BLACKSTART UTILIZATION OF REMOTE
COMBUSTION TURBINES

R. L. HOLMGREN

Power Affiliates Program
Department of Electrical Engineering
University of Illinois at Urbana-Champaign
Urbana, Illinois 61801

PAP-TR-80-5

September 1980
FOREWORD

This technical report is a reprint of the thesis written by Mr. R. L. Holmgren as partial fulfillment of the requirements for the degree of Master of Science in Electrical Engineering at the University of Illinois. His research was directly supported through the Power Affiliates Program.

R. D. Shultz
Thesis Advisor
September 1980
ACKNOWLEDGEMENTS

I wish to thank Prof. Richard D. Shultz for his guidance in writing this paper. I also wish to thank the University of Illinois Power Affiliates Program for their financial support and Illinois Power Company for their assistance.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. INTRODUCTION</td>
<td>1</td>
</tr>
<tr>
<td>1.1 Motivation</td>
<td>1</td>
</tr>
<tr>
<td>1.2 Literature Search</td>
<td>2</td>
</tr>
<tr>
<td>2. MACHINE MODELS</td>
<td>6</td>
</tr>
<tr>
<td>2.1 Generator Model</td>
<td>6</td>
</tr>
<tr>
<td>2.2 Exciter Model</td>
<td>9</td>
</tr>
<tr>
<td>2.3 Governor Model</td>
<td>11</td>
</tr>
<tr>
<td>2.4 Induction Motor Models</td>
<td>13</td>
</tr>
<tr>
<td>3. BLACKSTART PROGRAM</td>
<td>19</td>
</tr>
<tr>
<td>4. BLACKSTART EVALUATION</td>
<td>23</td>
</tr>
<tr>
<td>4.1 Blackstart Evaluation - Assumptions</td>
<td>23</td>
</tr>
<tr>
<td>4.2 Blackstart Evaluation - Results</td>
<td>30</td>
</tr>
<tr>
<td>5. EFFECT OF DAMPING COEFFICIENT</td>
<td>54</td>
</tr>
<tr>
<td>6. CONCLUSIONS AND RECOMMENDATIONS</td>
<td>56</td>
</tr>
<tr>
<td>REFERENCES</td>
<td>58</td>
</tr>
<tr>
<td>APPENDIX: PROGRAM LISTING</td>
<td>60</td>
</tr>
<tr>
<td>Figure</td>
<td>Description</td>
</tr>
<tr>
<td>--------</td>
<td>-----------------------------------------------------------------------------</td>
</tr>
<tr>
<td>1.</td>
<td>Equivalent circuit of two-axis generator model.</td>
</tr>
<tr>
<td>2.</td>
<td>Block diagram of exciter model.</td>
</tr>
<tr>
<td>3.</td>
<td>Block diagram of governor model.</td>
</tr>
<tr>
<td>4.</td>
<td>Equivalent circuit of induction motor during start-up.</td>
</tr>
<tr>
<td>5.</td>
<td>Equivalent circuit for on-line induction motor.</td>
</tr>
<tr>
<td>6.</td>
<td>Program flow chart.</td>
</tr>
<tr>
<td>7.</td>
<td>Transmission system</td>
</tr>
<tr>
<td>8a.</td>
<td>Two boiler pump motor start-up, terminal voltage vs. time</td>
</tr>
<tr>
<td>8b.</td>
<td>Two boiler pump motor start-up, frequency vs. time.</td>
</tr>
<tr>
<td>8c.</td>
<td>Two boiler pump motor start-up, motor slip vs. time.</td>
</tr>
<tr>
<td>9a.</td>
<td>One boiler pump motor start-up, terminal voltage vs. time</td>
</tr>
<tr>
<td>9b.</td>
<td>One boiler pump motor start-up, frequency vs. time.</td>
</tr>
<tr>
<td>10a.</td>
<td>One boiler pump motor start-up, one boiler pump motor on-line, terminal voltage vs. time</td>
</tr>
<tr>
<td>10b.</td>
<td>One boiler pump motor start-up, one boiler pump motor on-line, frequency vs. time</td>
</tr>
<tr>
<td>10c.</td>
<td>One boiler pump motor start-up, one boiler pump motor on-line, voltage behind reactance vs. time</td>
</tr>
<tr>
<td>10d.</td>
<td>One boiler pump motor start-up, one boiler pump motor on-line, on-line motor slip vs. time</td>
</tr>
<tr>
<td>11a.</td>
<td>Two ID motor start-up, two boiler pump motors on-line, terminal voltage vs. time</td>
</tr>
<tr>
<td>11b.</td>
<td>Two ID motor start-up, two boiler pump motors on-line, frequency vs. time.</td>
</tr>
<tr>
<td>11c.</td>
<td>Two ID motor start-up, two boiler pump motors on-line, ID motor slip vs. time</td>
</tr>
<tr>
<td>Figure</td>
<td>Description</td>
</tr>
<tr>
<td>--------</td>
<td>-------------</td>
</tr>
<tr>
<td>12a.</td>
<td>Two FD motor start-up, two boiler pump and two ID motors on-line, terminal voltage vs. time.</td>
</tr>
<tr>
<td>12b.</td>
<td>Two FD motor start-up, two boiler pump and two ID motors on-line frequency vs. time.</td>
</tr>
<tr>
<td>13a.</td>
<td>Four pulv. motor start-up with two boiler pump, two ID and two FD motors on-line, terminal voltage vs. time.</td>
</tr>
<tr>
<td>13b.</td>
<td>Four pulv. motor start-up, with two boiler pump, two ID and two FD motors on-line, frequency vs. time.</td>
</tr>
<tr>
<td>14a.</td>
<td>Sluice pump motor start-up with all other motors on-line, terminal voltage vs. time.</td>
</tr>
<tr>
<td>14b.</td>
<td>Sluice pump motor start-up, with all other motors on time, frequency vs. time.</td>
</tr>
<tr>
<td>15.</td>
<td>One boiler pump start-up, varying damping coefficient, D, frequency vs. time.</td>
</tr>
</tbody>
</table>
## LIST OF TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Combustion turbine generator stability data.</td>
<td>24</td>
</tr>
<tr>
<td>2.</td>
<td>Exciter data</td>
<td>25</td>
</tr>
<tr>
<td>3.</td>
<td>Dynamic response parameters for governor</td>
<td>26</td>
</tr>
<tr>
<td>4.</td>
<td>Transmission system data</td>
<td>26</td>
</tr>
<tr>
<td>5.</td>
<td>Induction motor data</td>
<td>27</td>
</tr>
<tr>
<td>6.</td>
<td>Blackstart evaluation results</td>
<td>53</td>
</tr>
</tbody>
</table>
1. INTRODUCTION

1.1 Motivation

Power systems in many areas of the country today are expanding. As a result, generating units are being placed at greater distances from their loads. Because of today's high voltage transmission lines, larger amounts of power are being sent over greater distances. These trends in the power industry have increased the exposure of power systems and groups of power systems to possible large-scale outages. Because quick recovery from such outages is the responsibility of the power industry, blackstart evaluations of power systems are becoming an increasingly important area of interest for electric utilities.

Power plants that rely on steam to generate bulk electrical power require a source of electricity to operate the power plant. This electrical power is needed to run large induction motors located at the power plant. Among other things, these induction motors run boiler pumps which circulate water through the boiler, large fans which circulate air through combustion chambers, and, in the case of coal burning plants, pulverizing mills. Normally, if a system loses its spinning generation, interconnections with other power systems are relied upon to operate these motors during restoration attempts. However, in the event of a massive, multicompany power outage, a utility might lose its ties with other systems as well as its own spinning generation.

Since waiting for an external source to restore its own system may involve an unacceptable amount of time, an alternative for the utility would be blackstarting.

The blackstarting would involve the use of a combustion-turbine generating unit (CTG), powered by a gas-turbine engine. These units can
be equipped to start without an external source of electrical power. A CTG unit could be used to operate the large power plant motors. Most utilities today own CTG units and use them for peaking units generally. The CTG unit itself might not be located at the power plant requiring start-up. The remoteness of the CTG might therefore cause stability and voltage problems.

This paper explores the problem of blackstarting a power plant with a remote combustion-turbine generating unit. Through the use of a digital computer, simulations are made of induction motor start-ups through a transmission system, focusing on stability and voltage level problems in the system. An actual array of large induction motors typically found in a power plant are tested to determine if they can be blackstarted (using a CTG) from a remote location.

1.2 Literature Search

Not only is a massive outage of large power systems a possibility, it has actually occurred. On December 19, 1978 the Electricité de France (EDF) system, similar in many ways to several U.S. power systems, lost the majority of its nationwide system load [1]. A major disturbance on the French national grid caused shedding of 29.0 GW out of an initial demand of 37.2 GW. Power plants that were not isolated on their own auxiliary loads had to wait until an electrical source was available from another operating plant. Although at this date some utilities have performed preliminary evaluations of their blackstart capabilities [2] and have considered blackstart capabilities in their planning processes [3], little information in the literature is available on this topic. Some studies [4], [5] have researched system restoration, but with the assumption of a strong, external source being available for use.
Three machine models are needed for the computer simulation. An appropriate synchronous generator model is required to represent the remote CTG unit. A paper by Lokay and Bolger [6] investigates the effects of turbine-generator representations. In a discussion of this paper, Kimbark summarizes the authors' study. Results seem to indicate machine damping, excitation control and speed-governor action both to be important factors to be included in machine modeling. Damping, if neglected, gives a more pessimistic stability limit. Therefore, the generator model used in this paper includes machine damping. Also of interest is the effect of steady-state stability problems which might be caused by exciter control and governor action on the CTG unit. The generator model used in this paper is the two-axis model developed in Anderson and Fouad [7]. This is a fourth-order, mathematical model derived from the complete model by neglecting subtransient effects. The exciter model used is an IEEE Type I [8], that is, a continuously acting regulator and exciter. A third-order mathematical model is used to represent governor action of the CTG. Together these models represent in sufficient detail the CTG response to system disturbances. These models are shown in the following chapter.

The behavior and modeling of the induction motor has been extensively examined in power system stability studies [9], [10], [11]. In a paper by Brerton, Lewis and Young [12], several induction motor models are reviewed: a model which uses the simple impedance is used when the induction motor has a relatively small effect on the system, a model which uses the steady-state equivalent circuit with only mechanical transients, a model which includes both mechanical and electrical transients called the transient model, and finally one which includes mechanical, rotor electrical and stator electrical transients.
Two different model representations are required in the blackstart study. A model is needed to represent an induction motor during start-up, that is, from standstill to rated slip. This represents a wide range of operating conditions. The model needed must be dependent on system frequency and motor speed. When an induction motor is brought on-line, the voltage at its terminals will dip and an initial rush of current into the motor occurs. These dips are important in that a fall in voltage below a certain value will cause stalling of the motor and a failure to start-up. Both of these effects occur at start-up and reduce as the rotor speed increases. In this paper, the model for a motor being started up is one utilizing the induction motor, steady-state equivalent circuit and the electrical torque equation. The equivalent circuit is an impedance model dependent on rotor slip and is convenient in that it can be inserted into the admittance matrix of the system to represent the motor. At zero rotor speed, the slip of the rotor equals unity and the equivalent impedance of the motor is much smaller than the equivalent impedance at rated speed. This model assumes that the electrical transients are much shorter than the mechanical transients. This model was chosen for representation during start-up because the average torque as opposed to the instantaneous torque is of interest during this period.

A second model is needed to represent the induction motor already operating on-line at rated speed and underload. This represents a situation different from the motor being brought on-line. In the case of blackstarting, all motors, whether already operating on-line or being started up, are connected to the same bus. Voltage changes brought on by the motor being started up are therefore also felt by motors already
As a result, on-line motors could momentarily fall into a generation mode if the initial voltage dip is drastic enough. This power would come from the flux linkages in the rotor. Therefore, rotor transients are important. The induction motor, transient model is used to represent the on-line motors in this paper. This model utilizes a voltage behind a reactance, and if the terminal voltage drops far enough and fast enough, power will be supplied to the system. These induction motor models are shown in the following chapter.
2. MACHINE MODELS

2.1 Generator Model

The two-axis model for the generator was derived in Anderson [7] starting with the complete eighth-order model of a synchronous generator. The model is reduced to a fourth-order representation by assuming the subtransient responses are negligible compared to the transient effects. The transient effects are dominated by the rotor circuits of the generator which are the field circuit on the d axis and an equivalent q axis derived from the solid rotor. The stator voltage equations assume the change in flux linkages of the d and q circuits with respect to time ($\dot{\lambda}_d$ and $\dot{\lambda}_q$) are equal to zero. This reduces the number of electrical equations describing the generator to four, that is, two stator circuits and two rotor circuits. The electrical equations are

$$E'_d = V_d + rI_d + X'_dI_q \quad (1)$$

$$E'_q = V_q + rI_q - X'_dI_d \quad (2)$$

$$\frac{dE'_d}{dt} = \frac{1}{\tau_{q0}}[-E'_d + (X_q - X'_q)I_q] \quad (3)$$

$$\frac{dE'_q}{dt} = \frac{1}{\tau_{d0}}[E_{FD} - E'_q + (X_d - X'_d)I_d] \quad (4)$$

Stator Equations (1) and (2) are algebraic because of the assumption that $\dot{\lambda}_d$ and $\dot{\lambda}_q$ are negligible. Rotor Equations (3) and (4) are differential. $E'_q$ and $E'_d$ are the q and d axis components of a voltage $E'$ behind the transient reactance. Equation (1) and (2) suggest the equivalent circuit shown in Figure 1. $\bar{E}'$ corresponds to transient flux linkages in the machine and is not constant but changes due to the changes of the flux linkages in the rotor circuits.
Figure 1. Equivalent circuit of two-axis generator model.
There are two mechanical equations describing the change in rotor angle and change in rotor speed with respect to time. The mechanical equations are

\[ \frac{d\omega}{dt} = \frac{1}{2H_G} [T_{MG} - D\omega - T_{EG}] \quad (5) \]

\[ \frac{d\delta}{dt} = \omega - 1 \quad (6) \]

In Equation (6), the term \( D\omega \) represents the machine damping torque. \( T_{MG} \) is the mechanical torque delivered to the generator through the shaft. \( T_{EG} \) is the electrical torque, which is derived in Anderson [7]. The equation for \( T_{EG} \) is

\[ T_{EG} = E_d' I_d + E_q' I_q - (L'_d - L'_q) I_d I_q \quad (7) \]

Symbols:
- \( E_d' \) = d axis component of voltage
- \( E_q' \) = q axis component of voltage
- \( V_d \) = d axis component of terminal voltage
- \( V_q \) = q axis component of terminal voltage
- \( E_{FD} \) = d axis stator emf corresponding to field voltage excitation
- \( I_d \) = d axis component of current
- \( I_q \) = q axis component of current
- \( \tau'_d \) = d axis open-circuit, transient time constant
- \( \tau'_q \) = q axis, open-circuit, transient time constant
- \( X_d \) = d axis synchronous reactance
- \( X_q \) = q axis synchronous reactance
- \( X'_d \) = d axis transient reactance
- \( X'_q \) = q axis transient reactance
- \( L'_d \) = d axis transient inductance
$L'_q = q$ axis transient inductance
$	au = \text{stator resistance}$
$T_{MG} = \text{mechanical torque on generator}$
$T_{EG} = \text{electrical torque on generator}$
$D = \text{damping coefficient of generator}$
$H_G = \text{inertia constant of generator}$
$\delta = \text{generator rotor angle}$
$\omega = \text{generator speed}$

2.2 **Exciter Model**

The excitation system representation used is an IEEE Type I representation, which is a continuously acting regulator and exciter, whose block diagram is shown in Figure 2. From the block diagram it is seen that this is a fourth-order representation. Choosing as state variables $E_{FD}$, $V_R$, $V_3$ and $V_1$, the differential equations are

$$\frac{dE_{FD}}{dt} = \frac{1}{\tau_E} [V_R - (SE + K_e)]$$ (8)

$$\frac{dV_R}{dt} = \frac{1}{\tau_A} [-K_A(V_3 + V_1) - V_R + K_A(V_S + V_{REF})]$$ (9)

$$\frac{dV_3}{dt} = \frac{1}{\tau_F} \left[ -V_3 - \frac{K_F}{\tau_E} (V_R - SE_{PD} - K_e_{E_{PD}}) \right]$$ (10)

$$\frac{dV_1}{dt} = \frac{1}{\tau_R} [V_t - V_1]$$ (11)

Note that these equations are coupled to the generator equations by $E_{FD}$ and $V_t$. 
Figure 2. Block diagram of exciter model (see ref [8]).
Symbols:  

\(E_{FD}\) = exciter output voltage  
\(V_R\) = regulator output voltage  
\(V_3\) = stabilizing circuit voltage  
\(V_1\) = filtered terminal voltage  
\(\tau_E\) = exciter time constant  
\(\tau_A\) = regulator time constant  
\(\tau_F\) = stabilizing circuit time constant  
\(\tau_R\) = regulator filter time constant  
\(K_A\) = regulator gain  
\(K_E\) = exciter constant  
\(K_F\) = stabilizing circuit gain  
\(V_t\) = generator terminal voltage  
\(V_{REF}\) = reference voltage  
\(V_S\) = other signals  
\(SE\) = exciter saturation function

SE, the exciter saturation function, is a provision made to include the effect of saturation in the exciter. (see Anderson [7]). The saturation function is approximated by

\[
SE = A_{EX} \exp(B_{EX} E_{FD}) \quad (12)
\]

\(A_{EX}\) and \(B_{EX}\) are derived from exciter data. Since the value of the regulator filter time constant is generally very small, it was assumed equal to zero.

2.3 Governor Model

The block diagram for the governor is shown in Figure 3. This governor diagram was taken from generator data. From the black diagram, it is seen that this is a third-order system. Choosing \(P_M\) and \(P_A\) as state variables, the differential equations are
Figure 3. Block diagram of governor model.
\[
\frac{dP_M}{dt} = \frac{P_0 + P_\Delta - P_M}{\tau_3}
\] (13)

\[
\frac{dP_\Delta}{dt} = \left[\frac{(\omega_{ref} - \omega)K_1}{\tau_1} - \frac{K_1\tau_2}{\tau_1} \frac{d\omega}{dt} - \frac{P_\Delta}{\tau_1}\right]
\] (14)

Note that these equations are coupled to the generator by \(\omega\), generator speed, \(\frac{d\omega}{dt}\), generator acceleration and \(P_M\). Since the generator equations are in terms of \(T_{MG}\), another equation relating the two is

\[
T_{MG} = \frac{P_M}{\omega}
\] (15)

Symbols:
- \(P_M\) = mechanical power input to generator
- \(P_0\) = initial mechanical power input to generator
- \(P_\Delta\) = change in power input to generator
- \(K_1\) = controller power gain
- \(\tau_1\) = controller lag
- \(\tau_2\) = controller lead compensation
- \(\tau_3\) = overall governor and combustor lag
- \(\omega\) = generator speed
- \(\omega_{ref}\) = initial generator speed
- \(\frac{d\omega}{dt}\) = generator acceleration

2.4 Induction Motor Models

The model representing an induction motor being started utilizes the induction motor equivalent circuit shown in Figure 4. This model assumes that the mechanical transients are more dominant than the electrical transients. The value of slip is calculated and, using the equivalent
Figure 4. Equivalent circuit of induction motor during start-up.
circuit, the equivalent impedance of the motor at that slip is then known. The rotor current, $I_2$, can be calculated knowing the terminal voltage. The equation for electrical torque is

\[ T_{El} = \frac{3|I_1| r_r}{\omega_s l} \]  \hspace{1cm} (16)

This value of torque is used in the mechanical equation for the machine rotor.

\[ \frac{d\omega}{dt} = \frac{1}{I} [T_M - T_{el}] \]  \hspace{1cm} (17)

Symbols: $r_s$ = stator resistance  
$x_s$ = stator reactance  
$r_r$ = rotor resistance (referred to stator)  
$x_r$ = rotor reactance (referred to stator)  
$x_m$ = magnetizing reactance  
$\omega_s$ = synchronous speed of new motor  
$\omega_l$ = speed of rotor of new motor  
$S_l$ = rotor slip = $\frac{\omega_s - \omega_l}{\omega_s}$  
$T_M$ = mechanical load torque  
$T_{el}$ = electrical torque of new motor  
$I$ = moment of inertia of rotor.

The mechanical torque, $T_M$, is approximated by an exponential function dependent on rotor slip and is given by

\[ T_M = A_M \exp(B_M \cdot S) \]  \hspace{1cm} (18)

where $A_M$ and $B_M$ are calculated from induction motor data.
The above model is also used to represent the motors already on-line during the load flow made prior to the stability analysis. It is inserted into the admittance matrix only during the load flow run.

A different model is used to represent the on-line motors during the stability run. The induction motor transient model, shown in Figure 5, is a voltage behind a reactance model. The electrical equations are

\[
\frac{dE_M'}{dt} = -j \omega_{s2} S_2 E_M' - \frac{1}{T_{d0}} [E_M' - j(X - X')I] \tag{19}
\]

\[
\bar{V} - \bar{E}_M' = (r_s + jX')I \tag{20}
\]

\[
T_{E2} = \text{Re}[E_M' \bar{I}^*] \tag{21}
\]

The mechanical equation is

\[
\frac{dS_2}{dt} = \frac{1}{2H_M} [T_{M2} - T_{E2}] \tag{22}
\]

\(E_M'\) is the voltage behind the transient reactance and corresponds to rotor flux linkages.

Symbols:  
- \(X\) = input reactance at zero slip  
- \(X'\) = input reactance at unit slip  
- \(T_{d0}'\) = rotor open circuit time constant  
- \(H_M\) = inertia constant of motor  
- \(T_{M2}\) = load torque of on-line motor  
- \(T_{E2}\) = electrical torque of on-line motor  
- \(\omega_{s2}\) = synchronous speed of on-line motor  
- \(\omega_2\) = speed of on-line motor  
- \(S_2\) = slip of on-line motor = \(\frac{\omega_{s2} - \omega_2}{\omega_{s2}}\)  
- \(\bar{V}\) = terminal voltage  
- \(\bar{I}\) = terminal current
Figure 5. Equivalent circuit for on-line induction motor.
The next chapter describes the digital computer program and the use of the models described in this chapter.
3. BLACKSTART PROGRAM

Shown in Figure 6 is a flowchart with a general description of the program used to simulate a blackstart. A copy of the program, which was written in Fortran, can be found in the Appendix.

Initially, the program reads in all the system data and then builds the appropriate network admittance matrix called $Y_{BUS}$. In order to represent any on-line motors during the load-flow calculations, the induction motor equivalent circuit, shown in Figure 3, with the appropriately rated slip, is inserted into $Y_{BUS}$. With this modified $Y_{BUS}$, along with any local scheduled loads due to auxiliary equipment, the initial system voltages are calculated by a Newton-Raphson load flow [13]. After the load flow is completed, the on-line motor equivalent impedances are removed from $Y_{BUS}$. The scheduled loads are replaced by equivalent impedances at the appropriate bus in $Y_{BUS}$.

The generator and all the on-line induction motors are represented as voltages behind impedances. As a result, $Y_{BUS}$ is next modified by adding one bus to the system for the generator and one bus for each on-line motor and inserting the appropriate impedances. From the bus voltages calculated in the load flow, the currents through these new impedances can be found and thus the voltages behind each impedance can be found also.

These pre-startup conditions are used to calculate the initial conditions of the generator, exciter, governor and on-line motors. The generator, exciter and governor differential equations are solved for the steady-state condition. This is accomplished by equating the derivatives to zero. The mechanical torque of the on-line motors is found from the power being absorbed by the voltage behind the impedance.
Figure 6. Program flow chart.
The initial slip of the new motor is set equal to one and used in the induction motor equivalent circuit. This circuit is then inserted into \( Y_{\text{BUS}} \) at the appropriate bus as an impedance to ground. It is assumed that at the instant the new motor is being brought on-line, all the voltages behind impedances of the machine models remain constant. Under these new conditions, the remaining bus voltages are found by solving the network performance equations using an iterative technique (see [13]). This changes all of the terminal currents of the machines at time \( t = 0^+ \).

The rotor current of the new motor is then found with the bus voltage and equivalent circuit. The electrical torque is calculated from the current and slip by using Equation (16). The mechanical torque is estimated by assuming an exponential torque curve dependent on the slip of the motor. The angular speed of the motor is calculated using Equation (17). The differential equation is solved using the forward Euler method of integration.

The generator differential Equations (3), (4), (5) and (6) are then solved simultaneously along with exciter Equations (8), (9), (10) and (11) and governor Equations (13) and (14). These are all solved using the fourth-order Runge-Kutta method (see [13]).

The on-line motor differential Equations (15) and (18) are then solved, again using the fourth-order Runge-Kutta. These equations yield values of rotor slip and voltage for the next time step.

With the speed of the new motor and the speed of the generator found for the next time step, the slip for the next time step is then calculated. This slip is used to update the impedance of the new motor with the equivalent circuit.

Time is then iterated and tested for a maximum value. If the maximum value is not yet reached, the updated motor impedance is again inserted into \( Y_{\text{BUS}} \) and another time step set of calculations made.
This program assumes that prior to the new motor being brought on line, all other machines are running at steady state. For each motor start-up, a separate run of the program is made.
4. BLACKSTART EVALUATION

4.1 Blackstart Evaluation - Assumptions

With the computer program outline in the last chapter, a blackstart evaluation of a power plant is made in this chapter. The generator data, shown in Table 1 are those of a CTG. Data for the exciter and governor are shown in Tables 2 and 3, respectively. Since the CTG unit is remote, a transmission system is required between the CTG and the power plant induction motor load. Figure 7 shows the representation of the transmission system being used. The system is simply a 138 kV transmission line with a transformer at each end. The CTG bus voltage is 13.8 kV and the induction motor bus is 2.3 kV. A base of 100 MVA is used throughout the system. Data for the transmission system are shown in Table 4.

The loads at the power plant end of the transmission system are large induction motors being brought on-line in a certain sequence. The data for these motors are shown in Table 5. These motors represent the typical array needed to operate the boilers powering steam turbines at a power plant. The two largest, each a 2500 horsepower boiler pump motor, serve to pump water into the boiler. The two 900 horsepower, induced-draught (or ID) fan motors draw the flue gases from the combustion chamber of the boiler. Next are two 600 horsepower, forced-draught (or FD) fan motors which force air into the boiler to help fuel the combustion process. The pulverizer mill, which crushes the coal fuel into dust before it enters the boiler, is powered by four 350 horsepower motors. Finally, there is one 400 horsepower motor which powers an ash sluice pump [14].

Certain assumptions are made in analyzing the blackstart capability of this system. Each motor is represented either with the equivalent
TABLE 1.

Combustion turbine generator stability data. 
(13.8 kV and 100 MVA base)

\begin{align*}
X_d &= 6.21 \text{ p.u.} \\
X'_d &= 9.43 \text{ p.u.} \\
X_q &= 6.04 \text{ p.u.} \\
X'_q &= 9.43 \text{ p.u.} \\
T'_{do} &= 5.48 \text{ sec} \\
T'_{qo} &= 0.47 \text{ sec} \\
D &= 2.0 \text{ p.u.} \\
WR^2 &= 101,956 \text{ lb-ft}^2
\end{align*}
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_A$</td>
<td>400.0</td>
</tr>
<tr>
<td>$K_E$</td>
<td>1.00</td>
</tr>
<tr>
<td>$K_T$</td>
<td>0.03</td>
</tr>
<tr>
<td>$\tau_A$</td>
<td>0.02 sec</td>
</tr>
<tr>
<td>$\tau_E$</td>
<td>0.46 sec</td>
</tr>
<tr>
<td>$\tau_T$</td>
<td>1.00 sec</td>
</tr>
<tr>
<td>$\tau_R$</td>
<td>0.005 sec</td>
</tr>
<tr>
<td>$SE_{(\max)}$</td>
<td>0.66</td>
</tr>
<tr>
<td>$SE_{(75% \max)}$</td>
<td>0.62</td>
</tr>
<tr>
<td>$E_{FD_{(\max)}}$</td>
<td>4.43 p.u.</td>
</tr>
<tr>
<td>$E_{FD_{(\min)}}$</td>
<td>0.00 p.u.</td>
</tr>
<tr>
<td>$V_R_{(\max)}$</td>
<td>7.37 p.u.</td>
</tr>
<tr>
<td>$V_R_{(\min)}$</td>
<td>-6.63 p.u.</td>
</tr>
</tbody>
</table>

**TABLE 2.**

Exciter data (13.8 kV and 100 MVA base)
TABLE 3.
Dynamic response parameters for governor.
(100 MVA base)

\[ K_1 = 0.0158 \]
\[ \tau_1 = 0.5 \text{ sec} \]
\[ \tau_2 = 1.25 \text{ sec} \]
\[ \tau_3 = 0.10 \text{ sec} \]

TABLE 4.
Transmission system data. (138 kV and 100 MVA base)

Transformers:

\[ X_{T1} = 0.1104 \text{ p.u.} \]
\[ X_{T2} = 0.1389 \text{ p.u.} \]

Transmission Line:

\[ R_L = 0.0121 \text{ p.u.} \]
\[ X_L = 0.1003 \text{ p.u.} \]
\[ B_L = 0.0273 \text{ p.u.} \]
### TABLE 5.

Induction motor data, (2.3 kV and 100 MVA base)

<table>
<thead>
<tr>
<th>Function</th>
<th>Quantity</th>
<th>Rated RPM</th>
<th>Rated HP</th>
<th>( I^2 ) (p.u.)</th>
<th>( X_S ) (p.u.)</th>
<th>( r_S ) (p.u.)</th>
<th>( X_r ) (p.u.)</th>
<th>( r_r ) (p.u.)</th>
<th>( X_m ) (p.u.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ID fan</td>
<td>2</td>
<td>890</td>
<td>900</td>
<td>900</td>
<td>16.4</td>
<td>2.23</td>
<td>8.94</td>
<td>4.47</td>
<td>484.0</td>
</tr>
<tr>
<td>FD fan</td>
<td>2</td>
<td>1180</td>
<td>600</td>
<td>375</td>
<td>24.6</td>
<td>4.02</td>
<td>13.4</td>
<td>6.03</td>
<td>849.0</td>
</tr>
<tr>
<td>Baler Feed Pump (BP)</td>
<td>2</td>
<td>3575</td>
<td>2500</td>
<td>400</td>
<td>5.90</td>
<td>0.322</td>
<td>4.83</td>
<td>0.912</td>
<td>228.0</td>
</tr>
<tr>
<td>Pulverizer mill</td>
<td>4</td>
<td>880</td>
<td>350</td>
<td>95</td>
<td>34.5</td>
<td>5.74</td>
<td>26.8</td>
<td>11.5</td>
<td>938.0</td>
</tr>
<tr>
<td>Ash Sluice Pump</td>
<td>1</td>
<td>1770</td>
<td>400</td>
<td>105</td>
<td>33.5</td>
<td>6.70</td>
<td>16.8</td>
<td>8.38</td>
<td>1040</td>
</tr>
</tbody>
</table>
Figure 7. Transmission system.
circuit model during start-up (see Figure 4) or the transient model after it has been started (see Figure 5). For each start-up attempted, a separate run of the program is made. If the start-up is successful, the newly started motor is then represented by the transient model on all successive runs. During each start-up attempt, the power input to the generator-exciter-governor system, shown as \( P_0 \) in Figure 3, is assumed to be constant. At the steady-state point reached after a start-up attempt, the frequency of the generator will be below 60.0 Hz. This is expected since the generator is being loaded. Another assumption made is that \( P_0 \) is increased an appropriate amount so as to allow a frequency of 60 Hz at the beginning of the next start-up attempt.

Protective relays in power systems guard against frequency drops which might occur during faults and other disturbances. If the frequency drops below a certain preset value, the relays will trip. It is assumed that the frequency settings are all 58.5 Hz. Thus, the system frequency cannot fall below this level for a successful start-up. Another stipulation for successful start-up is that the terminal voltage cannot fall below a certain level. Manufacturer's data state that a minimum voltage of 0.90 per unit is required for start-up. Therefore, the two conditions used for criteria determining successful start-up are

1. The frequency does not drop below 58.5 Hz and
2. The terminal voltage of a motor does not drop below 0.9 per unit.

Since all of the induction motors are connected to the same bus, only monitoring one bus voltage is required.

An order of start-up is required. The order assumed is
(1) 2 Boiler pump motors  
(2) 2 ID fan motors  
(3) 2 FD fan motors  
(4) 4 pulverizer motors  
(5) 1 sluice pump motor

This order is critical in determining the blackstart capabilities of power plant. With the case in point, starting the two boiler pump motors first is giving the generator its most disruptive disturbance when it is initially unloaded.

4.2 **Blackstart Evaluation - Results**

The first start-up attempted is the case of the two boiler pump motors. Figures 8a, 8b and 8c show the results of the run. Figure 8a shows the motor terminal voltage vs. time. Two cases are illustrated here. The first case was a start-up made with the terminal voltage of the generator initially at 1.00 per unit. The voltage at the motor terminals in this case dips down to a minimum value of 0.80 per unit. Since the motor terminal voltage cannot be allowed to drop below 0.90 per unit, this is an unsuccessful attempt. The other case shown is for initial generator terminal voltage of 1.04 per unit, which is an attempt to decrease the voltage dip. In spite of the raised generator voltage, however, the motor voltage still fell to a value of 0.83 per unit. The CTG unit then cannot successfully start the two boiler pump motors simultaneously from a remote location. Figure 8b shows the frequency of the system vs. time for both cases. In each case, the frequency dips down to approximately 59.77 Hz and then reaches a final value of approximately 59.80 Hz. There appears to be no stability problems as far as tripping the under-frequency relays in the system because these values are well above the settings. Therefore, the only problem is the voltage dip at the motor terminals.
Figure 8a. Two boiler pump motor start-up, terminal voltage vs. time.
Figure 8b. Two boiler pump motor start-up, frequency vs. time.
Figure 8c. Two boiler pump motor start-up, motor slip vs. time.
It is interesting to note that in both Figures 8a and 8b the most drastic changes in the frequency and voltage occur around the 2.0 second mark. A plot of motor slip vs. time is shown in Figure 8c. It is seen here that the motor is reaching its steady-state slip at just about the same time. Since this steady-state value of slip is very small, the equivalent impedance of the motor is significantly large. During the start-up time of the motor, the system is changing constantly and finally reaches a steady-state point of operation after the motor reaches a constant slip. The reaction of the generator-exciter-governor unit depends on the start-up time of each motor. This is the effect desired by using the equivalent circuit as a model for induction motor start-up.

Since starting two boiler pump motors at once produces unacceptable voltage dips, an alternative is to start the motors one at a time. This increases the equivalent impedance in the circuit of the system. Using an initial generator voltage of 1.00 per unit, however, still causes the motor voltage to drop slightly below 0.90 per unit. When a start-up is made with an initial generator voltage of 1.01 per unit, the voltage does stay above the minimum requirement. Figures 9a and 9b show the motor terminal voltage vs. time and frequency vs. time, respectively. The voltage dips to a value of 0.90 per unit and then, as the motor reaches rated slip, spikes to a value of 1.09 pu. For the purposes of this study, this is assumed acceptable and will not cause insulation problems in the motor since the voltage spike is very short. The frequency change is improved also from the first case and well above the limit set for a successful start-up. Next, the second boiler pump is started up.

In the start-up of the second boiler pump motor, the first pump is represented by the transient model of the induction motor. In order to keep
Figure 9a. One boiler pump motor start-up, terminal voltage vs. time.
Figure 9b. One boiler pump motor start-up, frequency vs. time.
the motor's terminal voltages above the 0.90 per unit level, the initial generator terminal voltage is again set at 1.01 per unit. Also, the power input is increased to the generator until a frequency of 60 Hz is obtained. Terminal voltage vs. time and frequency vs. time results for starting the second pump motor are shown in Figures 10a and 10b, respectively. Since this motor is identical to the first, the results are almost identical. The main difference is that the voltage spike is reduced to a peak value of only 1.08 per unit.

The response of the motor already on-line can be seen in Figures 10c and 10d, which show the magnitude of the voltage behind the reactance vs. time and the motor slip vs. time, respectively. The shape of this voltage curve is similar in shape to that of the terminal voltage of the motor. The slip decreases momentarily, due to the decrease in terminal voltage, and then returns to approximately its original value.

Prior to the next start-up, the frequency is again brought back to 60 Hz by increasing the power input to the generator. The second boiler pump motor is represented by the transient model from now on. The next step is to start-up the two ID fan motors. These fans have a much smaller power rating than the boiler pump motors, 900 horsepower for an ID motor compared to 2500 horsepower for a boiler pump motor. The rating for two fan motors is less than one pump motor. The per unit impedances of the ID motors are much greater than those of the boiler pump motors (see Table 5). There should be less difficulty in starting the ID fan motors. The results agree with this. Figures 11a and 11b show the terminal voltage vs. time and frequency vs. time for this start-up, respectively. The voltage dips down to a value of 0.91 per unit and then peaks up to 1.04 per unit before reaching steady state at 1.00 per unit. Note here, also, that the generator
Figure 10a. One boiler pump motor start-up, one boiler pump on-line, terminal voltage vs. time.
Figure 10b. One boiler pump motor start-up, one boiler pump motor on-line, frequency vs. time.
Figure 10c. One boiler pump motor start-up, one boiler pump motor on-line, voltage behind reactance vs. time.
Figure 10d. One boiler pump motor start-up, 1 boiler pump on-line motor slip vs. time.
Figure 11a. Two ID motor start-up, two boiler pump motors on-line, terminal voltage vs. time.
Figure 11b. Two ID motor start-up, two boiler pump motors on-line, frequency vs. time.
initial terminal voltage has been set back to 1.00 per unit. The spikes that occurred with the larger motors are less drastic here also. The frequency dips to a value of 59.93 Hz before reaching steady state at a value of 59.94 Hz. Both of the critical variables stay well above the allowed minimum values. Noticeable in both of these figures is the quicker response of the system than when the boiler pump motors were started. In the motor slip vs. time plot for the ID fan motors, shown in Figure 11c, the fans reach top speed in approximately 0.5 second. This corresponds well with the voltage peak in Figure 11a and the frequency dip shown in Figure 11b.

Following their start-up, the two ID fans are represented by the transient model for all successive runs. The frequency is again brought back to 60 Hz by increasing the power input to the generator. The next step is to start up the two FD fan motors. Since these motors are smaller in power rating than the ID fan motors, 600 horsepower compared to 900 horsepower for the ID fan motors, no problems are anticipated in starting both motors simultaneously. The results are shown in Figures 12a and 12b. The voltage dips to a minimum of 0.95 per unit and then peaks at a value of 1.03 per unit and then reaches steady state at 0.99 per unit. The initial terminal voltage of the generator was again 1.00 per unit. The frequency dips to a minimum of 59.95 Hz and then reaches steady state at 59.96 Hz. Again, both of the critical variables stay well above the allowed minimum values.

The FD motors are then represented by the transient model and the frequency is again raised to a value of 60 Hz before the next start-up. The four pulverizer motors which have a rating of 350 horsepower, are started next. Since the order of start-up happens to be of decreasing size and power rating, all four motors should be able to be started simultaneously. The results of the start-up are shown in Figures 13a and 13b. The voltage dips to a
Figure 11c. Two ID motor start-up, two boiler pump motors on-line, ID motor slip vs. time.
Figure 12a. Two FD motor start-up, two boiler pump and two ID motors on-line, terminal voltage vs. time.
Figure 12b. Two FD motor start-up, two boiler pump and two ID motors on-line, frequency vs. time.
Figure 13a. Four pulv. motor start-up, with two boiler pump, two ID and two FD motors on-line, terminal voltage vs. time.
Figure 13b. Four pulv. motor start-up, with two boiler pump, two ID and two FD motors on-line, frequency vs. time.
minimum of 0.93 per unit and then peaks to 1.00 per unit before reaching steady state at 0.99 per unit. The initial generator terminal voltage was again 1.00 per unit. The frequency dips down to 59.96 and remains there at steady state. Again, this is another successful start-up.

The four pulverizer motors are then represented by the transient model for the last start-up and frequency is again raised to 60 Hz by raising the power input to the generator. The last motor to be started up is the ash sluice pump motor. This power rating of this motor is 400 horsepower, and since only one such motor is being started, no difficulties are encountered in the start-up attempt. The results are shown in Figures 14a and 14b. The voltage dips to 0.97 per unit and then peaks at 1.00 before reaching steady state. The initial terminal voltage of the generator was again 1.00 per unit. The frequency dips only slightly to 59.99 Hz.

The resulting start-up order and data are summarized in Table 6.
Figure 14a. Sluice pump motor start-up, with all other motors on-line, terminal voltage vs. time.
Figure 14b. Sluice pump motor start-up, with all other motors on-line, frequency vs. time.
TABLE 6.
Blackstart evaluation results.

<table>
<thead>
<tr>
<th>Start-up No.</th>
<th>Motor</th>
<th>Quantity</th>
<th>Frequency (Hz)</th>
<th>Terminal Voltage (P.u.)</th>
<th>Initial Generator Terminal Voltage (p.u.)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>min</td>
<td>Steady State min</td>
<td>max</td>
</tr>
<tr>
<td>1</td>
<td>Boiler Feed Pump</td>
<td>1</td>
<td>59.89</td>
<td>59.90</td>
<td>0.90</td>
</tr>
<tr>
<td>2</td>
<td>&quot;</td>
<td>1</td>
<td>59.89</td>
<td>59.90</td>
<td>0.90</td>
</tr>
<tr>
<td>3</td>
<td>ID fan</td>
<td>2</td>
<td>59.93</td>
<td>59.94</td>
<td>0.91</td>
</tr>
<tr>
<td>4</td>
<td>FD fan</td>
<td>2</td>
<td>59.95</td>
<td>59.96</td>
<td>0.95</td>
</tr>
<tr>
<td>5</td>
<td>Pulverizer mill</td>
<td>4</td>
<td>59.96</td>
<td>59.96</td>
<td>0.93</td>
</tr>
<tr>
<td>6</td>
<td>Ash Sluice Pump</td>
<td>1</td>
<td>59.98</td>
<td>59.99</td>
<td>0.97</td>
</tr>
</tbody>
</table>

53
5. EFFECT OF DAMPING COEFFICIENT

As was mentioned in Section 1.2, if the generator model does not include machine damping, stability limits tend to be pessimistic. The manufacturer's data obtained for the combustion turbine generator did not include a value for the damping coefficient. A value of 2.0 per unit was chosen to represent the damping as this is a typical value. If the actual value of the damping coefficient is less than this value, the results obtained in the last section would yield frequency swings less drastic than in actuality. To see the effect of machine damping in the generator, simulations are made in starting up a single boiler pump motor through the transmission system. Four different cases are studied varying the damping coefficient, D (see Equation (5)), with values of 0.0, 2.0, 4.0 and 6.0 per unit. The frequency swings are shown in Fig. 15 for all four cases.

As expected, the swing is greatest when the damping coefficient was 0.0 per unit. This represents the case of neglecting the machine damping totally. Even in this case, however, the frequency reaches a steady-state minimum of 59.83 Hz. Since starting the boiler pump motor was the worst case for frequency swing, it can be assumed that even with machine damping neglected in the generator, the same procedure followed in the last chapter can still be used.
Figure 15. One boiler pump motor start-up, varying damping coefficient $D$, frequency vs. time.
6. CONCLUSIONS AND RECOMMENDATIONS

The objective of this thesis was to study the effects of utilizing remote, combustion-turbine generators for blackstarting a power plant. Using a computer stability program developed in this paper, an actual power plant was studied to determine if its steam-turbine generator could be blackstarted using a remote, combustion-turbine generator.

Previously developed machine models were discussed and chosen. A two-axis model was chosen to model the remote generator. To include possible steady-state stability effects, an exciter and governor model were included. Thus, a tenth-order, mathematical model describing the generator-exciter-governor unit was developed. Two models were chosen to represent the large induction motors. One induction motor equivalent circuit was used to represent a motor when it is being started up, and a different model was used to represent a motor already running on-line.

These models were then incorporated into a stability program. Then an actual power system was studied to determine its blackstart capability. Under-frequency relay settings and minimum start-up voltage were used as criteria for determining a successful start-up. Then, using a certain order for start-up, the motors were brought on-line, either in a group of the same type or one by one.

The terminal voltage of the boiler pump motors caused the only problems. These problems were alleviated by starting them up one at a time and raising the generator terminal voltage during each start-up. All other start-ups appear to occur successfully.

The only problems occurring were the terminal voltages of the motors. It is important to keep the voltage levels from dipping below the 0.9 per
unit mark to avoid stalling. The voltage spikes occurring with larger motors were assumed not to have harmful effects on the induction motors. All frequency levels remained well above the under-frequency relay settings, even if the machine damping of the generator was neglected.

Thus, the voltages of the induction motors seem to be the limiting factor in the order of start-up and quantity of motors to be started at one time. No stability problems were encountered. It appears, therefore, that this combustion-turbine generator can be used to remotely blackstart the power plant.
REFERENCES


APPENDIX

PROGRAM LISTING
PROGRAM BLACK(INPUT, OUTPUT, TAPE5=INPUT, TAPE6=OUTPUT)
COMPLEX Y(16, 16), YM(16), ZQ, ZP, ZER, V, I2, I3, BLDOAD(16), POU, CENI
COMPLEX VB(16), ZB(16, 16), Z(12), ZM(12), Z2(12), Z(12), ZO2, ZO3
COMPLEX ZN(4), ZMN(4), Z2N(4), Z3N(4), YIMN(4), VMON(200), EKEX
COMPLEX JAY, DUM, IRY, VEE
INTEGER ABUS, BBUS, BUS, LMAX2(12), BU(12), TYPE(12), NIM(12)
INTEGER NIMN(4), BUN(4), DNUM
REAL NG, VM(16), VA(16), IBASE, SLIP(12, 200), IX(12), WIM(4, 200)
REAL K, VMM, VMA, CG(13), GV(15), IXC(12), KA, KE, KF, CON2(4)
DIMENSION YMC16, 16), YAC16, 16), R2C12), R3C12), FSC200)
DIMENSION TIMEC200), SLIPNC4, 200), R2N(4), R3N(4), CON1(4)
REAL BK(12), TOP(12), TL(12), IP, IQ
COMPLEX XRIME(12), VTER, IKC12), EKC12, 200), VK(12), X0EN, VGEN
C READ IN NUMBER OF BUSES
READ(5, 10) BUS
10 FORMAT(6X, I2)
XI=4.0*K*TAN(1.0)
JAY=CMPLX(0.0, 1.0)
K=1.5**0.5
C INITIALIZE YBUS, LOADS TO ZERO
DO 11 I=1, BUS
BLOAD(I)=(0.0, 0.0)
DO 11 J=1, BUS
Y(I, J)=(0.0, 0.0)
11 CONTINUE
C DETERMINE YBUS
WRITE(6, 12)
12 FORMAT('LINES OF ORIGINAL SYSTEM')
READ(5, 13) ABUS, BBUS, ZO
13 FORMAT(6X, I2, 2F10.4)
IF (ABUS.EQ.0) GO TO 14
WRITE(6, 15) ABUS, BBUS, ZO
15 FORMAT('BUS', I2, ' TO ', I2, 3X, 'Z= ', F12.5, '+J', F12.5)
Y(ABUS, ABUS)=Y(ABUS, ABUS)+1.0/ZO
14 Y(ABUS, BBUS)=Y(ABUS, BBUS)+1.0/ZO
16 Y(BBUS, ABUS)=Y(BBUS, ABUS)+1.0/ZO
Y(BBUS, BBUS)=Y(BBUS, BBUS)-1.0/ZO
GO TO 16
C ADD GROUND TIES
READ(5, 17) ABUS, ZO
17 FORMAT(6X, I2, 2F10.4)
IF (ABUS.EQ.0) GO TO 18
WRITE(6, 19) ABUS, ZO
19 FORMAT('GROUND TIE AT BUS', I2, 3X, 'Z= ', F12.5, '+J',
+F12.5)
Y(ABUS, ABUS) = Y(ABUS, ABUS) + 1.0/Zo

GO TO 14

18 CONTINUE

C PRINT Y

WRITE(6,23)
23 FORMAT('1.',10('======='))

WRITE(6,24)
24 FORMAT('0',10X,'YBUS(ORIGINAL)')

WRITE(6,25)
25 FORMAT('0',10('======='))

WRITE(6,26)
26 FORMAT('0',6X,'YBUS MATRIX')

DO 27 I=1,BUS

DO 27 J=1,BUS

WRITE(6,28) I,J,Y(I,J)

28 FORMAT('5X,'Y(•,I2,•,•,r2,•)='F12.5,•tJ',F12.5)

27 CONTINUE

C READ IN LOADS

LMAX1=0

READ(5,71) ABUS, BBUS, Zo

READ(6,29) ABUS, BBUS, Zo

IF (ABUS.EQ.0) GO TO 73

BLOAD(BBUS) = Zo

LMAX2(ABUS) = BBUS

LMAX1=ABUS

73 CONTINUE

C READ IN BASE MVA, KV

READ(5,89) SBASE, VBASE

IBASE=(SBASE*1000.0)/(VBASE*(3.0**0.5))

ZBASE=(VBASE**2)/SBASE

C READ IN MACHINE CONSTANTS

C READ IN GENERATOR CONSTANTS

READ(5,29) EG, DELG, NG

READ(5,121)(CG(I),I=1,13)

CG(7) = CG(7)*120.0*XPI

CG(8) = CG(8)*120.0*XPI

CG(9) = CG(9)*120.0*XPI

CG(10) = CG(10)*120.0*XPI

GV(6) = (CG(1)-CG(6))/K
136 422 FORMAT(6F10.0/2F10.0)
137 NBUS=1
138 R2N(I)=REAL(Z2N(I))
139 R3N(I)=REAL(Z3N(I))
140 YMN(I)=Y(BUN(I),BUN(I))
141 CONTINUE
142 IF(NUMIM.EQ.1) GO TO 423
143 DO 103 I=2,NUMIM
144 READ(5,104)BU(I),SLIP(I,1),IX(I),Z(I),NIH(I)
145 104 FORMAT(I10,F10.0,E10.4,2F10.0,I10)
146 READ(5,105)ZM(I),Z2(I)
147 105 FORMAT(4F10.0)
148 R2(I)=REAL(Z2(I))
149 YIM(I)=Y(BU(I),BU(I))
150 ZIT1=AIMAG(Z2(I))
151 ZIT2=AIMAG(ZM(I))
152 BK(I)=(ZIT2**2.0)/(ZIT1+ZIT2)
153 TDO(I)=(ZIT1+ZIT2)/(120.0*PI*REAL(Z2(I)))
154 ZIT3=AIMAG(Z(I))+ZIT1*ZIT2/(ZIT1+ZIT2)
155 XPRIME(I)=CMPLX(REAL(Z(I)),ZIT3)
156 CONTINUE
157 423 CONTINUE
158 C READ IN DELTA T (TIME INCREMENT)
159 READ(5,32)DELT
160 32 FORMAT(6X,F10.4)
161 C
162 C READ LITER, IYES
163 READ(5,250)LITER,IYES,SMI
164 250 FORMAT(2I10,F10.0)
165 C PRINT CONSTANTS
166 WRITE(6,62)
167 62 FORMAT("1",20("=====")/*0","MACHINE CONSTANTS"/*0",
168 +10("=====")/6X,"GENERATOR BUS 1")
169 WRITE(6,61)EG,DELT,NG,GV(1),GV(2)
170 61 FORMAT(6X,"EG =",E10.4,6X,"DELT =",E10.4/6X,"NG =",
171 +E10.4,6X,"LD =",E10.4,6X,"LDC =",E10.4)
172 WRITE(6,140)(GV(I),I=3,9)
173 140 FORMAT(7X,"LF =",E10.4,8X,"LQ =",E10.4/6X,"LQC =",E10.4,
174 +8X,"MF =",E10.4,7X,"MD =",E10.4,8X,"MR =",E10.4,
175 +/7X,"MQ =",E10.4)
176 WRITE(6,141)(GV(I),I=10,15)
177 141 FORMAT(8X,"R =",E10.4,8X,"RF =",E10.4/7X,"RD =",E10.4,
178 +"RR =",E10.4,8X,"H =",E10.4,8X,"D =",E10.4)
179 WRITE(6,310)TAUJ,TAUD,TAUQ,TAQP
+10.4/6X,"XDP='*,E10.4,8X,"XD='*,E10.4/6X,
+"XDP='*,E10.4,7X)
WRITE(6,100)
100 FORMAT("0*/0",6X,"INDUCTION MOTOR(S)--1=NEW,O=ONLINE")
WRITE(6,101)
DO 106 I=1,NUMNI
WRITE(6,107)BUN(I),IXN(I),ZN(I),ZMN(I),Z2N(I),Z3N(I),
+SLIPN(I,1),NMN(I)
+/7X,I3)
106 CONTINUE
IF (NUMNI.EQ.1) GO TO 424
DO 114 I=2,NUMNI
WRITE(6,115)I,BU(I),IX(I),Z(I),ZM(I),Z2(I),SLIP(I,1),NMN(I)
+/7X,I3)
114 CONTINUE
424 CONTINUE
WRITE(6,116)
116 FORMAT("0")
WRITE(6,65)DELT,SBASE,VBASE
65 FORMAT("0",6X,"DELT=",F10.4,"SECS",7X,"SBASE=",F10.4,
+"MVA"/7X,"VBASE=",F10.4,"KV")
C ADD ON LINE MACHINES
IF (NUMNI.EQ.1) GO TO 285
DO 280 I=2,NUMNI
ZE2=CMPLX(R2(I)/SLIP(I,1),AIMAG(Z2(I)))
ZEQ=Z(I)+1.0/(1.0/ZM(I)+1.0/ZE2)
Y(BU(I),BU(I))=Y(BU(I),BU(I))+1.0/ZEQ
280 CONTINUE
285 CONTINUE
C FIND YM AND YA
DO 19 I=1,BUS
DO 19 J=1,BUS
YM(I,J)=CABS(Y(I,J))
19 IF (REAL(Y(I,J)) .NE. 0.0) GO TO 20
20 IF (AIMAG(Y(I,J)).EQ.0.0) GO TO 21
21 IF (AIMAG(Y(I,J)).LT.0.0) GO TO 22
22 YA(I,J)=XPI/2.0
23 GO TO 19
226  22  Y\(A(I,J) = XPI/(-2.0)\)
227  22  GO TO 19
228  21  Y\(A(I,J) = 0.0\)
229  20  GO TO 19
230  20  Y\(A(I,J) = ATAN2(\text{IMAG}(Y(I,J)), \text{REAL}(Y(I,J)))\)
231  19  CONTINUE
232  
233  C \text{SET ALL VOLTAGES TO GENERATOR VOLTAGES}
234  DO 53 I=1,BUS
235  \(V\text{M}(I) = E\text{G}\)
236  \(VA(I) = DELG\)
237  53 CONTINUE
238  CALL \text{NEWRAF}(Y\text{M}, Y\text{A}, VM, VA, BUS, IND, BLOAD, 16)
239  
240  C \text{PRINT BUS VOLTAGES, SCHEDULED LOADS, IF ANY}
241  WRITE(6,74)
242  74 FORMAT('1*20(****ervices****)\/*/0\/*/SYSTEM VOLT. AND LOADS(PU)**/\,')
243  +/'0\/*/10(#####services****)\/*/0\/*/6X,'\text{VBUS}',4X,'\text{MAG(PU)}',\,')
244  +10X,'ANG(DEG))'
245  DO 75 I=1,BUS
246  \(AN = VA(I)*180.0/XPI\)
247  WRITE(6,76)I,VM(I),AN
248  76 FORMAT(6X,'V('I2,'') = ',E12.5,5X,E12.5)
249  75 CONTINUE
250  WRITE(6,77)
251  77 FORMAT('0\/*/0\/*/6X,'SCHEDULED LOADS(INJECTED,PU)**/\,')
252  IF (LMAX1.EQ.0) GO TO 78
253  DO 80 I=1,LMAX1
254  WRITE(6,79)LMAX2(I),BLOAD(LMAX2(I))
255  79 FORMAT(6X,'B('I2,'') = ',E12.5,'+J',E12.5)
256  80 CONTINUE
257  GO TO 81
258  78 WRITE(6,82)
259  82 FORMAT('0\/*/6X,'NO SCHEDULED LOADS')
260  81 CONTINUE
261  
262  C \text{CONVERT VOLTAGES TO CARTESIAN VARIABLES}
263  DO 83 I=1,BUS
264  \(VBR = VM(I) * \text{COS}(VA(I))\)
265  \(VBI = VM(I) * \text{SIN}(VA(I))\)
266  \(VB(I) = \text{CMPLX}(VBR, VBI)\)
267  83 CONTINUE
268  
269  C \text{FIND GENI}
270  \text{GENI} = (0.0,0.0)
DO 162 I=1,BUS
GENI=GENI+Y(1,I)*VB(I)
162 CONTINUE

C REMOVE ON LINE MODEL FROM YBUS
IF (NUMIM.EQ.1) GO TO 411
DO 110 I=2,NUMIM
Y(BU(I),BU(I))=YIM(I)
110 CONTINUE
411 CONTINUE

C CONVERT SCHEDULED LOADS TO CONSTANT IMP. INSERT IN YBUS
IF (LMAX1.EQ.0) GO TO 84
DO 85 I=1,LMAX1
LD=LMAX2(I)
DO 109 J=1,NUMIM
IF (LD.NE.BU(J)).OR.(TYPE(J).EQ.1)) GO TO 109
Y(LD,LD)=1.0/(VM(LD)**2/CONJG(BLOAD(LD)))*(-1.0)+YIM(J)
YIM(LD)=Y(LD,LD)
GO TO 85
109 CONTINUE
85 CONTINUE
84 CONTINUE

C FIND IC'S FOR ON-LINE MODELS
IF (NUMIM.EQ.1) GO TO 410
DO 221 I=2,NUMIM
IB=BU(I)
ZD2=CMPLX(R2(I)/SLIP(I,1),AIMAG(Z2(I)))
ZP=1.0/(1.0/ZM(I)+1.0/ZD2)
ZEQ=Z(I)+ZP
EK(I,*1)=JAY*BK(I)*VTER/(TDO(I)*XPRIME(I))
DUM=120.0*XPI*SLIP(I,1)+BK(I)/(TDO(I)*XPRIME(I))
EK(I,*1)=EK(I,*1)/(1.0/TDO(I)+JAY*DUM)
IK(I,)=VTER-EK(I,*1)/XPRIME(I)
TL(I)=REAL(EK(I,*1)*CONJG(IK(I))
221 CONTINUE
410 CONTINUE

C PRINT IC7S FOR ON-LINE MOTORS
IF (NUMIM.EQ.1) GO TO 241
WRITE(6,240)
240 FORMAT("0","0","6X","ON-LINE MOTOR IC'S")
DO 242 I=2,NUMIM
WRITE(6,243)I,BU(I),IK(I),EK(I,1),TL(I)
243 FORMAT(3X,NO= *,I2,2X,BUS= *,I2,2X,IK= *,E10.4,*+J*,
+X10.4,2X,EK= *,E10.4,*+J*,E10.4,2X,TL= *,E10.4)
242 CONTINUE
241 CONTINUE

C ADD EXTRA BUSES
IEX=BUS+1
Y(IEX,1)=-1.0/XGEN
Y(1,IEX)=Y(IEX,1)
Y(1,1)=Y(1,1)+1.0/XGEN
Y(IEX,IEX)=1.0/XGEN
DO 270 I=1,BUS
IF (I.EQ.1) GO TO 270
Y(I,IEX)=(0.0,0.0,0.0)
Y(IEX,I)=Y(I,IEX)
270 CONTINUE
IF (NUMIM.EQ.1) GO TO 204
DO 200 I=2,NUMIM
IEX=BUS+I
IYE=BU(I)
DO 201 I=I,IEX
IF (I.EQ.IYE) GO TO 202
IF (I.EQ.IEX) GO TO 203
Y(IEX,I)=<O.O,O.O>
Y(I1,IEX)=<0.0,0.0,0.0>
GO TO 201
202 Y(I1,IEX)=-1.0/XPRIME(I)
Y(I1,I1)=Y(I1,IEX)
GO TO 201
203 Y(I1,I1)=1.0/XPRIME(I)
201 CONTINUE
Y(IYE,IYE)=Y(IYE,IYE)+1.0/XPRIME(I)
200 CONTINUE
204 CONTINUE

C PRINT NEW YBUS
IF (YES.EQ.0) GO TO 473
WRITE(6,476)
476 FORMAT(*1",10(*"="*10X,*"NEW YBUS"/"0".*
+10(*"="*10X))
475 IEX=BUS+NUMIM
DO 474 I=1,IEX
474 CONTINUE
DO 474 J=1,IEX

C
WRITE(6, 475) I*J, Y(I, J)
475 FORMAT(5X, 'Y('i12, ', i12') = ', F12.5, ',i12, F12.5)
474 CONTINUE
473 CONTINUE
C SAVE NEW MOTOR AXIAL COMPONENT
DO 426 I=1, NUMN
YIMN(I) = Y(BUN(I), BUN(I))
426 CONTINUE
C INITIALIZE VARIABLES
FS(1) = 60.0
NYUK = 0
RPMIM = 0.0
L = 0
WGN = 1.0
WREL = 1.0
TIME(1) = 0.0
DO 429 I = 1, NUMN
WIM(I, 1) = 0.0
429 CONTINUE
C FIND INITIAL DEL, VGEN
POW = VB(1) * CONJG(GENI)
IRV = CONJG(POW) / CABS(VB(1))
RC = REAL(IRV)
XC = AIMAG(IRV)
ARGU = CG(2) * RC / (CABS(VB(1)) - CG(2) * XC)
ANG2 = ATAN2(AIMAG(VB(1)), REAL(VB(1)))
DEL = ATAN(ARGU) + ANG2
C FIND TM, EFD
VEE = CMPLX(CABS(VB(1)), 0.0)
CALL TRANSF(VEE, DEL, 0)
VD = AIMAG(VEE)
VQ = REAL(VEE)
CALL TRANSF(GENI, DEL, 0)
IP = AIMAG(GENI)
IQ = REAL(GENI)
EDP = VD + IQ * XDP
EQP = VQ - IP * XDP
TM = D + EDP * IP + EQP * IQ
EFD = EQP + IP * (XDP - XD)
V1 = CABS(VB(1))
SE = AEX * EXP(BEX * EFD)
VR = EFD * (KE + SE)
V3=0.0
VS=(SE+KE)*EFD/KA
WREF=1.0
XPD=0.0
XPM=TM
XPNOT=TM
PRINT*, 'V1=', V1
PRINT*, 'SE=', SE
PRINT*, 'VR=', VR
PRINT*, 'VS=', VS
VGEN=CMPLX(EQP, EDP)
CALL TRANSF(GENI, DEL, 1)
CALL TRANSF(VGEN, DEL, 1)
PRINT*, 'DEL=', DEL
PRINT*, 'EDP=', EDP
PRINT*, 'EQP=', EQP
PRINT*, 'IP=', IP
PRINT*, 'IQ=', IQ
PRINT*, 'VGEN0=', VGEN
PRINT*, 'CON1=', CON1, ' CON2=', CON2

WRITE(6,68)
WRITE(6,67)
WRITE(6,66)
WRITE(6,65)
WRITE(6,64)
WRITE(6,63)
WRITE(6,62)
WRITE(6,61)
WRITE(6,60)
WRITE(6,59)
WRITE(6,58)
WRITE(6,57)
WRITE(6,56)
WRITE(6,55)
WRITE(6,54)
WRITE(6,53)
WRITE(6,52)
WRITE(6,51)
WRITE(6,50)
WRITE(6,49)
WRITE(6,48)
WRITE(6,47)
WRITE(6,46)
WRITE(6,45)
WRITE(6,44)
WRITE(6,43)
WRITE(6,42)
WRITE(6,41)
WRITE(6,40)
WRITE(6,39)
WRITE(6,38)
WRITE(6,37)
WRITE(6,36)
WRITE(6,35)
WRITE(6,34)
WRITE(6,33)
WRITE(6,32)
WRITE(6,31)
WRITE(6,30)
WRITE(6,29)
WRITE(6,28)
WRITE(6,27)
WRITE(6,26)
WRITE(6,25)
WRITE(6,24)
WRITE(6,23)
WRITE(6,22)
WRITE(6,21)
WRITE(6,20)
WRITE(6,19)
WRITE(6,18)
WRITE(6,17)
WRITE(6,16)
WRITE(6,15)
WRITE(6,14)
WRITE(6,13)
WRITE(6,12)
WRITE(6,11)
WRITE(6,10)
WRITE(6,9)
WRITE(6,8)
WRITE(6,7)
WRITE(6,6)
WRITE(6,5)
WRITE(6,4)
WRITE(6,3)
WRITE(6,2)
WRITE(6,1)
WRITE(6,0)

ZD2=CMPLX(R2N(I)/SLIPN(I,1),AIMAG(Z2N(I)))
ZD3=CMPLX(R3N(I)/SLIPN(I,1),AIMAG(Z3N(I)))
ZP=1.0/(1.0/ZMNCI+1.0/ZD2+1.0/ZD3)
ZEQ=Z2N(I)+ZP
Y(LU,LU)=Y(LU,LU)+1.0/ZEQ

CONTINUE

UPDATE VOLTAGES WITH NEW MOTOR
CALL DELVB(VB, Y, VGEN, EK, BUS, NUMIM, 16, 12, 200, L+1)
FIND GENI
LOW=BUS+1
GENI=Y(LOW, LOW)*VGEN
DO 470 I=1, BUS
GENI=GENI+Y(LOW,I)*VB(I)

DO 471 I=1,NUMIM
  IF (I.EQ.1) GO TO 471
  LOX=BUS+I
  GENI=GENI+Y(LOW,LOX)*EK(I,L+1)
CONTINUE

C PRINT CURRENT VALUES
LU=BUN(1)
VEE=1.0/(Y(LU,LU)-YMN(1))
WGEN=WREL*120.0*XPI
XVM=CMABS(VGEN)
XVGA=ATAN2(IMAG(VGEN),REAL(VGEN))*180.0/XPI
XGM=CMABS(GENI)
XGA=ATAN2(CMAG(GENI),REAL(GENI))*180.0/XPI
VMON(L+1)=VB(BUN(I))
WRITE(6,66)TIME(L+1),FS(L+1),XVGM,XVGA,XGM,XGA,WGEN,VEE

C FIND TORQUE
DO 428 I=1,NUMNU
  ZD2=CMPLX(R2N(I),SLIPN(I,L+1),AIMAG(Z2N(I)))
  ZD3=CMPLX(R3N(I),SLIPN(I,L+1),AIMAG(Z3N(I)))
  ZP=1.0/(1.0/ZMN(I)+1.0/ZD2+1.0/ZD3)
  ZEQ=ZN(I)+ZP
  V=VB(BUN(I))
  I2=V*ZP/ZEQ/ZD2*IBASE
  I3=V*ZP/ZEQ/ZD3*IBASE
  TORK=3.0*((CMABS(I2)**2)*R2N(I)+(CMABS(I3)**2)*R3N(I))
  TORK=TORK*ZBASE/(SLIPN(I,L+1)*240.0*XPI/NIMN(I))
  XX=CM2(I)*SLIPN(I,L+1)
  TLOAD=EXP(XX)
  TLOAD=TLOAD*CM1(I)
  T=TORK-TLOAD
  WIM(I,L+2)=(T*DELT/IIXN(I))+WIM(I,L+1)
CONTINUE

C SOLVE GENERATOR DIFF EQUATIONS
CALL TRANSF(GENI,DEL,O)
CALL TRANSF(VGEN,DEL,O)
EDP=AIMAG(VGEN)
EQP=REAL(VGEN)
IP=AIMAG(GENI)
IQ=REAL(GENI)
C
SOLVE DE WITH RUNGE KUTTA
VT=ABS(VB(1))
VT=VT
LL=1
DELL=DELT*120.0*XPI
EDP0=EDP
EQP0=EQP
WREL0=WREL
DELO=DEL
V30=V3
VR0=VR
EDD0=EDD
XP00=XP0
XP0D0=XP0D
EDK=0.0
EK=0.0
WRELK=0.0
DELK=0.0
V3K=0.0
VRK=0.0
EFDK=0.0
XPMK=0.0
XPDK=0.0
TM=XP0/WREL
EDD=(-EDD-(XQ-XQP)*IQ)/TAUQ
EDD=EDD-(EDP-(XQ-XDP)*IQ)/TAUQ
WRELD=(TM-DWREL-(EDP*IQ+EQP*IQ))/TAUQ
DELD=WREL-1.0
SE=AEX*EXP(BEX*EFD)
V3D=(-V3+(KF*VR/TAUE-KF*(SE+KE)*EFD/TAUE)*120.0*XPI)
V3D=V3D/TAU
VRD=(-KA*(V1+V3)-VR+KA*(VREF+VS))/TAU
EFDD=(VR-(SE+KE)*EFD)/TAU
XPDD=(XPNOT+XP0-XPM)/TEE3
XP0D=((WREF-WREL)*XK1/TEE1-XK1*TEE2*WRELD/TEE1-XPD/TEE1)
EDP=EDD*DELL
EQP=EDD*DELL
WREL=WRELD*DELL
DEL=DELD*DELL
V3=V3D*DELL
VR=VRD*DELL
EFD=EFDD*DELL
XPM=XPMD*DELL
72

541 XPD=XPDD*DELL
542 CONS=1.0
543 IF((LL.EQ.3).OR.(LL.EQ.2)) CONS=2.0
544 EDK=EDK+CONS*EDP
545 EQK=EQK+CONS*EQP
546 WRELK=WRELK+CONS*WREL
547 DELK=DELK+CONS*DEL
548 V3K=V3K+CONS*V3
549 VRK=VRK+CONS*VR
550 EFDK=EFDK+CONS*EFD
551 XPMK=XPMK+CONS*XPM
552 XPDK=XPDK+CONS*XPD
553 CONS=1.0
554 IF((LL.EQ.1).OR.(LL.EQ.2)) CONS=2.0
555 IF(LL.EQ.4) GO TO 502
556 EDP=EDP0+EDP/CONS
557 EQP=EQP0+EQP/CONS
558 WREL=WREL0+WREL/CONS
559 DEL=DEL0+DEL/CONS
560 V3=V30+V3/CONS
561 VR=VR0+VR/CONS
562 IF(VR.GT.VRMAX) VR=VRMAX
563 IF(VR.LT.VRMIN) VR=VRMIN
564 EFD=EFD0+EFD/CONS
565 IF(EFD.GT.EFDMA) EFD=EFDMA
566 IF(EFD.LT.EFDIMI) EFD=EFDIMI
567 XPM=XPM0+XPM/CONS
568 XP=XPDO+XP/CONS
569 LL=LL+1
570 GO TO 501
571 502 EDP=EDP0+EDK/6.0
572 EQP=EQP0+EQK/6.0
573 WREL=WREL0+WRELK/6.0
574 DEL=DEL0+DELK/6.0
575 V3=V30+V3K/6.0
576 VR=VR0+VRK/6.0
577 IF(VR.GT.VRMAX) VR=VRMAX
578 IF(VR.LT.VRMIN) VR=VRMIN
579 EFD=EFD0+EFDK/6.0
580 IF(EFD.GT.EFDMA) EFD=EFDMA
581 IF(EFD.LT.EFDIMI) EFD=EFDIMI
582 XPM=XPM0+XPMK/6.0
583 XP=XPDO+XPDK/6.0
584 C
585 C END OF R-G
586  VGEN=CMPLX(EPQ,EDP)
587  CALL TRANSF(VGEN,DEL,1)
588 C
589 C CALL MOTOR TO FIND NEW EK'S
590 IF(NUMIM.EQ.1) GO TO 235
591  WGEN=FS(L+1)*2.0*XPI
592  DO 236 I=2,NUMIM
593  SLI=SLIP(I,L+1)
594  EKEX=EK(I,L+1)
595  VK(I)=VBU(I))
596  CALL XMOTOR(KEK,VK(I),SLI,WGEN,T(I),BK(I),TDO(I),+
597     +DELT,I(I),XPRIME(I))
598  SLIP(I,L+2)=SLI
599  EK(I,L+2)=EKEX
600  236 CONTINUE
601  235 CONTINUE
602 C
603 C DETERMINE NEW FREQUENCY,SLIP
604  FS(L+2)=WREL*60.0
605  WSS=WREL*120.0*XPI
606  DO 430 I=1,NUMNU
607  SLIPN(I,L+2)=(WSS-WIM(I,L+2))/WSS
608  430 CONTINUE
609 C
610 C UPDATE MOTOR IN YBUS
611  LU=BUN(1)
612  Y(LU,LU)=YIMN(1)
613  DO 431 I=1,NUMNU
614  ZD2=CMPLX(R2N(I))/SLIPN(I,L+2),AIMAG(Z2N(I))
615  ZD3=CMPLX(R3N(I))/SLIPN(I,L+2),AIMAG(Z3N(I))
616  ZP=1.0/(1.0/ZMN(I)+1.0/ZD2+1.0/ZD3)
617  ZEQ=ZMN(I)+ZP
618  Y(LU,LU)=Y(LU,LU)+1.0/ZEQ
619  431 CONTINUE
620  L=L+1
621  TIME(L+1)=TIME(L)+DELT
622  IF (NYUK.EQ.1) GO TO 451
623  DO 450 I=1,NUMNU
624  IF(SLIPN(I,L+1),GT,SMI) GO TO 450
625  DELT=DELT/2.0
626  NYUK=1
627  GO TO 451
628  450 CONTINUE
629  451 CONTINUE
630  GO TO 57
300 CONTINUE
WRITE(6,432)
432 FORMAT(1,10('='*100')/"STABILITY DATA-NEW MOTORS")
+/*0',10('='*100')")
433 FORMAT(I10)
434 READ(5,433)MN NUM
435 FORMAT(0',10X,'DATA FOR NEW MOTOR M',I2,' BUS M',I2)
WRITE(6,436)
436 FORMAT(0',4X,'TIME',8X,'FS',8X,'SLIP',7X,'VMOT',13X,'VMOT')
437 CONTINUE
GO TO 439
438 CONTINUE
PRINT OUT DATA FOR ON LINE MOTORS
440 IF (NUMIM.EQ.1) GO TO 443
WRITE(6,441)
441 FORMAT(1,10('='*100')/"STABILITY DATA OL MOTORS")
+/*0',10('='*100')")
442 READ(5,442)OL NUM
443 FORMAT(I10)
444 IF (OL NUM.EQ.0) GO TO 443
WRITE(6,444)OL NUM,BU(OL NUM)
445 FORMAT(0',10X,'DATA FOR OL MOTOR M',I2,' BUS M',I2)
WRITE(6,445)
446 CONTINUE
GO TO 448
447 CONTINUE
STOP
END
SUBROUTINE NEWRAF(YMAG, YAOG, VMAG, VANG, BUS, INDICA, BLO, NR)

REAL MMP(16), MMQ(16), JAC(39, 39), DELV(16)

DIMENSION YMAG(NR), VMAG(NR), YANG(NR, NR), YMAG(NR, NR)

COMPLEX BLO(NR)

INTEGER BUS

IF (BUS.EQ.1) RETURN
DO 1 III=1, 30
C COMPUTE MISMATCH VECTOR

INDICA=0
DO 33 I=2, BUS
SPOSP=0.0
SPOSQ=0.0
MMF(I)=0.0
MMQ(I)=0.0
DO 34 J=1, BUS
ARGUM=YANG(I)-YANG(J)-YANG(I, J)
SPFLO=VMAG(I)*VMAG(J)*YMAG(I, J)*COS(ARGUM)*(-1.0)
SQFLO=VMAG(I)*VMAG(J)*YMAG(I, J)*SIN(ARGUM)*(-1.0)
IF (SPFLO.LT.0.0) GO TO 35
SPOSP=SPOSP+SPFLO
35 IF (SQFLO.LT.0.0) GO TO 36
SPOSQ=SPOSQ+SQFLO
36 MMP(I)=MMP(I)+SPFLO
MMQ(I)=MMQ(I)+SQFLO
34 CONTINUE
IF (REAL(BLO(I)).LT.0.0) GO TO 37
SPOSP=SPOSP+REAL(BLO(I))
37 IF (AIMAG(BLO(I)).LT.0.0) GO TO 38
SPOSQ=SPOSQ+AIMAG(BLO(I))
38 MMP(I)=MMP(I)+REAL(BLO(I))
MMQ(I)=MMQ(I)+AIMAG(BLO(I))
ERRP=0.00001*SPOSP
ERRQ=0.00001*SPOSQ
IF ((ABS(MMP(I)).LT.ERRP).AND.(ABS(MM(Q(I)).LT.ERRQ)))
+GO TO 33
INDICA=1
33 CONTINUE
C TEST FOR SOLUTION END
IF (INDICA.EQ.0) GO TO 51
C FORM JACOBIAN MATRIX

DO 40 I=2, BUS
DO 40 J=2, BUS
IF (I.EQ.J) GO TO 41
ARGU=YANG(I)-YANG(J)-YANG(I, J)
JAC(I-1, J-1)=VMAG(I)*VMAG(J)*YMAG(I, J)*SIN(ARGU)
JAC(BUS-2+I, J-1)=(-1.0)*VMAG(I)*VMAG(J)*YMAG(I, J)
+*COS(ARGU)
41 JAC(I-1, J-1)=0.0
JAC(BUS-2+I,J-1)=0.0
DO 43 L=1,BUS
IF (L.EQ.I) GO TO 43
ARGU=VANG(I)-VANG(L)-YANG(I,L)
JAC(I-1,J-1)=JAC(I-1,J-1)-VMAG(I)*VMAG(L)*YMAG(I,L)*COS(ARGU)
JAC(BUS-2+I,J-1)=JAC(BUS-2+I,J-1)+VMAG(I)*VMAG(L)*YMAG(I,L)*SIN(ARGU)
CONTINUE
43
CONTINUE
DO 44 I=2,BUS
DO 44 J=2,BUS
IF (I.EQ.J) GO TO 45
ARGU=VANG(I)-VANG(J)-YANG(I,J)
JAC(I-1,BUS-2+J)=VMAG(I)*YMAG(I,J)*COS(ARGU)
JAC(BUS-2+I,BUS-2+J)=VMAG(I)*YMAG(I,J)*SIN(ARGU)
GO TO 44
45
JAC(I-1,BUS-2+J)=2.0*VMAG(I)*YMAG(I,J)*COS(-YANG(I,I))
JAC(BUS-2+I,BUS-2+J)=2.0*VMAG(I)*YMAG(I,J)*SIN(-YANG(I,I))
DO 46 L=1,BUS
IF (L.EQ.I) GO TO 46
ARGU=VANG(I)-VANG(L)-YANG(I,L)
JAC(I-1,BUS-2+J)=JAC(I-1,BUS-2+J)+VMAG(L)*YMAG(I,L)*COS(ARGU)
JAC(BUS-2+I,BUS-2+J)=JAC(BUS-2+I,BUS-2+J)+VMAG(L)*YMAG(I,L)*SIN(ARGU)
CONTINUE
44
CONTINUE
LAST=2*BUS-2
CALL SHICOL(JAC,LAST,38)
DO 47 I=1,LAST
DELV(I)=0.0
DO 47 J=1,LAST
IF (J.GT.BUS-1) GO TO 48
DELV(I)=DELV(I)+JAC(I,J)*MMP(J+1)
GO TO 47
48
DELV(I)=DELV(I)+JAC(I,J)*MMP(J-BUS+2)
CONTINUE
47
CONTINUE
UPDATE SOLUTION
DO 49 I=1,LAST
IF (I.GE.BUS) GO TO 50
YANG(I+1)=YANG(I+1)+DELV(I)
GO TO 49
50 VMAG(I-BUS+2)=VMAG(I-BUS+2)+DELV(I)
CONTINUE
49
CONTINUE
1
CONTINUE
51
RETURN
END
SUBROUTINE TRANSF(X,ANG,LITE)
COMPLEX X
REAL ANG
IF (LITE.EQ.1) GO TO 10
XR=COS(ANG)
XC=-SIN(ANG)
X=X*CMPLX(XR,XC)
RETURN
XR=COS(ANG)
XC=SIN(ANG)
X=X*CMPLX(XR,XC)
RETURN
END

SUBROUTINE SHICOL(A,IS,NR)
C "A" IS MATRIX TO BE INVERTED
REAL A(NR,NR)
DO 50 I=1,IS
DO 51 J=1,IS
DO 51 K=1,IS
IF(J.EQ.I).OR.(K.EQ.I)) GO TO 51
A(J,K)=A(J,K)-A(J,I)*A(I,K)/A(I,I)
51 CONTINUE
A(I,I)=1.0/A(I,I)*(-1.0)
DO 52 J=1,IS
IF(J.EQ.I) GO TO 52
A(I,J)=A(I,J)*A(I,I)
A(J,J)=A(J,J)*A(I,I)
52 CONTINUE
50 CONTINUE
DO 53 I=1,IS
DO 53 J=1,IS
A(I,J)=A(I,J)*(-1.0)
53 CONTINUE
RETURN
END
SUBROUTINE DELVB(VB,Y,VGEN,EK,BUS,NUMIM,NR,NR2,NR3,ITIME)

COMPLEX VB(NR),Y(NR,NR),EK(NR2,NR3),VGEN,V,DELVO

INTEGER BUS

IEX=BUS+1

L=0

30 LITE=0

DO 10 I=1,BUS

V=-Y(I,IEX)*VGEN

DO 11 J=1,NUMIM

IF (J.EQ.1) GO TO 11

IBX=BUS+J

V=V-Y(I,IBX)*EK(J,ITIME)

11 CONTINUE

DO 12 II=1,BUS

IF (II.EQ.I) GO TO 12

V=V-Y(I,II)*VB(II)

12 CONTINUE

V=V/Y(I,I)

XR=REAL(V-VB(I))

XI=AIMAG(V-VB(I))

AXR=ABS(XR)

AXI=ABS(XI)

IF ((AXR.LT.0.0001).AND.(AXI.LT.0.0001)) GO TO 60

LITE=1

60 XR=XR*1.6

XI=XI*1.6

DELVO=CMPLX(XR,XI)

VB(I)=VB(I)+DELVO

10 CONTINUE

IF (LITE.EQ.0) RETURN

IF (L.GE.150) GO TO 20

L=L+1

GO TO 30

20 WRITE(6,50)

50 FORMAT(5X,'ERROR IN DELVB')

PRINT*,VB

STOP

END
SUBROUTINE XMOTOR(EK, VK, SK, WG, TL, BK, TDO, DELT, H, IMP)

COMPLEX EK, IK, DWM, DEK, DWM1, DWM2, DWM3, DWM4

COMPLEX DEK1, DEK2, DEK3, DEK4, EKO, J, VK, IMP

REAL SK, WG, TL, BK, TDO, DELT, H

K = 0

XP1 = 4.0 * ATAN(1.0)

J = CMPLX(0.0, 1.0)

X1 = -WG / 2.0 / H

X2 = BK / TDO

X3 = -1.0 / TDO

WM = (1.0 - SK) * WG

WMO = WM

EKO = EK

IK = (VK - EK) / IMP

DWM = X1 * (TL - REAL(EK * CONJG(IK)))

X4 = -120.0 * XPI * SK

DEK = CMPLX(X3, X4) * EK + J * X2 * IK

IF (K.EQ.1) GO TO 1

IF (K.EQ.2) GO TO 2

IF (K.EQ.3) GO TO 3

DWM1 = DWM * DELT

DEK1 = DEK * DELT

EK = EKO + DEK1 / 2.0

WM = WM0 + DWM1 / 2.0

SK = (WG - WM) / WG

K = K + 1

GO TO 4

1

DWM2 = DWM * DELT

DEK2 = DEK * DELT

EK = EKO + DEK2 / 2.0

WM = WM0 + DWM2 / 2.0

SK = (WG - WM) / WG

K = K + 1

GO TO 4

2

DWM3 = DWM * DELT

DEK3 = DEK * DELT

EK = EKO + DEK3

WM = WM0 + DWM3

SK = (WG - WM) / WG

K = K + 1

GO TO 4

3

DWM4 = DWM * DELT

DEK4 = DEK * DELT

EK = EKO + (DEK1 + 2.0 * (DEK2 + DEK3) + DEK4) / 6.0

WM = WM0 + (DWM1 + 2.0 * (DWM2 + DWM3) + DWM4) / 6.0

SK = (WG - WM) / WG

RETURN

END