Industrial Electrical Engineering and Automation

Voltage and Frequency Control for Island Operated Induction Generators

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1 The Induction Generator

It is well known that it is possible to run an induction generator with fixed terminal capacitors in island operation. Some work has also been performed with parallel induction generators in an island grid. The problem however is the voltage and frequency regulation.

To be able to bring up the voltage on an induction generator, fixed capacitors are connected to the generator terminals. The point is that the generator has a non-linear magnetizing curve while the capacitors have a linear voltage-current characteristic.
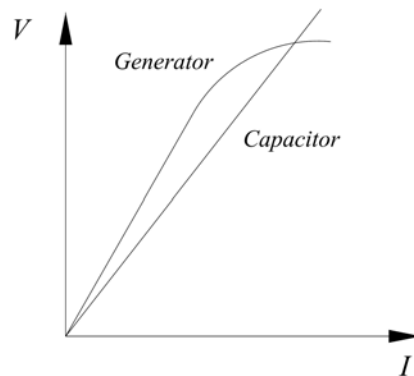

Figure 1.1 Induction generator magnetizing curve and capacitor characteristic.

When the generator is accelerated the remanence in the generator bring the LC circuit, formed by the generator and the capacitor, into oscillation. The voltage rises to the point where the magnetizing curve and the capacitor curve intersects. Then the voltage in the generator is not linear to the current any more and a stable operating point is obtained. If the capacitors are selected to compensate for the reactive power consumption in the generator, at no load, the terminal voltage at no load corresponds to the nominal voltage.

Then if the active power, supplied by e.g. a hydraulic turbine, and the reactive power from the capacitors could be controlled separately something similar to a synchronous generator is obtained. If the fixed capacitors are producing the no load reactive power to the generator then further reactive power needed for voltage regulation could be supplied by a STATCOM. The STATCOM is an IGBT based converter with the DC-link capacitors charged from the AC side. The reactive power output could be controlled to be either positive or negative.

2 Voltage and Frequency Regulation

Frequency as well as voltage regulation in island operation has to be different from the one used in a strong interconnected grid. Problem with the stability may appear when the regulators have a fast step response.

2.1 Turbine Governor

A turbine governor constructed for a large power plant connected to a strong grid is often equipped with a permanent droop function. This function introduces a permanent control error proportional to the output power, i.e. the gate opening, and allows parallel operating generators to share the load equally.

The problem with this kind of governor in an island grid is that large load steps may result in a large output signal from the regulator and this leads to overshoot in the gate opening and the frequency and may in the worst case lead to instability. Therefore an additional droop is introduced in the control loop, Figure 2.1. This transient droop is only active a fixed time after a rapid change in frequency.
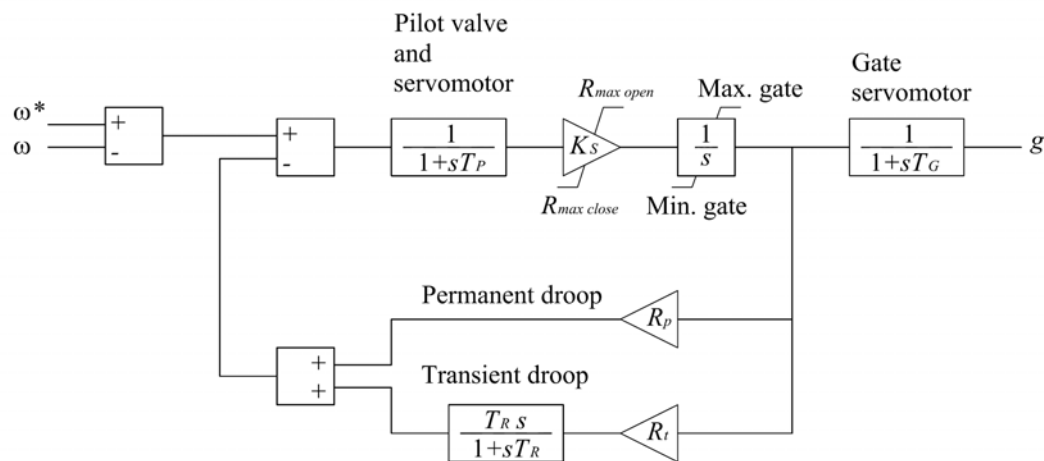

Figure 2.1 *Turbine governor with permanent and transient droop functions.*

If the load is increased the frequency decreases fast and the transient droop get a positive value very fast, Figure 2.2. The positive value from the transient droop is subtracted from the control error and contributes to reduce the output signal. The transient droop signal is then decreased at a rate determined by the reset time T_R. Due to this construction the overshoot in the gate opening is avoided and a stable operation is possible. This kind of governor is described in [1] and [2].

$R_{max\ open}$ and $R_{max\ close}$ are the maximum gate opening and closing speed, in pu/s, while *min gate* and *max gate* indicates the end positions of the gate. The output from the integrator, i.e. the control signal to the gate, is fed back to the droop functions.
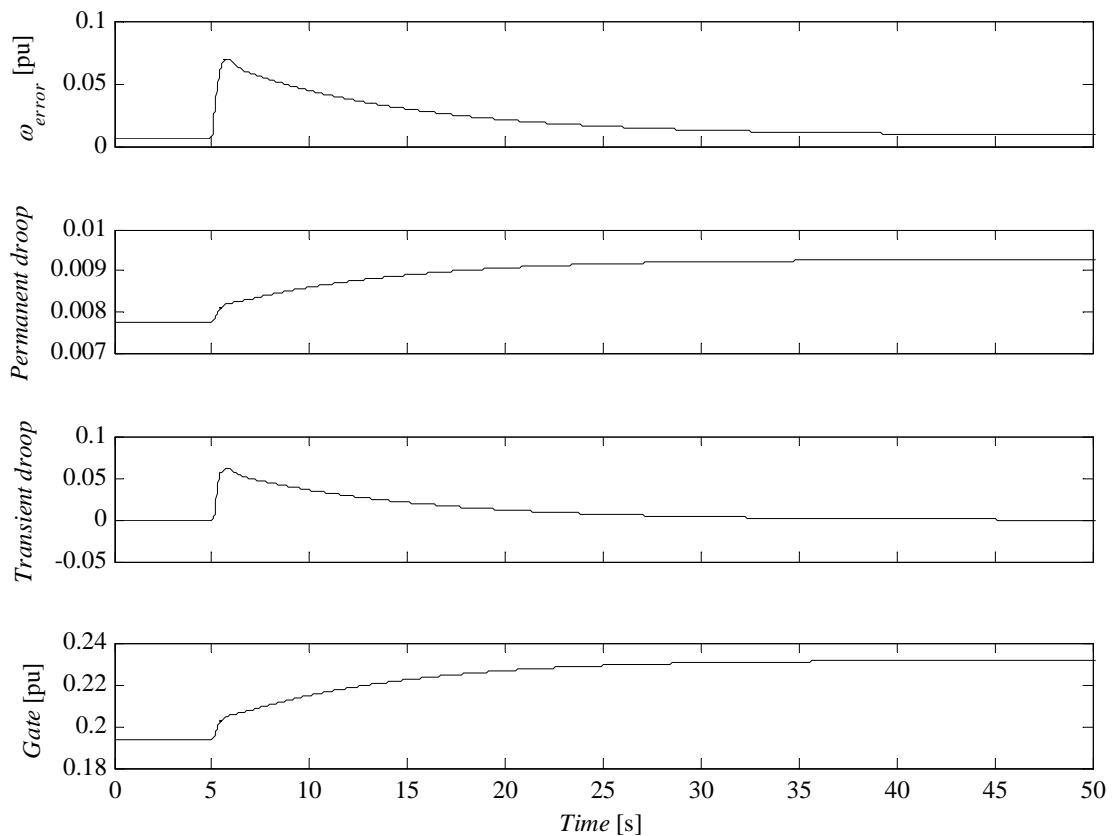
Figure 2.2 *Behaviour of permanent droop, transient droop and gate opening after a 200W (5%) load step.*

2.2 Voltage Regulator

A standard voltage regulator used for STATCOM control is based on a PI-controller with a permanent droop compensation that determines the voltage error according to the output reactive power. With the gain of the droop function selected according to the nominal power of each STATCOM, a desirable load sharing is achieved. This kind of controller operates well in a strong grid with synchronous generators.

However with an induction generator the voltage and frequency are cross-coupled so that a fast acting voltage regulator lowers the frequency even more after a load step. This leads to the proposal to use a voltage regulator with a permanent and a transient droop, just like the turbine governor described in chapter 2.1. Then the fast step response is suppressed by the transient droop function and facilitate the frequency regulation.
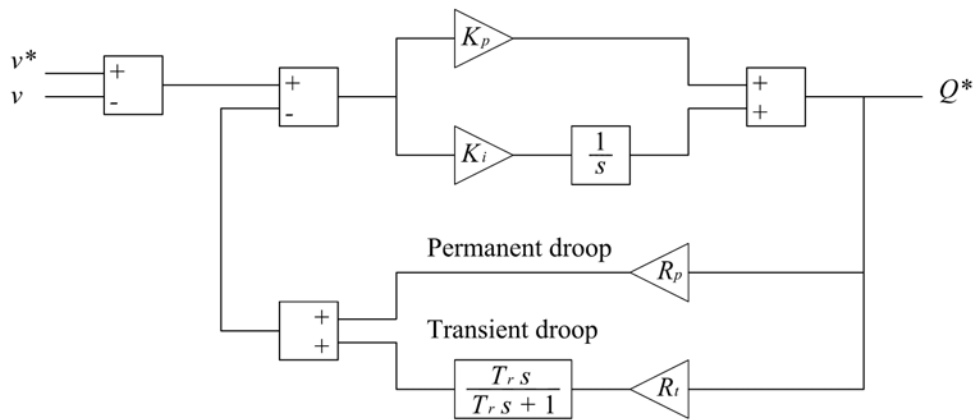
Figure 2.3 *STATCOM voltage regulator.*

3 Simulation Results

To evaluate the proposed control method and to determine suitable control parameters the test system in Figure 3.1 is first simulated in MATLAB SIMPOWERSYSTEMS and then tested in a laboratory experiment.
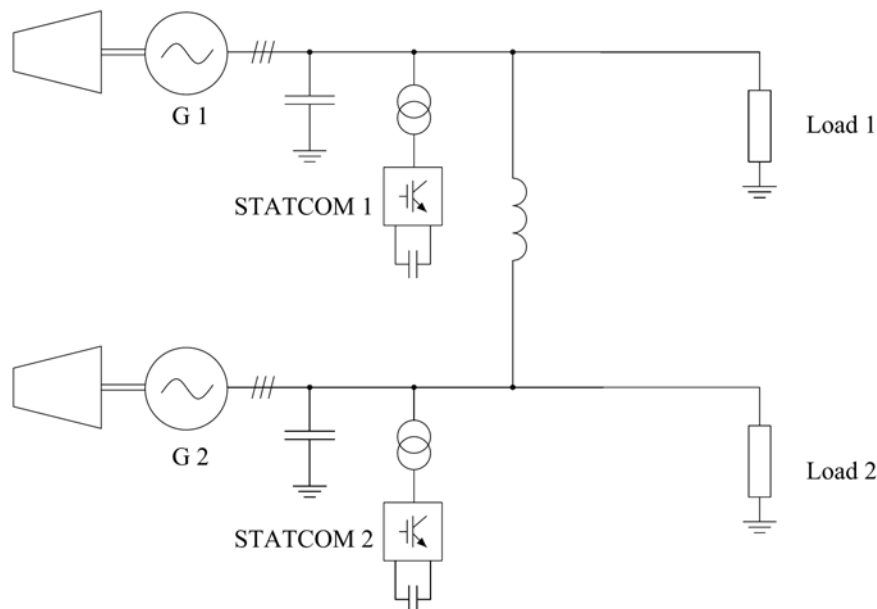

Figure 3.1 *Simulation model.*

The two generators are rated 230V 2kW and are magnetized by fixed capacitors and STATCOM. Parameters for the generators, determined by no-load test and locked-rotor test performed on the laboratory machines, are listed in the table below.

Table 3.1 *Generator parameters.*

S_n	2 kW
$V_{L\text{-}L}$	230 V
n_s	1500 rpm
R_s	1.2 Ω
R_r	1.0 Ω
X_{ls}	2.4 Ω
X_{lr}	2.4 Ω
X_m	22.1 Ω

The reason for using a transformer between the STATCOM and the rest of the grid is that the converters used in the laboratory cannot handle 230V. Therefore the voltage is transformed down to 145V.

The capacitors are selected to get a generator terminal voltage of 230V when operating at no load. This means that all the reactive power needed for magnetizing the generator at no load are produced by the capacitors. The values of the star connected capacitors are calculated from the generator parameters according to [3]. The calculated values are 131μF, this corresponds to a generated reactive power of 2.2kVAr at 230V. To be able to control the voltage at full load a 1.5kVAr STATCOM is connected in parallel with the fixed capacitors.

The two generator bus bars are connected together with a 3mH inductance. The turbine and the water are represented according to [2] in the simulation model. Parameters for turbine governor and voltage regulator are listed in the table below.

Table 3.2 *Regulator parameters.*

Turbine governor	
T_P	0.2s
K_S	5
T_G	0.2s
R_P	0.04
R_T	7
T_R	2s
$R_{max\ open} = R_{max\ close}$	1/30 pu/s
Min. gate	0.01
Max. gate	0.97
Voltage regulator	
K_P	1
K_i	0.5
R_P	0.04
R_T	0.9
T_R	12s

Standard parameters are chosen and calculated according to [2] and then adjusted in the simulations to obtain well operating regulators.

The speed of the generator is controlled instead of the electrical frequency. This is done to avoid problems with determining the frequency in the simulation and is acceptable under the assumption that the slip is small. Controlling the speed instead of the frequency should not have influence on the result obtained in the simulations.

3.1 Dynamic Properties of Load Changes

The generators are loaded by a 1000VA (0.25pu) load with cosφ=0.98. Connecting and disconnecting of an additional load of 160VA (0.04pu) is presented in Figure 3.2. The transient voltage and frequency droops act to reduce the step response for both active and reactive power. At about 20s after the step the values are close to their nominal values again.
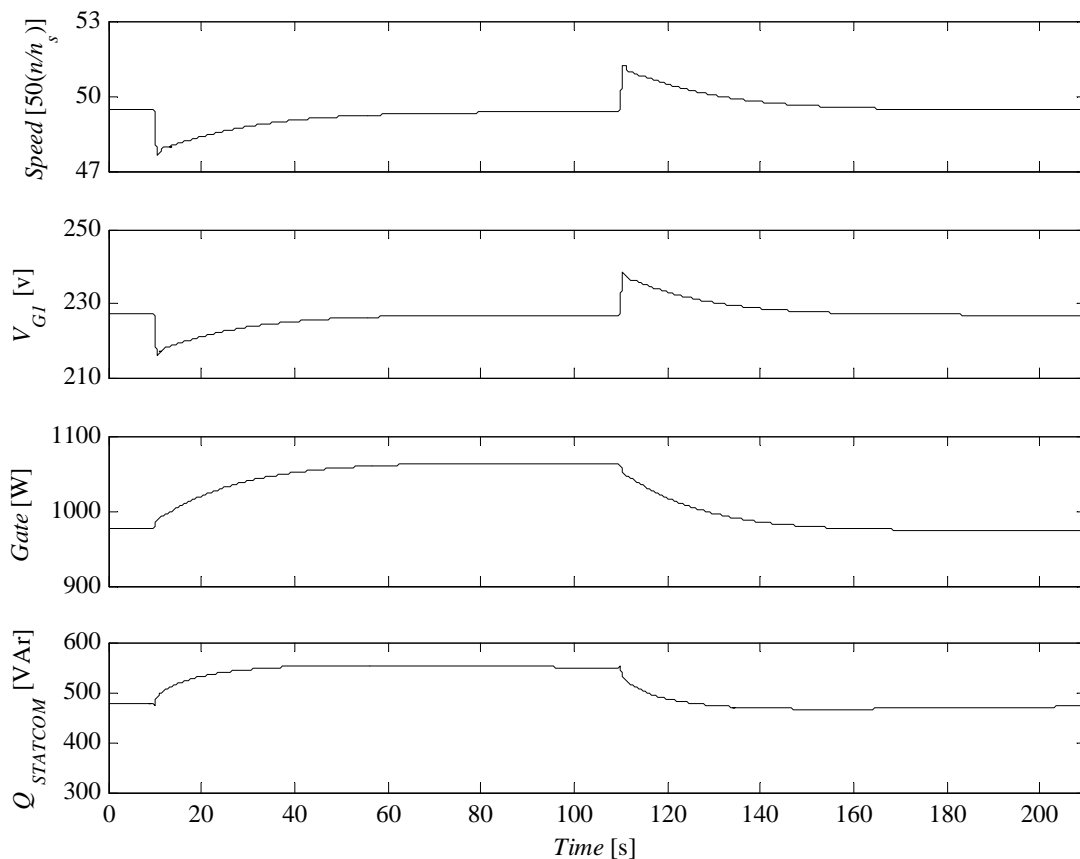
Figure 3.2 *Increasing load from 25% (1000VA) to 29% (1160VA), then back to 25%. From top: speed generator 1, terminal voltage generator 1, turbine gate opening generator 1, STATCOM 1 output reactive power.*

3.2 Influence of Turbine Governor

To be able to operate in island operation the governor is equipped with a transient droop compensation, Figure 2.1. The transient droop gain, R_T and the reset time, T_R, is selected to achieve a proper step response without any overshoot.

Provided that the highest allowed frequency deviation is ±2.5Hz, the largest load step is determined with different gate opening rates. The simulations show that with a gate opening time of less than 60s the time has no influence on the maximum step. This means that a standard turbine servo could handle this without any problem. However it does not mean that a fast servo is unnecessary in all situations. If a fault occurs and the generator is disconnected from the grid it is important to be able to stop the turbine as fast as possible. A shorter opening and closing time is also preferable if a larger frequency deviation than ±2.5Hz, and therefore larger load steps, is allowed.
In the simulations a opening and closing time of 30s is selected.

3.3 Influence of Voltage Regulator

The traditional way to control a SVC or STATCOM is to include a droop function in the regulator that sets the reactive output power in proportion to the error in voltage. This is however not preferable if the voltage regulator is included in an island operating system with induction generators. In such a system even a small load step has high influence on the voltage as well as the frequency. This is probably due to the strong

cross coupling between voltage and frequency in the induction generator. The load also contributes since it depends on voltage and affects the active power balance that determines frequency.

To get around this problem a voltage regulator consisting of two different droop functions is developed to control the STATCOM. The permanent droop determines the voltage in steady state. The transient droop contributes after a load step and operates to temporarily reduce the output signal from the regulator during a certain time after the step. This is illustrated in Figure 2.3.

The difference between a standard voltage regulator and the one with transient droop compensation is presented in Figure 3.3 where two induction generators run in parallel and the load is increased from 25% (1000VA) to 29% (1160VA). As can be seen in the figure a fast voltage regulator is not preferable when dealing with induction generators. Both frequency and voltage gets worse in case of fast voltage regulation.
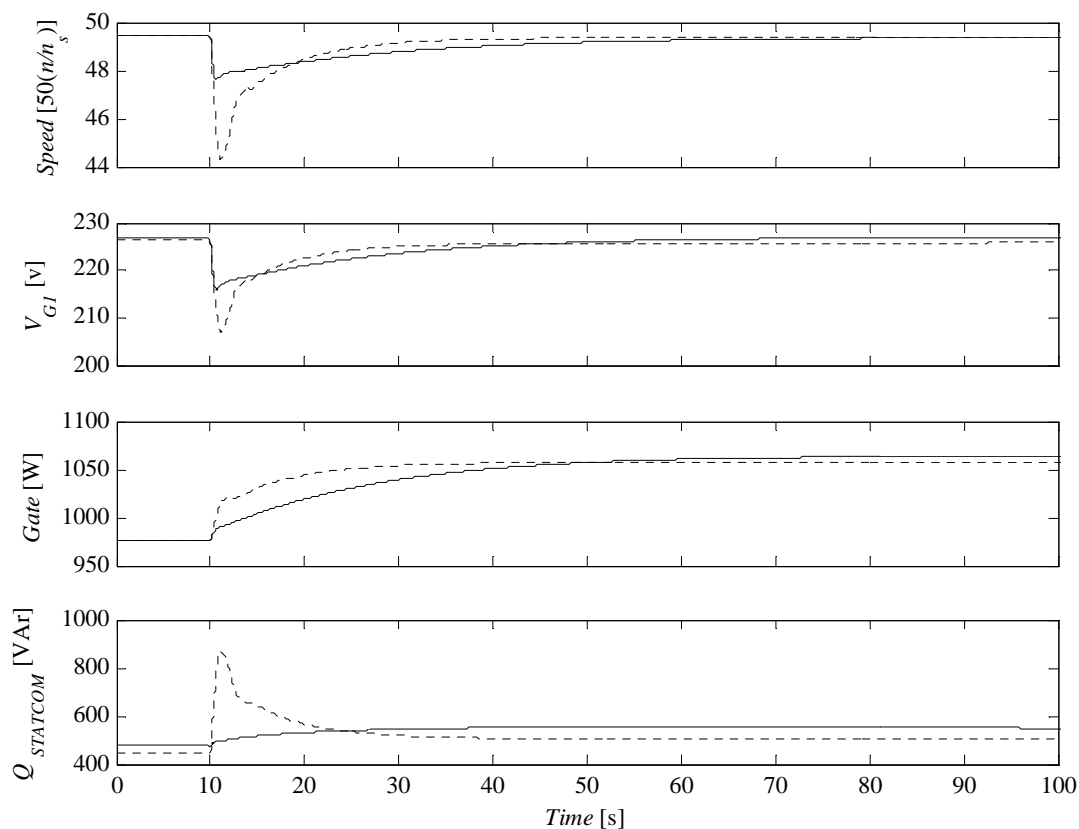

Figure 3.3   *Increasing load from 25% (1000VA) to 29% (1160VA). From top: speed generator 1, terminal voltage generator 1, turbine gate opening generator 1, STATCOM 1 output reactive power. Fast (dotted line) and slow (solid line) voltage regulator.*

The voltage step response is mainly determined by the transient droop gain, R_T, and the transient droop reset time, T_R.

In Figure 3.4 the transient droop reset time is held constant at 10s while a transient droop gain of 0.5, 1.0 and 2.0 is tested. The two parallel generators are loaded at 25%, with $\cos\varphi=0.98$. Then another load, 4% of the total rated power and with the same power factor, is connected.

As can be seen in the figure an increase in transient droop gain results in a decrease in the output from the STATCOM. This has a positive influence on the frequency, which does not reach such low values as with the low gain. Another positive effect is that the overshoot in the turbine gate opening is eliminated with a high transient droop gain in the voltage regulator. There is no difference in the lowest voltage achieved with the three different gains, the only difference is a slightly faster return to the stationary value if a low gain is used. This is however not very critical and therefore a high transient droop gain is preferable.
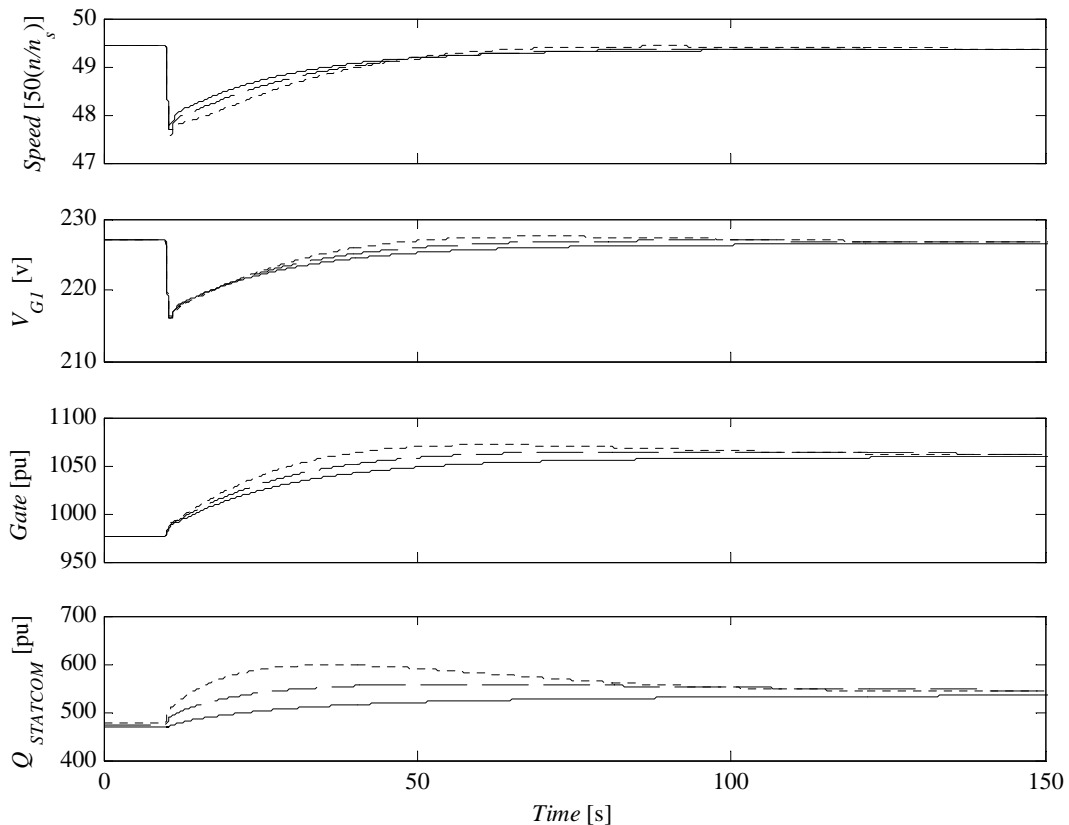

Figure 3.4   *Increasing load from 25% (1000VA) to 29% (1160VA). From top: speed generator 1, terminal voltage generator 1, turbine gate opening generator 1, STATCOM 1 output reactive power. Variation of R_T for constant $T_R=10$ in the voltage regulator. $R_T =0.5$ (dotted line) $R_T =1$ (dashed line) = $R_T =2$ (solid line).*

The other important parameter in the voltage regulator is the transient droop reset time, T_R. This parameter determines how long the transient droop is active and reducing the regulator output signal. In Figure 3.5 the transient droop reset time is varied between 5s and 20s while the transient droop gain is equal to 1. The loading is the same as above.

If a short time is used an overshoot is achieved, not only in the STATCOM output, but also in the turbine gate opening. The variation of T_R between 5s and 20s does not affect the lowest voltage and frequency after the step in load. With a long reset time the STATCOM output power is reduced and therefore the frequency returns to its nominal value a little bit faster than with a short reset time. The only drawback with a long reset time is that the return time to nominal voltage is getting longer.

With the observations made above it could be established that the transient droop reset time should be chosen high enough to eliminate the overshoot in reactive power

delivered by the STATCOM. It is however important that the regulator parameters are chosen in relation to each other to have the most efficient regulator.
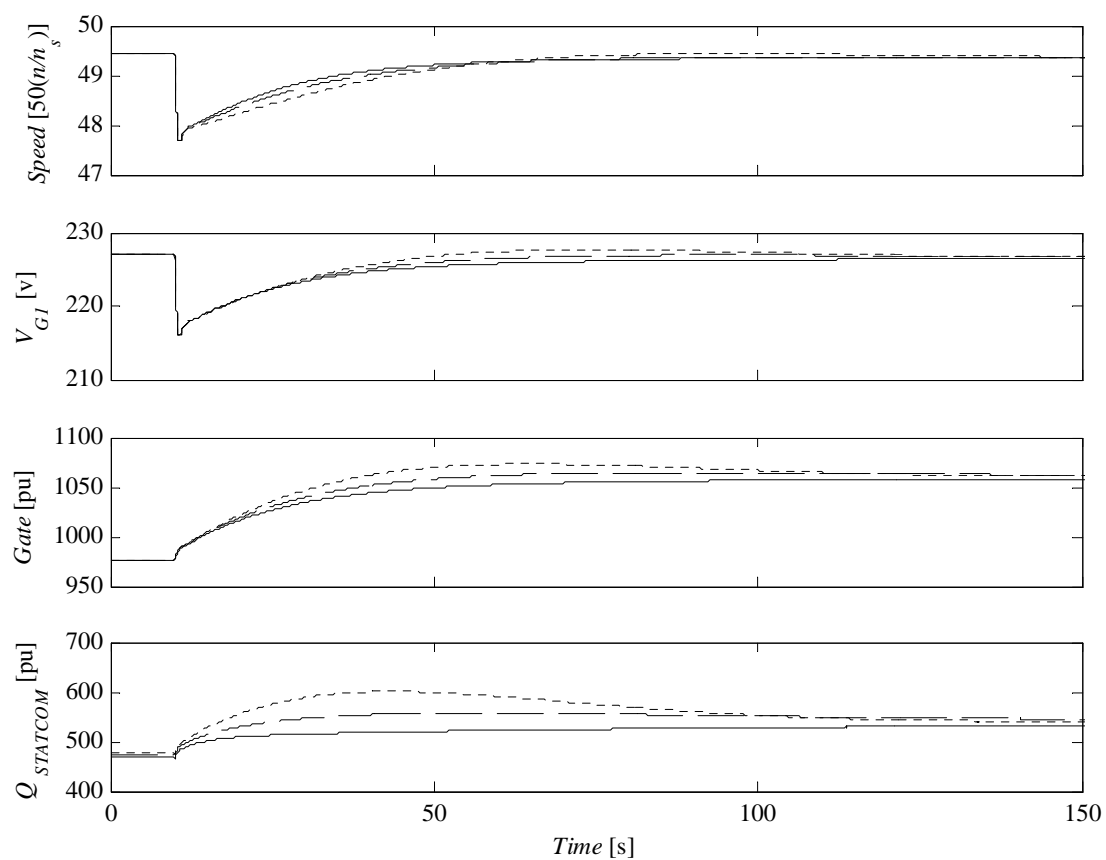

Figure 3.5   *Increasing load from 25% (1000VA) to 29% (1160VA). From top: speed generator 1, terminal voltage generator 1, turbine gate opening generator 1, STATCOM 1 output reactive power. Variation of T_R for constant $R_T =1$ in the voltage regulator. $T_R=5$ (dotted line), $T_R=10$ (dashed line), $T_R=20$ (solid line).*

3.4 Maximum Load Step

The sensitivity to load steps is investigated by determine the lowest frequency and voltage after a load step. This is done with different step sizes when the generators are running at no load. The result is depicted in Figure 3.6. At lower load steps the voltage and frequency is almost proportional to the step size.
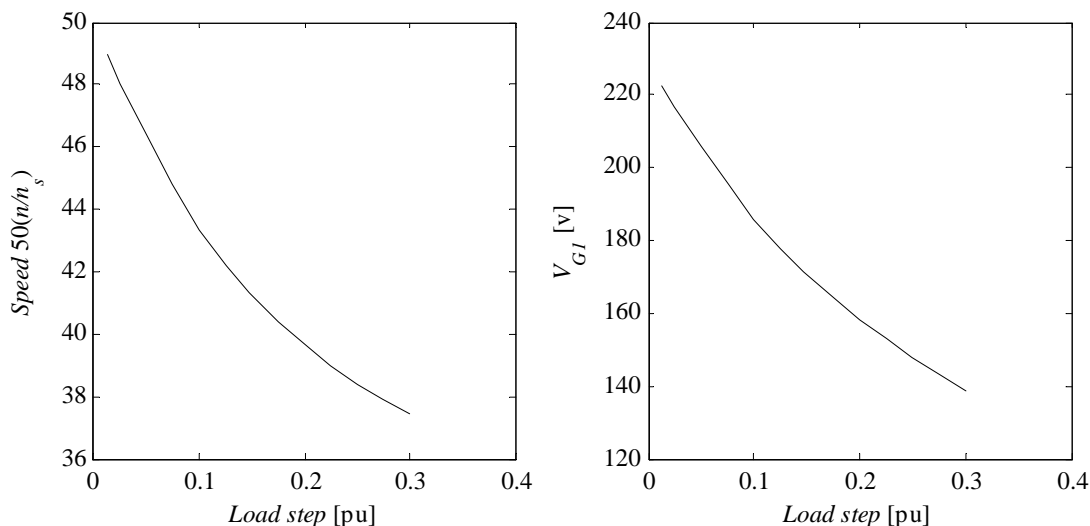

Figure 3.6   *Lowest frequency (left) and voltage (right) after a resistive load step as function of the step in per unit of the total generator capacity.*

To be able to determine the maximum load step the lowest, or highest, allowed frequency have to be known. In a power system the problem with too high or too low frequency is mainly connected to induction motors. At low frequency the motor is heated and in the worst case it stops. Therefore the IEC and NEMA standards for an induction motor are studied. There is a slight difference between them and in the IEC standard there are two different zones. In the innermost zone (A) the motors are supposed to provide their rated performance. The outermost zone (B) is not for continuous operation.
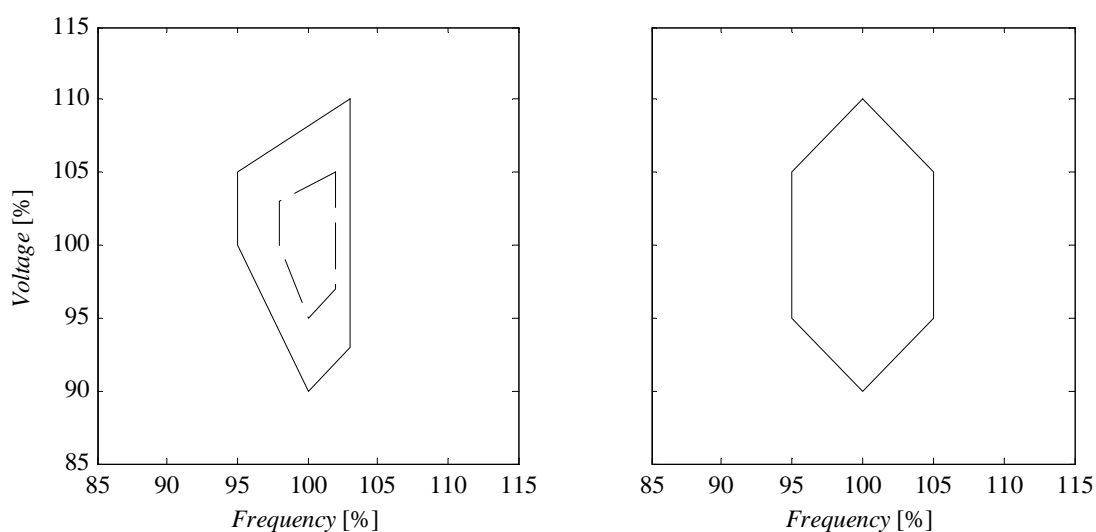

Figure 3.7   *Voltage and frequency variations according to IEC standard (left) and NEMA standard (right). For the IEC standard: Zone A (dashed line), Zone B (solid line).*

Based on the standards the frequency interval 47.5 – 52.5Hz is used when maximum load steps are determined.

In Figure 3.8 the maximum load step is depicted as a function of the load before the step. The function is linear in the regarded area. Due to the high losses in the generator readings above 0.5 pu is not reliable.
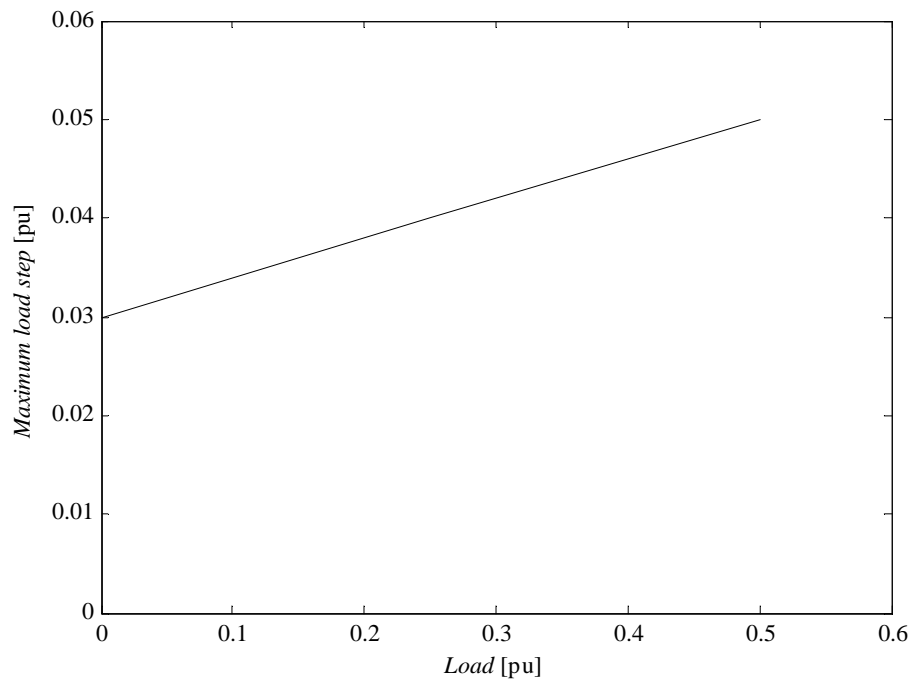

Figure 3.8 *Maximum load step as function of loading before the step, if frequency must be kept in the interval 47.5-52.5Hz.*

4 Experimental Results

To verify the simulations a test system according to Figure 4.1 is set up in the laboratory. DC machines controlled by power electronic converters drive the induction generators. In the DC machine controller code the dynamics of a hydraulic turbine and a turbine governor according to [2] are included. The dynamics of the current controller and the DC machine is fast and is therefore neglected in comparison with the turbine and governor. The STATCOM consists of a standard 3-phase voltage source converter with the DC-link voltage supplied from the AC side. The converters are connected to the grid via transformers due to the fact that the converters are constructed for a lower voltage than the nominal voltage of 230V. All parameters are equal to the ones used in the simulations.
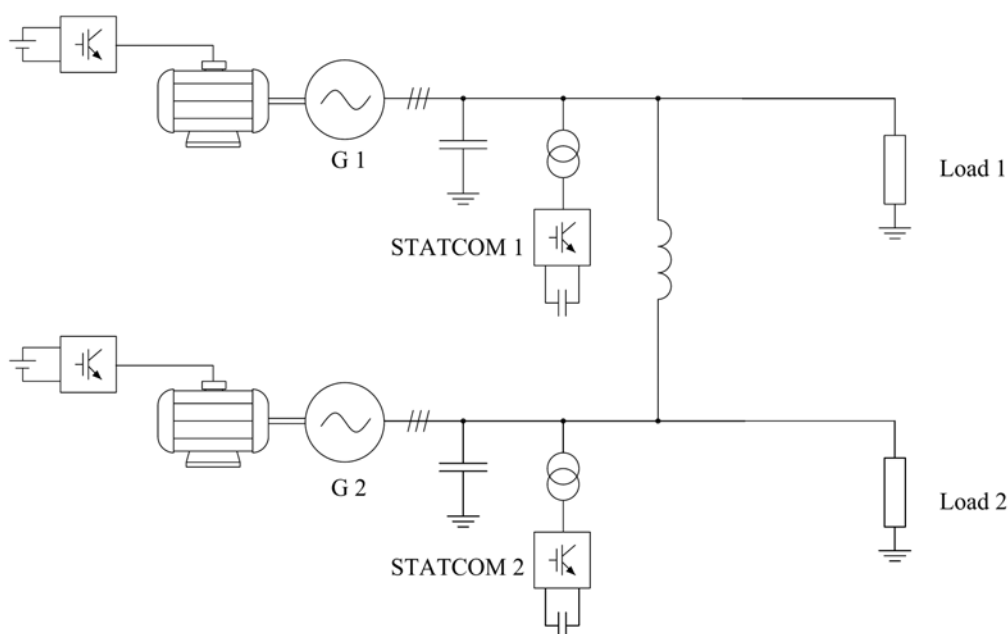

Figure 4.1 *The laboratory test system.*

4.1 Generator Start Up

To be able to build up the voltage in the induction generator fixed capacitors are connected to the terminals. The generator is accelerated, with the governor in operation, and reaches almost full speed before the voltage is beginning to rise. As can be seen in Figure 4.2 the generator first accelerates very quickly. Then when the magnetization and the voltage increase, the losses in the generator also increase, the speed is lowered and the gate opening increases to bring the speed back to its nominal value. When the generator reaches 50Hz the voltage is 230V due to the selection of the fixed capacitors.

If the generator has not been in use for a long time the remanence in the machine may be too weak. In that case large capacitors and high speed is necessary to bring up the voltage. This problem could also occur if the generator has been stopped with load connected.
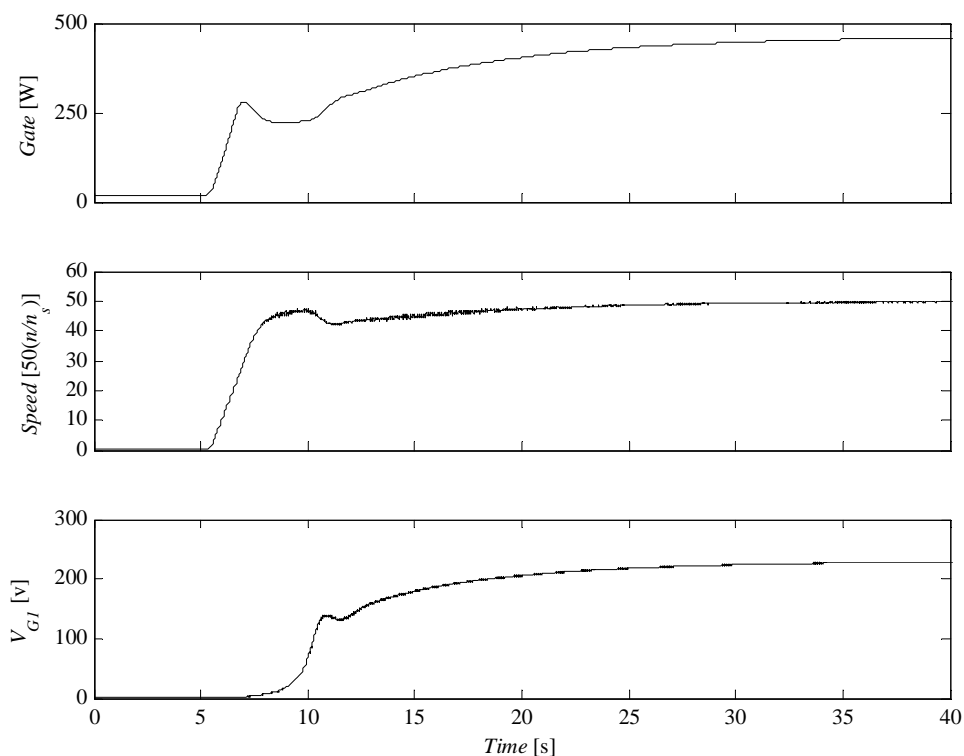
Figure 4.2   *Generator voltage build up. From top: turbine gate opening generator 1, speed generator 1, and terminal voltage generator 1.*

When the generator is operating at no load the STATCOM is started and finally the two generators are synchronized smoothly without any currents flowing between them. Neither voltage- nor frequency regulators have any problem handling the synchronization.

4.2 Load Variation

In Figure 4.3 the generators are loaded 25% of the total installed power 4000VA. Then at t=0 an additional load of 4% (160VA) with the power factor 0.98 is connected. At about 90 seconds the additional load is disconnected. The STATCOM reactive power output is calculated from the converter reference values and due to this and some noise in the measurements looks very rough. It is however possible to estimate the mean value from the measurements.

As can be seen the curve shapes are almost the same as simulated in Figure 3.2. The only difference is the level of the gate opening and the STATCOM output. The error in gate opening is mainly because the electrical losses in the DC-machine 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 measuring errors.

The results from the other generator look similar to those in Figure 4.3. Due to the equal nominal power of the generators they share the load equally. Tests have been carried out with different nominal power settings in the two regulators. Then they do not share the load equal but no stability problem is observed.
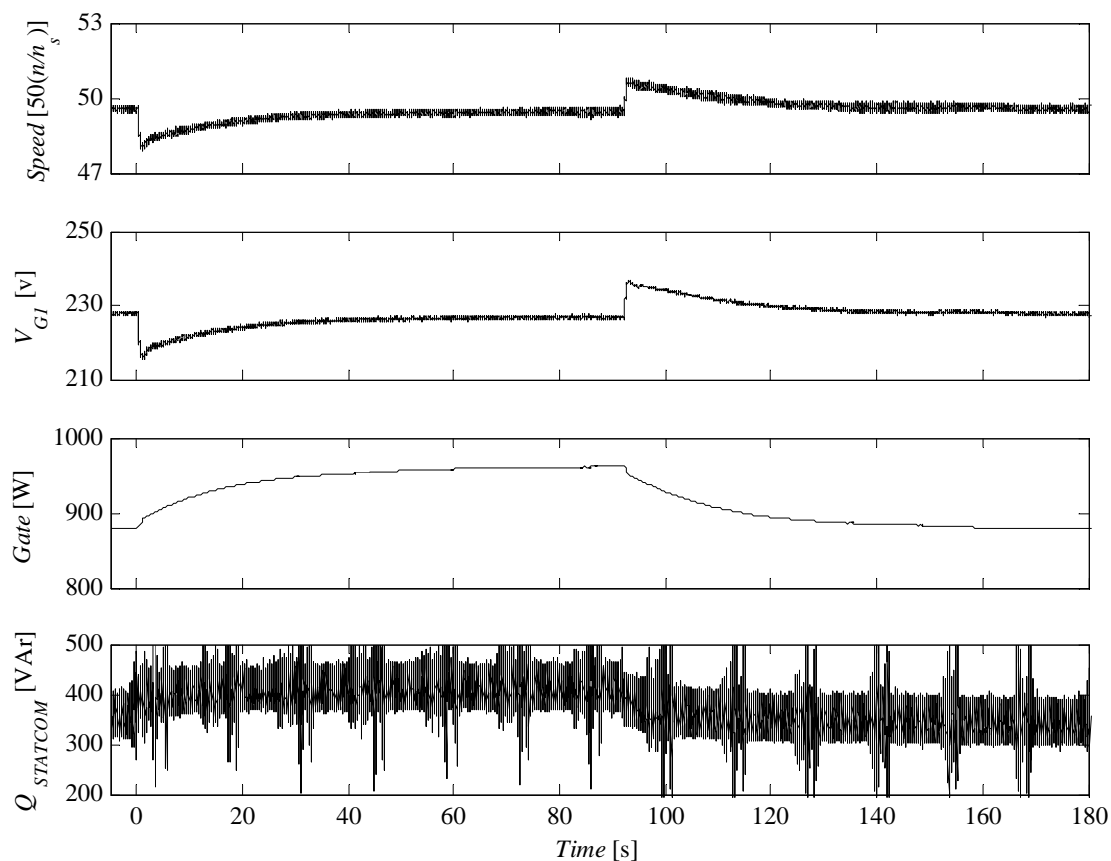
Figure 4.3   *Increasing load from 25% (1000VA) to 29% (1160VA), then back to 25%. From top: speed generator 1, terminal voltage generator 1, turbine gate opening generator 1, STATCOM 1 output reactive power.*

4.3 Active and Reactive Load

In the previous section only an almost resistive load was considered. However resistive load is favorable to the generator due to the load reduction when the voltage is decreased. To get around the dependency between voltage and load the case with a constant power load is investigated. In the laboratory a constant power load is achieved with one of the converters with the DC side connected to a DC source. Therefore only one STATCOM is used for the voltage control of the two generators in this case.

In Figure 4.4 a constant load of 250W is connected at *t*=10s. This load equals 6% of the total installed power but both frequency and voltage regulators handles this very well. At *t*=75s an additional reactive load of 250Var is connected. As depicted in the figure this has almost no effect on the speed, but on the voltage. The voltage regulator is quite slow but acts to bring the voltage back to its nominal value in some hundreds of seconds. The slow voltage regulator is preferable to avoid a drop in speed when the additional reactive power is connected. It is also observed that the active power, the gate opening, is increased when the reactive power is increased.
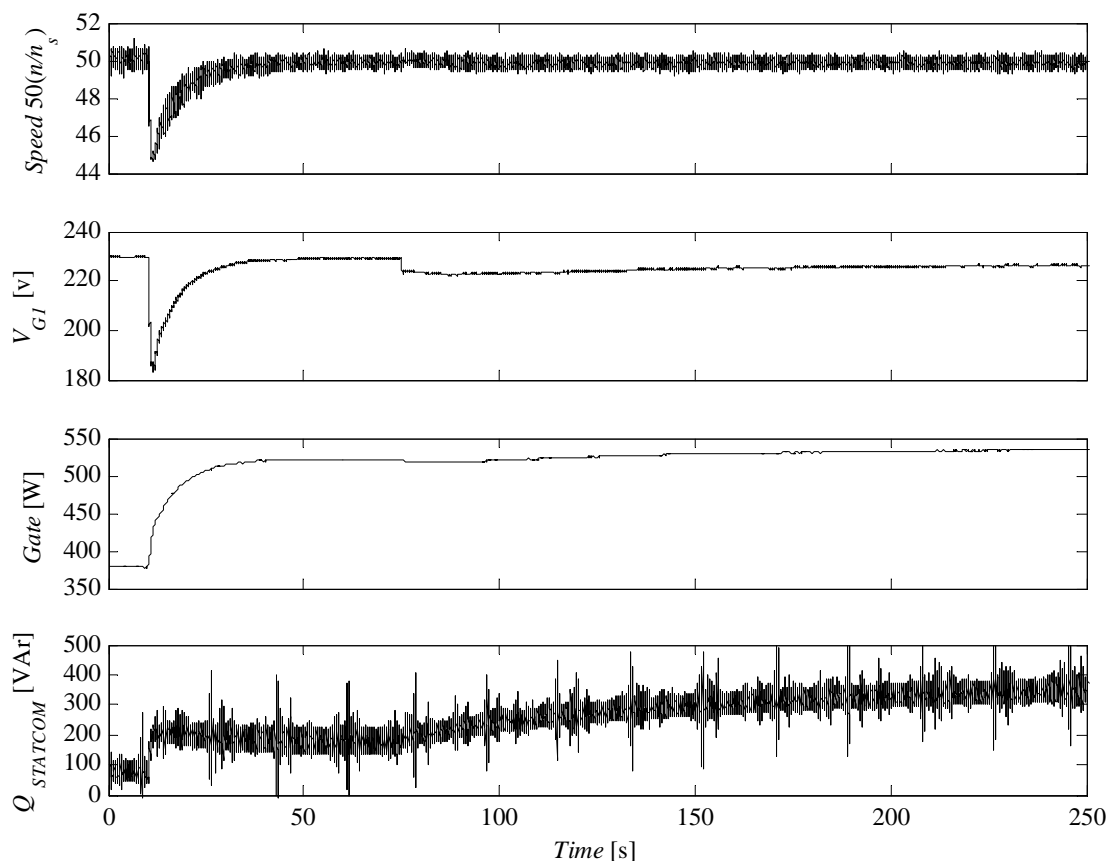
Figure 4.4 *Connecting constant power load, first 250W then 250VAr. From top: speed generator 1, terminal voltage generator 1, turbine gate opening generator 1,* STATCOM *1 output reactive power.*

4.4 Induction Motor Starting

The generator performance during a motor start is investigated with an induction motor connected to a fan. The torque characteristic for a fan, and for a pump as well, is $T \sim n^2$. The power is proportional to n^3. To make it even worse for the generators it would have been better with a compressor as load but the fact that the fan has a nominal power of 6% of the total installed power makes the experiment valid anyway. In Figure 4.5 a constant power load of 250W is connected at $t=10s$. Then at about $t=90s$ the fan is started and runs until it is stopped at $t=170s$. As can be seen from the figure both the frequency and the voltage are stable during the start up, though both these quantities reaches very low values.
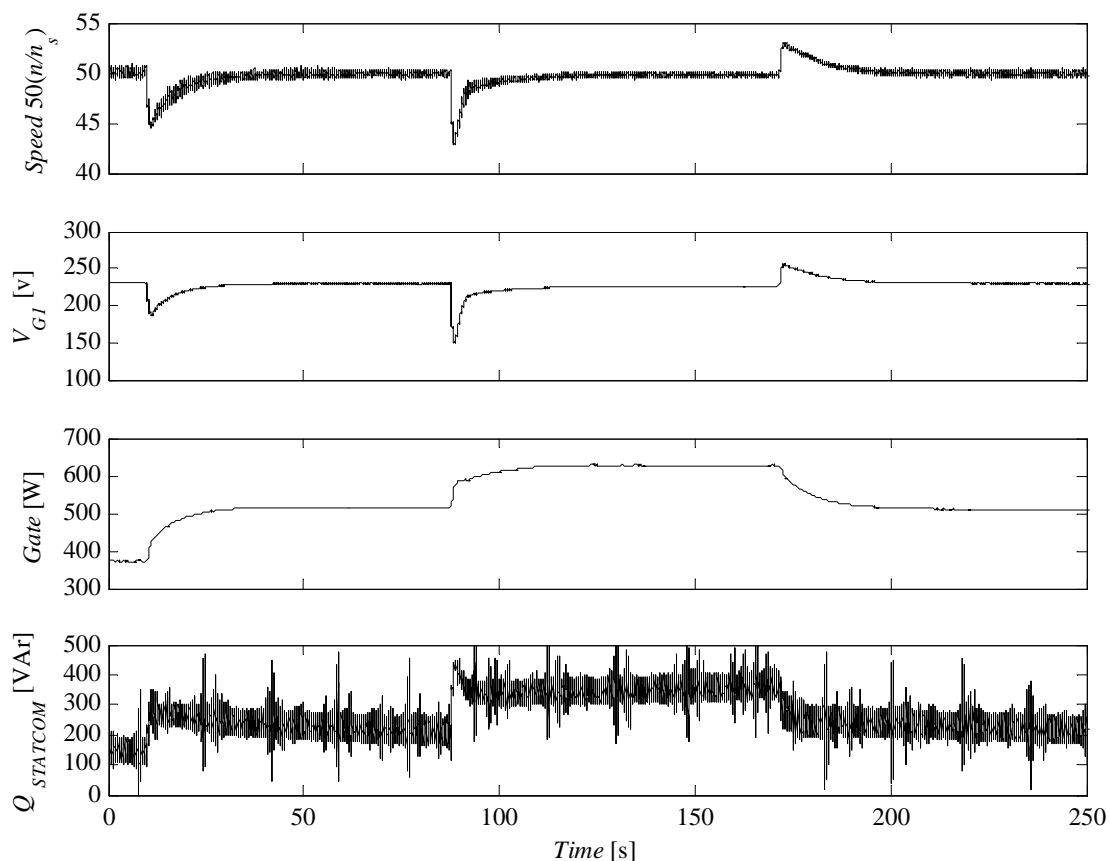
Figure 4.5 *First connecting 250W, then starting an induction motor fan of 250W and then stopping the fan. From top: speed generator 1, terminal voltage generator 1, turbine gate opening generator 1, STATCOM 1 output reactive power.*

4.5 Load Step

The dependence between the lowest frequency and voltage reached, when increasing the load, and the step size is investigated. The measurements are performed with both constant power load and resistive load.

To be able to consume a constant active power one of the converters is used as load and therefore only one STATCOM is used for the voltage regulation of the two generators. The resistances used in the laboratory have a power factor of 0.98.

The result is displayed in Figure 4.6 where only moderate load steps are considered. For the case with constant power load the lowest frequency is proportional to the load step while the voltage drops even more with larger load steps. When a resistive load is connected instead both voltage and frequency deviations decrease. This is due to the voltage dependency of the load. When comparing the results with the one simulated in Figure 3.6 it is clear that there is a difference in the frequency. This is mainly due to problem with modelling losses and inertia of the machine correctly in the simulation.
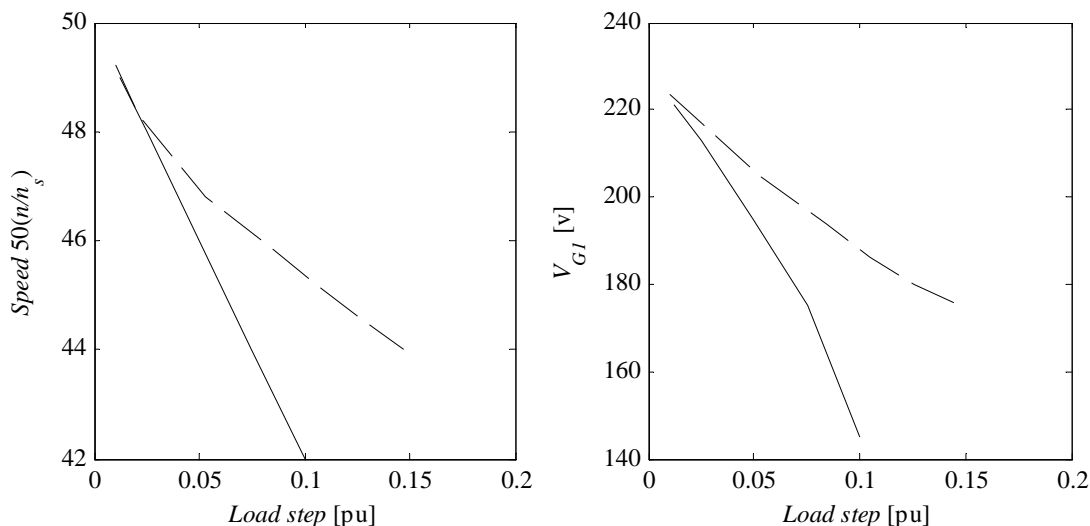
Figure 4.6   *Lowest frequency (left) and voltage (right) after a load step as function of the step in per unit of the total generator capacity. Solid line: with constant power load. Dashed line: with resistive load.*

4.6 Turbine Governor

In the tests the speed of the generators is controlled instead of the electrical frequency. However tests with frequency control have been performed as well. No differences between the two methods have been observed and it is even possible to control one generator with speed control and the other with frequency control without any instability.

4.7 Voltage Regulator

In the performed experiment the voltage regulator is found to be very sensitive to the parameter selection. With wrong parameter combination the voltage regulator starts to oscillate and the STATCOM over current protection is tripped. If the parameters are selected according to equation 4.1 the feedback loop has a gain smaller than 1 and the oscillations are damped.

$$\left(R_P + R_T\right)K_P < 1 \tag{4.1}$$

The influence of bad parameter choice is very obvious in the experiments due to the noisy feedback signal Q. A stable regulator with acceptable performance is achieved with parameters according to Table 3.2.

5 Conclusions

The behaviour of two parallel operated self excited induction generators, in island operation, was investigated in simulations and laboratory experiments. The generators were equipped with fixed capacitors and STATCOM for voltage regulation. DC machines behaving as hydraulic turbines were running the generators. No difference between the simulations and the experiments were observed.

When connecting and disconnecting different loads, both resistive and constant power loads, the system was found to be stable. An induction motor connected to a fan was also started. Both voltage and frequency reaches low values for some seconds but the system is still stable during the motor start.

The turbines are controlled by turbine governors with permanent and transient droop functions. The transient droop improves the transient stability. Both speed and frequency control is tested. No difference between them concerning stability is observed. The speed of the gate opening is not very critical when the load steps are moderate.

A voltage regulator with a permanent and a transient droop was used. The voltage regulator is slowed down by the transient droop and the slow voltage regulator improves both frequency and voltage regulation.

The relationship between the lowest frequency/voltage after a load step and the amount of power connected was investigated. Larger load steps give lower voltage and frequency and the relation is almost linear for moderate step sizes.

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[3]   A.K. Al Jabri, A.I. Alolah, "Capacitance Requirement for Isolated Self-exited Induction Generator," *IEE proc.*, Vol. 137, Pt. B, No. 3, May 1990.