Real Time Generation Station Simulator

by

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(ABSTRACT)

A real time generation station simulator which is to be used as an operator trainer is developed. The software developed simulates a Y-wound generator connected to an infinite bus through a Δ/Y step up transformer and two parallel lines. The operation of the generator is simulated under normal or abnormal conditions of the power system or the generator itself. The system is simulated in two micro-computers and interaction between the simulator and the operator is provided through the computer's screen and keyboard. Different screen representations show the behavior of the generator at any moment and based on these the operator can take any action through the generator controls provided in his keyboard.

Acknowledgements

I would like to express my deep gratitude to Dr. J. De La Ree for his constant encouragement and assistance over the course of this project. I wish to thank Dr. A.G. Phadke for all the help he also gave me and Dr. S.Rahman for serving on my advisory committee.

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NOMENCLATURE

B Mechanical losses coefficient.

δ Generator load angle

D Damping coefficient.

E_b Exciter feedback voltage.

E_{fd} Generator field voltage.

$E_{fd\,\max}$ Exciter output voltage top ceiling.

$E_{fd\,\min}$ Exciter output voltage lower ceiling.

E_g Excitation voltage or voltage behind generator impedance.

I_f Contribution to the fault from the infinite bus.

I_g Current contribution to the fault from the generator.

H Inertia constant.

K_a Regulator gain.

K_e Exciter constant related to self excited field.

K_f Regulator stabilizing circuit gain.

K_g Governor gain $= \dfrac{100}{\text{(Percent of steady state regulation)}}\,\omega_0$

P_e Electrical output power from the generator.

P_{gv} Input power to the turbine.

P_m Mechanical input power to the generator shaft in p.u.

P_{ref} Power set-point.

S_e Saturation function.

T_a Regulator amplifier time constant.

T_c Governor time constant.

T_d Open circuit field transient time constant.

T_e Exciter time constant.

T_f Regulator stabilizing circuit time constant.

V_r Regulator output voltage.

V_{ref} Regulator reference voltage setting.

$V_{r\max}$ Regulator output voltage top ceiling.

$V_{r\min}$ Regulator output voltage lower limit.

V_t Generator terminal voltage.

ω Generator speed in $\frac{Rad.}{Sec.}$

ω_s System frequency in $\frac{Rad.}{Sec.}$

X_{a1} ,X_{a2}, X_{a0} Sequence reactances for transmission line 1.

X_{b1} ,X_{b2}, X_{b0} Sequence reactances for transmission line 2.

X_d Direct axis transient reactance.

X_{d2} , X_{d0} Negative and zero sequence reactances of the generator.

X_{f1} ,X_{f2}, X_{f0} Infinite bus equivalent sequence reactances.

X_{gn} Generator ground impedance.

X_{l1} ,X_{l2}, X_{l0} Equivalent sequence reactances for both transmission lines.

X_r Series fault impedance created by arc when a phase opens.

X_{t1} ,X_{t2}, X_{t0} Sequence leakage transformer reactances.

X_{tn} Transformer ground impedance.

1.0 INTRODUCTION

A real time simulation of a generation station can be used to predict the behavior of a generator under fault conditions as well as for operator trainee to react on time and with the appropriate decision to any system condition.

1.1 REAL-TIME SIMULATION

A generator connected to an infinite bus as shown in Figure 1 serves for the purposes of simulation of the dynamic behavior of a remote generator. The voltage at the infinite bus is greatly influenced by large nearby generators in such a way that it is independent of events at the remote generator and thus different fault conditions happening at the generator itself or between the generator and the infinite bus, which affect the synchronous machine stability can be analyzed.

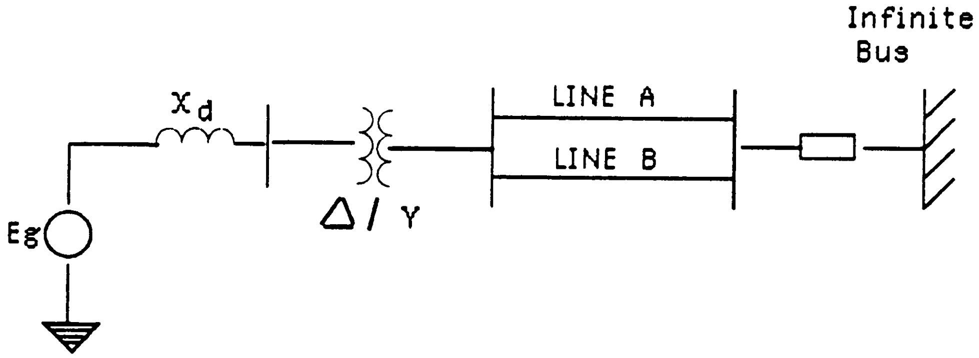


Figure 1. One-line Diagram

Individually each generator connected to a power system responds to transient events on the system with variations on the speed-governing systems, tending to keep each machine at synchronous speed, and with variations on the automatic voltage regulator trying to maintain a constant voltage at the terminals of the generator.

In the approach taken the dynamic model of the generator included the classical transient stability model for the representation of the synchronous machine [1]. The excitation system included the representation of saturation of the generator. Type I from reference [2] which represents the majority of the excitation systems now in use, was chosen. The prime mover considered in the simulation was a non-reheat steam turbine as presented in reference [3]. The automatic voltage regulator representation is part of the type I excitation system previously mentioned.

It is the interest of this work to show the behavior of the generator under any kind of abnormal conditions on the power system and on the generator itself which will provide a good understanding of the dynamics of the generator and will help the generator's operator to take the right decisions when these circumstances occur.

A diverse kind of abnormal conditions can be simulated at any location of the power system. An example of these are:

1. Three phase faults.

2. Phase to phase faults.

3. Double phase to ground faults.

4. Single phase to ground faults.

5. One, two or three open phases at the high voltage side of transformer

6. Change of load

The system was implemented in two computers, one representing the instructor's console and the othe the operator's console. The instructor from his console can simulate any of the given conditions. The behavior of the generator is shown on the operator's console and a decision based on the readings of the meters can be made in order to adjust the generator to the new system conditions. A training session is started by the instructor and is ended at any time by the operator or the instructor; at the end of the session a summary of activities is created on the operator's computer. The instructor inputs all the fault and abnormal conditions and the operator takes the appropriate action from his own console to change the operating conditions of the generator in the same way as he would do it in a control room. The control's room meters are simulated on his screen and he can access the generator controls through his own keyboard.

The final objective of this work was to develop a model capable of simulating the real time behavior of the generator under steady state as well as transient circumstances, provoked by any of the abnormal power system conditions listed above or by the generator itself as would be the case of generator start-up and synchronization to the system. For these situations simple models of the system elements including the generator were sufficient for the desired purposes.

1.2 THESIS LAYOUT

Chapter 2 describes the theoretical basis for the simulation. The set of equations describing the generator dynamics are presented together with the description and sequence representation of the system used. A sequence representation of the system is needed to represent the system unbalanced conditions. Two examples of unbalanced conditions are developed also in this chapter.

Chapter 3 describes how the real-time simulation was implemented to use as an operator trainer and it presents a detailed manual of the trainer usage and capabilities. A manual synchronization procedure is presented as an example of one of the trainer's capabilities to reinforce the understanding of the trainer's functioning.

Chapter 4 presents a sequence of simulated events which include unbalanced faults, in-phase and out of phase synchronization and loss of field. The simulation results are shown on plots of different generator parameters, showing the pre-fault, fault and post-fault situations. A list of the parameters shown on the results are:

- Voltage at the terminals of the generator.
- Line current.
- Load angle.
- Frequency.
- Active power out of the generator.
- Reactive power out of the generator.

Finally the conclusions are drawn and summarized.

2.0 SYSTEM SIMULATION

In the approach taken to obtain a real time simulation of the generator dynamics to be used as an operator trainer, the most emphasis was put into the representation of the exciter model, which controls the terminal voltage of the generator. The synchronous machine representation was chosen with the criterion of providing a good accuracy during the first swing of the machine (which determines the stability of the machine) and also the fact that the simulation had to be realized in real time was considered as factor on determining the complexity of the synchronous machine representation. The governor and turbine systems chosen provide an approximate representation for fossil-fired plants.

2.1 SYNCHRONOUS MACHINE MODEL

A simple model of a voltage behind a reactance was chosen. This model although not the most accurate provided the sufficient accuracy for the desired simulation purposes and also the execution time of the simulation was kept down as it was desired for the real time application. Model 1 as is referred in [4] is the simplest machine model and for some applications can be a good approximation. From Figure 1 the transferred power can be written as:

$$P_e = \frac{E_g V_t \sin \delta}{X_d} \tag{2.1}$$

The electromechanical equations of the synchronous machine are given by:

$$\frac{d\omega}{dt} = \frac{(P_m - P_e - D(\omega - \omega_s) - B\omega)\omega_s}{2H} \tag{2.2}$$

$$\frac{d\delta}{dt} = \omega - \omega_s \tag{2.3}$$

In these equations the factor D is included to represent the damping bars of the generator which try to keep the generator running at a constant synchronous speed. The factor B provides the generator mechanical and electrical losses at synchronous speed. Both factors must be obtained from the generator data.

2.2 EXCITATION SYSTEM

The excitation system used is shown in Figure 2 which corresponds to type I excitation system [2] with the regulator input filter time constant neglected since is usually very small compared to the other time constants. The saturation function, which represents a multiplier for E_{fd} to increase excitation when saturation is reached, is computed from the given excitation values at $E_{fd\,\max}$ and $0.75E_{fd\,\max}$ as it is recommended by IEEE in [2].

The set of differential equations which represent the excitation system is:

$$\frac{dE_g}{dt} = \frac{E_{fd} - E_g}{T_d} \tag{2.4}$$

$$\frac{dE_{fd}}{dt} = \frac{V_r - E_{fd}(S_e + K_e)}{T_e} \tag{2.5}$$

$$\frac{dE_b}{dt} = \frac{\frac{dE_{fd}}{dt} K_f - E_b}{T_f} \tag{2.6}$$

$$\frac{dV_r}{dt} = \frac{K_a(V_{ref} - V_t - E_b) - V_t}{T_a} \tag{2.7}$$

Along with these equations the regulator and field voltage ceilings have to be satisfied :

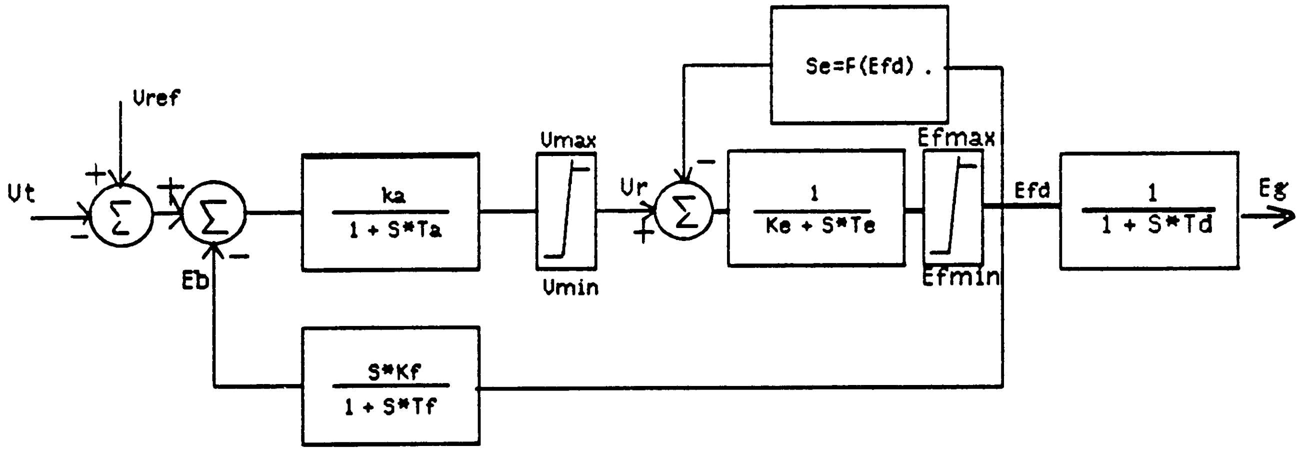


Figure 2. Excitation System

$$E_{fd\,\min} \le E_{fd} \le E_{fd\,\max} \tag{2.8}$$

$$V_{r\,\min} \le V_r \le V_{r\,\max} \tag{2.9}$$

The upper limit on E_{fd} is set to prevent overheating on the field winding due to the high field currents. The lower limit on the field voltage is set to prevent overheating on the rotor poles due to the flux concentration on one end of the pole when the machine is underexcited. $V_{r\max}$ and $E_{fd\max}$ need not always to be specified simultaneously.

The output of the regulator is clamped between the minimum and maximum limits, in order to keep the regulator response within practical limits.

The following expression must be satisfied in steady state condition :

$$V_r - (K_e + S_e)E_{fd} = 0 \tag{2.10}$$

which is also true for maximum values :

$$V_{r\,\max} - (K_e + S_{e1})E_{fd\,\max} = 0 \tag{2.11}$$

Where S_{e1} is the exciter saturation function defined at $E_{fd\max}$.

The exciter saturation function is assumed to have an exponential form given by:

$$S_e = K_1 e^{K_2 E_{fd}} \tag{2.12}$$

Where the K_1 and K_2 coefficients which determine the exciter saturation curve are obtained from the two points at which the saturation function is specified. Generally these two points are given for $E_{fd\,\max}$ and $0.75E_{fd\,\max}$. From Figure 3 the saturation function is defined as follows:

$$S_e = \frac{x - y}{y} \tag{2.13}$$

Where x and y are points given at the same field voltage and located on the constant resistance load saturation and air gap line curves respectively.

In the same way as S_{e1}, S_{e2} represents the saturation function at $0.75E_{fd\,\max}$ and they are defined as follows:

$$S_{e1} = \frac{A - B}{B} \tag{2.14}$$

$$S_{e2} = \frac{C - D}{D} \tag{2.15}$$

Since the exciter saturation function is assumed to have an exponential form the following equations must be satisfied:

$$S_{e1} = K_1 e^{K_2 E_{fd\,\max}} \tag{2.16}$$

$$S_{e2} = K_1 e^{K_2 0.75 E_{fd\,\max}} \tag{2.17}$$

Solving these equations together with equation (2.11) for K_1 and K_2 the following expressions are obtained:

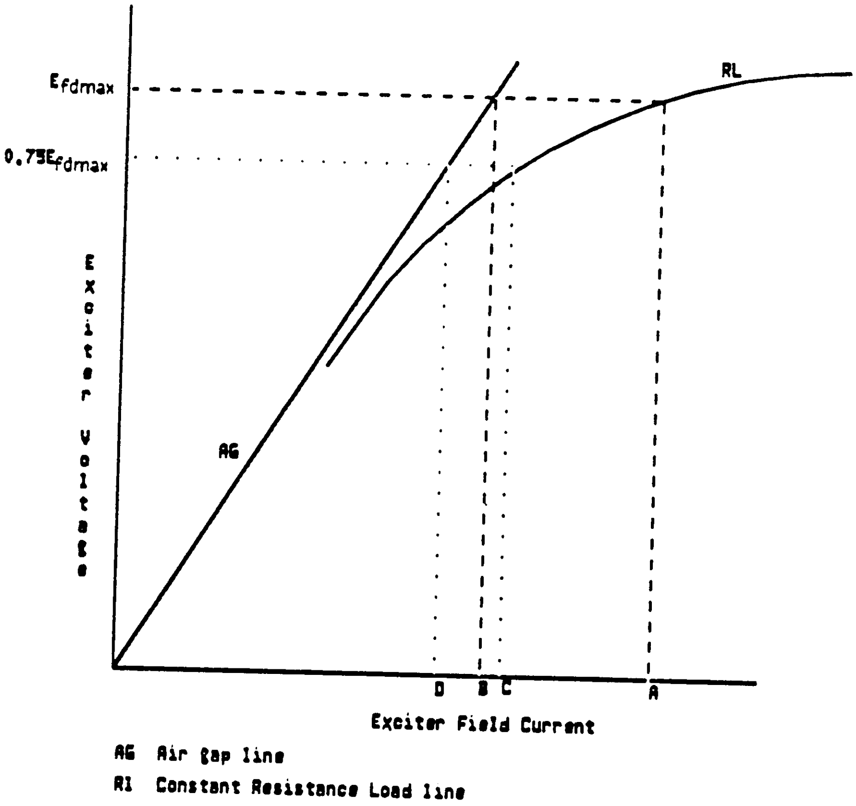


Figure 3. Exciter Saturation function

$$K_1 = \frac{S_{e2}^4}{S_{e1}^3} \tag{2.18}$$

$$K_2 = \frac{4(K_e + S_{e1})}{V_{r\max}} \ln\left(\frac{S_{e1}}{S_{e2}}\right) \tag{2.19}$$

2.3 GOVERNOR AND TURBINE SYSTEMS

The speed governing system together with the turbine are simply modeled to represent the delays introduced when any action is to take place through them. A block diagram of this system is shown in Figure 4 from where the dynamic equations can be written as :

$$\frac{dP_{gv}}{dt} = \frac{P_{ref} - K_g(\omega - \omega_s) - P_{gv}}{T_c} \tag{2.20}$$

$$\frac{dP_m}{dt} = \frac{P_{gv} - P_m}{T_t} \tag{2.21}$$

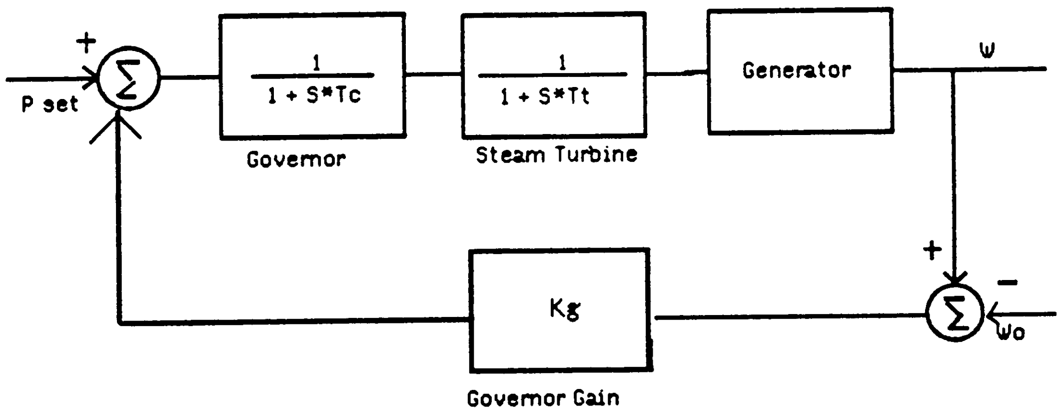


Figure 4. Governor and Turbine Systems

2.4 POWER SYSTEM REPRESENTATION

The generator is connected to an infinite bus, which represents a large (stiff) power system, through a Δ/Y step up transformer and two parallel lines, as shown in Figure 1. The representation neglects the magnetizing reactance of the transformer and the shunt susceptances of the power lines.

Since any kind of balanced or unbalanced faults are simulated, each element is represented using its adequate sequence model. A generalized system representation using sequence networks is shown in Figure 5. In this representation is assumed that the Y side of the transformer as well as the generator are connected to ground through impedances X_{tn} and X_{gn} respectively. When these impedances are zero the generator and transformer are solidly ground connected; on the other hand if these impedances are infinite the generator and transformer will not be ground connected.

Impedances X_{f1}, X_{f2}, and X_{f0} are equivalent large system impedances and will determine the system stiffness. Looking from the generator side X_t , X_a and X_b impedances also account for system stiffness; large values of these impedances will weaken the system contribution to events happening between the generator and the infinite bus. These element parameters could be varied to test the generator behavior under different tie conditions. A large impedance on the line will

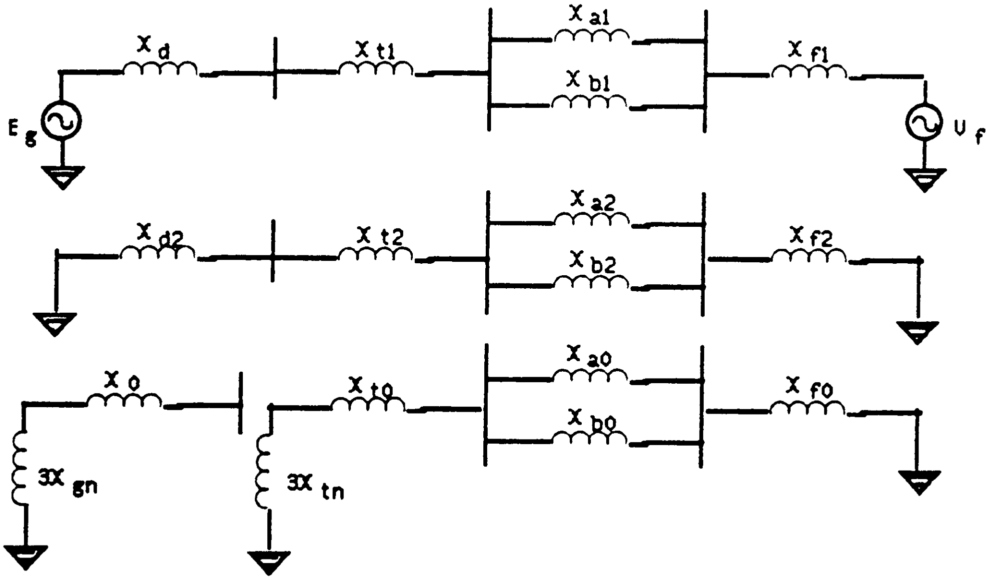


Figure 5. Sequence Network

permit the simulation of a remote generator or a small impedance will allow the simulation of a close generator.

Three phase faults, phase to phase faults, double phase to ground faults, single line to ground faults, opening of one, two or three lines at the high voltage side of the transformer and removal of a transmission line are the events simulated and for this events in different locations of the power system the generator real time response is calculated. The contribution of the generator to the system at any moment for all those situations is to be calculated. As an illustration the generator contribution to two particular situations is shown.

2.4.1 ONE OPEN PHASE AT THE HIGH VOLTAGE SIDE OF THE TRANSFORMER

The one open phase situation can be simulated considering that a very high impedance appear between the terminals of the broken conductor with no corresponding impedance on the unbroken phases [7]. Considering an impedance X_r appears between the broken phase terminals with X_a, X_b and X_c the impedance of each of the lines from the generator to the fault location as is shown in Figure 6 the following loop equations can be written:

$$V_{aA} = X_r I_{aA} \tag{2.22}$$

$$V_{bB} = 0 \tag{2.23}$$

$$V_{cC} = 0 \tag{2.24}$$

Which can be further written using symmetrical components as:

$$V_{aA} = V_{aA1} + V_{aA2} + V_{aA0} = X_r(I_{aA1} + I_{aA2} + I_{aA0}) \tag{2.25}$$

$$V_{bB} = a^2 V_{bB1} + a V_{bB2} + V_{bB0} = 0 \tag{2.26}$$

$$V_{cC} = a V_{cC1} + a^2 V_{cC2} + V_{cC0} = 0 \tag{2.27}$$

Where the subindices 1, 2 and 0 represent the positive, negative and zero sequence voltages and currents and a represent the complex operator 1120°

Subtracting equation (2.27) from equation (2.26) the following relationship is found:

$$V_{aA1} = V_{aA2} = V_{aA0} \tag{2.28}$$

And substituting back into equation (2.25) :

$$V_{aA1} = \frac{X_r}{3} (I_{aA1} + I_{aA2} + I_{aA0}) \tag{2.29}$$

Which can be represented as shown in Figure 7.

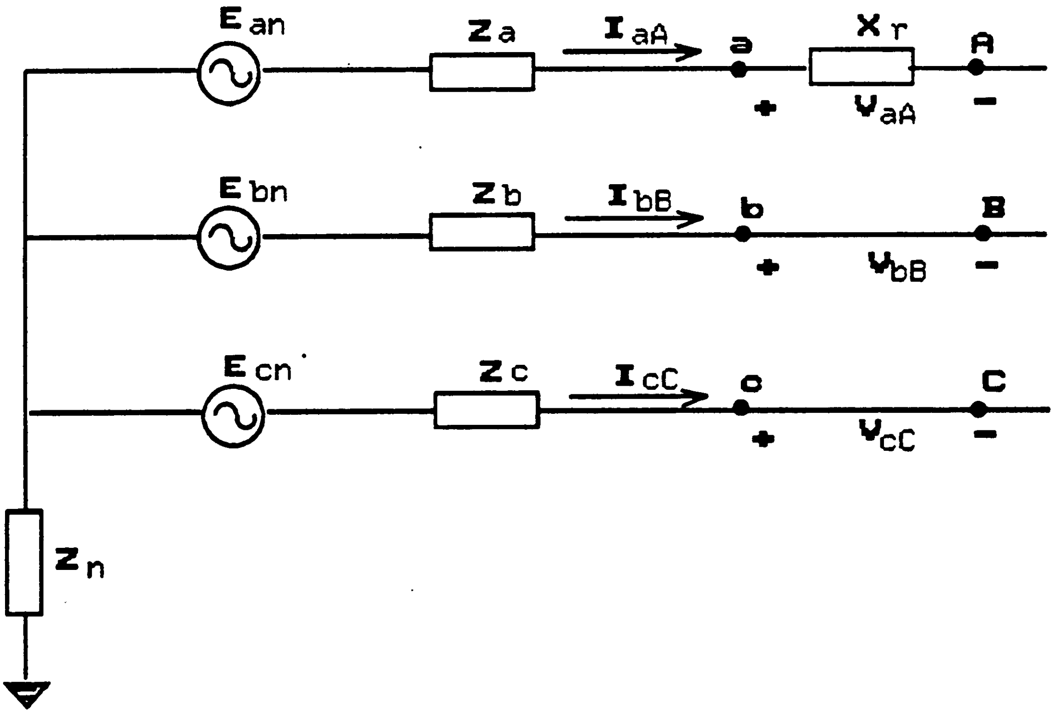


Figure 6. One Open-Phase Situation

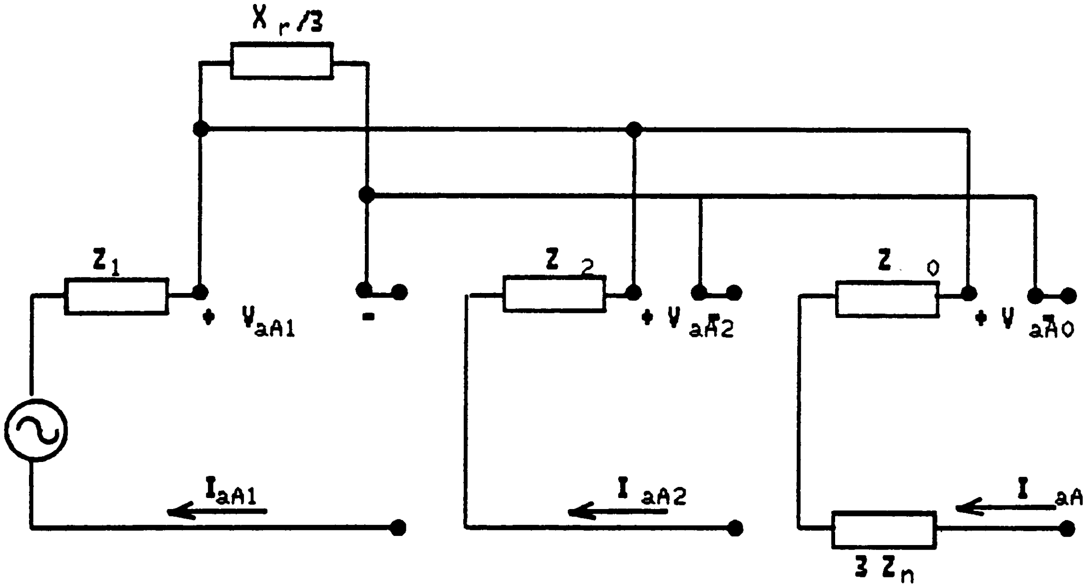


Figure 7. General One Open Phase Sequence Representation

For the case considered, open phase at the high voltage side of the transformer, a complete sequence representation is presented in Figure 8. From the circuit representation obtained it can be said that there is not any zero sequence coming from the generator, which is true since the Δ/Y transformer is isolating the zero sequence current from the generator. The system can be further solved for I_{g1} and I_{g2}, the positive and negative sequence currents coming out from the generator. Finally it has to be considered that the fault occurred at the high voltage side of the transformer which is a Δ/Y and if the American Standard for designating terminals H_1 and X_1 on Y/Δ transformers, which requires that the positive sequence voltage drop from H_1 to neutral lead the positive sequence voltage drop from X_1 to neutral by 30° regardless of whether the Y or the Δ winding is on the high tension side, a 90° phase shift when passing positive sequence values from the high voltage side to the low voltage side and $-90°$ when doing the same with negative sequence values has to be considered [8]. Taking this into consideration the final sequence voltages and currents at the generator terminals are:

$$I_{g1} = JI_1 \tag{2.30}$$

$$I_{g2} = -JI_2 \tag{2.31}$$

$$I_{g0} = 0 \tag{2.32}$$

$$V_{t1} = J(E_g - X_{d1}I_1) \tag{2.33}$$

$$V_{t2} = -J(X_{d2}I_2) \tag{2.34}$$

$$V_{t0} = 0 \tag{2.35}$$

2.4.2 SINGLE LINE TO GROUND FAULT AT INFINITE BUS

It has been demonstrated that for a single line to ground fault at phase a the positive, negative and zero sequence networks must be connected in series [8] to satisfy the following fault properties:

$$I_{a1} = I_{a2} = I_{a0} = \frac{I_a}{3} \tag{2.36}$$

$$\frac{I_a}{3} = \frac{E_{an}}{Z_1 + Z_2 + Z_0 + 3Z_n + 3Z_f} \tag{2.37}$$

Where 1, 2 and 0 represent the positive, negative and zero sequence currents and impedances. These equations are also satisfied on Figure 9. The system can be further reduced as shown on Figure 10 where:

$$Z_t = 3Z_f + Z_0 + Z_2 \tag{2.38}$$

$$Z_0 = \frac{(3X_{tn} + X_{t0} + X_{l0})X_{f0}}{3X_{tn} + X_{t0} + X_{l0} + X_{f0}} \tag{2.39}$$

$$Z_2 = \frac{(X_{d2} + X_{t2} + X_{l2})X_{f2}}{X_{d2} + X_{t2} + X_{l2} + X_{f2}} \tag{2.40}$$

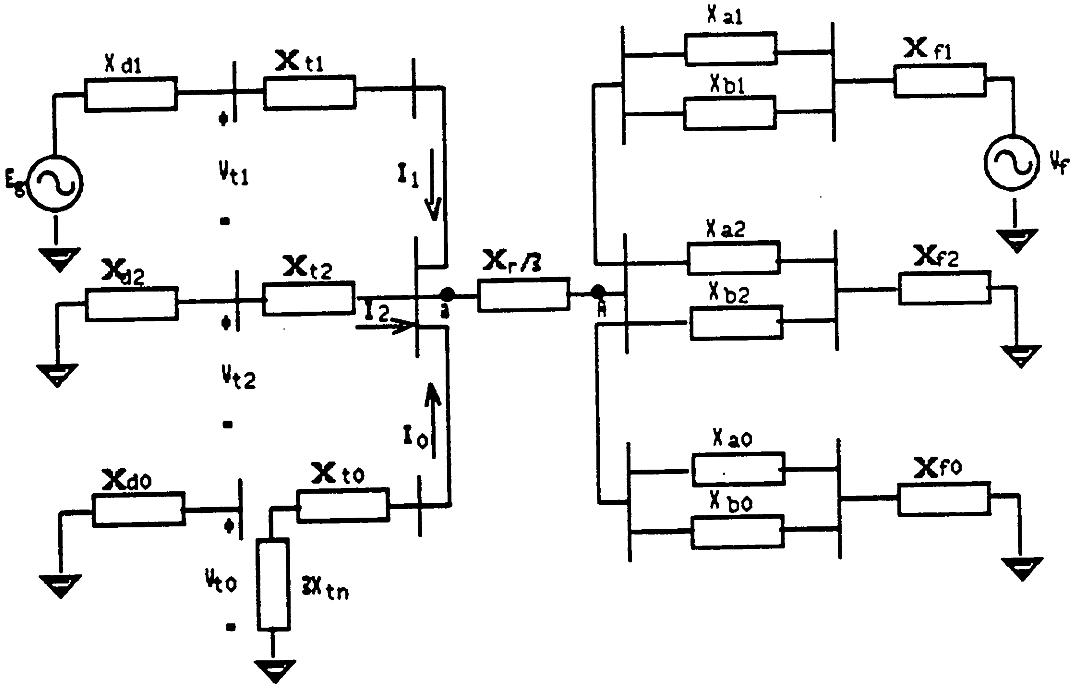


Figure 8. System One Open Phase Sequence Representation

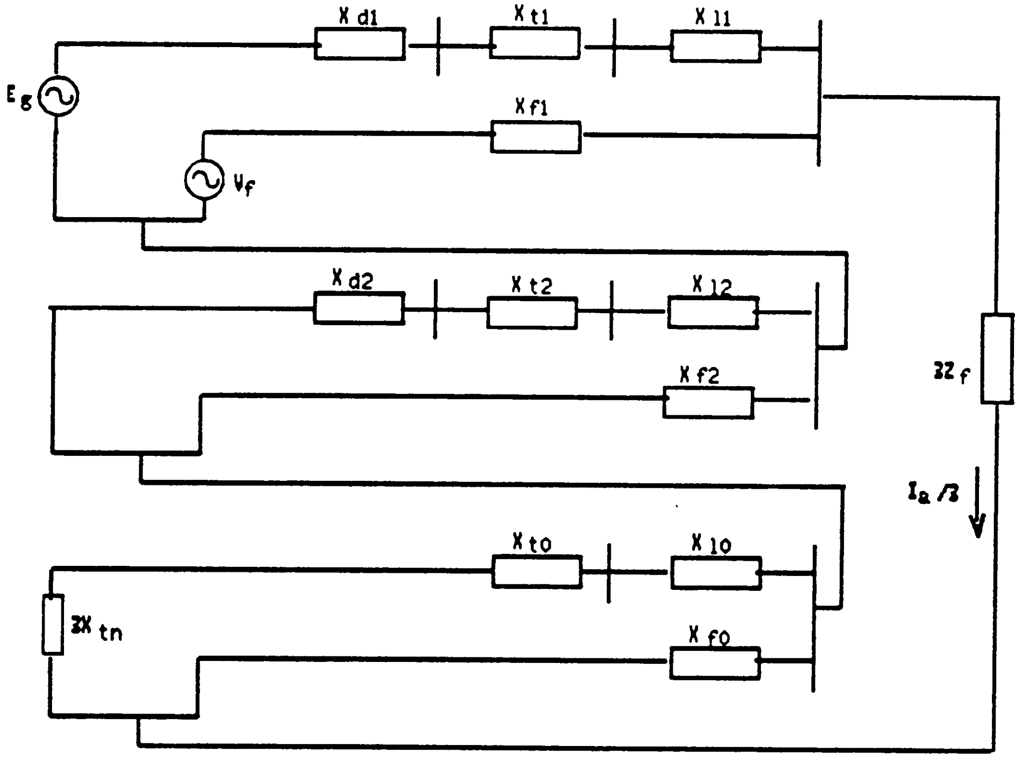


Figure 9. System Single Line to Ground Fault Sequence Representation

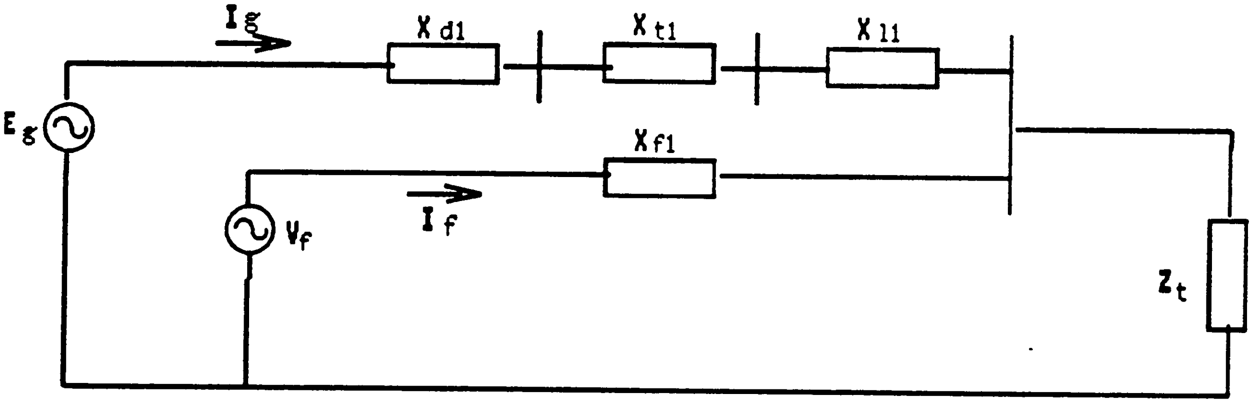


Figure 10. Reduced Phase to Ground Fault Sequence Representation

The loop equations can be solved for I_g and I_f the positive sequence currents from the generator and the infinite bus respectively with the following result:

$$I_g = \frac{(Z_t + X_{f1})E_g - Z_t V_f}{\Delta} \tag{2.41}$$

$$I_f = \frac{(Z_t + X_{d1} + X_{t1} + X_{l1})V_f - Z_t E_g}{\Delta} \tag{2.42}$$

Where:

$$\Delta = (Z_t + X_{d1} + X_{t1} + X_{l1})(Z_t + X_{f1}) - Z_t Z_t \tag{2.43}$$

And the total fault current is given by:

$$I = I_g + I_f \tag{2.44}$$

Applying current divisors on Figure 9 the negative and zero sequence currents from the generator can be calculated as:

$$I_2 = I \frac{X_{d2} + X_{t2} + X_{l2}}{X_{d2} + X_{t2} + X_{l2} + X_{f2}} \tag{2.45}$$

$$I_0 = I \frac{3X_{tn} + X_{t0} + X_{l0}}{3X_{tn} + X_{t0} + X_{l0} + X_{f0}} \tag{2.46}$$

But since the fault occurred at the high voltage side of the transformer and the generator is located on the low voltage side of it a phase shift must be made on the sequence quantities in order to show the corresponding phase shift on the phase quantities between the two sides of the transformer [8]. As in the case of the open phase at the high voltage side of the transformer the same phase shifts occur for the positive and negative sequence quantities. The zero sequence at the terminals of the generator does not exist. Then the final sequence currents and voltages are given by:

$$I_{g1} = JI_g \tag{2.47}$$

$$I_{g2} = -JI_2 \tag{2.48}$$

$$I_{g0} = 0 \tag{2.49}$$

$$V_{t1} = J(E_g - I_g X_d) \tag{2.50}$$

$$V_{t2} = -I_{g2} X_{d2} \tag{2.51}$$

$$V_{t0} = 0 \tag{2.52}$$

3.0 SIMULATOR'S IMPLEMENTATION

3.1 HARDWARE REQUIREMENTS

The final objective of this real time generator simulator is to use it as a generation station trainer. The system is implemented in two computers which communicate each other through the serial port. One of the computers is used by the instructor and the other by the operator.

The main program runs on the operator's computer and the instructor's computer serves as a station from where the simulation is started or finished and the system conditions are changed. The system was implemented in the following equipment available at the power systems laboratory:

1. IBM PS/2 Model 50 computer with math co-processor and VGA color monitor which served as the operator's station.

2. IBM PS/2 Model 30 computer which served as the instructor's station.

3. Both computers had available the COM1 serial port, for communication purposes.

4. Serial to serial port connection cable.

The main element of the simulation equipment is the model 50 computer which processor and co-processor run at a 10 Mhz speed. These were a requirement in order to achieve the real time simulation. The VGA color monitor was a very useful tool in the representation of all the system conditions on the operator's screen.

If an IBM PS/2 model 50 computer is not available the system can be run on a comparable system with at least the same speed on the processor and co-processor. An EGA color monitor is sufficient for a good screen representation of the system.

3.2 SOFTWARE IMPLEMENTATION

The set of algebraic and differential equations which represents the system can be solved using any of the methods available for the solution of this kind of problem. The Runge-Kutta and the trapezoidal methods for solution of differential equations were tried and the trapezoidal method was finally implemented on the simulation since represented the best choice for a numerically stable solution [5,6] even if the step size is larger than the smallest time constant together with the greatly improved execution time very critical in this application.

Given the typical values for the different time constants in the simulated system and taking into consideration also the smallest duration of a system fault and the accuracy of the model that didn't include subtransient reactances in the synchronous machine model, an integration step of 0.02 seconds was chosen in order to guarantee a real time simulation of the system.

The main program is written in FORTRAN language and the communication and control routines are written in ASSEMBLER language. Fortran optimizing compiler was used with all its capabilities in order to minimize the execution time.

Iterative calling of subroutines was avoided as much as possible in the main program and when done the number of parameters passed as subroutine arguments was also minimized; the COMMON statement was preferred to pass variables from one section of the program to another.

Due to the critical program execution time requirement the main program had to be structured on a way such that real time computation were minimized as much as possible. An example of this is the big number of pre-computations realized before the actual simulation starts.

3.2.1 KEYBOARD DEFINITION

The control actions normally present in a control room are implemented on the operator's keyboard. Figure 11 shows the location of the defined keys; its description and use is as follows:

- **INCREASE AND DECREASE INPUT POWER SETTING**

  These two controls are implemented respectively on the **UP AND DOWN ARROW KEYS** The power setting is increased or decreased as long as the keys are being pressed.

- **INCREASE AND DECREASE AUTOMATIC VOLTAGE REGULATOR SET-POINT**

  This control is implemented on the **RIGHT AND LEFT ARROW KEYS** The automatic voltage regulator set-point is changed as long as the key is pressed.

- **INCREASE AND DECREASE MANUAL VOLTAGE REGULATOR SET-POINT**

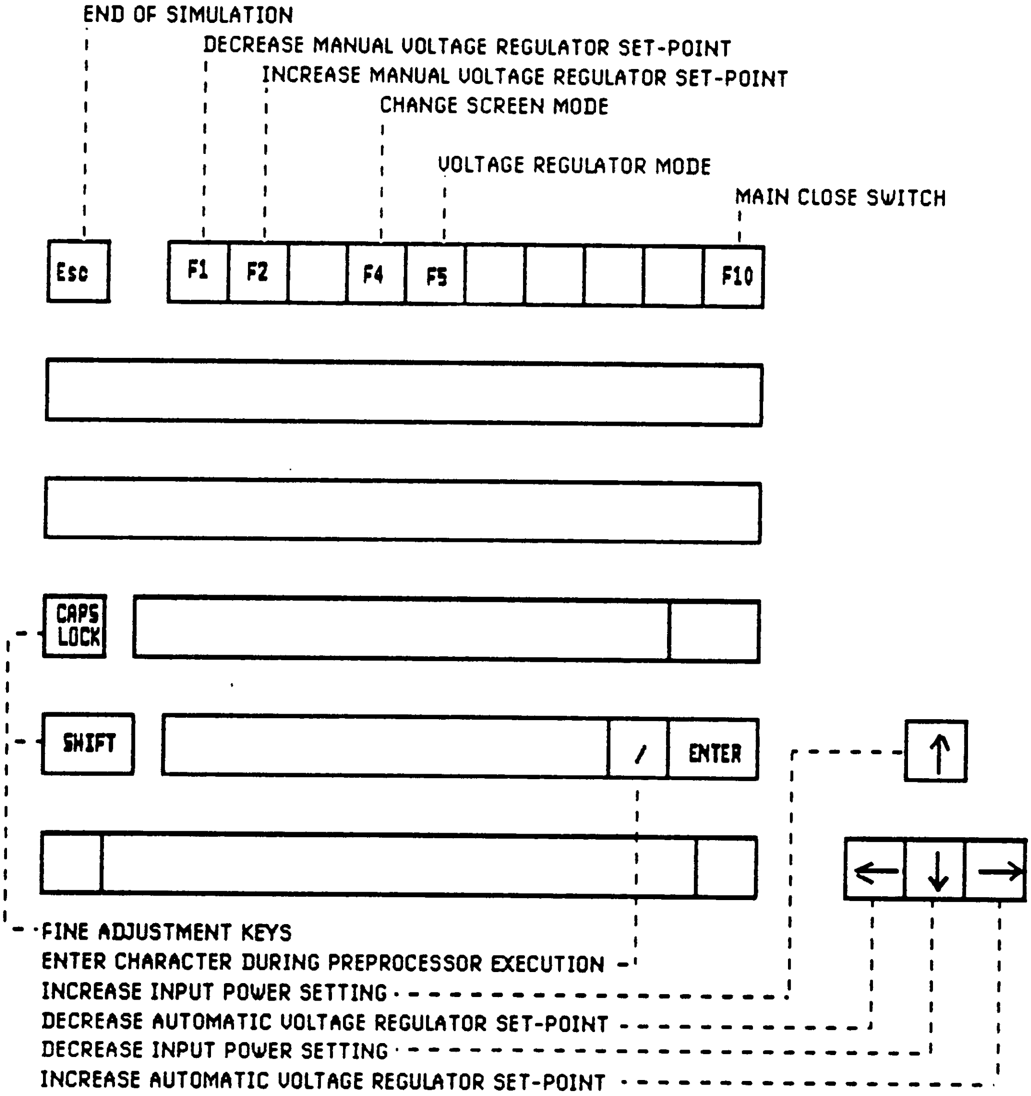


Figure 11. Operator's Keyboard defined Keys

This control is implemented on the **F1 AND F2 KEYS** respectively. The manual voltage regulator set-point is changed as long is the key is pressed.

- **CHANGE SCREEN MODE**

This control permits the operator to switch the screen from the normal digital meter representation to the visualization of the generator capability curve. This function is implemented in **F4 KEY** and changes screen mode in both directions anytime the key is pressed. During the visualization of the generator capability curve the actual load coordinates of the generator are shown at every instant.

- **MASTER CLOSE SWITCH**

This switch is implemented in **F10 KEY** and its function is to connect the generator to the system during the synchronization procedure. As soon as this key is pressed the generator is connected to the system and the screen is changed from synchronization to normal operation mode.

- **VOLTAGE REGULATOR MODE**

This control switch is implemented in **F5 KEY** and its function is to change the operation of the regulator from automatic to manual and vice versa.

- **END OF SIMULATION**

This software control is implemented in **ESC KEY** Once this key is pressed the simulation is ended by the operator and a message is sent back to the instructor.

- **FINE ADJUSTMENT KEYS**

Fine adjustment for power input setting, automatic voltage regulator reference and manual voltage setting is provided in the **CAPS LOCK KEY** . As the simulation is started gross adjustment is provided automatically by turning off the CAPS LOCK KEY; at any moment the fine adjustment is desired for any of the quantities the CAPS LOCK KEY should be turned on. A still finer adjustment is provided for the automatic voltage regulator reference if the **LEFT SHIFT KEY** is pressed at the same time the reference is changed.

- **ENTER CHARACTER DURING PREPROCESSOR EXECUTION**

If during preprocessor execution any of the data given is to be changed, then after selecting the option and entering the new value the **SLASH KEY** should be pressed as the enter key for the value just typed.

3.2.2 NORMAL GENERATOR'S CONTROL ROOM MIMIC

A model of this mimic can be seen on Figure 12. The following generator's meters are simulated during this phase of the simulation:

- **GENERATOR TERMINAL VOLTAGE METERS**

  Indicate the phase voltages in KV of the generator's terminal bus. During normal balance conditions the value shown is the same for all three phases, but during unbalanced conditions the values for each phase may greatly differ from one another.

- **SEQUENCE CURRENT METERS**

  The positive and negative sequence currents are shown. During normal operating conditions or balanced faults the only active meter will be the positive sequence meter but during unbalance conditions the negative sequence current will reach values that have to be supervised to determine the extent of damage that can be done to the machine by its presence during a given period of time.

- **GENERATOR CURRENT METERS**

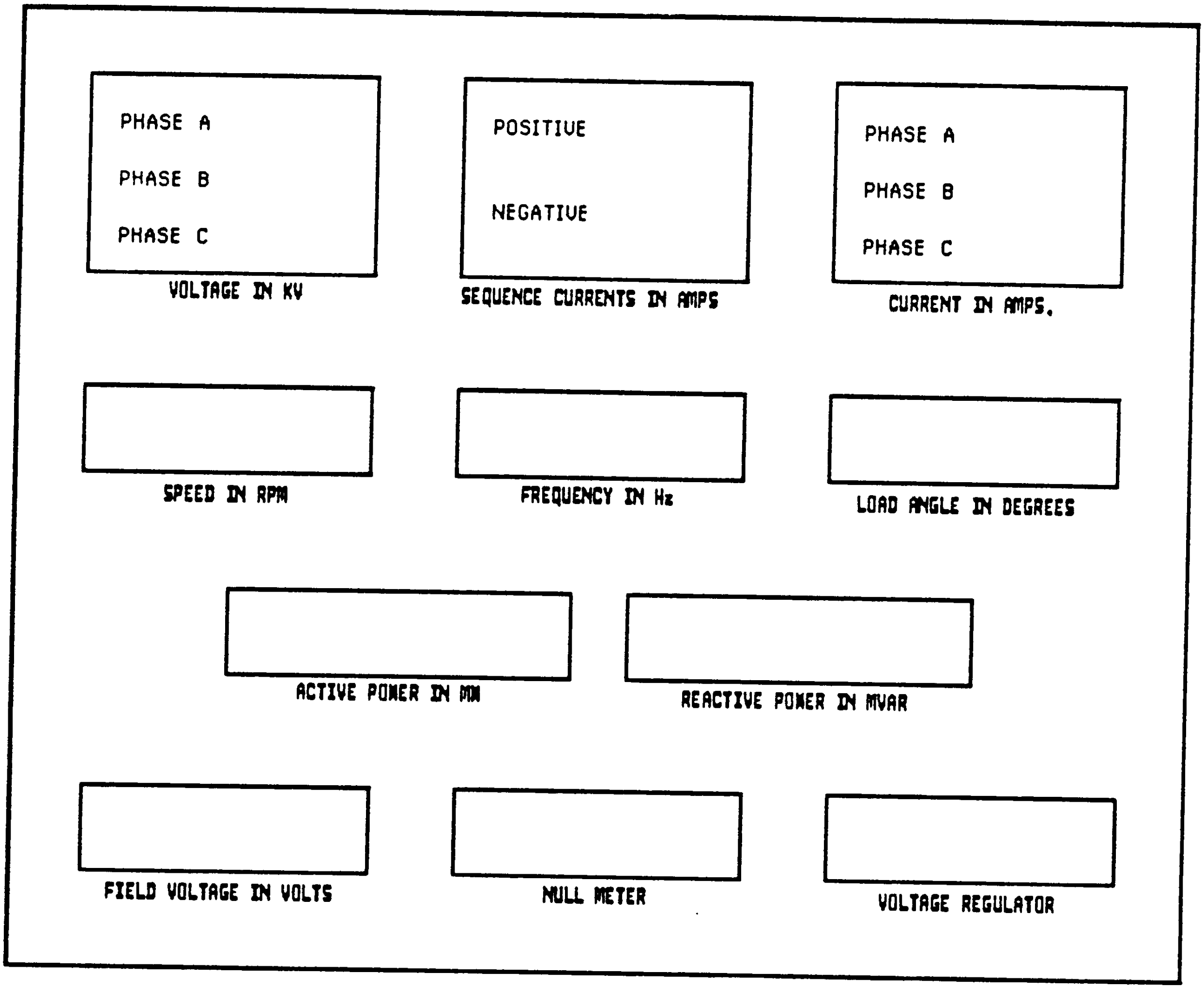


Figure 12. Normal Generator's Control Room Mimic

These meters indicate the current in Amperes in phases A, B, and C of the generator.

- **GENERATOR SPEED**

This meter indicates the speed of the generator in R.P.M.

- **GENERATOR FREQUENCY**

This meter indicates the generator frequency in cycles per second.

- **POWER ANGLE**

This meter indicates the power angle of the generator in degrees, which is the angle between the stator magnetic field and the rotor magnetic field. The meter has a range of 0 to 360 degrees. The slipping pole situation of the generator can be seen in this meter when during this condition the angle increases from its normal operating point value to instability values and back passing through the original operating angle. This is a very dangerous situation for the machine which will work as a generator and motor for consecutive periods of time gaining speed at all times while the input power is greater than the maximum output power given by Equation 2.1. Under transient instability as is the case of a fault or a drastic change of power, the may or may not restore stability depending on the operating condition previous to the event and the characteristics of the event itself.

- **ACTIVE POWER**

This meter indicates the generator's power output, in megawatts. The meter can have negative readings in which case will be indicating a motoring situation of the generator.

- **REACTIVE POWER**

This meter indicates the instantaneous reactive power to or from the generator, When the flow is out of the generator the indication will be positive corresponding to an overexcited condition; otherwise will be negative and will correspond to an under-excited condition.

- **FIELD VOLTAGE**

This meter indicates the instantaneous generator field voltage which is proportional to the generator's field current. (In steady state $I_f = \frac{V_f}{R_f}$)

- **NULL METER**

This meter indicates the difference between the manual voltage regulator set-point and the automatic voltage regulator set-point. This meter becomes important when a procedure to take the generator from automatic voltage regulation to manual voltage regulation or vice versa is to be initiated. In both cases a zero indication on this meter by means of varying the adequate voltage regulator setting, will be a necessary prior step to change the voltage regulator mode to eliminate any possible transient condition which may be undesirable.

- **VOLTAGE REGULATOR STATUS**

Gives the actual status of the voltage regulator as Manual or Automatic.

3.2.3 POWER CAPABILITY CURVE MIMIC

Access to this screen mode is possible by pressing the **CHANGE OF SCREEN MODE KEY** when the generator is already synchronized to the system. A representation of this mimic is shown on Figure 13. On this mode a dot representing the position of the active and reactive power is presented continuously. During normal operation the dot should stay inside the capability curve limits, but during transient conditions big momentarily excursions out of the curve could occur. Different machine design limits could be endangered if the machine is operated for a considerable amount of time outside the capability curve limits.

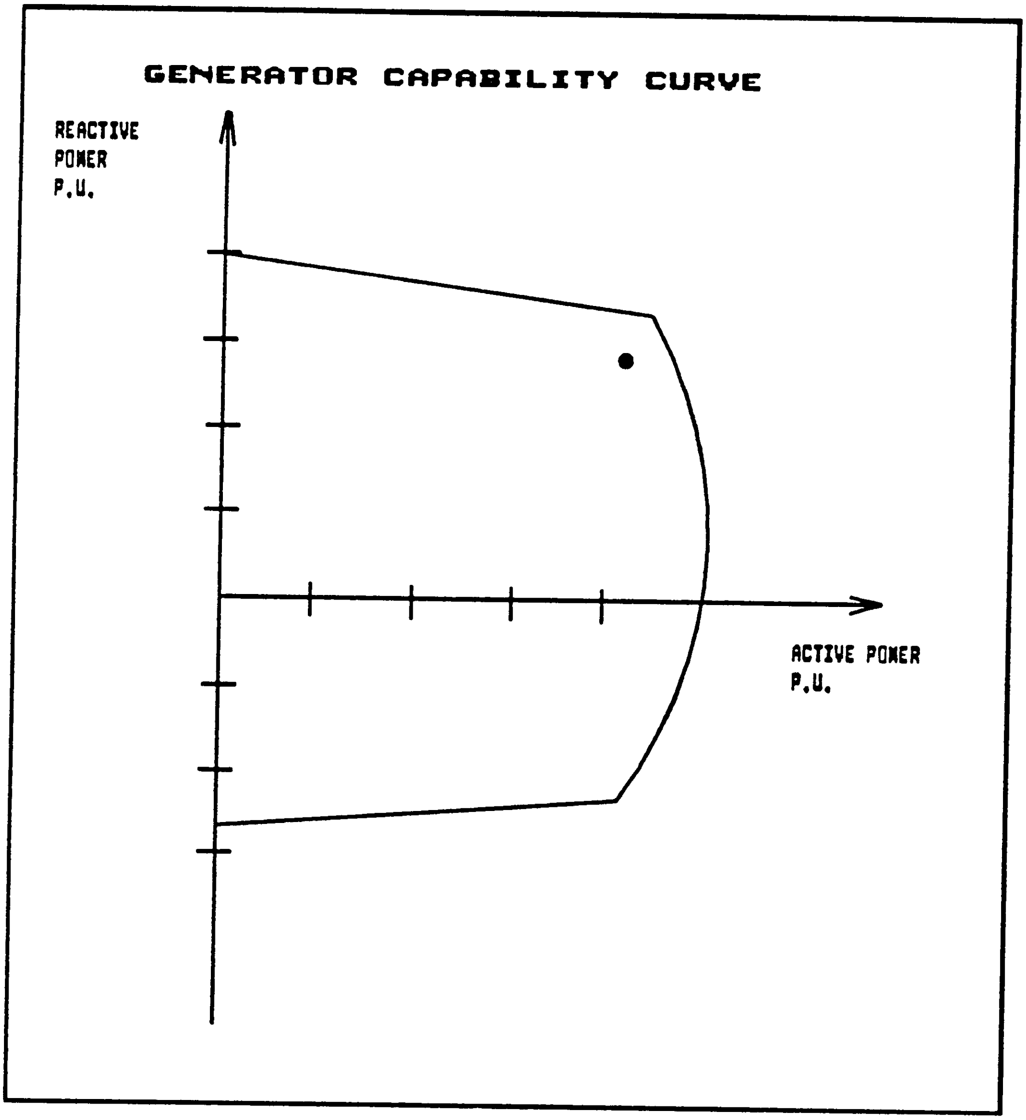


Figure 13. Power Capability Curve Mimic

3.2.4 SYNCHRONIZATION MIMIC

During synchronization a special control's room mimic is presented at the operator's screen showing the necessary meters and apparatus in order to be able to realize a successful synchronization. A model of this mimic is presented in Figure 14.

- **GENERATOR STARTING VOLTMETER**

  Indicates the reduced phase voltages of the generator at the starting bus in volts, with 120 volts representing 1 p.u. voltage at the terminals of the generator.

- **INFINITE BUS RUNNING-VOLTMETER**

  This meter indicates the reduced phase voltages of the infinite bus. During synchronization the voltage shown in this meter will be the correct voltage for the unit to be synchronized to the system. The reading is given in volts with 120 volts representing 1 p.u. voltage at the synchronizing bus. (The reading from 0 to 150 volts result after a PT that reduces the actual terminal voltage to this range.)

- **FREQUENCY METER**

Indicates at every moment the generator frequency in hertz. During synchronization this meter must indicate 60 or a slightly larger number indicating that the generator frequency is just over the system frequency. At the moment the synchronization is realized the frequency difference should be around 0.2 hertz.

- **PHASE DIFFERENCE METER**

Indicates the phase difference between the voltage at the generator starting bus and the system bus. At the moment of synchronization this difference must be zero or close to zero to avoid synchronization at different voltage potentials.

- **MASTER CLOSE SWITCH STATUS**

Shows the actual status of the main close switch. During synchronization procedure this switch remains on the OFF position; when activated the generator is connected to the system instantaneously.

- **SYNCHRONIZATION MODE INDICATOR**

Indicates whether the synchronization is being realized in manual or automatic mode

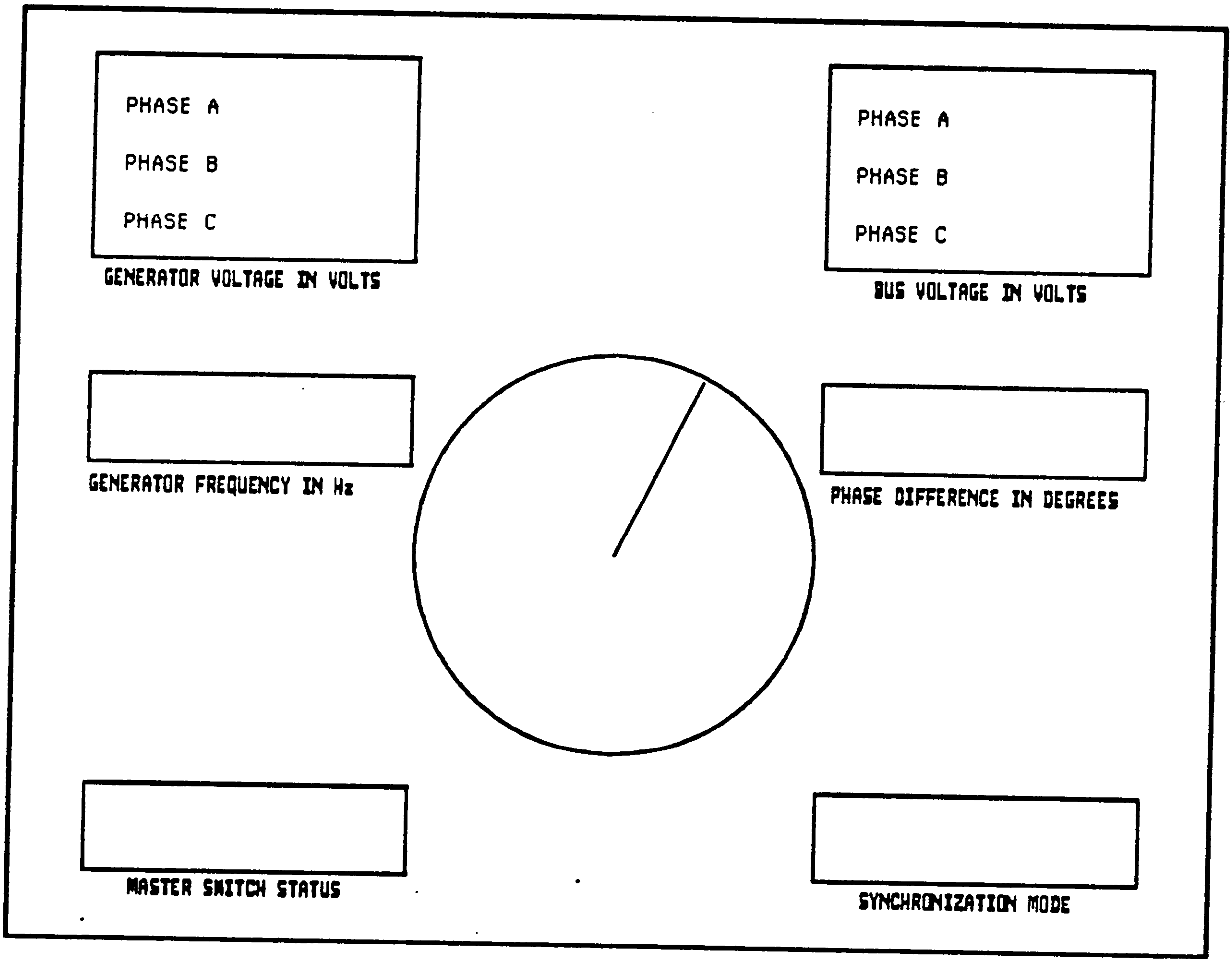


Figure 14. Synchronization Mimic

- **SYNCHRONOSCOPE**

A synchronoscope is implemented during synchronization and is activated when the frequency of the generator is between 95 and 105% of the frequency of the system. The synchronoscope indicates the difference in phase and frequency between the generator and the system before the unit is connected to the system. When the pointer on the synchronoscope is turning clockwise the generator frequency is larger than the system frequency which means than the generator is going too fast. When the pointer on the synchronoscope is moving counter clockwise the generator is moving too slow. When the pointer is at 12 o'clock the generator voltage and the system voltage are in phase and when the pointer is at 6 o'clock the generator voltage and the system voltage are 180 degrees out of phase.

3.3 EXECUTION PROCEDURE

Before starting the simulation the serial port communication cable which connects COM1 serial ports on both computers have to be installed.

Introduce the operator's diskette in drive A of the model 50 computer and then turn on the machine. Use the DOS diskette to start the instructor's computer.

To start the instructor's program introduce the instructor's diskette in drive A of the model 30 computer and type **INST** .

To start the operator's program, with the diskette still in drive A of the model 50 computer type **OPER.**

The first task the programs do is to set up the communication standards between both computers. So any bad connection on the serial port or failure to follow the above steps will be resembled on any one of the computers on in both if it is the case. If an incomplete communication procedure is detected by the operator's computer the following message will be printed on the screen:

............STARTING COMMUNICATIONS............

1. **CHECK SERIAL CABLE CONNECTIONS**
2. **TURN ON INSTRUCTOR'S COMPUTER**
3. **START INSTRUCTOR'S PROGRAM**

In the other hand if the incomplete communication procedure is detected by the instructor's computer the following message will be printed on the instructor's screen:

............STARTING COMMUNICATIONS............

1. **CHECK SERIAL CABLE CONNECTIONS**

2. **TURN ON OPERATOR'S COMPUTER**

3. **START OPERATOR'S PROGRAM**

In both cases the instructions have to be followed in the order given in order to be able to continue the simulation.

3.3.1 PREPROCESSOR

Once the communication is successful a presentation screen appears at the operator's station and the operator is asked for the data for his simulation.

After a program presentation screen is erased the operator is asked for his name (20 characters maximum). This name will form part of the final record when the simulation is finished. Next the operator is presented with the following screen:

CHOOSE ANY OF THE FOLLOWING

1. **CARDINAL**

2. **AMOS 1 & 2**

3. **AMOS 3**

4. **NEW**

PRESS 1..........4

Options 1 to 3 correspond to implemented systems representing those AEP (American Electric Power) owned generating units [9]. All of them are single-shaft units. Any one of these generating units can be chosen as a model for the simulation and changes are permitted to accommodate it to the particular needs. In any case the original data files remain unmodified and any change will be stored in the temporary unit called NEW.

If a complete new model wants to be simulated option 4 should be chosen and a new temporary data file will be created and stored for later use. In any case the modifications made are restricted by the model implemented and explained in chapter 2.

In this case and through all the preprocessor execution any keyboard input different than what the answer is expected to be is ignored and the program stays at the current position until the right answer is given. After a system is selected the following screen is presented:

DO YOU WANT TO SEE THE ACTUAL DATA - (Y/N)

If "Y" is answered the preprocessor will start showing the default values for the selected case (last system used if option 4 is chosen) and will accept any changes to the default data.

3.3.1.1 LINE DIAGRAM DATA

While the line diagram data is entered a line diagram of the system is presented in the upper part of the screen. All the entered impedances should be in p.u. of the generator base.If the Cardinal unit was selected the following data will appear on the screen:

1. **ZD1 = 0.00000 0.20000**

2. **ZD2 = 0.00000 0.20000**

3. **ZD0 = 0.00000 0.14500**

4. ZDN = 0.00000 0.00000

Choose parameter or enter C to continue

All impedances in p.u. of generator base

ZD1 represents the generator's transient reactance. ZD2 and ZD0 represent the negative and zero sequence reactances of the generator and ZDN represents the ground impedance of the generator. The ENTER character during the preprocessor execution for any system data changed is implemented in the **/ key** .

In case a parameter needs to be changed the new complex value for the impedance should be entered leaving a space between the real and imaginary components; again a maximum of 20 characters is accepted. Successively the transformer, lines and infinite bus impedances are shown and changed in the same way if desired. Finally some important characteristics of the generator are shown in successive menus. These characteristics include the rated power (MVA) of the generator, the power factor given by the manufacturer, the terminal voltage (KV), the field voltage (V), the open-circuit transient time constant, etc... These characteristics are very important for the determination of the generator capability curve as well as for the actual simulation.

3.3.1.2 EXCITATION SYSTEM DATA

For the next presented menus a visual aid representing the modeled excitation system is drawn in the upper part of the screen.

As in the line diagram data input the default values are presented and any change is accepted and updated immediately. In this case the input data will correspond to the excitation and regulator time and gain constants, together with the regulator and excitation limits and the data points for the calculation of the exciter saturation curve.

All the time constants must be given in seconds and the voltages in p.u. of the field voltage.

3.3.1.3 GOVERNOR AND TURBINE SYSTEMS DATA

In this case a control loop representing the governor and turbine systems is presented in the upper half of the screen as the data is presented and /or changed. As for the excitation system the data in this case corresponds to the governor and turbine time and gain constants.

3.3.1.4 GENERATOR CAPABILITY CURVE DATA

A generator capability curve is drawn with the existing data and a menu is presented to allow for any change on the capability curve limits. The variables presented in this case correspond as it is indicated in the capability curve to reactive power limiting the field current heating, and minimum reactive power limiting the stator core end iron heating.

The values are presented in p.u. of generator MVA base and should be entered in the same p.u. base.

At this point the preprocessor ends its task and the program will resume here if the (Y/N) question had been answered with "N" keeping the initial chosen unit without any change.

The following message is then printed on the operator's screen:

WAITING FOR THE INSTRUCTOR TO START SIMULATION

The operator then has to wait until the instructor from his station decides on the kind of simulation he wants to initialize on the operator's computer.

While the preprocessor is being run by the operator the instructor can decide on the kind of simulation he wants to start on the operator's computer based on the following menu presented on his screen:

1. **GENERATOR AT STEADY STATE AND CONNECTED TO THE INFINITE BUS**
2. **MANUAL SYNCHRONIZATION**
3. **AUTOMATIC SYNCHRONIZATION**

He can choose the desired option from this menu and subsequent menus will be presented if required, but all the input data is held by the instructor's computer until the operator's computer is ready to receive it; this is when the execution of the preprocessor is over.

3.3.2 MANUAL SYNCHRONIZATION

When this option is chosen by the instructor the synchronization screen appears on the operator's computer and he can change the generator settings from the keyboard to fulfill all the prerequisites before synchronization to the system is realized.

In general three basic steps must be realized by the operator prior to synchronization:

1. The generator voltage (or its transformer) must be equal to the voltage of the system to which it is to be connected.

2. The generator frequency must be equal to the system frequency.

3. The generator voltage must be in phase with the system voltage.

When synchronizing a generator a failure to follow any of these steps could result in serious electrical and/or mechanical damage to the generator and turbine. The simulation allows the synchronization even if the basic steps have not been followed, so a synchronization out of phase can be simulated.

In order to fulfill the prerequisites the operator has generator controls defined on the keyboard as described in section 3.2.1. A normal synchronization procedure is described as follows:

1. Bring the machine from zero to near synchronous speed by increasing the mechanical input power to the turbine.

2. When the machine is near synchronous speed start increasing the terminal voltage of the generator. It is not recommended to increase the voltage before

the generator has reached a near synchronous speed since the output voltage of the generator is speed dependant.

3. The synchronoscope which is only activated when the generator is within 5% of synchronous speed is the final tool to achieve a successful synchronization. The synchronoscope rotates counterclockwise (slow) when the generator frequency is lower than the system frequency and rotates clockwise (fast) when the generator frequency is higher than the system frequency. The position of the synchronoscope gives the angle difference between the voltage at the generator terminals and the voltage at the bus where the generator is to be connected.

At the moment of synchronization is preferred the generator frequency to be larger than the system frequency so the synchronoscope will be rotating in the fast direction at no more than one revolution every six seconds.

If the synchronization is made at 12 o'clock in these conditions, the phase difference between the generator and the bus voltages will be zero and since the voltages had been already equated, a complete in phase synchronization will be realized. In reality the master close switch is closed when the synchronoscope passes 11 o'clock to allow for the delay on the operator's response. A synchronization with the syncronoscope steady at 12 o'clock is not desirable since this could be due to malfunctioning of the synchronoscope.

In a synchronization realized at 6 o'clock the voltages of the generator and the system bus will be completely out of phase and the voltage difference between both busses will actually be as much as twice of that of the generator or system bus voltages.

At the moment the synchronization is wanted the operator closes the **MAIN CLOSE SWITCH** and the synchronization screen will disappear and will be replaced by the normal operation screen, where new conditions can be started by the instructor.

The operator must now change the voltage regulator from manual to automatic mode since the synchronization is realized with the voltage regulator in manual operation, to provide a better control over the generator's terminal voltage. If the operator decides to stay with the manual voltage control, at any time the load is increased the manual voltage reference will also have to be increased. Otherwise an undesired under-excited generator situation may occur where the generator will start consuming reactive power from the system.

3.3.3 AUTOMATIC SYNCHRONIZATION

As in manual synchronization the prior steps to synchronization need to be taken by the operator. He has to bring the machine to near synchronous speed and equate the generator voltage with the voltage of the bus to which the generator is to be connected, but in this case the computer takes over after these conditions have been met and adjust the necessary controls to realize an in phase synchronization. When the synchronization is finished, as in the manual synchronization case, the simulation will continue with the normal operation of the generator connected to the infinite bus and at his point the instructor can introduce any new system changes.

3.3.4 GENERATOR CONNECTED TO THE INFINITE BUS

If option 1 is chosen by the instructor he is requested with the following input:

ELECTRICAL POWER BEING DELIVERED BY THE GENERATOR TO THE SYSTEM IN p.u.

And immediately he will be requested with:

GENERATOR TERMINAL VOLTAGE IN p.u.

These data will determine the initial operating point of the generator and at this point this data is sent to the operator's screen and the actual simulation is started.

As soon as the data is received by the operator's computer its screen is unfrozen from the message that was displaying and instead a mimic of the generator's control room is shown. At the same time the operator's keyboard is enabled to allow him to take control actions over the generator.

The operator at this moment will see the steady state operating point, set by the instructor, reflected on his screen. The operator can at any moment change the screen mode to see the generator operating point situated on the capability curve. He can also change any of the settings of the generator like the input power setting, the automatic voltage regulator setting, the manual voltage regulator setting and change the regulator mode from automatic to manual and vice-versa.

The instructor's screen will present the following menu:

ENTER ONE OF THE FOLLOWING OPTIONS

1. **CHANGE IN THE SYSTEM CONDITION**

2. **FINISH SIMULATION**

3.3.4.1 CHANGE IN THE SYSTEM CONDITION

If **Option 1** is selected then the instructor will have the following menu available to choose a system condition to be simulated:

SELECT SYSTEM CONDITION

1. NORMAL STEADY STATE SYSTEM
2. THREE PHASE FAULT AT GENERATOR TERMINALS
3. THREE PHASE FAULT AT RING BUS
4. THREE PHASE FAULT AT INFINITE BUS
5. PHASE TO GROUND FAULT AT GENERATOR TERMINALS
6. PHASE TO GROUND FAULT AT RING BUS
7. PHASE TO GROUND FAULT AT INFINITE BUS
8. PHASE TO PHASE FAULT AT GENERATOR TERMINALS
9. PHASE TO PHASE FAULT AT RING BUS
10. PHASE TO PHASE FAULT AT INFINITE BUS
11. DOUBLE PHASE TO GROUND FAULT AT GENERATOR TERMINALS
12. DOUBLE PHASE TO GROUND FAULT AT RING BUS
13. DOUBLE PHASE TO GROUND FAULT AT INFINITE BUS

14. OPEN PHASE ON HIGH VOLTAGE SIDE OF TRANSFORMER

15. TWO PHASES OPEN ON HIGH VOLTAGE SIDE OF TRANSFORMER

16. THREE PHASES OPEN ON HIGH VOLTAGE SIDE OF TRANSFORMER

17. ONE TRANSMISSION LINE REMOVED

Any of the options presented can be selected by the instructor and he will be asked for the following data afterward:

TIME AT WHICH CONDITION STARTS IN SECONDS

The instructor has here the opportunity to introduce a delay on the starting of the new condition. This allows him to start conditions at any time without the operator knowing it.

DURATION OF THE SYSTEM CONDITION IN SECONDS

The duration of the new system condition can be on the order of fraction of a second, seconds or can also be a permanent condition in which case the digits **9999** should be input as duration, by the instructor.

Consecutive system changes can be input by the instructor. While one condition is being executed on the operator's computer, another system change can be input by the instructor and the execution will be started after the first condition is finished.

3.3.4.2 FINISH SIMULATION

If this option is selected by the instructor then the simulation at the operator's computer is stopped and a summary of the simulation will be ready for evaluation at the operator's computer.

Through all this simulation the operator sees on his screen the mimics already described on sections 3.2.2 and 3.2.3 and shown on Figures 12 and 13. The operator can also at any moment change the settings of the generator through the keys defined on the keyboard and already described on section 3.2.1 and shown on Figure 11. One of these keyboard defined functions is the ending of the simulation itself in the same way the simulation was ended by the instructor.

3.4 EXAMPLE OF A SIMULATION EXECUTION

The operator and the instructor should follow the starting procedure given at the beginning of section 3.3. For the completeness of the example a manual synchronization is chosen as an example.

The instructor should select this option by introducing option 3 on the first menu presented to him and although a new menu is presented to him any new input condition will only be executed after the generator has been synchronized by the operator. So it is better for him to wait until the generator is synchronized and the synchronization transients have died to start inputting new conditions to the system.

Before starting the synchronization the operator has the choice of going through the preprocessor and changing any of the given parameters for a chosen example or creating its own by choosing the adequate option. Let's assume that the CARDINAL UNIT is the one chosen and no parameters are going to be changed. After taking the appropriate decisions to escape the preprocessor the operator will be able to start the synchronizing procedure. He will have to execute the following tasks in order to realize a successful synchronization:

1. Start increasing the mechanical input power in order to bring the machine to synchronous speed. He has to consider that the only power needed to achieve

this is the turbine and generator mechanical and electrical losses and this quantity is usually a small percentage of the total rated output power of the machine. Any excess of power will increase the speed beyond the synchronous speed and will be very difficult to bring the machine back to synchronous speed. Usually a synchronization procedure takes around 5 minutes. Start always with the smallest step (CAPS LOCK ON) when increasing the input power. The smallest step provides an increment of 0.01 p.u. each time while the gross step provides an increment of 0.1 p.u.

2. When the machine reaches 95% of rated speed or frequency (57 hertz for a 60 hertz generator) the synchronoscope will be turned on and will start on the counter-clockwise direction since the generator frequency is smaller than the system frequency. At this time the operator should also start bringing up the terminal voltage of the generator; this is achieved by incrementing the manual voltage reference since during the synchronization procedure the automatic voltage regulator is disconnected. The gross adjustment at the beginning and the fine adjustment at the end should be used to bring the voltage to the desired level which is the same as the voltage indicated by the voltmeters connected to the synchronizing bus on the upper right hand side of the screen. This voltages should be equated before the machine reaches 60 hertz at which moment the synchronoscope starts going clockwise. The voltages shown on the generator terminals and on the synchronizing bus voltmeters are reduced voltages, 120 volts corresponding to 1 p.u. voltage at either bus.

3. As the frequency reaches 60 hertz the synchronoscope will slow down to the point that at exactly 60 hertz will stop completely at the phase difference indicated at that moment and then will start turning clockwise. The synchronoscope will start now accelerating in this direction and the operator should synchronize, CLOSE THE MAIN SWITCH, when the synchronoscope is slowly moving and approaching 12 o'clock. A common practice is to close the main switch when the synchronoscope is passing through 11 o'clock and the turning speed is less then 6 seconds per revolution (frequency below 60.16 hertz).

4. As the generator is synchronized a small transient is created and the generator will stabilize at some operating point where the output active and reactive power is around zero. This can be seen by the operator in the normal screen mode or switching to the capability curve mode. Before any attempt is made to increase this power the generator should be switched from manual voltage control to automatic voltage control. But before doing this the null meter at the bottom of the screen has to be reading a number close to zero which will mean that the manual voltage setting and the automatic voltage regulator setting will produce the same generator terminal voltage. This is achieved by increasing the automatic regulator voltage setting using the four different scales provided until the null meter reads the closest number to zero.

5. After the voltage regulator is in automatic mode, the generator is ready to start picking up load. Active power is increased by adding the mechanical

power to the turbine and reactive power is increased by moving the automatic voltage regulator setting to the appropriate point. A normal operating point is located at some point in the first quadrant of the power capability curve, considering that the generator's normal main purpose is to generate as much active power as possible but that should also supply some of the reactive power needed by the system. Care should be taken when increasing the power since there is a considerable time delay between the moment the power is input to the turbines and the actual time the generator's active power starts increasing. It is suggested that this procedure is done slowly, letting the electrical power catch up with the input power at given intervals to avoid increasing the power beyond the machine limits. The reactive power response to increments on the regulator setting is really fast since the response takes action within the excitation system which is a fast system compared to the governor-turbine system. In the case of the reactive power the increment step of the automatic voltage regulator setting should be well selected since the reactive power is usually very sensitive to changes on the terminal voltage and in general big jumps in the operating point are undesirable.

The generator is now running at synchronous speed completely synchronized to the system and operating at the operator's chosen point. The instructor can now select to change the system condition by introducing any of the 17 abnormal system options presented to him. Let's assume that the instructor chose **fault number 6** which is a **phase to ground fault at the high voltage side of the transformer** ; to the next question, **time at which condition starts in seconds** , he responded **60** ; and to the question **Duration of the system condition in seconds** he responded **0.08** This means that 60 seconds after he finished entering the fault duration, an 80 millisecond phase to ground fault will be simulated on the operator's computer and after that the fault is cleared and the system returns to its normal steady state configuration.

The operator on the other hand will be at his console waiting for any condition to be started from the instructor's console. He will not know when the condition will be started due to the delay allowed on the instructor's console to the starting of the fault condition. With the condition just input, the chances are he will not be able to identify the kind of fault due to the short duration of the fault; but with longer conditions he may be able to identify the situation by looking at the voltage and current phase meters as well as to the sequence meters, the power operating point either on the digital meters or in the capability curve. For example for a three phase fault at the generator terminals he should be able to see the generator terminal voltage drop to zero at the same time that the current increases equally on all three phases and he should not observe any negative sequence current. The active and reactive power will drop to zero during the duration of the fault and this can be seen very clearly if the operator switches to capability curve mode.

The operator will continue to see in his screen all the events sent from the instructor console and in some of those he may need to take control actions. The simulation is finished by either the operator or the instructor.

4.0 RESULTS AND CONCLUSIONS

4.1 SIMULATED EVENTS

Various tests were made on the CARDINAL unit which data was obtained from AEP [9]. The unit is connected to the infinite bus through the standard Δ/Y transformer and the two parallel lines system implemented in the simulation.

The results presented are part of the variables that are normally displayed on the screen. The results on the screen are updated 2 times per second while in the graphs presented a very fine updating time of 0.02 seconds was used.

Figure 15 shows the corresponding diagrams for a manual in phase synchronization. Although an actual 0 degree phase difference is difficult to acomplish manually, it can be seen that the transients created due to a phase difference between the generator terminal voltage and the synchronizing bus voltage of approximately 5 degrees are very small and the machine comes to steady state very rapidly.

Figure 16 on the other hand shows a synchronization attempt at 180 degrees out of phase. In this case very big excursions in all the plotted variables occured. If for example the current variations in both synchronizations are compared it can be seen that while during the in phase synchronization the highest value for current was 0.13 p.u, during out of phase synchronization it reached values close to 1.8 p.u. A situation like this is very likely to damage the machine.

Figure 17 shows a permanent phase to ground fault at the generator terminals. A situation very likely to happen since usually the brakers are situated at the high voltage terminals of the transformer. While the voltage on the faulted line remains at 0 volts, the automatic voltage regulator brings up the voltage on the other phases which results on the situation shown on which the machine still supplies active and reactive power to the system at a smaller load angle and at a very high and dangerous current through the faulted phase. Since the situation is unbalanced, negative sequence components are also created and the machine could be easily damaged.

In Figure 18 a phase to ground fault at the high voltage terminals of the transformer is presented; the fault is assumed to be cleared after 5 cycles. This is a common fault situation for the system and during the transient created in this case the machine stays in synchronism.

Figure 19 represents a temporary loss of one phase at the high voltage terminals of the transformer. The transient created in this case is not a critical one and the machine stays in synchronism.

Figure 20 shows a permanent loss of one of the transmission lines of the system. The regulator action brings the voltage to the original level and the governor action keeps the output power at the level set by the power input reference. The main characteristic of the new steady state situation is that the machine will be operating at a higher load angle and so it will be closer to instability if a new fault on the system occurs.

A very common mistake by power plant operators happens during the synchronization procedure. When the machine is already synchronized to the system, the operator must change the voltage regulator from manual to automatic operation before he actually starts loading the machine. Figure 21 shows how the machine starts absorbing reactive power from the system as the machine is loaded when the voltage regulator is in manual operation, and the manual voltage reference is not changed during the procedure.

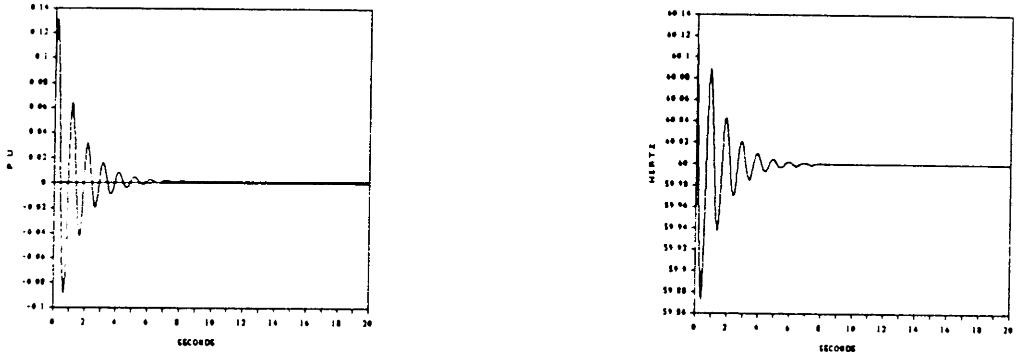
The loss of field situation is ilustrated in Figure 22. The machine was operating giving active and reactive power to the system when suddenly the field is lost. The machine will not be able to generate any active power since the induced voltage becomes zero and at the same time will start absorbing reactive power from the system. The machine rapidly losses synchronism. This situation is never wanted in a synchronous machine and good protections exist to limit the damage done to it.

Another similar situation to the machine happens when the voltage regulator is changed from normal automatic operation to manual operation without the required pre-requisite of nulling the corresponding meter. In the case shown in Figure 23 the machine was operating at a normal operating point and when the voltage regulator was changed from automatic to manual, the manual voltage reference was set such that the machine would be underexcited. The machine rapidly losses synchronism and stays in a slipping pole situation changing operating points continuously.

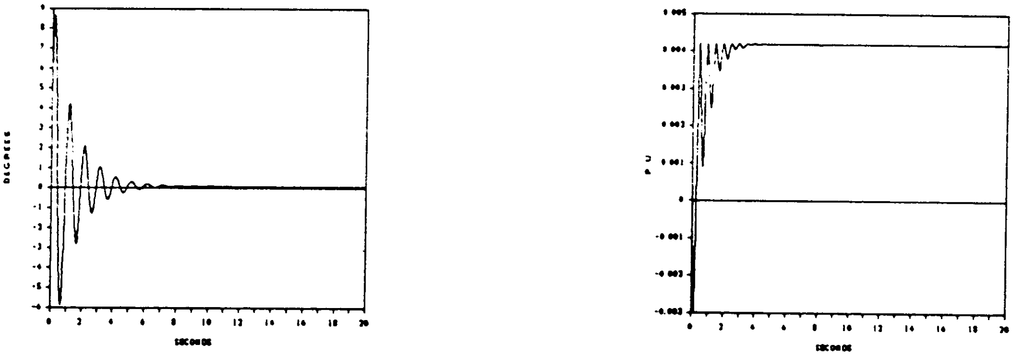
4.2 CONCLUSIONS

A real time generation-station simulator which represents the behavior of the generator under normal or abnormal conditions was developed. The model developed included an approximate model for the synchronous machine, a very good model for the excitation system and an approximate model to simulate the governor action.

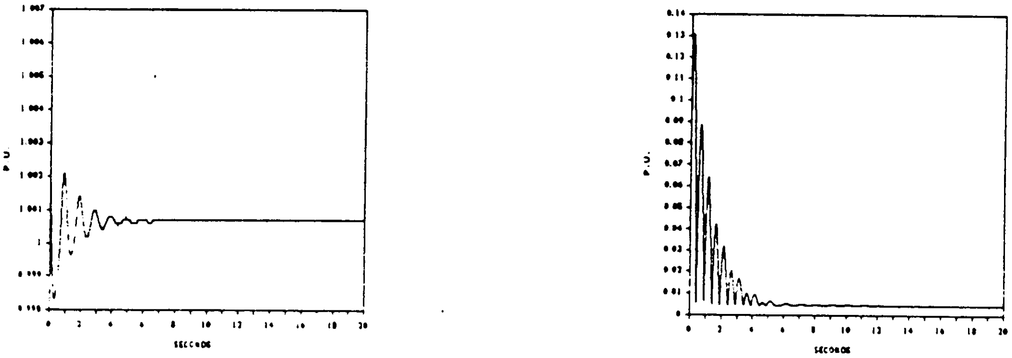
With the developed model, the generator respond to slow transients can be modeled. The transients can be either produced by external faults on the system tying



a. Active power b. Frequency

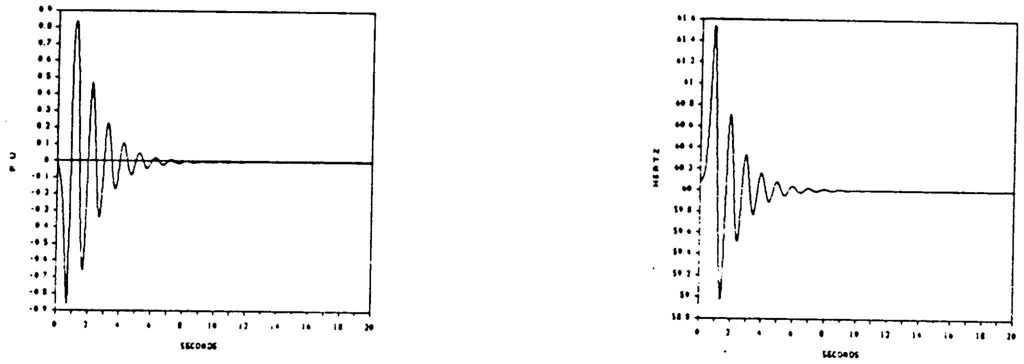


c. Load Angle d. Reactive Power

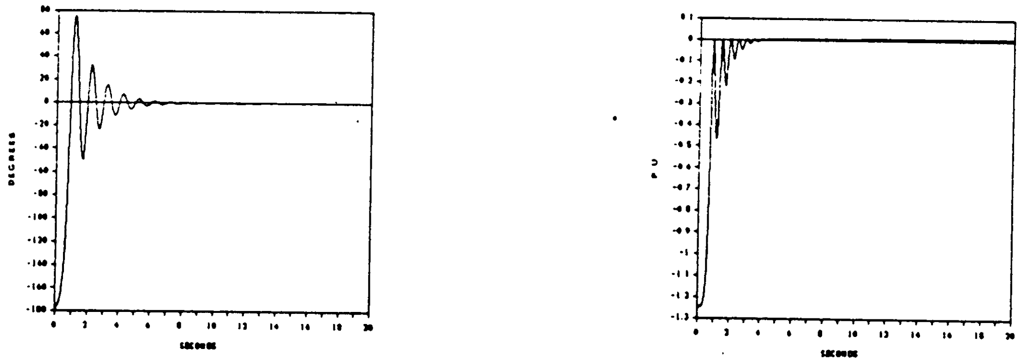


d. Terminal voltage e. Current

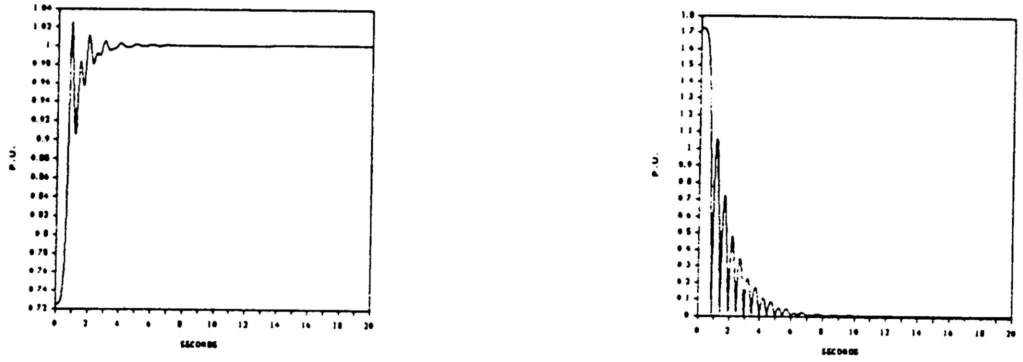
Figure 15. **Manual Syncronization in Phase**



a. Active power b. Frequency

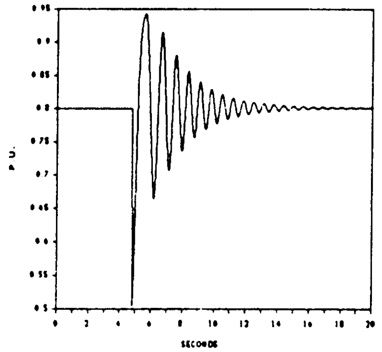


c. Load Angle d. Reactive Power

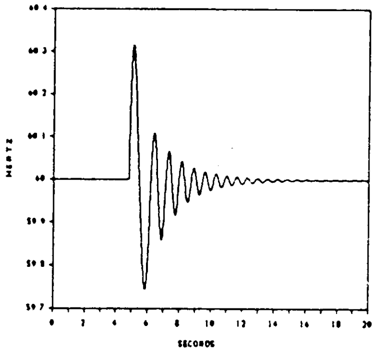


d. Terminal voltage e. Current

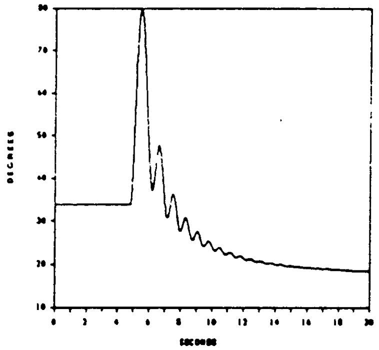
Figure 16. Syncronization 180 degrees out of Phase



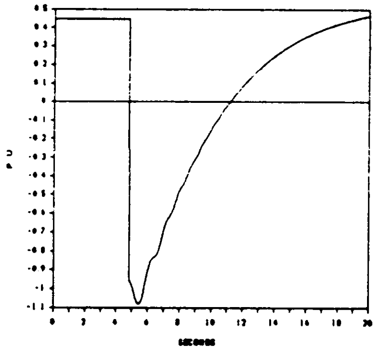
a. Active power



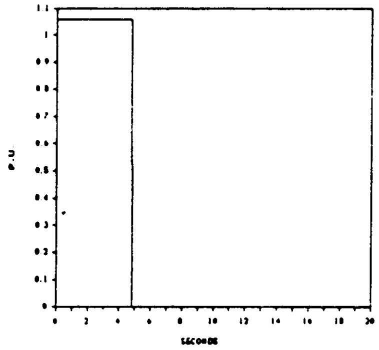
b. Frequency



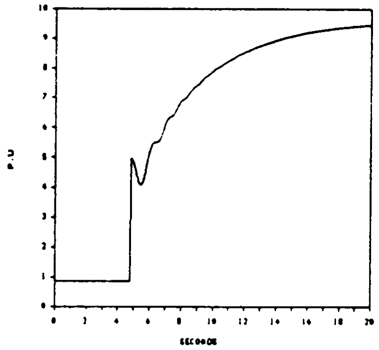
c. Load Angle



d. Reactive Power

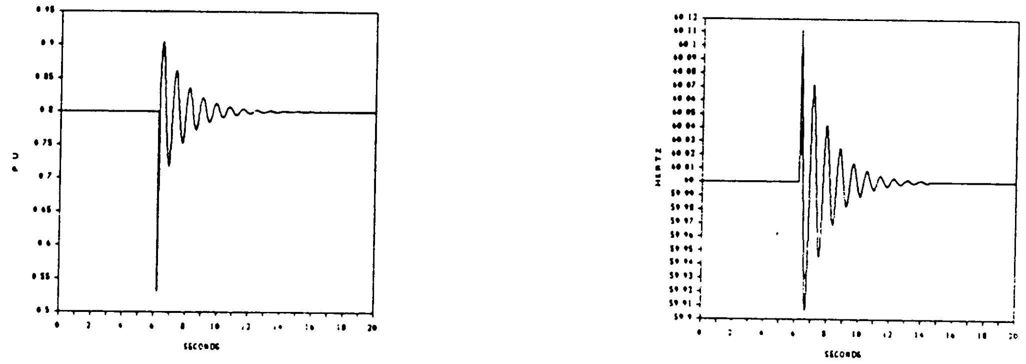


d. Terminal voltage

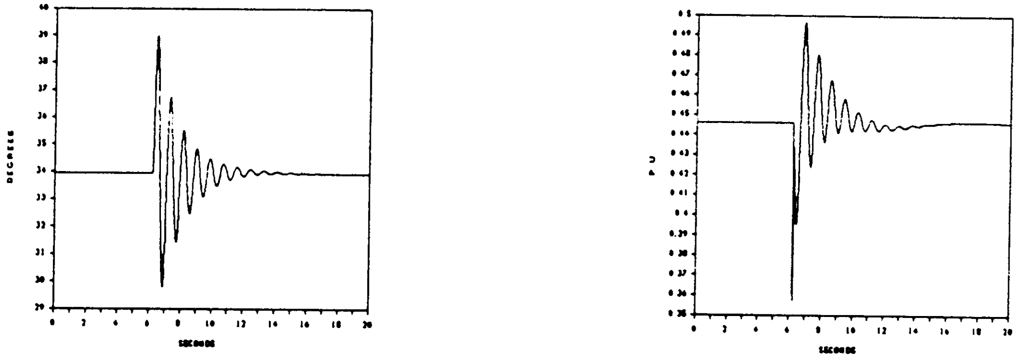


e. Current

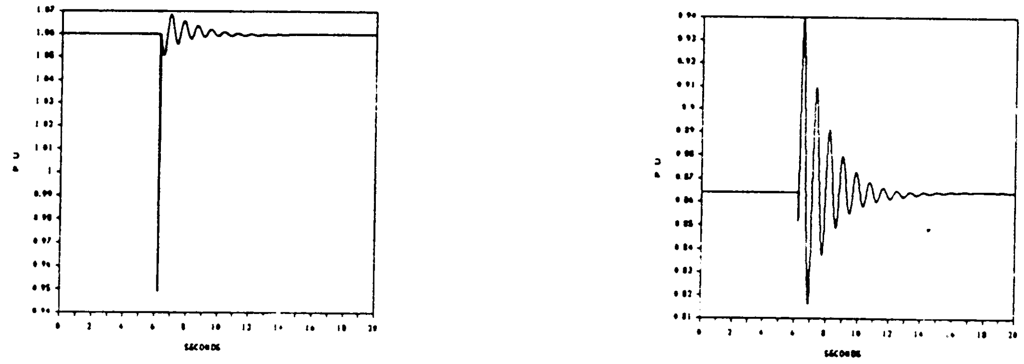
Figure 17. **Permanent Phase to Ground Fault at the Terminals of the generator**



a. Active power b. Frequency

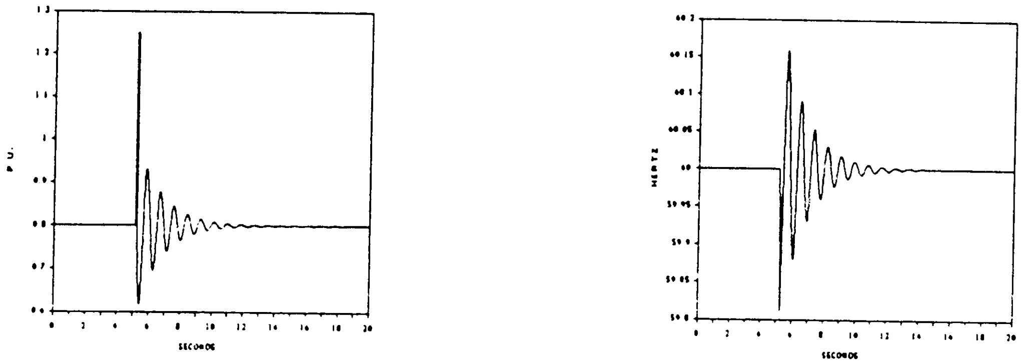


c. Load Angle d. Reactive Power

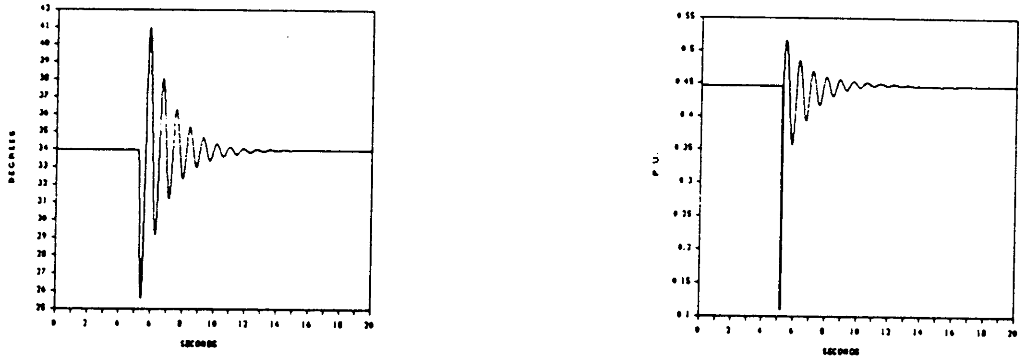


d. Terminal voltage e. Current

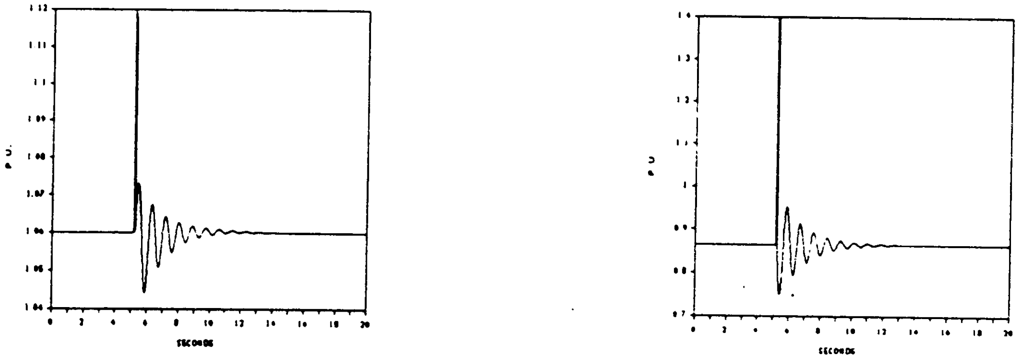
Figure 18. Phase to Ground Fault at he High Voltage Terminals of the transformer



a. Active power b. Frequency

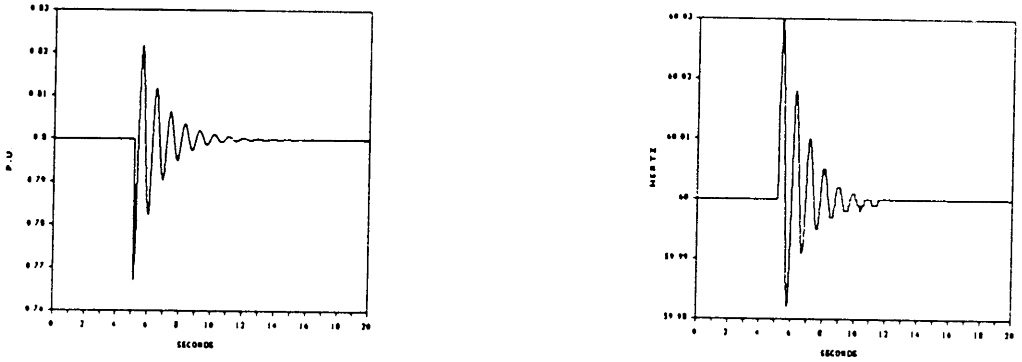


c. Load Angle d. Reactive Power



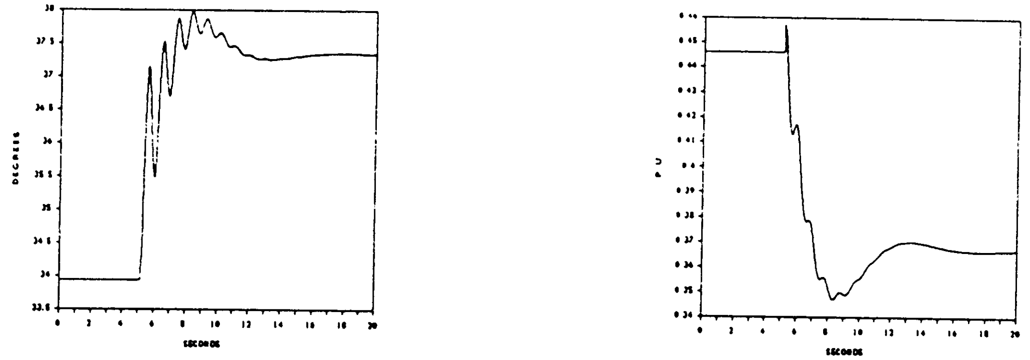
d. Terminal voltage e. Current

Figure 19. Open Phase at the High Voltage Terminals of the Transformer



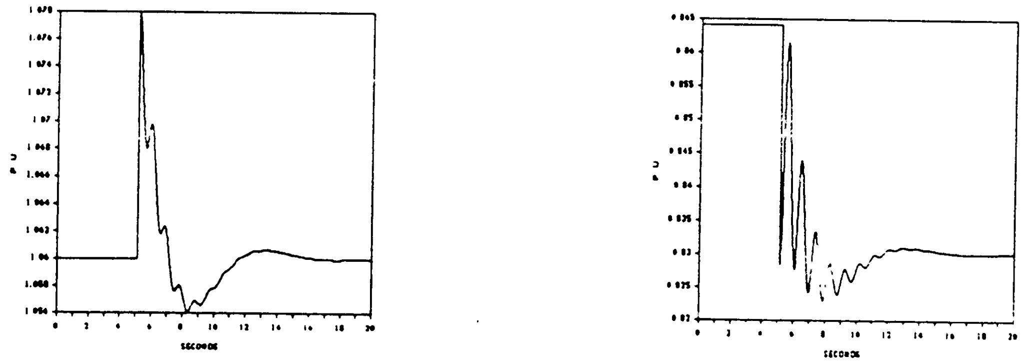
a. Active power

b. Frequency



c. Load Angle

d. Reactive Power



d. Terminal voltage

e. Current

Figure 20. One Transmission Line Removed

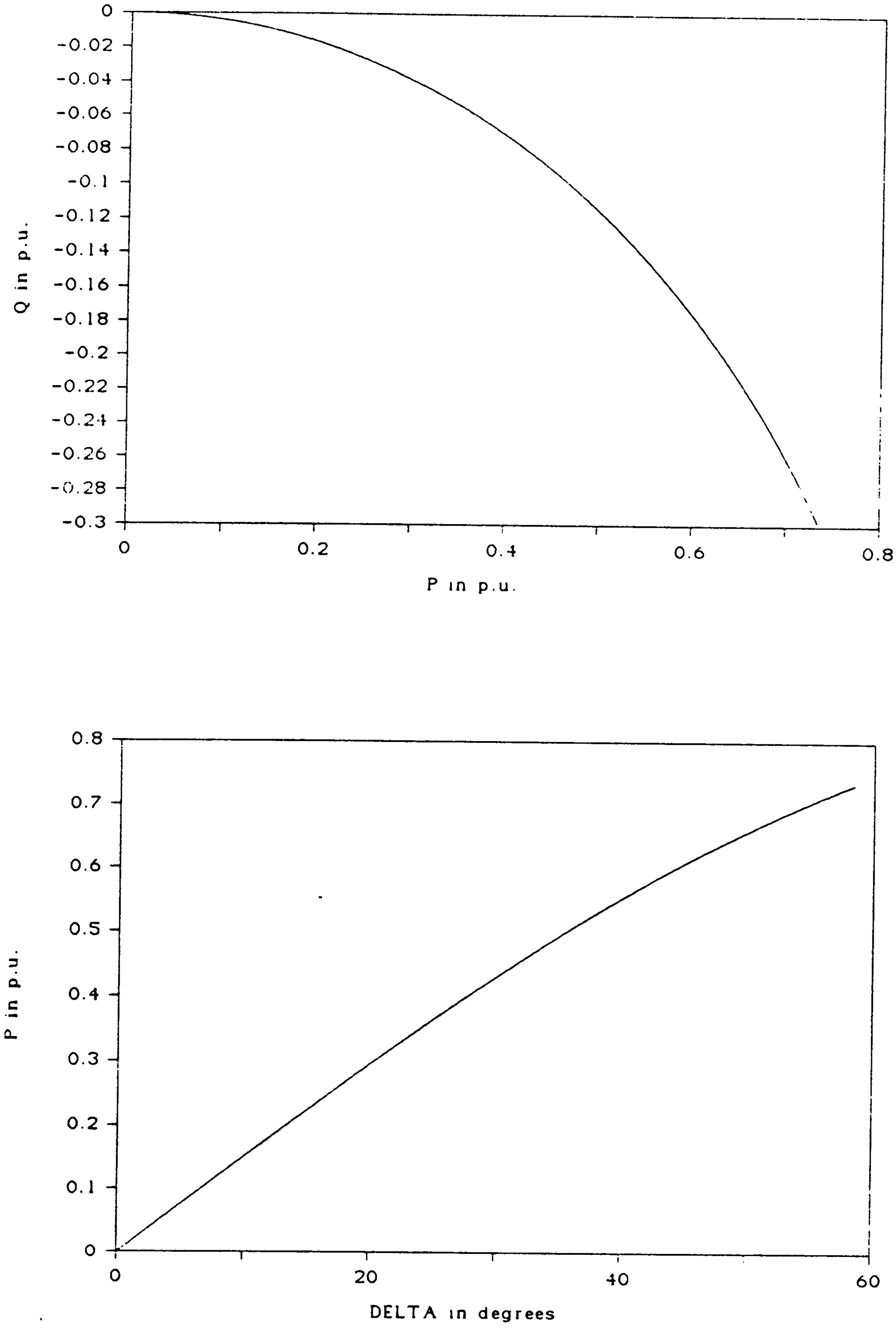


Figure 21. Loading of Generator with Voltage Regulator in Manual Operation

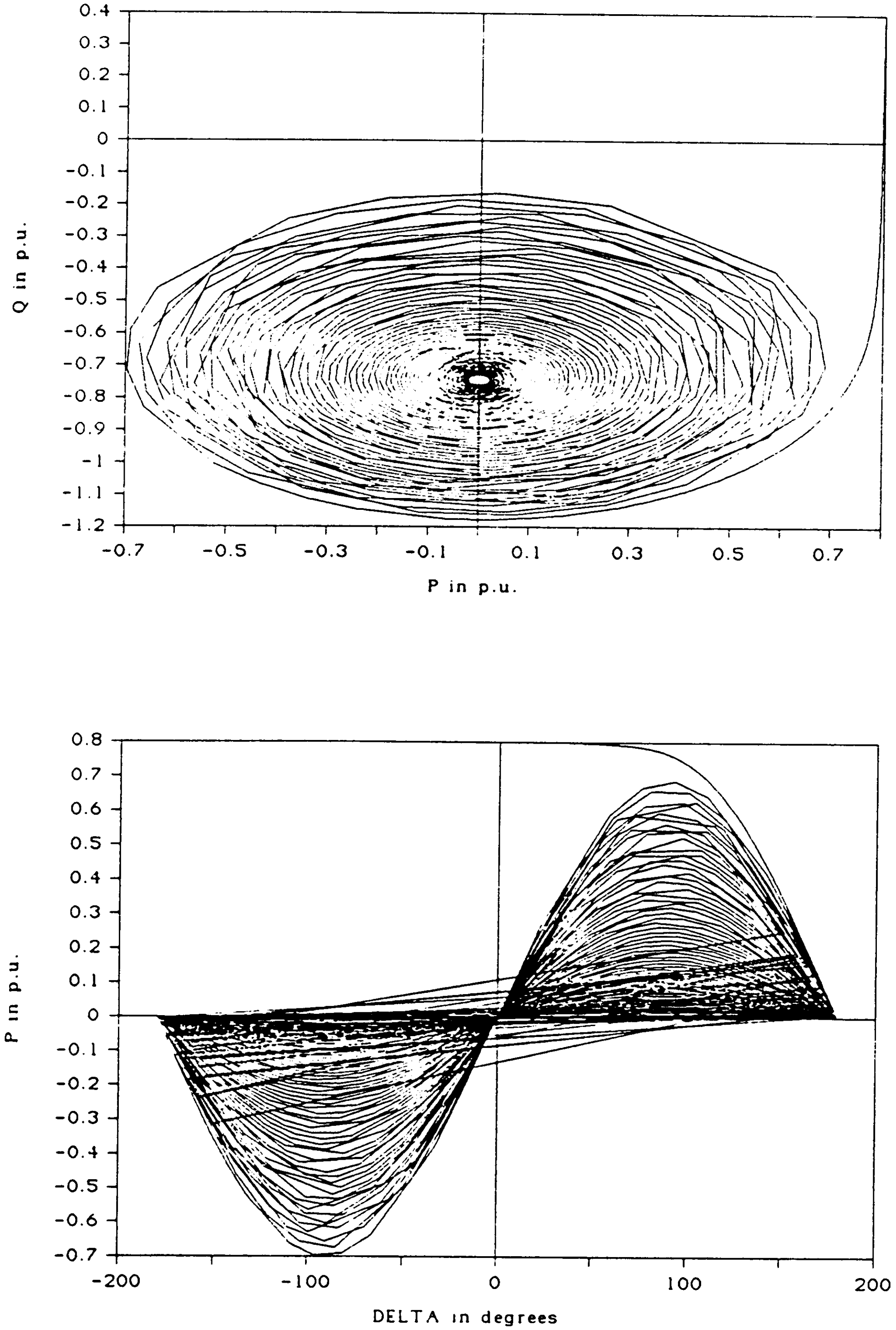


Figure 22. Loss of field

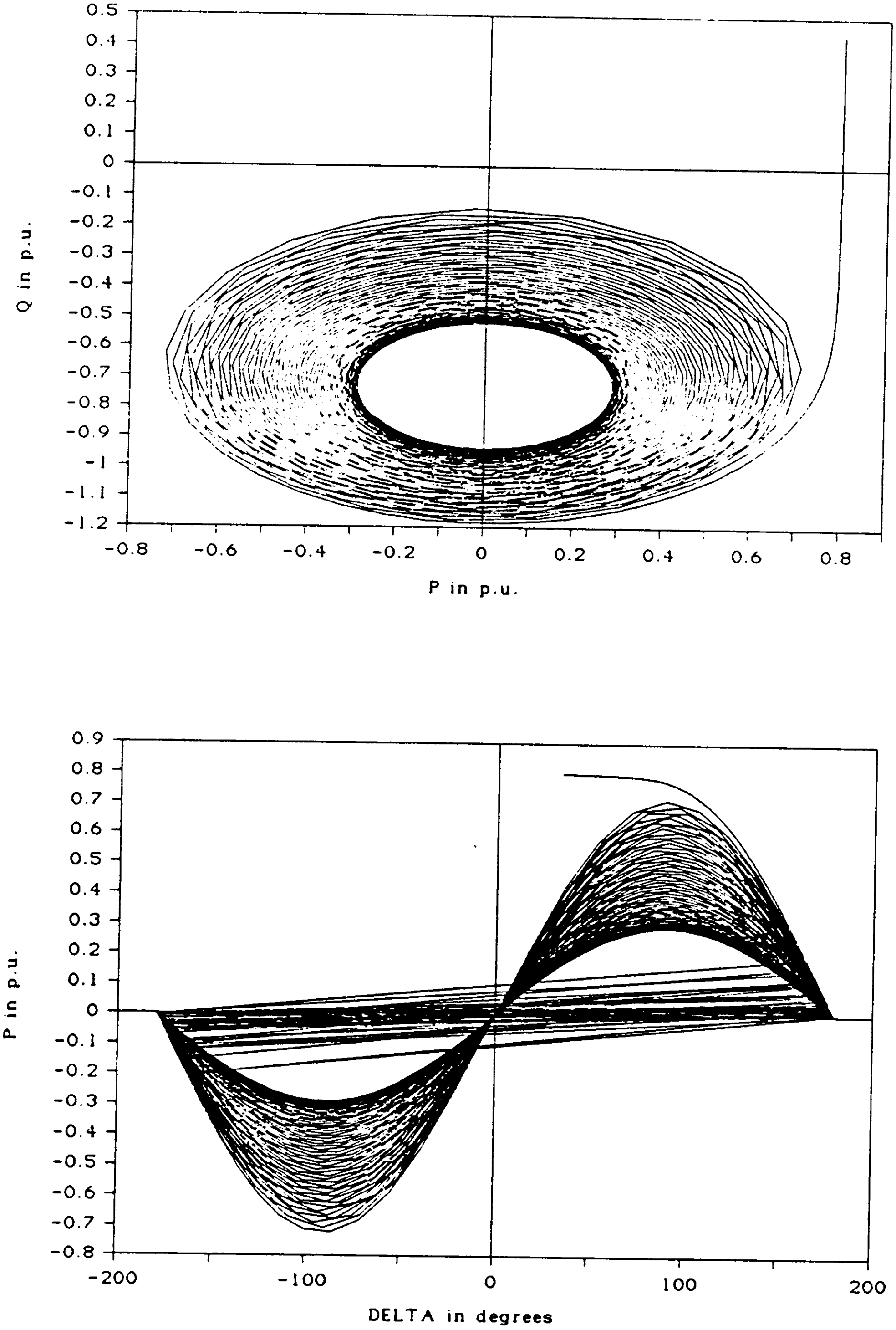


Figure 23. Abnormal Voltage Regulator Switch from Automatic to Manual

the generator to the infinite bus or by variations of the settings of the generator or even internal faults in the generator like a loss of field situation.

The system implemented in two computers representing an instructor and an operator can simulate a good number of faults from the instructor's computer and at the same time the operator can vary all the generator settings to move the generator from one operating point to another, including start-up and synchronization to the system, and thus becomes an excellent tool for training ofgeneration-station operators.

The power capability curve dynamic screen representation becomes very important in the simulation of some if not all operating conditions of the generator. In particular the excursion of the operating point during a loss of field situation becomes very representative of the actual conditions at which the generator is working.

The meter representing the negative sequence component of the current becomes also a very useful tool for the operator to make any decision, when this meter indicates an abnormal reading during a considerable period of time.

4.3 FURTHER WORK

For the system developed all the interaction between the simulation and the operator is through the screens representing the meters and the keyboard representing the controls normally available at a generation station control room. But a further and more reallistic development would be if the actual generation station enviroment is included in the simulation.

In order to achieve this the screen representation could be changed by actual analog meters implemented in a similar panel like in the generator's control room together with the necessary switches or controls to change the generator settings from the same panel. The developed simulation can be interacted with this panel by the use of the corresponding D/A, A/D and I/O cards. The digital generator output can also be used to reconstruct a sine wave in order to drive a real synchronoscope which would form part of the generator's panel.

With this implementation developed, more functions could be added to the actual software developed. Actually a large number of additional tools could be implemented to allow anybody interested to have a clearer idea of the behavior of the generator under different situations.

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