Development of a Method of Analyzing the Control Characteristics of Thermal Power Plants and their Interaction with Power Systems

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by

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Abstract

This thesis describes a network simulator system that has been developed in order to simulate special type of network conditions, e.g. islanding operation, for networks connected to thermal power stations, especially with regard to frequency control.

The simulator has been developed so that it can operate both connected to an actual power station in operation or to a power station simulator. It has been designed primarily with regard to the Stenungsund thermal power station, but is of a general design and will in the continuation of this project be adapted also for other types of power stations.

The main principle of the simulator is that it can be applied to a power station in operation and perform simulations where special network conditions are simulated in spite of that the power station is still connected to its normal network.

This simulator has been developed as a tool for further studies of special operating conditions for power stations, in particular islanding operation. Certain such studies have been carried out and are described in this thesis.

The studies have shown that islanding operation is a complex situation where unexpected behavior of the power station can sometimes lead to very unwanted consequences and that it is therefore necessary to be able to test such situations in advance, as it is otherwise highly unlikely that the station will be able to remain in operation under such conditions.

Tests as described above can show the need for new control systems or systems settings as well as new routines for operating the stations under such conditions and also for operator training so that the station operators know how to handle these situations. The simulator can be used as a tool for all these purposes.

Keywords:

Network simulator, thermal power station, frequency control, islanding operation

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I also like to thank the staff and management of the Stenungsund power station, who have been very cooperative and whose assistance has been extremely valuable.

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Introduction

This project has been aimed at developing a method for simulating the external environment of a power station. This environment can consist of a larger or smaller portion of a power system network, or in the most extreme case it can consist of the internal loads of the power station; i.e. in-house operation.

The idea has been to develop a system that can be connected either to a simulator of the power station (where available) or directly to the power station itself.

The project was started in 1987 at the Department of Electrical Power systems at Chalmers University of Technology and has been sponsored by the Swedish State Power Board (Vattenfall). Essential for the project has also been the support of the Stenungsund thermal power station, which has been the site where the system has been developed and tested.

The simulator system has been developed to a level where it is fully operational, but in order to get a suitable tool for use in commercial power applications further work is required.

A considerable portion of the work involved in developing the system has been to develop and to build suitable physical interface systems to the actual power plant.

Symbols

The symbols used for quantities and units coincide with the IEC recommendations, except for the decimal sign which in this thesis is represented by a *dot*.

Contents

Chapter 1

Main Outline and Prerequisites

Power stations are in most cases connected to large power systems, as shown in Figure 1.1. The task of obtaining frequency control of the network is then allocated to a number of power stations that are suitable for this purpose, which in the case of the Swedish national network always means that it is given to hydroelectric power plants.

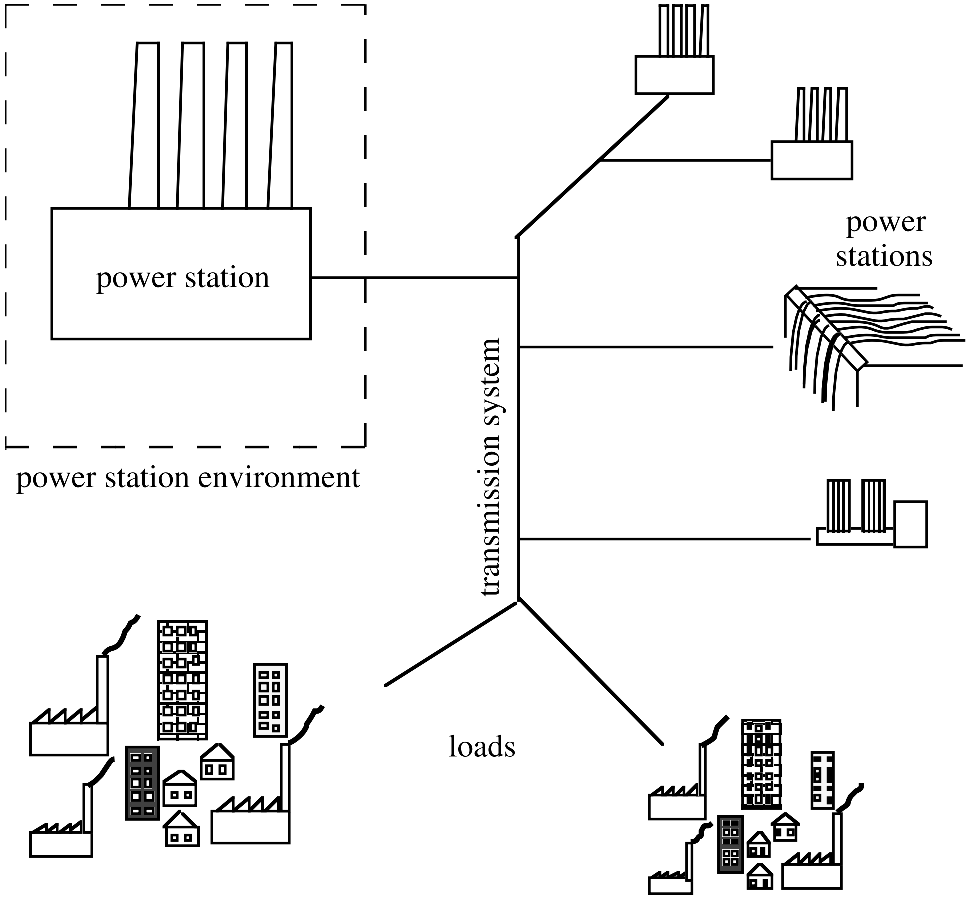

Figure 1.1 Power station and external network.

However, conditions could well be anticipated where the main network can not be held operational. Such conditions could be the result of very severe disturbances in the systems; e.g. following extreme storms or hurricanes, in case of war or sabotage etc. If these conditions are of long duration it may become necessary to let certain power stations supply a geographically restricted area without connection to other parts of the network, so called islanding operation. This type of operation is never used in the Scandinavian network under normal operating conditions and it is therefore basically unknown how the power stations would respond in such cases.

The task of frequency control becomes much more difficult during islanding operation. There are several reasons for this: power stations less suitable for frequency control may have to exercise it, the moment of inertia of the system gets much smaller which means that power unbalancies lead to rapid frequency deviations and also the anticipated load changes get much larger in relation to the total load of the system.

It is only in rare cases possible to test the behavior of a power station connected to special network configurations by actually physically connecting it to these types of loads. The costs and the risks involved, as well as the possible inconveniences to the customers, would in most cases be prohibitive.

The idea behind this type of system is therefore instead that the power station generator is physically connected to the normal network, whereas the control systems are connected, via suitable interfaces, to the computers that perform the network simulation. This will allow for the testing of islanding operation conditions. The simulator should also be able to work against a power station simulator, so that a large number of tests can be run at a low cost and in order to allow for testing more extreme cases.

It was however found while the system was developed that the cases where the network is extremely limited, e.g. in-house operation, may well also be interesting. It is often desirable to verify that a power station can e.g. transfer into an in-house operation state, but it is not common to actually perform such tests except subject to very tight restrictions.

In normal operation the power station interacts with the network, with its loads and generating stations, through the network connection itself, as shown in Figures 1.1 and 1.2. There is no external source through which any control parameters are being brought into the station. Instead the regulator systems sense the frequency and the voltage at the point of connection and regulates the station accordingly, in accordance with the regulating modes that are being set by the station operators.

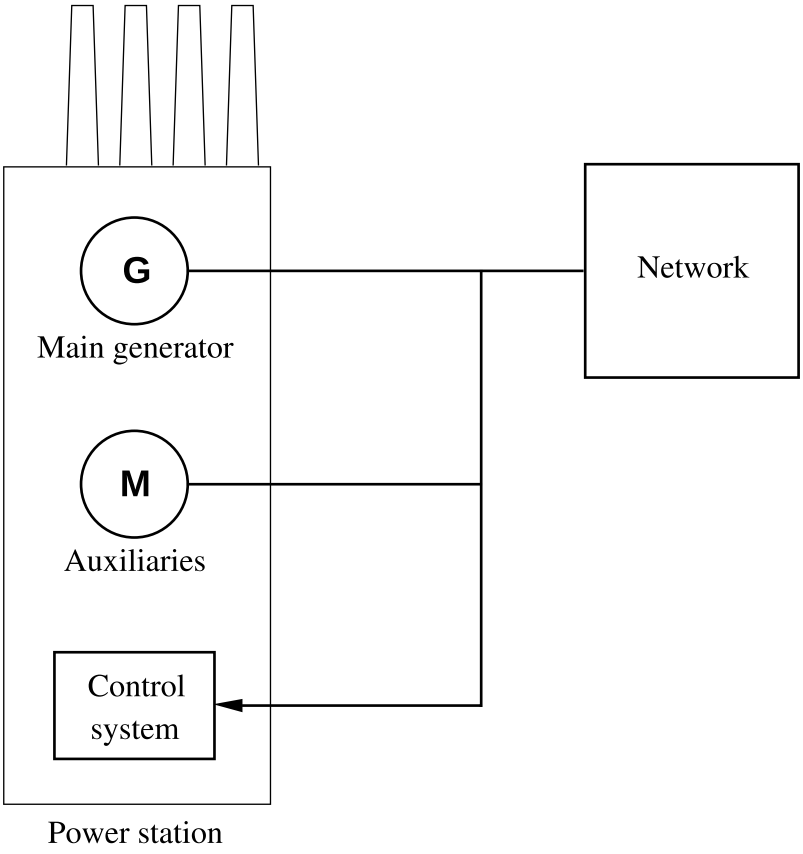

Figure 1.2 Normal operation - schematic.

The choice of regulating modes is in Sweden normally such that thermal power plants are not used for frequency control; i.e. they are operated with a large governor dead-band and they do thus deliver a constant output power as set by the operator. The voltage control system is however normally active and the station tries to regulate the voltage accordingly.

The power station delivers a certain active power to the network, as well as some reactive power. The station can not "feel" any changes in the network, other then changes of frequency or voltage. In normal operation the frequency is extremely stable and can, apart for regulator purposes, be seen as constant.

In various emergency operation modes much larger frequency variations can be anticipated. Such modes can not be tested by running against a normal network, as it would require creating unacceptable disturbances on the network.

If the station is connected to a simulator that simulates a network with a more variable frequency then this would ideally be like in Figure 1.3, where a true network with a variable frequency is created. Such a simulator could however not be built in practice. It would require artificial, variable loads in the order of several 100 MW and this would be extremely expensive. Such a system would also be very costly to use, as all the generated power would be lost.

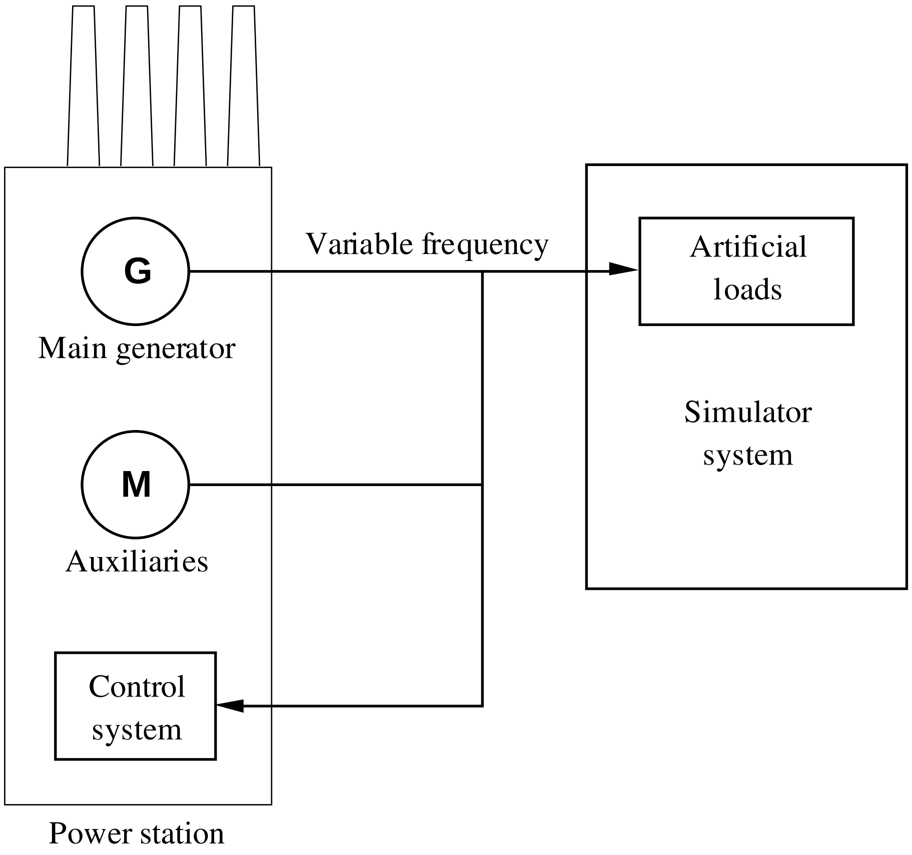

Figure 1.3 Ideal simulator construction - completely artificial network.

A first approximation is done by letting the main power into the power network; i.e. the generator is still phased in on the normal network. In this case the turbine- and generator systems will clearly rotate at constant speed. Such a simulator would give a complete and accurate representation of the behavior of the station with the exception of effects relating to true turbine speed; e.g. certain vibration phenomena and similar. As the auxiliary systems are fed with the simulated frequency any effects on these systems would be accurately simulated. See Figure 1.4.

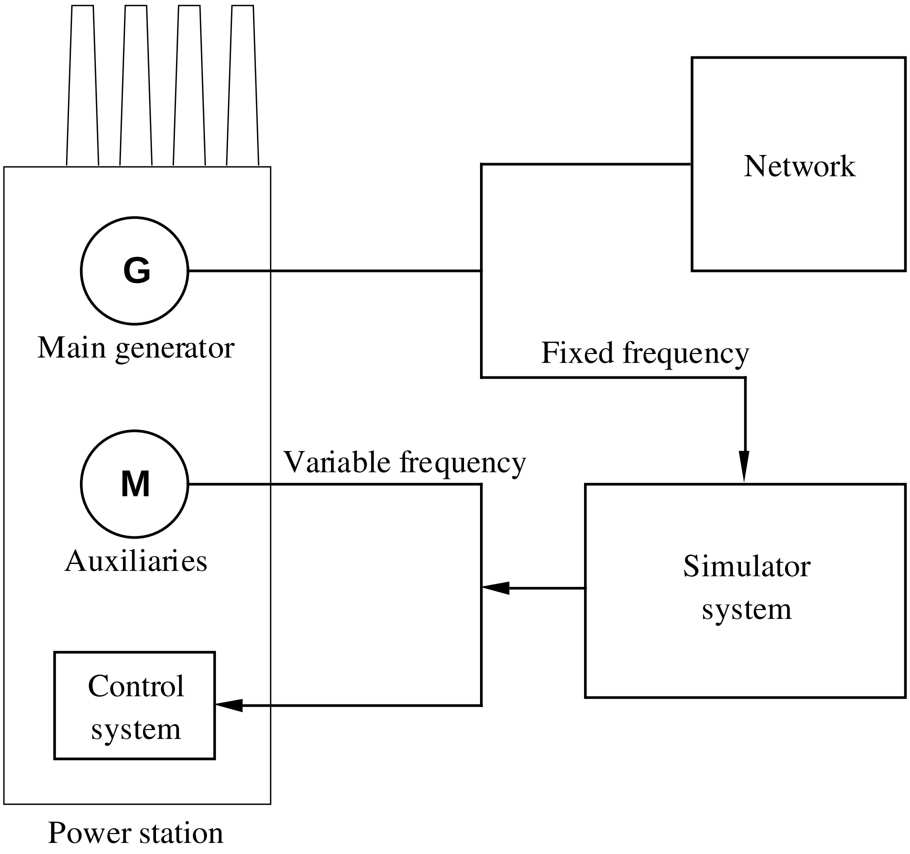

Figure 1.4 Simulator with the auxiliaries supplied from the simulator.

Such a simulator would however be costly and bulky. The output power required in order to supply the systems with a variable frequency would be in the order of several MW, a power level that can only be reached if the simulator uses some kind of built-in power plant.

If the effects on the auxiliary systems due to variations in frequency can be said to be very small, within the range of frequencies that can be anticipated, then the simulator can be simplified much further by using a setup as indicated in Figure 1.5. In this case the simulated frequency is used only to supply a signal to the control systems and instead of several MW we will then need just a few W. In practice this is the only realistic approach and it is therefore important to verify that this approach can be used. If it can not then the idea of developing a simulator for practical tests must probably be thought of as unrealistic and too costly.

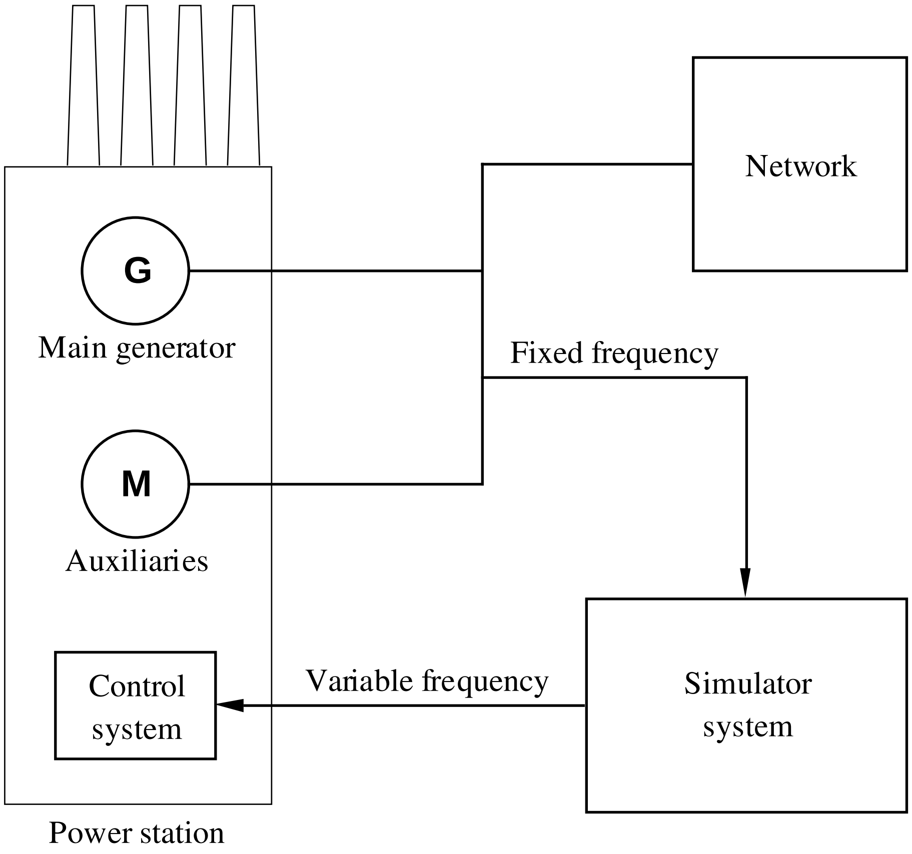

Figure 1.5 Simplified simulator construction - auxiliaries supplied from the normal network.

Chapter 2

Islanding Operation - Special Concerns and Findings

There are many special difficulties that have to be considered if a power station is to be used in islanding operation. Most of these problems grow worse the smaller that the island in question is.

As the actual power station has not been in operation so that simulations against it have been possible, the findings in this chapter are based on simulations against the power station simulator.

2.1 Methods for frequency control

The basic principle for frequency control in a network is shown in Figure 2.1; here on the assumption of that only one unit is responsible for the frequency control of the network.

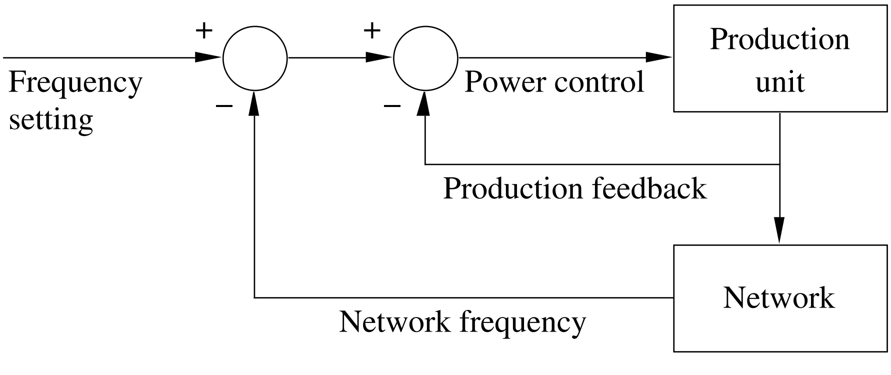

Figure 2.1 Frequency control, general principle.

The production feedback is always some quantity that is somehow closely related to the power output of the unit. In some cases the actual electrical output of the unit is used as a feedback signal, but this has definite drawbacks, in particular when the unit is used for islanding operation. The problem is that when there is an increase of frequency (= the system is accelerated) then all moments of inertia present in the system are accelerated (see Section 2.2). If the internal moment of inertia; i.e. the moment of inertia of the turbine and generator systems themselves, is reasonably large compared to the total moment of inertia present in the system (a very reasonable assumption in islanding operation), then the feedback signal gets incorrect, as the power that is produced but that is needed in order to accelerate the internal masses will not be included in the measured electrical output and hence the power feedback gets incorrect. The same in reverse applies when there is a drop in frequency. Changes of the load will also give incorrect action; a sudden load reduction means a reduction of the electrical output of the unit and the unit will then respond by increasing its output, which is totally opposite to what it should do.

A more correct approach is to use some kind of quantity that reflects the gross power produced by the turbine, rather than the electrical output of the unit. In the case of the Stenungsund power station, units 3 & 4, the control valve position is used as a feedback signal. A basic control diagram for the frequency control systems of these units is shown in Figure 2.2.

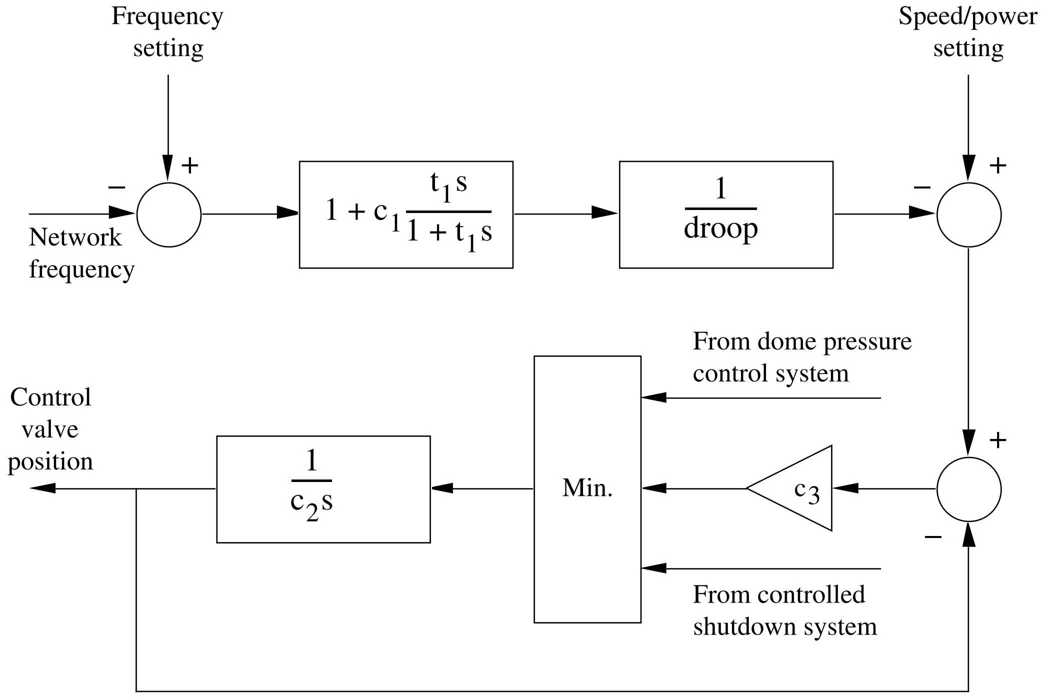

Figure 2.2 Frequency control system of units 3 & 4 of the Stenungsund power station.

2.2 Moment of inertia considerations

The most fundamental problem concerns the frequency control of the system. In all power system operation the power generated and the power used (= loads plus losses) must always be equal. If this is not the case we get a change of frequency. The change in frequency is governed by the mechanical swing equation:

$$\frac{d}{dt}(0.5 \cdot J \cdot \omega^2) = \Delta P \tag{2.1}$$

where		
where	J	is the total moment of inertia of the system
	ω	is the angular velocity
	ΔP	is the difference between produced and consumed active power in the total system, losses included.

and where ω is directly given by the frequency:

$$\omega = 2 \cdot \pi \cdot f \tag{2.2}$$

The value of J is therefore highly important for the frequency stability of a power system, the higher the J value the larger is the value of power unbalance that can be tolerated without unacceptable frequency changes, or vice versa: a higher J gives a slower change of frequency for a given power unbalance.

The value of J consists of two parts:

$$J = J_G + J_L \tag{2.3}$$

where J is the total moment of inertia of the system

J_G is the moment of inertia of the generators in the system

J_L is the moment of inertia of the loads

The J value of each generator unit will depend on the actual physical geometry and the weight of the moving parts and of the speed of rotation. Normally this figure is not given directly in the data specifications of a unit. Instead an H value is given, which is related to the total kinetic energy of the unit by the equation:

$$H = \frac{W_{kin}}{S_n} \tag{2.4}$$

where W_{kin} is the kinetic energy of the unit when it is rotating at its rated speed

S_n is the rated power of the unit

The kinetic energy of the unit is given by:

$$W_{kin} = \frac{J \cdot \omega^2}{2} \tag{2.5}$$

and thus J as:

$$J = \frac{2 \cdot S_n \cdot H}{\omega^2} \tag{2.6}$$

In the case of units 3 or 4 at Stenungsund, the ones used for the simulations so far, the resulting J is 0.023×10^6 kgm^2. If one such unit is the only source of moment of inertia in the system, then the system gets very light, i.e. it swings very easily, at least if it is used at power levels representing a reasonable load on the station. As a result the control systems get too slow compared to the changes of the system and as a result we get rapid and very considerable oscillations in output power from the unit.

When it comes to the contribution to J from the loads (rotating machines) this one is very difficult to estimate and methods for this will have to be developed in the second part of the project.In most of the test runs this one has so far been set to 0.

A typical result is shown in Figure 2.3, which shows a run against the power station simulator, simulating the case of a load of 110 MW applied to a situation where the station had a load of 150 MW. The dashed curve is here the network frequency, the solid one is the turbine power and the dotted curve indicates the load shedding system. Rapid and sizeable oscillations occur and the resulting damping of these is very slow and they are damped only to a certain degree, after that standing oscillations occur. This shows that the control systems are not able to properly handle a situation of this nature.

Figure 2.3 Transition from 150 MW to 110 MW with $J = 0.023 \cdot 10^6$ kgm^2.

As was mentioned above the behavior of a system in islanding operation depends to a very large extent on the total J-value. This is shown very clearly if we compare Figures 2.4, 2.5 and 2.6, that show three simulated cases: In Figure 2.4 we have one unit only, $J = 0.023 \times 10^6$ kgm^2, at a power level of 230 MW. The resulting oscillations are very large and operation under such conditions would be very cumbersome if at all possible. Figure 2.5 shows the same case but with J increased to 0.0663×10^6 kgm^2, which is the resulting J value if all four units at Stenungsund are in use.

Such a parallel operation can be done in two ways: the most logical one is that they are all in use and producing power, but one can also imagine a situation where one unit is producing power and the others are just used as giant flywheels, by running them as synchronous compensators.

With this increase in J the oscillations are much smaller and the operation is much better. But it takes a further increase of J to get stable operation. Figure 2.6 shows the result if the J value is further doubled, to 0.1326×10^6 kgm^2. We now get moderate oscillations that are well damped and that thus reduce to a stable operation.

The J value is clearly very important and any increase that one can get here is of great help, but it is often hard to achieve. Changes in the very control parameters of the power station are clearly much easier, but may not always be that efficient. Further studies of the influence of these parameters will be done later, but some tests have been done in order to test the influence of one of the most important parameters, the droop.

It should be noted that in a real case there would have been additional damping due to the damping windings of the generator in all cases where more than one generator is involved. These effects are not included in the simulator and would not show up even if the simulator was used against an actual power station unit; not as long as it is phased in on the network. These windings will not have any effect unless there are true, physical oscillations of the real generator, and a method to simulate these effects will therefore have to be developed, as a part of the second part of this research project.

Figure 2.4 Transition from 257 MW to 230 MW with $J = 0.023 \cdot 10^6$ kgm^2.

Figure 2.5 Transition from 257 MW to 230 MW with $J = 0.0663 \cdot 10^6\ \mathrm{kgm}^2$.

Figure 2.6 Transition from 257 MW to 230 MW with $J = 0.1326 \cdot 10^6$ kgm^2.

2.3 Influence of the droop value

The droop indicates the amount of deviation of the frequency that one gets for each change in power. A typical general control case is shown in Figure 2.7. The point of operation is the point of intersection between the load curves and the control curve of the station. The droop is the angle of inclination of the control curve. The droop has a direct influence on the control behavior: if the droop is very small we get accurate frequency control but very rapid changes in power, as a small oscillation in frequency translates into a large power oscillation. Also, with a small droop value it is not possible to achieve reasonable parallel operation of two or more generating units on the same network, as the droop also serves to distribute the loads in between the units.

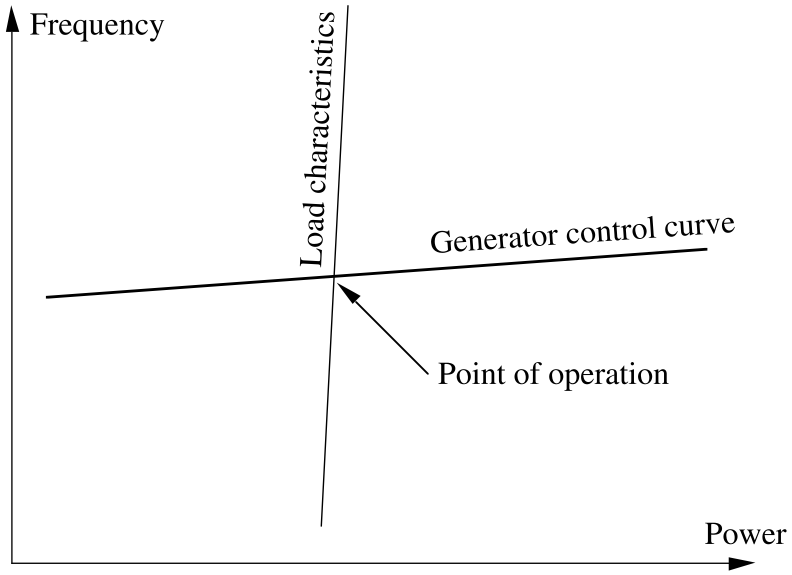

Figure 2.7 Control curves and droop.

In a case like the Stenungsund power station it is essential that proper parallel operation between different units can be achieved, as we have four units in the station. Figure 2.8 shows how the droop serves to distribute the loads between two generating units working in parallel:

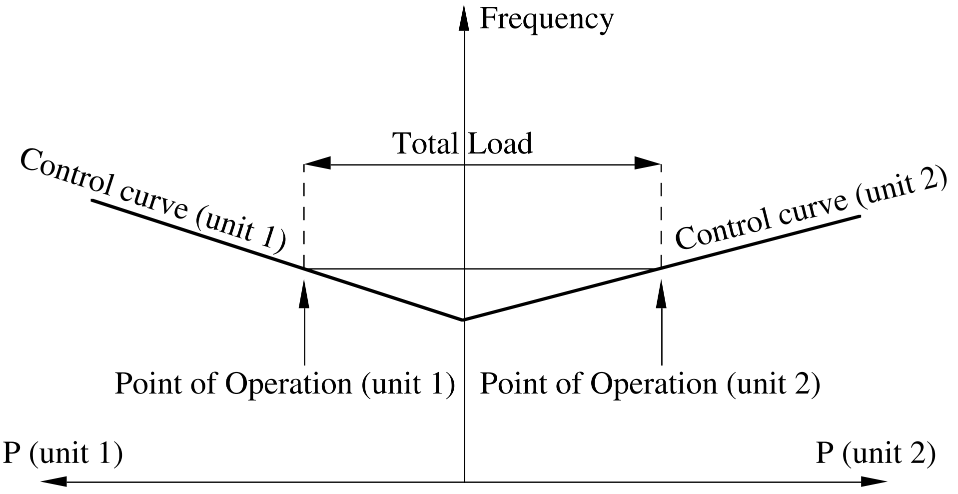

Figure 2.8 Parallel operation with a reasonable droop value.

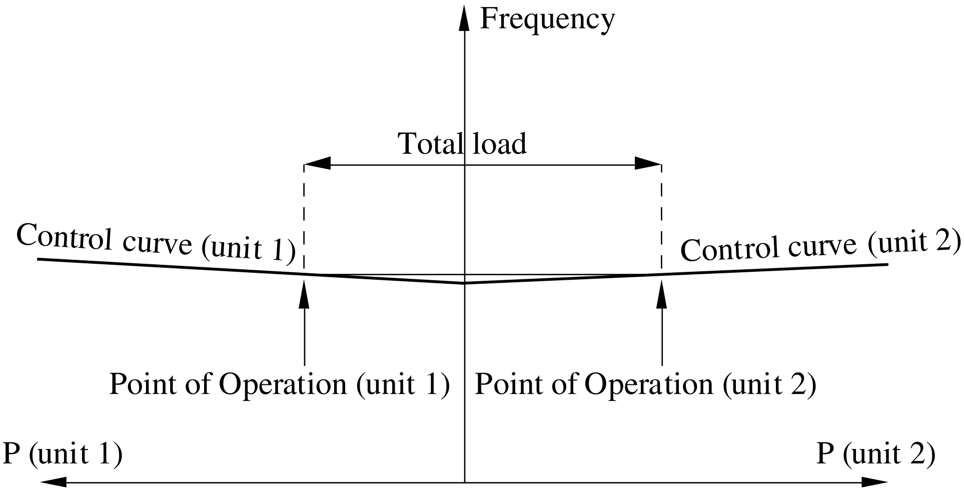

Figure 2.9 Parallel operation with a very low droop value.

In a case like the one shown in Figure 2.9 with very low droop values the distribution of load onto the two different units gets very unprecise and unruly and oscillating situations can be expected.

A very large droop on the other hand gives stable control behavior, but the frequency changes considerably when the power level is changed and this can generate several problems. Some of these problems concern the loads: if the frequency deviates more than ± 5 % or so from its nominal value proper operation of motors and machines can no longer be guaranteed. But also the power station itself gets problems: low frequencies can lead to turbine oscillations and high frequencies means stress on the turbines and also that we get control system interaction in such a way that proper operation is not possible.

A comparison of three different cases with different droop values show the effects very clearly. In Figure 2.10 we have a case with 4 % droop at a power level of 110 MW. In Figure 2.11 the droop has been reduced to 2 %. As can be seen this leads to a much more unruly operation, which is clearly undesirable. In Figure 2.12 the droop has instead been doubled to 8 %. The operation gets more stable (note though the frequency scale is different!), but instead the frequency changes a lot: the quite reasonable change of power from 150 MW load to 110 MW gives a frequency increase to 51.0 Hz! And when the load is reduced even further, to 50 MW a very unstable operation suddenly occurs. To find out why this is so we must take a look at Figure 2.13, which shows the operation of the main control systems of the unit.

Normally the control of the power is taken care of by the primary steam control valve (dashed curve). The control valve limiter is automatically made to track the current control valve position; this in order to avoid sudden large increases in output power that the steam system would not be able to handle. But when the power level drops to 50 MW with this high droop value we get a different effect: the frequency increases so much, up to about 53 Hz, that the overspeed protection circuits of the turbine system become active. As a result the intercept valve closes rapidly, only to open again when the frequency drops. We now have a kind of frequency control where the intercept valve rather than the normal steam control valve regulates the flow of steam and thus the output power. As a result of this we get a very unruly regulation with large standing oscillations. Such massive use of the intercept valve is also likely to cause internal problems in the unit, due to rapid changes in pressure and steam flow through the various turbine stages.

Figure 2.10 Transition from 150 MW to 110 MW. Droop = 4 %.

Figure 2.11 Transition from 150 MW to 110 MW. Droop = 2 %.

Figure 2.12 Transition from 150 MW to 110 MW and later to 50 MW. Droop = 8 %.

Figure 2.13 Control System interaction for the case in Figure 2.12.

2.4 Load characteristics and their influence

The various types of loads on a power system often have different characteristics when it comes to how they respond to changes in frequency and voltage. In this project only the effects of their frequency response have so far been of interest, as voltage control will be studied later on.

Basically, loads can somewhat simplified be divided into five different cathegories with regard to their frequency characteristics:

1. Loads with no frequency dependance at all. Typical examples are all kind of heaters or radiators, regular incandescent lamps etc.
2. Loads with only a minor dependance on frequency. This applies to e.g. fluorescent lights, street lighting etc.
3. Loads where the load is approximately proportional to the frequency. This applies to motor loads where the motors drive machinery with a constant torque,e.g. cranes and elevators, piston type pumps or compressors running against a constant pressure etc.
4. Loads with a power proportional to the square of the frequency. This applies to motor loads if the torque of the driven unit is proportional to the speed. Such applications are very rare and this load cathegory can be neglected for network purposes.
5. Loads where the power depends on the frequency to the power of three. This is the case for motor applications where the torque is proportional to the square of the speed. This applies to all kinds of fans and to centrifugal pumps operating against a constant pipe cross-section restraint, i.e. not against constant pressure.

It was assumed that the load composition would have a considerable effect on the behavior of the islanding system, but this turned out not to be the case. A comparison between two extremes shows this: in Figure 2.14 we have type 1 load only whereas in Figure 2.15 we have 100 % type 5. The difference is quite small. The reason for this is that the standing oscillations in power are so large that they in any case become much larger than the influence of the change of the loads. Also one can notice that the phase relationship between the changes in load and the changes in output power is such that the load changes are not likely to be helpful to the situation, as the peak load comes when the output power is on its way down.

The difference between the average of the load and the average of the turbine power is due to a measurement error, see Section 10.1.

It can be assumed that the influency of the load characteristics will have to be studied more in detail if later on such control methods can be developed that the large oscillations can be controlled, but at the moment the latter overshadow any influence of the frequency dependencies of the loads.

Figure 2.14 Transition from 150 MW to 110 MW. 100 % type 1 load.

Figure 2.15 Transition from 150 MW to 110 MW. 100 % type 5 load.

2.5 Auxiliary systems control considerations

When standing oscillations occur these affect the entire unit and give rise to oscillations in oil flows, air flows, control settings etc. This can have effects that are unexpected. In one case the unit was shut down due to excessive air pressure in the combustion system after only two minutes of operation as can be seen in Figure 2.17. The system seems to behave in a normal fashion until it is shut down after two minutes. Figure 2.18 shows the reason why. The dashed curve is the total air input, the solid curve the air fan guide vane position. As one can see the fan puts more and more air into the system, and clearly this leads to an uncontrollable situation. As to avoid this further simulations were mostly done with manual air flow control.

If one looks into the control system that regulates the airflow one can see why this effect occurs. Figure 2.16 shows a simplified control diagram for this circuit.

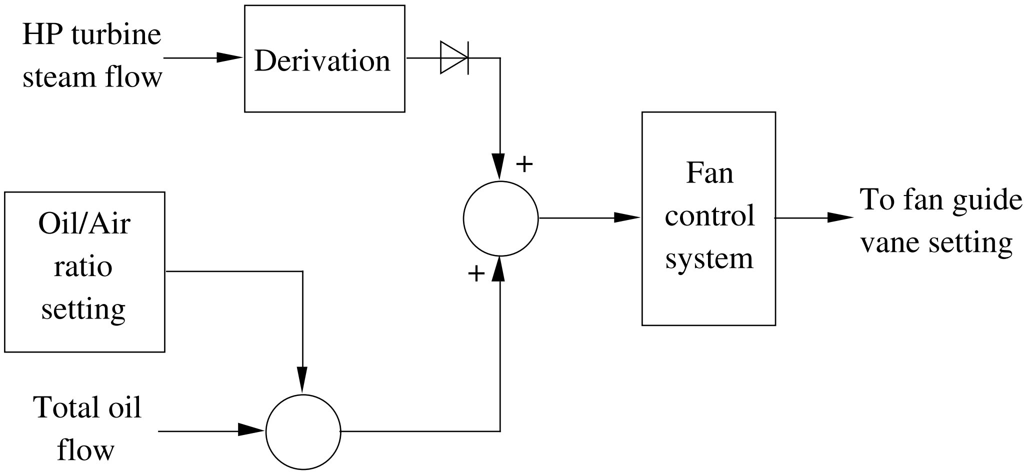

Figure 2.16 Simplified control diagram for the fan control system.

The airflow is normally regulated in such a way that there is a constant ratio of air to oil; i.e. the system follows the oil control system. But a special link has been made to the steam flow, using its derivative to increase the airflow. This is done to give an extra amount of air if there is a sudden increase of power (=steam flow) in order to prevent improper combustion, which would generate smoke and cause unnecessary emissions. This works well for a single step increase, but in this case the rapid oscillations gives an increase pulse to the system so often that the control system has no chance to return to its proper value in between (the time constants are much longer than the time in between the pulses). As a result the airflow increases in an uncontrolled fashion.

Rerunning the same testcase with the fan control turned off (manual control only) shows that we can stay in operation, and that even though we have standing oscillations, we can still manage the situation. Figures 2.19 and 2.20 show this case.

A test was done where the air control system was altered so that the steam flow sensitivity was removed (oil /air ratio control only) and this worked well; we got proper air control and no shutdown. See Figures 2.21 and 2.22.

Further tests will be made later in order to check this behavior of the air system. If the facts found while running against the simulator will hold also on the actual unit it may indicate a need to alter the air control system; e.g. so that the steam flow sensitivity can be turned off if this type of operation becomes necessary.

Figure 2.17 Transition from 150 MW to 110 MW. Automatic fan control active.

Figure 2.18 Air flow and control activity for the case in Figure 2.17.

Figure 2.19 Transition from 150 MW to 110 MW with manual fan control.

Figure 2.20 Air flow and control system activity for the case in Figure 2.19.

Figure 2.21 Transition from 150 MW to 110 MW with modified automatic fan control.

Figure 2.22 Air flow and control system activity for the case in Figure 2.21.

2.6 Protection system considerations

The protection systems of a power station are set to give adequate protection with a minimum of interference during normal operation. As islanding operation differs considerably from normal network operation these systems may in such cases not behave adequately.

A typical example of these kind of considerations is that of the oil-electricity power differential protection systems of units 3 & 4 at Stenungsund. These systems are set up so that they will order a controlled shutdown of the unit if a condition occurs where the difference between the amount of oil injected into the combustion process and the amount of electric power generated exceeds 30 %. It will thus protect against conditions such as excessive amounts of water in the oil, major steam leaks, extreme system losses etc. However, in islanding operation it can also intervene in cases where it is not needed.

A typical example of this is shown in Figure 2.21. The testcase is basically the same as the previously mentioned case in Figure 2.3, but with one major difference: the protection circuit mentioned above, which was deactivated in the test shown if Figure 2.3, is now active. It reacts immediately to the sudden drop in output power and orders a shutdown. This is a gradual controlled shutdown and at first one notices no effect. But when the shutdown has reached a point where the output power is limited to a value below that of the load the system can no longer hold frequency, the frequency drops and the system is saved only temporarily by the load shedding system. Eventually this will of course lead to a total breakdown of the network, if no operator intervention prevents it.

In this case the control system activation was completely unnecessary, as there was no risk present to any system of the station.

Similar conditions are quite likely to apply to other control or protection systems and by using further simulations like this one can find ways to develop alternative operating instructions or alternative settings for islanding operation. A typical example would be to include in the operating instructions that in the case of islanding operation the protection system mentioned above should be turned off or turned to a signal-only state.

Figure 2.23 Transition from 150 MW to 110 MW with the power diff. protection active.

2.7 Load shedding considerations

The load shedding system of the network serves to protect the system in cases where sufficient power to supply the loads present is not available. By automatically disconnecting various loads at given frequency limits it prevents a total breakdown of the system. Typically such systems are set up so that they can shed up to about 50 % of the total load if necessary. In Sweden this is done in five stages.

The load shedding system is extra important in the case of islanding operation. A lack of power has much more drastic effects on such a small system and emergency backup power may not be readily available.

However, the load shedding system is set up for a normal network, and just like for the protection systems, it may not be optimal for islanding operation. A typical case where it acts in an unwanted fashion is shown in Figure 2.21. The load is here first reduced from 257 MW to 230 MW. This goes without any major problem, as we have assumed a fairly high J-value ($J = 0.1326 \times 10^6$ kgm^2). After 40 s the load drops to 150 MW (e.g. due to a line that is disconnected). About 80 s. later the load returns to 230 MW (could be due to reconnection of the same circuit). The unit has enough power available to supply this load without any problems, but in spite of this stage 1 of the load shedding system is activated; this simply because the load shedding system was faster than the power control system and the delays inherent in the turbine system. In other words some loads were disconnected for no reason.

By making further simulations of this kind it should be possible to find optimal alternative settings for the load shedding systems, to be used in emergency cases like islanding operation. Such alternative settings could then be prepared so that they could just be activated when needed. They could then serve to avoid unnecessary disconnections as well as to protect the network in the best way possible. There is no reason to believe that the normal load shedding settings are optimal in this respect either.

Figure 2.24 Transition from 257 MW to 230 MW, then to 150 MW and back to 230 MW.

2.8 Temperature considerations

Temperature considerations are very important when it comes to any control situation that requires a thermal power plant to change its power production level in a short timespan. These considerations can be of two kinds:

1. Avoiding excessive temperatures, that can lead to component damage and/or the activation of protection systems; leading to a unit shutdown.

2. Avoiding rapid temperature changes; i.e. steep temperature gradients, as this leads to metal fatigue and the possible formation of cracks; this in turn reducing the life expectancy of vital components in the power plant, and also possibly to safety problems in the long run.

Temperature problems can also be divided into two main cathegories:

1. Short term problems (time scale of seconds or minutes).

2. Long term problems and restraints (time scale tens of minutes up to hours).

The short term problems are almost invariably caused by sudden reductions of the output power. As the combustion system can not respond instantaneously to these changes over-temperatures occur. These can be quite considerable if the unit is subjected to a fast and radical power reduction.

The long term problems are more of a restraint when it comes to achieving a higher power level; i.e. responding to a load increase. The manufacturers of the boilers have prescribed limits for allowable temperature / pressure increase for a specified period of time. These time constants are in the order of hours. It is therefore not possible to get a fast increase of the generated power; not even with operator intervention.

Thermal power stations can be operated in different control modes with regard to how the steam pressure is regulated. The most economical method is usually to leave the control valve fully open and to regulate the power output by regulating the combustion and thus in turn the steam pressure. This mode of operation is impossible when the station has to perform frequency regulation, as the response time is in the order of tens of minutes to hours.

An operating mode where the dome pressure is regulated to a level a bit above the required minimum for a set power level and the power then instead regulated by using the control valve gives a much faster response (within seconds) and is the only mode possible when frequency control is a must; e.g. in islanding operation.

The two modes of operation are illustrated in Figure 2.25 and 2.26.

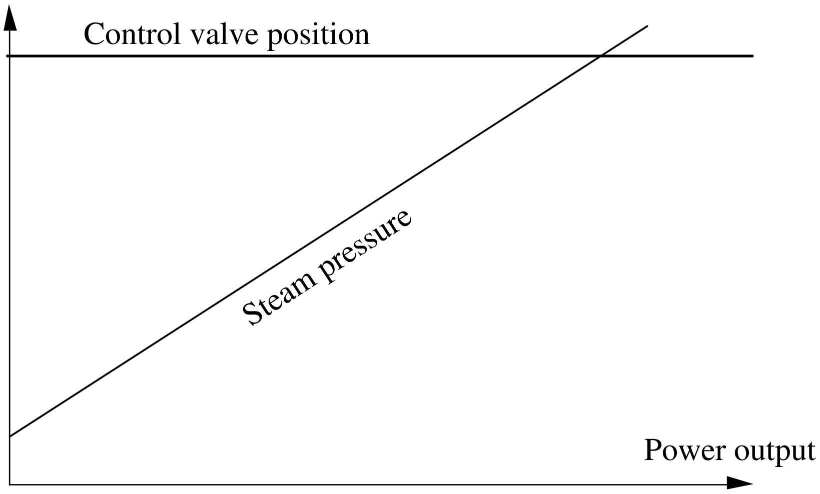

Figure 2.25 Pressure variation control mode.

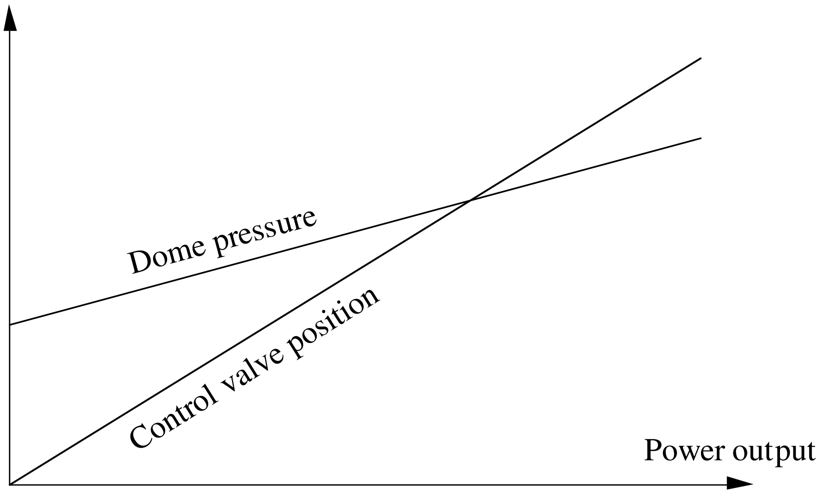

Figure 2.26 Valve control mode.

In the latter mode of control it is possible to regulate the dome pressure with different levels of margin with regard to the output power. The higher this margin is set the better the response in case of an increase of the load, but unfortunately a higher margin also leads to more operating losses and thus to a lower overall efficiency. A reasonable comprise has to be found here and this one has to be dependent on the network situation.

Simulations using this system can therefore be a valuable tool in finding suitable operating instructions for emergency situations such as islanding operation. This will be studied further in the second part of this project and this analysis may perhaps have to be linked to some kind of efficiency / cost analysis with regard to the fuel consumption. In a short time emergency situation the efficiency is likely to be of little importance, but in an extended situation like war or war-like situations this aspect has to be taken into account, as a lower efficiency will also mean that the available emergency fuel supplies will not last for as long as they would otherwise.

As most of the simulations were limited to four minutes of operation or less, the temperature problems that were studied were of the short term kind. In particular the problem was to avoid excessive temperatures of the superheaters during fast load reductions. These temperatures would often get too high and also oscillate considerably; thereby causing a risk of creating metal fatigue problems.

It is a well known fact that thermal power stations with several superheaters are very sensitive to this kind of problems. As a result of this they are normally not demanded to participate in control events requiring rapid load reductions.

Figure 2.26 shows a typical temperature behavior for the three superheaters when the unit is subjected to an instantaneous load reduction from 150 MW to 110 MW.

A special temperature consideration concerns the temperature of superheater number 1. This one is very sensitive to changes in the combustion process and rises rapidly if the combustion takes place with too much excess air flow. This was shown very clearly when the earlier mentioned air flow control problems led to an extreme airflow. This can be seen by comparing Figures 2.26 to 2.21. The latter case had the same load reduction but had the automatic fan control system active. In this particular case a unit shutdown was activated due to extreme combustion air pressure, but if this had not been the case the unit would very soon have been shut down anyhow; due to excessive superheater temperature (the alarm signal was already present). But these temperature problems with superheater number 1 can be solved through improved air flow control.

When it comes to the temperatures of superheaters two and three the situation is more complicated. Even with proper air control we get high temperatures here in many situations.

With a low value of the total moment of inertia of the system these temperature problems are in the form of an initial peak temperature problem when a load reduction comes, but also as temperature peaks corresponding to each oscillation when a standing oscillation of the entire system occurs.

If the moment of inertia is sufficient so that standing oscillations are prevented, then these temperature problems are far less severe. We still get the initial peak temperatures, but this is over a very limited period of time and it is therefore far less likely to cause any damage to the unit. Once the unit has stabilized at a new point of operation the temperatures return to normal values.

Figure 2.27 Superheater temperatures. Transition from 150 MW to 110 MW. Manual fan control.

Figure 2.28 Superheater 1 temperature. Transition from 150 MW to 110 MW with automatic fan control.

Chapter 3

Influence of the Auxiliary Systems

3.1 Sensitivity analysis regarding the effects of the auxiliary systems

The proposed system deals with simulating the signals supplied to the control systems only. The auxiliary machinery of the station will still be operated at normal power frequency. It is therefore highly essential to verify that the influence of the network frequency on the auxiliary systems is not such that it has any considerable effect on the power output of the unit.

The experience of station operators and of various studies that have been made regarding the behavior of the auxiliaries in case of system disturbances (see Reference 1) suggest that the assumption that the auxiliaries can be neglected seems reasonable. This is also the result of the sensitivity analysis below. It was however considered necessary to have this verified by actual measurements, as it is not possible to consider all the mechanisms involved in a structure as complicated as a thermal power plant in a theoretical analysis.

The auxiliary systems do mainly consist of pumps and fans. Pumps can be either of the screw type or centrifugal pumps. Fans can be radial or axial type.

The auxiliaries are almost invariably driven by asynchronous motors. Synchronous motors can be used in some cases, although there are none in the Stenungsund power station. The number one auxiliary when it comes to power consumption is the feed water pump and this one is usually not electrical but has instead a drive system with a steam turbine. This means that this flow is independent of electrical conditions on the network. At the Stenungsund power station there are also electrical feed water pumps, but these are for back-up / emergency operation purposes only.

The speed of asynchronous motors is almost directly proportional to the power frequency. The voltage has only a very limited effect on the speed, at least when it comes to variations within ± 10 % of the nominal voltage. Variations beyond that can easily create overload / overheating conditions if it is sustained for any period of time and can therefore normally not be tolerated.

As for the machinery itself, its sensitivity to speed variations vary. Centrifugal pumps and fans are the main concern, as screw type pumps are less sensitive to frequency / speed variations. For centrifugal pumps and for fans the following equations apply:

$$Q = k_1 \cdot n \tag{3.1}$$

$$p = k_2 \cdot n^2 \tag{3.2}$$

$$P = k_3 \cdot n^3 \tag{3.3}$$

where: k_1, k_2, k_3 are constants.

Q is the flow of liquid or gas.

p is the liquid or gas pressure generated by the device.

P is the power consumtion of the device.

n is the speed (rpm).

It seems reasonable to believe that the actual production of power in a power plant unit would primarily be proportional to Q, i.e. the amount of oil, air etc. One can imagine that certain processes can depend highly upon p. For an extreme worst case analysis it is assumed that we have dependence on both Q and p. This means that the unit output power could be proportional to the device input power and thus to the network frequency to the power of three.

The maximum frequency swing that can be anticipated if reliable network operation shall be maintained would in an emergency be in the order of ± 2 Hz, with outer limits at 48 Hz and 52 Hz respectively. As n is proportional to the frequency F we get that if we set the nominal power output at F = 50 Hz to 1, then the outer limits would be:

$$P_{max} = P_{nom} \cdot \left(\frac{52}{50}\right)^3 = P_{nom} \cdot 1.125 \tag{3.4}$$

$$P_{min} = P_{nom} \cdot \left(\frac{48}{50}\right)^3 = P_{nom} \cdot 0.885 \tag{3.5}$$

The total variations due to influence from the auxiliaries would then be in the order of 25 % of the power output, whereas the frequency control system would for the same variations vary the power by 100 % (if F = 52 Hz P will be set to 0, for 48 Hz to maximum possible). This is then truly assuming an extreme worst case situation, where the power production depends on both the pressure and the flow for all auxiliary systems **and** where no interaction of the internal control systems have been considered.

In practice, the internal control systems for the auxiliaries tend to nullify any changes in the capacity of the pump or fan concerned and the influence of these changes reduces to a small fraction of what was calculated above. Also, for most parameters only the flow is of direct importance for the power production and hence the dependence reduces to first order instead of third order for the majority of the systems.

The assumption that for most practical purposes the influence of frequency variations on the auxiliaries can be negligible does therefore seem very reasonable and this assumption is furthermore supported by the measurements made (see Section 4.2) so constructing a simulator system with this in mind should be a good approximation.

3.2 Measurements regarding the effects of the auxiliary systems

The ideal way to verify the effects of frequency change on the auxiliary systems would have been to vary the network frequency while the station was in operation and then make measurements on the various auxiliary systems in question. That could not be done by in-house operation, as then it would be impossible to separate the cause from the effect, and to alter the main network frequency just to perform these measurements is of course not feasible.

There are however natural frequency changes on the network all the time. Mostly these are fairly slow and quite subtle changes that are just a result of the normal frequency regulation and such changes are not sufficient when it comes to verifying the behavior of the auxiliaries. However, there are also certain changes that are of a more drastic nature. These are the result of a sudden loss of a major generating unit and if the unit in question is e.g. a major nuclear generating station then the effects are quite noticeable. They often show a frequency drop of 0.5 to 0.7 Hz for a few seconds, until the networks responds to the change.

Frequency changes of this type are almost always due to the loss of a nuclear generating unit. The 12 nuclear power plants that are in operation in Sweden show operating statistics such that around 25 such cases per year would be typical; i.e. one case every second week. By simply making measurements of all critical system parameters of a thermal power plant in actual normal operation it would therefore be possible to sooner or later trap such an event and get recordings of the actual behavior of the auxiliary systems.

Measurements of this nature has been performed on units 2, 3 and 4 at the Stenungsund power plant. Unfortunately the measurements have been hampered by two conditions:

1. Due to the presently low load in the Scandinavian network, this due to the economic recession as well as the mild weather, the Stenungsund station is hardly in use at all. The only chances to make measurements have therefore been when the station has been in test operation. These runs are usually limited to a day or two because of the high costs involved and the chances of trapping an event of the type mentioned is therefore quite limited.

2. Following difficulties with a certain type of reactor insulation five of the twelve units were shut down for several months. This did of course further reduce the chances of finding these situations.

The measurements were performed using the hardware setup described in Chapter 4.

Chapter 4

The Measurement System

The system developed for the measurements was designed to be an integral part of the complete simulator system and it uses the same computer that is used to control the physical interface between the power station and the simulator. The basic layout is shown in Figure 4.1.

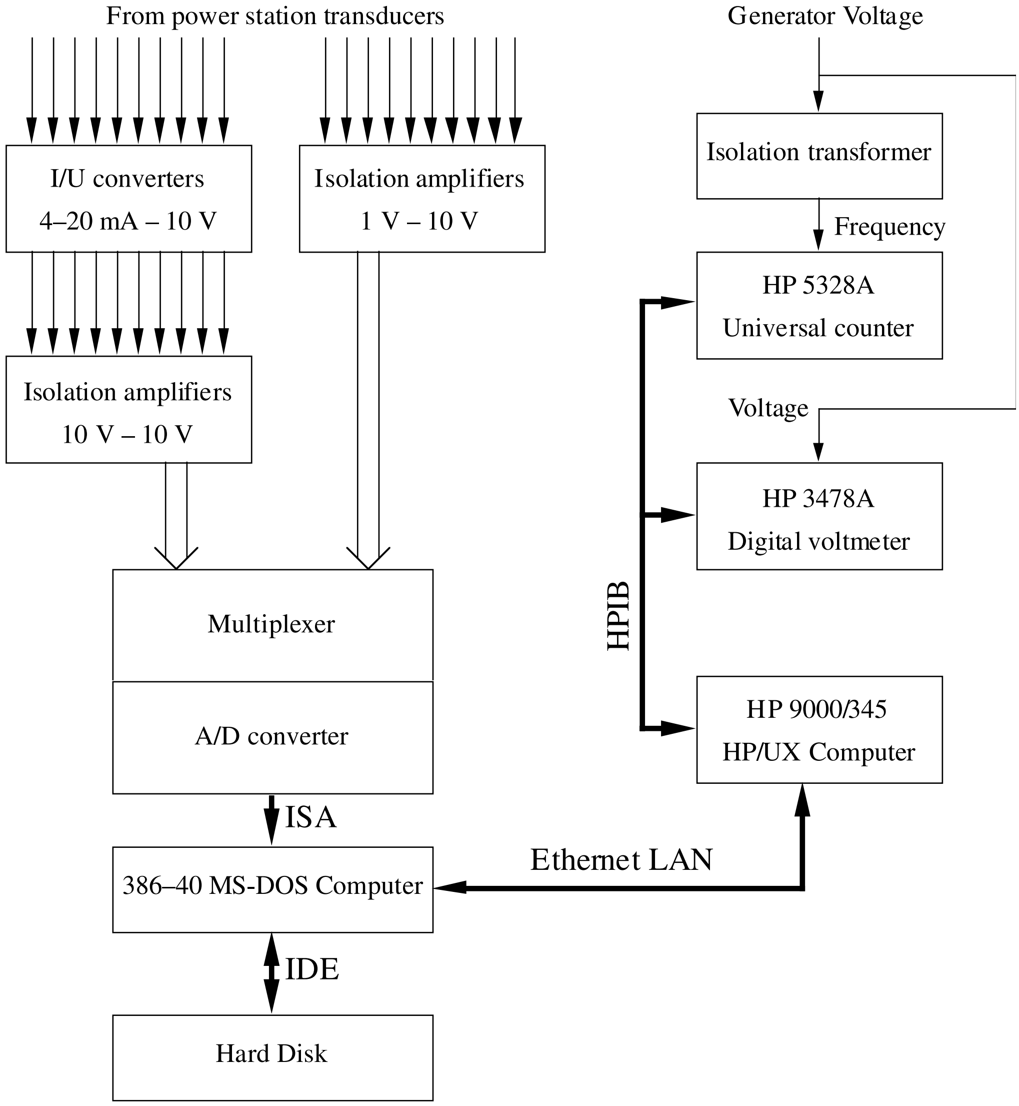

Figure 4.1 Measurement system - block diagram.

As all signals in the power station at Stenungsund, like at most power stations, are of the current loop type it was necessary to use current-to-voltage converters and since the current loops are at various potentials against ground it was also necessary to use individual isolation amplifiers.

The current loop systems were somewhat different for the different units; using mostly 0–20 mA or 4–20 mA on units 1 and 2 and 0–50 mA or 0–100 mA on units 3 and 4.

All signals are fed via an analog multiplexer to a 12-bit A/D converter and the recorded values are stored on the computers hard disc. When used for a simulation some values; primarily the MW and MVAr readings, are also used directly in by the simulation process.

The disc capacity of the computer allows for about six to seven hours of continuous measurements. To allow for longer tests, data was transferred via a high-speed Ethernet local network to another computer and from there transferred unto magnetic tape. By using this method the measurements can be extended indefinitely, as long as enough tape is available.

Ten isolation amplifiers and current loop converters were built and combined into one interface unit. Normally this will be sufficient. In certain cases other insulation amplifiers, namely those belonging to the power station, were used because of the current levels in use. A diagram of the isolation amplifier system is shown in Figures 4.2 and 4.3.

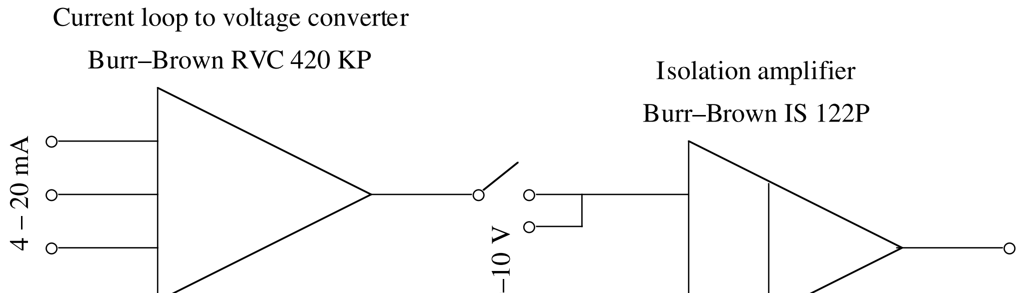

Figure 4.2 Current to voltage converters and isolation amplifiers.

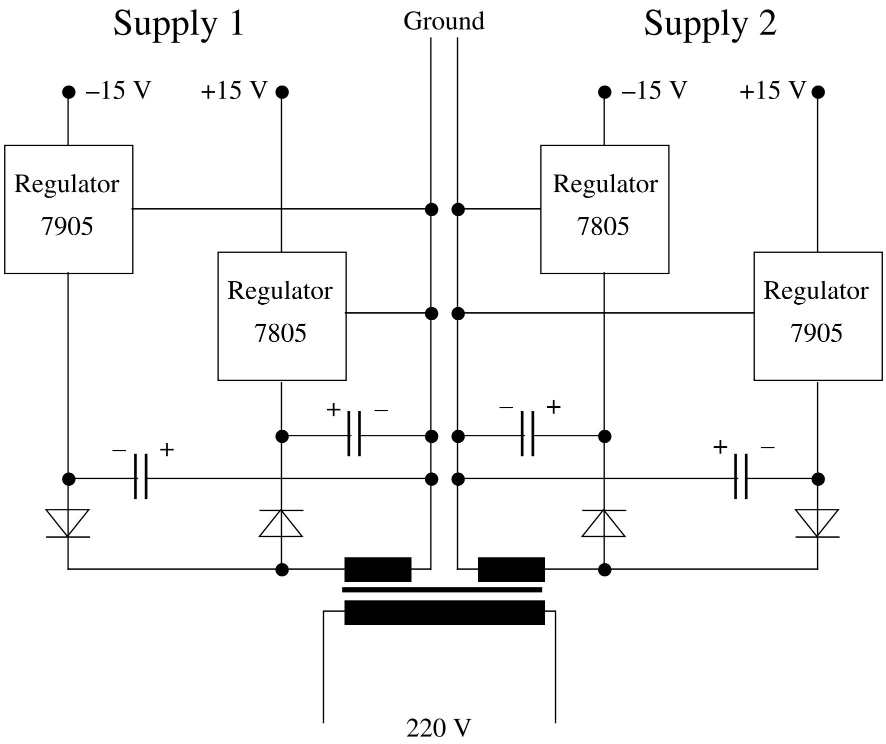

Figure 4.3 Power supply for the current to voltage converters and isolation amplifiers. Each amplifier channel has two separate supplies as shown.

The system is capable of about thirty measurements per second. This is clearly enough to get accurate recordings of all pertinent events, as processes faster than 0.05 s are not to be expected.A faster data acquisition rate would also lead to severe problems with data storage, as the amount of data would grew very large.

The system has 16 A/D-channels.

Two different software setups were used for the measurements. One was a program written entirely for this purpose. This was a simple GW-BASIC program. Its basic layout is shown in Figure 4.4.

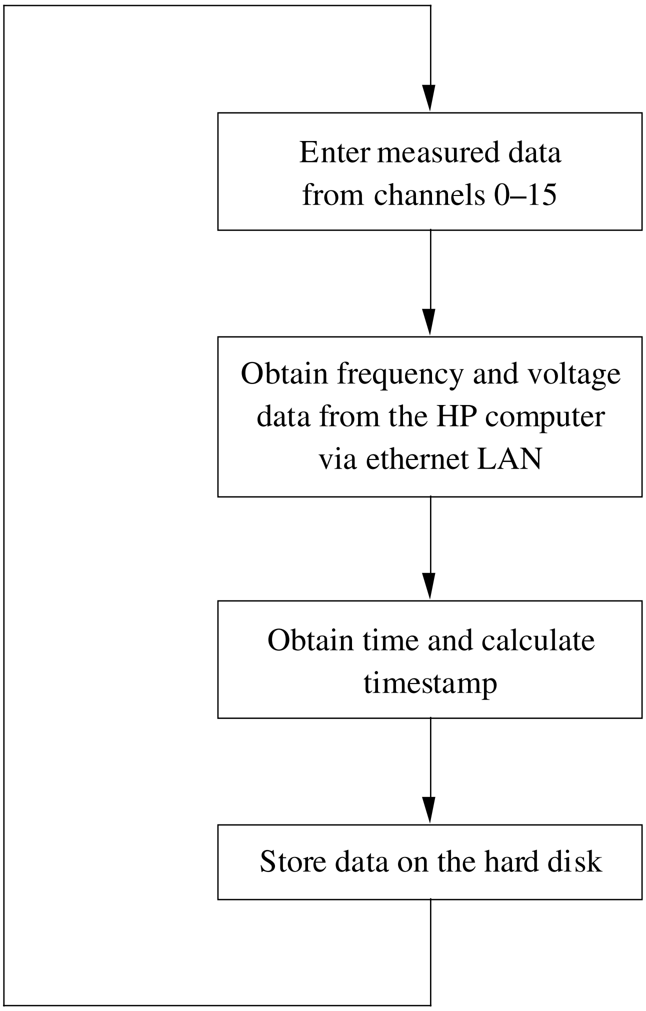

Figure 4.4 GW-Basic measurement program.

The other setup uses the log facility in the main simulator package. For a further description of this program see Section 8.3. This program is written in the C language.

Both measurement programs were found to be operating without any problems. In order to improve compatibility the C program will be used for any future measurements of this kind.

The measured data were recorded without any kind of analysis at the time of measurement. The analysis was done afterwards, using the methods described in Section 4.1.

4.1 Analysis of measurements

This chapter deals with the software for analyzing the mesurements.For the results of the measurements made to determine the behavior of the power plant and in particular the effects of the auxiliary systems, see Section 4.2. Measurements made during simulations are discussed in Chapters 2 and 10.

Since the measurements are done with a fairly high sampling rate over extended periods of time the amount of recorded data is very considerable. As a result thereof all data analysis must be done using computerised methods.

The ANALYZIS program package consists of routines for reading the recorded data from the main data file and for displaying the requested parameters in the form of suitable diagrams. An outline of the program is shown in Figure 4.5.

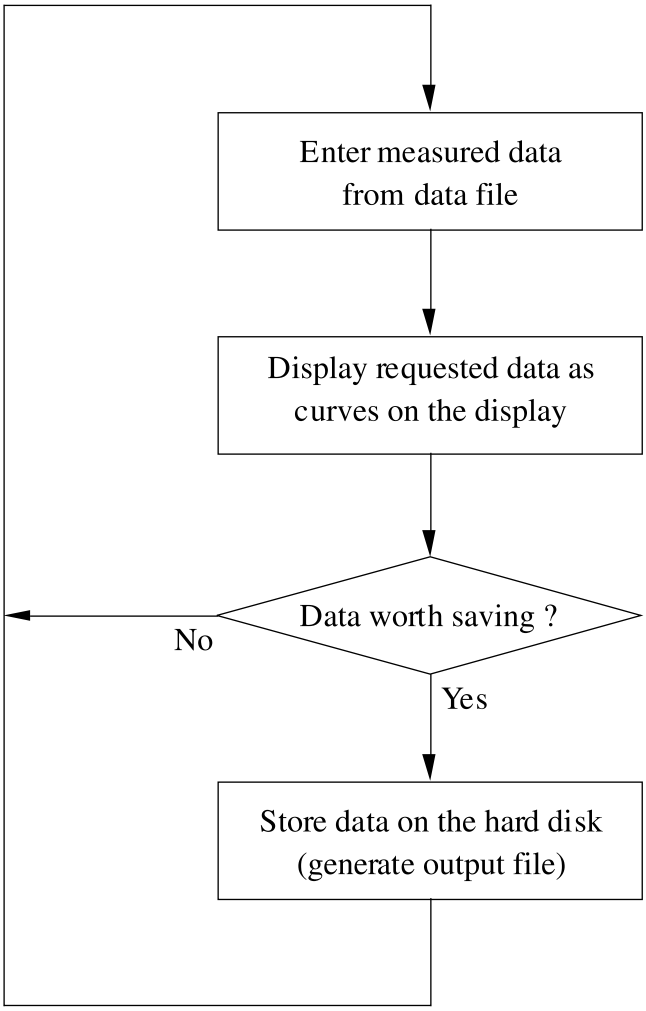

Figure 4.5 Data analysis program.

The program generates output files, using the subroutine DATA_OUT, where the original information is kept unchanged except that only the data from a short period of time is cut out and saved. The original data file can thus be broken up into subfiles. Only the most interesting and relevant portions of the measurements are saved in these files and the data volume is therefore reduced most considerably.

This reduction process can be used repeatedly, in order to further reduce the subfiles into smaller portions.

Finally the selected portions can be plotted onto the screen and also onto paper. The program contains software for generating diagrams, axes etc. and allows for variable expansion or amplification of interesting sections. Thus the measurements can be analyzed in detail and all relevant information extracted from them.

4.2 Results of measurements

As has been previously mentioned it was hoped that a sudden change of network frequency would be observed at some point during the measurements. If such a frequency drop would be in the order of 0.5 Hz or so it would be possible to verify the behavior of the auxiliary systems with regard to their frequency response.

Unfortunately no such drop took place during the time that these measurements were made. When running some tests on unit 2 we had at one point a drop of approximately 0.15 Hz, but unit 2 has a problem with control system instability of some kind and all values oscillated up and down even in the case of normal operation; thus making it impossible to separate any effects of this frequency drop from the constant changes that affected virtually all system parameters.

During the measurements on unit 4 there were no problems of the above nature, but instead the problem was that there were simply no large frequency changes on the network during these measurements. The largest recorded changes were in the order of 0.05 – 0.07 Hz, which is not sufficient to get any significant influence on any auxiliary system. If the dependence would be the very worst case one, such as outlined in chapter 3, we would get a variation of only 0.4 %. Under more reasonable assumtions regarding the influnce of the frequency on the auxiliary systems we get less than 0.1 %, which is lower than the measurement accuracy (approx. 0.25 %) and thus impossible to record.

A typical evaluation result for some measurements made on unit 4 are shown in Figure 4.6, where the network frequency is plotted along with a number of process parameters. None of the curves show any changes that can somehow be related to the changes in network frequency.

Figure 4.6   Process parameters and network frequency.

Chapter 5

Simulator Hardware Structure

The total simulator system consists of three computer systems and a power station interface. See Figure 5.1, which shows the outline for the case that the simulator is connected to the actual power station.

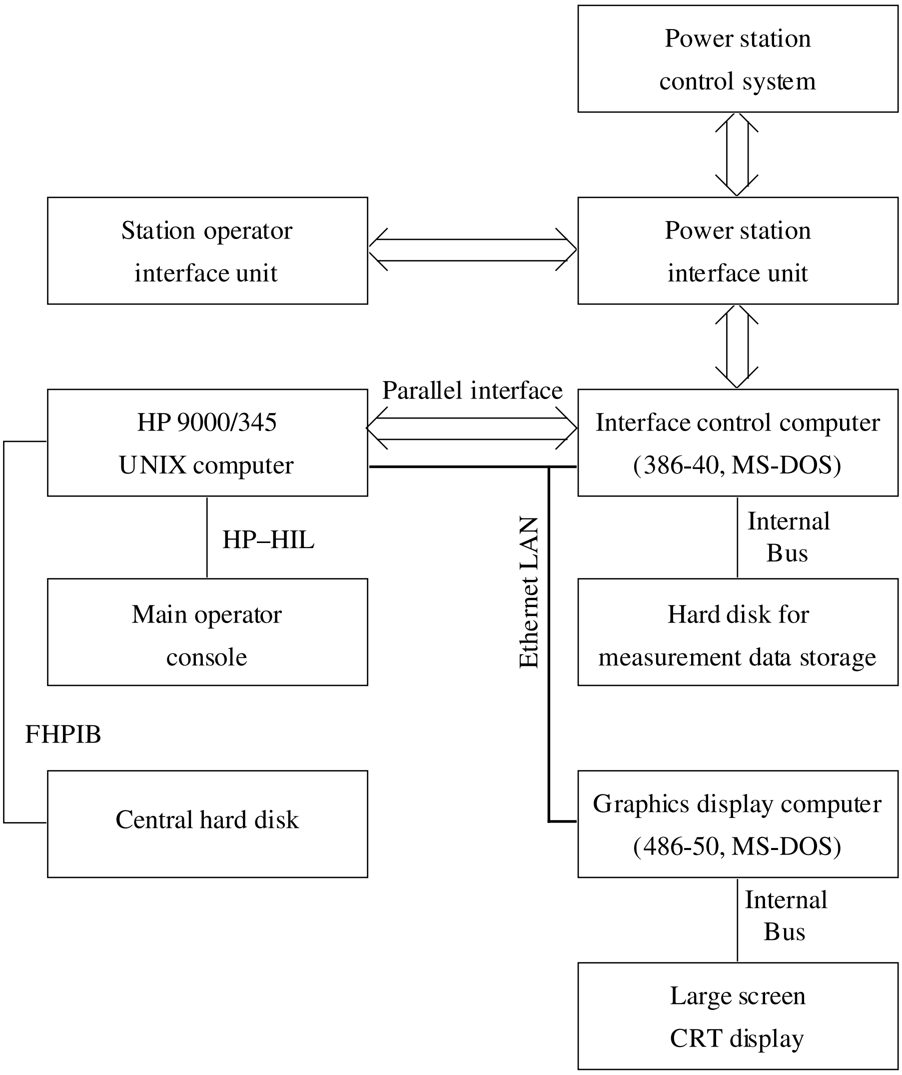

Figure 5.1 Simulator - block diagram.

The most advanced computer system in the system is a Hewlett-Packard 345 system. This system runs under the UNIX operating system, which means that it can handle several processes simultaneously. It is therefore also serving as a communications server for the other computers.

The two other computers involved are IBM compatible personal computers operating under the DOS operating system. The operating system chosen is DR-DOS 6.0. This system was preferred over the more common MS-DOS as it has excellent facilities for file compression built in and is therefore able to handle large amounts of data without the need for extremely large hard disks. The simulator programs would however run just as well under MS-DOS.

One of the PCs is a type 386 computer with a clock frequency of 40 MHz. This computer is quite inexpensive; still it handles the most vital calculations within the simulator. The actual swing equation resides here, as well as the routines for communicating with the power station or the power station simulator and the routines for making measurements. This computer is the only one with a direct physical connection to the power station.

The second PC is a type 486 computer with a large 20" color monitor. It serves as a graphics display unit, displaying the present network status to the operators. In a minimum configuration simulator this computer can be dispensed with; however that makes it harder for the operators to follow what is happening. This computer does certain calculations as well, but this is done just to relieve the HP 345 of certain burdens and these tasks are so programmed that they are taken over by the HP computer if the auxiliary computer is not present.

The three computers communicate primarily via an Ethernet LAN. The software used is PC-NFS by SUN Microsystems Inc. This software allows the PCs access to the HP UNIX file systems as if they were file systems on the PC itself. The different computers can therefore read from and write to common files and thus share any necessary information.

A clear advantage with this type of an arrangement, rather than more common way of linking computers, is that the systems can operate totally unsynchronized. There is no need for any interrupt handling; each computer will handle its tasks independently and deliver the information that the other systems want to the files in question.

A drawback with this file-to-file communication is that it is a bit slow, in that each opening and closing of a file takes time. The UNIX system operates via buffers and it is necessary to close a file each time in order to make the information available to the other computers (otherwise only the buffer is changed).

This slow-down is more noticable when the PCs are writing information onto the HP file systems then when they are reading from it. The communication with the graphics output computer is not time critical, so here there was no problem at all and all communication could be done using this file sharing strategy.

When it comes to the communication with the PC responsible for the contact to the power station the situation was different. Here it is essential that the communication is very fast, as the simulations get inaccurate if the PC is slowed down too much (would mean fewer cycles per second in the process). It was therefore decided to use a system with a parallel interface in addition to the Ethernet communication. The parallel interface uses 16 lines; 8 in each direction. They are connected to the HP system via an HP 3421 Data acquisition and control unit; which has digital input and output facilities, 8 of each, and to the PC via the digital input and output lines on the power station interface card. See Figure 5.2.

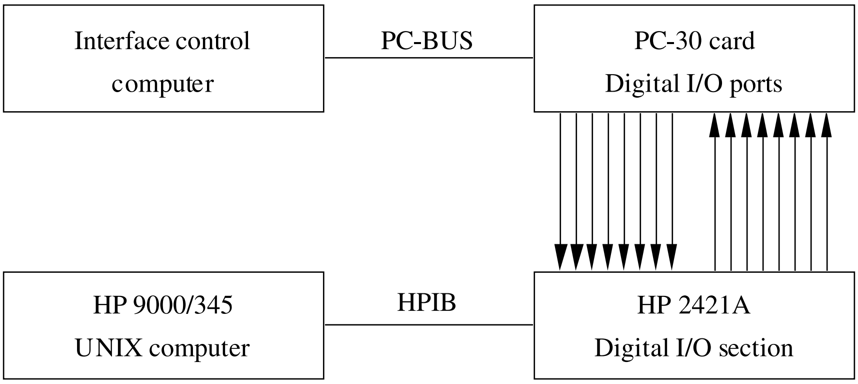

Figure 5.2 Parallel interface system.

The original idea was to use one part of this interface to transfer the figure for the active power required by the load from the HP computer, where the network calculations run, to the PC, and to use the other part to transfer the simulated power frequency from the PC to the HP.

Originally a very slow computer, of the IBM XT type with a clock frequency of 8 MHz, was used for the PC. The reason for this was that the interface card for the power station interface had software supplied with it that according to the manufacturer would work only on XT computers.

The software in question was very sensitive and getting the interface card to work properly with it was very cumbersome. A large amount of time was spent trying to get the system to work correctly, but it was still too sensitive to be relied upon and the XT computer was so slow that virtually all communication necessarily had to be handled over the parallel interface in order to get reasonable cycle times for the simulations. Only in exceptional cases would the computer make a disk to disk information transfer; this only if the operating conditions specifically called for it or if the other computer requested it by setting all bits high on the parallel interface.Attempts to run all communication via file sharing slowed down the system so much that only 0.5 cycles per second could be achieved.

After much work other interface routines were found. These came from a different manufacturer, Techsell AB in Stockholm. They proved to be far superior to the routines used previously. The only real drawback was that they were not available in FORTRAN, which was the language selected for the simulator software. As a result all software for the interface PC had to be rewritten in C. This was a very considerable job, but the improvement of getting the interface card drivers to work properly was so major that it was worth the change.

The new software were not limited to XTs and the computer could therefore be upgraded to a 386 / 40 Mhz. As a result of this the speed increased so much that it was not necessary to rely on the parallel interface to the same extent. It was found that a speed of approximately 20 updates per second could be maintained even if all the information transfer from the HP to the PC was done via the file sharing system. This part of the parallel interface was therefore not used from this point onwards.

It was also tested to let also the communication the other way around be done using file sharing. This worked OK but slowed down the process to about 5 cycles per second. For most simulations, where the simulated processes are not too “violent”; involving very rapid changes etc; this could most likely be acceptable and the simulator then built without any parallel interface. As the speed could be increased and as the interface had already been developed it was however decided to use the parallel interface as the prime transfer of information from the PC to the HP; using disk to disk transfer only occasionally as required.

When the simulator was used against the power station simulator it was of course necessary to communicate with the power station simulator computer. Unfortunately this turned out to be a fairly old system, a Norsk Data ND-100. This computer had no communication ports other than ordinary RS-232 serial connections. At the same time the ND-100 is a slow computer and it had a very considerable workload in running the real-time programs of the power station simulator, so it was important to choose a means of communication that would not somehow slow it down, e.g. by interrupting it or by holding it in wait states.

The best way to solve this problem was to use the PC that was used as interface to the station when connected to the actual power station, to serve as a communications interface between the ND-100 and the HP system. The PC communicates with the ND-100 via an RS-232 serial link and transfers the information to or from the HP via LAN and file sharing. In this situation the PC is relieved of certain other duties and an acceptable turnaround can be achieved without using the parallel interface. Also, as it's the PC that is waiting for the ND-100 and not the other way around there is no problem with slowing down the ND-100.

Chapter 6

Software for the HP–UX system

6.1 Software - UNIX

Approximately 70 % of the software is written for the Hewlett-Packard 345 UNIX (HP-UX) system. The code used is however of a quite general nature and there should be no major problem in porting the program package to another system should this be desired.

The programming language used is to about 95 % FORTRAN. Only a few system interface routines are written in C. There are also certain portions for interactive operator control that are written in HP Basic and run in the BASIC-UX programming environment.

FORTRAN was the natural choice of language, as it is easy to work with and has become a de facto standard within the electric power industry. As opposed to most other languages it also supports the use of complex variables.

An alternative would of course have been to use HP Basic throughout, but this would have two serious drawbacks: one is that the resulting code is slower for numeric calculations, and this would have been a serious drawback in this real time application where maximum speed is desired. The other drawback is that HP Basic is a machine specific language and there would therefore be a loss of portability if that language had been used.

A block layout of the software used on the HP-345 is shown in Figure 6.1.

Certain parts of the software are not used during the actual simulation but are test routines or routines used to generate the data files that are used during the simulations.

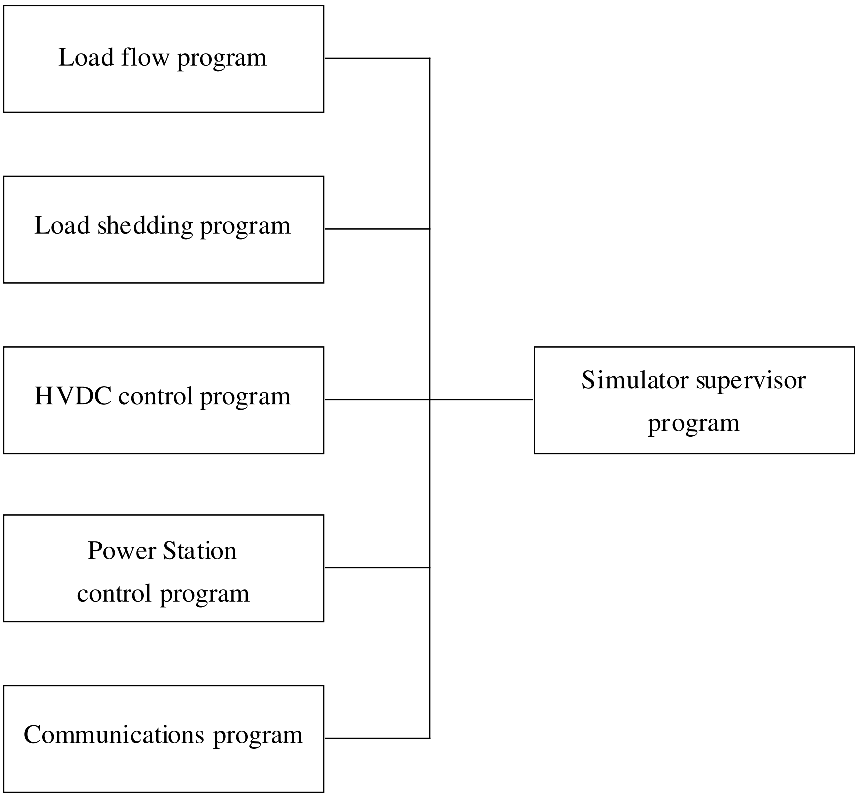

Figure 6.1 HP 345 software, basic outlay.

Special data entry programs have been created to allow for easy input of all necessary parameters. All software has been designed so that all input can be done by interactive methods; thus there is no need for creating data files by using file editors or similar.

With the help of the data entry programs the operator can create a number of data files used by the simulator system:

1. main data file - contains network parameters such as number of nodes, number of lines etc.,electrical data for all components (R, X, B, turn ratios, tap changers etc.).

2. load shedding file - contains data for the load shedding system, such as from which nodes the loads will be disconnected, activation frequencies, time delays etc.

3. control file - contains data for control systems and governors.

4. generator file - contains electrical and mechanical data for the generators.

5. limits file - this file is usually created for each simulation process. It contains the system operating limits for the simulation; i.e. these limits can be set so that the simulation is either aborted or stopped at limit in case that any limit is reached.

6. protection file - contains data for the protective systems, e.g. current limits, relay settings etc.

7. HVDC file - contains data for any HVDC system that may be present.

8. graphics file - contains graphics display data required by the graphics display (e.g. location of nodes etc.).

The main structure of the power network is established by the use of a load flow program (E4FLOW). This program, which was especially created for this application even though it can also be used separately, is described in Section 6.2.

Likewise the load shedding and HVDC part are described in Sections 6.3 and 6.4 respectively.

The supervisor program is responsible for all communication with the operator during an actual simulation. It uses an interrupt type structure; where the program runs in a continuous loop unless it is interrupted by pressing one of the softkeys.This type of signal handling is difficult in FORTRAN and the supervisor program is therefore written in HP Basic.

By pressing the different softkeys the operator can at any time perform any of the following commands:

START	enter simulation mode
STOP	leave simulation mode
EMERGENCY	leave simulation mode immediately without using the gradual phase-out procedure
LOADS	alter the load figures at any point in the network
CONTROL	to manually disconnect or reconnect network elements, to operate breakers etc.
VIEW	alters the displayed network information on the PC monitor
LIMITS	alters the limits within which the simulation is performed.

RESET	to reset elements or loads in cases where load shedding or protection systems have been activated.
GENERATION	to alter the figures for power generation at other generating stations.

The supervisor program also monitors the simulation process and alerts the operator in case of special circumstances; e.g. in the case that any simulation limit has been reached.

The same program is also responsible for the simulation start-up process. The operator will be asked to set a number of parameters and these are then entered into a file that can be read by the PC that controls the power station interface. The actual start-up of the simulation is however done by the interface computer.

The Ethernet LAN communication and the file handling/buffering is taken care of by the HP-UX operating system without the need for any additional software.

All software on the HP-UX system is in the compiled form, also the HP Basic. The supervisor is the only program running in the foreground mode; all other processes are in the background. The load-flow program has been given a lower scheduler priority rating. This is done so that the load-flow calculations, that can be time-consuming if done on a large network, will not force the supervisor program into a wait state. It is not a major problem if the load-flow process is not updated instantaneously, as its effects on the simulation process are not as immediate as e.g. if the load shedding is activated or if there is an operator intervention via the supervisor program.

6.2 Load-flow program

The load-flow program is the largest program block within the system. A block layout of the program is shown in Figure 6.2 and in more detailed form in Figure 6.3.

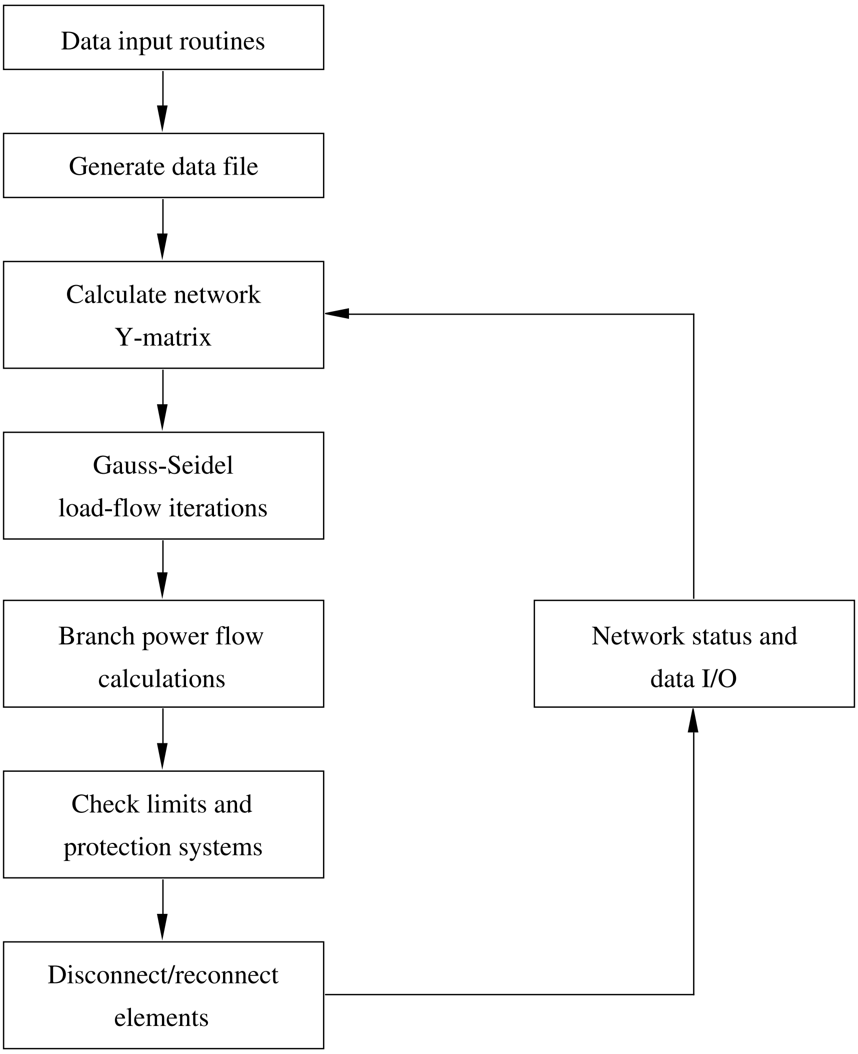

Figure 6.2 Load-flow program - block diagram.

The load-flow block has two main programs plus a number of subroutines; of which almost all are common to the two main programs.

One of the main programs, E4MAIN, is a normal load-flow program and does not run in real time mode. It allows the load-flow program to be used separately for normal load-flow calculations, e.g. prior to a simulation or for completely independent tasks. It is also used to input the necessary network data prior to a simulation. It is interactive and it generates the main data file.

As it is a completely interactive and easy to use load-flow program the E4MAIN program is also an excellent load-flow program for many network calculations. It allows for lines and transformers to be disconnected / reconnected, it can handle transformers with tap changers, phase shift transformers etc.

The other main program, E4RTMAIN, runs in real time mode and is used during the actual simulation. This program is designed to run in the background mode and hence it asks no questions but assumes that all necessary data are already available on the data files. The main consideration for this program has been to design it for as high processing speed as possible.

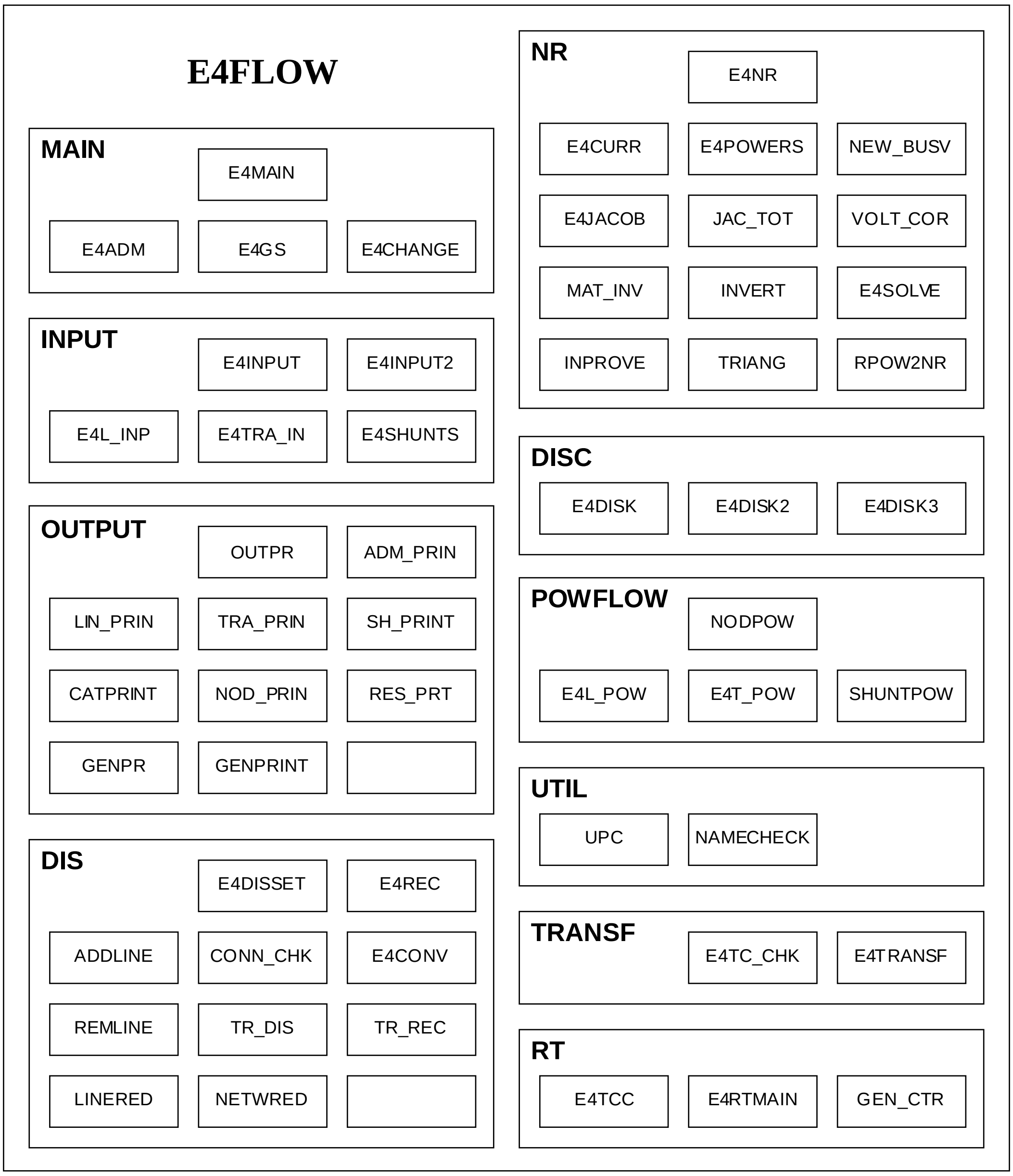

Figure 6.3 Load-flow program.

Two mathematical calculation methods are used by these programs: the Gauss-Seidel method and the Newton-Raphson method. Thorough testing of both methods has led to the conclusion that the Gauss-Seidel method is faster than the Newton-Raphson method for all network configurations within the size (up to 60 nodes) that are used in this simulator system. This method is also more reliable in that it handles sudden changes in the network better and in that the risk of non-convergence is minimal. The Gauss-Seidel method is therefore the only method that is used when running in real time mode.

In regular load-flow mode the operator has a choice of either method or of using them both by running the Gauss-Seidel method first and then switching to the Newton-Raphson method for the final iterations. This is to make optimum use of the advantages of each method: the Gauss-Seidel method will arrive at a solution with a reasonable accuracy faster and the Newton-Raphson method is better for getting results accurate to several decimal positions.

The program uses special routines in order to disconnect and to reconnect elements. Each time that an element (a line or a transformer) is disconnected the program checks the network (using the subroutine CONN_CHK) to verify that all nodes are still connected to the system. If this is not the case the system is reduced accordingly. In the case that the network splits up the main network is always defined as that part of the network that contains the reference node.

When the program is used in the real-time mode for simulations the reference node is always the node to which the power station that is undergoing simulation is connected. Thus the net power balance of the system is always transferred to that station and it is left to its governor system to regulate the power output of the station accordingly.

Using the power station as the reference node assumes that the voltage of the station can be assumed to be constant. If this is not the case then the actual voltage of the bus will be transferred from the interface computer to the HP-UX system and used to correct this figure.

The load-flow program is set up to handle up to 60 nodes, 130 lines and 30 transformers. This is considered to be well adequate for use with the simulator. There is no need to represent the network to levels lower than the regional networks (in Sweden that is the 132 kV level) and making the system too large would drive the calculation times up to levels too high for real-time mode operation.

The program was partially based on a program that was developed in HP Basic for load-flow calculations. This program was however much too slow for real-time operation and lacked several facilities necessary for the simulator use. It was therefore decided to write an entirely new program and just make use of certain modules from the old program. The new program was written in FORTRAN.

For a 50 node network typical calculation time with the old program was in the order of 100-140 seconds. The new program completes that job in about 2 seconds on the same computer. By using the values already calculated on the previous run for each update of the load-flow the turnover time can be reduced still much further in actual real-time mode operation. The exact figure depends heavily on the amount of change that has occurred in the system since the last update, but typical handling times are less than one second and this is well adequate for these purposes. As mentioned in Section 6.1 the load-flow programs runs at reduced priority so that it will not create any problems for the more essential processes if the load-flow process takes some time.

The load-flow process in not synchronized with the other processes in any way. It runs at whatever speed it can and then updates the network status files as soon as it has completed one run of calculations.

The output from the load-flow program is used as input for the graphics display program that runs on one of the PCs. This information is made available to the PC as the load-flow program writes it onto a file that is then read by the PC.

The load models used in the calculations are fairly simple. The loads can be divided into four portions: one which is a fixed impedance load (e.g. like heating systems), one which is constant power load and one part where the load is proportional to the network frequency and one where the load power is proportional to the frequency to the power of three (e.g. fan loads, centrifugal pumps etc.). No dynamic effects of the loads are taken into consideration.

6.3 Load shedding system

The load shedding system is highly important in situations such as those that are likely to be simulated. It was therefore necessary to model the load shedding procedures as accurately as possible and to design them so that they would be activated fast enough in a situation where they would be used.

The design of the load shedding system is in principle based on the load shedding system that is used in Sweden. The sole basis for activation is the network frequency. If the frequency falls below certain set limits then a certain portion of the load is shed. As this is done by disconnecting certain network portions rather than certain prescribed loads it is somewhat inaccurate, but as the load shedding has been divided up into five steps with different activation frequencies it will still achieve the desired effect: the amount of load shedding will increase as the frequency drops.

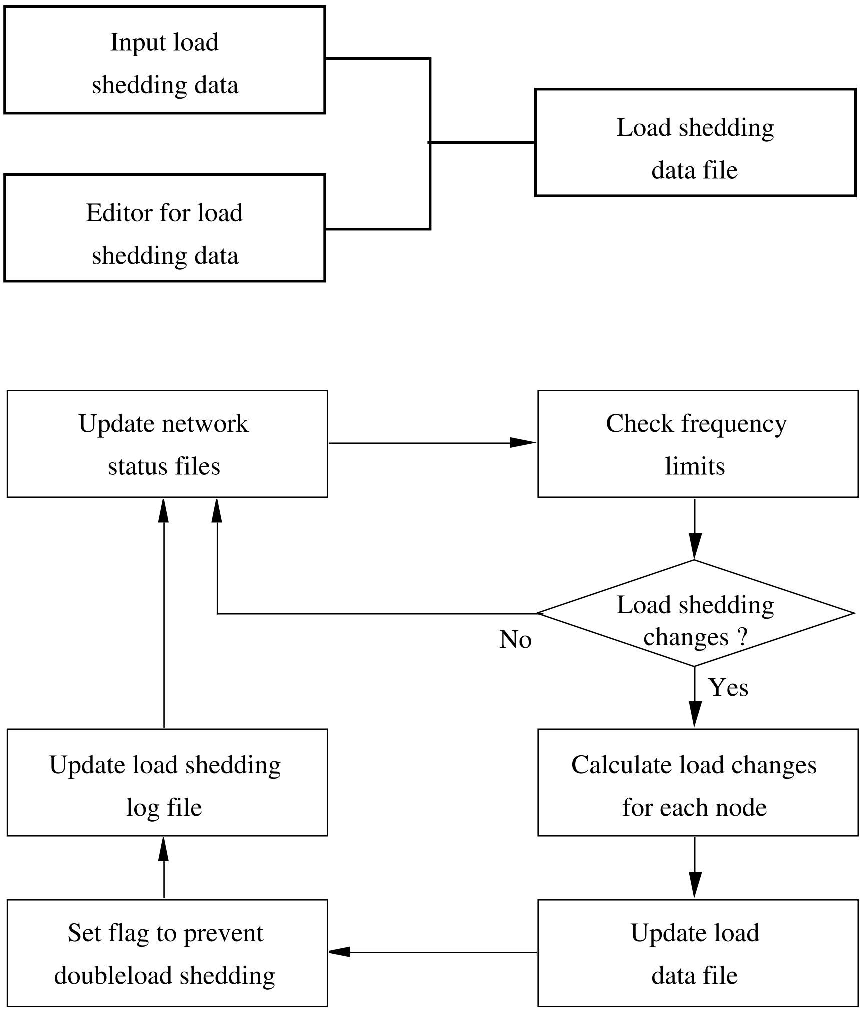

Figure 6.4 Primary load shedding system.

The load shedding is normally almost instantaneous. The set time delay in case of a severe reduction of frequency is only 0.15 s. There is also a delayed load shedding, which acts on a higher limit but with 20 s delay. In the case of islanding operation the first kind (rapid disconnection) is the one of prime interest, but both have been modelled in the simulator.

The load shedding program package consists of several parts. One is an input module that is used prior to a simulation and that inputs the required data for the load shedding process by interactive methods and then stores them in the load shedding data file. Similarly there is a program for updating the load shedding data.

The load shedding is defined by defining for each node that has load shedding the amount of load (in %) that is shed in each of the five steps and by defining the activation frequency for the step and the time delay involved, as well as the requirements for reconnecting the load (frequency limit plus time delay or manual reset).

For each load shedding update the load shedding program checks the network frequency. If the frequency is above 49.0 Hz and no load shedding is active then the program performs no further checks. If the frequency falls below that level then it checks every node that has a load shedding system connected to it and sees whether or not load is to be shed at that node. If this is the case then it sets a flag and after the elapse of the set time limit it activates the shedding; thus reducing the load at that node with the set portion. After the next load-flow update the new load situation will be properly represented.

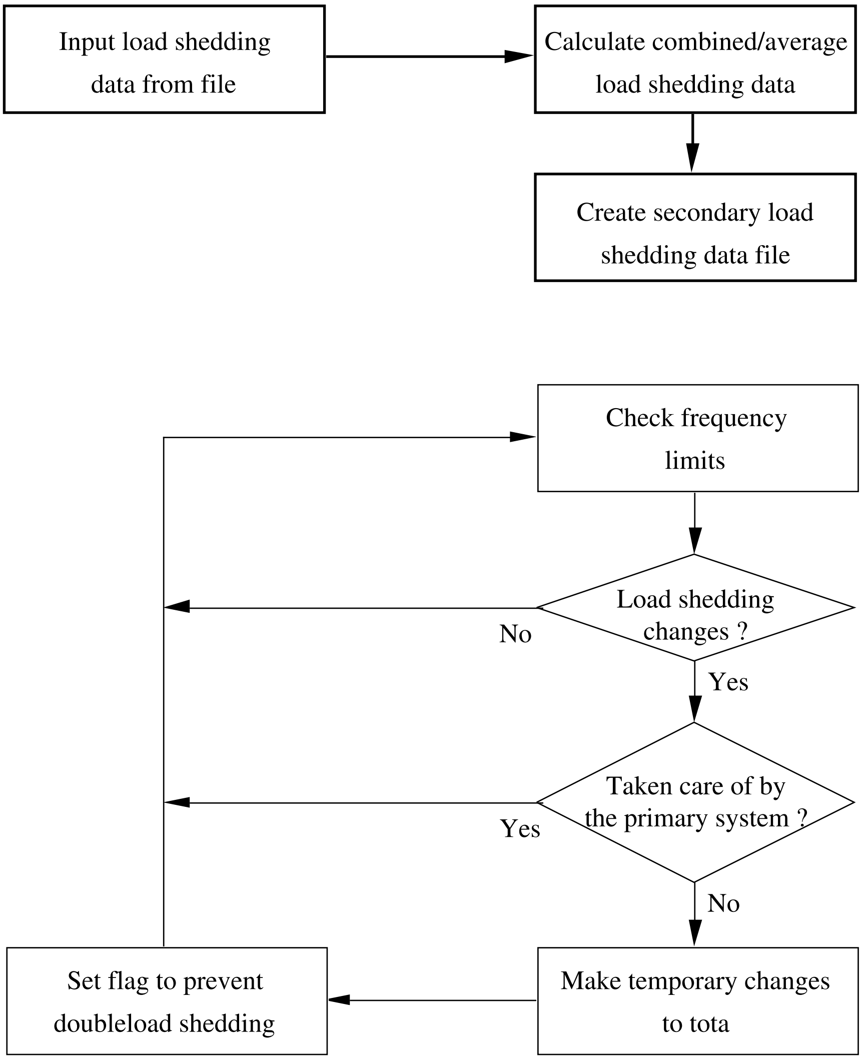

Figure 6.5 Secondary load shedding system.

In situations where the network frequency drops rapidly; i.e. when there is a considerable lack of active power in the system, then the system as mentioned above is not fast enough to give proper simulation of the process. A secondary load-shedding system has therefore been introduced to handle this. This load-shedding program is a subroutine within the program package that runs on the PC that serves the power station interface. Thus its effect is immediate, without the delays caused by the process to process communication and by waiting for the load-flow process to be completed.

The secondary load-shedding system works on the same principles as mentioned above except that it considers the network as being one lump and uses pre-calculated figures for the load reductions for each frequency limit, with no regard to how they are distributed within the network.

Each time that the main load-shedding program on the HP-UX system has completed a run of calculations for a specified frequency and this has worked its way through the load-flow program then it sets a special flag for this in the communication file that transfers data from the HP-UX system to the station interface PC. Thus the PC knows that the new load figure presented is one where the effects of load shedding have been accounted for and it then deactivates the secondary load shedding before using the new power figure. Thus it is avoided that the same load would be incorrectly accounted for twice as it is indicated as a load decrease by both systems.

6.4 HVDC systems and control

The simulator system was designed using western Sweden as a model area. In this system there is an HVDC link to Denmark, the so called Kontiskan intertie.

Under normal operating conditions, this intertie, as well as any HVDC link, can merely be represented as a constant flow of power in or out of the network area. However, in an emergency the system behaves differently.

The Kontiskan intertie is fitted with emergency power control systems. These work so that if the network frequency drops below certain levels the flow of power is set up (in steps) so that as much power as possible is supplied into the area in order to support the network.

In the case of the Kontiskan intertie the normal operating condition is that it is used to export power from Sweden to Denmark. Under the emergency control this power flow reverses and power is imported instead. If this leads to a severe stress on the system on the Danish side then additional assistance can be brought in from

Norway, using a similar emergency control system on the Skagerack HVDC intertie that connects Norway with Denmark.

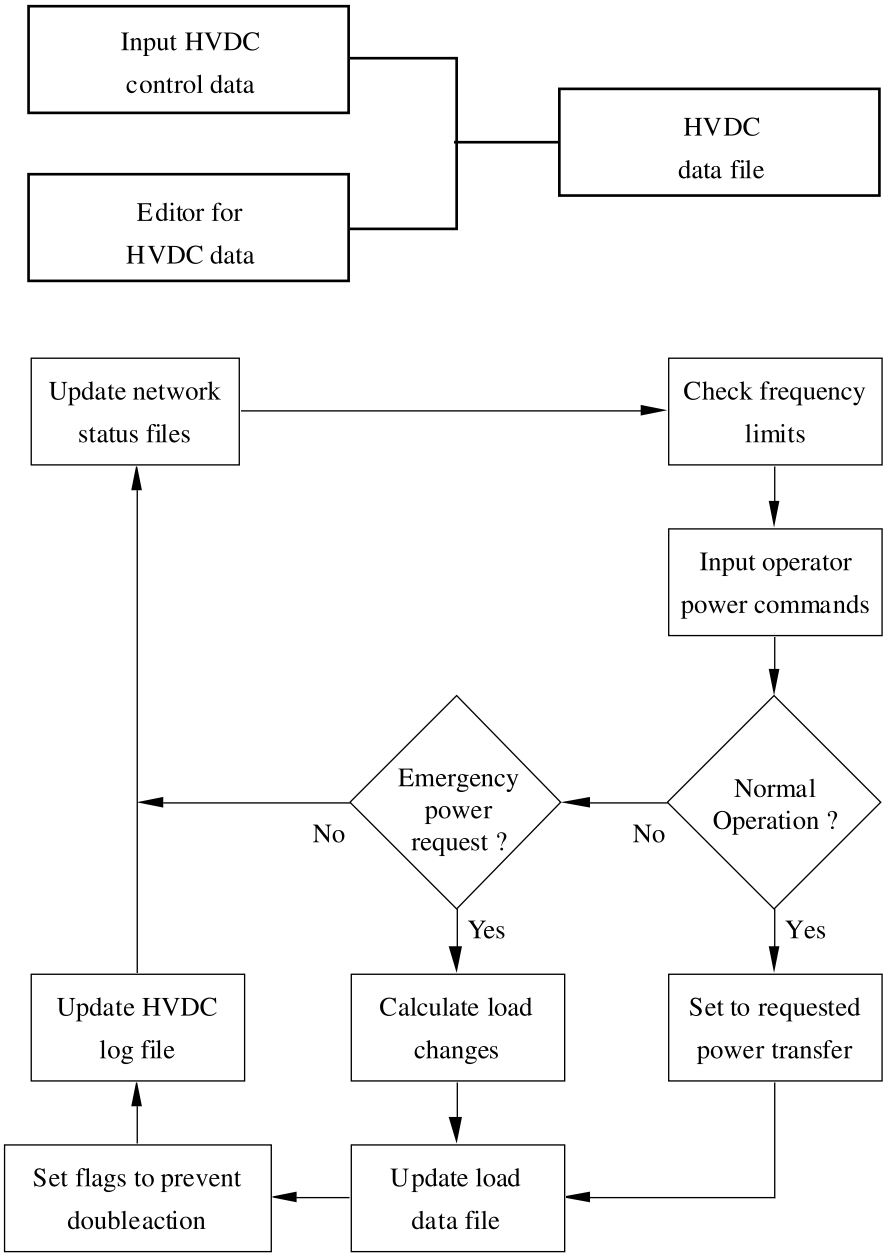

Figure 6.6 Primary HVDC system.

The effects of the HVDC emergency control systems on the local power system simulated are almost identical to those of the load shedding system. There is really no difference in reducing the load or in bringing active power in from outside. However the HVDC control systems are slower than the load shedding, as the power flow can not be changed too rapidly. Also, the change in power is gradual rather than instantaneous as for the load shedding.

The HVDC systems have been represented as constant power flows with the addition of routines similar to those for load shedding to handle the emergency situations. Just like the load shedding system the HVDC representation has had to be divided up into a primary system, running on the HP-UX system and performing the correct calculations with the HVDC system connected to its proper place in the network, and a secondary, simpler but faster, system running on the station interface PC. In the same way as for the load shedding system the two processes communicate via a control file to prevent the same changes from being accounted for twice.

Block diagrams for the HVDC systems are shown in Figure 6.6 and 6.7.

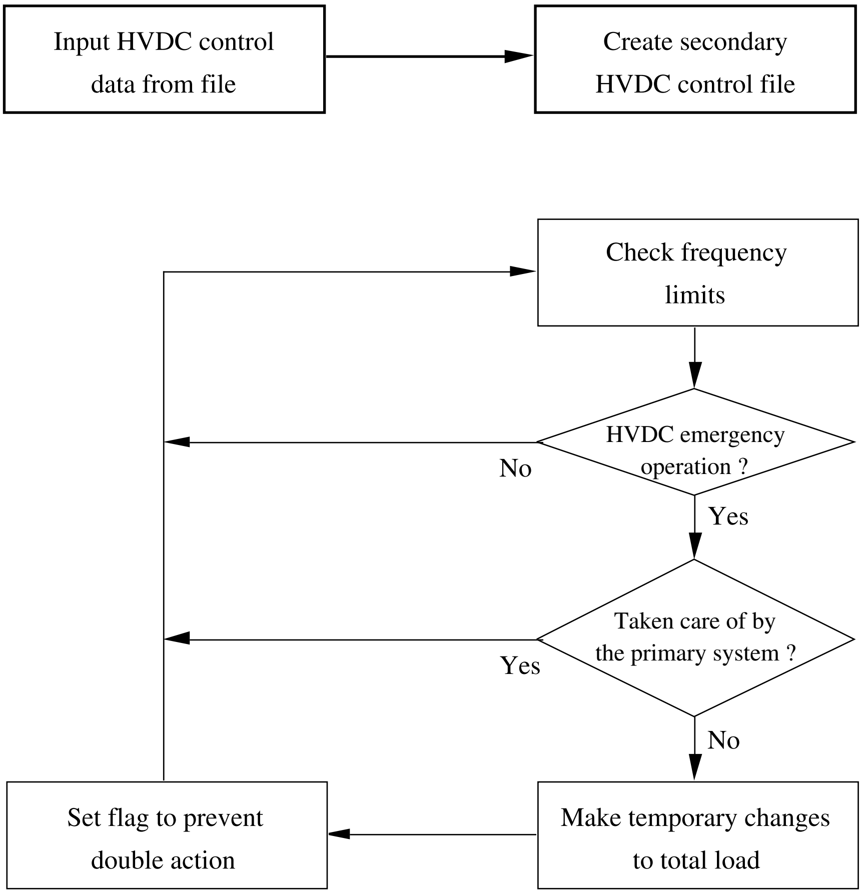

Figure 6.7 Secondary HVDC system.

6.5 Other regulating power stations

The first simulations were all done on the assumption that the station used for the simulations was the only power station within the network that was exercising frequency control; i.e. either it was simply the only station on the network or all other stations were running in constant power mode.

In a practical operating situation this is most often not likely to be the case. If there is e.g. hydroelectric power available within the network area then that will most likely also be used for frequency control, considering the ease at which such stations can be controlled.

In the specific geographical area studied there are several hydroelectric power stations available for such purposes: at Trollhättan there is a total of 16 units with a total power output of approximately 250 MW. There are also units at Lilla Edet plus a few smaller ones.

The control systems of these stations have so far been represented with a very simplified method, taking into account only the slope of their control characteristics and using a constant MW/s change rate for adjustments.

The systems for representing other regulating power stations need to be upgraded and developed in order to properly represent a situation where several regulating stations are involved. This is one of the areas suggested for further developments, see Chapter 12.

Figure 6.8 shows an outline of the control system that is being used in the present state of the simulator.

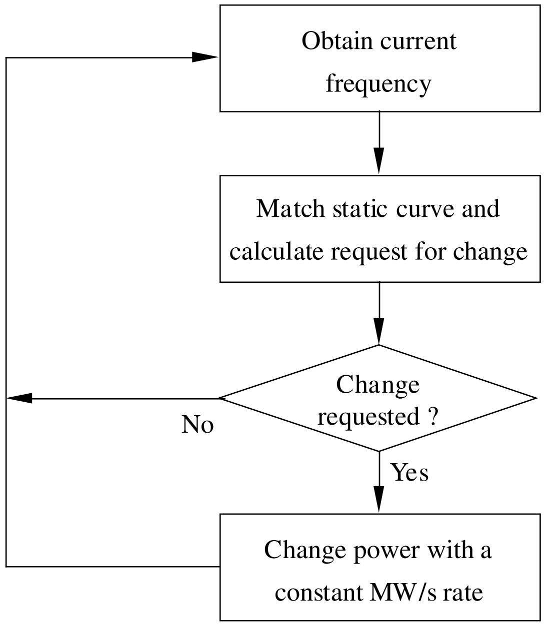

Figure 6.8 System for the modelling of control systems at other regulating power stations.

Chapter 7

Connecting the Simulator to the Power Station Simulator

7.1 Simulator to simulator interface

As mentioned in Chapter 1 the simulator has been designed to operate connected to a power station simulator as well as connected to the actual power station. This is most essential, as it allows for the safe testing of numerous operating conditions.

The system can thus be used both to test conditions that are later on to be tested against the actual power station and also for testing the behavior of the system / station in more extreme situations that would not readily lend themselves to actual testing on the station. Furthermore, it allows for testing a large number of situations, whereas, because of the operating costs involved, the number of situations that can be tested against the actual power station is highly limited.

When working against the power station simulator the entire interface process consists of transferring information between two computers. Also, it is not necessary to apply special safety control measures, as there is really no cost involved in the case of a system crash.

The number of parameters that have to be transferred between the two systems is quite limited: the network simulator needs to tell the power station simulator what the current network frequency is, as well as the voltage at the point of connection in the case that voltage simulation is used. The station simulator need to tell the network simulator what the actual power output, and in the case of voltage simulation also the reactive power output, is. These are really all the parameters that are required.

As mentioned in Chapter 5 there were some additional complications due to the age of the station simulator computer, an ND-100. In order to get around these difficulties it was decided to use a PC as a communications server between the two main computer systems. As the power station interface PC was unused while running against the power station simulator the natural choice was to let this one take care of the task.

The PC and the ND-100 communicate via an RS-232 C connection at a speed of 9600 baud. The PC buffers the information and communicates with the HP-UX system using two different data files, one for input to the PC and one for output. The actual communication between the PC and the HP computers is then done on Ethernet LAN, using the PC-NFS system for file sharing as described earlier. An outline of the system is shown in Figure 7.1.

The serial communication system works fine when it comes to sending data from the PC to the ND computer, but it required some extra programming to get proper data reception on the ND. The normal FORTRAN I/O required too much memory for this purpose and made the simulator program on the ND grow beyond its memory bounds, as very little free memory space was available. Also, the FORTRAN I/O does not allow for reading a data if it is available but continuing on if no new data is present. A third requirement was that data was to be read in such a way that always the last data that was available was used. Input buffering could otherwise lead to the opposite result.

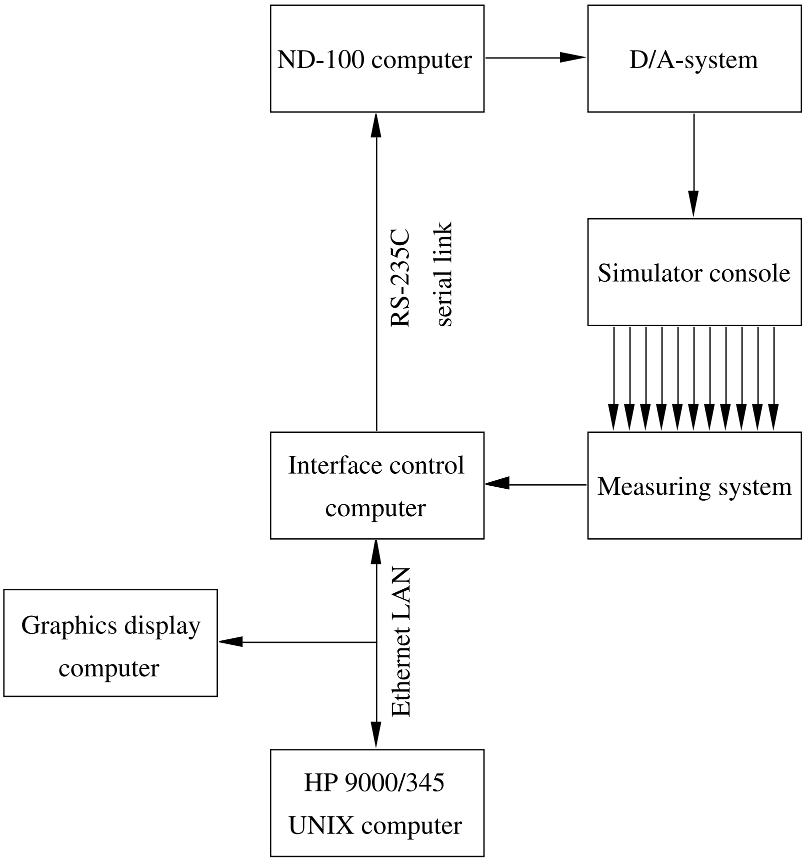

Figure 7.1 Simulator to simulator interface.

As a result of these difficulties an input routine in ND assembler language had to be written and incorporated into the ND Fortran program.

As for the communication from the ND computer to the PC, the serial link did not work at all. It turned out to be very difficult to get any data across, as the two computers did not handshake properly and the lack of I/O buffering on the PC gave rise to data loss in many situations. No satisfactory solution has so far been found. Instead the data from the ND is brought to the PC using the measurement system; just like the case would be if the simulator was running against the actual power station. The values of the various panel meters of the power station simulator are fed to the measurement system, A/D- converted and thus made available to the PC. This required some modifications to the circuit boards of the simulator console, but once this was done the system worked very well.

7.2 Changes to the power station simulator

The power station simulator was constructed to be a full-scale simulator for the units 3 and 4 of the Stenungsund power station, but it was built for the purpose of training station operators and not for research use. Certain short-cuts were taken in the way it was constructed and whereas these were mostly invisible when the simulator was used for its original purpose they were of such a nature that they had to be taken care of before reliable simulations against this simulator could be made. Some of the main changes were:

1. The governor frequency deadband was not at all included in the actual simulation program. The push-button ”deadband on/off” just activated a pilot light. In normal operation this power station uses a frequency deadband of ±0.3 Hz and this had to be modelled properly.

2. The voltage control system was only a dummy model and had to be remodelled completely in order to get a mode of operation that was close to reality.

3. The low frequency protection system was omitted from the model and a correct model had to be built.

4. The governor droop value was set to a fixed and incorrect value. For the purpose of these tests it had to be made adjustable; so that its settings could be controlled by the network simulator.

5. Program sections for the communication with the network simulator had to be added. Unfortunately this led to that the part of the simulator program that

simulates the dynamic processes no longer fitted into the memory segment, and in order to get around this parts of the processes had to be moved between memory segments.

6. A problem was found in the control system for the boiler fans. There is a connection from the steamflow variable to the airflow in the way as is shown in Figure 7.2. This regulator exists in order to give the fan regulators advance notice of a need to increase the airflow when there is an increase in the flow of steam (= in power output). If the flow of steam is then subject to a constant oscillation, fast enough so that the system can not resettle in between them, this leads to an unlimited increase in airflow; which in turn drives the temperatures of parts of the steam system out of control and leads to a unit shutdown. A number of further tests, including actual testruns of the boiler ventilation system, will have to be made in order to determine to which extent this is a deficiency also found in the real control system.

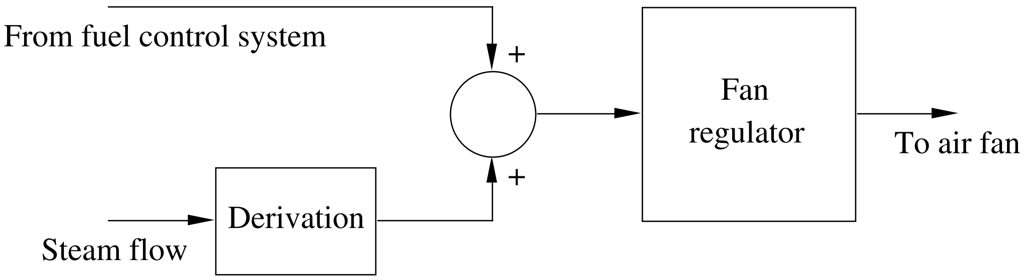

Figure 7.2 Steam flow influence on the fan control system.

7. The exhaust fan control system was found to be overly sensitive. It gave rise to very rapid changes of the combustion air pressure and the station operators said that they had noticed this problem as well, but that it existed only on the simulator. It turned out that the controller model was incorrect and certain corrections had to be made.

8. The station is fitted with a power-difference protection system that shuts down the unit if the calculated oil combustion power exceeds the electric power output by more than 30 %. This system can in reality be turned off, which was not the case in the simulator. Such a cutout switch had to be added to the simulator, as several tests showed that disconnecting this protection system, or at least putting it into a warning-only state, was necessary for many types of islanding operation.

9. The dynamics of the turbine were modelled incorrectly in that a constant grid frequency had been assumed and hence the damping term in the equation that

governs the dynamic behavior of the turbine was not correctly included. The correct version of this equation is:

$$0.5 \cdot J \cdot \frac{d}{dt}\omega^2 = P_T - P_E - (c \cdot p_{cond} \cdot \omega^2) \tag{7.1}$$

where J is the moment of inertia

P_T is the turbine power

P_E is the electric power output

c is a constant

p_{cond} is the condenser pressure.

Several simulations showed that in many situations the damping term (the term in brackets) was extremely important and had a very significant role in stabilizing the system, in particular in situations where the J value was very low; e.g. when the moment of inertia of the actual unit was the only moment of inertia of the whole system (islanding operation against a passive load).

10. The control system for the intercept valves was incorrect and thus the intercept valves were not activated as long as the unit was phased in on the network, even if there was a rapid increase of the frequency. As the intercept system is highly important in situations involving load-loss or a sudden reduction of the load it was important to correct this.

Chapter 8

The Power Station Interface

8.1 The power station interface

The interface to the actual power station was considerably more complicated than the interface to the power station simulator. It consists of several different units, even though they were all built into one box.

The station interface is controlled by a PC that is dedicated to this purpose. The actual interface to the computer is via a Boston Technology PC-30 multipurpose measurement and control card. The card is inserted into the PC and communicates with it via the PC bus.

The PC-30 card has 16 channels for A/D input, 2 channels for D/A output of 12 bits each, 2 channels for D/A of 8 bits each, three 16 bit counters that can be set under program control and three digital I/O ports of 8 bits each.

The A/D channels are used for the measurement system as described in Chapter 4. The inputs were always connected via isolation amplifiers in order to eliminate the risk of creating undesirable and unpredictable ground loops.

In order for the simulations to be possible it was of course necessary to develop a way of feeding a false control signal to the frequency control system of the power station, and in the case of a voltage simulation also a voltage signal to the voltage control system.

The frequency control systems of units 3 and 4 at the Stenungsund power station consist of a tachometer generator on the turbine axis and various control circuits. A simplified block diagram is shown in Figure 8.1.

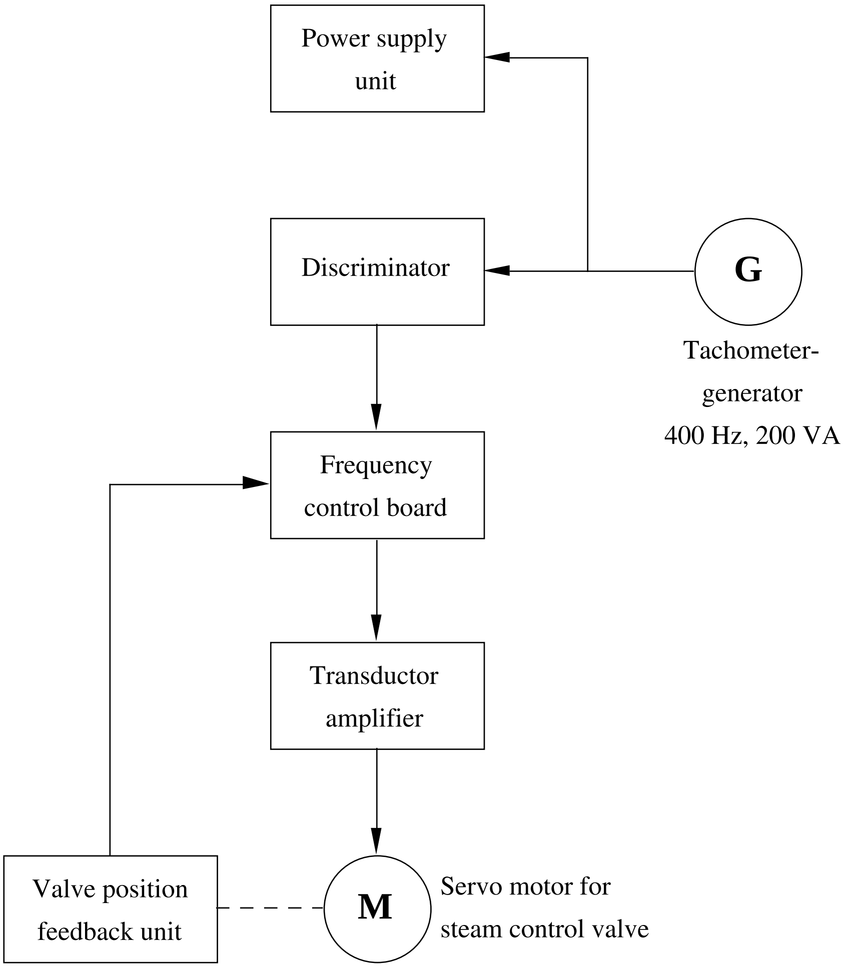

Figure 8.1 Basic diagram for the frequency control system used for units 3 & 4 at Stenungsund.

The first approach for supplying a simulated signal to the system was to build a computer controlled power signal generator, able to generate a 400 Hz sine signal at 110 V level just like the tachometer generator. The frequency could then be accurately controlled by the computer and it was thought that this would be a true representation of the tachometer signal.A further description of the signal generator is found in Section 8.2.

The above approach failed. Several tests showed that the output signal from the discriminator circuit was very different when it was fed from the simulator and its signal generator as opposed to its normal operation when the signal comes from the tachometer generator. The reason for this was that whereas the frequency of the tachometer generator signal varies on a continuous basis the frequency of the signal generator would change step-wise each time that the simulator had completed one loop and thus updated the frequency. Even when the change in frequency was very modest the output of the discriminator still became unpredictable, with lots of chirp and unwanted spurious signals each time that there was a change of frequency.

The approach above therefore had to be abandoned. Instead the signal generator was used to supply a controllable signal to the discriminator and the output of the discriminator was recorded. This was done by applying a signal of a certain frequency, waiting for a couple of seconds so that the discriminator would settle to its final output and then recording the output of the discriminator, using the measurement system. For this purpose the measurement system had temporarily been readjusted for bipolar measurements, as the output of the discriminator is normally in the range of ±10 V.

Using a special computer program these measurements were done for each 0.005 Hz in the range 47.0 Hz to 53.0 Hz. The resulting discriminator output signals were recorded in a special file. See Figure 8.2. Thus, instead of using the signal generator for the actual simulations, it was possible to use a DC signal.

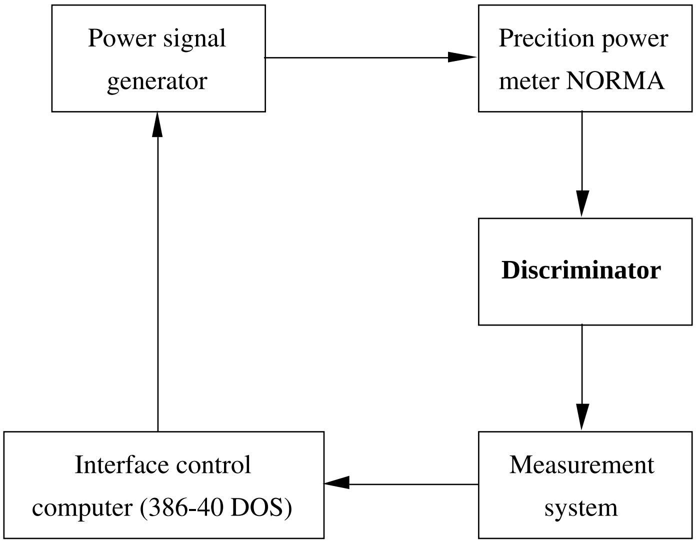

Figure 8.2 Test setup for determining the discriminator response curve.

The value of the DC signal is calculated for each update by taking the value recorded in the discriminator file for the frequency that is the closest fit to the simulated frequency at any given point of time. One of the 12-bit D/A outputs is then used to generate the requested D/A signal. The signal is then fed, via a precision isolation amplifier, to the frequency control system. The system is outlined in Figure 8.3.

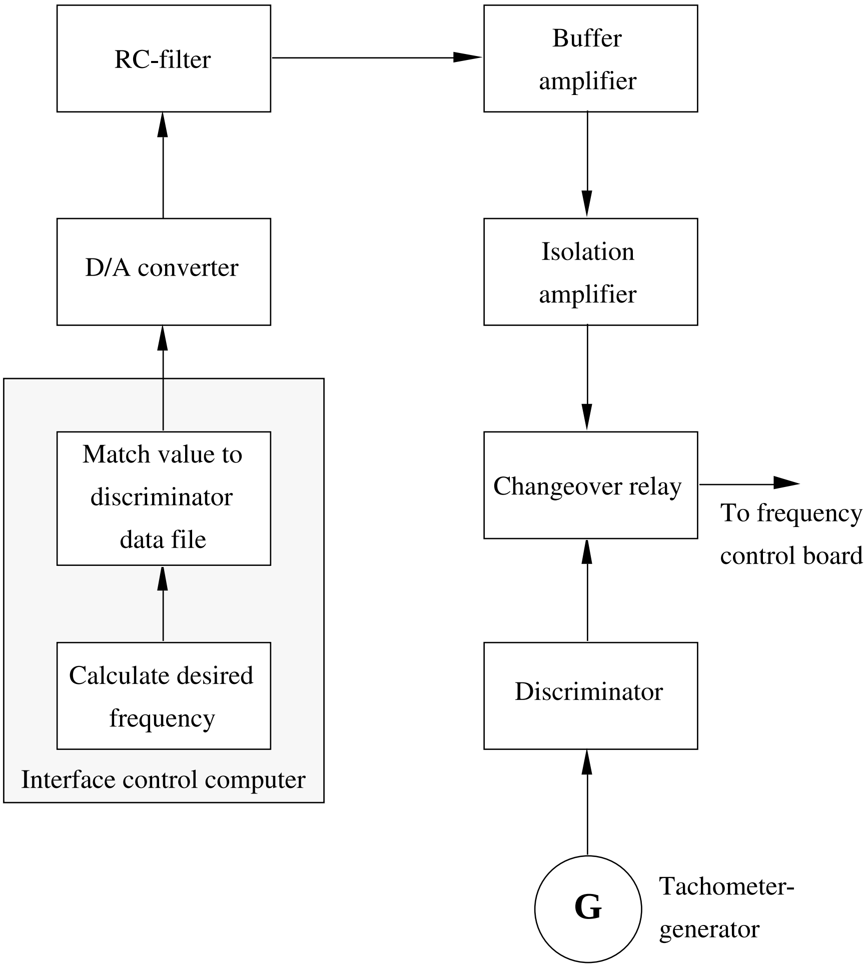

Figure 8.3 System for frequency simulation.

The frequency control card contains circuits that are sensitive to the derivative of the frequency. This is to speed up the response in situations where there is a rapid change of frequency, e.g. in case of a loss of load or similar. In order for these circuits to react correctly during simulations the signal must change on a continuous basis and not in steps. A simple RC circuit with a time constant approximately equal to the normal cycle time of the simulator program (≈ 50 ms) was therefore inserted in between the D/A converter and the isolation amplifier. In order to avoid errors due to the fairly low input impedance of the isolation amplifier an OP-amp was introduced as a buffer amplifier. See Figure 8.4.

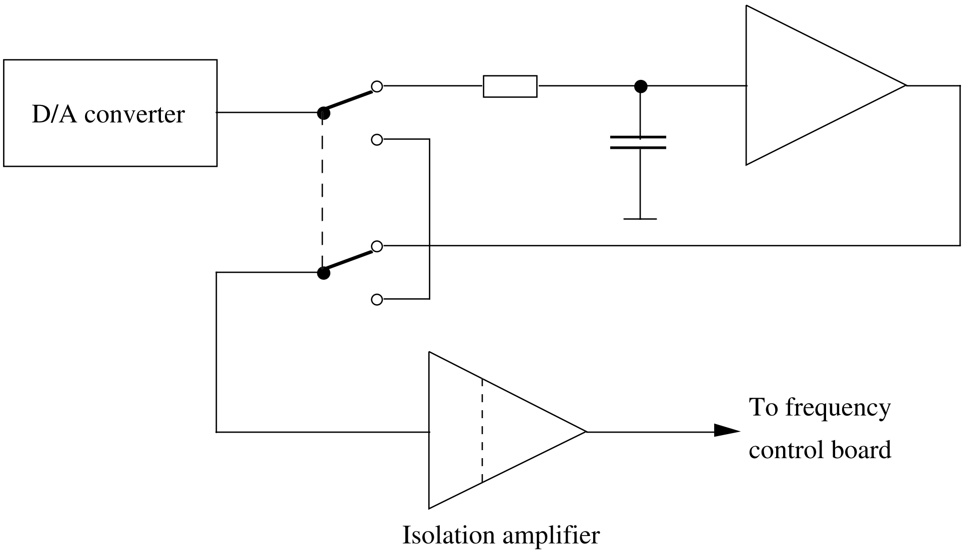

Figure 8.4 RC-circuit and buffer amplifiers.

The system must of course allow for switching between the simulator and normal operation in an easy and controllable fashion. This is done by a switch-over relay that is activated by program control. The relay is controlled using one of the digital outputs of the PC-30 card.

In a similar way it was necessary to be able to control the voltage control system in case of simulations involving voltage control.

The voltage control system of units 3 and 4 of the Stenungsund power station is outlined in Figure 8.5. The electronic control circuitry controls an SCR rectifier, and the output is fed to the exciter. The exciter is mounted directly on the generator axis.

One approach would have been to simply take over the control signal from the voltage control system (point 1 in Figure 8.5) and to supply that from the interface via a D/A converter. This approach was however considered too risky, as if for some reason the simulator did not respond correctly to any changes in voltage then the voltage would become uncontrollable and hazardous situations could occur in two ways: one could be the generation of overvoltages, even though the protection systems would of course disconnect the generator in case of excessive voltages; another and more likely risk would be that the generator would under such circumstances influence the voltage of the surrounding actual power network in such a way that it could create problems for power consumers. This would be particularly undesirable at Stenungsund, as several petrochemical industries in the area are very sensitive to voltage variations.

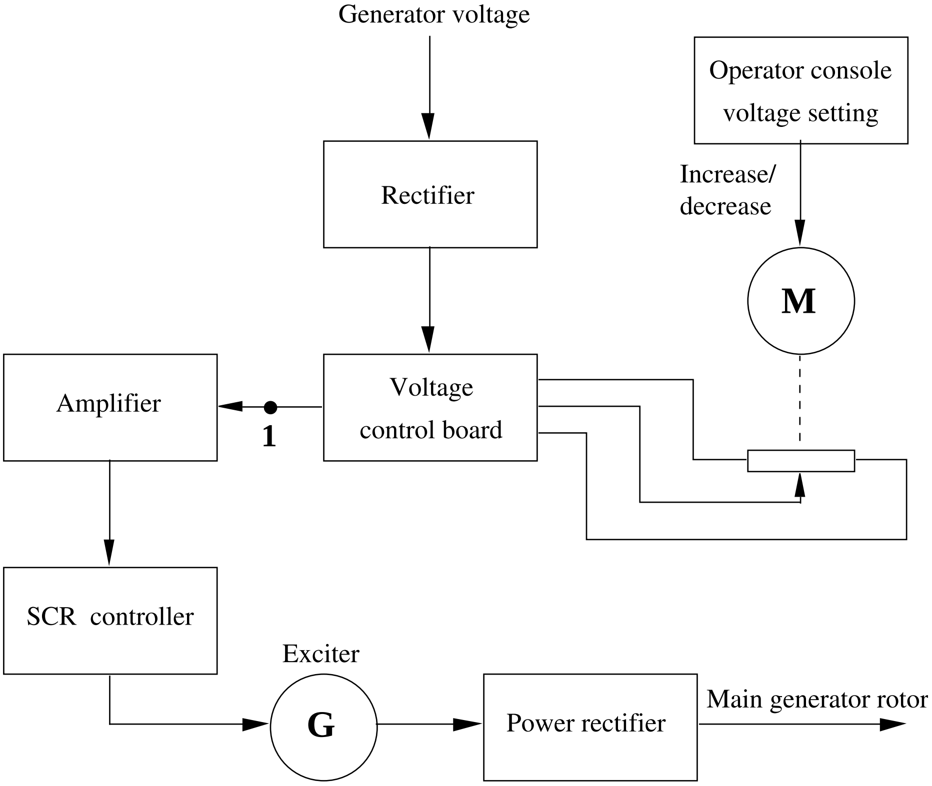

Figure 8.5 Voltage control systems, units 3 and 4 at Stenungsund.

Instead it was decided that the correct way of controlling the voltage was to control the actual request value, normally set by the voltage potentiometer, and then let the normal control system handle the voltage control in the normal fashion. In this case there would be no hazards involved if the computer system should get stuck or similar; the voltage would just settle to its new value.

Just as for the frequency control system it was found proper to introduce an RC circuit so that the control inflicted on the system would be continuous rather then step-wise; even though there is no circuit in the voltage control system that uses the voltage derivative in any way.

The voltage setting signal is generated by one of the 8-bit D/A converters, as the 12-bit ones had already been assigned to the signal generator and to the disciminator output simulator circuit. In order to allow for a good resolution a fixed voltage of an adjustable value (adjusted manually via a potentiometer) was added to the signal, so that the entire 8-bit range of the D/A converter could be used for controlling the voltage within the limits that it could possibly vary within.

A changeover relay, controlled via one of the digital I/O lines of the PC-30 card, switches between simulator mode and normal operation.

The final design of the voltage control system of the simulator is shown in Figure 8.6.

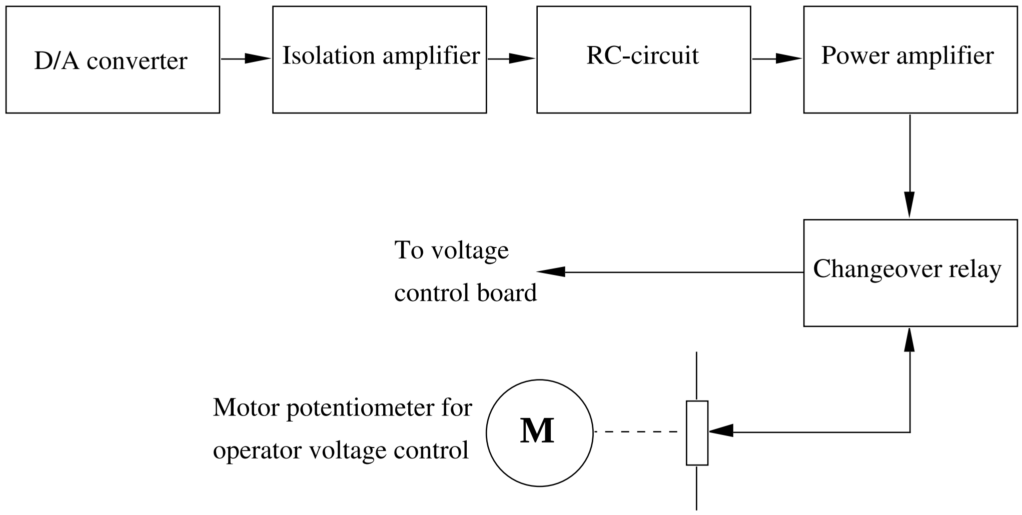

Figure 8.6 Voltage simulation circuit.

The power station interface also contains an 8-bit parallel interface to allow for the transfer of frequency information from the interface PC to the HP system. This system was describer in Chapter 5.

The interface unit also contains the circuitry that is required for driving the power station operator interface unit. For a further description of these circuits see Chapter 9.

During the tests performed at the Stenungsund power station it was found that various kinds of interference or transients could sometimes enter the circuits. This could result in that certain measured values were completely in error and this in turn could lead to incorrect action by the simulator.

In order to prevent these problems from presenting a risk for malfunction certain precautions had to be taken. Some were implemented in hardware; e.g. by adding decoupling capacitors and RC or LC filters to certain connections within the interface unit. Other measures were included in the software; e.g. that measured values are checked against set limits and against previous values and rejected if found to be out of bounds.

At a test at the Stenungsund power station, unit 4, in February 1993 a protection system was activated and the unit was shut down automatically. The exact cause of this could not be established but the incident led to a number of safety precautions.

One of them was that a separate protection / supervisor card was added to the interface unit. This card performs the following functions:

1. It monitors the voltage difference between the voltage delivered by the discriminator and the voltage output by the simulator unit, see Figure 8.7. If these are not very close to each other immediately prior to a simulation the card will block the simulation from being started by inhibiting the activation of the changeover relay.

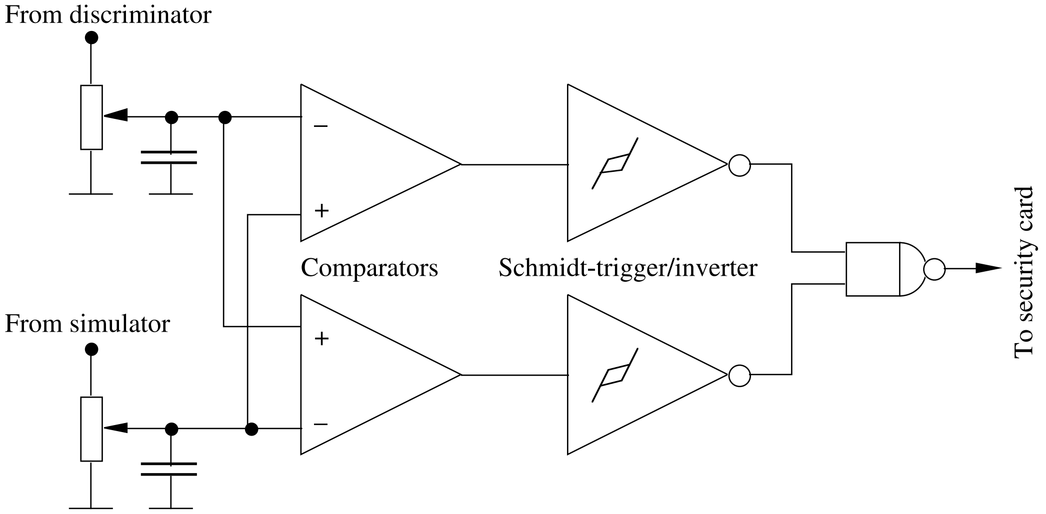

Figure 8.7 Frequency differential protection circuit.

2. In exactly the same fashion it monitors the normal signal for the requested voltage level and the output from the voltage simulator circuit and compares the two, see Figure 8.8. If there is a noticeable difference it will prevent the voltage simulation relay from being activated.

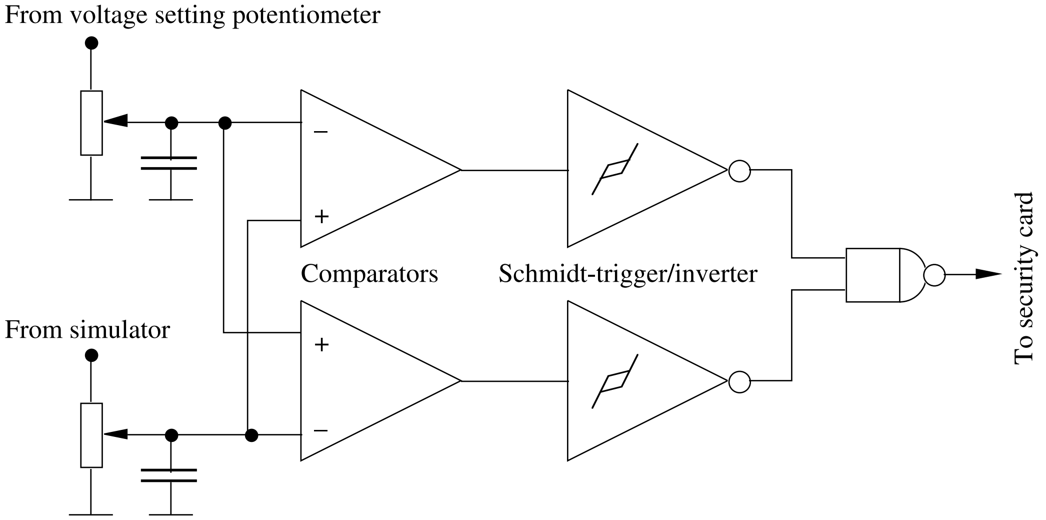

Figure 8.8 Voltage differential protection circuit.

3. It monitors the simulator output during the actual simulation to see to that it stays within certain set limits, see Figure 8.9. The simulator programs have similar limit check functions and normally these ones are to intervene first. The hardware implementation in the protection card gives an extra safety check, as this system is completely independent of the other systems. If it detects an operation out-of-bounds it terminates the simulation by deactivating the control relay. Its limits are set manually prior to start-up.

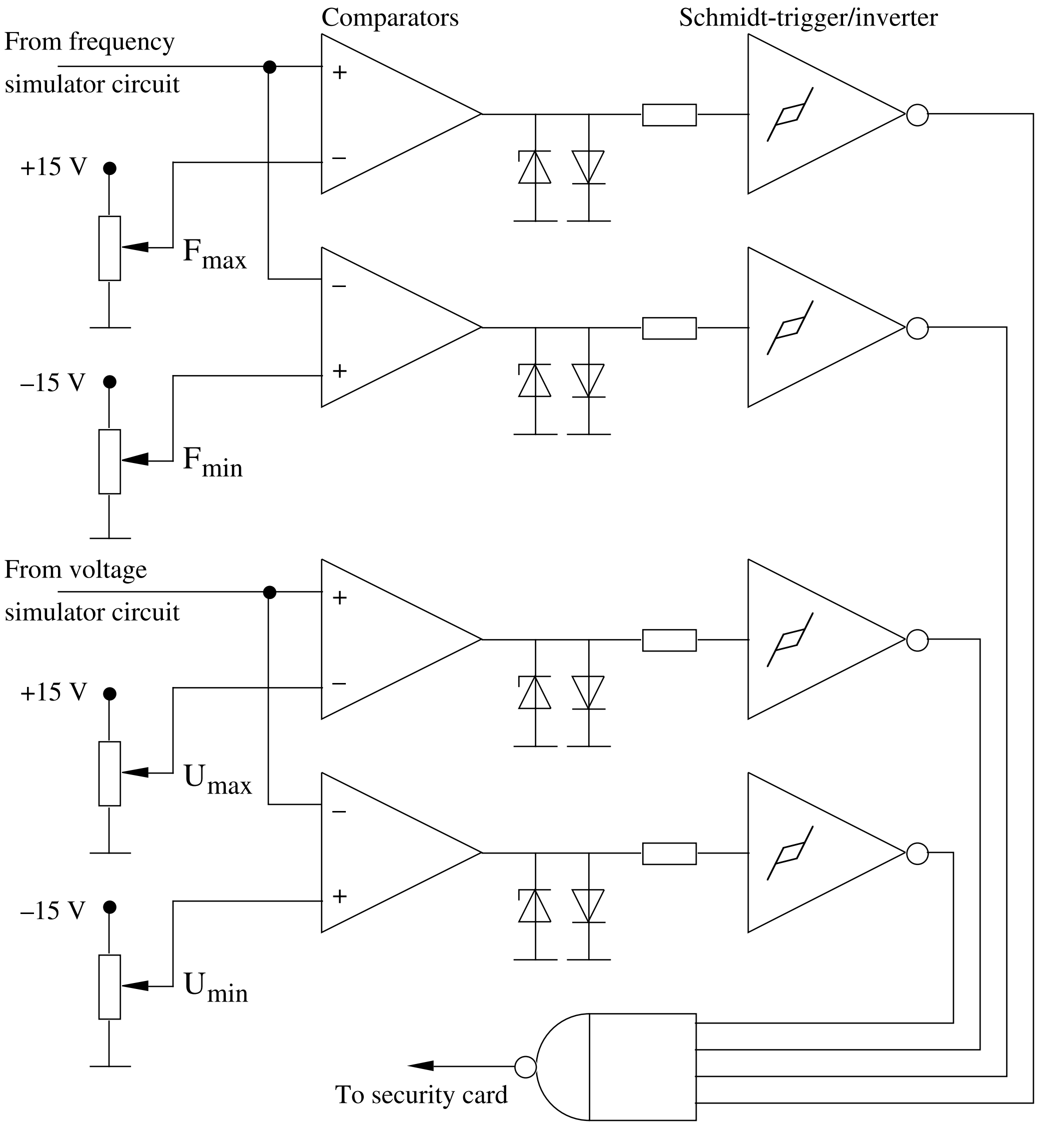

Figure 8.9 Frequency and voltage limiter circuit.

4. During a simulation the PC is programmed to flash one of the LEDs on and off for each cycle that is completed, see Figure 8.10. This is monitored by the security card. If this particular signal does not change for a period of more than 0.5 s this indicates that the PC has a problem or is stuck somehow and the simulation is then terminated.

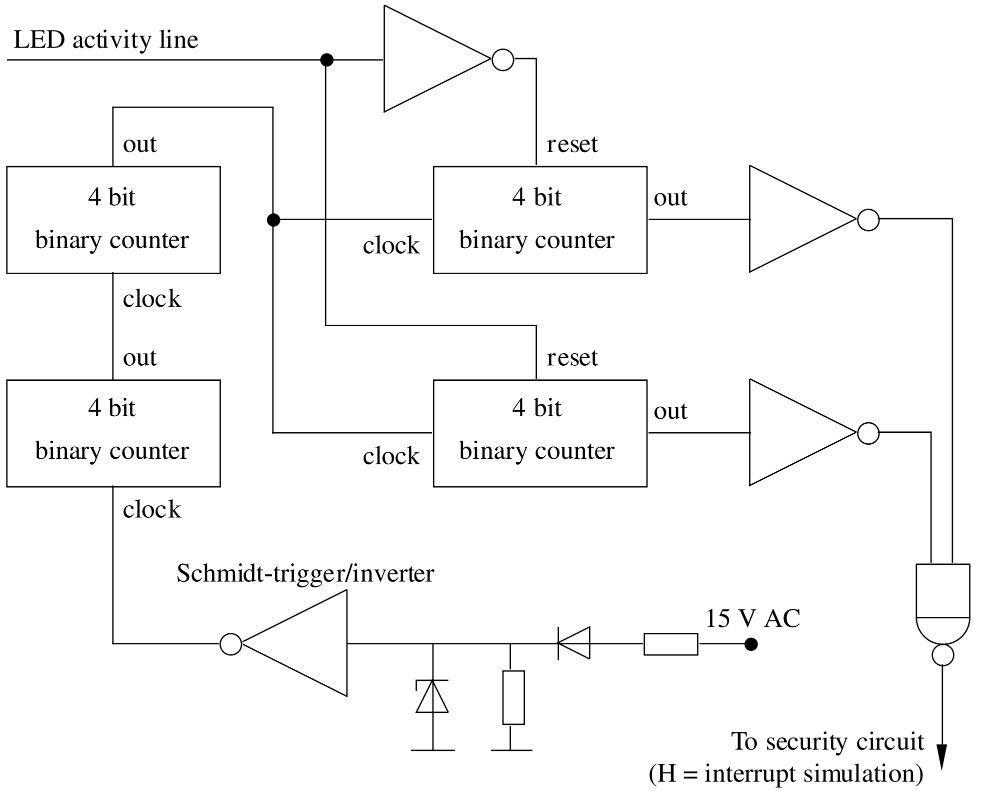

Figure 8.10 LED monitor circuit.

An additional safeguard is the introduction of a special relay to disable the special frequency derivative circuit of the frequency control unit of the power station. This relay is activated by a driver in the interface unit, using one of the digital output lines of the PC-30 card. By deactivating the frequency derivative sensing circuit at the time when a simulation is terminated it prevents that a transient resulting from the changeover will cause the control systems to take incorrect action. See Figure 8.11.

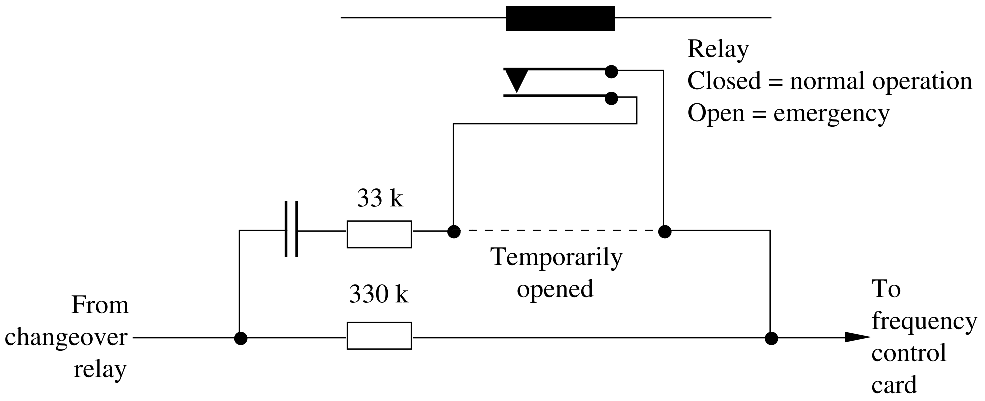

Figure 8.11 Frequency derivative circuit.

8.2 Signal generator system

The power signal generator was, as was mentioned in the previous chapter, originally designed to serve as the direct interface to the frequency control systems of the power station. Instead it was used to calibrate the discriminator circuit in order to obtain the voltage curve.

The generator was also used in order to supply 400 Hz operating voltage to the frequency control circuits of the power station in order to allow for these control circuits to be tested independently without the need for the station to be in operation (i.e. without the need for any output from the tachometer generator.

The generator was constructed to fulfil the following requirements:

1. An output of at least 30 W was considered to be necessary. It was not possible to obtain any exact load figure prior to the testing. The tachometer generator has a rating of 200 VA but this was considered to be much more than what was actually required. At testing time the power input to the discriminator (active power component) was measured to be approximately 11 W.

2. The frequency had to be controllable with a high degree of accuracy. A resolution of 0.01 Hz, corresponding to 0.00125 Hz at 50 Hz was considered to be more than adequate.

3. The output voltage had to be controllable as well and the system should have a control system in order to hold that voltage constant also in the case of a varying load.

4. The system should be capable of generating output voltages in the range 70–120 V. The most common use would be 110 V, which is the output of the tachometer generator of units 3 and 4 at the Stenungsund power station.

With these considerations in mind a signal generator was constructed in accordance with the block diagram of Figure 8.12.

The primary signal is a square wave signal that is generator by one of the 16 bit digital counters of the PC-30 card. This counter is set to square wave generation mode and a value is loaded into the counter. The counter counts the clock pulses of the PC bus and the resulting output is a square wave whose frequency is inversely proportional to the value that the counter is loaded with.

When the system was developed an XT type computer was used and its clock frequency turned out to be too inaccurate for the purpose of providing the clock pulses, as the frequency tended to drift considerably with time. A separate high precision oscillator was therefore provided for the clock pulses to the counter.

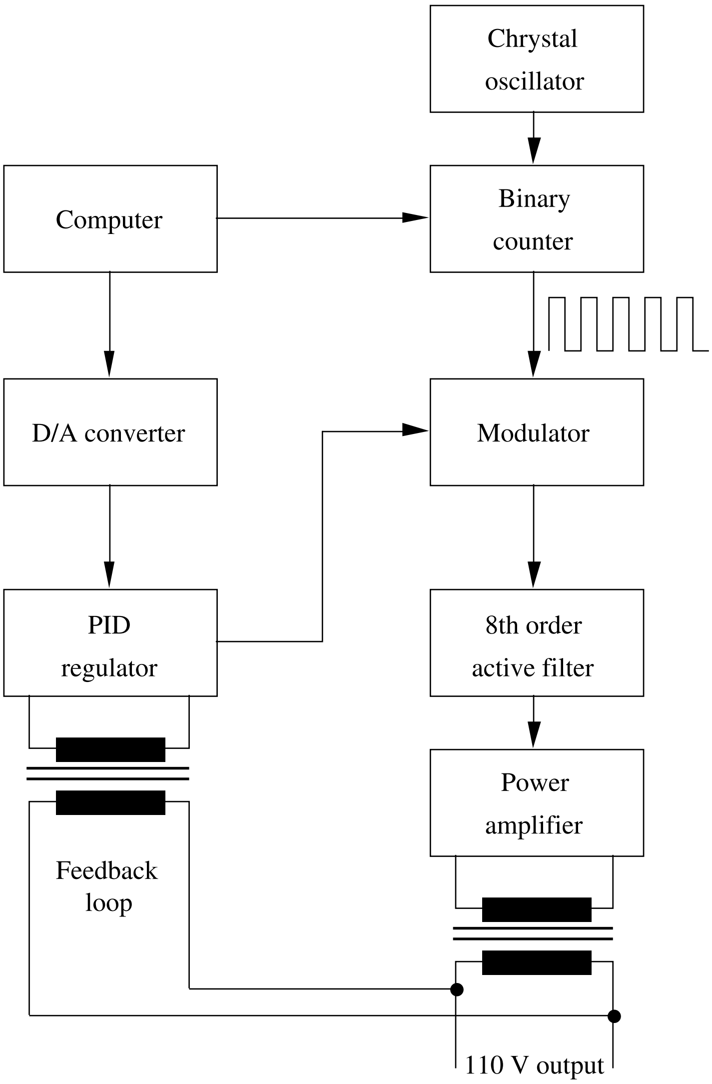

Figure 8.12 Power signal generator - block diagram.

It was desirable that the generator could generate 50 Hz, 60 Hz or 400 Hz, as this would make it more useful for various tasks. This was easily done with the chosen oscillator, as its output frequency could be set by the use of control inputs on the IC and by choosing different outputs from it. The control inputs were set up with a three position switch and at first the choice of the outputs was done the same way. It was however found that the resulting long leads from the oscillator to the switch emitted RF signals of such strength that they interfered with the computers disk interface system. Instead a gating system was inserted and the switch used to control the gates. The oscillator circuit is shown in Figure 8.13.

According to its specifications the timer/counter circuits of the PC-30 card are capable of operation at frequencies up to 2.5 MHz. It was however desirable to use a higher frequency as this meant a higher count per signal period and hence a better frequency resolution. The circuit was therefore tested with various clock frequencies and it was found to operate in a correct manner even for a frequency of 20 MHz, which was the final choice for the 400 Hz operation mode (consequently 2.5 MHz for the 50/60 Hz mode, 5.0 and 10 MHz for 100 and 200 Hz respectively). This gives a frequency resolution of about 0.008 Hz for the 400 Hz range (0.001 for 50/60 Hz) which is well adequate.

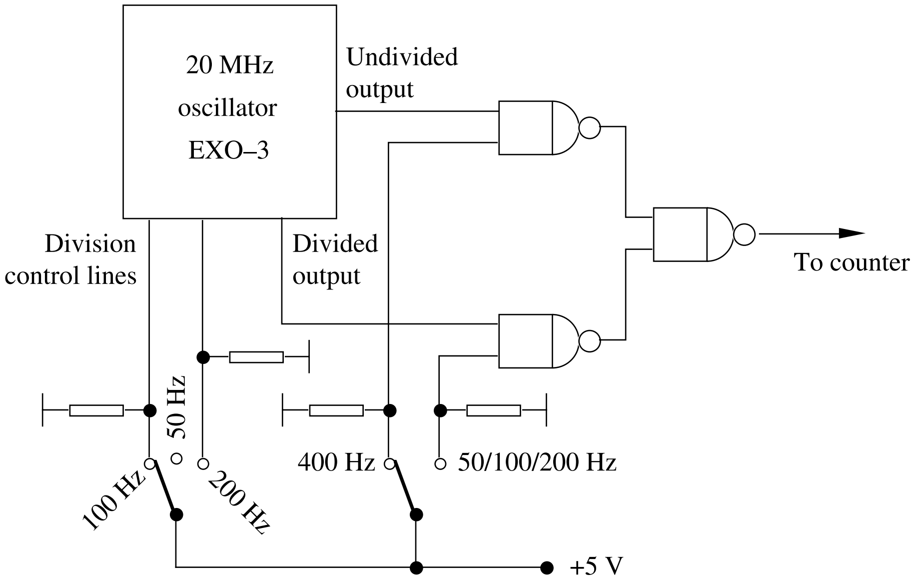

Figure 8.13 Oscillator circuit.

The square wave signal is fed to a modulator which is controlled by the output from a 12-bit D/A converter on the PC-30 card. This allows for setting the voltage to any desired level within the range of the generator. The voltage from the D/A circuit is however not fed directly to the modulator, as this would not allow for regulation. Instead it is used to feed a regulator circuit that compares it to the voltage taken by rectifying the generator output. The regulator is a common type PID regulator and it keeps the output voltage constant to the set value even at varying loads.

The square wave signal has to be filtered in order to be converted to a sinusoidal signal. This is done by using an 8th order Butterworth active low pass filter. It cuts off all harmonics down to less than 0.5 % which is well adequate and gives a good sine wave output. Two different filters are included in the generator, one for the 50/60 Hz range and one for 400 Hz. If 100 Hz and 200 Hz operation will later be desirable then additional filters can be inserted. The two filters are identical apart from the R and C values used.

After filtering the output signal is fed to a power amplifier.In order to make use of what could be readily bought a car stereo power amplifier was used. This one boosts the output to the desired level. It is capable of delivering approximately 50 W of pure sine wave at 400 Hz and 110 V at the generator output. When tested at this level the amplifier broke down after 10 minutes. Whether this was just an ordinary component failure or a result of overload (should not be possible, as the power rating is 160 W and as various protection circuits are fitted to the amplifier) could not be determined. After repair the unit was long-term tested with a 30 W power level with no problems.

The output of the power amplifier is fed to a transformer to step it up to the desired voltage level. Testing showed that the voltage could be varied in the range 50–150 V which is well adequate.

As mentioned later in Section 10.3 it was found necessary to use the signal generator also for supplying certain additional circuits within the frequency control system. This represented an extra load, but it was found to be within the limits of the generator and it was successfully used also for these tests.

8.3 Power station interface PC software

The basic layout of the main software running on the station interface PC is shown in Figure 8.14, which shows the program package that is used during simulation against the actual power station (E4CONTR). In addition there is software for calibrating the discriminator, for testing the interface unit and also for use when running simulations against the power station simulator. These programs will be discussed later.

The station interface software was originally developed in FORTRAN. As it turned out to be impossible to obtain reliable drivers for the PC-30 card in FORTRAN the software had to be rewritten in C. It is possible to use these two languages in combination by using Microsoft FORTRAN and C, but this requires matching versions of the compilers and creates problems when it comes to updating the software, so it was decided to use C for all routines on the interface PC. The version used was Microsoft C, version 5.1, as this was required in order to match the PC-30 drivers.

The program runs in a loop, with one loop completed per simulation update.

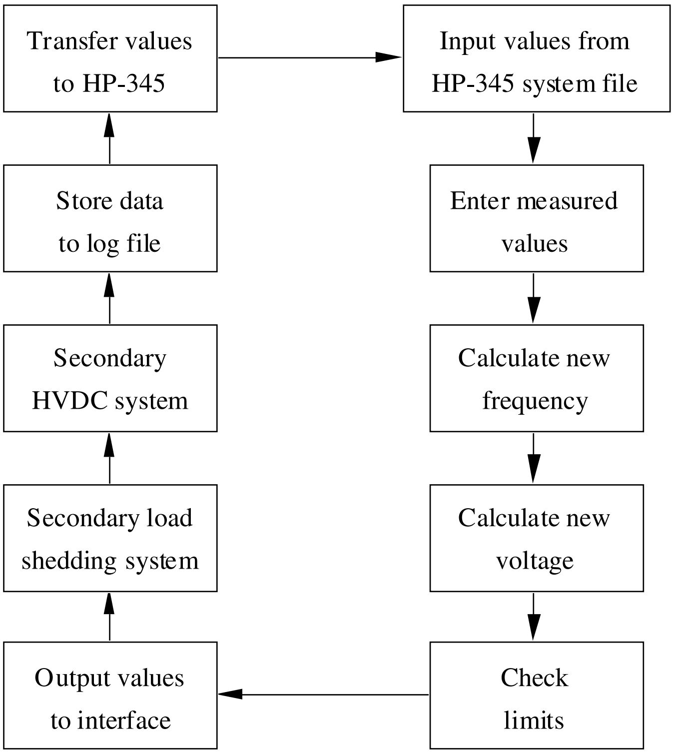

Figure 8.14 Software in the interface PC - main simulation loop.

When first started the program enters a HOLD state. During this state only the measuring parts of the station interface are active. All measured values are continuously logged to a special log file for further examination afterwards. In the HOLD state the PC also checks the 'infile' file on the HP computer. From this it obtains various information, including the IMODE variable which controls the operation of the interface. As long as this variable is set to 0 the system remains in the HOLD state.

When the value of IMODE changes the interface unit is activated and an actual simulation is started. The following modes are possible:

0 Hold

1 Frequency simulation

2 Voltage simulation by direct control (normally not used)

3 Voltage simulation by controlling the voltage setting

4 frequency and voltage simulation, modes 1 + 2

5 frequency and voltage simulation, modes 1 + 3

When a change of mode is detected the program enters the routines required for phasing a simulation in and out. These are designed to allow for as smooth a transition as possible in order to suppress transient effects at the point of changeover.

There are separate phase-in and phase-out routines for the different modes of operation. At the end of each such routine it activates (phase-in) or deactivates (phase-out) the control relay in question, thereby switching the power station between normal operation and simulation.

A separate emergency routine is called either by the operator or on certain detected error conditions and this routine terminates the simulation immediately and returns the power station to its normal operation by deactivating all changeover relays.

The central part of the simulator program on the interface PC is the simple mechanical swing equation:

$$\frac{d}{dt}(0.5 \cdot J \cdot \omega^2) = \Delta P \tag{8.1}$$

where J is the moment of inertia of the system

ω is the angular velocity

ΔP is the difference between produced and consumed active power

or in its integrated form as it is used in the program:

$$\Delta\omega^2 = \Delta P \cdot \frac{\Delta t}{2J} \tag{8.2}$$

where Δt is the time interval between updates

Delta P is calculated taking the value of the load as handed over from the HP system via the communications file and comparing it to the actual power station output as measured by the measuring system of the interface unit.

The value of J is also handed to the PC by the HP system. It is normally constant if there are no major changes in the network, but will of course vary if generating units or other synchronous machines on the network are connected or disconnected.

In addition to this basic function the interface PC also has routines for checking that the simulation stays within certain set limits, drivers for the station operator interface unit, communications routines for communicating with the HP system via file sharing and via the parallel interface, a routine (AD_IN) that makes measurements (both for calculating the actual P and for log purposes) and a special routine for supervising the turbine system. For a description of the latter see Section 10.3.

The basic outlay of the software used to obtain the response curve of the discriminator is shown in Figure 8.15. The system will set a frequency, order the signal generator to output the desired frequency, wait for the discriminator to stabilize and then measure the output and record the value, thereby creating the discriminator response data file (DISCR).

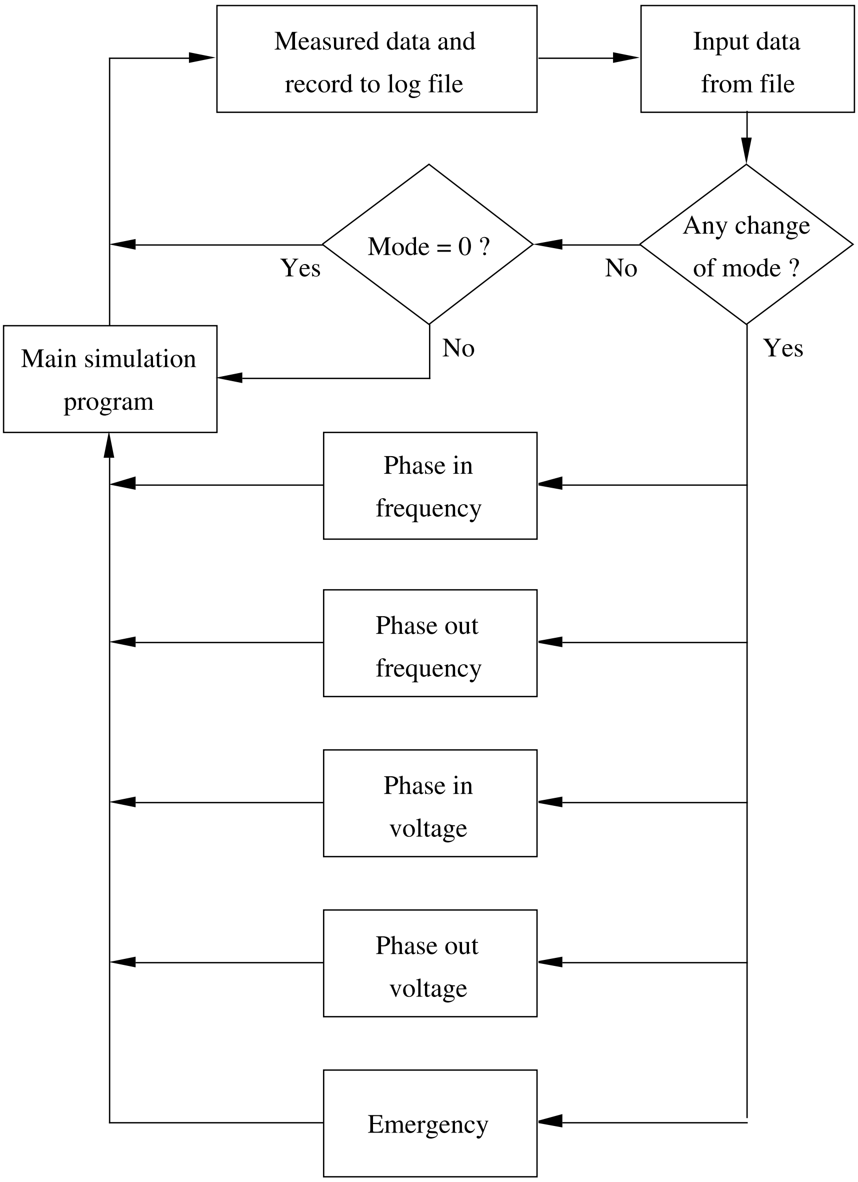

Figure 8.15 Routines for changing the simulation mode - overview.

The program package used for testing the interface unit consists of two main programs, both written in C. One program is used to test the very interface unit and has functions whereby the operator can order various output signals, close and open relays, test the measurement system etc. Its block diagram is shown in Figure 8.16.

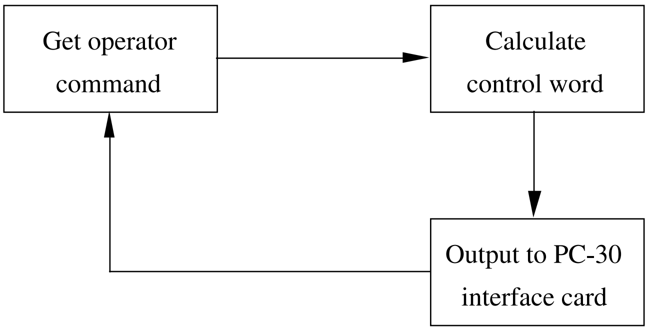

Figure 8.16 Interface test program, block diagram.

The other test program is used for testing the interface unit together with the frequency control components of the power station.

This program allows for different test modes: the simplest one involves running the interface unit plus the discriminator and the frequency control circuitry of the power station. In the second mode of operation the turbine governor /valve control system is also active and included in the testing. In the third mode an artificial control loop is created as a subprogram simulates the behavior of the actual turbine system, thereby allowing for a full test of the simulation process, without that the turbine system is running.

The block diagrams of the different modes of operation are shown in Figures 8.17, 8.18 and 8.19.

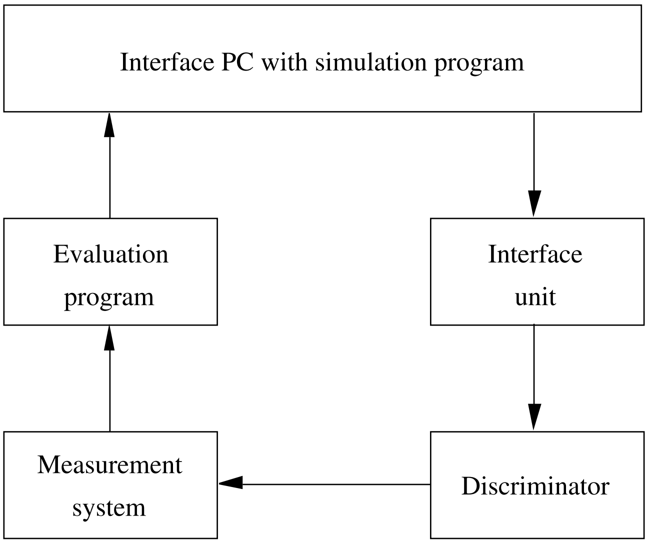

Figure 8.17 Test setup including the discriminator.

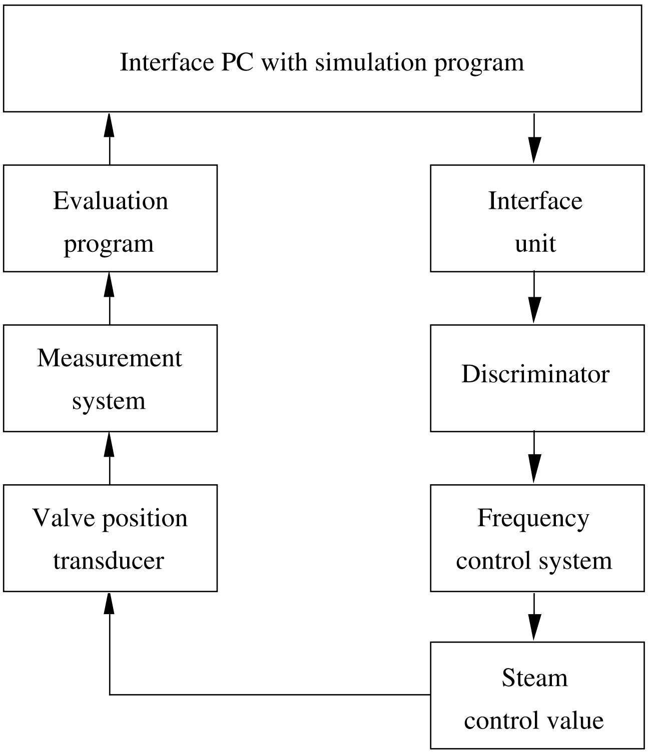

Figure 8.18 Test setup including the steam control valve.

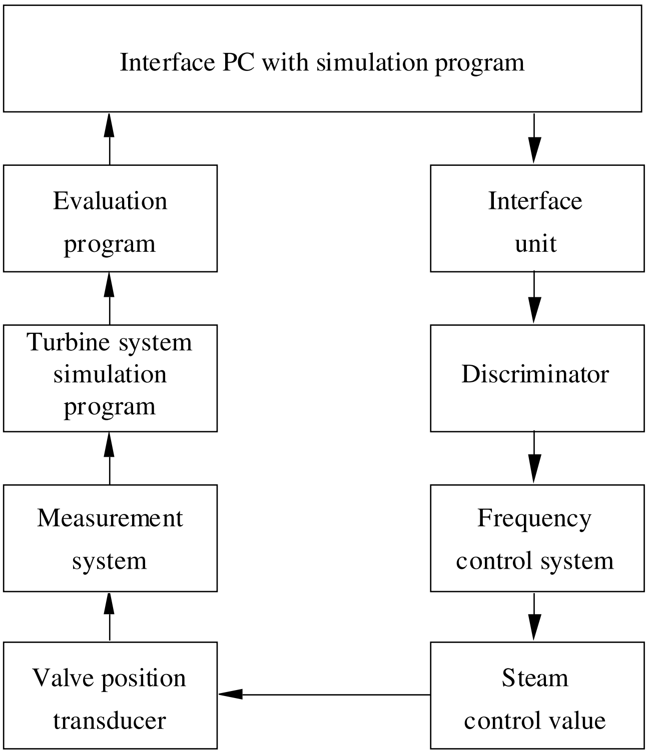

Figure 8.19 Test setup with turbine simulator program.

Chapter 9

Communicating with the Operator

9.1 Operator interfaces

There are basically three operator interfaces during a simulation: there is the console terminal of the HP system, which serves as interface to the simulator operator. There is also the graphics display system to supply information about the status of the simulated network. In addition there is a special power station operator interface unit, which is described below.

All operations concerning changes in the simulated network are done using the HP console terminal. Basic data (like current network frequency, current load balance etc.) is supplied on the screen on a continuous basis. All interaction via this terminal is for the operator of the simulator only.

The operators of the actual power station use the special operator interface unit. This consist of a box that is placed on the control console of the power station and it performs the following functions:

1. Two analog panel instruments display the current simulated frequency and voltage (if voltage simulation is used).
2. An emergency switch allows the station operator to return the station to normal operation by deactivating all switchover relays instantaneously.
3. A separate switch serves as a safety latch; it must be set in order for a simulation to be allowed.
4. Two red large-size LEDs serve to help with phasing the simulator in and out. One LED starts flashing when the phase-in process is in progress. The other LED lights up when the changeover relay is actually activated.

Two other LEDs confirm that the interface unit is working correctly.

The operator interface unit is connected to the power station interface unit via a special cord.

9.2 Graphics display system and software

The simulator was fitted with a graphics display system in order to allow the operator to constantly monitor the status of the simulated network.

The graphics display system uses a separate PC. This PC is a high-speed computer with a 486 processor. The fast processor was chosen so that the PC can not only update all the graphics data on a continuous basis but also relieve the HP system of certain calculation duties; thereby allowing it to complete the computation intensive load-flow runs faster.

The system was designed so that the PC is dispensable; i.e. the simulator can still run even if this computer is not present. In such a case the calculations normally performed by it are taken over by the HP system (at the cost of longer times between load-flow updates) and there is of course no graphics display feature.

A setting in the simulator setup file on the HP informs the system of whether or not a graphics display PC is present.

The calculations that are taken over from the HP consists of calculating the power flows through the different lines and transformers and checking these against the settings of the protection systems; triggering protection cutout if called for.

The display system uses a 20" color VGA monitor and a SVGA graphics interface card with 1 MB of memory. It is however not possible to run the card in its high resolution mode, as Microsoft FORTRAN does at this point not support SVGA. It is believed that this will come with one of the next updates.

The software running on this PC is outlined in Figure 9.1.

The program gets the coordinates for the different nodes from a graphics data file on the HP system and it obtains voltages and phase angles for all nodes from another file on this system. It then calculates the power flows, checks the protections (with data from the protection data file) and then displays the voltages for all buses and the active and reactive power flows for all lines and transformers on the screen.

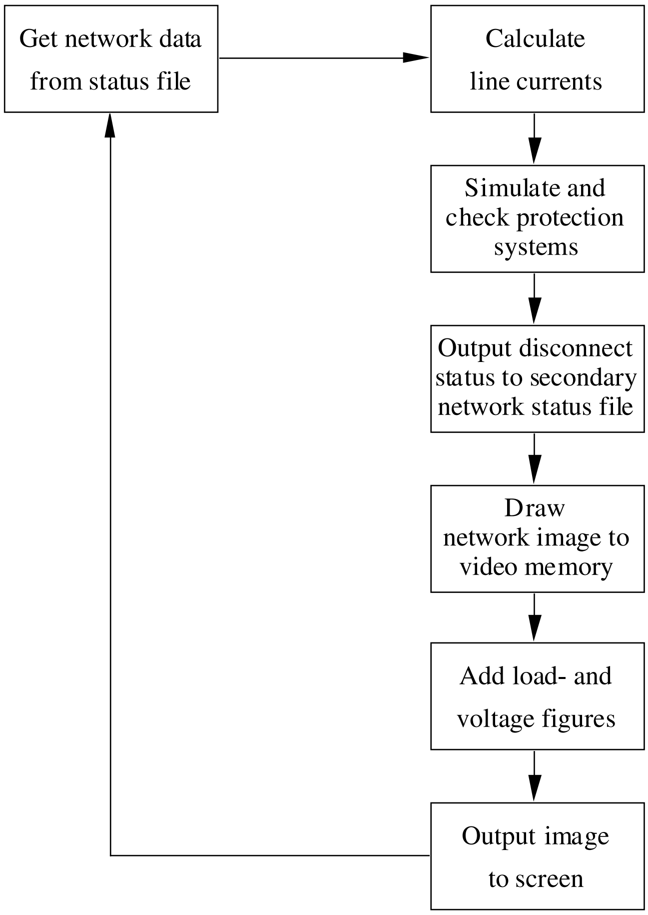

Figure 9.1 Graphics display program - block diagram.

Color is used to enhance the display in the following way:

white	elements in normal operation
yellow	elements loaded to near critical values or having voltages out of normal operating limits
red	overload conditions or unacceptable voltages
green	circuits disconnected / unenergized

Figures are shown in white for voltages, yellow for phase angles, red for active power and green for reactive power.

All communication between the display PC and the HP system is done over the Ethernet LAN using the PC-NFS system for file sharing.

There is no input to the PC keyboard except to start the program at start-up.

Chapter 10

Simulations

10.1 Simulations against the power station simulator

Quite many simulations were made against the power station simulator. During these, actual process parameters were measured and logged on file, just like it would be done in the case of simulations against the actual power station. Some parameters were however not available for measurement, as they were only presented on the video screens of the simulator and a proper interface to utilize this information has not yet been developed. However, they could be recorded by using the simulators video hard copy unit and then digitizing the curves, using a normal digitizer. This method was not very accurate but at least it gave a reasonable picture of how these parameters behaved. This method was primarily used for recording the temperatures of the superheaters.

It was attempted to get the information in question by direct information transfer from the simulator computer. This approach failed, as it slowed down the computer too much and it could no longer stay within real time processing.

The same A/D system in the power station interface that was used for recording process parameters in the power station was also used here, by connecting it to the output of the D/A-cards that drive the panel meters of the simulator.

This connection was first done using isolation amplifiers, but it turned out that all ground potentials were very closely matched and therefore direct connections were used instead. In this changeover process one calibration factor was unfortunately not replaced immediately; hence some of the simulations show an error in the output power level. It has been estimated to 3 to 4 % and should have no major impact on the results, but it will of course be corrected for future simulations.

For most simulations the following parameters were recorded:

1. turbine power
2. simulated network frequency
3. load shedding system activity
4. HP steam line temperature
5. MP steam line temperature
6. superheater 1 temperature (indirectly via video / digitizer)
7. superheater 2 temperature (indirectly via video / digitizer)
8. HP turbine steam flow (indirectly via video / digitizer)
9. feed water flow (indirectly via video /digitizer)
10. feed water tank level (indirectly via video / digitizer)
11. dome pressure
12. dome pressure controller setting
13. dome pressure deviation control signal
14. total fuel flow
15. main control valve position
16. control valve limiter position
17. intercept valve position
18. speed / power setting
19. speed / power control deviation signal
20. voltage setting
21. total combustion air flow
22. air fan control vane position
23. air fan regulator deviation control signal

These parameters were recorded into the log file for each simulation and could later on be plotted against time.

Most of the simulations were over a time period of approximately 3.5 minutes, but some were extended to 30 minutes. As so far the oscillations etc. are of such a size and nature that they cause immediate problems it was considered that the short term tests were the most valuable so far. However, since the steam pressure control and other similar parameters are slow-acting and temperature / strain concerns have to be taken, it will later on be necessary to study also more long term cases.

As a result of the relatively short duration of each simulation certain parameters, like e.g. the dome pressure, turned out to be of fairly little interest, as changes here are slow. In a longer time perspective these systems will of course also have to be verified for proper control function under these special operating conditions.

A simulator is of course always a simulator and it is important that the simulations can also be tested against the actual power station at a later time. It does however seem like the simulator, with the adjustments and changes that have been done to it in the course of this project, is a very valuable tool for testing the system behavior in numerous different situations. As opposed to with the real power station it is possible to run an almost unlimited number of tests and there is no problem in carrying these tests so far that we get to, or even beyond, the limits for what the power station can handle.

When it comes to tests regarding the behavior of protection systems and similar it is definitely the only way possible, as testing this in reality would be excessively costly.

Another advantage with the power station simulator is that it is relatively easy to make changes to the control systems or the protection systems. E.g. one can test with different control variables and one can also e.g. turn off certain protection systems and see what the outcome is. A typical example of the latter is the combustion - generation differential protection circuit, which has been disconnected for most of the cases simulated. With this one active we got a shutdown order almost immediately in most of the cases simulated.

The following pages, Figures 10.1 through 10.6 show a typical set of curves generated by a simulation.

Figure 10.1 Transition from 150 MW to 110 MW. Frequency, turbine power and load shedding values.

Figure 10.2   Transition from 150 MW to 110 MW. Airflow and fan control values.

Figure 10.3 Transition from 150 MW to 110 MW. Temperature and fuel flow values.

Figure 10.4 Transition from 150 MW to 110 MW. Dome pressure, setting and deviation values.

Figure 10.5 Transition from 150 MW to 110 MW. Control value, limiter and intercept valve position.

Figure 10.6 Transition from 150 MW to 110 MW. Speed/power setting and deviation signal.

10.2 Simulations against the actual power station

So far it has only been possible to test the simulator system against the actual power station at one time, using unit no. 4 at the Stenungsund power station, on Feb.15th 1993.

Unfortunately there have been no other occasions for actual tests, as the power situation in Sweden, has, due mainly to mild winters, been such there it has not been necessary to use the thermal power stations.

Two simulations were done at the Feb.15th test. One involved a frequency simulation and one involved a voltage simulation.

The test with a frequency simulation failed, in that the unit was shut down by its protection systems after only 30 s. of simulation.

The exact cause of the shutdown has not yet been established and further tests will have to be made, involving mainly tests on the control systems (with the turbine at standstill).

The actual shutdown indication the activation of an overheat protection system for the turbine system. This is activated if the pressure in the connection between the high- and medium pressure turbines stays above a certain set value for a period of time exceeding 15 s.

The actual recordings from the test show a decrease in generated power for a few seconds only. It is therefore a mystery as to how a shutdown could occur.

During the simulation the simulated frequency increased. Normally this should have led a reduction of the actual power output, demanded by the frequency control system. This did not happen. For some reason the controller did not react and the power stayed constant. A theory is that it could have been caused by improper settings of the controls; namely the speed/power control and the power limit setting. Tests with the simulator and testing the control system while at standstill must be done in order to check if this is a possible explanation.

When the unit did not respond correctly to the simulation, the simulation was terminated. A power reduction to about 65 % of the previous value and of short duration, approximately 3 s, followed. Either this was a result of a delayed response to the simulated frequency increase or it could have been caused by a transient when the changeover relay switched back to normal operation.

The increase in pressure in between the turbine stages indicates that the power reduction was the result of an intervention by the interceptor valves rather than by the normal controller. This is surprising and could be caused either because the simulated frequency had reached an exceptional value due to the no-response situation or as a result of a transient leading the system into believing that there was a rapid change of frequency (like a load-loss condition).

A very surprising fact is that the disconnection comes on the indication of excessive inter-turbine pressure and that this pressure can sustain for as long as 15 s., given the short duration of the power reduction. As soon as the excessive pressure signal comes this should automatically result in that the pressure relieve valve should open and discharge steam to the drain. According to the station operators at the time this valve was never activated. Further investigations must be done to determine why. A malfunction of either the valve or its control system seems likely.

Also the protection system itself will have to be checked for possible malfunctions. It can not be excluded that the disconnection could be the result of protection system failure; e.g. that the time delay did not come into effect or that the pressure-sensing transducer somehow gave incorrect information.

A diagram of the circuits involved in the overheat protection system is shown in Figure 10.7.

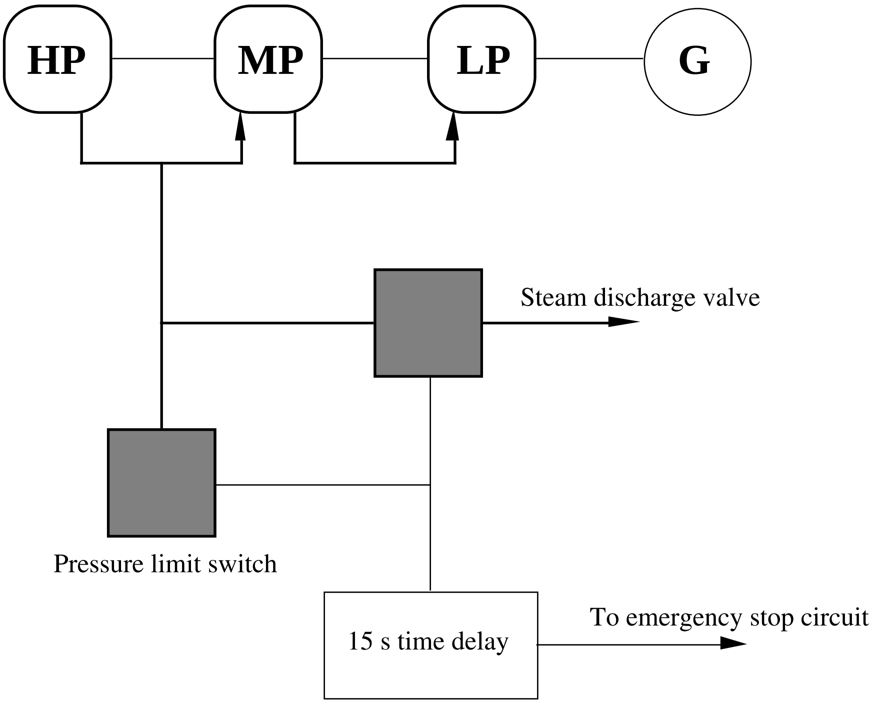

Figure 10.7 Turbine overheat protection system.

The voltage simulations were done in order to try to find out why the station was shut down by the protection system at the units previous run in December 1992. The system was then shut down on indication of excessive exciter current and generator overvoltage.

Following that shutdown the excitation and control systems were inspected but no fault could be found. Fortunately the bus voltage and active power at the time of shutdown were recorded by the measurement system of the simulator system. The voltage recording showed a sharp increase in voltage immediately prior to the shutdown. The voltage increase was about six percent in 18 seconds. In order to increase the voltage that much while phased in on the network the unit must have been outputting 250 Mvar or more. Figure 10.8 shows the recording made at the time of the incident.

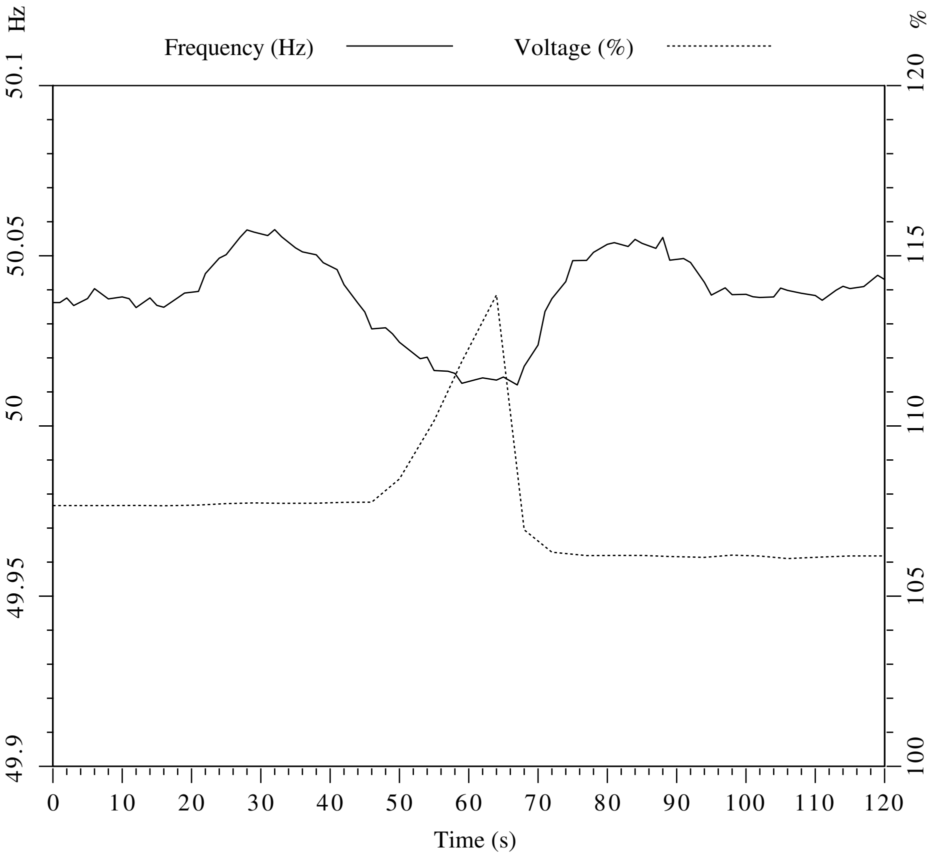

Figure 10.8 Voltage and frequency recording at station shutdown in December 1992.

A block diagram of the excitation and voltage control system is shown in Figure 8.5.

An analysis of the voltage control circuits of the unit came up with the following causes as the most probable ones:

1. Malfunction of the electronic control circuits.

2. Thyristor commutation failure in the controlled rectifier, leading to excessive excitation.

3. The motor potentiometer kept on moving due to a stuck control button.

4. Operator error; i.e. someone held the button down accidentally for too long; possibly while observing the wrong instrument.

As these different causes were likely to give different time constants regarding the increase in voltage tests were done to see how the circuits responded to different simulated increases in voltage.

In order to record all values of all relevant voltages and powers two measurement systems were used. One was the measurement system of the simulator, the other was a high-speed data acquisition system, built with Hewlett-Packard equipment and developed at our department.

The first two tests were manual ones. The measurement systems were left running and the motor potentiometer was then run up and down twice, using the control buttons.

The three following tests were done using the simulators voltage simulation capacity. A step change was applied to the voltage setting signal, each time for a period of 3 s. The size of the step was gradually increased.

Comparisons of the recorded values and the recordings made in December showed clearly that of the above mentioned causes only number 3 or number 4 were possible. These included the motor potentiometer and gave time constants similar to the manual runs. The step-wise changes gave considerably shorter time constants. See Figures 10.9, 10.10, 10.11 and 10.12.

It was therefore concluded that either no. 3 or number 4 must have been the relevant cause and as testing of the buttons showed no sign of them wanting to stick the most likely cause was no 4, operator error.

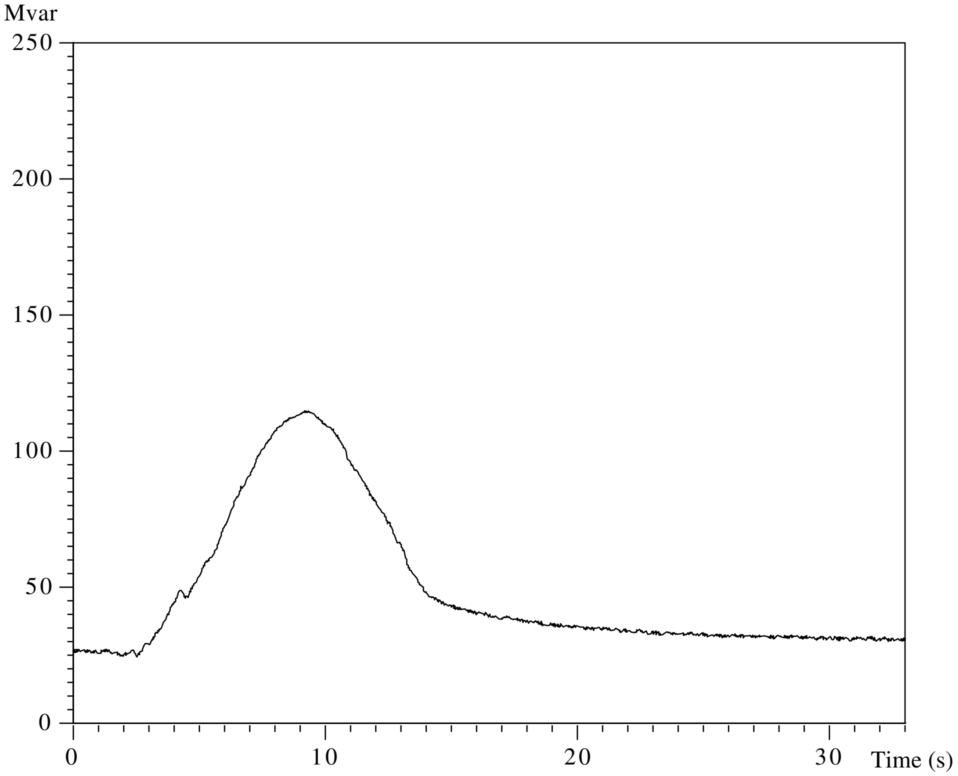

Figure 10.9 Reactive power when activating the motor potentiometer.

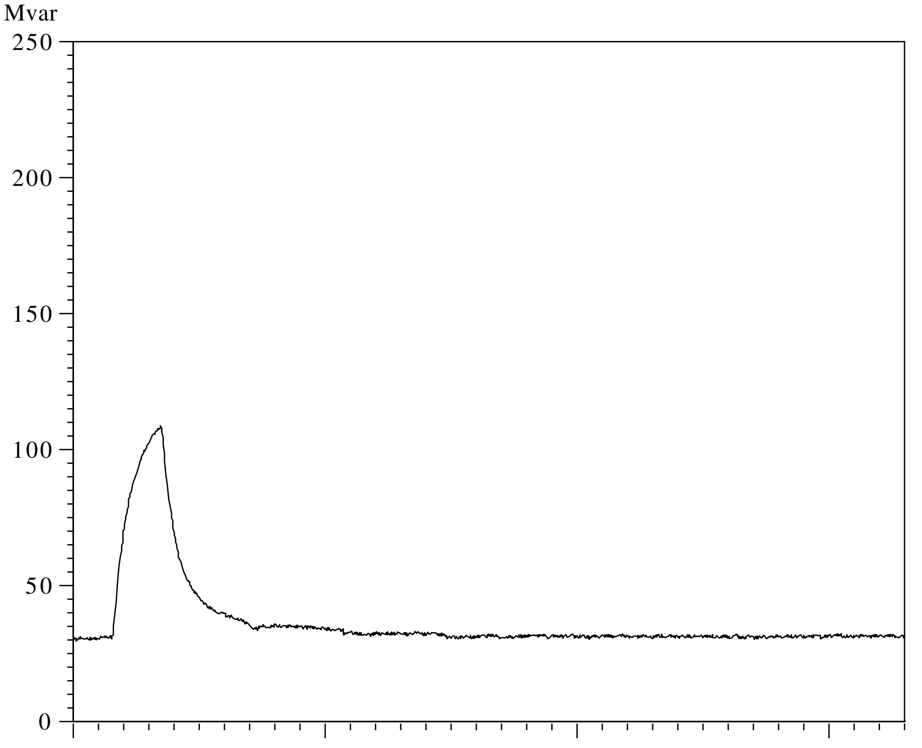

Figure 10.10 Reactive power when a step is applied to the control system.

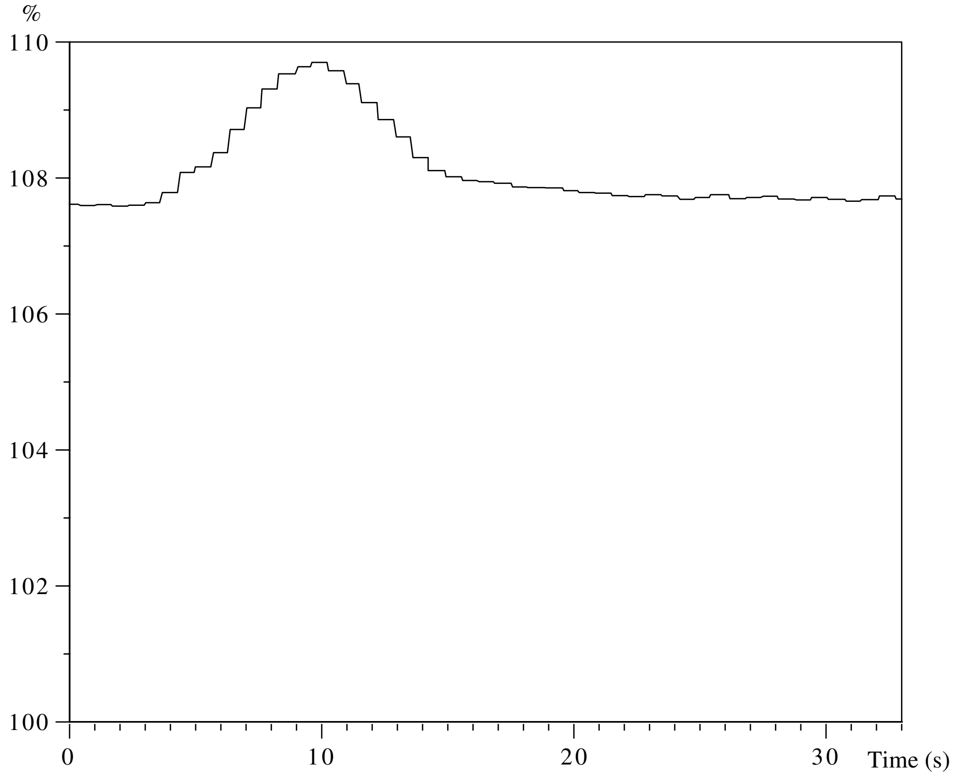

Figure 10.11 Voltage response when activating the motor potentiometer.

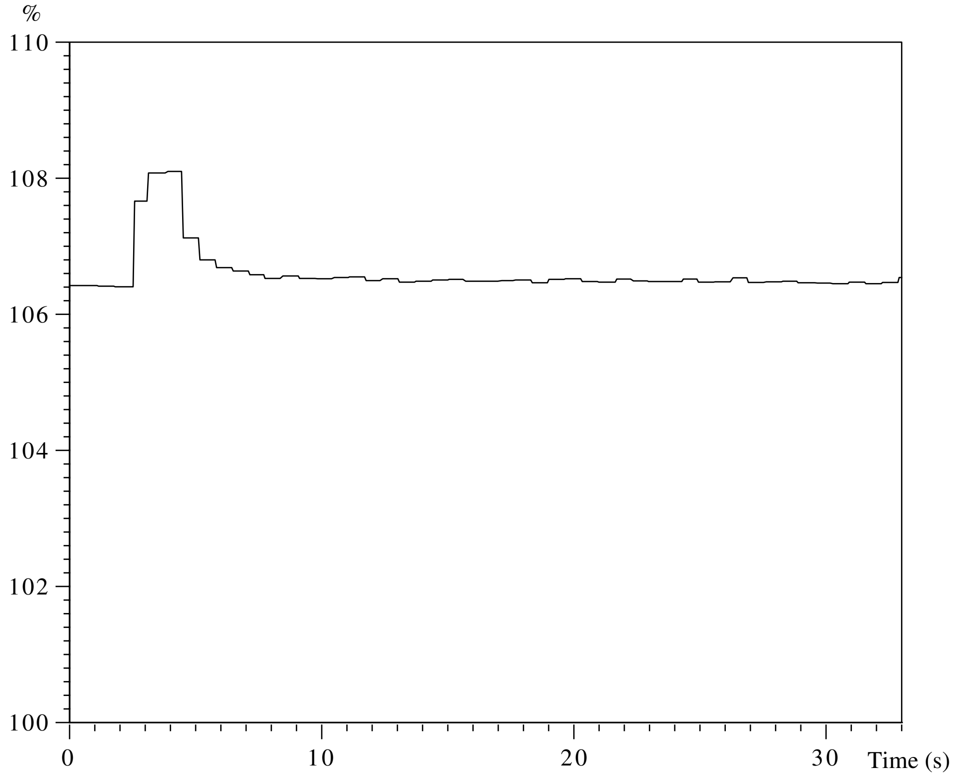

Figure 10.12 Voltage response when a step is applied to the control system.

10.3 Security considerations and improvements

Several safety functions were built into the system from the start. Nevertheless there arose a situation during a test at the Stenungsund number 4 unit when the unit was disconnected by its protection systems during a simulation. As a result of this considerable work had to be put into making the simulator system as safe as at all possible with regard to unwanted disconnections and several security functions were added to the system.

One such measure was to reprogram part of the software running on the power station interface PC, so that it would default to a normal operation in case of any unexpected events. Routines were added that will halt the simulation process if any of the following conditions occur:

1. The active power measurement value is not within a prescribed reasonable range.
2. The communication on the parallel interface breaks down.
3. The input file from the HP becomes static for a period of time longer than the maximum time between updates, indicating that the HP system is stuck or out of order.
4. The turbine supervision system is activated (see below).
5. The frequency falls outside set limits.
6. The generated power falls outside of set limits.
7. The rate of change of the power output for a period of 5 s or more is such that there is a risk of activating the units protection systems.
8. The voltage of the generator falls outside of set limits.
9. Reverse active power is indicated.

A special security card was also added to the system. This one was described in Chapter 8. It adds extra checking directly in hardware and will thus safeguard also against computer failure and similar. This means a very considerable safety improvement.

In addition, circuits, equipment and programs were developed, as was described in previous chapters, so that the entire frequency control system of the power station unit can be tested against the simulator without the need for the turbine to be running.

The unit disconnection during the test was a result of that a turbine overheat protection circuit had been activated. As mententioned in Section 10.2 this may have partially due to an error in the unit itself, but special measures have in any case been taken to prevent this from possibly happening again.

The protection system in question consists of a signal for excessive pressure in between the high and the medium pressure stages. When this pressure has stayed above the set limit for 15 s the unit is disconnected. In order to avoid this from happening the same control signal is fed to a special turbine supervision card in the station interface unit. If the signal in question comes on it alerts the operator immediately and if the signal does not disappear within 5 s it terminates the simulation.

Another problem that was observed during the testing was that there were points of measurement where the values were completely in error, usually just for one single point. This is believed to be due to electrical interference from other circuits in the power station. As mentioned earlier there were certain steps taken in the hardware design of the measurement circuits. In addition the software was updated so that it always checks a measurement against the previous ones and if the difference is unreasonable it uses a calculated value based on the previous measurements until a correctly measured value is again available. This process is only used for measured quantities that are critical for the simulation process, i.e. power output and in the case of a voltage simulation reactive power output and current output voltage.

With all these safeguards taken the risk of possibly causing a unit disconnection should be reduced to a minimum. Nevertheless the next few tests of the simulator should preferably be done when the unit is about to be shut down anyhow, so that it is not critical if a premature shutdown occurs.

When additional work has been done on improving these safety features and adjusting them properly it should be fully possible to arrive at such a level of safety that simulations can be tested also in normal operation without any fear of unwanted disconnections or similar.

The discussions above all concern safety with regard to unwanted disconnections or similar strange behavior of the unit under simulation. There is of course another safety aspect as well and this concerns risk of unwanted effects on the power network.

When it comes to frequency simulation these effects are negligible in the case of the Stenungsund power station. The national network of Sweden is connected to the Norwegian and the Finnish networks and also to parts of the Danish system. The combined total power and total regulating capacity of these systems is such that there is no way that any changes in input power from the Stenungsund units, each with a maximum capacity of 304 MW, can cause network frequency control problems or network stability problems.

In cases where the simulator would be used on a power station connected to a smaller and/or weaker network the possible effects thereof will of course have to be examined prior to a simulation.

In the case of a simulation involving voltage, i.e. when also the reactive power output of the generating unit is controlled by the simulator, then the risks of unwanted network effects are much greater, as the power station clearly has the capacity to drive the local bus voltage out of bounds, thus creating problems for power consumers in the area.

In the case of the Stenungsund power station this is, as was earlier mentioned, very sensitive, as the industries in the area are sensitive to voltage variations and can suffer considerable costs in case of a malfunction.

So far no tests involving voltage simulation as such have therefore been made at Stenungsund, other then those that were made in order to troubleshoot the voltage control system of unit 4.The voltage simulation system is later to be tested against a laboratory setup in a safe environment. If such tests show that the units are found to operate with full reliability then actual tests at the power station could possibly be done if the voltage limits are set quite tightly, so that the simulation is halted before the voltage reaches any level that could possibly cause problems for the consumers.

Chapter 11

Typical Uses of the Simulator

The simulator system can be used to simulate the behavior of the power station and its control systems under a nunber of different operating conditions. Some suitable applications can be:

1. Testing of islanding operation, i.e. where the power station, alone or with the help of other generating units in the area, are responsible for supplying power to a local or regional network and where there is no connection to the national network. Such islands can vary in size and configuration, as can the composition of the loads etc.

2. Testing in-house operation, i.e. when the station is disconnected from any surrounding networks and is just producing the power needed for its own use.

3. Testing sudden transition from normal operation to in-house operation; i.e. when the station is suddenly without previous warning disconnected from the network.

4. Testing the behavior of the frequency control systems under certain, set and controllable conditions. This can be useful both for improving settings etc. and for troubleshooting the systems.

5. Testing the voltage control systems in a similar fashion. As mentioned earlier the system has already been successfully used in this capacity at the Stenungsund power station.

6. If part of the system was available in duplicate; namely the station interface PC and the station interface unit, then parallell operation between two units in the same power station could be tested and it could be verified that their control systems interact correctly under prescribed operating conditions.

7. Testing different control system settings to obtain suitable values for special types of operation.
8. Training power station operators to handle special operations in proper ways.
9. Testing different ways of running a network in islanding operation in order to train operators and to develop suitable operating instructions for such operations.

When fully developed the simulator can thus be a useful tool both in adjusting and testing the power station and in allowing for testing special operating conditions so that the behavior of the units is known; which can be of great importance in the making up of emergency operation plans, plans for supplying the network in case of war or major disasters etc.

Chapter 12

Further Developments and Improvements

There is still more work to be done before the simulator is a tool ready for practical use.

As mentioned earlier the simulator has to be tested and improved so that the risk of unwanted disconnections is to be considered negligible.

This is not to say that the simulator can never cause a unit to be disconnected.If the result of the test is such that the unit *would* in fact be disconnected if this was real operation under the circumstances given then it is no error if a disconnection occurs during the test. However, because of practical and economic considerations it should be possible to set the simulator in such a mode that it will then just inform the operator that in reality the unit would have been disconnected but now it was just the simulation that was terminated. Systems to give the operator this choice should be developed.

It is important that a reasonable number of tests can be run both against the simulator and against actual power stations.Unfortunately this has so far not been possible because of the low frequency of operation of the Stenungsund power plant at the moment.

Another area of future improvements concerns the models used for other regulating stations on the network. At the present these routines are quite primitive and can hardly be said to be a true and accurate representation of the actual systems.

The load models can also be developed further. At the moment the loads are only divided into four parts as described earlier and the possible dynamic effects of the loads have been neglected. It should be possible to improve this, maybe using some of the results from the load modelling projects that have been carried out at the Department of Electrical Power Systems.

Another aspect that needs further studies concerns the influence of the damping windings of the generator. This was originally not considered to be of any importance, as these are important only when there are sudden changes in frequency, but as the work so far has shown that unstable operation with rapid frequency changes that are very poorly damped or even undamped can occur under many conditions that are considered to be quite realistic, then it is necessary to take these windings into account. These effects can not be tested unless a true islanding situation can be created, but it may be possible to develop routines that simulate this and then compensates for them.

Another aspect of development concerns the very physical hardware setup used. If the simulator system is to become a commonly used tool that can be connected to different power stations then it should be developed in such a way as to become as physically small and portable as possible. A special approach to this is mentioned below, but there may also be solutions in between that one and the present configuration.

12.1 The mini simulator

The present simulator uses three computer systems plus a large-size station interface unit. For many tests a much smaller setup could most likely be used.

For such a setup the network representation in the form of the load-flow process would be eliminated and the network lumped together into one bus, namely the one that is connected to the power system. For tests where only the actual behavior of the power station itself is of concern this would most likely be sufficient.

As mentioned earlier the special graphics display PC can easily be dispensed with and in the case of a one bus network it would hardly serve any purpose.

If the output curve of the discriminator circuit, or its equivalent in other types of control circuits, is already known, either because an identical discriminator has already been tested or because the information is available from the manufacturer, then the power signal generator can also be dispensed with. As for physical interfaces to the power station all that is needed is the D/A output part and the A/D section for the measurement system, plus the changeover relays and their associated control circuits. None of these parts involve any high power circuits.

With the above in mind it would be possible to build a portable "mini simulator" based on one single computer, preferably then a lap-top version. As the only computer system that would be used would be that for the station interface, with its associated software (swing equation, load shedding etc.), and as this one is an ordinary 386 (40 MHz) system, it could easily be replaced by a lap-top version.

A physical interface unit, containing a PC-30 card or its equivalent plus the isolation amplifiers and the relays could then easily be built. Such a unit would most likely be possible to build approximately to the same physical size as the lap-top computer and a very compact and portable system consisting of two briefcase size units would be the result.

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Additional material that has been used as references consists of various internal reports and similar.