REDUCED ORDER POWER SYSTEM MODELS FOR TRANSIENT STABILITY STUDIES

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ELECTRICAL ENGINEERING

(ABSTRACT)

As the load on the power system grows and new transmission facilities become increasingly difficult to build, the utilities must look to ways to make the most of the current transmission system. Adaptive relaying is one way to enhance the ability of the power system. On the Florida - Georgia interface an adaptive out-of-step relay is being installed. This relay determines if swings on the power system will remain stable by performing a better then real-time transient stability study. Because of the computing capacity required for a transient stability study, the study cannot be performed on the full power system. A reduced model must be used. In this thesis, various methods of obtaining reduced models for use in the relay will be explored. The models will be verified with a full system model using Electric Power Research Institute's (EPRI) Extended Transient-Midterm Stability Package (ETMSP).

Acknowledgment

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Chapter 1

Introduction

1.1 Problem Statement

The Florida Power System is unique since it is a peninsular power system connected to the rest of the country through Florida Power and Light's (FP&L) Duval 500-kV Substation. Figure 1.1 shows the 500-kV transmission system in Florida along with the two tie lines to Georgia Power Company (GPC). As can be seen in the map, the 500-kV transmission system in Florida consists of a double circuit backbone running down the eastern coast with a spur to the west coast in the south. FP&L does not have enough generation to serve their current peak load demand. To supply their load, FP&L imports power from GPC. Approximately 93% of the transfer power flows on the two 500-kV tie lines with the other 7% flowing on the lower voltage lines. The 500-kV transmission system plays an important role in delivering the imported power from GPC. Only one tie line is necessary to import the power from GPC. However, if only one tie line is in service when there is a fault on that line, FP&L will become virtually separated from the rest of the country. The Florida generators will lose synchronism with the rest of the country if drastic measures are not taken. When generators become unsynchronized, they experience severe mechanical stress. They can even be severely damaged under such conditions.

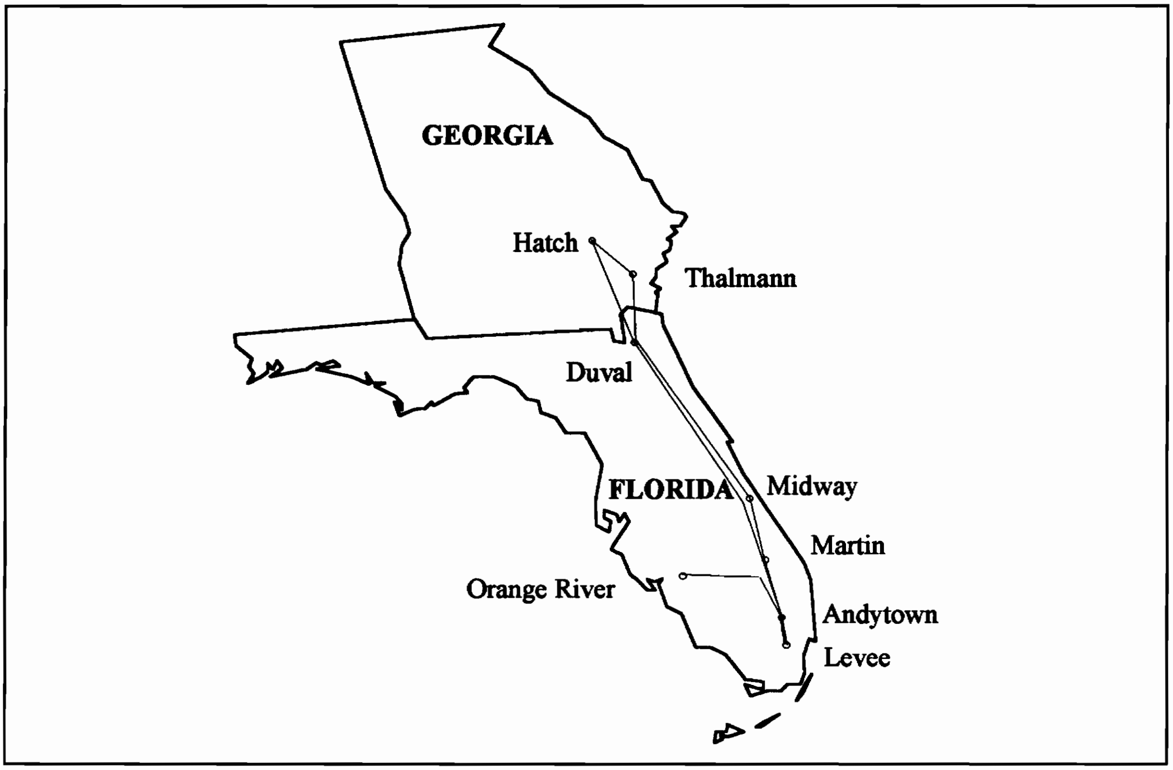


Figure 1.1 Florida 500 kV Lines

In the past, Florida has experienced several separations from the rest of the country. In 1987 and 1989 they separated from the rest of the country because both tie lines opened, interrupting the power transfer. In both cases only one tie line should have opened. The other line opened due to a sympathetic trip. Therefore when there is a fault on one of the tie lines which will not cause instability of the power system, a block signal should be given so that the relays of the unfaulted line will not operate. It is this block signal which failed in 1987 and 1989. Because both lines opened instead of just one, the Florida power system separated from the rest of the country. [1,2] They have improved their transmission facilities and machines to reduce the probability of a separation. They have also developed an elaborate system load shedding scheme to control any separation [3,4,5,6]. They are developing a digital adaptive out-of-step relay as part of their continuing efforts to ensure the proper operation of their power system. It is the out-of-step relay which issues the block or trip signal which failed in 1987 and 1989.

1.2 Stability of a Power System

There are three types of power system stability. Steady state stability is the ability of the power system to remain stable given the constantly changing load and generation. If the system is unstable, the generators will slowly drift out of synchronism as the load changes. Dynamic stability is the ability of the power system to remain stable with small disturbances. If a system is dynamically unstable, a small disturbance will cause small oscillations which will grow and not damp out. The third type of stability is transient stability. If the system is transiently unstable, a large and/or sustained disturbance on the power system will cause some generators to accelerate or decelerate until they are out of synchronism with the rest of the system [7]. Transient stability or instability is the condition the out-of-step relay will detect.

Under steady state operating conditions the generators are in equilibrium. In other words the mechanical power (P_m) input into the generator equals the electrical power output (P_e). The difference between the mechanical and electrical power is the accelerating power (P_a). During equilibrium the accelerating power is zero.

$$P_m - P_e = 0 = P_a \tag{1.1}$$

The electrical output power of a machine is given by the following equation:

$$P_e = \frac{E_1 E_2}{X_d}\sin(\delta) \tag{1.2}$$

where E_1 is the machine bus voltage, E_2 is the machine internal node voltage, X_d is the machine reactance, and δ is the machine rotor angle in reference to the angle of the swing bus. (Figure 1.2). Figure 1.3 is a plot of the electrical and mechanical power.

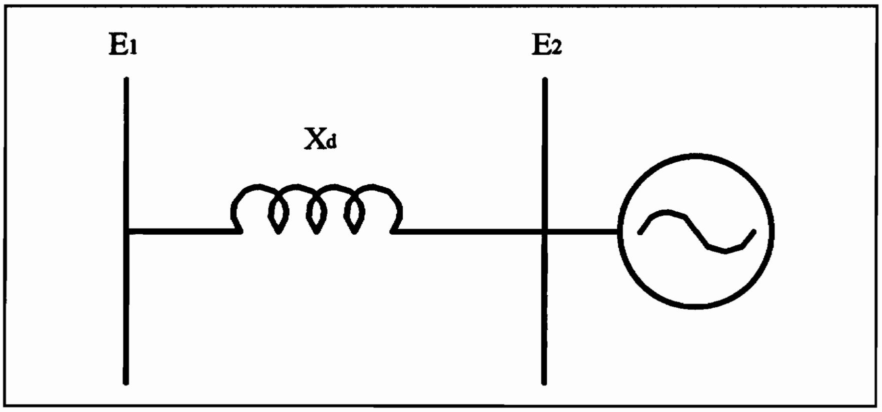


Figure 1.2 Machine Bus Model

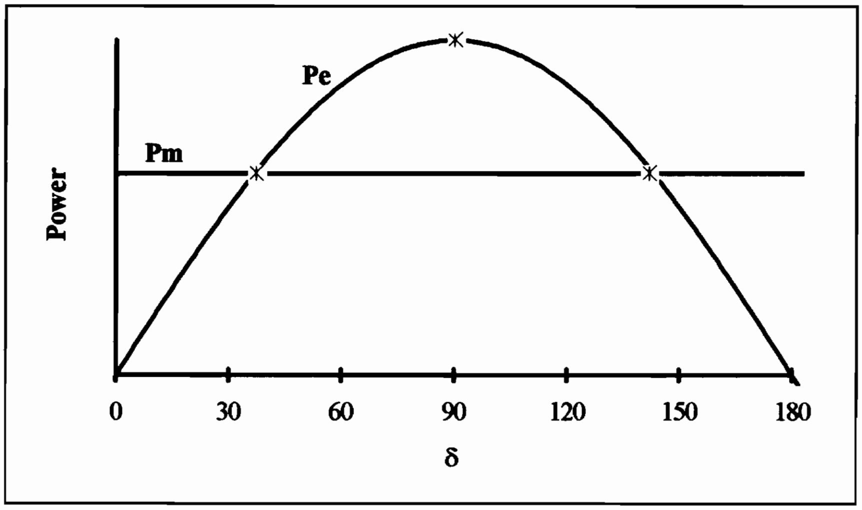


Figure 1.3 Power Angle Curve

During steady state, the system is operating at the first marked point where mechanical and electrical powers are equal. The second marked point is the steady state stability boundary. Once the machine angle passes 90°, in steady state, the system will be unstable. The third marked point is the unstable equilibrium point. This is a theoretical operating point of the system, at which the system will remain in equilibrium as long as there are no changes in the power system. The slightest change will cause the system to go unstable. The power system is constantly making small changes, so for all practical purposes this cannot be an operating point of the power system.

When an event occurs on the power system, the generators will either speed up or slow down as a consequence of the event. Suppose a line trips following a fault. Afterward, the steady state operating point of the power system has changed. Before reaching this new steady state operating point, the power system will go through a transient. Although the new operating point may be stable in the steady state, the generators may go unstable during the transient. During the transient, the generator angle can swing from the first point on figure 1.3 past the second point and up to the third point and will be able to return to a stable operating point. As long as the generator rotor angle does not pass the third point during a transient, it will not lose synchronism

1.3 Out-of-Step Relays

Out-of-Step relays are designed to detect an unstable swing and then perform controlled tripping to minimize the damage and/or outages. The relay should avoid tripping during a stable swing but at the same time it should block uncontrolled tripping for an unstable swing.

When a disturbance occurs on a power system and the rotor angles start to swing, the apparent impedance seen by relays will also start to swing. The relay must determine if a change in impedance is caused by a fault or by rotor swings. For a fault, the impedance changes almost instantaneously. For a swing, the impedance changes according to the frequency of the swing. For example, if the swings are on the order 0.8 Hz (such as some of the swings in the FP&L system) the impedance will go from maximum to minimum in 0.625 seconds.

The traditional out-of-step relay is a combination of distance relays and timers. There are two blinders, creating an outer and inner zone. As the impedance passes the outer zone a timer starts. If the impedance passes the inner zone before the timer ends then it is assumed to be a fault. If the impedance never passes the inner zone, then it is assumed to be a stable swing. If the impedance passes the inner zone after the timer is up then it is assumed to be an unstable swing and controlled tripping is initiated.[8] Figure 1.4 shows the blinder characteristics of the out-of-step relay.

The settings for the inner and outer zones as well as the amount of time for the timer is done by performing many transient stability studies.

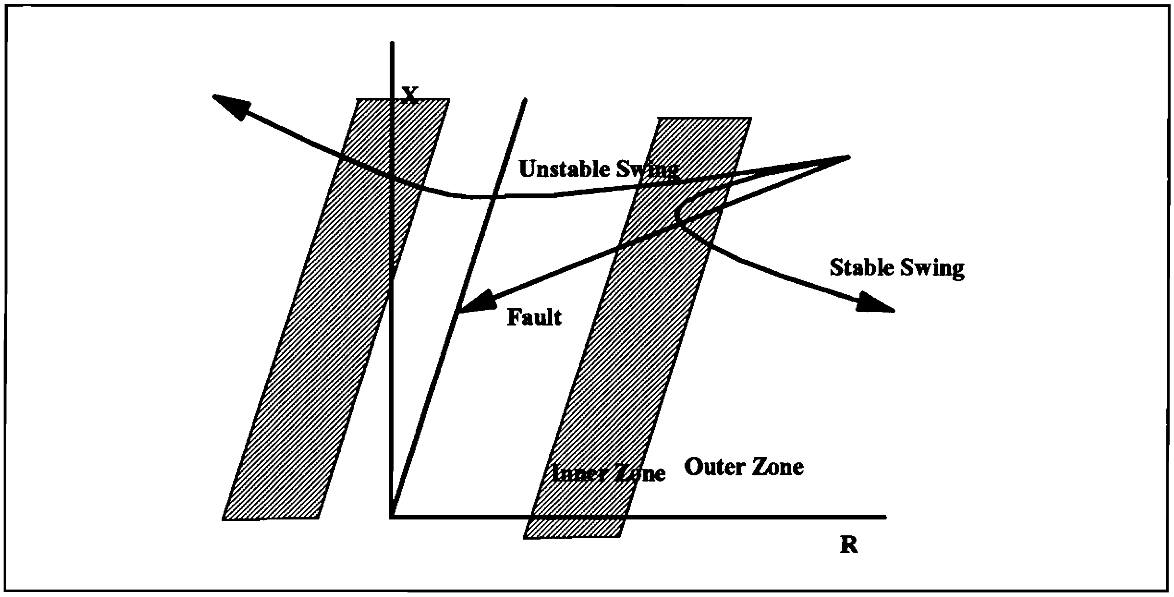


Figure 1.4 Out-of-Step Relay Characteristics

1.4 The Solution

An adaptive digital out-of-step relay is being developed for the Florida / Georgia interface. The relay consists of a 486 computer to be used with Phasor Measurement Units (PMU). A PMU is a device which will measure current and voltage, as phasors. In other words the PMU measures both the magnitude and the angle of a phasor. The PMU uses a Global Positioning Satellite (GPS) to time stamp the data. The PMU is accurate to 1 μs which translates to 0.022^0 for a 60 Hz power system[9]. Since the data is time stamped, phase angles collected from PMUs at different locations can be compared accurately and in real time. PMUs allow for phase angle comparison on a real-time basis which has not been available to the power industry before. The data from the PMUs will be collected in the 486 computer and analyzed. The relay will then make a decision to either trip or block.

When an event occurs such as a fault or a line tripping, the generator rotor angles start to swing. Swings in the generator rotor angles will cause swings in the bus voltage angles on the power system. The PMUs will measure the bus voltages and angles and then send this data to the relay. The relay will then run a real-time transient stability study based on this data. The outcome of the study will be stable or unstable. If the relay predicts the system will become unstable, then controlled tripping can be done to minimize the impact of the disturbance on the power system. If the system will remain stable, then tripping can be blocked.

This thesis will concentrate on the model used in the transient stability study for this adaptive relay. "Adaptive protection is a protection philosophy which permits and seeks to make adjustments in various protection functions automatically in order to make them more attuned to prevailing power system conditions."[10] This definition of adaptive relaying implies that the model of the power system must be based on the prevailing power system conditions. Therefore instead of obtaining a model for use in the relay, this thesis will investigate algorithms for determining a model. As the power system conditions change the algorithm can be used to update the model in the relay. These updates can take place in a quasi-real time. When a line goes out or a generator goes off line the model can be updated. This will ensure that the relay is operating on a fairly up to date model. When an event occurs on the power system there will not enough time to update the model for the event but the model will be accurate for any steady state changes. Since the relay is constantly monitoring the tie lines, an event involving the tripping of a tie line can be updated in real-time in the model of the relay.

Chapter 2

Ward Reduction

2.1 Basic Ward Equivalent

The basic Ward Equivalent is a method of obtaining an external equivalent of a power system. The method is based on the following principle. There is an external system (*e*) and an internal system (*i*) connected by boundary buses (*b*). Figure 2.1 shows a two area system.

There are 9 buses in this figure. Bus numbers 1 through 3 are the internal system. Buses 4, 5 and 6 are the boundary buses and buses 7 through 9 are the external system. Both external and internal systems can be described separately with Y bus matrices.

$$\begin{bmatrix} I_i \\ I_b \end{bmatrix} = \begin{bmatrix} Y_{ii} & Y_{bi} \\ Y_{ib} & Y^{i}{}_{bb} \end{bmatrix} \begin{bmatrix} E_i \\ E_b \end{bmatrix} \tag{2.1}$$

and
$$\begin{bmatrix} I_b \\ I_e \end{bmatrix} = \begin{bmatrix} Y^{e}{}_{bb} & Y_{eb} \\ Y_{be} & Y_{ee} \end{bmatrix} \begin{bmatrix} E_b \\ E_e \end{bmatrix} \tag{2.2}$$

Where the current I is the current injected into the bus and the voltage E is the voltage at that bus. The off-diagonal elements of the Y bus Y_{ij} are obtained from the negative admittance's of the line between bus i and bus j. The diagonal element of the Y bus Y_{ii} is the sum of all the admittance's of the branches connected to bus i to include the shunts, if any, connected from the bus to ground. For this example the dimensions of the matrices are $i = 3$, $b = 3$, and $e = 3$. The two Y bus matrices can be combined into one to describe the entire system:

$$\begin{bmatrix} I_i \\ I_b \\ I_e \end{bmatrix} = \begin{bmatrix} Y_{ii} & Y_{bi} & 0 \\ Y_{ib} & Y^{i}_{bb} + Y^{e}_{bb} & Y_{eb} \\ 0 & Y_{be} & Y_{ee} \end{bmatrix} \begin{bmatrix} E_i \\ E_b \\ E_e \end{bmatrix} \qquad (2.3)$$

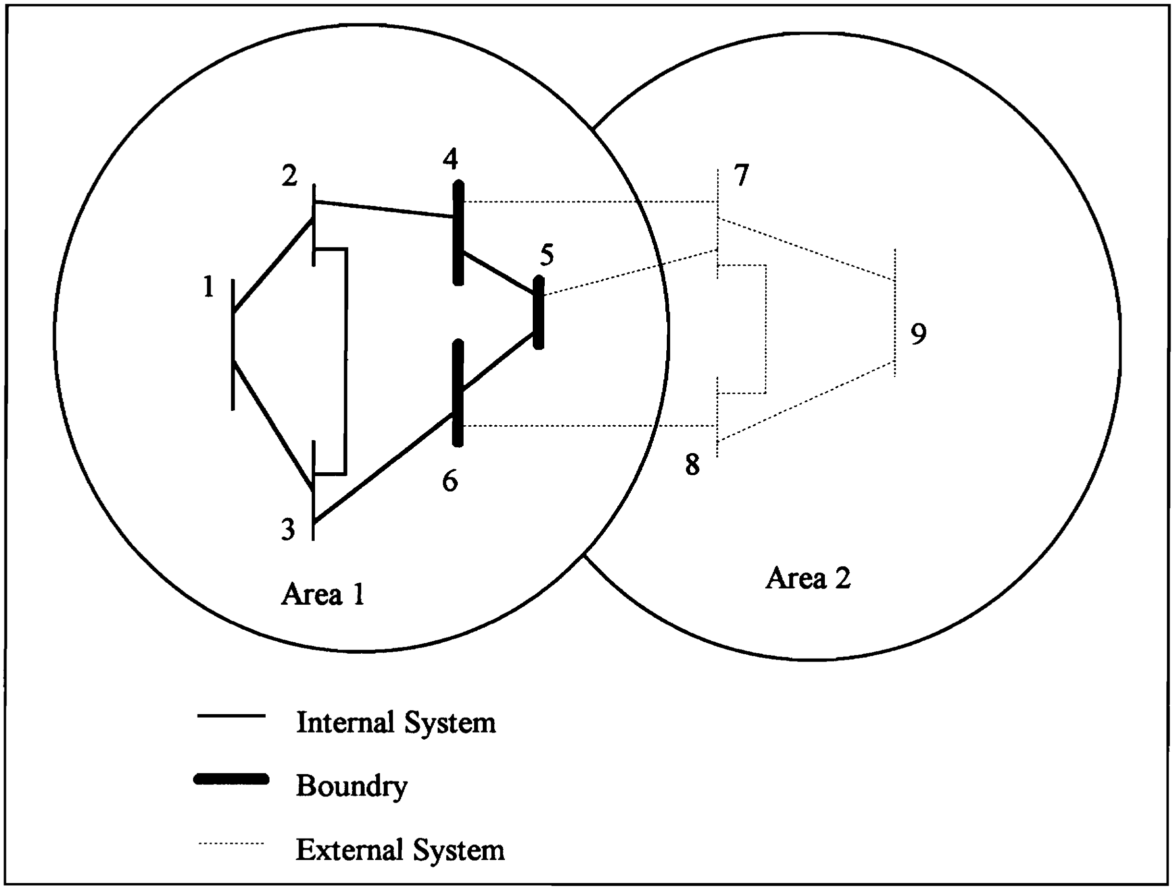


Figure 2.1 Example Power System Map

The full Y bus will have the dimensions of 9 X 9. The goal of the ward equivalent is to model this system with the internal system intact and an equivalent system added instead of the external system. The Y bus for such a system would be the 6 X 6 matrix system:

$$\begin{bmatrix} \mathrm{I_i} \\ \mathrm{I_b} + I_{eq} \end{bmatrix} = \begin{bmatrix} \mathrm{Y_{ii}} & \mathrm{Y_{bi}} \\ \mathrm{Y_{ib}} & \mathrm{Y^{i}{}_{bb}} + Y_{eq} \end{bmatrix} \begin{bmatrix} \mathrm{E_i} \\ \mathrm{E_b} \end{bmatrix} \tag{2.4}$$

The equivalent current, I_{eq}, and the equivalent impedance, Y_{eq}, would be obtained from the following formulas.

$$Y_{eq} = Y_{bb}^{e} - Y_{be} Y_{ee}^{-1} Y_{eb} \tag{2.5}$$

$$I_{eq} = Y_{be} Y_{ee}^{-1} I_{e} \tag{2.6}$$

This formula is called Kron reduction. This is the basis of most network reduction techniques. [11]

There are many variations of this reduction technique. Normally an equivalent is used in power systems for a variety of reasons. How the equivalent is to be used determines how the reduction is performed. One of the reasons to use an equivalent system is that the user may not know or may not care what is going on in the external system. Another reason could be that the external system is too large to be modeled. When there is a change in the internal system, the external system will influence the response to this change in the internal system. The user wants an equivalent system that will cause a similar response in the internal system for the same change.

For this thesis there will be a slight variation on the internal and external systems. There is not enough computing capacity in the relay to run a stability study on the entire power system in a real-time mode. The relay can perform a real-time transient stability study on a system with only a few buses and generators. Due to the computing constraint, most buses on the FP&L power system must be eliminated. Only a few buses may be retained and these buses will be considered the internal system or boundary buses. All buses not retained will be considered the external system.

In the case of FP&L, the retained buses may not be connected to each other as in figure 2.1, but rather they may be connected through the external system. The buses where there is a PMU will be retained since the reduced model must know the conditions at the PMU location for the relay to work. Currently Duval and Hatch 500-kV Substations are the PMU location sites. Thalmann 500-kV Substation is located between Duval and Hatch and exact data will be known at Thalmann from the PMUs at Duval and Hatch. Transient stability of a power system is mostly concerned with what is going on at the generators. There are 19 generators in the FP&L system. This is too many generators to perform a real time transient stability study. Equivalent generators will be made. These equivalent generator buses will also be retained.

2.2 Constant Current Model

In the discussion of the Ward Equivalent there was no mention of load. Load on a power system is made up of a variety of many different sources. Some load is constant impedance such as lighting. This means that as the voltage at the load bus varies the amount of current the load draws will also vary according to Ohm's Law. The amount of power that is used will be proportional to the square of the voltage. Some load is constant power such as motors, which means that no matter what the voltage is, the load will use the same amount of power. The rest of the load is constant current. The power drawn by the load will be proportional to the voltage as the current will stay the same. The Kron reduction is a linear operation which means that a constant power model can not be used since it involves the square of the voltage. The Kron reduction can model loads as either constant current or constant impedance.

To obtain a constant current model of the power system all the loads and shunts at a bus would be modeled as current sources. Figure 2.2 shows a bus model and the data which needs to be taken into account at each bus.

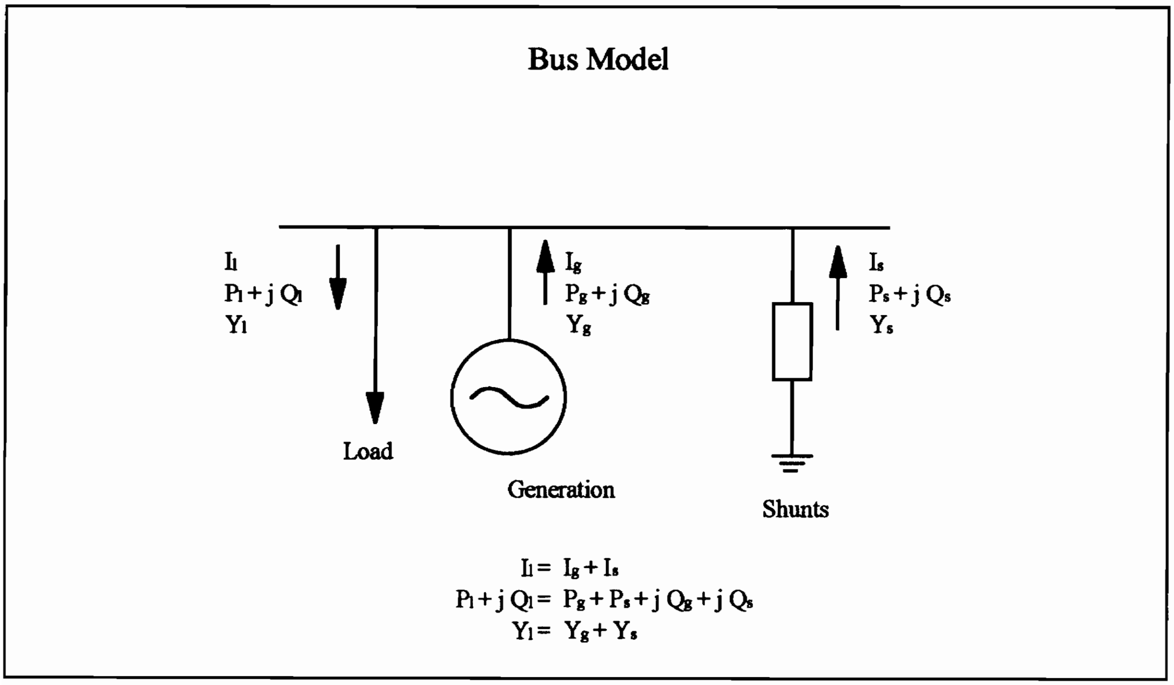


Figure 2.2 Bus Model

In equations (2.1) and (2.2) the current would be either negative for loads and shunt reactors or positive for capacitors and generator current. The complex sum of the generation, shunt, and load currents would be the injected current in the Kron reduction. If all the shunts are modeled as current sources this would mean the Y bus matrix in equation (2.3) would be singular. Since all the shunts are modeled in the current vector the diagonal element of the Y bus is the sum of the admittances of all the lines connected to that bus. This is equal to the negative sum of the rest of the elements in either that row or column. The row and column sums of the Y bus are equal to zero. This is a property of a singular matrix. The Kron reduction would still work on a singular Y bus matrix because the inverse is taken of only one partition of the matrix not the whole matrix. As long as the Y_{ee} submatrix is non-singular then the Kron reduction will work. The Y_{ee} submatrix will only be singular if the external system is not connected to any internal or boundary buses. A singular Y bus gives interesting properties which will be discussed later.

The following is the bus data (Table 2.1) and the impedance data (Table 2.2) for a five bus system (Figure 2.3) to be used as an example problem.

Table 2.1 Example Load Flow Data

Bus Number	Area	V pu	Angle	Pg MW	Qg MVAR	Pl MW	Ql MVAR	Shunt MVAR
1	1	1.0291	-5.1			200	60	42.4
2	1	1.0350	0.0	503.3	6.3	100	30	
3	1	1.0319	-3.5			100	30	21.3
4	2	1.0300	-4.6	100.0	2.4	100	30	
5	2	1.0293	-4.9			100	30	21.2
Total:				603.3	8.7	600	180	84.9

Table 2.2 Example Impedance Data

From Bus	To Bus	R	X	B/2
1	2	0.0060	0.0600	0.0600
1	3	0.0080	0.0800	0.0800
1	4	0.0150	0.1500	0.1500
2	3	0.0040	0.0400	0.0400
2	5	0.0110	0.1100	0.1100
3	4	0.0090	0.0900	0.0900
4	5	0.0030	0.0300	0.0300

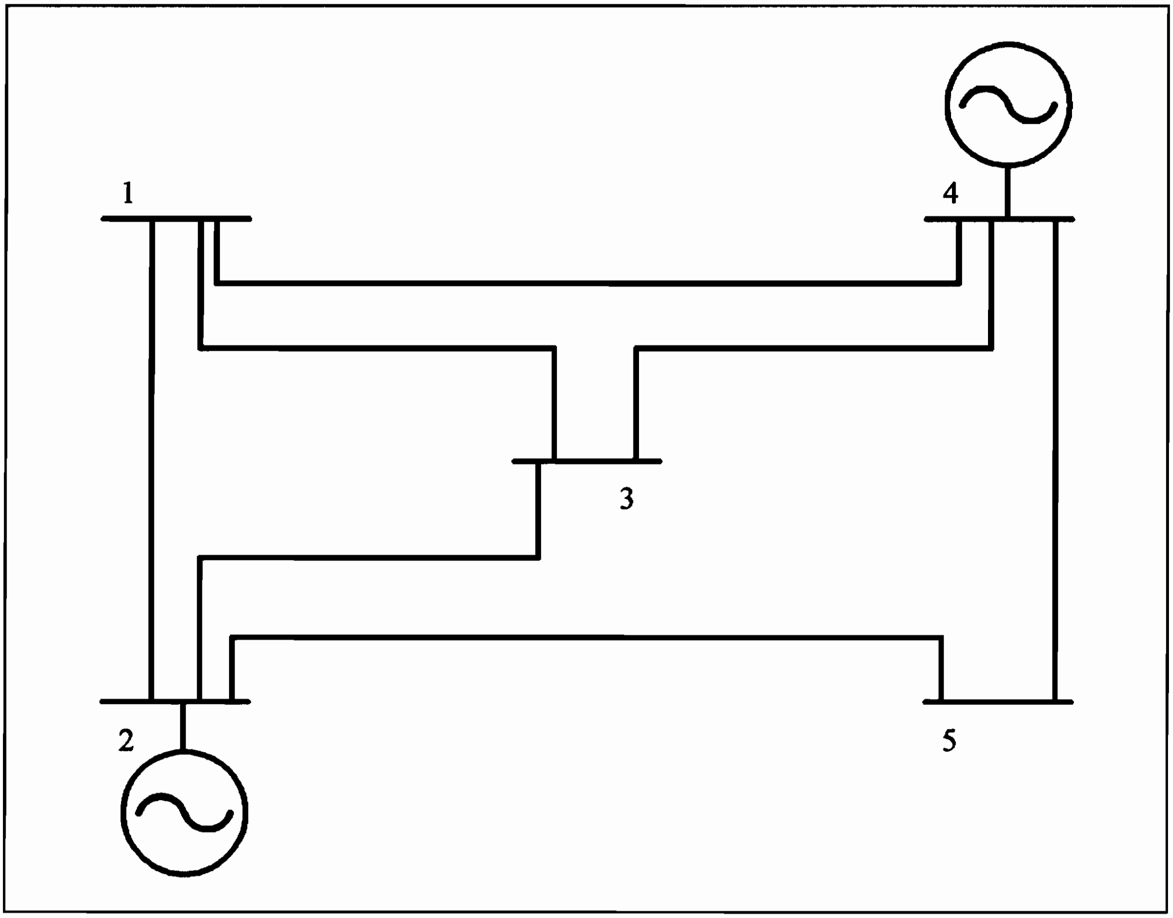


Figure 2.3 Example 5 Bus System

With this data the following Y bus can be obtained (Table 2.3). Note that this Y bus is singular because no shunts have been included in the Y bus.

Table 2.3 Example Y Bus

	1	2	3	4	5
1	-3.5479 +j35.4785	1.6502 -j16.5017	1.2376 -j12.3762	0.6601 -j6.6007	0 j0
2	1.6502 -j16.5017	-5.0255 +j50.255	2.4752 -j24.7525	0 j0	0.9001 -j9.0009
3	1.2376 -j12.3762	2.4752 -j24.7525	-4.813 +j48.1298	1.1001 -j11.0011	0 j0
4	0.6601 -j6.6007	0 j0	1.1001 -j11.0011	-5.0605 +j50.6051	3.3003 -j33.0033
5	0 j0	0.9001 -j9.0009	0 j0	3.3003 -j33.0033	-4.2004 +j42.0042

The injection current vector would be the vector sum of the generation, load, and shunt current. The entries I_2 and I_3 are computed for an example. Bus 2 has a load of $S=100+j30$ MVA and generation of $S=503.3+j6.3$ MVA with a voltage of 1.0350

Bus #2:

$$I_l = \frac{1.00 - j0.30}{1.035} = 0.96618 - j0.28986 \qquad I_g = \frac{5.033 - j0.063}{1.0350} = 4.8628 - j0.06087$$

Although there are no capacitors or reactors at bus #2 there are shunts. The line charging is considered a shunt. The total charging modeled at bus #2 would be the sum of *B/2* of all the lines connected to bus #2.

Total Charging: $= j0.06 + j0.04 + j0.11 = j0.21$

$$I_s = -j0.21 * 1.035 = -j0.21735$$

$I_2 = I_l - I_s - I_g = -3.8966 - j0.0116$

Bus #3:

$$I_l = \frac{1.00 - j0.30}{1.0319\angle -3.49} = 0.9496 - j0.3492$$

$$I_s = \frac{-j0.213}{1.0319\angle 3.49} - 1.0319\angle -3.49 * (j0.08 + j0.04 + j0.09) = -0.258 - j0.4223$$

$I_3 = I_l - I_s = 0.9753 + j0.0731$

Using a similar method for the other three buses the injected current vector can be calculated. With that the following equality is obtained:

$$I_l - I_g - I_s = I = \begin{bmatrix} +1.9470 - j0.0466 \\ -3.8966 - j0.0116 \\ +0.9753 + j0.0731 \\ +0.0008 + j0.0101 \\ +0.9730 - j0.0250 \end{bmatrix} = \left[Ybus\right] \begin{bmatrix} 1.0250 - j0.0917 \\ 1.0350 + j0.0000 \\ 1.0300 - j0.0628 \\ 1.0266 - j0.0831 \\ 1.0255 - j0.0883 \end{bmatrix} = YE$$

Now area two can be reduced. Since all area one buses are connected to an area two bus they are considered boundary buses. From equations 2.5:

$$Y_{bb} = \begin{bmatrix} -3.55 + j35.5 & 1.65 - j16.5 & 12.4 - j12.4 \\ 1.65 - j16.5 & -5.03 + j50.3 & 2.48 - j24.8 \\ 1.24 - j12.4 & 2.48 - j24.8 & -4.81 + j48.1 \end{bmatrix} \text{ and } Y_{be} Y_{ee}^{-1} Y_{eb} =$$

$$\begin{bmatrix} 0.66 - j6.6 & 0 \\ 0 & 0.9 - j9.0 \\ 1.1 - j11.0 & 0 \end{bmatrix} \begin{bmatrix} -0.004 - j0.04 & -0.0032 - j0.032 \\ 0.0032 - j0.032 & -0.0048 - j0.048 \end{bmatrix} \begin{bmatrix} 0.66 - j6.6 & 0 & 1.1 - j11 \\ 0 & 0.9 - j9 & 0 \end{bmatrix}$$

$$Y_{eq} = Y^{e}_{bb} - Y_{be}Y_{ee}^{-1}Y_{eb} = \begin{bmatrix} -3.3713 + j33.7128 & 1.8394 - j18.3936 & 1.5319 - j15.3192 \\ 1.8394 - j18.3936 & -4.6299 + j46.2992 & 2.7906 - j27.9057 \\ 1.5319 - j15.319 & 2.7906 - j27.9057 & -4.3225 + j43.2249 \end{bmatrix}$$

Note that the equivalent Y bus is singular like the original. Having a singular Y bus matrix did not prevent the reduction. The off diagonal entries in the equivalent Y bus are the admittances between bus *i* and *j* just as in the original Y bus. The only difference is that there are only 3 buses in the new system. The equivalent injection current can be obtained from equation 2.6. An equivalent current can be found by multiplying the current from area 2 by a distribution factor obtained from the Y bus. The distribution factor is:

$$-Y_{be}Y_{ee}^{-1} =$$

$$\begin{bmatrix} 0.66 - j6.6 & 0 \\ 0 & 0.9 - j9.0 \\ 1.1 - j11.0 & 0 \end{bmatrix} \begin{bmatrix} -0.004 - j0.04 & -0.0032 - j0.032 \\ 0.0032 - j0.032 & -0.0048 - j0.048 \end{bmatrix} = \begin{bmatrix} 0.2675 & 0.2102 \\ 0.2866 & 0.4395 \\ 0.4459 & 0.3503 \end{bmatrix}$$

The distribution factor for the equivalent current is all real. The rows also sum to 1. This is because the original Y bus is singular. To obtain an equivalent generation current, multiply the generation current of area 2 by the distribution factor.

$$I_{geq} = -Y_{be}Y_{ee}^{-1}I_{garea2} = \begin{bmatrix} 0.25484 - j0.0272 \\ 0.2768 - j0.0291 \\ 0.4306 - j0.0453 \end{bmatrix}$$

The only generation in area 2 is at bus #4. The sum of this equivalent generation current I_{geq}, is equal to the amount of current generation on bus #4. Load, shunt, or even total injected current can be handled similarly.

If an equivalent amount of power is required then the conjugate of equivalent current at a bus is multiplied by the voltage at that bus. Since the equivalent current for load, generation, and shunts can be found separately, the amount of power can also be determined separately. In the original system there is only generation in area1 at bus #2. For the reduced system this has changed and there is generation at all the buses. This can be a problem in modeling generators. There can also be a problem with the equivalent power if the bus voltage angle of the retained buses are very different from the bus voltage angles of the reduced buses. If the bus angles are the same, then the P/Q ratio of the total equivalent power would be the same as that of the original power. If the voltages are the same both in magnitude and angle then the total amount of power of the reduced system would be the same as the full system.

For this system the new total load and generation powers are listed in Table 2.4. These numbers can be compared with those from Table 2.1.

Table 2.4 Total Generation and Load of Example

	P MW	Q MVAR
Generation	603.32	11.69
Load	597.97	187.66

2.3 Constant Impedance Model

In a constant impedance model, the load and shunts are modeled as impedances. From figure 2.2, $-Y_l$ and Y_S are added to the Y_{ii} element in the Y bus matrix. The only injected current would be that of the generation. The Y bus is no longer singular. The shunts for bus #2 are:

$$Y_l = \frac{P_l - jQ_l}{\|V\|^2} = \frac{1.0 - j0.3}{1.035^2} = 0.9335 - j0.2801 \text{ and } Y_s = \frac{-jQ_s}{\|V\|^2} = \frac{j0.225}{1.035^2} = j0.21$$

Notice that the impedance from the shunts is equal to the sum of the of the charging connected to bus #2.

From similar calculations the total shunts are listed in Table 2.5

Table 2.5 Shunts of the Constant Impedance Model

Bus #1 =	-1.8885 - j0.1235	Bus #4 =	-0.9426 + j0.0128
Bus #2 =	-0.9335 + j0.0701	Bus #5 =	-0.9439 + j0.0568
Bus #3 =	-0.9391 - j0.1283	Total Shunts =	-5.6476 - j0.2257

Once these shunts are added to the diagonal elements of the Y bus, the matrix will no longer be singular.

The new equivalent Y bus matrix will be:

$$Y_{eq} = Y_{bb} - Y_{be}Y_{ee}^{-1}Y_{eb} = \begin{bmatrix} -5.3679 + j33.5952 & 1.6812 - j18.3862 & 1.3516 - j15.3093 \\ 1.6812 - j18.3862 & -5.8213 + j46.3775 & 2.5271 - j27.8934 \\ 1.3516 - j15.3093 & 2.5271 - j27.8934 & -5.5621 + j43.1131 \end{bmatrix}$$

The admittances of the branches in this model are different then the admittance of the constant current model. The load and shunts are included in the Y bus. Some of the shunts which were only in the diagonal of the original matrix are now represented in the off diagonal elements. This has the physical interpretation that some of the load, which has been reduced, will be represented in the loss of the transmission lines.

The equivalent generator current of area 2 is:

$$I_{eq} = -Y_{be}Y_{ee}^{-1}I_{garea2} = \begin{bmatrix} 0.2650 - j0.0161 & 0.2076 - j0.0173 \\ 0.2832 - j0.0236 & 0.4357 - j0.0283 \\ 0.4417 - j0.0269 & 0.3461 - j0.0289 \end{bmatrix} I_g = \begin{bmatrix} 0.2543 - j0.0425 \\ 0.2711 - j0.0516 \\ 0.4238 - j0.0708 \end{bmatrix}$$

With this method of reduction, the multiplication factor does not sum to one and it also is complex. The total equivalent generator current is no longer equal to the generator current from bus #4 as in the constant current model. The sum of the equivalent current and the generator current from area 1 is the injected current for the equivalent system.

$$I_{eq} = \begin{bmatrix} -0.2543 + j0.0425 \\ -5.1339 + j0.1124 \\ -0.4238 + j0.0708 \end{bmatrix} = Y_{eq}E$$

Since the injected current is all generation, the generation power can be obtained from multiplying the conjugate of the current by the voltage. The total generation of the reduced system is: 601.91 + j18.3 MVA. The total load or the load at each bus cannot be determined since it was incorporated into the Y bus and is indistinguishable from the rest of the shunts. The total shunts of the equivalized matrix is: 5.6315 + j0.0922. This corresponds to a total shunt power of 599.33 - j9.69 MVA. This includes load and shunts. Compare this to the value in Table 2.5.

2.4 Hybrid Model

In the power system, shunts normally consist of charging capacitance, shunt reactors, and capacitor banks which are all impedances. If these were equivalized it would be logical that the equivalent would model these as constant impedance. Loads, however, are not normally constant impedances. In the Hybrid Model, the loads are modeled as constant currents and the shunts are modeled as constant impedances. The injected current vector would be the complex sum of the load and generation current. The diagonal values of the Y bus would include charging and any bus shunts. As in the constant impedance model the Y bus would not be singular. The load and generation could be uniquely determined as in the constant current model. The shunts would all be lumped into one model. Table 2.6 lists the total shunts in the Y bus. The load and generation would be the same as the Constant Current Model.

Table 2.6 Total Shunts of the Hybrid Model

Bus #1 =	-j0.69	Bus #4 =	-j0.27
Bus #2 =	-j0.21	Bus #5 =	-j0.34
Bus #3 =	-j0.41	Total Shunts =	-j1.92

The equivalent Y bus is:

$$Y_{eq} = Y_{bb} - Y_{be}Y_{ee}^{-1}Y_{eb} = \begin{bmatrix} -3.3714 + j32.9876 & 1.8392 - j18.4470 & 1.5318 - j15.3778 \\ 1.8392 - j18.4470 & -4.6301 + j45.9993 & 2.7903 - j27.9947 \\ 1.5318 - j15.3778 & 2.7903 - j27.9947 & -4.3227 + j42.7172 \end{bmatrix}$$

As can be seen, the impedances of this system are different from the impedances of the other two equivalent models. The distribution factor used in determining the equivalent current is:

$$I_{eqg} = -Y_{be}Y_{ee}^{-1}I_{garea2} = \begin{bmatrix} 0.2728 - j0.0005 & 0.2161 - j0.0006 \\ 0.2946 - j0.0008 & 0.4494 - j0.0010 \\ 0.4546 - j0.0009 & 0.3601 - j0.0010 \end{bmatrix} I_g = \begin{bmatrix} 0.2634 - j0.0282 \\ 0.2845 - j0.0307 \\ 0.4390 - j0.0471 \end{bmatrix}$$

Similar calculations are done for the load current. The equivalent current is added to the existing current to obtain the following equality.

$$I_{eq} = I_{eql} - I_{eqg} = \begin{bmatrix} 2.0813 - j0.9080 \\ -3.4798 - j0.4766 \\ 1.2787 - j0.6061 \end{bmatrix} = Y_{eq}E$$

The total load and generation of this model is listed in table 2.7.

Table 2.7 Total Load and Generation for Hybrid Model

	P MW	Q MVAR
Generation	605.52	12.05
Load	602.52	189.76

2.5 Conclusions

As stated earlier none of these methods are equivalents for constant power. The total generation and load in each of these models changed from the original value. As the system gets larger and the bus angle differences are greater the difference in power becomes larger. This will be seen in later chapters.

Chapter 3

2 Machine Equivalent Model

3.1 Introduction

Relaying is sometimes considered an art as well as a science. The word art is used because of the fine subtleties and understanding of the power system that allows the relay engineer to set relays such that they will operate optimally between dependability and security. There is always a trade off between dependability and security. A relay is dependable if it operates when it should. A relay is secure if it does not operate when it should not [12]. Adaptive relaying will take relaying more toward science and less toward art. The relay now will have more information on which to base its decision, such as the current power system conditions. Adaptive relays will lessen the trade off between security and dependability. There is another trade off which will become more important as adaptive relays are developed. This is the trade off between speed and accuracy. There will be so much data to process that a high speed relay may not be able to operate in a timely manor.

The relay being developed for FP&L and GPC must perform a transient stability study and make a decision in a quarter of a second. Because of this speed requirement, it is necessary to be able to perform the transient stability study faster then real time. This is the trade off between speed and accuracy. A transient stability study of the full system would take several minutes to perform. Therefore the stability study must be performed on a reduced model. One of the fastest methods for performing a stability study is the equal area criterion. This method can only be used on a system which has two machines. Since Florida is a peninsula and the 500-kV transmission system is connected to the rest of the country through Duval 500-kV Substation, a two machine model is not a bad approximation. This assumption will be verified later.

3.2 Equal Area Criterion

This is an explanation of the Equal Area Criterion for a two machine system where one of the machines is an infinite bus (figure 3.1).

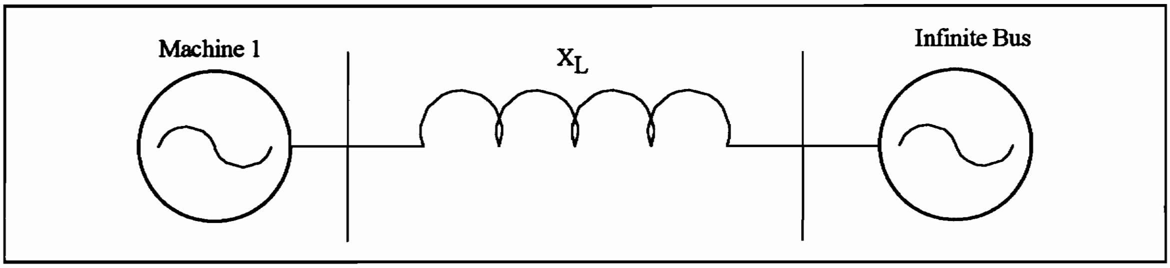


Figure 3.1 Two Machine System

Recall the discussion from Chapter 1 on stability, the accelerating power is equal to the difference between the mechanical and electrical power. If the accelerating power is no longer zero it can be described by the equation:

$$P_m - P_e = P_a = \frac{2H}{\omega_s}\frac{d^2\delta}{dt^2} \tag{3.1}$$

$$\omega_r = \omega - \omega_s = \frac{d\delta}{dt} \tag{3.2}$$

Where H is the inertia constant of the machine, ω_S is the synchronous speed of the system, ω is the speed of the machine, and ω_r is the relative speed of the machine. Using these equations, one can derive the equation:

$$P_m - P_e = \frac{2H}{\omega_s}\frac{d\omega_r}{dt} \tag{3.3}$$

$$\frac{d\delta}{dt}(P_m - P_e) = \frac{2H\omega_r}{\omega_s}\frac{d\omega_r}{dt} = \frac{H}{\omega_s}\frac{d(\omega_r^2)}{dt} \tag{3.4}$$

$$\int_{\delta_0}^{\delta_1}(P_m - P_e)d\delta = \frac{H}{\omega_s}(\omega_{r1}^2 - \omega_{r0}^2) \tag{3.5}$$

Since at the minimum and maximum δ the rotor is at synchronous speed, the difference between ω_{r1} and ω_{r0} is zero.

$$\int_{\delta_0}^{\delta_1}(P_m - P_e)d\delta = 0 \text{ or } \int_{\delta_0}^{\delta_c}(P_m - P_e)d\delta + \int_{\delta_c}^{\delta_1}(P_m - P_e)d\delta = 0 \tag{3.6}$$

δ_0 is the angle of the rotor when the disturbance occurs, δ_C is the angle at which the fault is cleared, and δ_1 is the maximum value the angle obtains during the transient. This equation can be represented graphically by figure 3.2. This is similar to the power angle curve of figure 1.3

An assumption is made that the mechanical power remains constant during the study. Since the time constant of the mechanical system is much greater than the period of interest, this is a valid assumption. The system is operating at δ_0 when there is a fault at the machine terminal. At such time the electrical power goes to zero. The machine will accelerate since the mechanical power is greater then the electrical power. Some time later the fault clears when the rotor angle is at δ_C. At this time the electrical power jumps back to the original curve. The machine will decelerate now since the electrical power is greater than the mechanical power. The rotor angle will continue to increase for some time due to the inertia of the machine. The amount of increase in rotor angle will slow until at some point the angle will stop increasing and start decreasing. If the rotor angle never passes δ_{max} then the system will remain stable. In figure 3.2 if the accelerating area A1 is less than or equal to the decelerating area A2 than the rotor angle will not go past δ_{max} and the system will remain stable.[13]

$$A1 = \int_{\delta_0}^{\delta_c} (P_m - P_e) d\delta \text{ and } A2 = \int_{\delta_c}^{\delta_1} (P_m - P_e) d\delta \tag{3.7}$$

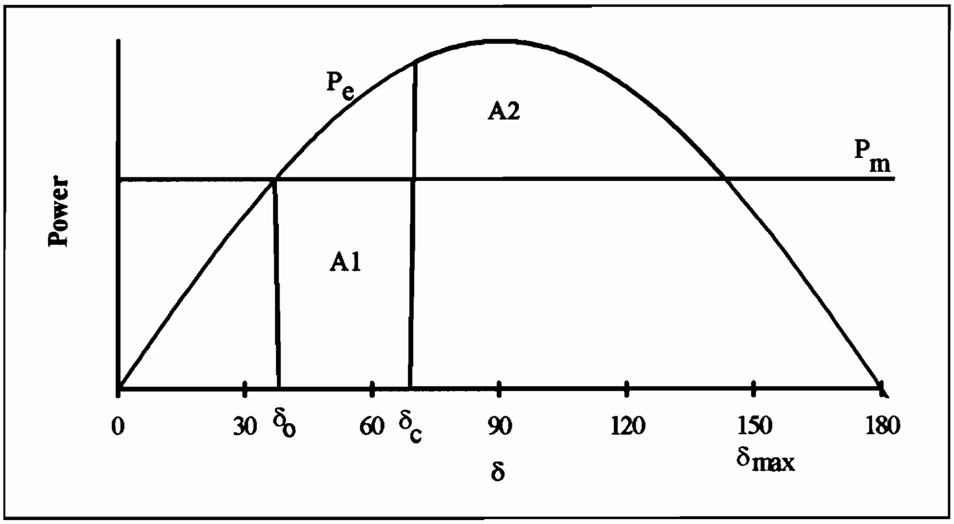


Figure 3.2 Equal Area Criterion

This is a simplified version of the Equal Area Criterion. The calculations are more complicated if neither of the two machines can be considered as an infinite bus or if the impedance between the two machines includes resistance. The electrical power during the fault does not have to go to zero as depicted in figure 3.2. In his Master of Science

Thesis, Steve Turner discussed the algorithm to use the Equal Area Criterion for a two machine model in the adaptive out-of-step relay being developed for FP&L.[14]

3.3 The Model

Steve Turner also developed a model for the two machine system to test his algorithm. His mo7del, with some slight variations, is the model used in the current version of the relay. The two machine model contains 5 buses, the two equivalent machine buses, the two buses which have PMUs, and Thalmann. Thalmann is located between Duval and Hatch (figure 3.3) so the bus data at Thalmann can be determined from the PMUs. The tie lines are the only actual lines in the system.

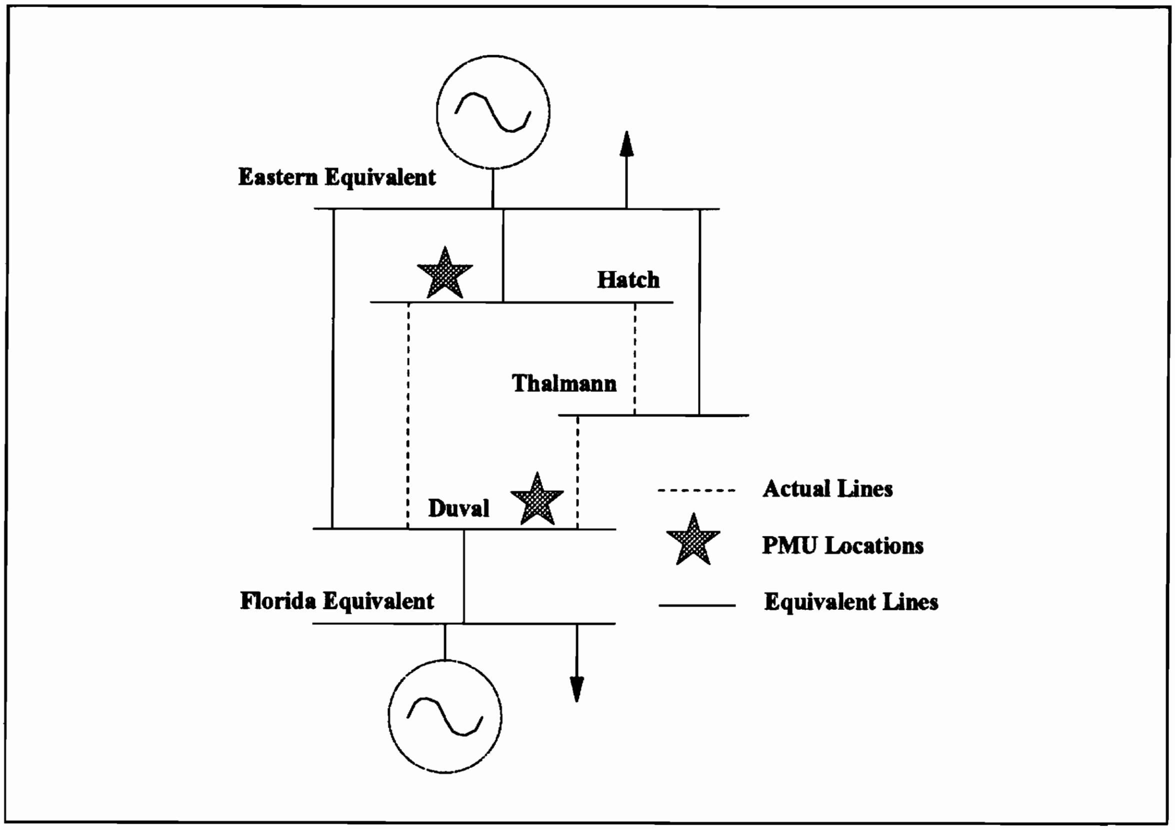


Figure 3.3 Two Machine Model

The impedances of the equivalized lines are calculated using short circuit data. With all lines north of Duval disconnected, a short circuit study at Duval was performed by FP&L. From the Thevenin impedance, the transient reactance of the equivalent Florida machine was subtracted. The remainder is the equivalent transfer impedance between Duval and the Florida equivalent generator. The impedances of the equivalent lines from Hatch and Thalmann to the Eastern Equivalent bus were calculated in a similar manner. A fault was placed on Duval with the rest of the Florida peninsula disconnected. The impedance of the tie lines and the equivalent transient reactance of the Eastern Equivalent Machine were subtracted from the system impedance and then the remaining impedance was split according to fault current flowing on the two tie lines. Table 3.1 lists the impedances used in the model. This data is in per unit on a 100 MVA, 500-kV base.

Table 3.1 Impedances for 2 Machine Model

From Bus	To Bus	R	jX	B/2
Duval	Hatch	0.0016	0.0268	1.2782
Duval	Thalmann	0.0010	0.0166	0.7953
Thalmann	Hatch	0.0008	0.0138	0.6585
Fla. Eqv	Duval	0.0004	0.0044	0.0000
Hatch	E. Eqv	0.0003	0.0080	0.3816
Thalmann	E. Eqv	0.0026	0.0441	2.0424
Duval	E. Eqv	0.0375	0.3780	0.5005

Models for the equivalent machines were also required. Machine data from an FP&L transient stability study was used. Machines were divided into two categories, Florida and the rest of the East Coast. It was assumed that the generators in Florida would swing together. The same assumption was made for the generators in the rest of the East Coast. These assumptions, while not totally accurate, are valid especially for faults on the tie lines. If it is assumed that generators will swing together then they can be equivalized by assuming they are located at the same bus. If generators are located at the same bus then their parameters can be paralleled to make an equivalent generator. The inertial constants of each machine are added for an equivalent H. The impedances are paralleled. The time constants are averaged. Table 3.2 contains the machine data. Note that all machine data is on a 100 MVA base. The Energy data is the inertia constant *H* multiplied by the MVA base of 100 MVA.

Table 3.2 Machine Data for 2 Machine Model

Machine	Energy MWS	X_d	X'_d	X''_d	Xq	X'q	X"q
Fla. Eqv	94898	0.0057	0.0010	0.0007	0.0055	0.0016	0.0007
E. Eqv	375882	0.0016	0.0003	0.0002	0.0016	0.0005	0.0002

	R_a	T'_{do}	T'_{qo}	T''_{do}	T''_{qo}	X_l
Fla. Eqv	$2 X 10^{-5}$	5.05	0.75	0.058	0.077	0.0007
E. Eqv	$2 X 10^{-5}$	5.27	0.62	0.043	0.080	0.0002

This data was used as input for two of Electric Power Research Institute's (EPRI) programs. The load flow program was used to solve the original load flow. The Extended Transient/Midterm Stability Package (ETMSP) was used to run a transient stability study. Input into ETMSP are the output from the EPRI load flow and four other input files. Listings for the input files are in the Appendix.

3.4 Verification with Full System Model

In order to determine the accuracy of this model it must be compared with the real system. Steve Turner had FP&L run stability studies under different load and power transfer conditions to determine whether his model matched the stable and unstable conditions but never compared any bus data. Since the two machine model retains the buses which contain the PMUs, a comparison between bus data at the PMU sites and the real system bus data could be done. In order to determine how well the two machine model matched the real system, a full system model was also developed. The development of the full system model will be described more in Chapter 4.

There are several factors which will affect the stability of the system. In the case of FP&L, one of the main factors is the amount of power transferred. Other important factors are the amount of load and generation. To test the accuracy of the two machine model, several test cases were developed. An ETMSP simulation for a fault on one of the tie lines was developed. The table 3.3 is the time line for this simulation:

Table 3.3 Time Line for ETMSP Simulation

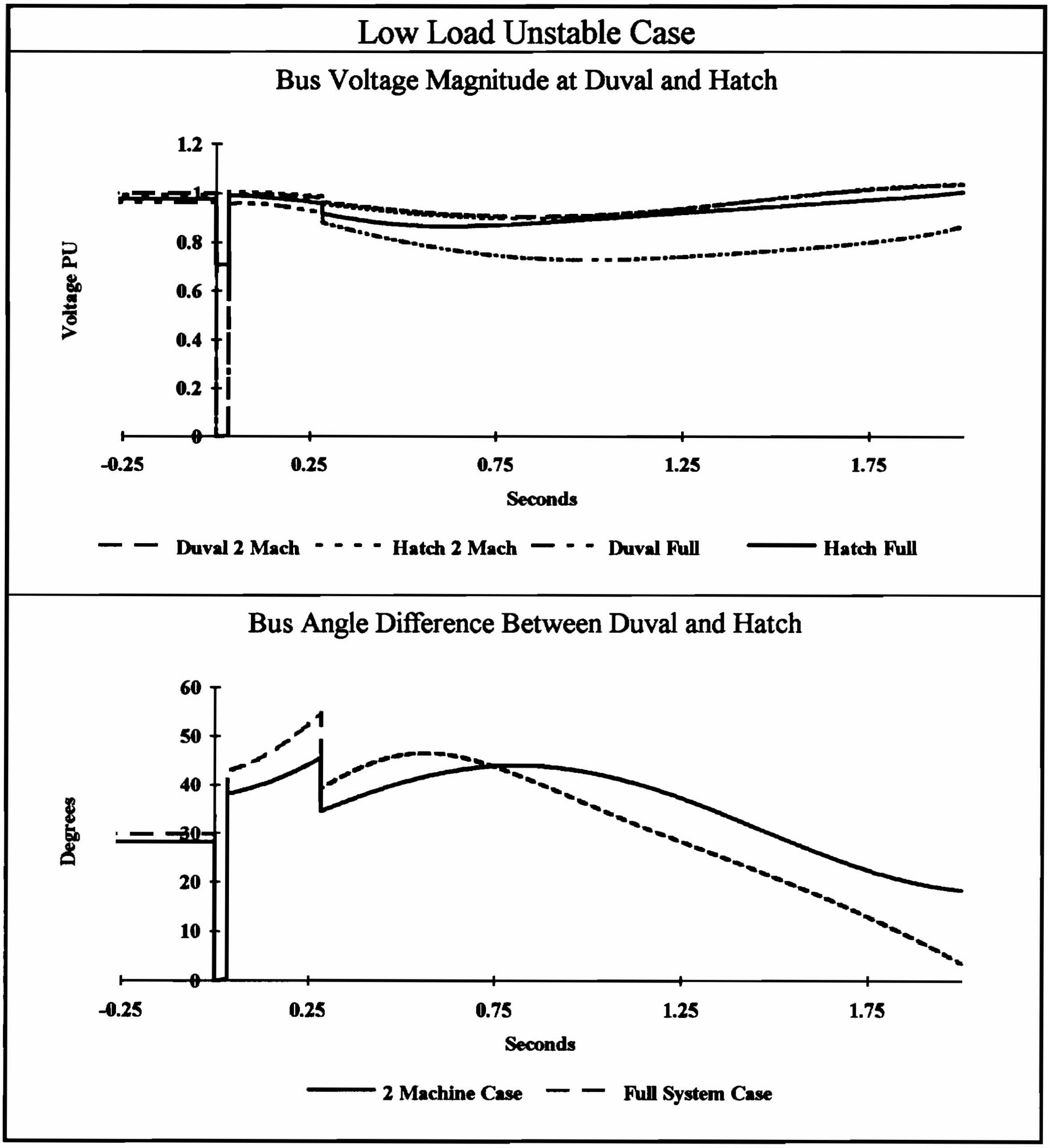
Time	Action
0 - 30 cycles	Steady State
30 cycles	3 phase fault on the Duval-Hatch 500-kV Line at the Duval end
35 cycles	Fault is cleared by the opening of the Duval-Hatch 500-kV Line
65 cycles	Duval-Hatch 500-kV Line is successfully reclosed ***
2.5 sec	End of simulation

There are eight cases which were developed for this simulation. A large amount of load was placed on the Eastern Equivalent bus. This is done to closely model the rest of the country. The load that was placed there for all cases is 95,000 + j25,000 MVA. Two load levels were chosen for Florida. FP&L has a peak load of 13,000 MW. A low load level of 60% of peak was used. A high load level of 90% of peak was also used. For each load level, a transfer level was used which produced a stable and unstable case. A case is considered to be a stable case if the power system will remain stable without the reclosure of the Duval-Hatch 500-kV Line. This step is noted in table 3.3. The system is conditionally stable if and only if it is stable when the faulted tie line is successfully reclosed. The adaptive relay will make the distinction between stable and conditionally stable. Therefore simulations will be done for conditionally stable cases also. For each conditionally stable case two simulations are run, one with the line reclosing and one without the line reclosing. Table 3.4 lists the specifications for the eight cases being studied. Note that once the load and power transfer is specified the amount of generation is predetermined so it does not need to be specified.

Table 3.4 Specifications for Load Flows

Case	Load MW	Load MVAR	Power Transferred
Low Load Stable	7,800	2,275	2,000
Low Load Unstable	7,800	2,275	4,000
Low Load Conditionally Stable	7,800	2,275	3,700
High Load Stable	11,700	3,412	2,000
High Load Unstable	11,700	3,412	4,500
High Load Conditionally Stable	11,700	3,412	4,000

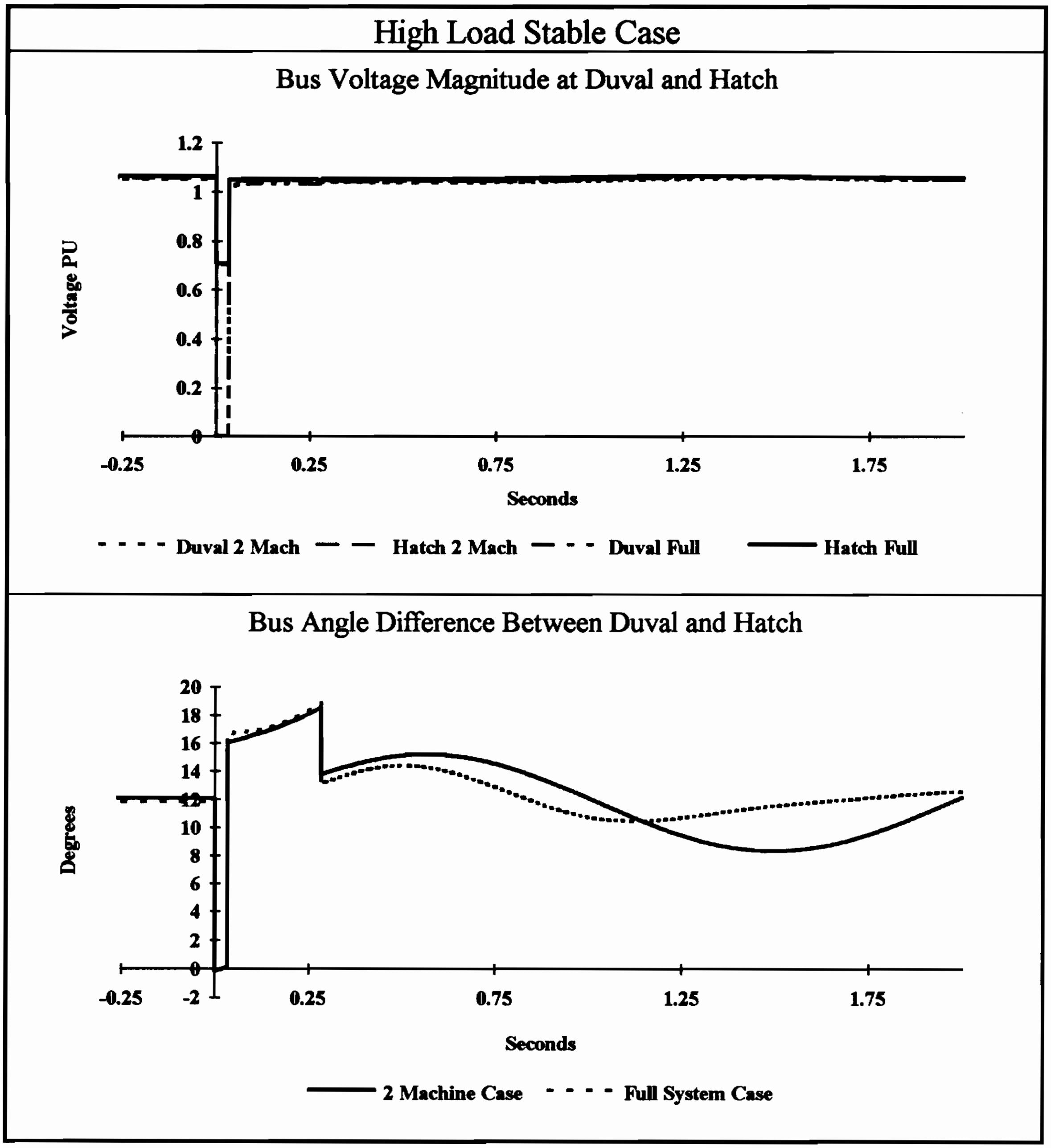
The following two figures contain voltage and bus angle comparisons between the two machine model and the full system model.


Low Load Unstable Case

Bus Voltage Magnitude at Duval and Hatch

Bus Angle Difference Between Duval and Hatch

Figure 3.4 Full and Two Machine System Comparisons



High Load Stable Case

Bus Voltage Magnitude at Duval and Hatch

Bus Angle Difference Between Duval and Hatch

Figure 3.5 Full and Two Machine System Comparisons

3.5 Comparisons with EMTP

Before a relay is installed in the field it must be tested in the laboratory. Traditional steady-state tests used on electro-mechanical relays are insufficient for the testing of the adaptive out-of-step relay. Kang-Chuen Kong for his Masters Thesis, developed a testing method for this relay. It is based on real-time playback techniques to simulate the transients of the system. The method uses EPRI's Electromagnetic Transients Program (EMTP) to produce the three phase transients voltage for the different test cases. EMTP produces the three phase instantaneous voltages for the PMU locations. Using a VME computer module, a GPS signal, and a D/A converter, a real-time analog signal is feed into the PMUs to test the relay.[15]

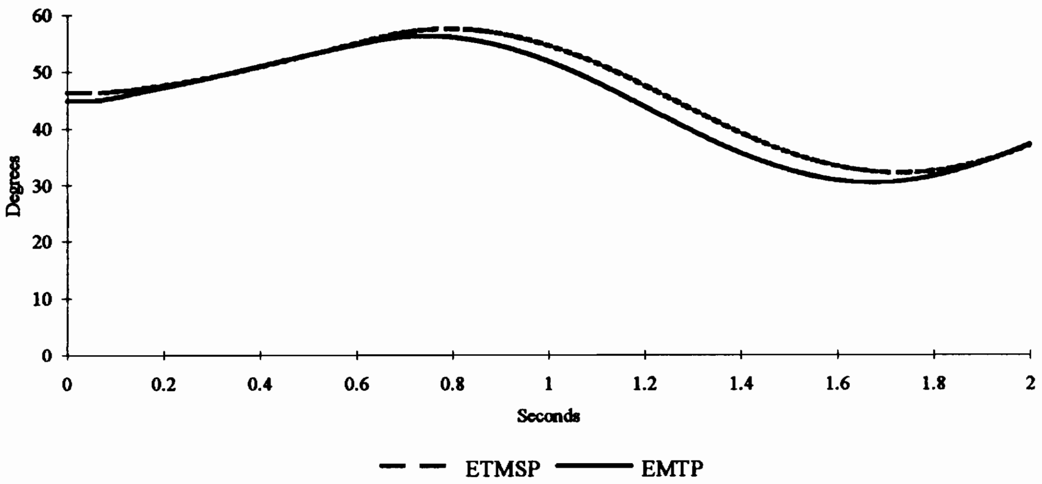
EMTP is a highly computationally intensive program. The time constraints evolved in constructing a simulation and in the simulation itself makes it unfeasible to model a system of more than a few generators in EMTP. Because of this fact the model was developed on ETMSP where, as seen, it can be verified with a full system model. The EMTP model used in the testing of the relay also needed to be verified. The following figures compare the EMTP two machine model with the ETMSP two machine model.

3.6 Conclusions

Due to the uniqueness of the FP&L power system, a two machine model is adequate to determine stability of the power system. It has the advantages of being easy to calculate the model and the transient stability study can be performed very quickly using the equal area criterion.

High Load Stable Case

Generator Angle Difference



Low Load Unstable Case

Generator Angle Difference

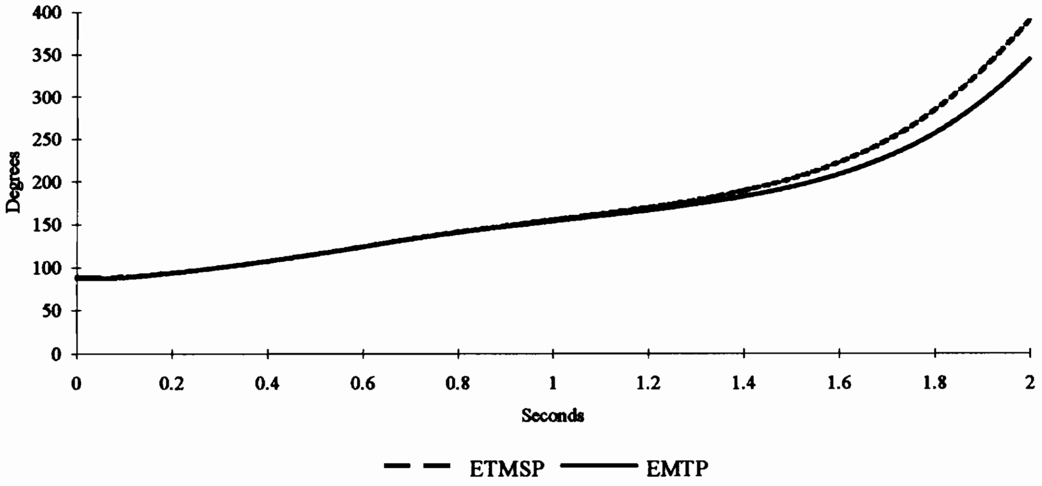


Figure 3.6 Comparisons Between ETMSP and EMTP

Chapter 4

Reduced Model with no Equivalized Generators

4.1 The Full System Model

To obtain a reduced model one must start with a full system model. The FP&L system has high voltage transmission lines at 500-kV and 230-kV. The high side of most generator step up transformers are at either of these two voltages. Since transient stability studies concentrate on the generators it was decided to model the FP&L power system only at these two voltages. The two generators which are not on the high voltage system are modeled with an equivalent impedance between the closest high voltage bus and the generator. With this a 19 generators, 166 bus load flow was developed. The transmission line impedances were obtained from FP&L's transmission line data sheets. The loads and power flows were obtained from a FP&L state estimation print-out. Four of the generators modeled are generators that do not actually belong to FP&L but are modeled due to their proximity to the FP&L system. They have an impact on the FP&L system when performing a transient stability study, so to not include them would have decreased the accuracy of the model. One of these external generators and 3 of the buses represent the rest of the East Coast. Hatch and Thalmann are actual buses but the third bus is an equivalent generator bus. All three of these buses will be retained and considered part of the internal system when the reduced model is made. The model once complete was compared to the state estimation print-out to verify the accuracy of the load flow. Also to verify the accuracy of the load flow model, the short circuit impedance at Duval was compared with the data from FP&L. From this full system load flow, all other models are produced. All reduced models will be compared to this full system model.

4.2 The Reduction

Before reducing the system to a four machine model or less, the system was reduced to machine buses only plus the tie lines, Duval, Hatch, Thalmann and the Eastern Equivalent buses. The model will be able to match data with the PMU's placed at Duval and Hatch. The generator angles of a transient stability study will be compared from both the full system and reduced system.

The reduction programs are included in the Appendix. The program consists of several different programs. There is a FORTRAN routine which converts IEEE load flow data to several files containing bus voltage and angles, bus loads and generation, and line impedances. A MATLAB routine reads the data into the MATLAB environment. The Y bus is created along with several vectors containing complex bus voltages, load current, generation current, total current, load shunt impedances, and total power at each bus. A reduction routine will use the appropriate data depending on the method of reduction to obtain an equivalent Y bus and an equivalent injected current.

4.3 Constant Current Model

The method for reduction described in section 2.2 was used on the full FP&L system. The result was a 22 bus load flow. Table 4.1 compares specifications of the original system to that of the constant current model. The charging and the shunt equivalent currents are added and then are converted back to an equivalent impedance. This impedance is modeled in the EPRI load flow as a constant impedance load. To convert the equivalent charging capacitance back to charging capacitances on lines would be very difficult. Since the lines are modeled as pi equivalents in ETMSP, charging capacitance is the same as a bus shunt.

Table 4.1 Constant Current Load Flow Specifications

	Original Case	Constant Current Case
Florida Load	9,276.4 +*j*1,634.9 MVA	8,985 +*j*2,871.8 MVA
Eastern Load	95,000 +*j*25,000 MVA	95,000 +*j*25,000 MVA
Total Florida Generation	7,514.25 +*j*1,600.81 MVA	7,517.24 +*j*1,758.59 MVA
Total Generation	104,572 +*j*26,279.2 MVA	104,575 +*j*26,462.9 MVA
Total Florida Losses	256.85 +*j*614.58 MVA	169.45 +*j*2,620.32 MVA
Power Transfer	2019 +*j*3.1 MVA	2019 +*j*23 MVA
Total Florida Charging	*j*3857.27 MVAR	*j*327.88 MVAR
Total Florida Shunts	*j*645.79 MVAR	381.78 +*j*3,710.59 MVA

Even though the amount of load and shunt current is the same, the amount of load and shunt power has changed due to the fact that the voltage magnitude and angle of the retained buses is not equal to that of the original buses. The only charging capacitance in the reduced system comes from the charging capacitance at Duval on the tie lines with GPC. All other charging capacitance is represented in the shunt equivalent.

Since the generation was not changed, the generation power of both cases is the same. This means that the shunts, losses and load must add up to the original generation. The shunts were originally reactive impedances but in the reduced case there are real shunt impedances. Both the losses and the load of the reduced case is less then the original case. The increase in shunt impedances make up the difference between the loads and losses.

4.4 Constant Impedance Model

The method for reduction described in section 2.3 was used on the full FP&L system. The result was a 22 bus load flow. Table 4.2 compares specifications of the original system to that of the constant impedance model.

Table 4.2 Constant Impedance Load Flow Specifications

	Original Case	Constant Impedance Case
Florida Load	9,276.4 +j1,634.9 MVA	0 **
Eastern Load	95,000 +j25,000 MVA	95,000 +j25,000 MVA
Total Florida Generation	7,514.25 +j1,600.81 MVA	7,852.15 +j1,677.01 MVA
Total Generation	104,572 + j26,279.2 MVA	104,910 +j26,309 MVA
Total Florida Losses	256.85 +j614.58 MVA	189.24 +j2,564.96 MVA
Power Transfer	2019 +j3.1 MVA	2019 +j91.8 MVA
Total Florida Charging	j3857.27 MVAR	j335.44 MVAR
Total Florida Shunts	j645.79 MVAR	9681.91 +j925.28 MVA

** There is no load in this case because all the load is contained in the shunts.

4.5 Hybrid Model

As can be seen from the pervious case, there is no way to distinguish between shunts which are loads and shunts which are capacitors and reactors. The method for reduction described in section 2.4 had the advantage of separating shunts, loads, and generation. All the shunts, both charging and bus shunts will be lumped into one shunt. Generation and loads were considered constant currents while the shunts, which are usually impedances anyway, are considered to be constant impedances. This method of reduction was also used on the full FP&L system. The result was a 22 bus load flow. Table 4.3 compares specifications of the original system to that of the hybrid model.

Table 4.3 Hybrid Model Load Flow Specifications

	Original Case	Hybrid Model Case
Florida Load	9,276.4 + j1,634.9 MVA	9,358 + j3,030 MVA
Eastern Load	95,000 + j25,000 MVA	95,000 + j25,000 MVA
Total Florida Generation	7,514.25 + j1,600.81 MVA	7,522.34 + j1,727.17 MVA
Total Generation	104,572 + j26,279.2 MVA	104,580 + j26,427 MVA
Total Florida Losses	256.85 + j614.58 MVA	168.02 + j2,774.3 MVA
Power Transfer	2019 + j3.1 MVA	2019 + j20.3 MVA
Total Florida Charging	j3857.27 MVAR	j328.2 MVAR
Total Florida Shunts	j645.79 MVAR	15.31 + j4056.83 MVA

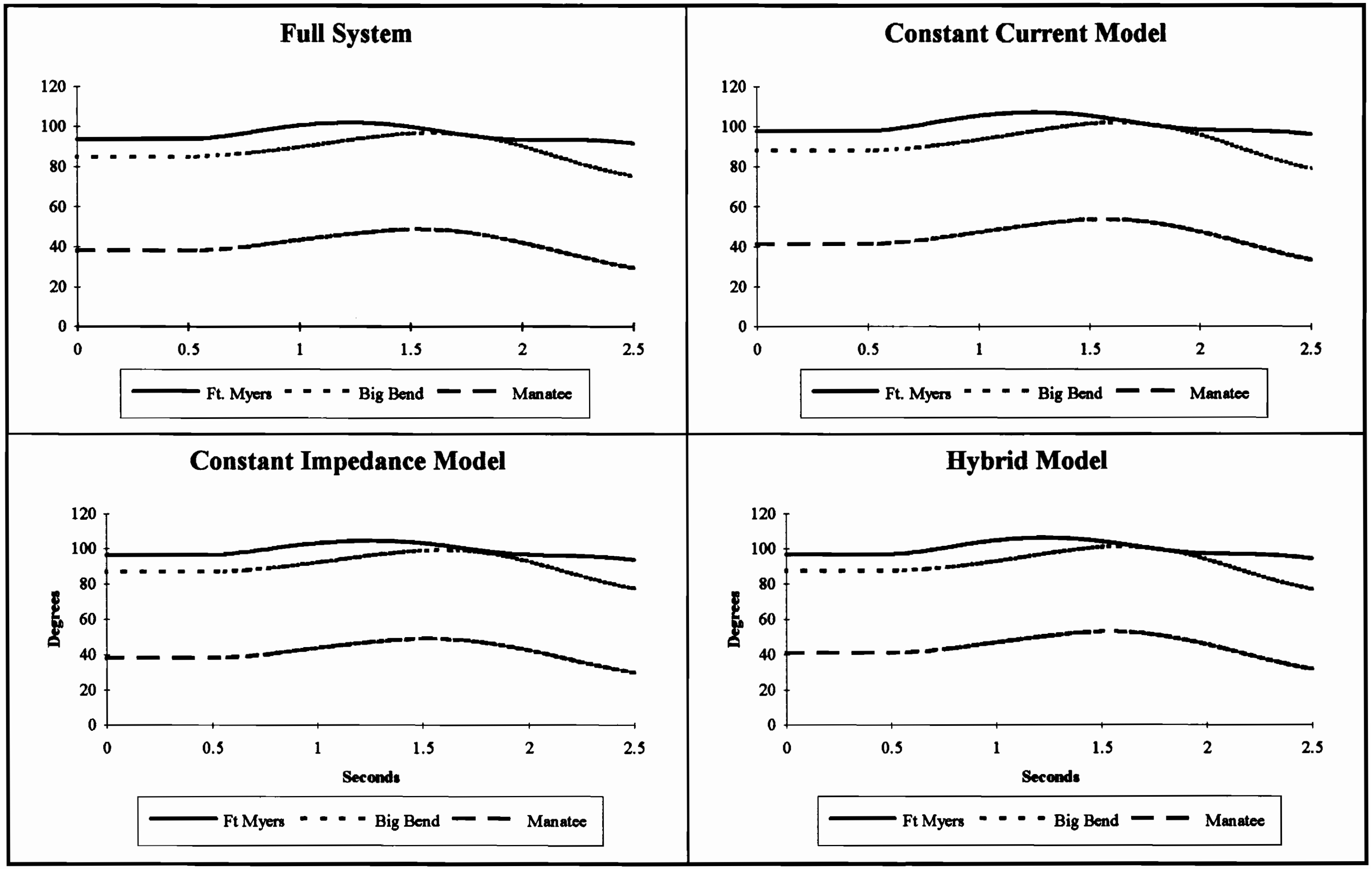


Figure 4.1 Comparison of the Generator Angles in the Western Area

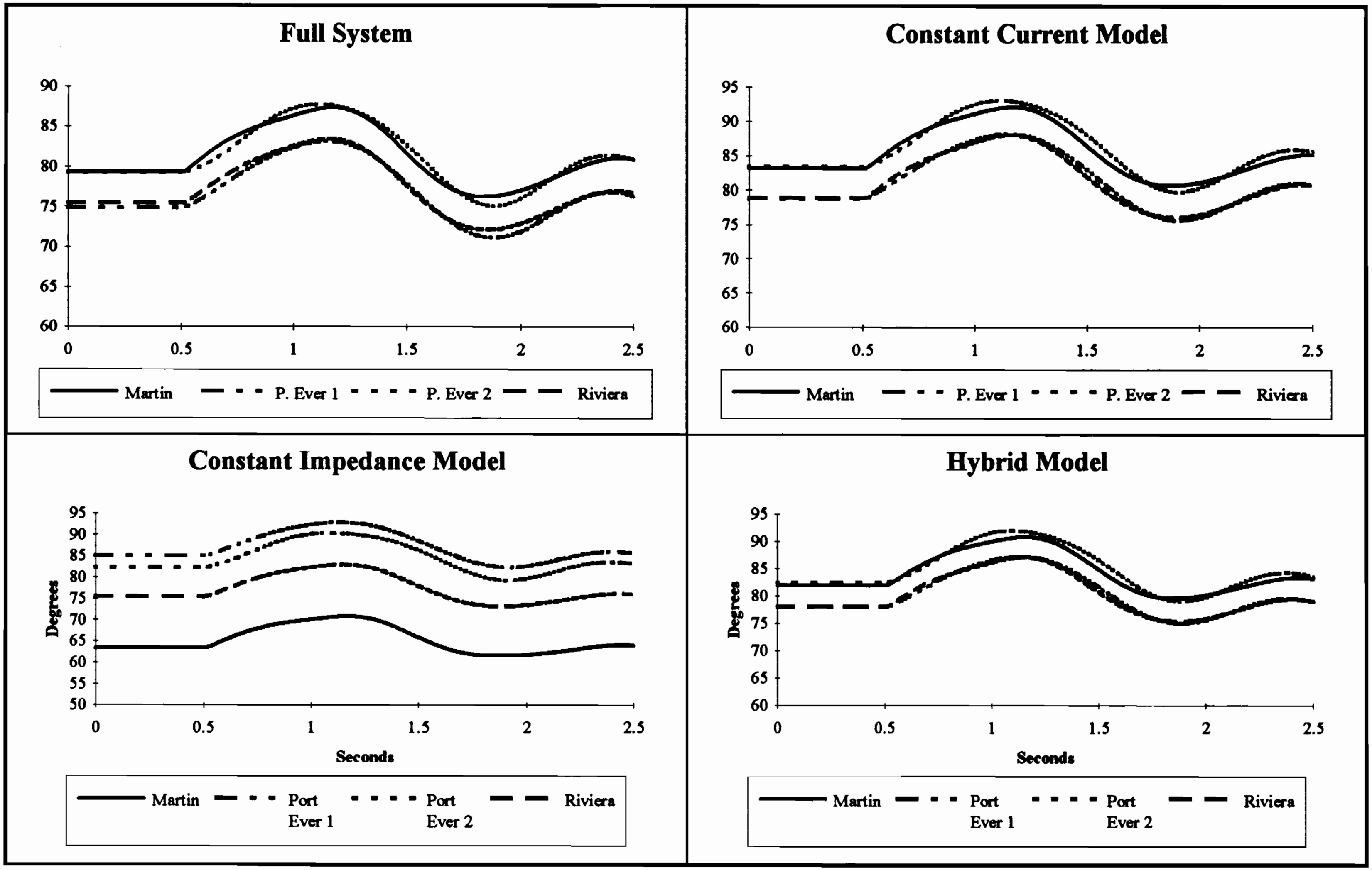


Figure 4.2 Comparison of the Generator Angles in the Southern Area

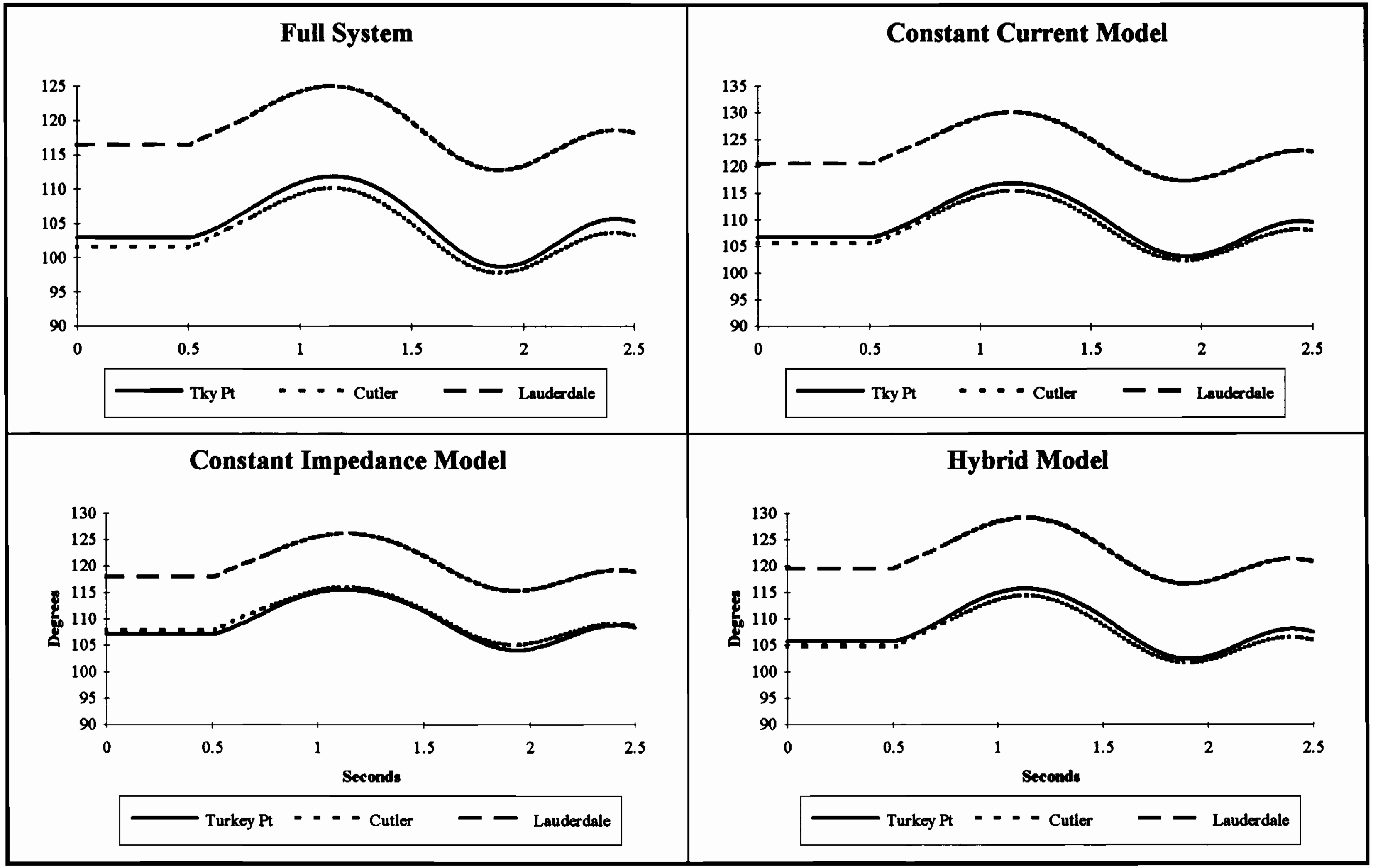
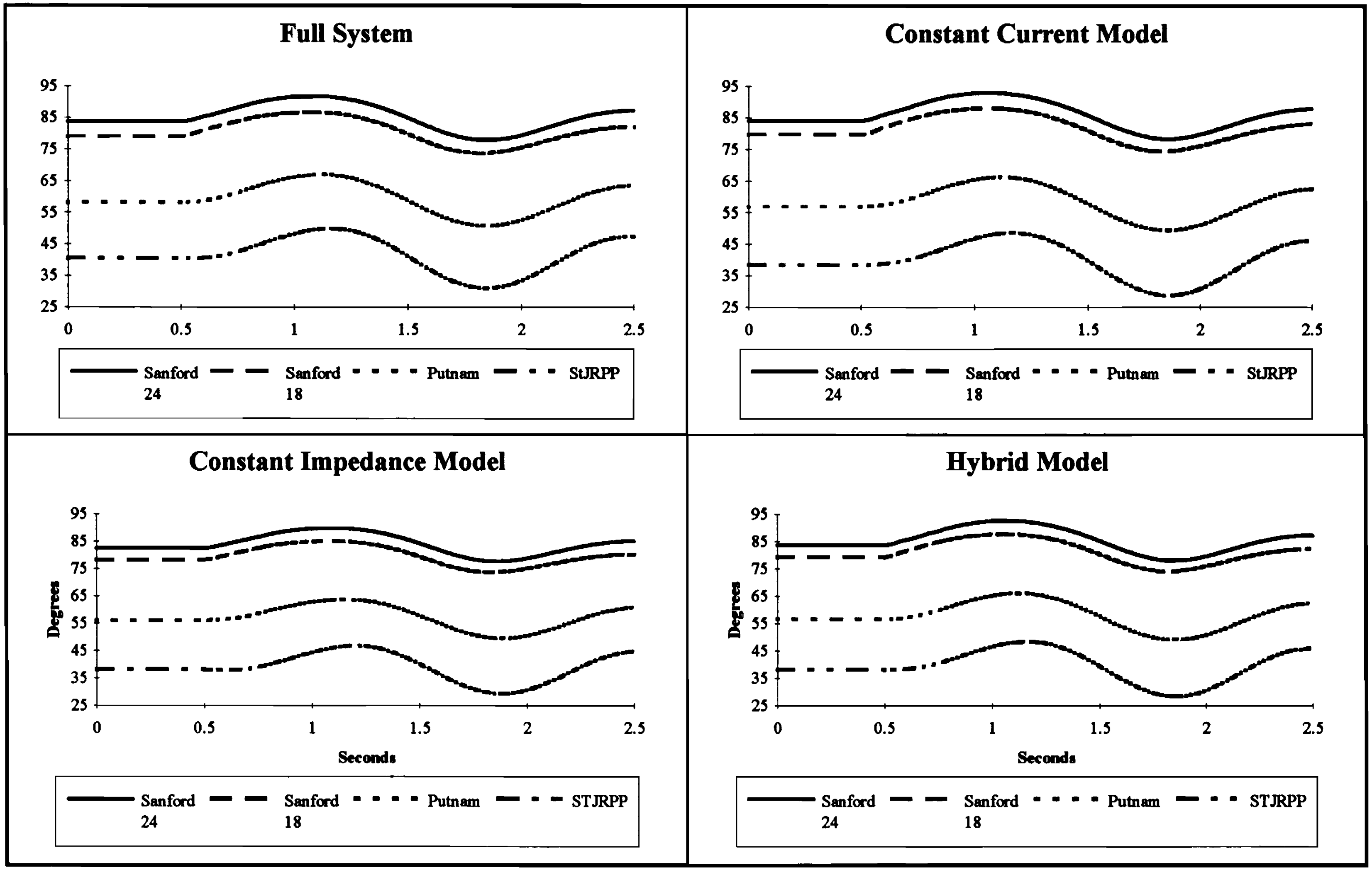


Figure 4.3 Comparison of the Generator Angles in the Southern Area



Full System

Constant Current Model

Constant Impedance Model

Hybrid Model

Figure 4.4 Comparison of the Generator Angles in the Northern Area

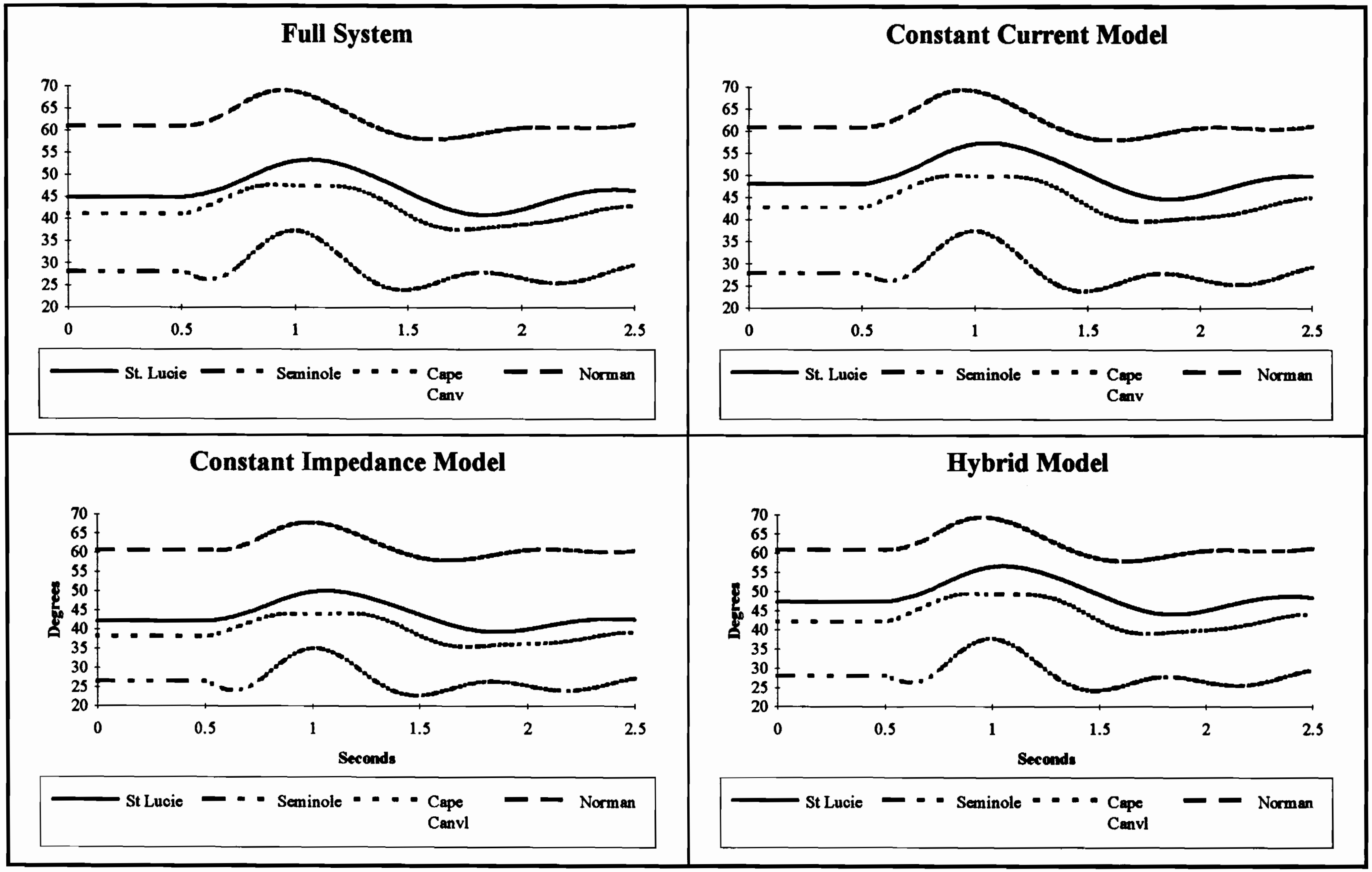


Figure 4.5 Comparison of the Generator Angles in the Northern Area

4.6 Conclusions

Since all the generators are still modeled, the transient stability studies of each model are very similar. This can be seen in the graphs in figures 4.1 to 4.5. The purpose of these reductions is to find a model for the relay. The data that the relay sees is the bus data at Duval and Hatch. The algorithm which will be of most interest will be the one which can match the bus data best. The following graph (figure 4.6) compares the bus angle difference between Duval and Hatch for each of these cases. Since bus angles are relative, the graph will only show the bus angle difference.

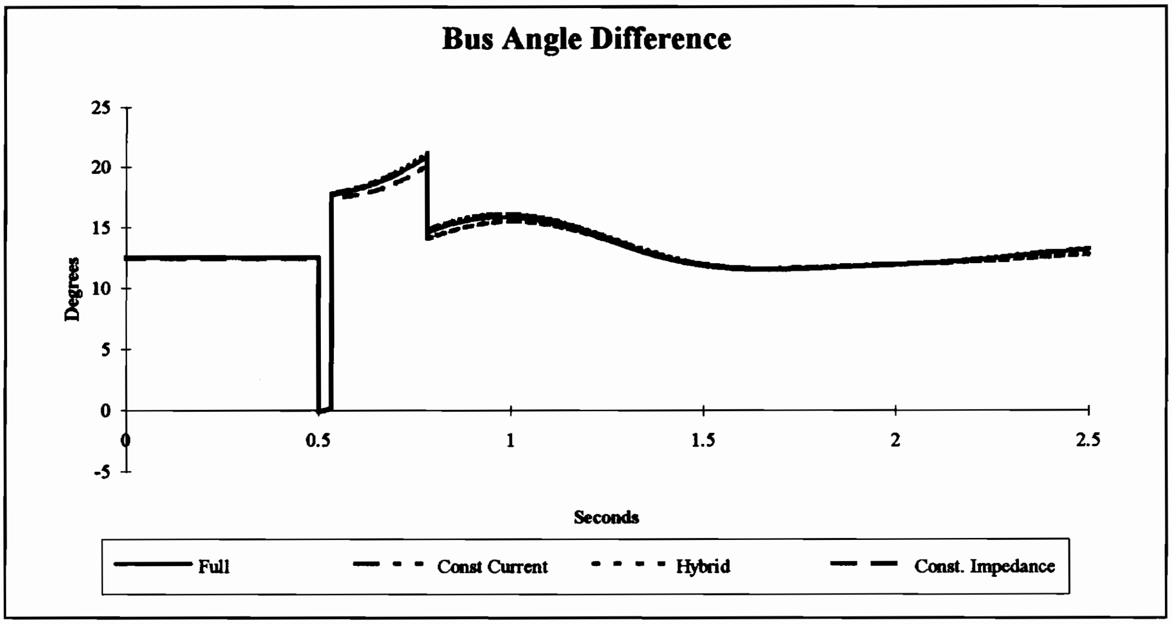


Figure 4.6 Bus Angle Comparison Between Reduction Methods

It can be seen from this graph that the hybrid model and the constant current model match the full system better then the constant impedance. The plots of the bus voltage magnitudes are even closer.

Chapter 5

4 Machine Equivalents

5.1 The 4 Machine Model

Even though the reduction techniques discussed in chapter 4 are very accurate, there is not enough time to run a transient stability study on a 19 machine system in faster then real time. The relay must decide in approximately a quarter of a second and the transient stability study must look a couple seconds in the future. Although the two machine model works fairly well, the Florida system can be more accurately modeled as a four machine system.

In the generator angle graphs in chapter 4, the generators can be split into three groups of Florida machines. Since the case studied in chapter 4 was a very stable case, the groups are not as pronounced but, as shall be seen, the three groups become more pronounced as the system approaches instability. The fourth machine is the Eastern Equivalent machine.

One group is the western generators. These generators are not well connected to the rest of the generators in Florida. The connections consist of one 500-kV line, one 230-kV line (figure 1.1) , and a few lower voltage lines. When a disturbance occurs, the system will oscillate between east and west because of the overall weak connection.

The other two groups are on the eastern side of Florida. There is a northern and a southern group. These two groups are connected to each other with stronger ties. With the Florida 500-kV transmission lines going down the east coast as well as many 230-kV lines paralleling the 500-kV system, there are many connections between north and south. These generator do not swing against each other because of weak connections but rather because of the long distance between the generators. The swing is not as pronounced as the east west swing but is none the less there. Table 5.1 contains a list of the groupings of generators.

Table 5.1 Generator Groupings for the 4 Machine Model

South	West	North
Turkey Point (4)	Fort Myers (2)	St Lucie (2)
Cutler (1)	Manatee (2)	Putnam (4)
Lauderdale (2)	Big Bend (*)	Cape Canaveral (2)
Port Everglades (4)		Sanford (3)
Riviera (2)		Seminole (2*)
Martin (2)		St John's River Power Park (2)
		Norman (*)

* Generators not belonging to FP&L

The numbers in parenthesis are the number of units at each location. In some cases the unit are on different buses so they are modeled as separate generators in the full system model. Big Bend and Norman generators are equivalent generators for generators outside the FP&L system. From a geographical standpoint St. Lucie would be with the southern generators but after the studies were done it was discovered that St. Lucie was more of a northern generator. The dividing line between north and south is just below St Lucie.

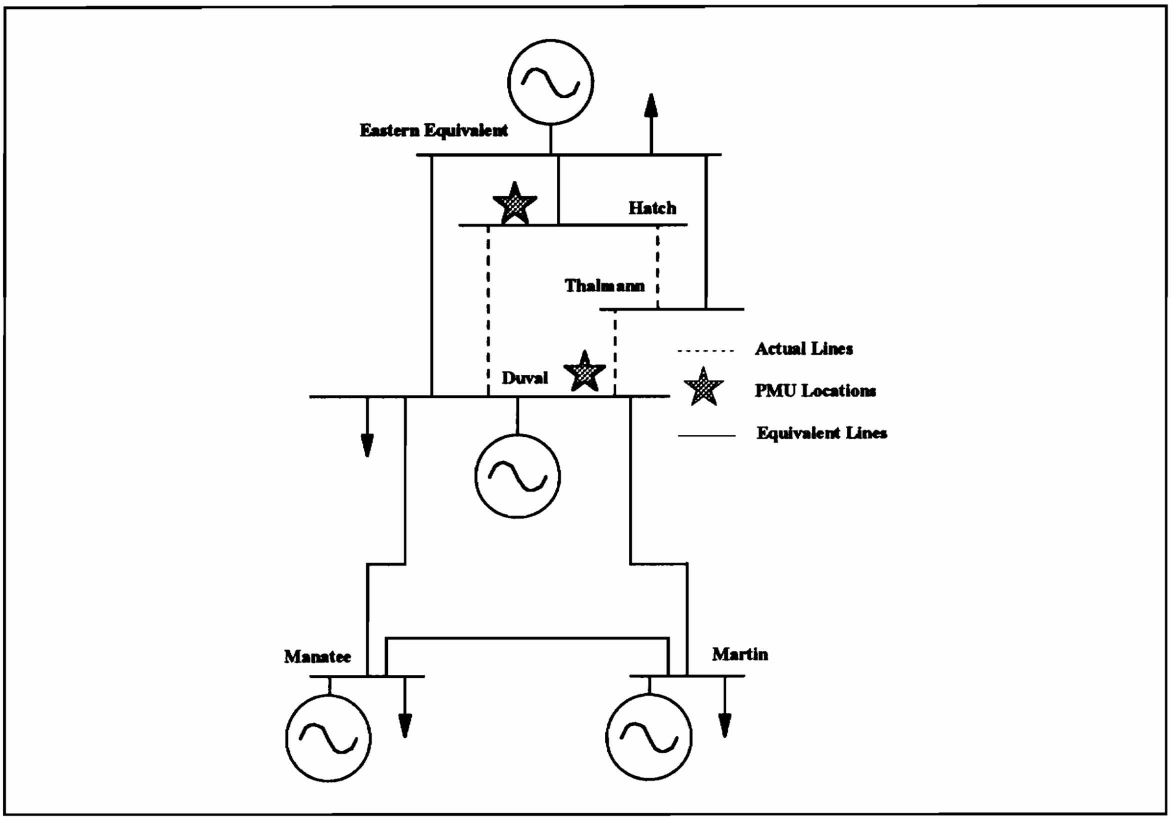


Figure 5.1 Four Machine Model

As was discussed in chapter 2, using the ward equivalent will cause generators to be placed at the retained buses which may not have previously had a generator. There will be a generator added at Duval since it is a retained bus. This will be a northern generator. Two other buses must be retained to represent the southern and western generators. Martin and Manatee were chosen to represent these two generators. Since both buses are already generator buses it does not matter that the ward equivalent will place generators at these buses. Table 5.2 lists the machine data for the 4 Machine Model.

Table 5.2 Machine Data for the 4 Machine Model

Machine	Energy MWS	X_d	X'_d	X''_d	Xq	X'q	X"q
Martin	21458	0.0237	0.0045	0.0034	0.0230	0.0074	0.0034
Manatee	34003	0.0147	0.0024	0.0019	0.0142	0.0040	0.0019
Duval	39437	0.0150	0.0026	0.0019	0.0147	0.0042	0.0019
E. Eqv	375882	0.0016	0.0003	0.0002	0.0016	0.0005	0.0002

	R_a	T'_{do}	T'_{qo}	T''_{do}	T''_{qo}	X_l
Martin	2 X 10^{-5}	4.57	0.86	0.059	0.084	0.0032
Manatee	4 X 10^{-5}	4.75	0.67	0.058	0.076	0.0018
Duval	7 X 10^{-5}	5.52	0.74	0.057	0.076	0.0022
E. Eqv	2 X 10^{-5}	5.27	0.62	0.043	0.080	0.0002

Many different load flows of the 4 machine model were studied to include all the cases listed in Table 3.4. Only the low load conditionally stable case will be shown in this chapter. The different reduction techniques discussed in chapter 2 will be used here. Plots of generator angles and bus data will be shown in figures 5.2 to 5.5 at the end of the chapter.

5.2 Constant Current Model

The constant current method of reduction was used on the Low Load Conditionally Stable case. Table 5.3 compares the load flow specifications between the two cases. The only charging capacitance for Florida in this and all other reductions is from the unequivalized lines connected to Duval heading north to Georgia.

Table 5.3 Load Flow Specifications of Constant Current 4 Machine Model

	Low Load Conditionally Stable Case	Constant Current Case
Florida Load	7,800.8 + j2,278.2 MVA	6,501 + j4,329 MVA
Eastern Load	95,000 + j25,000 MVA	95,000 + j25,000 MVA
Total Florida Generation	4,415.99 + j2,800.79 MVA	3,782.45 + j2,930.27 MVA
Total Generation	103,249 + j27,253 MVA	104,580 + j26,427 MVA
Total Florida Losses	315.19 + j1,845.41 MVA	141.71 + j2,700.64 MVA
Power Transfer	3,700 - j78.2 MVA	3,700 - j78.0 MVA
Total Florida Charging	j3,410.68 MVAR	j324.67 MVAR
Total Florida Shunts	j1,399.93 MVAR	839.73 + j4,177.36 MVA

As can be seen, the amount of generation and load in the reduced case is significantly lower than in the full case. In the models of Chapter 4, all the generators were retained. This is a much more severe reduction, from 166 buses and 19 generators to 6 buses and 4 generators. In the previous case, all the generators were retained so that the reduced system had the same amount of generation as the original, but the load, shunts, and losses were different. With these reductions, the load, shunts, losses and generation characteristics will become more mixed. This can be seen in table 5.3.

5.3 Constant Impedance Model

The next reduction technique was the constant impedance reduction. Table 5.4 compares the Low Load Conditionally Stable Case with the 4 Machine Constant Impedance Case. Note there is no load in Florida because it is represented in the shunt impedance.

Table 5.4 Load Flow Specifications of Constant Impedance 4 Machine Model

	Low Load Conditionally Stable Case	Constant Impedance Case
Florida Load	7,800.8 +*j*2,278.2 MVA	0 MVA
Eastern Load	95,000 +*j*25,000 MVA	95,000 +*j*25,000 MVA
Total Florida Generation	4,415.99 +*j*2,800.79 MVA	2,888.58 +*j*3,319.6 MVA
Total Generation	103,249 + j27,253 MVA	101,721 +*j*27,772 MVA
Total Florida Losses	315.19 +*j*1,845.41 MVA	-707.37 +*j*2,579.19 MVA
Power Transfer	3,700 -*j*78.2 MVA	3,700 -*j*78.0 MVA
Total Florida Charging	*j*3,410.68 MVAR	*j*324.67 MVAR
Total Florida Shunts	*j*1,399.93 MVAR	7,295.96 -*j*662.43 MVA

In this case the amount of generation in the reduced case is significantly less than in the original case. Some of the reduced generation is in the impedances of this case. All of the equivalized lines have a negative impedance. Of course this does not occur on normal transmission lines but it is one of the drawbacks of equivalents.

5.4 Hybrid Model

The hybrid reduction technique was used on the Low Load Conditionally Stable Case. Table 5.5 compares the 4 Machine Case with the full system case.

Table 5.5 Load Flow Specifications of the Hybrid 4 Machine Model

	Low Load Conditionally Stable Case	Hybrid Model Case
Florida Load	7,800.8 +*j*2,278.2 MVA	7,669 +*j*5,298 MVA
Eastern Load	95,000 +*j*25,000 MVA	95,000 +*j*25,000 MVA
Total Florida Generation	4,415.99 +*j*2,800.79 MVA	3,782.45 +*j*2,930.27 MVA
Total Generation	103,249 + j27,253 MVA	102,996 +*j*27,7779 MVA
Total Florida Losses	315.19 +*j*1,845.41 MVA	151.24 +*j*3,316.51 MVA
Power Transfer	3,700 -*j*78.2 MVA	3,700 -*j*78.0 MVA
Total Florida Charging	*j*3,410.68 MVAR	*j*324.67 MVAR
Total Florida Shunts	*j*1,399.93 MVAR	43.43 +*j*5,366.33 MVA

As expected this method of reduction produced the closest specifications to the original case. The graphical results are in the next section. It is interesting to note that the amount of real and reactive power transfer is the same in all three reduction techniques. This did not occur in the reductions of the previous chapter. The reason for this is that there is a generator at Duval. The bus voltage is regulated by the VAR output of the generator. With the real power transferred specified, if the voltage at Duval remains constant, the reactive power also remains constant. The slight difference between the reduced cases and the original case has to do with the significant digits of the voltage specification in ETMSP. The output of ETMSP has voltages with 5 significant digits and the input only allows for 4 significant figures. The fact that once the voltage magnitude and the real power transferred are fixed then the reactive transfer power is also fixed will be used in the next chapter.

5.5 Results

The generator angles of the Full System Case are plotted against the generator angles of the 4 Machine Case. The bus data at Duval and Hatch are also compared in plots. These plots are in figures 5.2 to 5.5. The Full System generators are grouped into the regions as described in table 5.1. For example the western equivalent machine in all three reduced cases is plotted with the generator angles of Manatee, Fort Myers, and Big Bend. To make the graphs less hectic the full system machine angles are the solid lines and the reduced machine angles have the dashed and dotted lines. As can be seen from the graphs the Hybrid Model Case comes the closest to matching the Full System Case.

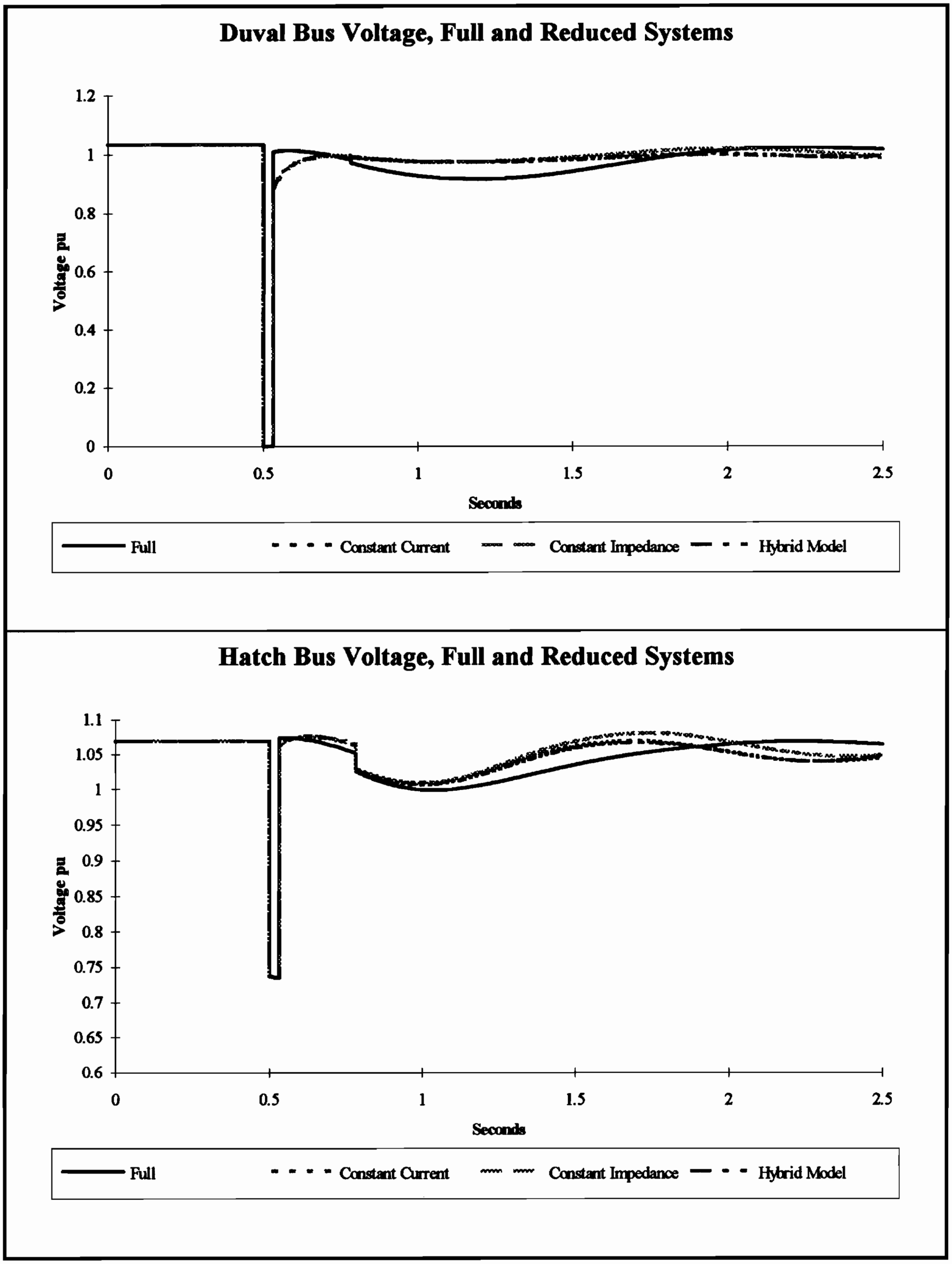
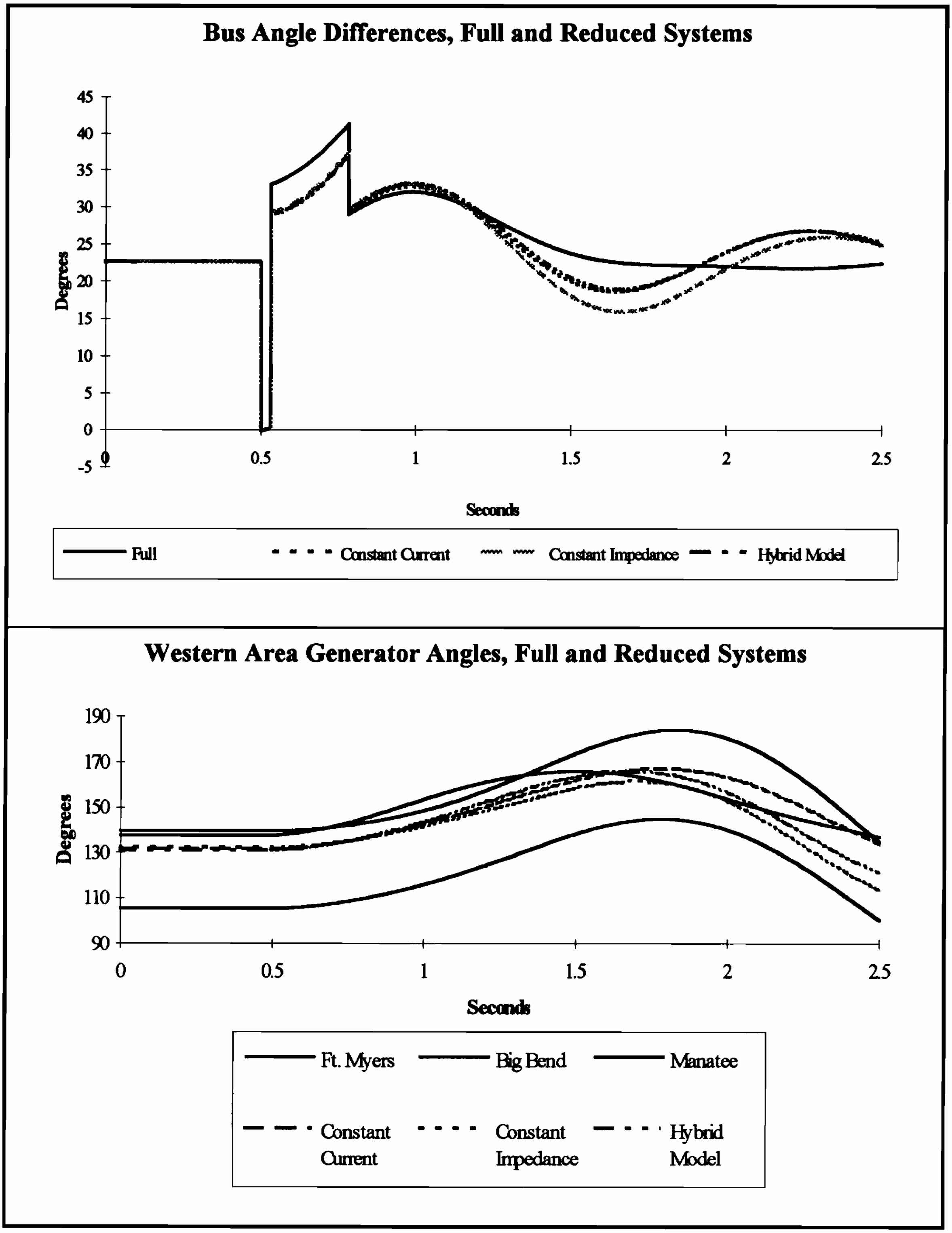


Figure 5.2 Bus Voltage Comparisons Between Full and 4 Machine Cases


Bus Angle Differences, Full and Reduced Systems

Western Area Generator Angles, Full and Reduced Systems

Figure 5.3 Bus and Generator Angle Comparisons Between Full and 4 Machine Cases

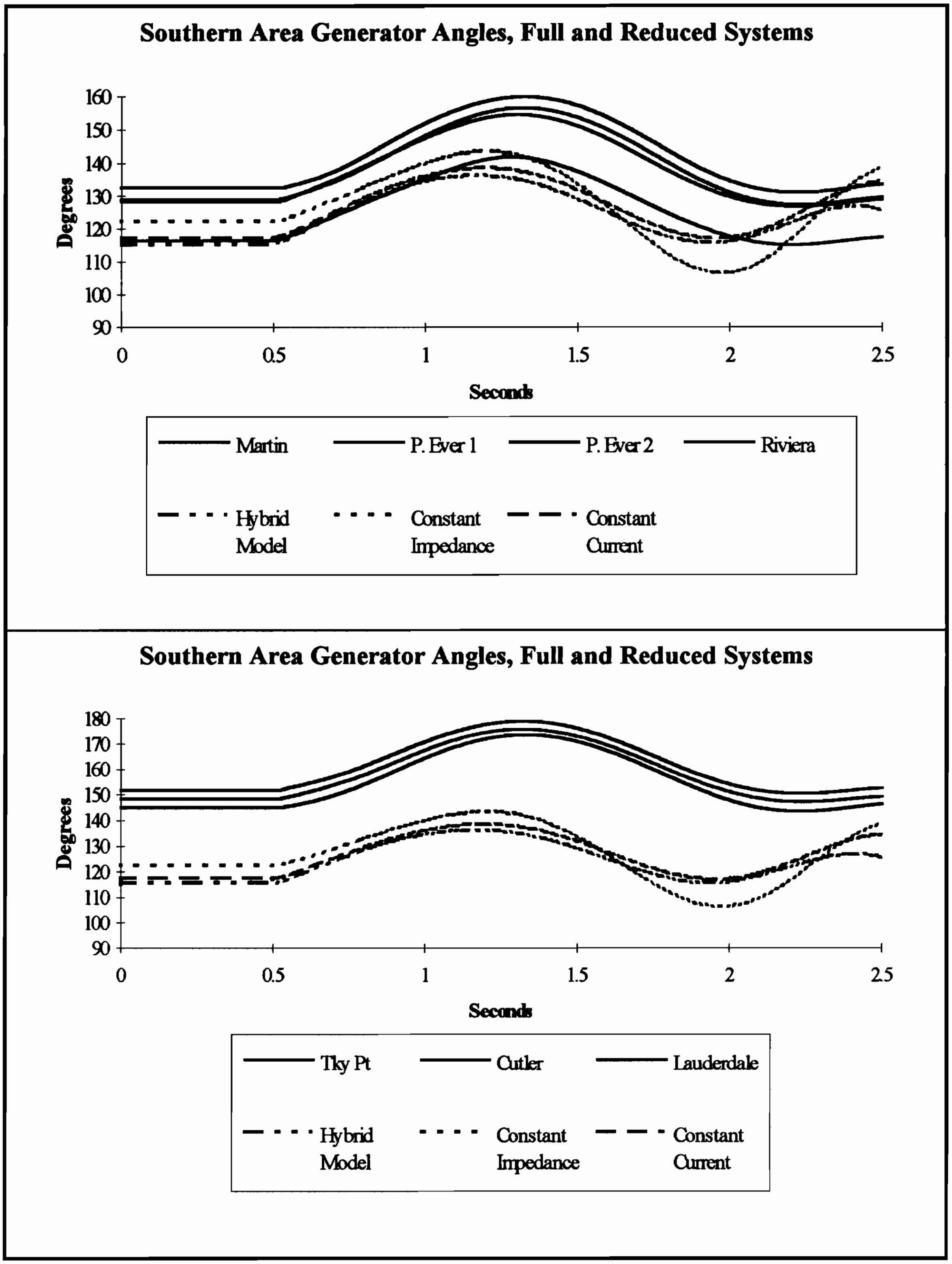


Figure 5.4 Generator Angle Comparisons Between Full and 4 Machine Cases

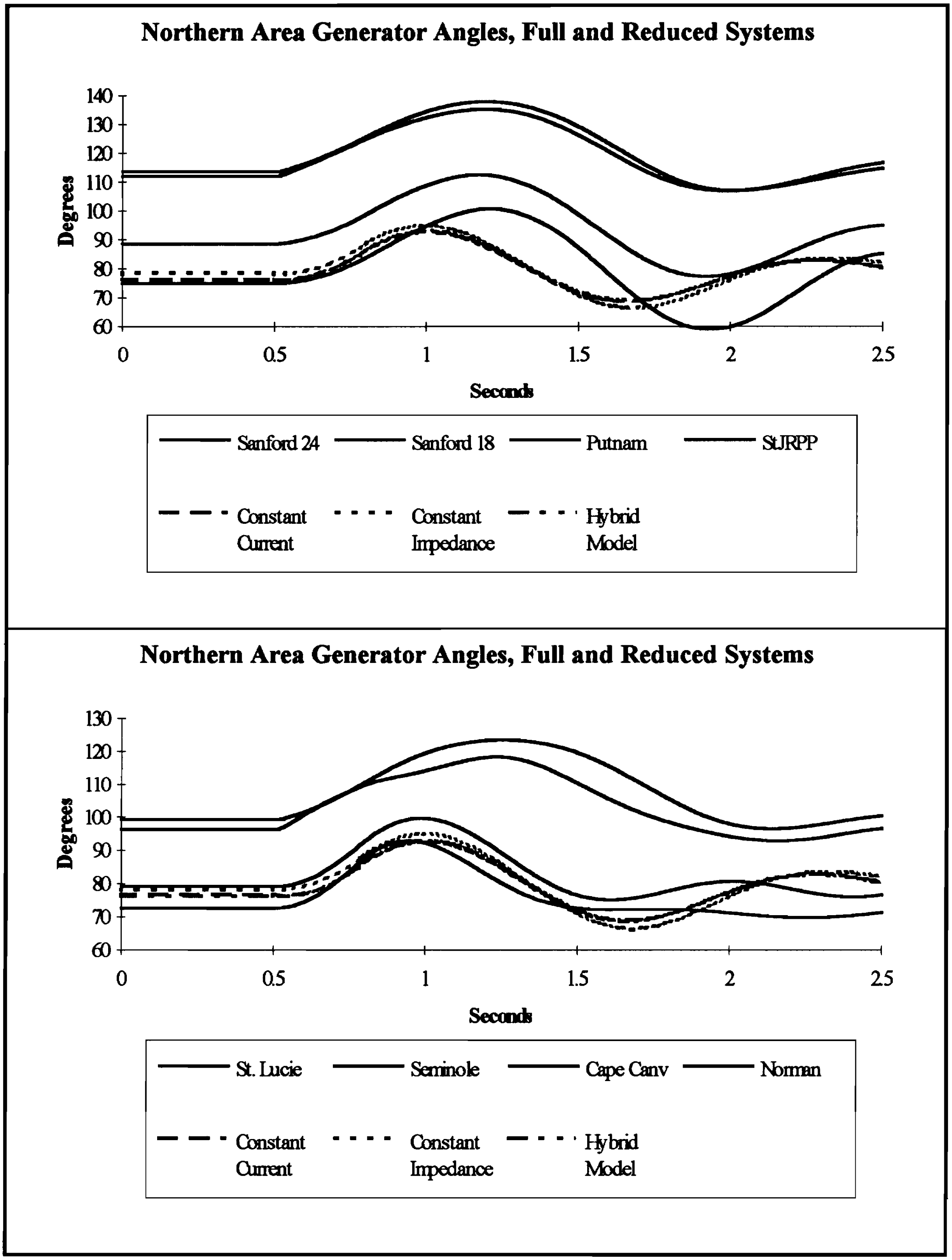


Figure 5.5 Generator Angle Comparisons Between Full and 4 Machine Cases

Chapter 6

3 Machine Equivalents

6.1 Development

So far a 4 Machine Model and a 2 Machine Model have been developed. The next logical step is to try for a three machine model. A 3 Machine Model would be more accurate than the 2 Machine Model but would save on computations in the relay as compared to the 4 Machine Model. As discussed in chapter 5, the swing between the northern and southern machines is not as large as the swing between the western and eastern machines. The northern and southern machines could be equivalized into one equivalent machine. Since there is no actual generator at Duval, the Duval machine would be good to eliminate. The response of machine buses differs to that of load buses in a power system. Having a generator modeled at a PMU location when there is not one actually there can cause oscillations in the model data which are not in the real system. This is why the 4 Machine bus angle plots in figure 5.3 show an oscillation which is not there in the full system.

Using Kron reduction techniques would not work in this case. As stated before one of the disadvantages of this method is that generators are distributed between the remaining buses. If Duval was not one of the retained buses then the Florida generators would be equivalized to the Georgia buses since they would become boundary buses. Another method would have to be used.

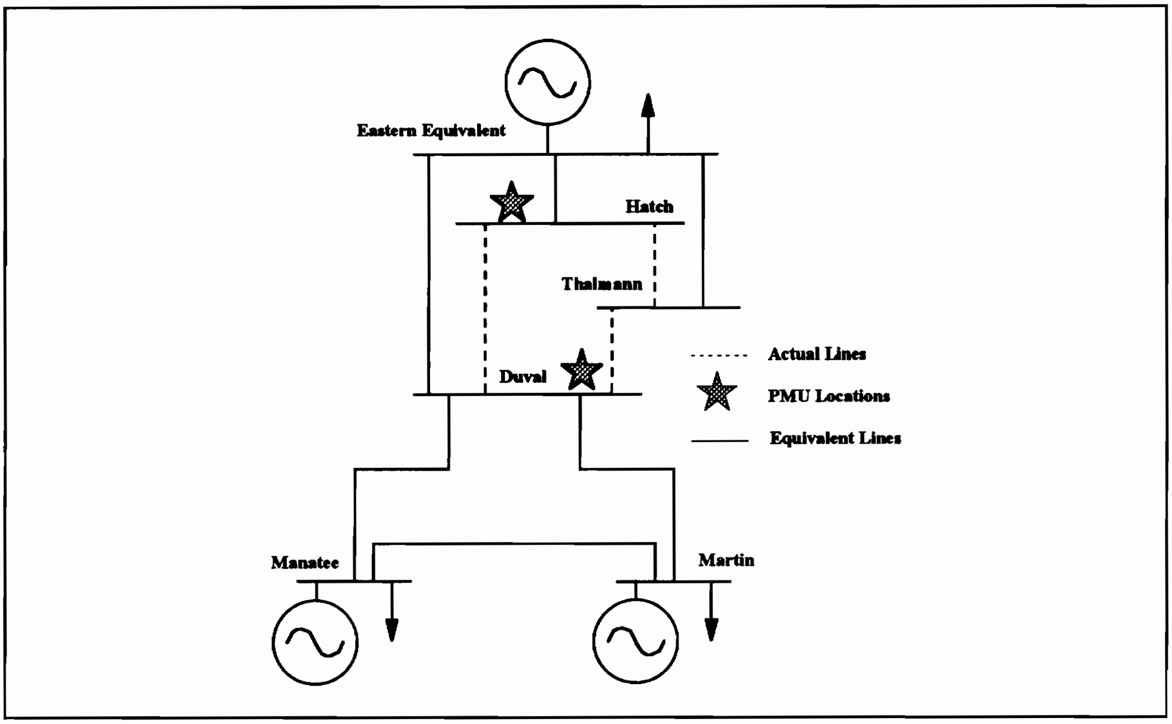


Figure 6.1 Three Machine Model

The goals in eliminating the generation at Duval were the following:

1. The voltage at Duval should remain essentially the same.
2. The real and reactive power transferred across the tie lines should also remain the same.
3. The system should obey Kirchoff's current laws
4. The system should be a solvable load flow
5. The system should give correct stability predictions

At first, the generation was removed from Duval and split onto the other two FP&L buses. This did not work. With all the load at Duval, the voltage was very low. It soon became apparent that this was a reactive power supply problem. Most reduced equivalents have problems with reactive power supply. The shunts become so large that a small change in voltage produces a large change in reactive power.[11] The load was also removed from Duval. The reactive was left to hold the voltage. Finally a load flow was solved which satisfied the first four conditions listed above but the transient stability study proved to be unstable for a case which was actually stable.

The voltages at the other two FP&L buses were allowed to vary. If the voltages at these buses were allowed to be high, not as many shunts were needed at Duval. A load flow could be solved and this met all 5 conditions listed previously.

To determine how much of the power transferred from Duval to add to the other two buses, eleven cases were run. The split of the Duval load between Martin and Manatee varied as in table 6.1. The machine parameters of the Duval equivalized machine were split according to table 6.1.

6.2 Results

Figure 6.2 shows the bus angle differences for several different cases from table 6.1. Not all the cases are shown because the graph would not be easily read. There is a trend with all these cases. As the case number gets higher (in other words more power is transferred to Manatee) the closer the 3 Machine Model matches the Full System Model. Case # 11 matches the best.

Table 6.1 Case Number Listing for 3 Machine Simulations

Case Number	% at Martin	% at Manatee
Case #1	100%	0%
Case #2	90%	10%
...	...	...
Case #10	10%	90%
Case #11	0%	100%

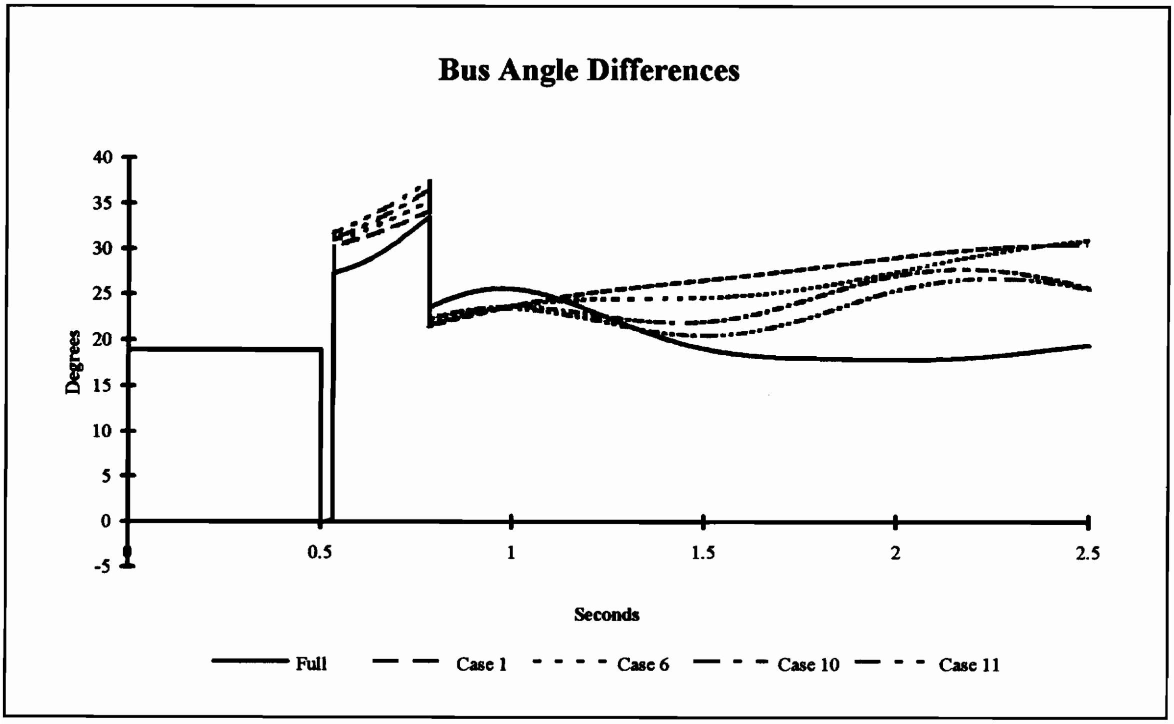


Figure 6.2 Bus Angle Differences for Different Cases

In figure 6.3, the generator angles of Case # 11 are compared with those of the 4 Machine Model. The generators of these two models behave similarly. The generator angles have been subtracted from the reference machine.

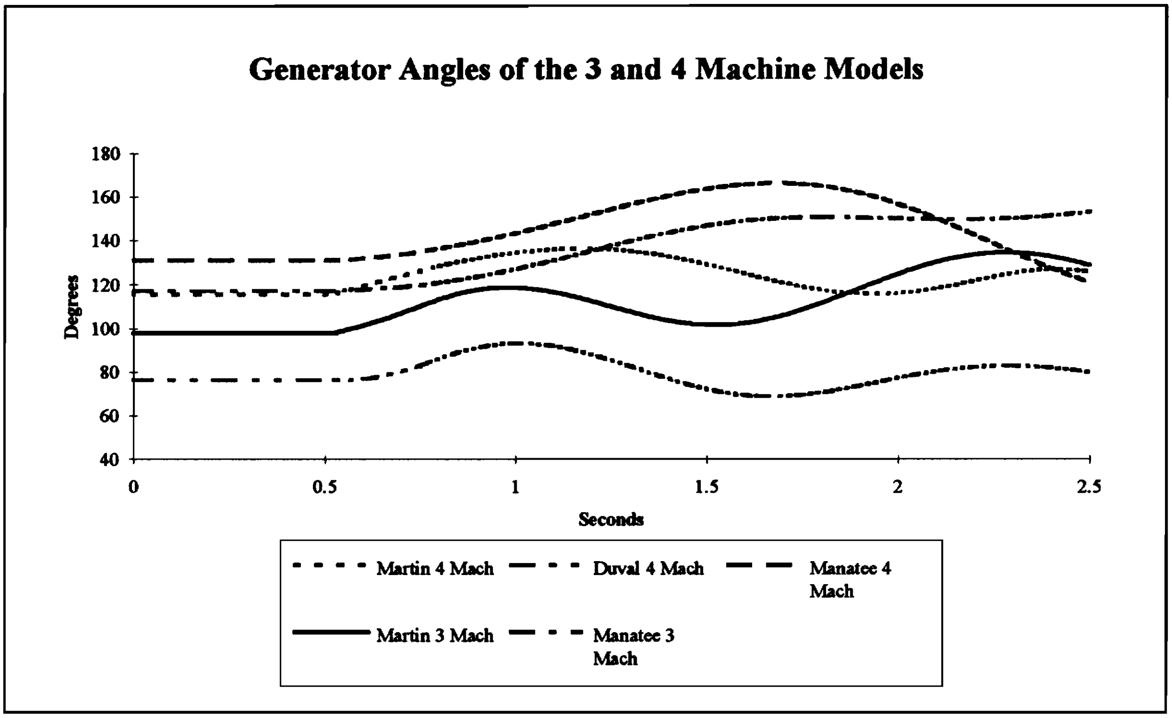


Figure 6.3 Generator Angle Comparison Between 4 and 3 Machine Models

The 3 Machine model would lessen the computational burden of the relay over the 4 Machine Model in real-time. The off-line algorithm is much more complicated than the 4 Machine Model.

Chapter 7

Eigenvalues

7.1 Eigenvalues

When a system is disturbed from steady state it will produce a certain transient response. For a power system this response is oscillatory. For small disturbances these oscillations will dampen very quickly if the system is dynamically stable. The frequencies of these responses for a nonlinear system will not only be determined by the disturbance but also by the natural frequencies of the power system. The natural frequency of the system can be found by linearizing the system around an operating point. This can be done by determining the response of the system to a small momentary disturbance which does not change the operating point of the system. The system will oscillate around the operating point at the natural frequencies until it settles at the original operating point. If the system can be modeled as a first order differential system such that:

$$\left[\dot{x}\right] = [A][x] + [B][u] \tag{7.1}$$

where *x* is the state vector and ***u*** is the input vector. The natural frequencies of the system would be the eigenvalues of the matrix $[A]$. To determine the eigenvalues, λ, the following equation must be solved:[16]

$$\det\begin{bmatrix} a_{11}-\lambda & a_{12} & \dots & a_{1n} \\ a_{21} & a_{22}-\lambda & \dots & a_{2n} \\ \dots & \dots & \dots & \dots \\ a_{n1} & a_{n2} & \dots & a_{nn}-\lambda \end{bmatrix} = 0 \qquad (7.2)$$

7.2 Calculation of Eigenvalues for a Power System

To calculate eigenvalues for a multi-machine system, one must start with the formulas for the acceleration of machine equation (3.1). The model of the power system must be reduced to machine internal nodes. This is done using the constant impedance ward reduction as discussed in section 2.3. A branch between the generator bus and the internal node of the generator is added for each generator. This branch has the impedance of the transient reactance. The voltage of the internal node of machine *i*, E_i, is determined from the bus voltage, V_i, by:

$$E_i = V_i + X'_d I_g \qquad (7.3)$$

After the reduction to machine internal nodes, there remains an n-bus system, where *n* is the number of generators. Since the constant impedance reduction was used the only injected currents are the generation currents. This is done to isolate the generation power in the Y bus equation.

The machine electrical power at each bus can be calculated by multiplying the conjugate of the generation current by the voltage. Since the generation current is equal to the injected current it is also equal to the Y bus times the voltage vector. The electrical power used in equation (3.1) can be written as:

$$P_{ei} = E_i^2 G_{ii} + \sum_{\substack{j=1 \\ j \neq i}}^{n} E_i E_j (B_{ij} \sin\delta_{ij} + G_{ij} \cos\delta_{ij}) \tag{7.4}$$

where $\delta_{ij} = \delta_i - \delta_j$ and δ_i is the electrical rotor angle of machine *i*.

and $G_{ij} + jB_{ij} = Y_{ij}$

This analysis is based upon a linearization around the operating point. If the operating point is perturbed then the power at each machine will change. That change in power can be found using a linerarized incremental model:

$P_{ei} = P_{ei0} + P_{ei\Delta}$ and $\delta_{ij} = \delta_{ij0} + \delta_{ij\Delta}$ such that

$\sin\delta_{ij} \cong \sin\delta_{ij0} + \delta_{ij\Delta}\cos\delta_{ij0}$ and $\cos\delta_{ij} \cong \cos\delta_{ij0} - \delta_{ij\Delta}\sin\delta_{ij0}$

The change in power is:

$$P_{ei\Delta} = \sum_{\substack{j=1 \\ j \neq i}}^{n} E_i E_j (B_{ij} \cos\delta_{ij0} - G_{ij} \sin\delta_{ij0})\delta_{ij\Delta} = \sum_{\substack{j=1 \\ j \neq i}}^{n} P_{sij}\delta_{ij\Delta} \tag{7.5}$$

P_{sij} is the synchronizing power coefficient between nodes *i* and *j*. The synchronizing power coefficient can be physically defined as the change in power at machine *i* for a change in the angle between *i* and *j* with all other angles held constant.

Since the mechanical power is assumed to remain the same, the change in accelerating power is equal to the change in electrical power. From equation (3.1):

$$\frac{2H_i}{\omega_s}\frac{d^2\delta_{i\Delta}}{dt^2} + P_{ei\Delta} = 0 = \frac{2H_i}{\omega_s}\frac{d^2\delta_{i\Delta}}{dt^2} + \sum_{\substack{j=1 \\ j \neq i}}^{n} P_{sij}\delta_{ij\Delta} \tag{7.6}$$

There are n equations in equation (7.6), but they are not independent because the reference is arbitrary.. If the n^{th} equation is subtracted from the rest then this becomes $n-1$ independent equations of the form:

$$\begin{bmatrix} \ddot{\delta}_{1n\Delta} \\ \ddot{\delta}_{2n\Delta} \\ \cdots \\ \ddot{\delta}_{(n-1)n\Delta} \end{bmatrix} = \begin{bmatrix} \alpha_{11} & \alpha_{12} & \cdots & \alpha_{1n} \\ \alpha_{21} & \alpha_{22} & \cdots & \alpha_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ \alpha_{n1} & \alpha_{n2} & \cdots & \alpha_{nn} \end{bmatrix} \begin{bmatrix} \delta_{1n\Delta} \\ \delta_{2n\Delta} \\ \cdots \\ \delta_{(n-1)n\Delta} \end{bmatrix} = [A] \begin{bmatrix} \delta_{1n\Delta} \\ \delta_{2n\Delta} \\ \cdots \\ \delta_{(n-1)n\Delta} \end{bmatrix} \tag{7.7}$$

where

$$\alpha_{ii} = \frac{\omega_s P_{sni}}{2H_n} + \sum_{\substack{j=1 \\ j \neq i}}^{n} \frac{\omega_s P_{sij}}{2H_i} \quad \text{and} \quad \alpha_{ij} = \frac{\omega_s P_{snj}}{2H_n} - \frac{\omega_s P_{sij}}{2H_i} \tag{7.8}$$

This is a second order system. As stated before a first order system is required to perform this analysis. From equation (3.2) $\omega_{ij} = \frac{d\delta_{ij}}{dt}$. Using this, a *2(n-1)* system of equations can be obtained. The state vector $[x]$ of $\delta_{in\Delta}$, can now be divided into two vectors $[x_1] = \delta_{in\Delta}$ and $[x_2] = \frac{d\delta_{in\Delta}}{dt} = \omega_{in\Delta}$, each of which is *(n-1)* in length. The system can now be written as:

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} = \begin{bmatrix} 0 & U \\ A & 0 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} \tag{7.9}$$

and the eigenvalues can be computed by the determinant of the following matrix:[17]

$$\det\begin{bmatrix} -\lambda & U \\ A & -\lambda \end{bmatrix} = 0 \qquad (7.10)$$

The eigenvalues of the Full System, the 4 Machine Model and of Case #11 of the 3 Machine Model are computed and listed in Table 7.1.

7.3 Changing the Eigenvalues of the 3 Machine Model

Everything about the power system determines the eigenvalues including, operating conditions, machine parameters, transmission line impedances, loading, and generation dispatch, all have an effect. Since there are only two eigenvalues of the 3 Machine System, there is not a unique set of conditions to produce a given set of eigenvalues. In other words if there are two eigenvalues, a unique 3 Machine System cannot be obtained from these values alone.

The only parameters which could be varied without changing the load flow were the machine parameters, X_d, and H. To determine how these different parameters affect the eigenvalues, the machine parameters were varied systematically. Figures 7.1 and 7.2 show how the eigenvalues will vary with the machine parameters. The machine parameter is varied with the original parameter and the delta marked on the graph. The eigenvalues of the 4 Machine Model are also marked on the graphs.

Table 7.1 Eigenvalues of the Full System Compared to the Reduced Systems

Eigenvalues		Eigenvalues		Eigenvalues	
$\lambda=\omega$ rads/sec		$\lambda=\omega$ rads/sec		$\lambda=\omega$ rads/sec	
Full	14.0098	4 Machine	6.1277	3 Machine	**4.7295**
System	13.4535	System	**4.4981**	System	**1.2746**
	13.2740		**2.0845**		
	12.7864				
	11.8908				
	11.7350				
	11.2304				
	10.7593				
	2.5811				
	9.7242				
	4.3312				
	8.4167				
	7.8118				
	5.4291				
	5.9615				
	6.4019				
	7.2647				
	7.0081				

As can be seen in figures 7.1 to 7.2, varying the machine parameters has a large effect on λ_1 but little effect on λ_2. Linear superposition can be assumed to apply in this case. If a change in H_1 will change an eigenvalue Δ_1 and a change in H_2 will change the eigenvalue Δ_2 then changing H_1 and H_2 will change the eigenvalues $\Delta_1 + \Delta_2$. All four parameters were changed such that the λ_1 of the 3 Machine Model matched that of the 4 Machine Model and λ_2 was closer. This point is also marked in figures 7.1 and 7.2. A transient stability study was done using these new machine parameters. The results are plotted in figure 7.3. The bus angles of the 3 Machine Model with and without matched eigenvalues are compared to the Full System Model as well as the 4 Machine Hybrid Model. The generator angles are compared with the 4 Machine Hybrid Model.

Changing the eigenvalues of a system is an effective way to manipulate the response of a system. In this case there is a large system with many different natural frequencies. The reduced model cannot retain all the frequencies but it can have the most important ones which are the slow frequencies or small eigenvalues. In this case only the machine parameters were changed. The eigenvalues are also determined by the power system itself. The eigenvalues can also be changed by changing the load flow. This was not done in this thesis but it would make an interesting subject for further research.

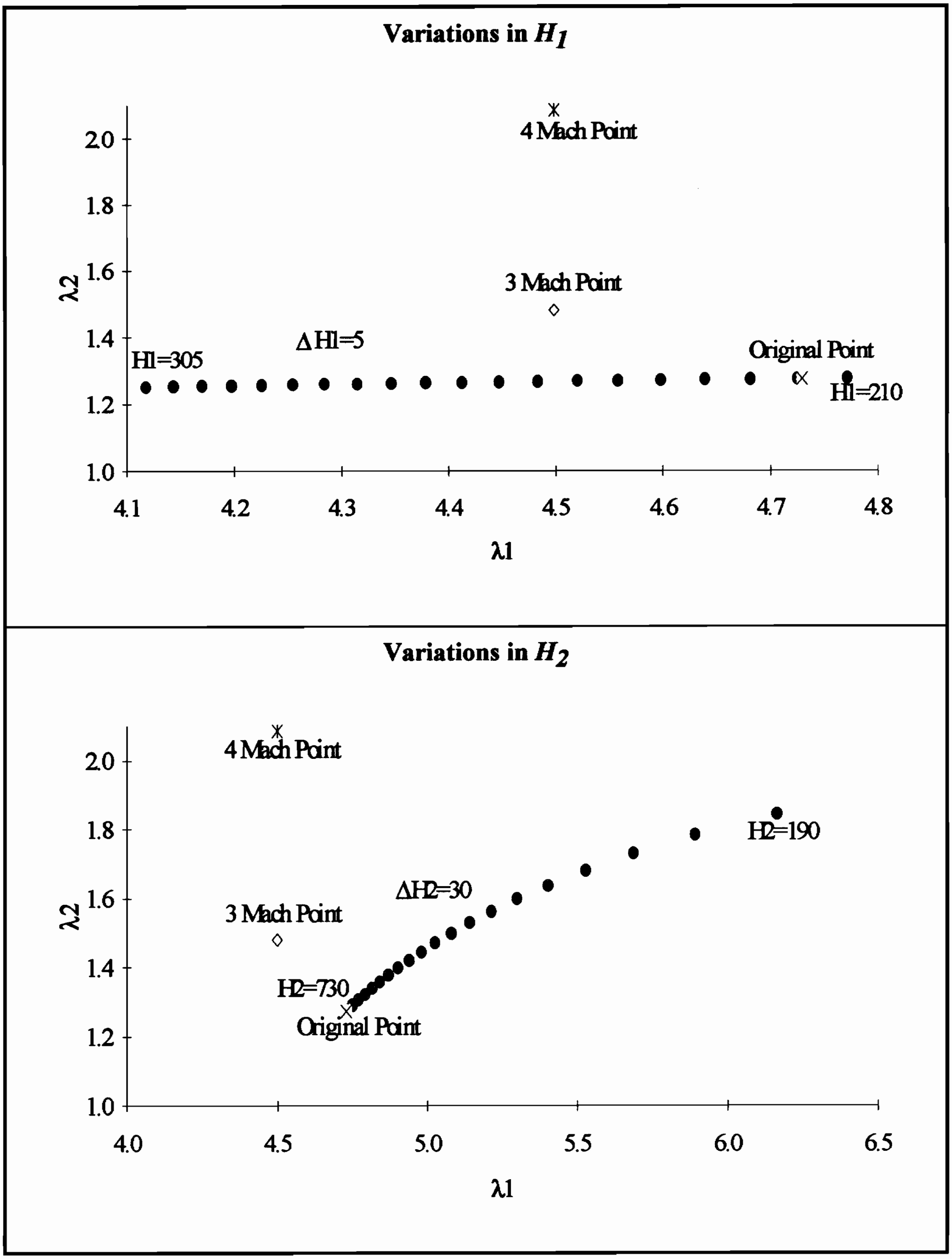


Figure 7.1 Variations in Machine Interias

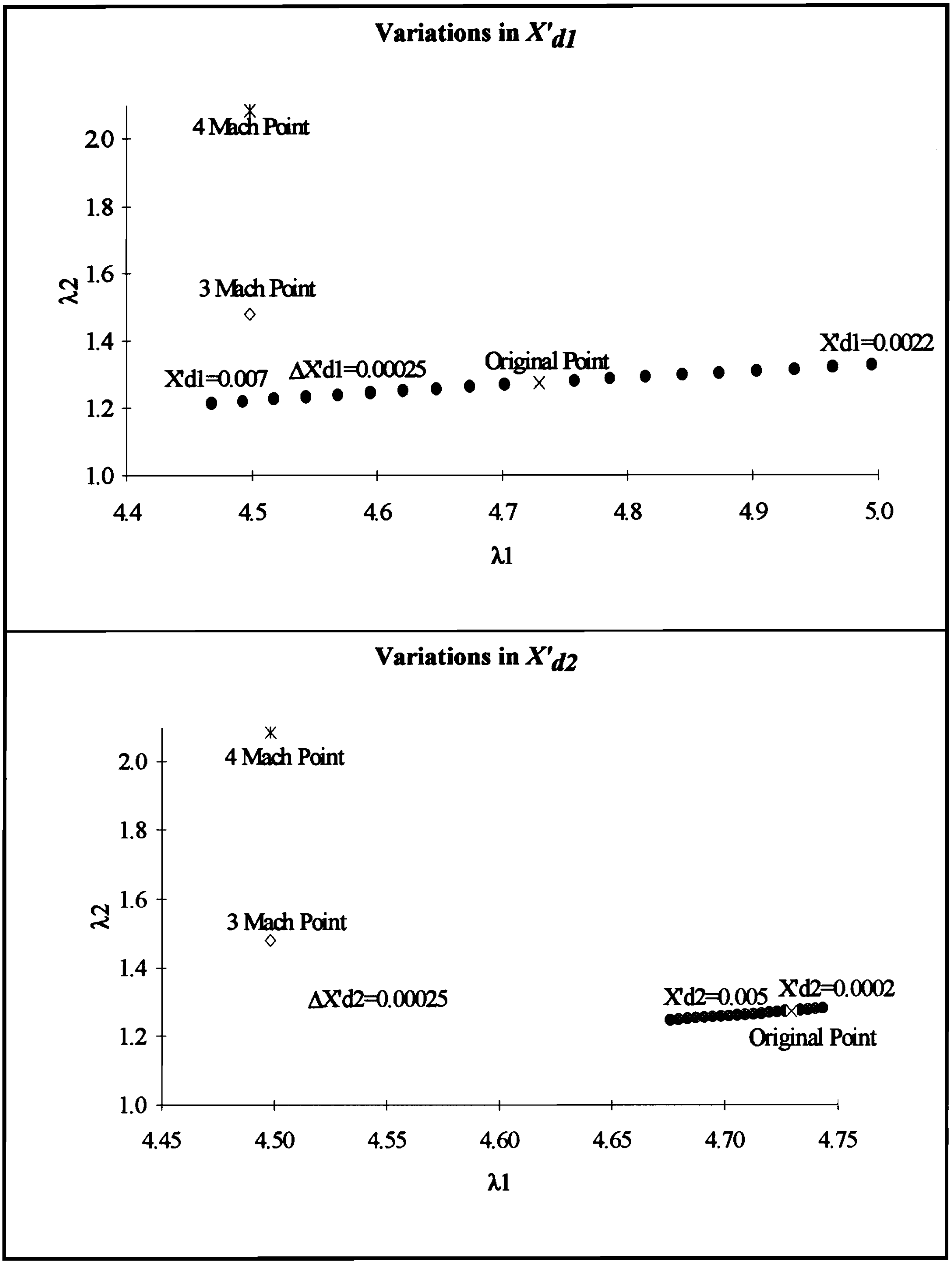


Figure 7.2 Variations in Machine Transient Reactances

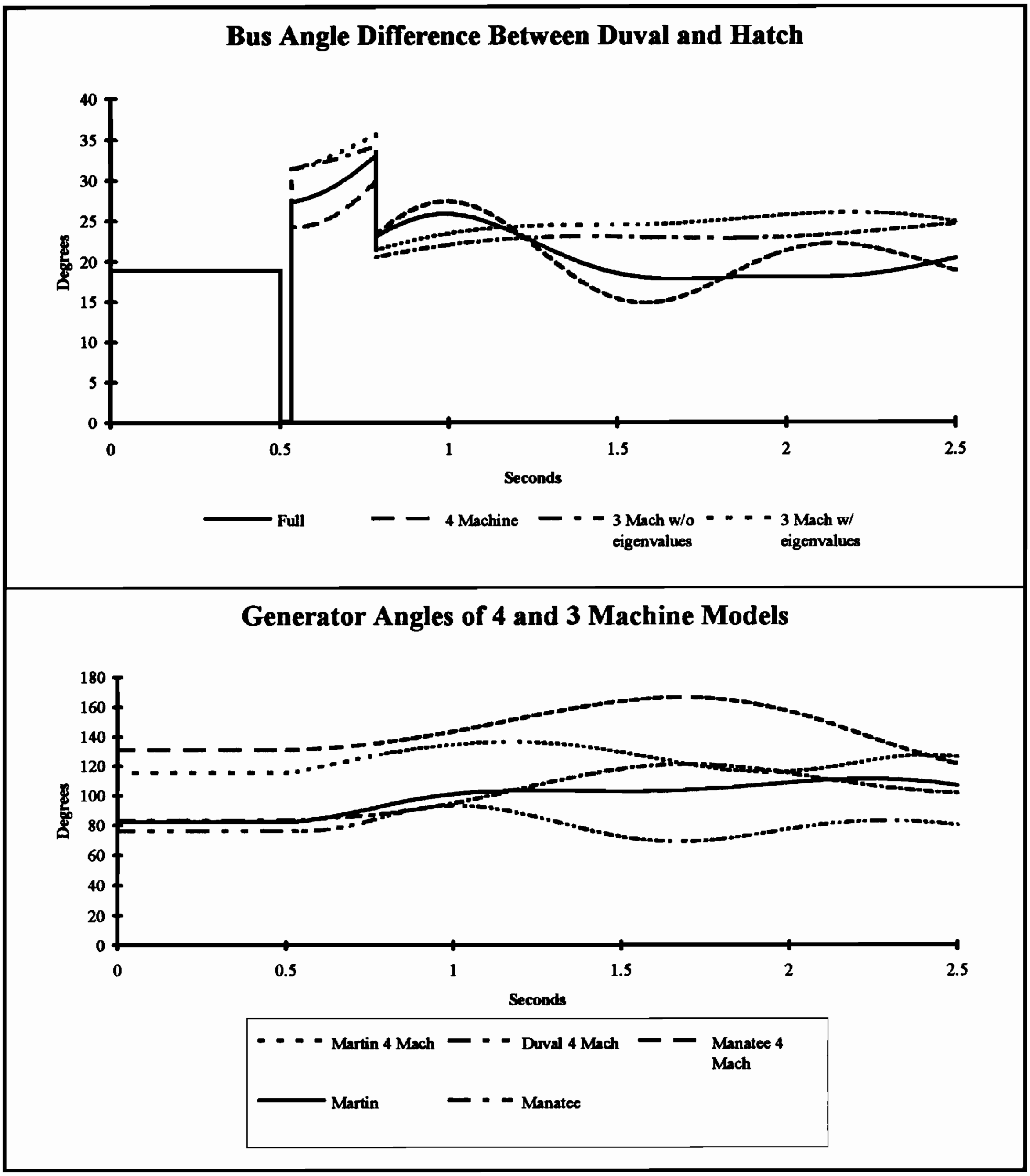


Figure 7.3 Transient Stability Study Output Comparison

Chapter 8

Conclusions

8.1 Implementation

The current version of the relay uses a Two Machine Model. The algorithm in the relay uses the equal area criterion to perform the transient stability study. The equal area criterion can only be used in a two machine system.

Before the relay was put into the field, it was tested in the Power System's Laboratory at Virginia Tech. The testing system described in chapter 3 was used. The relay had very good results during this testing. The relay is currently installed in the field and is under evaluation. The relay will issue commands but it is not actually connected to any trip circuits so that its performance may be evaluated without any misoperations.

8.2 Future Work

In the future FP&L is considering adding more PMUs to their system. With the extra data available, a more complicated model can be used. As has been seen in this thesis, the 4 Machine Model is more accurate then the Two Machine Model. In order to use this model, the equal area criterion cannot be used in the transient stability study. The research team at Cornell University has been working on methods to determine if a swing is stable or unstable in real-time on multi-machine Models. One method that has been proposed is to use Decision Trees. Many simulations are run off-line to train a decision tree process. The training is based on a short window of post disturbance data so that the decision can be made fairly quickly. Once the tree has been set up, it should be able to determine if a swing will be stable or unstable. [18] Another method is based on taking measurements at all buses of interest, namely generator buses and major tie lines. With this real-time data a prediction of the rotor angle is made about 10 cycles into the future. This may not be long enough to determine whether a swing will be stable or unstable but control actions can be taken on generators who appear to be in danger of losing synchronism. [19] For each of these methods, the simpler the model the faster and more accurate the prediction. Once stability predictions in real-time can be extended to multi-machine models, adaptive out-of-step relays can be applied to more general power systems.

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Appendix

Full System Load Flow

The following is the input file used in the FP&L load flow. It is the original case taken from the state estimation printout.

```
HDG

 06/23/92 FPL    Full System Load Flow  State Estimation Case

BAS
B     AVENTURA 230 0  1.4  7.6                0  0.0
B     DADE     230 0588.3 30.2                0  0.0
B     DAVIS    230 0309.6 29.4                0  0.0
B     FLA CITY 230 0159.4 12.3                0  0.0
B     FLAGAMI  230 0289.0 52.6                0  0.0
B     GREYNOLD 230 0251.6  7.1                0  0.0
B     KILLIAN  230 0 21.6  6.6                0  0.0
B     LEVEE    500 0  0.0  0.0                0  0.0
B     LEVEE    230 0  0.0  0.0                0  0.0
B     LINGREN  230 0 82.8 19.2                0  0.0
B     MAULE    230 0  4.2  1.4                0  0.0
B     MIAMI 1  230 0158.9 51.6                0  0.0
B     MIAMI 2  230 0167.7 48.0                0  0.0
B     MIAMI LK 230 0 52.8 19.4                0  0.0
B     MIAMI SH 230 0192.4  6.2                0  0.0
B     MILAM    230 0 98.4 45.5                0  0.0
B     MILLER   230 0 17.4 -0.5                0  0.0
B     OLMPA HT 230 0 25.4  9.2                0  0.0
B     PENNSUCO 230 0 13.3  3.3                0  0.0
B     SWEETWAT 230 0 33.5 10.9                0  0.0
B     8 TH ST  230 0  0.0  0.0                0  0.0
B     ANDYTOWN 500 0  0.0  0.0                0  0.0
B     ANDYTOWN 230 0  0.0  0.0                0  0.0
B     BROWARD  230 0380.9-18.2     171        0  0.0
B     DAVIE    230 0 25.2  0.4                0  0.0
B     GRAHAM1N 230 0  0.0  0.0                0  0.0
B     GRAHAM2N 230 0  0.0  0.0                0  0.0
B     GRMN1 TP 230 0  0.0  0.0                0  0.0
B     GRMN2 TP 230 0  0.0  0.0                0  0.0
B     HIATUS   230 0 28.6  4.2                0  0.0
B     HOLYBROK 230 0 25.9 15.0                0  0.0
B     IMAGNATN 230 0 35.1  0.5                0  0.0
B     LAKEVIEW 230 0 24.9 15.8                0  0.0
B     LAUDANIA 230 0  0.0  0.0                0  0.0
B     MALLARD  230 0 62.3 22.1                0  0.0
B     MOTOROLA 230 0 77.2 -0.8                0  0.0
B     PHOENIX  230 0 37.5  8.5                0  0.0
B     SISTRUNK 230 0184.8125.1                0  0.0
B     SPNGTREE 230 0 54.8  7.4                0  0.0
```

```
B     STONEBRG 230 0 39.6 -2.2                0  0.0
B     TMBRLAKE 230 0 29.2  1.1                0  0.0
B     TRACE    230 0 21.7  2.2                0  0.0
B     VALENCIA 230 0 11.1  1.0                0  0.0
B     WOODLNDS 230 0 24.5 -2.0                0  0.0
B     ADAMS    230 0  2.7  1.4                0  0.0
B     BUTTS    230 0 31.4 13.7                0  0.0
B     CEDAR    230 0177.8-22.2                0  0.0
B     CLINTMOR 230 0 58.1 16.0                0  0.0
B     CORBETT  500 0  0.0  0.0                0  0.0
B     CORBETT  230 0  0.0  0.0                0  0.0
B     CRANE    230 0  7.8 -0.1                0  0.0
B     DELMAR   230 0 11.2  4.0                0  0.0
B     DELTRIAL 230 0 12.1 18.8                0  0.0
B     EMERSON  230 0129.0-20.1                0  0.0
B     FLA STEL 230 0  6.7  3.6                0  0.0
B     FRONTIER 230 0  8.5 -0.4                0  0.0
B     FRONT TP 230 0  0.0  0.0                0  0.0
B     HOBE     230 0191.8  4.0                0  0.0
B     HTCHNSON 230 0 15.6  2.7      81        0  0.0
B     INDNTOWN 230 0  0.0  0.0                0  0.0
B     JOG      230 0 15.9  9.0                0  0.0
B     KIMBERLY 230 0 19.0  3.1                0  0.0
B     LOXHATCH 230 0 35.9 12.6                0  0.0
B     MARTIN   230 0 29.2 -0.1                0  0.0
B     MIDWAY   500 0  0.0  0.0                0  0.0
B     MIDWAY   230 0 67.2 10.2                0  0.0
B     PRT WTNY 230 0 27.6 10.9                0  0.0
B     RANCH    230 0348.3 22.1     174        0  0.0
B     SANDALFT 230 0 27.4 14.7                0  0.0
B     SANPIPER 230 0 62.3  9.7                0  0.0
B     SHERMAN  230 0 53.8  3.9                0  0.0
B     TARTAN   230 0  2.1  3.7                0  0.0
B     TURNPIKE 230 0 32.2 -0.4                0  0.0
B     YAMATO   230 0142.0 29.6                0  0.0
B     BALDWIN  230 0 74.8 -6.5                0  0.0
B     BLACK CK 230 0 77.1 20.4                0  0.0
B     BRADFORD 230 0 37.6  5.7                0  0.0
B     BREVARD  230 0186.4 19.8                0  0.0
B     COLLEGE  230 0 14.6  6.6                0  0.0
B     DELTN TP 230 0  0.0  0.0                0  0.0
B     DELTONA  230 0 16.7  3.8                0  0.0
B     HUDSON   230 0 30.7 16.0                0  0.0
B     MALABAR  230 0279.9 76.0                0  0.0
B     NORRIS   230 0 55.2 16.9                0  0.0
B     ORNGEDLE 230 0  8.0  3.8                0  0.0
B     POINSETT 500 0  0.0  0.0                0  0.0
B     POINSETT 230 0 66.0 -1.0      91        0  0.0
B     RICE     500 0  0.0  0.0                0  0.0
B     RICE     230 0  0.0  0.0                0  0.0
B     RICE 2   230 0  0.0  0.0                0  0.0
B     STELBALD 230 0 32.4 12.9                0  0.0
B     ST JOHNS 230 0123.0-36.3                0  0.0
B     STLBD TP 230 0  0.0  0.0                0  0.0
B     TOCOI    230 0  0.0  0.0                0  0.0
B     TOMOKA   230 0  4.5 -0.2                0  0.0
B     VOLUSIA  230 0372.5 74.7      81        0  0.0
B     W NASSAU 230 0  4.3  3.5                0  0.0
B     YULEE    230 0  3.1 13.8                0  0.0
B     ALICO    230 0  0.0  0.0                0  0.0
B     AUBURN   230 0  7.2  3.8                0  0.0
B     CALUSA   230 0  0.0  0.0                0  0.0
B     CARLSTRM 230 0 12.0 -0.3                0  0.0
B     CASTLE   230 0 20.3 -4.4                0  0.0
B     COLLIER  230 0125.1 10.7                0  0.0
B     FRTMBLTP 230 0  0.0  0.0                0  0.0
B     JETPORT  230 0 18.6  2.1                0  0.0
B     JOHNSON  230 0120.8 -3.0                0  0.0
B     KEENTOWN 230 0  6.1 -3.1                0  0.0
B     LAURELWD 230 0179.2 21.5                0  0.0
```

```
B     LEE       230 0150.5 25.0                 0  0.0
B     MYAKKA    230 0100.6-29.7                 0  0.0
B     ORANGE R  500 0  0.0  0.0                 0  0.0
B     ORANGE R  230 0  0.0  0.0                 0  0.0
B     PARK      230 0 24.7 -1.1                 0  0.0
B     RINGLING  230 0399.9 24.3                 0  0.0
B     RUBONIA   230 0 13.1 -0.3                 0  0.0
B     WHIDDEN   230 0  3.6 -0.3                 0  0.0
B     JACARADA  230 0 30.7  6.4                 0  0.0
C
C  LOAD BUSES OUT OF THE FPL NETWORK
C
B     SEMINOL2  230 0  0.0  0.0                 0  0.0
C
C  GENERATION HIGH SIDE BUSES
C
B     DUVAL     230 0  0.0  0.0                 0  0.0
B     BUNNELL   230 0-12.0-12.0                 0  0.0
B     BUCKEYE   230 0  0.0  0.0                 0  0.0
B     CHARLOTE  230 0 -7.0  0.0                 0  0.0
B     SAMPSON   230 0  0.0  0.0                 0  0.0
B     DORAL     230 0-25.0 20.6                 0  0.0
BC    SANFRD    230 0  0.0  0.0                 0  0.0     1036
B     SANFRD    115 0  0.0  0.0                 0  0.0
BC    PUTNAM    230 0  0.0  0.0                 0  0.0     1042
BC    STJRPP    230 0  0.0  0.0                 0  0.0     1036
BC    C CNVL    230 0  0.0  0.0                 0  0.0     1036
BC    NORMAN    230 0  0.0  0.0                 0  0.0     1042
BC    P EVER    230 0  0.0  0.0                 0  0.0     1047
B     P EVER    138 0  0.0  0.0                 0  0.0
BC    TKY PT    230 0  0.0  0.0                 0  0.0     1046
BC    RIVIERA   230 0413.3 51.2                 0  0.0     1050
BC    CUTLER    230 0170.2 19.4                 0  0.0     1050
BC    LAUDLE    230 0473.5  1.7                 0  0.0     1030
BC    ST LUCIE  230 0  0.0  0.0                 0  0.0     1040
BC    FT MYERS  230 0  0.0  0.0                 0  0.0     1038
BC    BIG BEND  230 0  0.0  0.0                 0  0.0     1056
BC    SEMINOL1  230 0617.6582.0                 0  0.0     1050
BC    MARTIN    500 0000.0000.0                 0  0.0     1035
BC    MANATEE   230 0  0.0  0.0                 0  0.0     1047
C
C  GENERATION BUSES
C
BG    SANFRD     24 0  0.0  0.0         9999   40  999 -9991036    SANFRD   230 50
BG    SANFRD     18 0  0.0  0.0         9999   20  999 -9991036    SANFRD   230 50
BG    PUTNAM   13.8 0  0.0  0.0         9999   91  999 -9991042    PUTNAM   230100
BG    STJRPP     24 0  0.0  0.0         9999  287  999 -9991036    STJRPP   230100
BG    C CNVL     22 0  0.0  0.0         9999  594  999 -9991036    C CNVL   230100
BG    NORMAN     20 0  0.0  0.0         9999  147  999 -9991042    NORMAN   230100
BG    P EVER1    22 0  0.0  0.0         9999  378  999 -9991047    P EVER   230 50
BG    P EVER2    22 0  0.0  0.0         9999  379  999 -9991047    P EVER   230 50
BG    TKY PT     22 0  0.0  0.0         9999  450  999 -9991046    TKY PT   230100
BG    RIVIERA    20 0  0.0  0.0         9999  381  999 -9991050    RIVIERA  230100
BG    CUTLER     18 0  0.0  0.0         9999   66  999 -9991050    CUTLER   230100
BG    LAUDLE     18 0  0.0  0.0         9999    0  0.1 -0.11030    LAUDLE   230100
BG    ST LUCIE   22 0  0.0  0.0         9999 1382  999 -9991040    ST LUCIE 230100
BG    FT MYERS   20 0  0.0  0.0         9999   83  999 -9991038    FT MYERS 230100
BG    BIG BEND   23 0  0.0  0.0         9999  259  999 -9991056    BIG BEND 230100
BG    SEMINOL1   23 0  0.0  0.0         9999 1235  999 -9991050    SEMINOL1 230100
BG    MARTIN     22 0  0.0  0.0         9999  526  999 -9991035    MARTIN   500100
BG    MANATEE    22 0  0.0  0.0         9999 1284  999 -9991047    MANATEE  230100
C
C  Georgia Power Busses Equivalent and Duval
C
B     DUVAL     500 0  0.0  0.0                 0  0.0
B     THALMAN   500 2  0.0  0.0     -1569999    0  0.0
B     HATCH     500 2  0.0  0.0     -1569999    0  0.0
B     VOGTLE    500 2  0.0  0.0     -1569999    0  0.0
C     E. EQV    500 2  0.0  0.0         9999 2047  999 -999104
BQ    E. EQV    500 29500025000              204799999-99991040
```

```
C
C  LINES FOLLOW
C
L     AVENTURA 230 GREYNOLD 2301      0.00030.00130.00000.1919
L     AVENTURA 230 LAUDANIA 2301      0.00070.00300.00000.4242
L     DADE     230 DORAL    2301      0.00050.00430.00000.0055
L     DADE     230 LEVEE    2301      0.00120.01180.00000.0141
L     DADE     230 LEVEE    2302      0.00130.01180.00000.0141
L     DADE     230 MIAMI LK 2301      0.00080.00830.00000.0088
L     DADE     230 MIAMI SH 2301      0.00130.01110.00000.0154
L     DADE     230 GRAHAM2N 2301      0.00090.00850.00000.0094
L     DAVIS    230 CUTLER   2301      0.00180.01630.00000.0122
L     DAVIS    230 LEVEE    2301      0.00190.01810.00000.0216
L     DAVIS    230 LEVEE    2302      0.00190.01810.00000.0216
L     DAVIS    230 TKY PT   2301      0.00260.02480.00000.0289
L     DAVIS    230 TKY PT   2302      0.00260.02460.00000.0296
L     DAVIS    230 TKY PT   2303      0.00260.02460.00000.0296
L     FLA CITY 230 TKY PT   2301      0.00170.01130.00000.0129
L     FLAGAMI  230 MIAMI 2  2301      0.00110.00430.00000.6134
L     FLAGAMI  230 MILAM    2301      0.00060.00400.00000.0067
L     FLAGAMI  230 OLMPA HT 2301      0.00050.00320.00000.0050
L     FLAGAMI  230 8 TH ST  2301      0.00050.00420.00000.0059
L     FLAGAMI  230 GRAHAM1N 2301      0.00160.01300.00000.0165
L     KILLIAN  230 MILLER   2301      0.00070.00470.00000.0076
L     KILLIAN  230 TKY PT   2301      0.00320.03000.00000.0363
L     LEVEE    500 ANDYTOWN 5001      0.00020.00350.00000.1479
L     LEVEE    500 ANDYTOWN 5002      0.00020.00350.00000.1479
T     LEVEE    230 LEVEE    5001 1500  0005  0063             230  500
T     LEVEE    230 LEVEE    5002 1500  0005  0063             230  500
L     LEVEE    230 MILAM    2301      0.00140.01240.00000.0157
L     LEVEE    230 TKY PT   2301      0.00450.04270.00000.0512
L     LINGREN  230 SWEETWAT 2301      0.00080.00760.00000.0091
L     LINGREN  230 TKY PT   2301      0.00320.03010.00000.0361
L     MAULE    230 PENNSUCO 2301      0.00000.00010.00000.0002
L     MIAMI 1  230 8 TH ST  2301      0.00070.00350.00000.3557
L     MIAMI LK 230 P EVER   2301      0.00350.03570.00000.0374
L     MILLER   230 OLMPA HT 2301      0.00040.00280.00000.0045
L     PENNSUCO 230 SWEETWAT 2301      0.00140.01330.00000.0152
L     DORAL    230 PENNSUCO 2301      0.00060.00550.00000.0059
L     ANDYTOWN 500 MARTIN   5001      0.00120.01750.00000.8604
L     ANDYTOWN 500 MARTIN   5002      0.00120.01750.00000.8602
L     ANDYTOWN 500 ORANGE R 5001      0.00150.02240.00001.1004
T     ANDYTOWN 230 ANDYTOWN 5001 1500  0004  0069             230  500
T     ANDYTOWN 230 ANDYTOWN 5002 1500  0005  0070             230  500
L     ANDYTOWN 230 GRMN1 TP 2301      0.00160.01470.00000.0176
L     ANDYTOWN 230 GRMN2 TP 2301      0.00160.01470.00000.0176
L     ANDYTOWN 230 IMAGNATN 2301      0.00100.00940.00000.0112
L     ANDYTOWN 230 LAUDLE   2301      0.00240.02340.00000.0264
L     ANDYTOWN 230 PHOENIX  2301      0.00310.02910.00000.0347
L     ANDYTOWN 230 STONEBRG 2301      0.00110.01070.00000.0128
L     ANDYTOWN 230 TMBRLAKE 2301      0.00180.01690.00000.0201
L     ANDYTOWN 230 TRACE    2301      0.00130.01200.00000.0168
L     BROWARD  230 IMAGNATN 2301      0.00360.03370.00000.0402
L     BROWARD  230 LAKEVIEW 2301      0.00030.00310.00000.0040
L     BROWARD  230 MALLARD  2301      0.00120.01180.00000.0141
L     BROWARD  230 RANCH    2301      0.00450.04270.00000.0510
L     BROWARD  230 SANDALFT 2301      0.00110.01050.00000.0125
L     DAVIE    230 LAUDLE   2301      0.00050.00460.00000.0064
L     DAVIE    230 JACARADA 2301      0.00040.00350.00000.0049
L     GRAHAM1N 230 HOLYBROK 2301      0.00110.01120.00000.0202
L     GRAHAM2N 230 GRMN2 TP 2301      0.00150.01530.00000.0244
L     GRMN1 TP 230 HOLYBROK 2301      0.00040.00420.00000.0043
L     HIATUS   230 SPNGTREE 2301      0.00060.00530.00000.0074
L     HIATUS   230 VALENCIA 2301      0.00070.00610.00000.0085
L     LAKEVIEW 230 DELMAR   2301      0.00030.00280.00000.0034
L     LAUDANIA 230 LAUDLE   2301      0.00070.00680.00000.0077
L     LAUDANIA 230 P EVER   2301      0.00040.00380.00000.0042
L     MALLARD  230 PHOENIX  2301      0.00020.00230.00000.0027
L     MOTOROLA 230 SPNGTREE 2301      0.00040.00370.00000.0052
L     MOTOROLA 230 JACARADA 2301      0.00020.00210.00000.0030
```

```
L     SISTRUNK 230 P EVER   2301      0.00050.00200.00000.2884
L     LAUDLE   230 STONEBRG 2301      0.00130.01230.00000.0146
L     TMBRLAKE 230 LAUDLE   2301      0.00060.00590.00000.0070
L     TRACE    230 VALENCIA 2301      0.00080.00700.00000.0098
L     WOODLNDS 230 CEDAR    2301      0.00450.04540.00000.0478
L     WOODLNDS 230 LAUDLE   2301      0.00120.01170.00000.0124
L     ADAMS    230 EMERSON  2301      0.00210.01310.00000.0132
L     ADAMS    230 MIDWAY   2301      0.00140.00890.00000.0084
L     BUTTS    230 CLINTMOR 2301      0.00060.00540.00000.0065
L     BUTTS    230 DELMAR   2301      0.00020.00210.00000.0026
L     CEDAR    230 JOG      2301      0.00160.01470.00000.0196
L     CEDAR    230 RANCH    2301      0.00220.02150.00000.0234
L     CEDAR    230 TARTAN   2301      0.00010.00010.00000.0001
L     CLINTMOR 230 YAMATO   2301      0.00040.00390.00000.0044
L     CORBETT  500 MARTIN   5001      0.00030.00710.00000.2993
T     CORBETT  230 CORBETT  5001 1500  0004  0057             230  500
L     CORBETT  230 JOG      2301      0.00230.02210.00000.0257
L     CORBETT  230 KIMBERLY 2301      0.00450.04330.00000.0509
L     CORBETT  230 LOXHATCH 2301      0.00100.00930.00000.0107
L     CORBETT  230 RANCH    2301      0.00240.01820.00000.0182
L     CORBETT  230 ORANGE R 2301      0.01890.13740.00000.1343
L     CRANE    230 TURNPIKE 2301      0.00110.00960.00000.0134
L     DELTRIAL 230 TARTAN   2301      0.00080.00680.00000.0095
L     DELTRIAL 230 YAMATO   2301      0.00110.00990.00000.0135
L     EMERSON  230 MALABAR  2301      0.00980.06160.00000.0589
L     FLA STEL 230 INDNTOWN 2301      0.00160.01160.00000.0113
L     FLA STEL 230 MARTIN   2301      0.00090.00650.00000.0063
L     FRONTIER 230 FRONT TP 2301      0.00000.00010.00000.0000
L     FRONT TP 230 MIDWAY   2301      0.00490.03080.00000.0291
L     FRONT TP 230 MALABAR  2301      0.00800.04960.00000.0468
L     HOBE     230 INDNTOWN 2301      0.00230.02340.00000.0239
L     HOBE     230 RIVIERA  2301      0.01970.11070.00000.0767
L     HTCHNSON 230 ST LUCIE 2301      0.00000.00010.00000.0001
L     INDNTOWN 230 MIDWAY   2301      0.00260.02690.00000.0489
L     INDNTOWN 230 PRT WTNY 2301      0.00090.00940.00000.0171
L     KIMBERLY 230 SANDALFT 2301      0.00050.00510.00000.0061
L     LOXHATCH 230 RANCH    2301      0.00070.00710.00000.0082
L     MARTIN   230 SHERMAN  2301      0.00420.02830.00000.0310
L     MARTIN   500 MIDWAY   5001      0.00030.00590.00000.2500
L     MIDWAY   500 POINSETT 5001      0.00100.02100.00000.8781
T     MIDWAY   230 MIDWAY   5001 1500  0005  0063             230  500
L     MIDWAY   230 RANCH    2301      0.00610.05950.00000.1043
L     MIDWAY   230 SHERMAN  2301      0.00380.03740.00000.0408
L     MIDWAY   230 ST LUCIE 2301      0.00080.01330.00000.0223
L     MIDWAY   230 ST LUCIE 2302      0.00080.01340.00000.0226
L     MIDWAY   230 ST LUCIE 2303      0.00080.01340.00000.0226
L     MIDWAY   230 TURNPIKE 2301      0.00140.01290.00000.0161
L     MARTIN   500 POINSETT 5001      0.00120.02470.00001.0345
L     PRT WTNY 230 RANCH    2301      0.00220.02310.00000.0420
L     RANCH    230 RIVIERA  2301      0.00300.02450.00000.0444
L     SANPIPER 230 TURNPIKE 2301      0.00080.00760.00000.0106
L     BALDWIN  230 STLBD TP 2301      0.00010.00050.00000.0007
L     BLACK CK 230 DUVAL    2301      0.00220.02260.00000.0231
L     BLACK CK 230 SEMINOL2 2301      0.00490.04310.00000.0514
L     BRADFORD 230 DUVAL    2301      0.00550.04020.00000.0389
L     BRADFORD 230 RICE     2301      0.00580.04110.00000.0416
L     BREVARD  230 C CNVL   2301      0.00120.01220.00000.0124
L     BREVARD  230 C CNVL   2302      0.00120.01220.00000.0124
L     BREVARD  230 C CNVL   2303      0.00120.01220.00000.0124
L     BREVARD  230 MALABAR  2301      0.00630.03950.00000.0373
L     BREVARD  230 MALABAR  2302      0.00630.03950.00000.0373
L     BREVARD  230 POINSETT 2301      0.00230.01660.00000.0166
L     BREVARD  230 POINSETT 2302      0.00100.00880.00000.0149
L     BUNNELL  230 PUTNAM   2301      0.00550.03960.00000.0382
L     BUNNELL  230 VOLUSIA  2301      0.00480.03460.00000.0334
L     COLLEGE  230 POINSETT 2301      0.00920.05740.00000.0542
L     COLLEGE  230 SANFRD   2301      0.00160.01010.00000.0096
L     DELTN TP 230 DELTONA  2301      0.00060.00370.00000.0035
L     DELTN TP 230 SANFRD   2301      0.00300.01880.00000.0177
L     DELTN TP 230 VOLUSIA  2301      0.00500.03100.00000.0293
```

```
L     HUDSON   230 SEMINOL2 2301      0.00090.00730.00000.0103
L     HUDSON   230 PUTNAM   2301      0.00140.01370.00000.0152
L     NORRIS   230 VOLUSIA  2301      0.00830.06030.00000.0583
L     C CNVL   230 NORRIS   2301      0.00390.02850.00000.0279
L     ORNGEDLE 230 SAMPSON  2301      0.00100.00710.00000.0069
L     ORNGEDLE 230 TOCOI    2301      0.00170.01250.00000.0121
L     POINSETT 500 RICE     5001      0.00140.02860.00001.1982
L     DUVAL    500 POINSETT 5001      0.00190.03900.00001.6333
T     POINSETT 230 POINSETT 5001 1500  0002  0080             230  500
T     RICE 2   230 RICE     5001 1500  0003  0057             230  500
L     DUVAL    500 RICE     5001      0.00050.01040.00000.4349
L     PUTNAM   230 RICE     2301      0.00300.02130.00000.0209
L     RICE 2   230 SEMINOL1 2301      0.00050.00820.00000.0165
L     RICE 2   230 SEMINOL1 2302      0.00050.00820.00000.0165
L     STELBALD 230 STLBD TP 2301      0.00010.00070.00000.0008
L     DUVAL    230 STLBD TP 2301      0.00040.00270.00000.0026
L     ST JOHNS 230 TOCOI    2301      0.00230.01530.00000.0174
L     PUTNAM   230 TOCOI    2301      0.00380.02730.00000.0264
L     TOMOKA   230 VOLUSIA  2301      0.00110.00820.00000.0080
L     SANFRD   230 VOLUSIA  2301      0.00680.04930.00000.0476
L     DUVAL    230 W NASSAU 2301      0.00310.02990.00000.0347
L     W NASSAU 230 YULEE    2301      0.00180.01900.00000.0311
L     ALICO    230 COLLIER  2301      0.00390.03680.00000.0440
L     ALICO    230 JETPORT  2301      0.00160.01540.00000.0170
L     AUBURN   230 LAURELWD 2301      0.00050.00490.00000.0059
L     AUBURN   230 MYAKKA   2301      0.00180.01590.00000.0223
L     CALUSA   230 CHARLOTE 2301      0.00360.02360.00000.0380
L     CALUSA   230 FT MYERS 2301      0.00030.00180.00000.0029
L     CALUSA   230 LEE      2301      0.00180.01590.00000.0161
L     CALUSA   230 LEE      2302      0.00140.01450.00000.0179
L     CARLSTRM 230 CHARLOTE 2301      0.00380.03370.00000.0380
L     CARLSTRM 230 WHIDDEN  2301      0.00070.00760.00000.0078
L     CASTLE   230 JOHNSON  2301      0.00080.00310.00000.0055
L     CASTLE   230 RUBONIA  2301      0.00110.00450.00000.0075
L     COLLIER  230 ORANGE R 2301      0.00520.04870.00000.0582
L     FRTMBLTP 230 LAURELWD 2301      0.00210.01930.00000.0230
L     FRTMBLTP 230 RINGLING 2301      0.00090.00890.00000.0107
L     JETPORT  230 ORANGE R 2301      0.00110.01070.00000.0123
L     JOHNSON  230 PARK     2301      0.00140.00530.00000.0093
L     KEENTOWN 230 MANATEE  2301      0.00270.02780.00000.0283
L     KEENTOWN 230 WHIDDEN  2301      0.00530.05390.00000.0550
L     CHARLOTE 230 LAURELWD 2301      0.00460.04650.00000.0475
T     ORANGE R 230 ORANGE R 5001 1500  0003  0065             230  500
L     FT MYERS 230 ORANGE R 2301      0.00020.00260.00000.0056
L     FT MYERS 230 ORANGE R 2302      0.00020.00270.00000.0058
L     PARK     230 RINGLING 2301      0.00100.00380.00000.0065
L     MANATEE  230 RINGLING 2301      0.00180.02810.00000.0507
L     MANATEE  230 RINGLING 2302      0.00180.02790.00000.0510
L     MANATEE  230 RINGLING 2303      0.00180.02530.00000.0565
L     CHARLOTE 230 RINGLING 2301      0.00910.06570.00000.0645
L     DUVAL    230 NORMAN   2301      0.00080.00860.00000.0192
T     DUVAL    230 DUVAL    5001 1500  0001  0064             230  500
T     DUVAL    230 DUVAL    5002 1500  0001  0062             230  500
L     BUCKEYE  230 RUBONIA  2301      0.00220.01130.00000.0152
L     BUCKEYE  230 BIG BEND 2301      0.00400.02780.00000.0315
L     CHARLOTE 230 FT MYERS 2301      0.00450.03290.00000.0318
L     CHARLOTE 230 FT MYERS 2302      0.00320.03250.00000.0337
L     SAMPSON  230 STJRPP   2301      0.00400.03970.00000.1079
T     SANFRD   230 SANFRD    241       0004  0143             230   24
T     SANFRD   230 SANFRD   1151       0009  0307             230  115
T     SANFRD   115 SANFRD    181       0021  0596             115   18
T     PUTNAM   230 PUTNAM  13.81       0015  0632             230   138
T     STJRPP   230 STJRPP    241       0004  0080             230   24
T     C CNVL   230 C CNVL    221       0005  0175             230   22
T     NORMAN   230 NORMAN    201       0004  0080             230   20
L     LAUDLE   230 P EVER   2301      0.00110.01060.00000.0118
L     LAUDLE   230 P EVER   2302      0.00110.01060.00000.0118
T     P EVER   230 P EVER1   221       0006  0180             230   22
T     P EVER   230 P EVER   1381       0006  0274             230  138
T     P EVER   138 P EVER2   221       0006  0209             138   22
```

```
T     TKY PT   230 TKY PT    221       0002  0057             230   22
T     RIVIERA  230 RIVIERA   201       0055  0170             230   20
T     CUTLER   230 CUTLER    181       0022  0548             230   18
T     LAUDLE   230 LAUDLE    181       0010  0314             230   18
T     ST LUCIE 230 ST LUCIE  221       0001  0064             230   22
T     FT MYERS 230 FT MYERS  201       0017  0581             230   20
T     BIG BEND 230 BIG BEND  231       0001  0061             230   23
L     MANATEE  230 BIG BEND 2301      0.00280.02620.00000.0449
L     MANATEE  230 BIG BEND 2302      0.00280.02520.00000.0469
T     SEMINOL1 230 SEMINOL1  231       0002  0065             230   23
T     MARTIN   500 MARTIN    221       0001  0059             500   22
T     MANATEE  230 MANATEE   221       0002  0058             230   22
L     HATCH    500 DUVAL    5001      0.00160.02680.00001.2782
L     THALMAN  500 DUVAL    5001      0.00100.01660.00000.7953
C     E. EQV   500 DUVAL    5001      0.03750.37800.00000.5005
C     E. EQV   500 DUVAL    5002      0.03500.34990.00000.4633
L     E. EQV   500 DUVAL    5001      0.01810.18170.00000.9638
L     HATCH    500 THALMAN  5001      0.00080.01380.00000.6585
L     THALMAN  500 E. EQV   5001      0.00260.04410.00002.0424
C     THALMAN  500 VOGTLE   5001      0.00190.03230.00001.5043
L     HATCH    500 E. EQV   5001      0.00030.00800.00000.3816
C     VOGTLE   500 E. EQV   5001      0.00070.01180.00000.5381
C
C |AREANAME |BUSNAME| kV|schexpor|
A         FPLMARTIN    22    -2019  0
A         GPAE. EQV   500     2019  2
ZZ
REM    2
         1         2         3         4         5         6         7
 2345678 0 2345678 0 2345678 0 2345678 0 2345678 0 2345678 0 2345678 0
SOL    0              5   30  E. EQV   500                             0
OUT    1
ALL         YES  YES                 YES
ZZ
LST
SAV    8      9999            DUA0:
END
```

EMTP Input Files

There are four input files to the ETMSP program. The first one is the H file. It sets the parameters of the stability study.

```
!  The H_FLA.dat file (166-Bus, 19-unit system)
! Format for this is on pp 3-1 onwards of ETMSP-2P manual
!-----------------------------------------------------------
! CARD # 1: LOAD FLOW INFORMATION
! LFNO    |  ISTNO   | LFFORM  |
         1         1         5
!-----------------------------------------------------------
! CARD # 2: STUDY DESCRIPTION
Florida System 166 Busses and 19 Generators
!-----------------------------------------------------------
! CARD # 3: SOLUTION SPECIFICATION
!ISP!KSAL!MPRI!MAXI!ISKI!MAXN!IPRE!IJMC!
    0    0    5  500    0    0    0    0
!-----------------------------------------------------------
! CARD # 4: SOLUTION SPECIFICATION
! ERTOL  !  RESTOL ! PNL 1   !  VTHZL  ! VTHZH   ! ZILTOL  !
   0.00005       0.0       0.0       0.3       0.5    0.0001
!-----------------------------------------------------------
! CARD # 5: STABILITY  CHECK VOLTAGE LIMITS
! GVTMIN ! GVTMAX  ! BUVMIN  ! BUMAX   !
```

```
       0.0       0.0       0.0       0.0
!------------------------------------------------------------
! CARD # 6: SYSTEM BASE SPECIFICATION
! GNET   ! BASPC   !  FBASE  !  IBASE  !
     500.0     100.0      60.0
!------------------------------------------------------------
! CARD # 7: REFERENCE BUS (FOR ANGLE REFERENCE)
!NRF!
E. EQV   500
!------------------------------------------------------------
```

The next file is the generator or G file. It lists the generator data of the machines. In this file there will be both classical and detailed generator data. The load can be modeled as a percentage constant power, constant current and constant impedance. This is specified in this file.

```
! The G_FLA.dat file (166-Bus, 19-unit system)
!Format for this is on pp 2-7 & pp 5-5,6 of ETMSP-2P manual
!P and Q are taken as 1.0 pu if the columns're left blank
!! !         !!!    !! !! !!  !!  !!    !!    !!    !!    !!  !! !!    !
!     name       emws  p  q  mva Ra  x'd  x'q    xd    xq T'd0T'q0 xl
!!-!----------!!!----!!-!!-!!--!!--!!---!!---!!---!!---!!--!!-!!---!!---!!--!!-!
 EPGE
MF SANFRD    24 3087.0      100    .0322.1040.1778.17775.261.5.0244
M  SANFRD    24               S     .0257.0257.060.150
MF SANFRD    18 437.44      100    .1670.5261.8433.82154.001.5.1251
M  SANFRD    18               S     .1332.1332.060.140
MF PUTNAM  13.8 3461.0      100    .0468.0761.2794.27256.03.67.0361
M  PUTNAM  13.8               S     .0380.0380.060.099
MF STJRPP    24 3805.2      100    .0192.0325.1245.11994.00.53.0126
M  STJRPP    24               S     .0132.0132.040.055
MF C CNVL    22 2451.0      100    .0291.0523.1860.18953.70.46.0221
M  C CNVL    22               S     .0233.0233.060.060
MF NORMAN    20 12854.      100    .0074.0101.0436.04255.82.69.0050
M  NORMAN    20               S     .0053.0057.057.066
MF P EVER1   22 1632.1      100    .0539.2040.2803.27624.701.5.0418
M  P EVER1   22               S     .0440.0440.060.160
MF P EVER2   22 2451.0      100    .0291.0523.1861.17793.70.46.0221
M  P EVER2   22               S     .0233.0233.060.060
MF TKY PT    22 8584.5      100    .0142.0188.0650.06285.21.61.0091
M  TKY PT    22               S     .0095.0095.060.063
MF RIVIERA   20 1912.3      100    .0384.0685.2485.23804.10.46.0279
M  RIVIERA   20               S     .0294.0294.060.060
MF CUTLER    18  609.7      100    .1491.2285.8596.82154.20.48.0930
M  CUTLER    18               S     .0979.0979.060.062
MF LAUDLE    18  874.9      100    .0835.2631.4217.41084.001.5.0625
M  LAUDLE    18               S     .0658.0658.060.140
MF ST LUCIE  22 6640.0      100    .0219.0283.0903.08786.54.73.0139
M  ST LUCIE  22               S     .0146.0146.060.070
MF FT MYERS  20 1833.9      100    .0437.0847.2579.24893.85.99.0323
M  FT MYERS  20               S     .0340.0340.060.100
MF BIG BEND  23 26872.      100    .0029.0049.0185.01794.78.59.0022
M  BIG BEND  23               S     .0023.0023.058.076
MF SEMINOL1  23 6701.4      100    .0189.0283.1140.10964.73.80.0144
M  SEMINOL1  23               S     .0151.0151.060.060
MF MARTIN    22 5393.2      100    .0191.0291.0965.09525.251.1.0143
M  MARTIN    22               S     .0150.0150.050.052
MF MANATEE   22 5296.2      100    .0201.0292.0969.09585.201.5.0156
M  MANATEE   22               S     .0164.0164.060.060
MF E. EQV   500 375882      1002E-5.0003.0005.0016.00165.27.62.0002
M  E. EQV   500               S     .0002.0002.043.080
!  CLASSICAL MACHINE DATA
!MC SANFRD     24 1543.5       100    .0645
```

```
!MC SANFRD    18 1543.5       100    .0645
!MC PUTNAM  13.8 3461.0       100    .0468
!MC STJRPP    24 3805.2       100    .0192
!MC C CNVL    22 2451.0       100    .0291
!MC NORMAN    20 12854.       100    .0074
!MC P EVER1   22 1632.1       100    .0539
!MC P EVER2   22 2451.0       100    .0291
!MC TKY PT    22 8584.5       100    .0142
!MC RIVIERA   20 1912.3       100    .0384
!MC CUTLER    18  609.7       100    .1491
!MC LAUDLE    18  874.9       100    .0835
!MC ST LUCIE  22 6640.0       100    .0219
!MC FT MYERS  20 1833.9       100    .0437
!MC BIG BEND  23 26872.       100    .0029
!MC SEMINOL1  23 6701.4       100    .0189
!MC MARTIN    22 5393.2       100    .0191
!MC MANATEE   22 5296.2       100    .0201
!MC E. EQV   500 375882.      100    .0003
EDATA
 NLBS
!CARD 1 SPECIFY RANGE
!RANGE IF ALL FIELDS FOLLOWING THE KEYWORD ARE BLANK ALL BUSES ARE
!CONSIDERED
!   !!2345!2345!2345!2345!2345!2345
RANGE
!CARD 2 SPECIFY MW AND MX MIN VALUES (DEF 5.0)
!MVA RANGE
!234567890!234567890!
!  MWMIN  !  MXMIN  !
        5.0      5.0
!CARD 3 SPECIFY %AGE OF LOAD MODEL
!XXXX12345123451234512345123451234512345123451234512345!
!    !ICOP!ICOQ!ICPP!ICPQ!    !    !    !    !    !

EDATA
  END
```

The output or O file is next. This determines which data will be available.

```
! The O_FLA.DAT file for the Florida system (166-Bus, 19-unit system)
!Format for this is on pp 16-1 onwards of ETMSP-2P manual
!----------------------------------------------------------------------
!1234567890123456789012345678901234567890123456789012345678901234567890
!              GENERATORS
 CGEO
!          !!!
SANFRD    24
SANFRD    18
PUTNAM  13.8
STJRPP    24
C CNVL    22
NORMAN    20
P EVER1   22
P EVER2   22
TKY PT    22
RIVIERA   20
CUTLER    18
LAUDLE    18
ST LUCIE  22
FT MYERS  20
BIG BEND  23
SEMINOL1  23
MARTIN    22
MANATEE   22
E. EQV   500
EDATA
```

```
!---------------------------------------------------------------------
!     MONITORED BUS
 MVBS
!          !!          !!          !!          !!          !!          !
DUVAL    500MARTIN    22MANATEE   22THALMAN  500HATCH    500VOGTLE   500
E. EQV   500MANATEE  230MARTIN   500
EDATA
!---------------------------------------------------------------------
!     MONITORED LINE
 LINE
!          ! !          !!!
HATCH    500 THALMAN  5001
THALMAN  500 DUVAL    5001
DUVAL    500 THALMAN  5001
HATCH    500 DUVAL    5001
THALMAN  500 VOGTLE   5001
HATCH    500 E. EQV   5001
VOGTLE   500 E. EQV   5001
DUVAL    500 E. EQV   5001
EDATA
!---------------------------------------------------------------------
  END
```

The last file is the simulation or S file. This gives the timing sequence of events. This is the case which was decribed table 3.3 of the thesis.

```
!  The S_FLA.DAT file (166-Bus, 19-unit system)
!Format for this is on pp 17-1 onwards of ETMSP-2P manual
!-------------------------------------------------------------------------------
!  #1 SWITCHING DESCRIPTION
!THIS CARD CAN BE USED TO DESCRIBE A FAULT IN THE SYSTEM
TS ANALYSIS OF A 3 PHASE FAULT AT DUVAL ON THE DUVAL TO HATCH LINE
!-------------------------------------------------------------------------------
!  #2: SIMULATION CONTROL
!  XMAX  !   TL    !    HN   !
      0.05        2.5      0.001
!  #3: SWITCHING OPERATION CARD
!  #4: END OF SWITCHING CARD
ESC
!  #5: NEXT SWITCHING TIME CARD
!   TN   !    H    ! IDC! IMT!IPRT!IPLT! INT!
   0.500000.00333333    0    0    1    5    1
!-------------------------------------------------------------------------------
!  #3: SWITCHING OPERATION CARD
! !!!   NAME   !!  R   !!  X   !!  R   !!  X   !
!  #4: END OF SWITCHING CARD
! !!!   NAME   !!   NAME   !
ESC DUVAL    500DUVAL     500
!  #5: NEXT SWITCHING TIME CARD
!   TN   !    H    ! IDC! IMT!IPRT!IPLT! INT!
0.533333330.00333333    0    0    1    5    1
!-------------------------------------------------------------------------------
!  #3: SWITCHING OPERATION CARD
! !!!   NAME   !!   NAME   !!!!       !
DLI HATCH    500DUVAL     5001
!  #4: END OF SWITCHING CARD
! !!!   NAME   !!   NAME   !
ESC
!  #5: NEXT SWITCHING TIME CARD
!   TN   !    H    ! IDC! IMT!IPRT!IPLT! INT!
0.783333330.00333333    0    0    1    5    1
!-------------------------------------------------------------------------------
!  #3: SWITCHING OPERATION CARD
! !!!   NAME   !!   NAME   !!!  !      !!      !!      !
RLI HATCH    500DUVAL     5001
```

```
!  #4: END OF SWITCHING CARD
! !!!   NAME   !!   NAME   !
ESC
!  #5: NEXT SWITCHING TIME CARD
!   TN    !     H     ! IDC! IMT!IPRT!IPLT! INT!
   99999.0     0.005     0    0   50    1    1
!--------------------------------------------------------------------------------
```

FORTRAN and MATLAB Conversion Programs

The following file is the FORTAN file which converts an IEEE load flow into data which a MATLAB program can use to compute the Y bus.

```
C  This program takes IEEE data input and outputs data such that a MATLAB
C   program can read in voltage and current vectors as well as Y bus data
$DEBUG
      INTEGER DIM
      PARAMETER (dim=175,Pi=3.141593)
      DIMENSION VMB(dim),VAB(dim),PSB(dim),QSB(dim),PGEN(dim)
     *,QGEN(dim), ZLATER(dim)
      INTEGER BN,BT,NB(dim),BTY(dim),BLATER(dim)
      CHARACTER*12 BNAME(dim),BNA
      COMPLEX YC,ZC,A,YFF,YSS,YSF,YFS,ZLATER,Z, YB(DIM,DIM),s,il,vml,ig
     *,ilt,igt
      DIMENSION ybmag(dim,dim),teta(dim,dim)

      open(2,file='flaieee.dat')
      open(3,file='flabus.dat')
      open(4,file='flabran.dat')
      open(5,file='flapram.dat')
      open(6,file='temp.dat')
      open(7,file='flaybus.dat')
      open(10,file='bus.mat')
      open(11,file='volt.mat')
      open(12,file='curnt.mat')

      iym=0
      KR=0
      LATER=0
      FR=0.0
      READ(2,104) NBUS
104   FORMAT(/,36X,I3)
      WRITE(*,*) '                NUMBER OF BUSES =',NBUS


C******************** Nbus, j0 -> # of PQ, j2-> # of PV, j3 -> # of swing
      J0=0
      J2=0
      J3=0
C******************** JBR -> # of branches
      JBR=0

C******************** THIS FIRST RUN IS TO IDENTIFY AND COUNT DIFFERENT BUS TYPES
      DO 1 I=1,NBUS
      READ(2,100) BN,BNA,BT,VM,VA,PL,QL,PG,QG,G,B
100   FORMAT(I3,1X,A12,7X,I2,1X,F6.4,F7.2,3F9.2,F8.2,31X,2F8.4)
      IF(BT.EQ.0) J0=J0+1
      IF(BT.EQ.2) J2=J2+1
      IF(BT.EQ.3) J3=J3+1
      IF(J3.GT.1) STOP ' more than 1 swing bus'
1     CONTINUE

C*************   THIS SECOND RUN READS THE DATA AND CONVERTS FOR OUTPUT
      REWIND (2)
```

```
C ...........  BN  -> bus number
C ...........  BNA -> bus name
C ...........  BT  -> bus type
C ...........  G+jB -> zhunt admitance
      READ(2,104) NBUS
      DO 2 I=1,NBUS
      READ(2,100) BN,BNA,BT,VM,VA,PL,QL,PG,QG,G,B
      NB(i)=BN
      BNAME(i)=BNA
      BTY(i)=0
      VMB(i)=VM
      VAB(i)=VA
      PSB(i)=PL
      QSB(i)=QL
      PGEN(i)=PG
      QGEN(i)=QG
      YC=CMPLX(G,B)
c................. shunt admitance
      IF(CABS(YC).GT.0.0) THEN
      ZC=1.0/YC
      later=later+1
      BLATER(later)=i
      zlater(later)=ZC
      JBR=JBR+1
      ENDIF
2     CONTINUE

C
C   Write Bus Data for Check
C
      DO 6 I=1,NBUS
      WRITE(3,101) I,NB(I),BNAME(I),BTY(I),VMB(I),VAB(I),PSB(I),QSB(I)
     *,PGEN(I),QGEN(I)
101   FORMAT(I4,',',I4,',',A12,',',I1,',',F7.4,',',F8.3,',',F10.3,',',
     &F10.3,',',F10.3,',',F10.3)
C
C   Calculate the voltage and current vectors and write to a file
C
      VANG=VAB(I)*pi/180
      vr=vmb(i)*cos(VANG)
      vi=vmb(i)*sin(VANG)
      vml=cmplx(vr,vi)
      psb(i)=psb(i)/100
      qsb(i)=qsb(i)/100
      s=-cmplx(psb(i),qsb(i))
      il=conjg(s)/conjg(vml)
      ilt=ilt+il
      ril=real(il)
      gil=imag(il)
      pgen(i)=pgen(i)/100
      qgen(i)=qgen(i)/100
      s=-cmplx(pgen(i),qgen(i))
      ig=conjg(s)/conjg(vml)
      igt=igt+ig
      rig=real(ig)
      gig=imag(ig)
      write(12,*)i,ril,gil,rig,gig
6     write(11,*)i,vr,vi


C **************************************************    READ BRANCH INFORMATION
      READ(2,104) NBRA
      WRITE(*,*) '               NUMBER OF BRANCHES = ',NBRA

C************ WRITE BRANCHES DUE TO SHUNTS
      DO i=1,later
         JOC=BLATER(i)
         ZC=ZLATER(i)
         R=REAL(ZC)
         X=AIMAG(ZC)
```

```
        WRITE(4,102) KR,JOC,R,X
      ENDDO
102   FORMAT(I4,',',I4,',(',E14.7,','E14.7,')')

C********************** Read branch information
c........ NI     -> 1-4
c........ NF     -> 6-9
c........ id     -> 17
c........ NT     -> 19
c........ Rl     -> 20-29
c........ Xl     -> 30-39
c........ Bl     -> 41-49.    Total charging susceptance
c........ C      -> 77-82.    Transformer ratio=a
c........ B      -> 84-90.    Phase shift = phi
      DO 7 I=1,NBRA
      READ(2,103) NI,NF,id,NT,RL,XL,BL,C,B
103   FORMAT(I4,1X,I4,7X,I1,1x,I1,F10.6,F10.6,1X,F9.5,27X,F6.4,1X,F7.2)
      ZC=CMPLX(RL,XL)
      B=B*PI/180.0
      RA=C*COS(B)
      AIA=C*SIN(B)
      A=CMPLX(RA,AIA)

c............ origfrom=nb(k), origto=nb(l); from=k, to=l
      DO 8 J=1,NBUS
      IF(NI.EQ.NB(J)) IS=J
      IF(NF.EQ.NB(J)) IF=J
8     CONTINUE

      IF(NT) 9,9,10

c.......... line
9     WRITE(4,102) IS,IF,RL,XL
      JBR=JBR+1

c....... Bl
      IF(ABS(BL).EQ.0) GO TO 7
      BL=-2.0/BL
      WRITE(4,102) KR,IS,FR,BL
      WRITE(4,102) KR,IF,FR,BL
      JBR=JBR+2

      GO TO 7

c.......... transformer without phase shift
10    IF(AIA.EQ.0.) THEN
      YC=1.0/ZC/A
      RLSF=REAL(1.0/YC)
      XLSF=AIMAG(1.0/YC)
      WRITE(4,102) IS,IF,RLSF,XLSF
      JBR=JBR+1

      IF(RA.NE.1.0) THEN
      YC=(A-1.0)*YC
      RLF=REAL(1.0/YC)
      XLF=AIMAG(1.0/YC)
      YC=-YC/A
      RLS=REAL(1.0/YC)
      XLS=AIMAG(1.0/YC)
      WRITE(4,102) KR,IS,RLS,XLS
      WRITE(4,102) KR,IF,RLF,XLF
      JBR=JBR+2
      ENDIF

      ELSE
c.......... transformer with phase shift (AIA.NE.0.)
      YFF=1.0/ZC
      YSS=YFF/(CABS(A)**2.0)
      YFS=-YFF/A
      YSF=-YFF/CONJG(A)
```

```
c  .     elements of Ybus
      WRITE(6,102) IS,IS,YSS
      WRITE(6,102) IF,IF,YFF
      WRITE(6,102) IS,IF,YSF
      WRITE(6,102) IF,IS,YFS
      iym=iym+4
      ENDIF

c.........Bl
      IF(ABS(BL).EQ.0) GO TO 7
      BL=-2.0/BL
      BLIS=BL*CABS(A)**2
      WRITE(4,102) KR,IS,FR,BLIS
      WRITE(4,102) KR,IF,FR,BL
      JBR=JBR+2

7     CONTINUE


c******* Copy the contents of scratch file to branch_file.
      IF(iym.gt.0) THEN
      REWIND(6)
      DO i=1,iym
         READ(6,102) is,if,ysf
         WRITE(4,102) is,if,ysf
      ENDDO
      ENDIF

      Write(5,*) nbus,jbr,j0,iym
      nbra=jbr
      npq=j0


C  Part 2 of 3

C     . NBUS=NUMBER OF BUSES
C     . NBRA=NUMBER OF BRANCHES
C     . NPQ=NUMBER OF PQ BUSES
C     . iym=number of admitance branches due to phase shifters.
C     . NPV=NUMBER OF PV BUSES
      NPV=NBUS-(NPQ+1)

C     . YB(NBUSxNBUS)=0;

      DO 21 I=1,NBUS
      DO 21 J=1,NBUS
21    YB(I,J)=CMPLX(0.0,0.0)

C     . READ THE IMPEDANCE OF BRANCH I. WHICH GOES FROM J TO K

      rewind(4)
      DO 22 I=1,NBRA
       READ(4,*) J,K,Z
       IF(J.EQ.0) then
       yc=yc+1.0/z
       GO TO 23
       end if
       YB(J,K)=YB(J,K)-1.0/Z
       YB(K,J)=YB(J,K)
       YB(J,J)=YB(J,J)+1.0/Z
23       YB(K,K)=YB(K,K)+1.0/Z
22     CONTINUE
C
C
C     . YBUS HAS BEEN FORMED
C     . YBMAG = MAG OF YB
C     . TETA = ANG OF YB
C     . NELEYB = NUMBER OF ELEMENTS IN YBUS NOT EQUAL TO ZERO
      NELEYB=0
      WRITE(7,207)
```

```
207   FORMAT(/,10X,'****** YBUS ********',/)

      DO 24 I=1,NBUS
        DO 25 J=1,NBUS
           RE=REAL(YB(I,J))
           AIM=AIMAG(YB(I,J))
            YBMAG(I,J)=SQRT(RE**2+AIM**2)
            IF(RE.EQ.0.0.AND.AIM.NE.0.0) TETA(I,J)=
     *                                 SIGN(PI/2.0,AIM)
            IF(RE.EQ.0.0.AND.AIM.EQ.0.0) TETA(I,J)=0.0
            IF(RE.NE.0.0) TETA(I,J)=ATAN2(AIM,RE)
        IF(YBMAG(I,J).NE.0.0) THEN
               WRITE(7,208) I,J,RE,AIM,YBMAG(I,J),TETA(I,J)
               write(10,215) i,j,re,aim
               NELEYB=NELEYB+1
        ENDIF
25         CONTINUE
24       CONTINUE
208   FORMAT(1x,'(',I3,',',I3,')','  RE=',f17.7,'  IM=',f17.7
     *,/,1x,'     MAG=',f17.7,'    ANG=',f17.7)
      WRITE(5,213) NELEYB
      write(5,*)'total y shunt = ',yc
      write(5,*)'total il = ',ilt,' total ig = ',igt
215   format(1x,2i4,2f17.7)
213   FORMAT(1X,I4)


205   FORMAT(1X,I3,1x,I4,6(F11.5,2x))
206   FORMAT(1X,'BUS=',1X,'OrBus',2X,'=VOLTAGE=',5X,'=ANGLE=',7X,'=Pl=',
     *9x,'=Ql=',9x,'=Pg=',9X,'=Qg=')
      STOP
      END
```

The next file is the MATLAB program which loads the output data from the FORTRAN program into the MATLAB environment. The program also reduces the system to a 4 Machine system.

```
%
% load the ybus
%
load bus;
nbra=size(bus);
nbra=nbra(1);
nm=6;
nb=165;
npq=143;
ne=nb-nm;
ns=ne+1;
n=bus(:,1);
m=bus(:,2);
r=bus(:,3);
im=bus(:,4);
%
%  Construct the Y bus
%
for i=1:nbra
  y(n(i),m(i))=r(i)+j*im(i);
end
clear n;
clear m;
clear r;
clear im;
clear bus;
%
```

```
%  load in the voltage data
%
load volt;
r=volt(:,2);
im=volt(:,3);
v=r+j*im;
vm2=abs(v).^2;
clear r;
clear im;
clear volt;
%
%  load in the load data
%
load curnt;
r=curnt(:,2);
im=curnt(:,3);
il=r+j*im;
sl=v.*conj(il);
slt=sum(sl);
clear r;
clear im;
%  load generator data
r=curnt(:,4);
im=curnt(:,5);
ig=r+j*im;
sg=v.*conj(ig);
sgt=sum(sg);
clear r;
clear im;
clear curnt;
%
%  partition the y matrix
%
eb=diag(v(ns:nb));
ee=diag(v(1:ne));
yee=y(1:ne,1:ne);
ybe=y(ns:nb,1:ne);
yeb=y(1:ne,ns:nb);
zee=inv(yee);
factor=-eb*conj(ybe)*conj(zee)*inv(ee);
%
%   Generator Equivalent
%
ieg=ig(1:ne);
ieqg=-ybe*zee*ieg;
seg=ee*conj(ieg);
seqg=factor*seg;
seqgt=sg(ns:nb)+seqg;
sgeq=sum(seqgt);
ieqgt=ieqg+ig(ns:nb);
%
%   Load Equivalent
%
ie=il(1:ne);
%  calculate equivalent current
ieq=-ybe*zee*ie;
se=ee*conj(ie);
%  calculate equivalent load
seq=factor*se;
sleq=sum(seq);
seqt=seq+sl(ns:nb);
ieqt=ieq+il(ns:nb);
%
%  Y bus Equivalent Calculation
%
yeq=ybb-ybe*inv(yee)*yeb;
yeql=sum(yeq);
yp=yeq;
for i=1:nm
  yp(i,i)=yeql(i);
```

```
end
%
%   Calculate Equivalent Impedances, deleting values greater than 5 pu
%
imp=-1 ./yeq;
for n=1:nm
  for m=1:nm
    if abs(imp(n,m)) > 5
      imp(n,m)=0;
    end
  end
end
```

The last file takes the Full System in the MATLAB environment and calculates the eigenvalues of the system.

```
 %
 %  This is the MATLAB routine to calculate the eigenvalues of the
 %    full FP&L system.
 %
 %  The Y bus, voltage, and current vectors are already in the MATLAB
 %    environment with the loads, shunts, and charging modeled in the
 %    diagonal elements of the Y bus.
 %
 %  gfla is the file containing the generator data from the g_fla.dat file
 %
 load gfla
 emws=gfla(:,1);
 mbase=gfla(:,2);
 h=emws./mbase;
 xd=j*gfla(:,3);
 nb=165;
 y11=sum(y);
 y(184,184)=0;
 nbus=165;
 nmach=19;
 ng=144;
%
%  The Y bus needs to be modified to include the transient reactance.
%  The dimesions are increased from 165 to 184 busses as the internal
%    nodes are added.
%
 for i=1:nmach-1
   ii=i+nbus;
   ij=ii-nmach-3;
   y(ii,ii)=y(ii,ii)+1/xd(i);
   y(ij,ij)=y(ij,ij)+1/xd(i);
   y(ii,ij)=-1/xd(i);
   y(ij,ii)=-1/xd(i);
   v(ii)=v(ij)+ig(ij)*xd(i);
 end
 y(165,165)=y(165,165)+1/xd(19);
 y(184,184)=y(184,184)+1/xd(19);
 y(165,184)=-1/xd(19);
 y(184,165)=-1/xd(19);
 v(184)=v(165)+ig(165)*xd(19);
%
%  Kron Reduction is now performed on the system leaving only internal nodes
%
yee=y(1:nbus,1:nbus);
ybe=y(166:184,1:nbus);
yeb=y(1:nbus,166:184);
ybb=y(166:184,166:184);
yeq=ybb-ybe*inv(yee)*yeb;
yeq1=sum(yeq);
e=v(166:184);
```

```
ieqg=yeq*e;
em=abs(e);
del=angle(e);
%
%  The synchronizing power coeffecents are calculated
%
for i=1:19
  for ii=1:19
   del0(i,ii)=del(i)-del(ii);
   temp=(imag(yeq(i,ii))*cos(del0(i,ii))-real(yeq(i,ii))*sin(del0(i,ii)));
   ps(i,ii)=em(i)*em(ii)*temp;
  end
end
wr=pi*120;
%
%  Alpha is calculated
%
for ii=1:18
  a(ii,ii)=(wr*ps(19,ii))/(2*h(19))+(wr*ps(ii,19))/(2*h(ii));
  for jj=1:18
    if jj~=ii
      a(ii,jj)=(wr*ps(19,jj))/(2*h(19))-(wr*ps(ii,jj))/(2*h(ii));
      a(ii,ii)=a(ii,ii)+(wr*ps(ii,jj))/(2*h(ii));
    end
  end
end
%
%  The m matrix is formed
%
m(1:18,19:36)=eye(18);
m(19:36,1:18)=-a;
%
%  lamda is the eigen values of the m matrix
%  There are 2*(n-1) eigen values but they are imaginary conjugate pairs.
%
lamda=eig(m);
for i=1:18
  ii=i*2;
  l(i,1)=lamda(ii);
end
%
%  The frequency and time constants are also calculated.
%
lf=l/(2*pi)
ts=1 ./lf
```

VITA

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