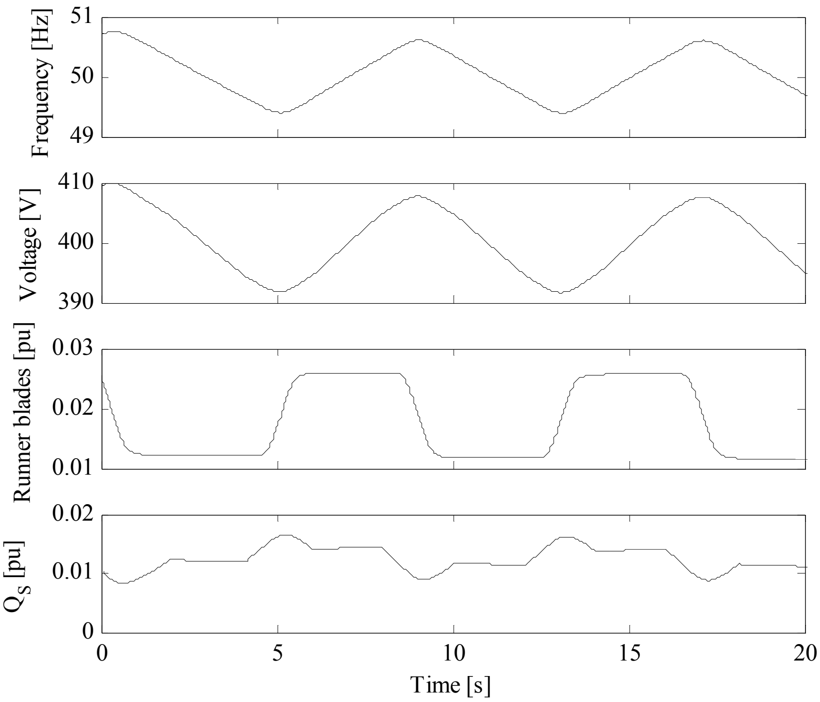

Figure 8.21 Induction generator running without any load connected. From top: frequency, generator voltage, runner blade angle, STATCOM output reactive power.

Frequency and Speed control

In a synchronous generator the mechanical speed and the frequency are closely related to each other. The shaft speed is easy to measure and is therefore used as feedback signal to the turbine governor. In an induction generator on the other hand the frequency differs from the mechanical speed by the slip which is dependent on the generator loading. Hence frequency feed back is required in order to achieve a frequency at exactly 50 Hz. However the electrical frequency is more difficult to measure accurately and may not be as stable as the mechanical speed. This may lead to stability problems. A comparison between speed and frequency feedback is therefore performed.

The result of connecting a 7.5 % resistive load with speed control and frequency control is shown in Figure 8.22. Both control methods are equal from the stability point of view. Due to the dead band in the controller the controlled quantity is not exactly at its nominal value. The peak in the frequency when connecting load is due to error in the frequency calculation but owing to the low governor gain at high frequencies this does not affect the stability. In an island grid it is not very critical with a frequency exactly at 50 Hz. The slip is only some few percent of the speed and it would therefore be possible to control the speed instead of frequency. Even though the slip is not constant it is possible to compensate for it and control the speed to a value slightly above the synchronous speed.

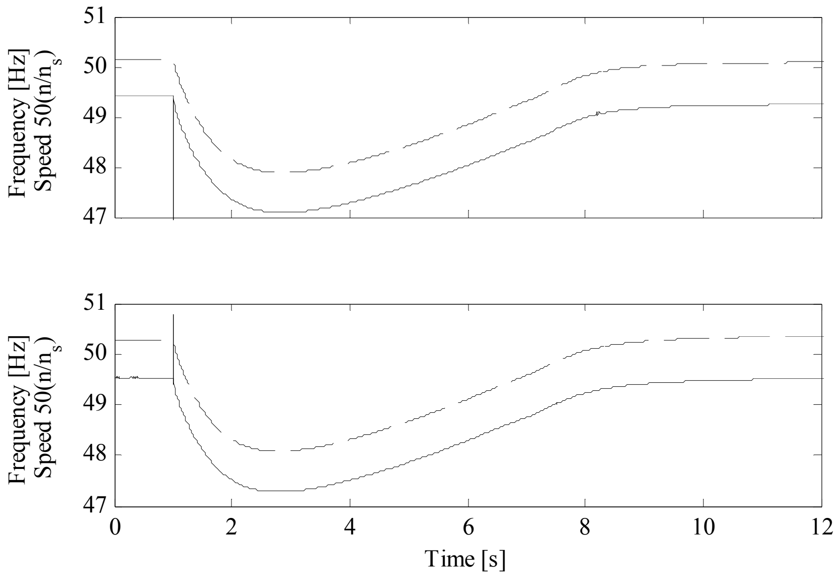

Figure 8.22 Connecting 7.5 % resistive load with speed control on top and frequency control below. Frequency (solid) and machine speed (dashed).

Influence of Water Starting Time

In the previous simulations a water starting time of 1 s is used for the modelling of the turbine and waterways. This value is only approximately calculated from the dimensions of the waterways and the volume flow through the turbine. Due to the uncertainty in this value it is interesting to see what influence the water starting time has on the control performance. In Figure 8.23 the simulation results with T_W=0.5, T_W=1 and T_W=1.5 are shown.

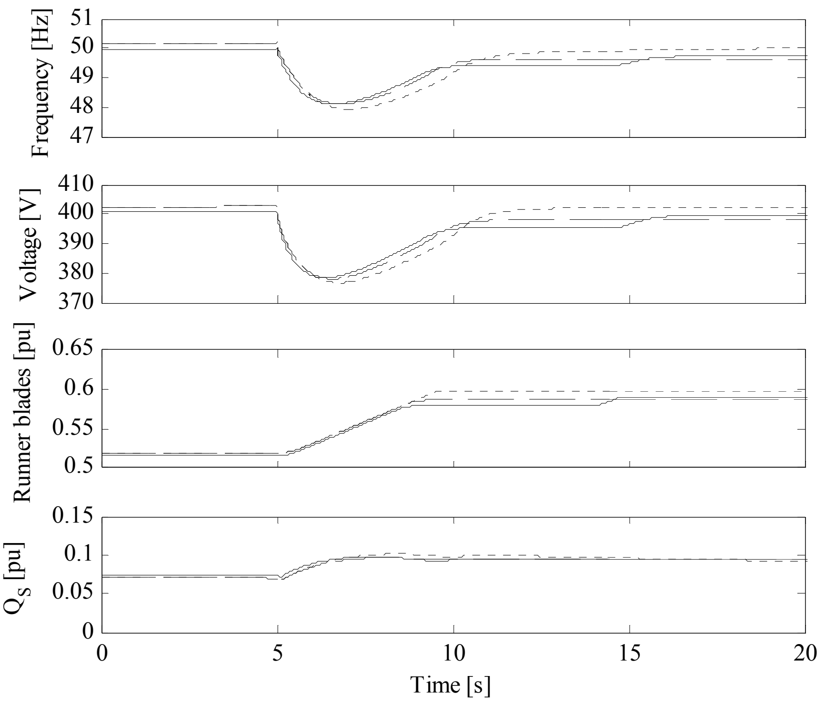

Figure 8.23 Connecting 7.5 % resistive load with water starting time T_W=0.5 (solid), T_W=1 (dashed) and T_W=1.5 (dotted). From top: frequency, generator voltage, runner blade angle, STATCOM output reactive power.

There are no major differences when the time constant is increased. The frequency and voltage reach slightly lower values with the longest time constant but from the stability point of view there are no problems. According to (Penche 1998) the ratio between mechanical starting time and water starting time, T_M/T_W may not be less than 4 in order to have a stable operation. In this case the ratio is

$$\frac{T_M}{T_W} = \frac{2H}{T_W} = \frac{2 \cdot 0.46}{1} = 0.92 \tag{8.3}$$

without causing instability. One explanation for this is the strong influence of generator speed on voltage in an induction generator. If a load is suddenly disconnected the generator accelerates and the voltage increases. The increased voltage leads to additional power consumption in the impedance load and a higher braking electrical torque on the generator which helps to decrease the frequency peak.

With a synchronous generator with fast excitation control there is no stabilizing effect from the impedance load and the system may go unstable if the mechanical inertia is small in comparison to the water starting time.

Influence of Servo Motor Speed

One important question when planning to operate a power station in island operation is the requirements on the control equipment such as servo motor speed. A fast servo is preferable in order to have a fast control but is also more expensive. The influence of servo motor speed is therefore investigated. In Figure 8.24 a 21 kW resistive load is connected with a servo motor speed of 1/20 pu/s, 1/40 pu/s, 1/60 pu/s and 1/80 pu/s. It is then clear that the servo motor speed does not affect the control very much. Only a slightly lower frequency and voltage is achieved with a slower servo compared to the fastest servo. The time for restoring the frequency and voltage is slightly increased with a slower servo motor. The same turbine governor is used in all four simulations. Although it seems as if the servo speed is not important it is preferable to have a fast servo in an abnormal operating situation, for example when a big load is suddenly disconnected or when a fault occurs in the grid. To fully utilize a fast servo the turbine governor and STATCOM voltage regulator parameters have to be tuned for each specific speed.

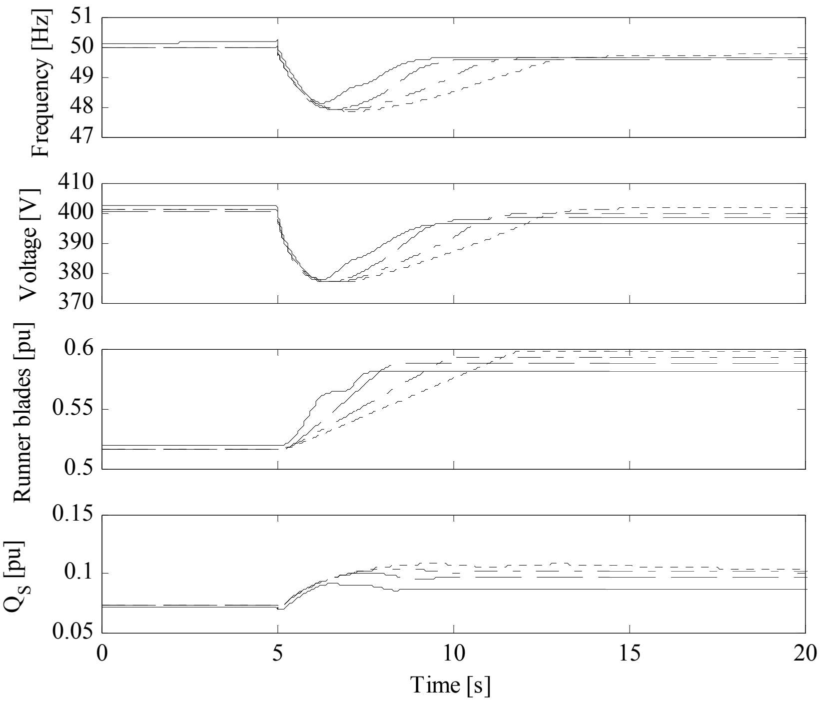

Figure 8.24 Connecting 7.5 % resistive load with servo motor speed 1/20 pu/s (solid), 1/40 pu/s (dashed), 1/60 pu/s (dash-dotted) and 1/80 pu/s (dotted). From top: frequency, generator voltage, runner blade angle, STATCOM output reactive power.

8.3 Summary

A real hydro power station with semi-Kaplan turbine and induction generator was successfully simulated. Switching of impedance load and induction motor load is handled well by the simple turbine control equipment and the STATCOM voltage regulator.

Chapter 9

Conclusions

The possibility to use induction generators, excited by fixed capacitors and a STATCOM, in island operation has been investigated. It is shown in simulations and laboratory experiments that parallel operation of two induction generators in an island grid is possible. Due to the strong connection between generator speed and voltage and to the influence of voltage on the active power in the island grid, it is preferable not to have a fast voltage control. If the voltage control is fast, the reactive power supplied from the STATCOM increases rapidly when connecting a load. This is devastating to both voltage and frequency. Despite large voltage and frequency deviations when applying big load steps, the system is stable.

There are mainly three different types of small hydro power stations. Those with synchronous generator, those initially constructed with synchronous generator but updated with induction generator and those constructed with induction generator. Only the first two types are designed to operate at no-load. The third type, equipped with semi-Kaplan turbine, has simplified control equipment. Field tests have shown that output power of a semi-Kaplan turbine operated at small gate openings does not simply increase with the runner blade angle but has a maximum. Beyond this point reverse action is observed and the output is fluctuating heavily. It is shown that the resulting graph is equivalent to the nose curve used in power system voltage stability analysis.

No-load operation of the semi-Kaplan turbine is not practically achievable by means of controlling the gate and runner blades and a local load corresponding to the minimum output power of the turbine is required to perform black-start. This dump load also has a stabilizing effect on the generator when operating with low external load.

A hydro power station with semi-Kaplan turbine in island operation was successfully simulated. When operating at 50 % loading it is possible to switch about 7 % load without achieving a frequency outside 47.5 – 52.5 Hz. The starting of an induction motor rated 7 % of the turbine power is handled well and both voltage and frequency are well within their limits. Damping increases with loading and thus the generator is able to handle larger load steps when operating on higher loadings.

It is shown that it is not possible to control the voltage without controlling the mechanical power at the same time. If the reactive power to the generator is increased with constant mechanical power the frequency decreases and the voltage decreases instead of increasing. A coordination of voltage and frequency control is therefore preferable.

Due to an uncertainty in the turbine parameters different water starting times were tested together with different servo motor speeds. It is shown that the parameter variation does not affect the control performance very much. A comparison between speed and frequency feedback was performed. The control methods yield practically identical performance.

A mechanical analogy is developed that explains the cross-coupling between voltage and frequency, the self-excitation process and the impact of changes in load and turbine power. This offers a way to intuitively understand the dynamics of the self-excited induction generator.

9.1 Future Work

In this thesis the possibility to control the voltage of an island operated induction generator by means of a STATCOM is investigated. However a STATCOM is a big investment if it is supposed to be used only during island operation. It would therefore be of interest to investigate a less expensive solution with switched capacitors where the voltage control is coordinated with the frequency control.

This thesis focuses on the island operated induction generator but in reality, a combination of induction generators and synchronous generators is likely to be found in an island grid. An investigation of this combination and a combination with power electronics as well, would be of interest.

Today there are no requirements on voltage and frequency directly applicable to island operation of a small part of the distribution system. Further the expected load steps in such a system are not very well known.

If these areas were investigated it would be much easier to compare different control algorithms and to decide whether island operation is acceptable or not from the costumers point of view.

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