LOSS OF FIELD PROTECTION AND ITS IMPACT ON POWER SYSTEM STABILITY

By

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To the Faculty of Washington State University:

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LOSS OF FIELD PROTECTION AND ITS IMPACT ON POWER SYSTEM STABILITY

ABSTRACT

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The aim of this thesis is to study the impact of Loss of Field (LOF) protection at generators on the grid stability of the interconnected power system. Specifically, we will show the relationship between the operational speeds of the partial loss of field protection at critical plants on voltage stability of the neighboring power grid near the plants. Model based simulations will be studied in order to duplicate the actual TVA events using a detailed eastern system data.

A back-up protection scheme which is based on terminal measurements is proposed for such a generator using synchrophasors which would trip the generator under LOF conditions by observing the line measurements at the plant. The real and reactive power-flows on some transmission lines near the plant are monitored to design the proposed back-up protection for the plant. The LOF is typically characterized by high MW flow out of the generator with large Q flow into the generator. An inverse time-characteristic logic on the reverse Q flow into the plant (above a preset threshold) under high MW flow out of the plant is suggested. Reset logic is needed in order to prevent false tripping under stable system swings. Accordingly, tripping can be made slower

under partial LOF conditions by encoding an inverse time characteristic on the trigger logic. This back-up protection scheme's settings will be based on P-Q and Q-V curve studies.

Last, a LOF protection scheme which is based on internal measurements will be introduced. We will use the Q-V curve and two-axis model calculation in MATLAB to find the Efd threshold which will likely lead the system to voltage collapse.

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CHAPTER 1 INTRODUCTION

Power system stability problem has been a great concern for power engineers over the past several decades. The increasing of loads and power system deregulation make the power system more complex than ever. Major blackouts caused by power system instability have illustrated the importance of this phenomenon [1]. Due to the continuing growth of the power system such as in interconnections, use of new controls and technologies and so on, different forms of system stability have emerged. Voltage stability and transient stability have become more problematic than in the past [1]. In order to prevent large blackouts such as August 2003 in north eastern part of United State and August 1996 of western interconnection in North America which cost billions of dollars [16-18], real-time monitoring tools are needed for the operator to take quick and appropriate actions to correct the problems.

Loss-of-Field (LOF) condition of a generator on the power system can be caused by faults or unforeseen problems in the automatic field voltage control in the synchronous generators. A generator may completely or partially lose its excitation due to accidental field breaker tripping, field open circuit, field short circuit, voltage regulator failure, or loss-of-excitation system supply [3]. LOF is typically partial though complete loss of field can occur in rare instances. LOF causes the generator to absorb a large amount of reactive power from the power grid. LOF causes the machine speed to go above the synchronous speed, and the machine will start to operate like an induction generator [2, 4-11]. When this happens, the machine will draw a large amount of reactive power from the rest of the power system which means an increasing reactive power demand on the neighboring system near the LOF generator. This will cause the bus voltages to decline near the LOF generator.

LOF condition at a large generator such as at major fossil plants can drag down nearby voltage of the system very fast and can jeopardize the voltage stability of the rest of the power system. If LOF conditions persist, it can also cause severe damage to the generator itself possibly related to heavy loading on the generator armature windings, thermal heating in the rotor windings, loss of magnetic coupling between rotor and stator, and large voltage drop in the transmission system [2-11]. Therefore, LOF condition on a generator of the power system should be detected as fast as possible, and the effect of LOF on the power system stability and voltage stability has to be understood in order to prevent voltage or system collapse.

Tennessee Valley Authority (TVA) has experienced three LOF related generator-tripping events in the past two years at a Paradise fossil unit [20-22] and one LOF related generator-tripping event in 2008 at Gallatin unit 3 [23]. For instance, during the December 3, 2006 event, Paradise plant absorbed nearly 1000 MVAR for about 15 seconds from the TVA system before the LOF relay tripped the unit. Evidence of large amount of reactive power flow into the Paradise generator and fast declining voltages has been seen in PMU and DFR responses near the Paradise plant during all three events. Fortunately, the loss of excitation relays operated correctly during all four events preventing damage to the generators and voltage stability of the TVA system. However, if the operating conditions were more stressed at that time such as from outages of some transmission lines or if the LOF relays respond more slowly, the consequences could have been more problematic. One aim of this thesis is to study the impact of LOF at Paradise plant on the neighboring TVA system with a focus on the relationship between LOF conditions and voltage stability.

Even though the LOF relays operated correctly in all four events, the potential failure or slow operation of the LOF relays can still be problematic for the system stability. For that reason, a back-up protection scheme which is based on terminal measurements is proposed for such a generator using synchrophasors, which could trip the generator under LOF condition by observing the reactive power flow measurements on the 500kV transmission line from Montgomery to Paradise. The first back-up protection scheme will be the same as we proposed in [19]. Then a new back-up protection scheme will be introduced which will be based on the P-Q and Q-V curve at the Paradise Plant side. The generator capability curve will be approximated using the settings we proposed. Another back-up protection scheme is also proposed which will be based on some off-line studies of the internal measurements. First, we will use Transient Stability Analysis Toolbox program (TSAT) to run some simulations in order to find the exact point corresponding to a particular field voltage Efd which the system voltage will collapse. Then we will use the PSAT program to perform the Q-V curve calculation in order to find the Q_margin. Lastly, we will calculate the reactive power absorbed by the generator using the two-axis model in MATLAB. Once all the calculations are done, the appropriate Q threshold setting will be obtained which will be say 20% or 30% of the Q margin. Then the Efd limit which will likely lead the system to voltage collapse will be obtained by comparing the Q threshold to the MATLAB calculation.

The structure of this dissertation is as follows. In Chapter 2, we discuss the motivation of this research. The background of Paradise unit and protection schemes will be discussed as well as some of the recent LOF events at TVA. In Chapter 3, we will study the effect of LOF on the two-area system [11] at several different operating conditions with simulation results using MATLAB and PSS/E to illustrate. Some main observations are draw here. In Chapter 4, we will show the study of LOF conditions on a detailed planning model of the TVA power system as part of the eastern interconnection. We will develop a simulation model that matches well with the recorded PMU and DFR measurements during the events and the model is then used for carrying out several 'what-if' studies. In Chapter 5, back-up protection schemes based on the terminal measurements will be introduced. In Chapter 6, LOF protection based on internal measurements will be introduced. Some main conclusions and observations will be in Chapter 7.

CHAPTER 2 MOTIVATION

2.1 INTRODUCTION

In the past three years, TVA Paradise unit 3 has experienced three loss-of-field related events. Therefore, the study of why this happened so frequently and what may the consequences are necessary. In order to better study the actual LOF events that happened at Paradise unit 3, an understanding of the Paradise unit 3 structures and protection scheme and the surrounding transmission connections are also necessary. This part is mainly written by TVA engineer Gary Kobet which can be found in [19, 20].

2.2 BACKGROUND OF PARADISE UNIT 3

Paradise Unit 3 is a 1278 MVA cross-compound unit connected to the transmission system over a single 53 mile 500 kV transmission line. The unit is comprised of two 639 MVA generators rated 24 kV, bussed together and sharing a common steam system as well as a 1260 MVA 500/22 kV generator step-up (GSU) transformer (Figure 2-1).

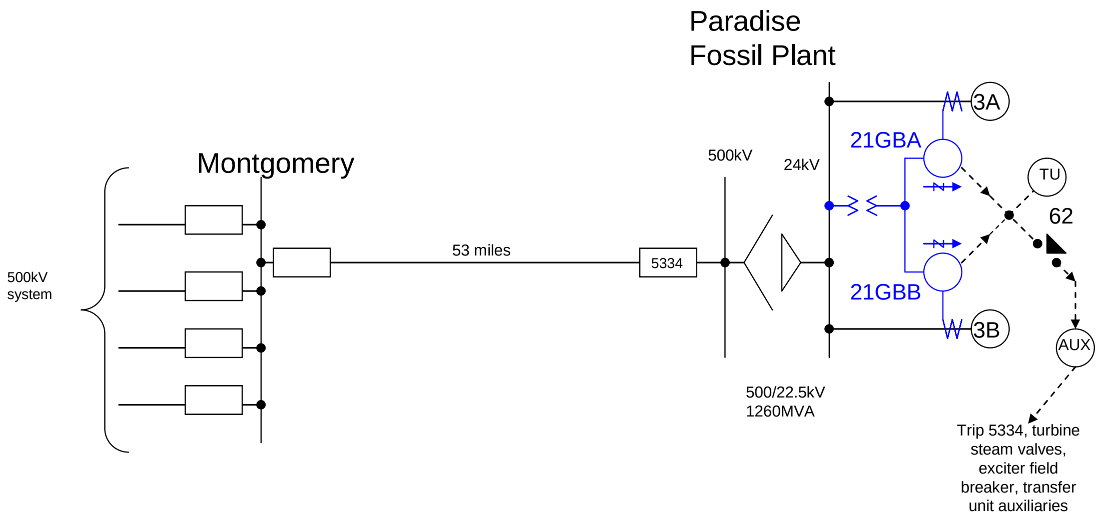


Figure 2-1: Paradise Unit 3 and Transmission System Connections [20]

This 1970 vintage unit has single-function electromechanical relays providing protection for each generator. Conventional phase differential relays provide stator phase fault protection, and a single neutral overvoltage relay protects both stators from ground faults (A-generator neutral is grounded, B-generator neutral ungrounded). Abnormal operating conditions are protected for reverse power (low-pressure unit only), overexcitation/overvoltage, unbalanced currents, and field ground. Voltage-restrained overcurrent relays provide backup protection for system faults.

Loss-of-excitation protection for many such generators is provided by conventional mho elements with 90 degree maximum torque angle, a diameter set equal to the generator synchronous impedance, a negative offset equal to one-half the generator transient reactance; a short time delay is typically used to avoid tripping on stable swings [3-10]. However, in the 1960s TVA engineers began using a more commonly available distance relay with a 75 degree maximum torque angle, and deciding against the use of an offset. Each generator has its own distance relay, with a diameter set on 125% of the generator synchronous impedance, and a time delay of 10 cycles.

A comparison of the two methods is shown in Figure 2-2. From this Figure, it seems that the two approaches are very similar in coverage. Either method would provide backup protection for phase faults.

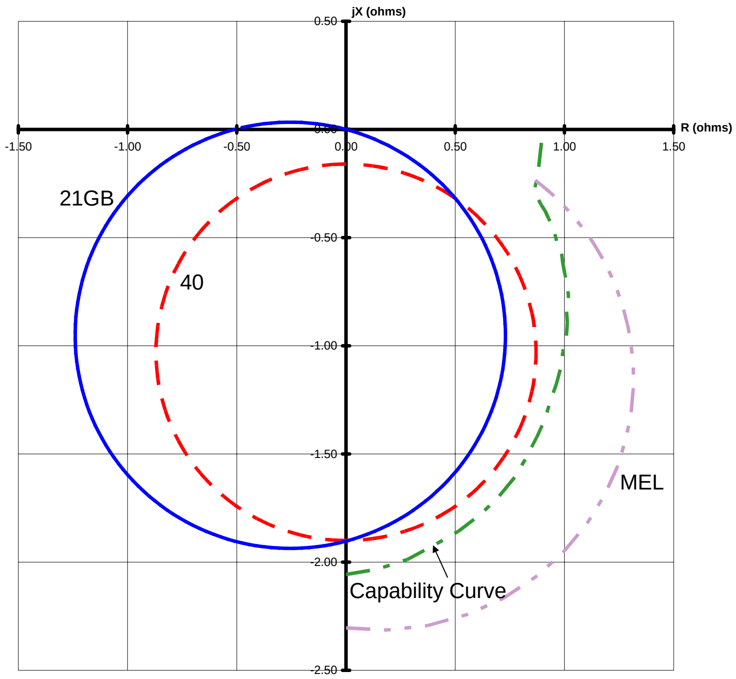


Figure 2-2: Loss-of-excitation protection for Paradise generators 3A/3B [20]

It should be noted that the 21GB relays share a common timer and lockout relay. On a loss-of-excitation condition for either generator, a failure of any single component in this scheme would prevent the scheme's operation.

2.3 THEORY OF CURRENT PROTECTION SCHEME

A synchronous generator requires adequate dc voltage and current to the field winding to maintain synchronism with the power system. The greater the dc supply to the field winding, the "tighter" the electromagnetic connection to the power system, and the more stable the generator will be. As excitation to the field is reduced, the weaker the electromagnetic connection will be, and the generator tends to be less stable. In extreme cases of underexcitation or complete loss of excitation, the machine can actually lose synchronism with the system even without a system disturbance (e.g., fault, loss of load, line switching, etc). At this level the machine is said to have exceeded its steady state stability limit.

For round rotor machines such as the two cross-compound generators at Paradise, on loss-of-excitation the machine will over-speed and act as an induction generator. The generator will continue to provide real power (MW), while receiving its excitation (MVAR) from the transmission system. This change is not instantaneous, but will occur over a time period (seconds), depending on the characteristics of the unit and the connected system. If the machine is initially at full load, the machine will speed to 2% to 5% above normal. Significantly, the level of MVAR drawn by the machine can be greater than the generator MVA rating! If the machine is at reduced load, the speed could only be 0.1% to 0.2% above normal, with a reduced level of MVAR drawn. When discussing adverse effects of loss-of-excitation, there are two aspects to consider: (1) Effects on the machine itself; and (2) Effects on the connected system.

Regarding the machine itself, a generator that experiences loss-of-excitation can sustain damage to the stator end iron due to high stator and induced field currents. This can occur in as little as ten seconds up to several minutes. And, as previously stated, the machine could lose synchronism (pull out-of-step). A generator that has lost synchronism experiences high peak currents and off-frequency operation, which causes winding stresses, pulsating torques, and mechanical resonances that are potentially damaging to the generator and turbine generator shaft.

A loss-of-excitation not only can damage the machine, but the condition can also be harmful to the connected transmission system. This is especially true if the machine draws excessive MVAR, which can depress system voltage. Worse, if machine tripping is slow, it could result in delayed voltage recovery or even voltage collapse.

The primary control guarding against loss-of-excitation protection is the minimum excitation limiter (MEL), provided with the voltage regulator. The MEL should be set such that limiting action occurs before operation of the loss-of-excitation protection (21GB at Paradise), and should allow for maximum leading power factor operation. However, should the MEL fail or be out of service (regulator in manual), a distance relay as previously described is provided [12, 13].

At the advent of the use of such protection, many users did not trip the machine on loss-of-excitation, but rather connected it to alarm only. Later on, after becoming familiar and comfortable with the protection and seeing the benefits, most if not all users now connect the protection to trip the machine.

Causes of loss-of-field include:

- ✓ Accidental trip of field breaker
- ✓ Field open circuit
- ✓ Field short circuit (slip ring flashover)
- ✓ Voltage regulator system failure
- ✓ Loss of supply to the excitation system

On loss-of-field, the apparent impedance of a fully loaded machine travels from the first quadrant to the fourth quadrant close to the negative Y axis at a value just above the direct-axis transient reactance (taking about 2-7 seconds). The final impedance point will depend on the initial load, varying between one-half the machine transient reactance at full load the direct-axis synchronous reactance at no load. The locus of impedance trajectory depends on the system impedance. Generally, for system impedance less than 20%, the impedance trajectory takes a direct path. At higher system impedance, the impedance trajectory will spiral toward a final point (faster than the direct path).

2.4 Paradise Plant LOF Events

In the past two years, TVA Paradise unit 3 (PAF 3) has experienced three generator tripping events due to LOF condition on 3A machine [21-23]. The cause was a malfunctioning MEL on PAF generator 3A. The relay target was 321GB-A. In the following of this section, we will show some detailed information about those three events. The one-line diagram of the surrounding system of PAF 3 is shown below (Figure 2-3).

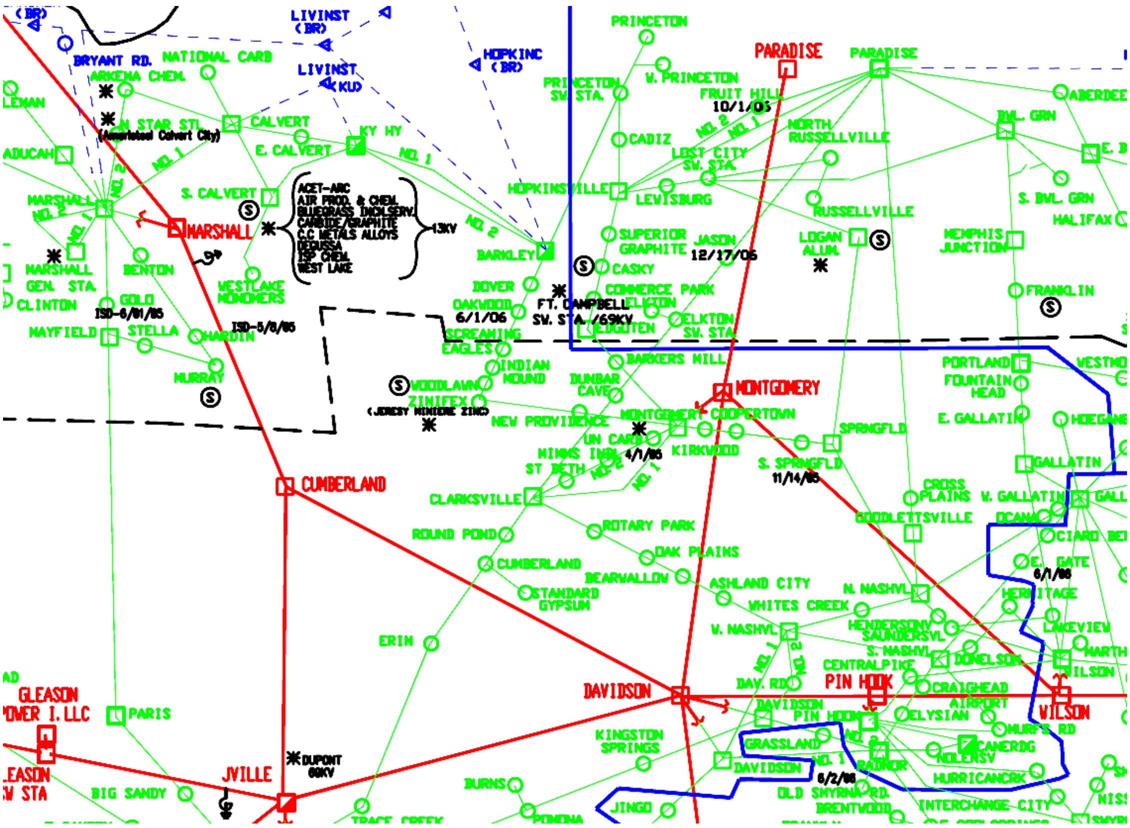


Figure 2-3: One-line Diagram of PAF 3 surrounding area [20]

The first event happened on December 3, 2006. At the time of LOF, PAF3 generating about 1000 MW, but over 15 seconds absorbed nearly 1000 MVAR. In that time, Cumberland (CUF) 500kV line bus voltage dropped about 6 kV (Figure 2-4). CUF machines sensed the trip and responded with a 400 MW swing which damped out in about 10-15 seconds. There is no PMU located at Paradise or Montgomery 500 kV buses and the nearest PMU is at CUF 500 kV bus. Recordings from the CUF PMU along with DFR recordings from Paradise and Davidson are discussed next.

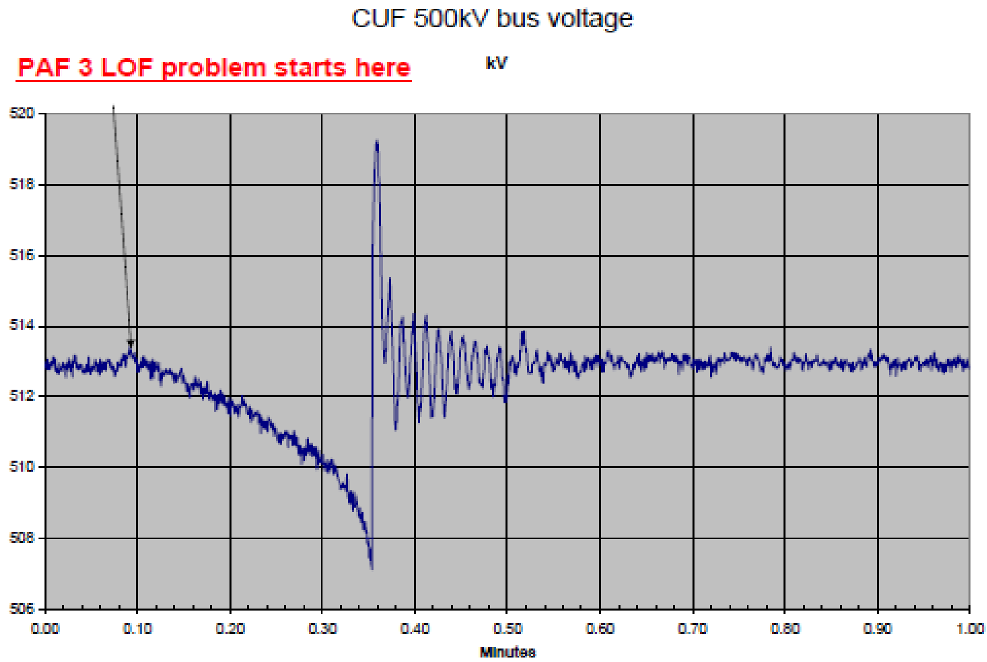


Figure 2-4: CUF 500kV bus voltage ---12-03-06 Event [21]

Figure 2-4 shows the Cumberland 500 kV bus voltage during the event. We observe that the CUF 500 kV voltage declined from 513 kV to 507 kV over 25 seconds when PAF3A plant was experiencing the LOF conditions. CUF voltage recovers back to the nominal value of 513 kV after PAF3 is tripped out by protection at 0.35 minutes in

Figure 2-4. The active power MW output of the CUF generators show a somewhat poorly damped response after the PAF3 plant is tripped at 12.53.21 in Figure 2-5.

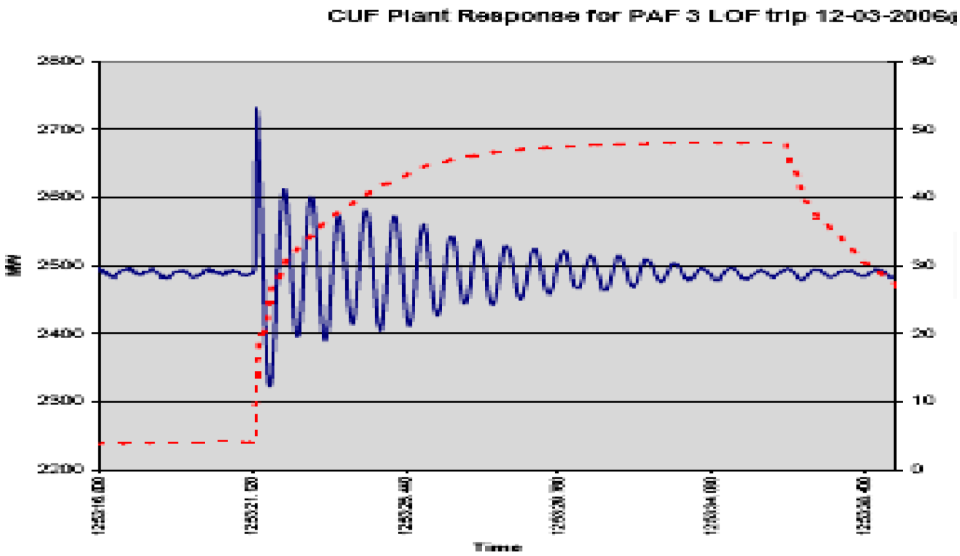


Figure 2-5: CUF Plant MW Response due to LOF Trip---12-03-06 Event [21]

Next, DFR recordings from the event are presented in Figures 2-6, 2-7 and 2-8. In these plots, we can notice changes in MW flows (colored red) and MVAR flows (colored green) when PAF3A unit is tripped at about 370 sec. From the DFR recordings, we can see that due to LOF, heavy MVAR flows exist from the nearby buses into PAF 3 (Figure 2-6, 2-7, and 2-8) prior to the PAF3 tripping.

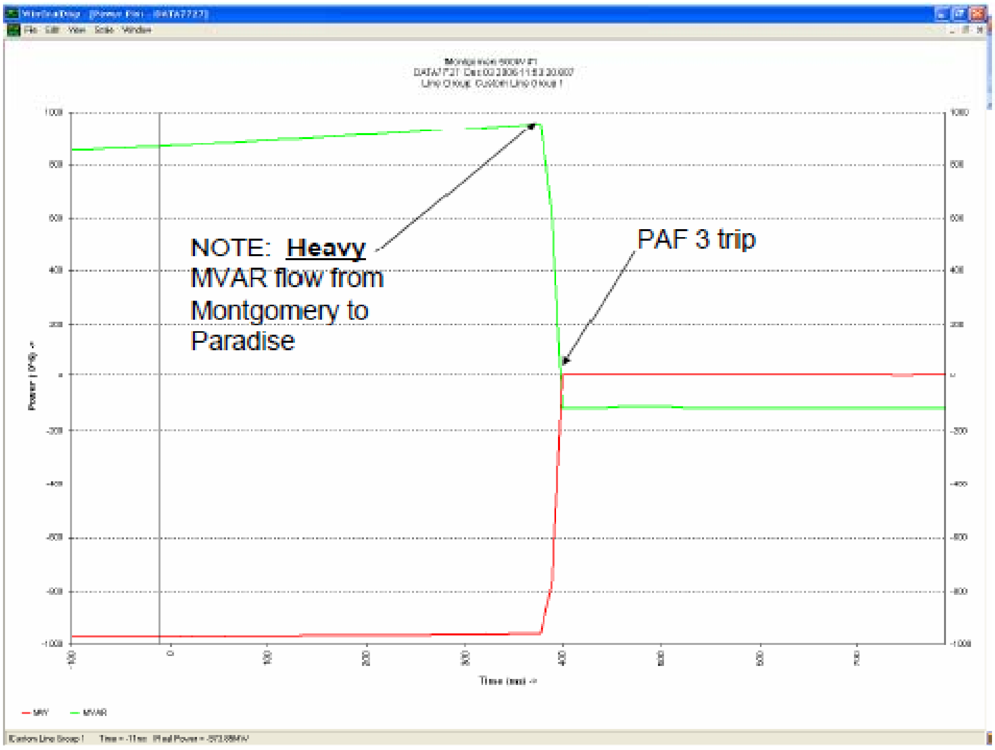


Figure 2-6: MW (red) and MVAR (green) flows from Montgomery-Paradise [21]

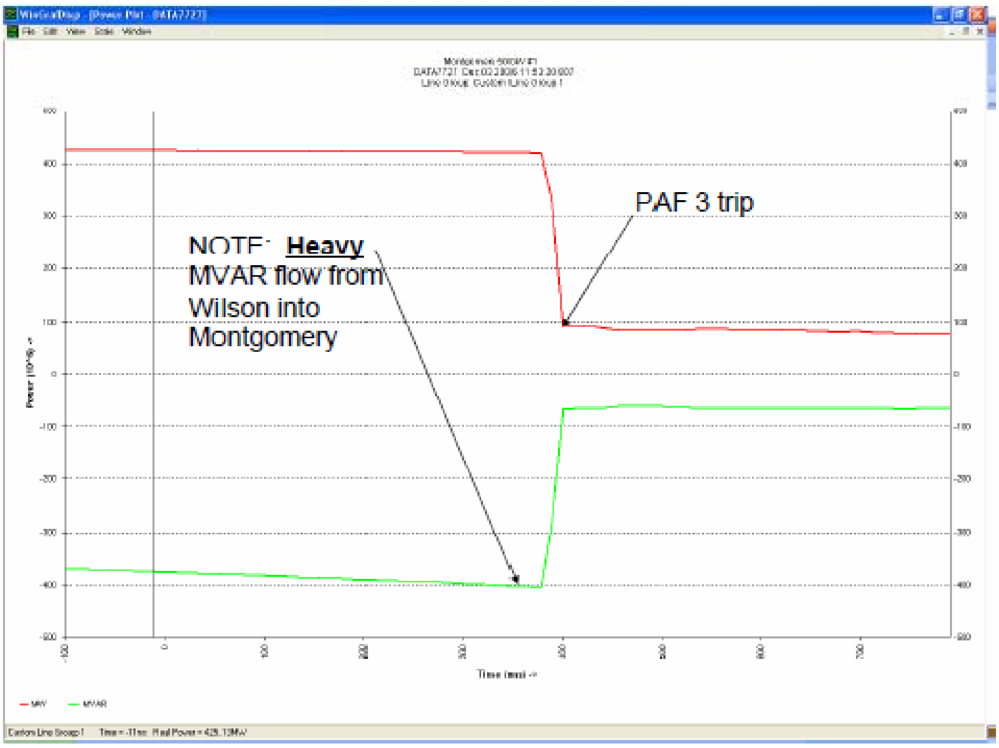


Figure 2-7: MW (red) and MVAR (green) flows from Wilson-Montgomery [21]

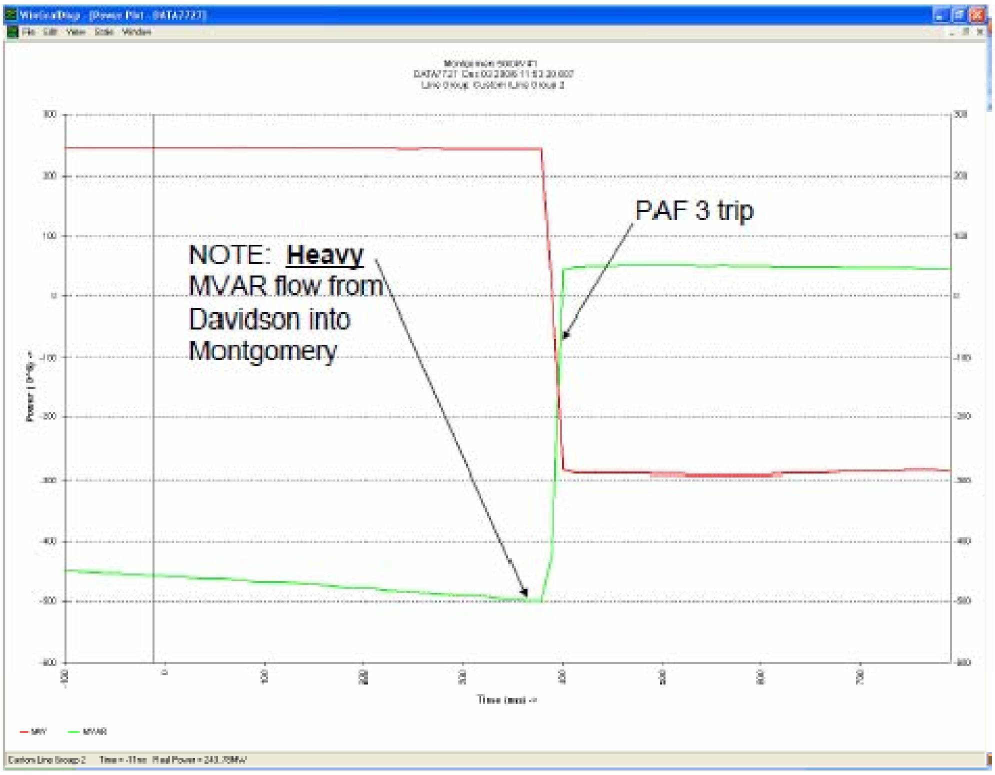


Figure 2-8: MW (red) and MVAR (green) flows from Davidson-Montgomery [21]

Specifically in Figure 2-6, MW flow on Paradise to Montgomery 500 kV line drops from 1000 MW to zero as the PAF3 is tripped. More interestingly, we notice the heavy reactive power flow of nearly 1000 MVAR from Montgomery to Paradise 500 KV buses from the LOF condition at PAF3A prior to the tripping of PAF3. Similarly, Figure 2-7 shows heavy 400 MVAR flow from Wilson to Montgomery 500 kV buses prior to PAF3 tripping. Figure 2-8 shows the MVAR flow from Davidson to Montgomery at about 500 MVAR prior to PAF3 tripping.

Due to the heavy MVAR flow from the nearby buses into PAF 3, the LOF conditions depressed the neighboring bus voltages to abnormal low operating levels. In

Figure 2-9, Montgomery 500 kV line bus voltage sagged to 0.96pu (485 kV). In Figure 2-10, Davidson 500 kV line bus voltage sagged to 0.98pu (487 kV) just prior to PAF 3 tripping.

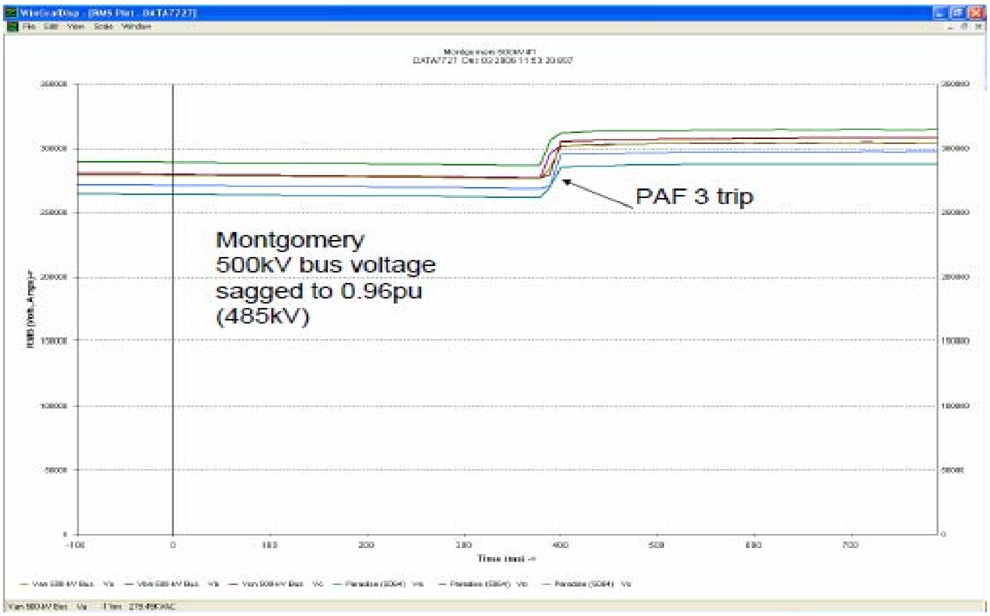


Figure 2-9: Montgomery 500kV Bus Voltage [21]

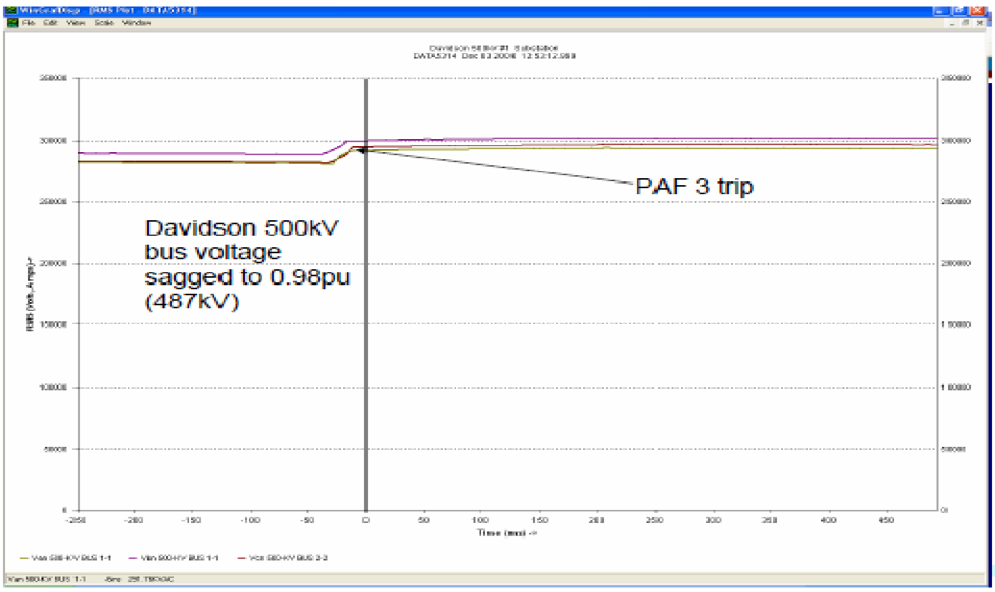


Figure 2-10: Davidson 500kV Bus Voltage [21]

The second event happened on December 19, 2006. At the time of LOF, PAF 3 was generating about 1000 MW, but over 10 seconds it absorbed nearly 600 MVAR. The condition lasted for about 10 seconds prior to the trip. Cumberland 500 kV line bus voltage was dropped by about 3 kV during LOF conditions at PAF 3 (Figure 2-11). CUF machines sensed the trip and responded with a 300 MW swing which damped out in about 10-15 seconds (Figure 2-12).

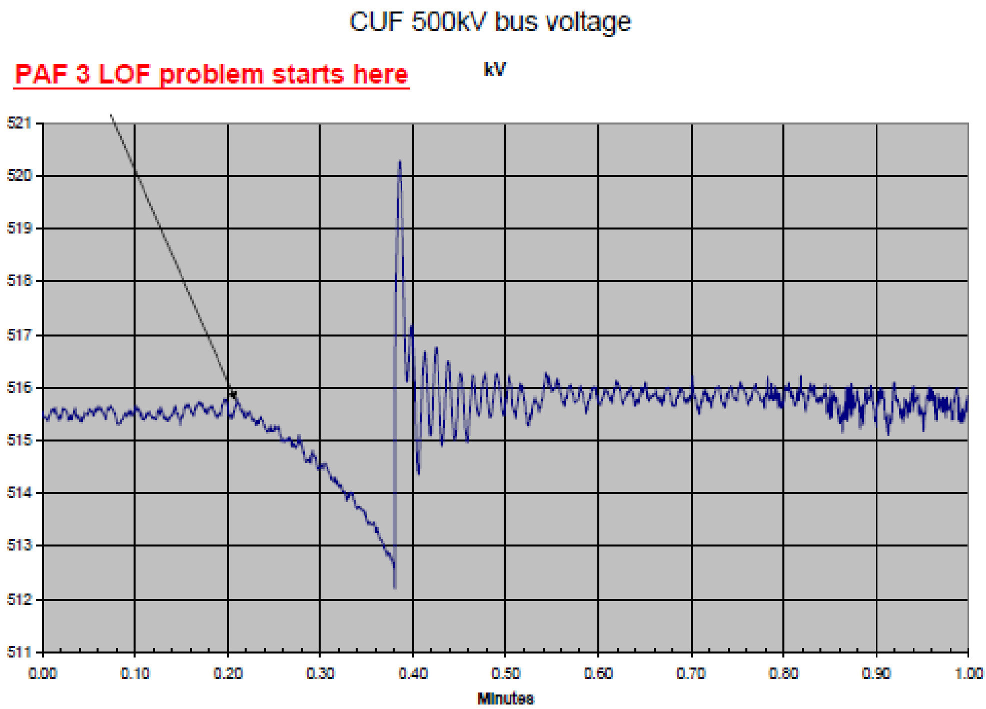


Figure 2-11: CUF 500kV Bus Voltage---12-19-06 Event [22]

From the DFR recordings, we can again see that heavy MVAR flows from the nearby buses into PAF 3 existed prior to PAF 3 tripping. Like during the December 3, 2006 event, the heavy MVAR flows from the neighboring buses into PAF 3 led to bus voltage declines near PAF 3. Montgomery 500 kV line bus voltage sagged to 1pu which typically should be at 1.06pu. Davidson 500 kV line bus voltage sagged to 1.01pu which typically is at 1.04pu. After PAF 3 tripping, the MVAR flows as well as voltages recovered to their nominal values.

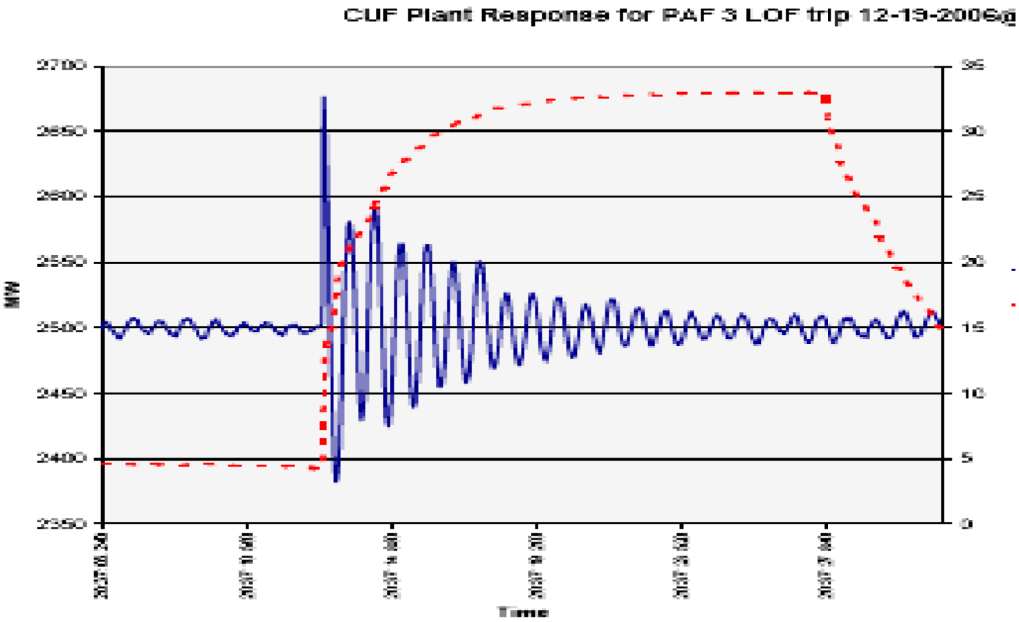


Figure 2-12: CUF MW Response due to LOF Trip---12-19-06 Event [22]

The most recent event happened on November 29, 2007. At the time of LOF, PAF 3 was again generating about 1000 MW. The relays tripped PAF 3 after about 25 seconds. Over this period of 25 seconds, PAF 3 absorbed nearly 700 MVAR. During the LOF period at PAF 3, Cumberland 500kV line bus voltage dropped by about 6 kV (Figure 2-13).

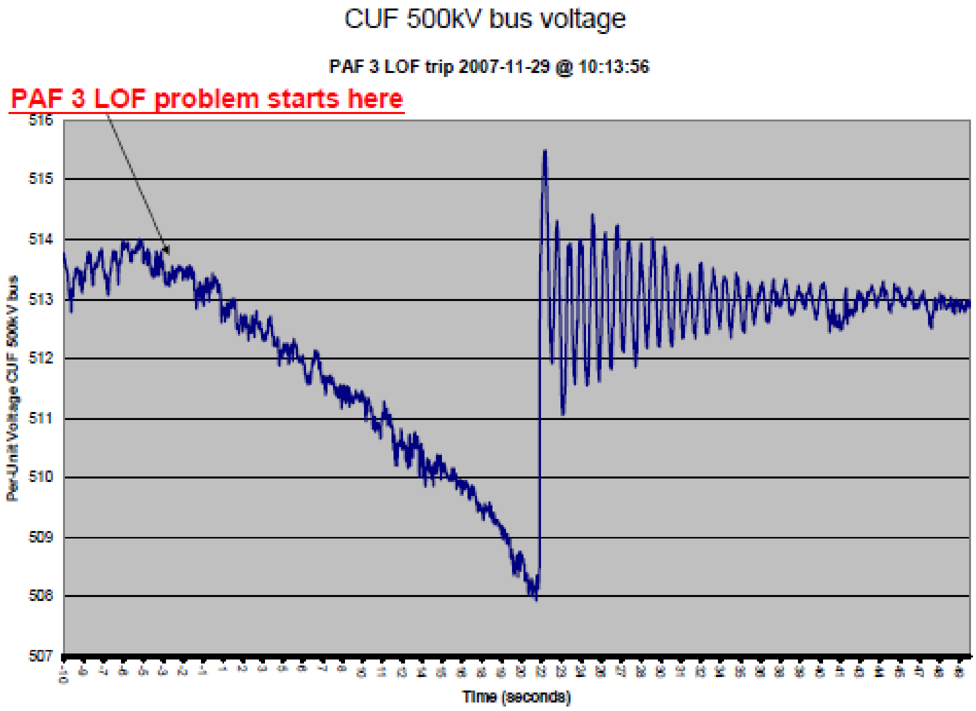


Figure 2-13: CUF 500kV Bus Voltage---11-29-07 Event [23]

Like for the previous two events, DFR recordings show heavy MVAR flows from the nearby buses into PAF 3. Just prior to PAF 3 trip, 280 MVAR was flowing from Wilson to Montgomery, another 370 MVAR from Davidson to Montgomery providing a heavy 700 MVAR from Montgomery to Paradise (Figure 2-14). Again, we notice that the MW flow is in the opposite direction from Paradise to Montgomery 500 kV buses. Because of the LOF conditions and heavy MVAR flows, Montgomery 500 kV bus voltage sagged to 0.98pu while it normally is at 1.06pu. Similarly, Montgomery 161 kV bus voltage sagged to 1.01pu while it should be about 1.04pu. Neighboring bus voltages declined as well. North Nashville 161kV line bus voltage sagged to 1.0pu which typically is at 1.02pu. Springfield 161 kV line bus voltage sagged to 1.0pu which typically is at

1.03pu. This event will be studied in more detail in Chapter 4 by simulating the LOF condition at Paradise 3A plant in a planning model of the eastern interconnection.

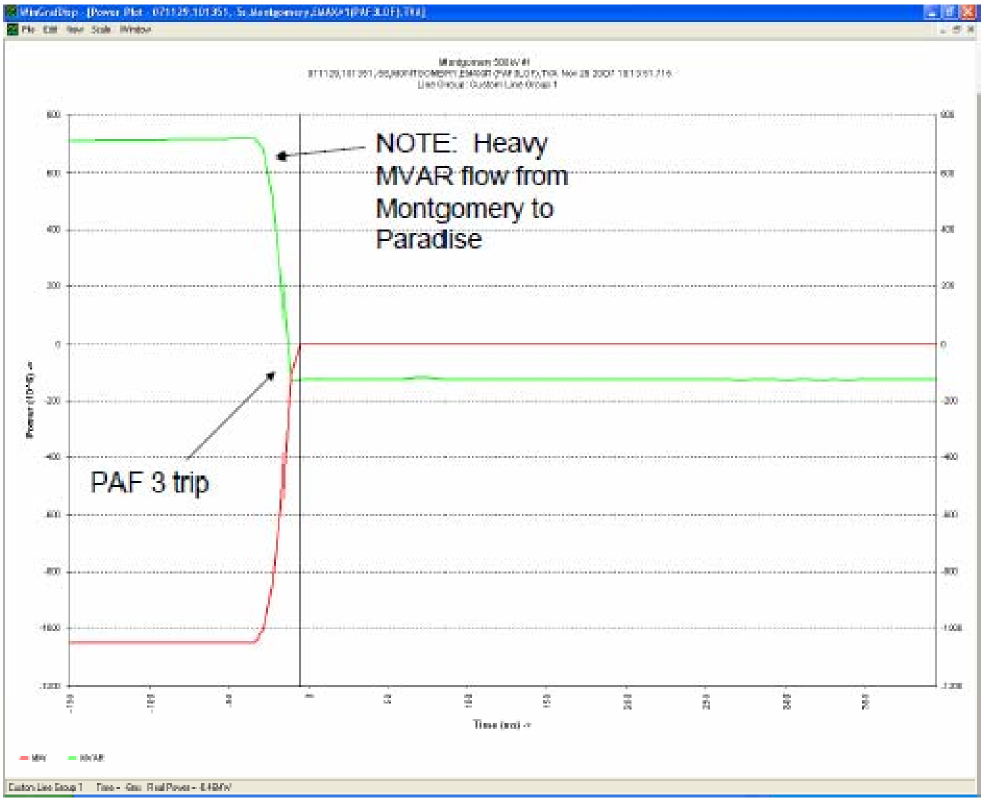


Figure 2-14: MW (red) and MVAR (green) flows from Montgomery-Paradise [23]

2.5 CONCLUSIONS

In all three LOF events at PAF 3 discussed above, we can see that the LOF affects not only the LOF generator, but also has an impact on nearby plants and bus voltages. Fortunately, the loss of excitation relays operated correctly during all three events. The tripping of Paradise 3 plants prevented damage to the LOF generator and to system stability. However, if the LOF relays did not operate correctly which means the relays may not sense the LOF or if they operated more slowly, the consequences may have been more problematic. Detailed simulations of the LOF conditions and their relationship to potential voltage collapse are studied in the following chapters.

CHAPTER 3 LOF SIMULATIONS ON THE TWO-AREA SYSTEM (PSS/E)

3.1 INTRODUCTION

In order to study the LOF effect on the system stability and voltage stability of a large power system, we will first study the effect on the two-area system from the textbook [11] (Figure 3-1) using PSS/E program so that we have a basic understanding of what may happen due to LOF. In our simulations, we assume that Generator 4 will experience LOF at time t=0 sec throughout the study. The models and model parameters that are used in the simulations can be seen in Appendix B.

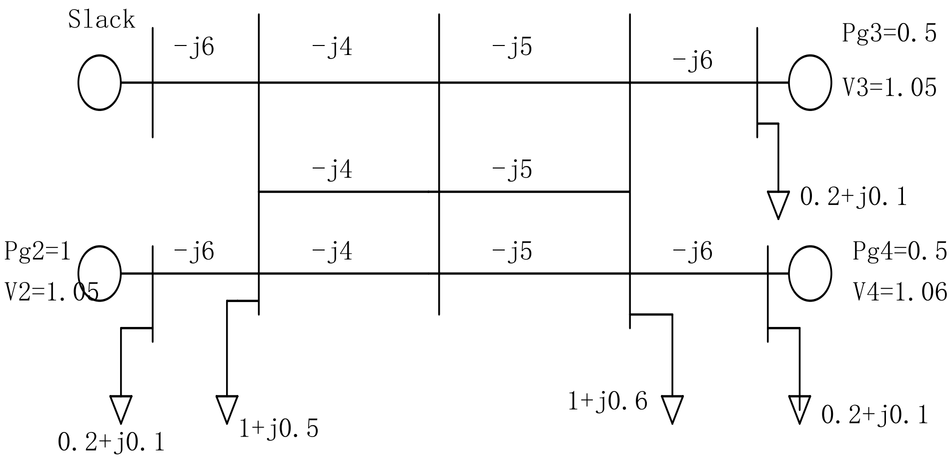


Figure 3-1: One-line Diagram of Two-Area System

3.2 FULL LOF ON THE TWO-AREA SYSTEM WITHOUT OEL

We will first examine the system response under full loss of field condition. In PSS/E, we choose a simple exciter model for all the generators which will be the SEXS model. Since it has the Efd limit, then we can just set the Efd min and max of generator 4 to zero which means the field voltage of generator 4 will be zero at time t=0 second (Figure 3-2). It means generator 4 experiences full LOF condition. From the simulation results below, we can see that at the instance of LOF on generator 4, the machine speed of generator 4 is increasing. Real power output is still about constant until the generator loses its synchronism (Figure 3-3).

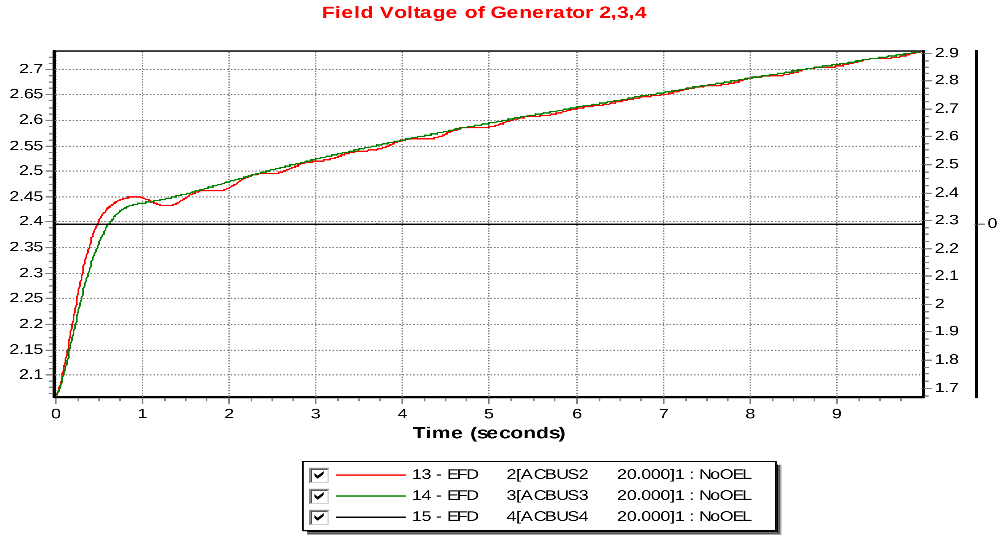


Figure 3-2: Field Voltage of Generator 2, 3, 4

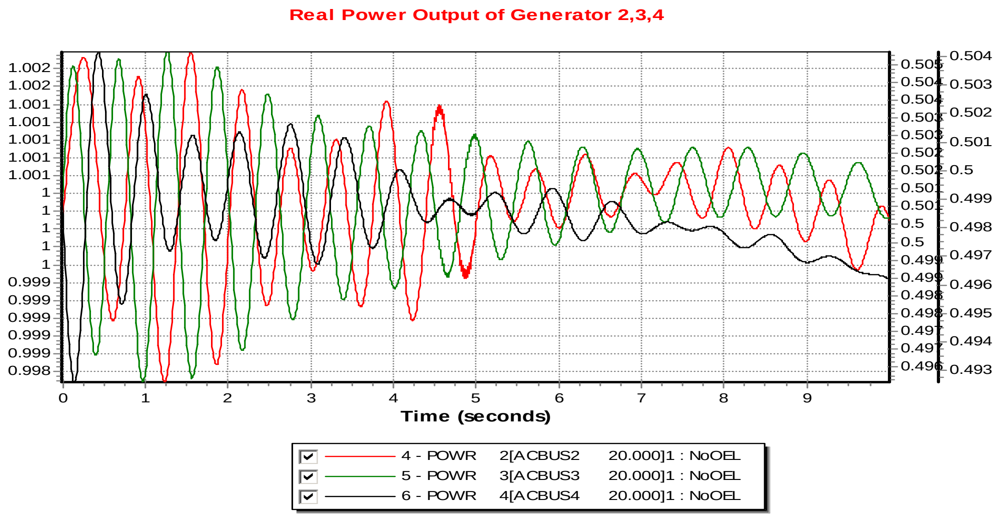


Figure 3-3: Real Power Output of Generator 2, 3, 4

When the speed of generator 4 increases above the synchronous speed, the machine will act like an induction generator. From the reactive power output graph (Figure 3-4), we can see that generator 4 absorbs large amount of reactive power soon after the LOF. Also, generator 2 and 3 reactive power output is increasing a lot during a short period of time. Due to LOF, the bus voltages of the entire system decrease to some abnormal low value (Figure 3-5). If the LOF generator 4 is not tripped, eventually, the system will experience the voltage collapse phenomenon.

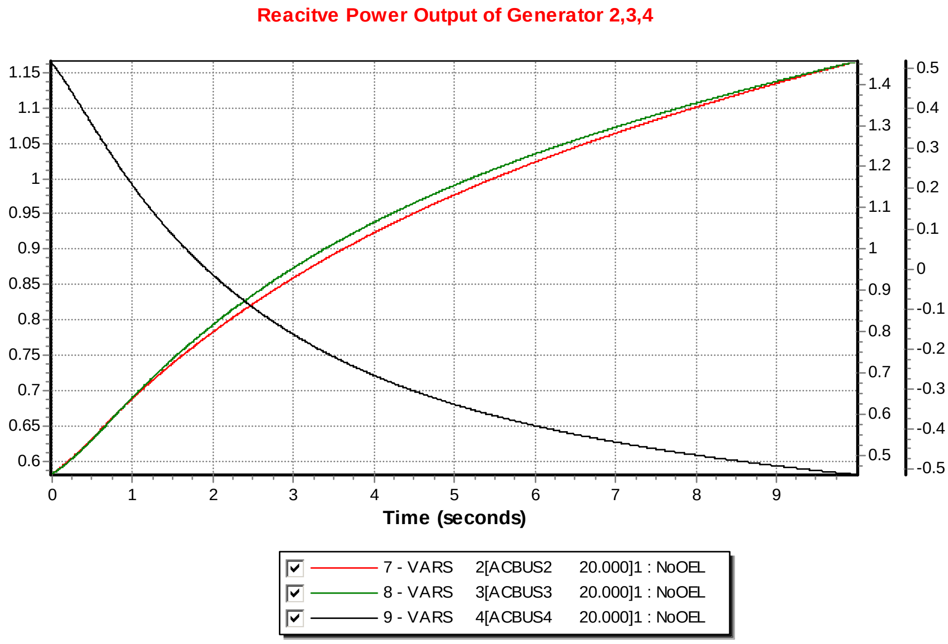


Figure 3-4: Reactive Power Outputs of Generator 2, 3, 4

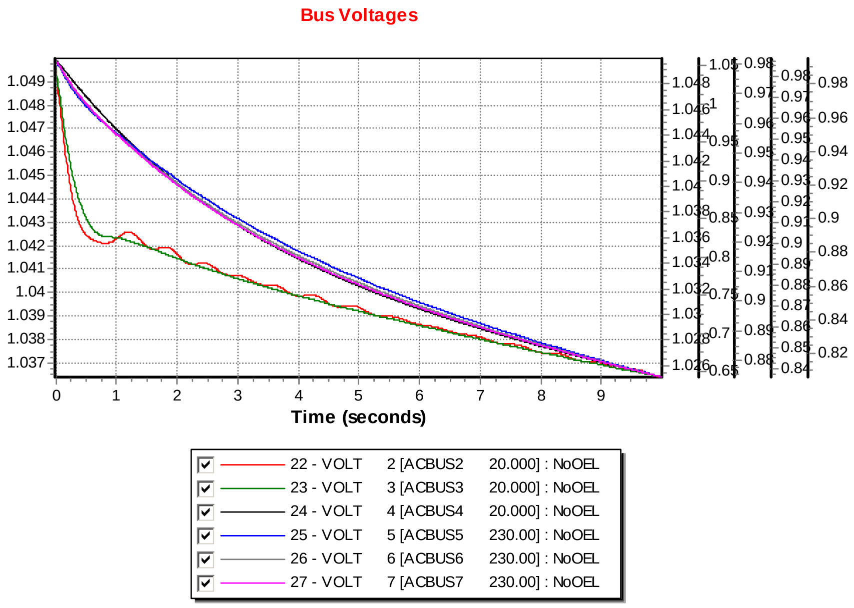


Figure 3-5: Bus Voltages

From the above simulations, we can see that LOF condition on generator 4 does not only affect the LOF generator itself, but also affect the entire system. Since the LOF generator tries to absorb large reactive power. This means the rest of the system has to produce heavy MVAR to make up for the additional reactive power demand. If the rest of the system cannot provide the desired amount of reactive power that the generator needs due to LOF condition, the LOF condition can then degenerate into a voltage collapse. We also have to study that under different operating conditions to understand the system response due to different LOF condition.

3.3 FULL LOF ON THE TWO-AREA SYSTEM WITH OEL

Now, we will put an over-excitation limiter (OEL) at generator 3 at time t = 5 seconds (Figure 3-6) which means generator 3 cannot produce that large amount of reactive power any more beyond t = 5 sec. The rest of the system has to provide for the reactive power shortage which means it depresses the system voltages even more. The OEL action prevents generator 3 exciter from overheating due to excessively large reactive power output. However, the OEL action at generator 3 hastens the bus voltage declines towards voltage collapse.

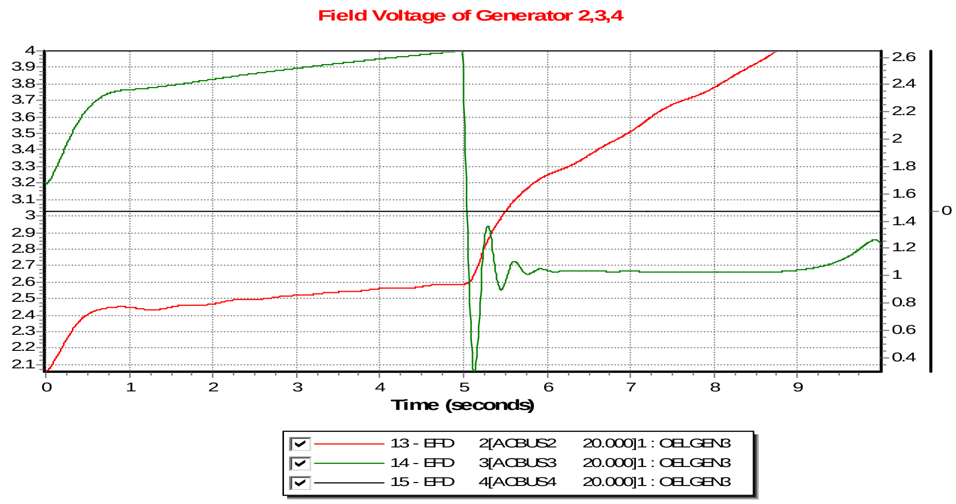


Figure 3-6: Field Voltage of Generator 2, 3, 4 with OEL on Generator 3 activated at time t = 5 sec.

From the simulation results shown below, we can see that the system voltages drop to even lower and eventually collapse much faster than the previous case (Figure 3-7).

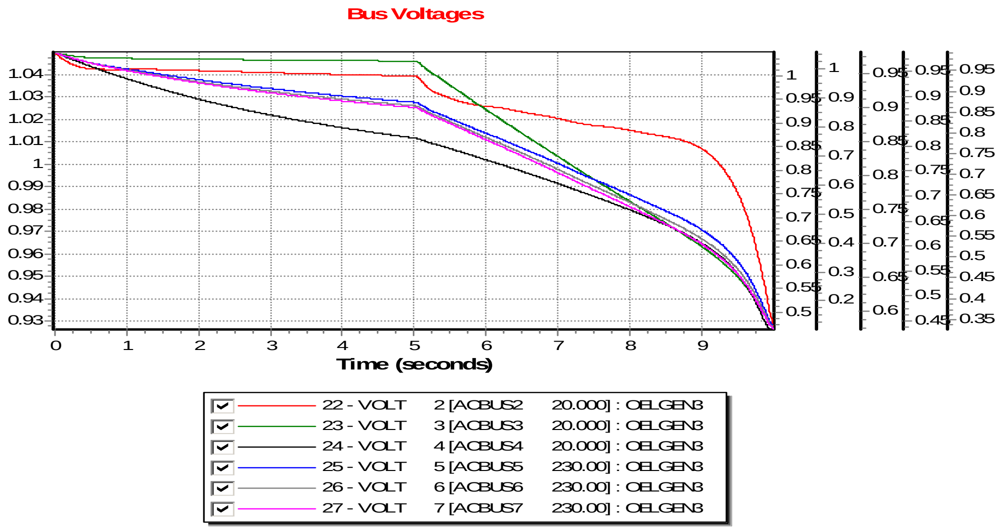


Figure III-7: Bus Voltages with OEL on Generator 3

Since Generator 3 cannot produce that large amount of reactive power as before, Generator 2 will try to match the mismatches. From the simulation, we can see that after 5 sec, reactive power output of generator 3 is decreasing. Reactive power output of generator 2 is increasing rapidly (Figure 3-8).

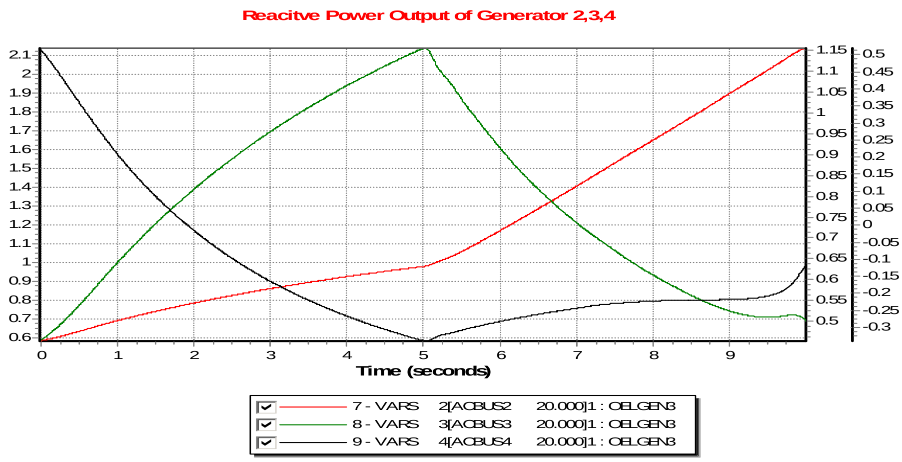


Figure 3-8: Reactive Power Output of Generator 2, 3, 4 with OEL

3.4 FULL LOF ON THE TWO-AREA SYSTEM WITH OEL AND INITIAL MW GENERATION OF LOF GENERATOR CHANGE

3.4.1 Decreasing initial MW generation of LOF generator

Now, we will examine how the initial MW loading of the LOF generator affects the system response due to LOF. Now, let us decrease Pg4 at generator 4 by 40% which means decrease it to 0.3pu with OEL on generator 3. From the simulation results, we can see that in the same time period as we did in the previous simulation the voltage declines is much less which means it helps the system in slowing down the voltage collapse (Figure 3-9).

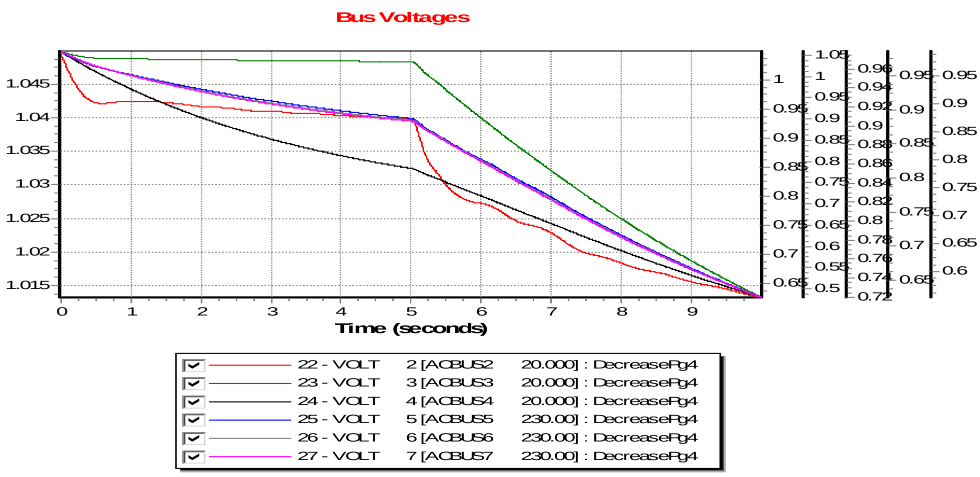


Figure 3-9: Bus Voltages when decreasing Pg4

Since the voltage declines lesser compared to higher MW loading, it means the reactive power absorbed by generator 4 will be lesser. Therefore, generator 2 and 3 reactive power output will also be lesser compare to the previous case (Figure 3-10).

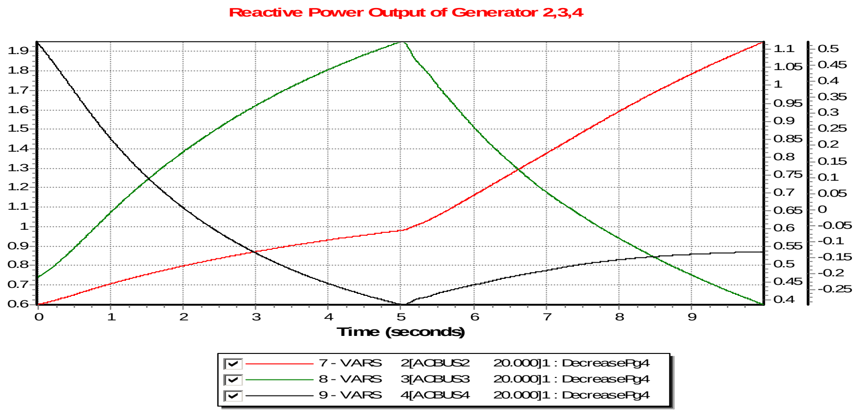


Figure 3-10: Reactive Power Output of Generator 2, 3, 4 when decreasing Pg4

3.4.2 Decreasing initial MW generation of LOF generator

When we decrease Pg4, it seems to help avoid voltage collapse. When we increase Pg4 by 50% which means increase Pg4 to 0.75 pu, it will make the LOF condition worse in that the reactive power demand of generator 4 is higher under LOF conditions, which means voltage declines will be faster than before. From the simulation results, we can verify that (Figure 3-11).

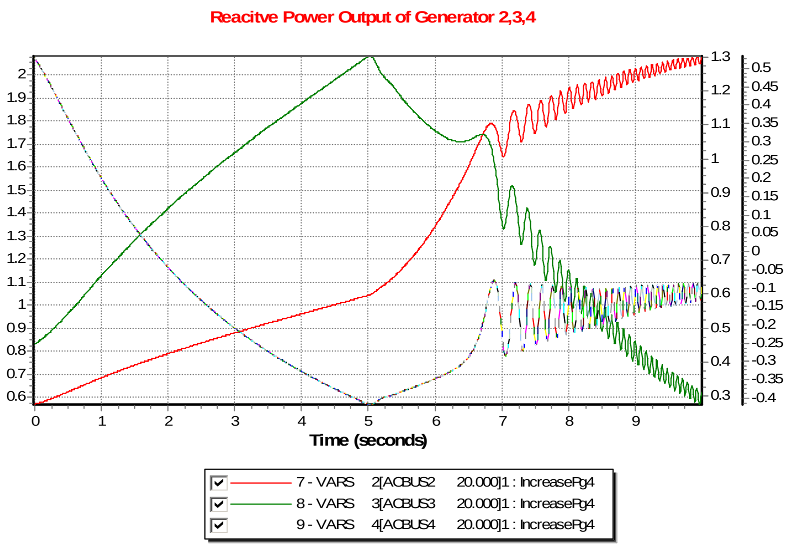


Figure 3-11: Reactive Power Output of Generator 2, 3, 4 when increasing Pg4

Also, since the voltage declines much faster, generator 4 will absorb more reactive power and generator 2 and 3 will produce more reactive power in a shorter time period (Figure 3-12).

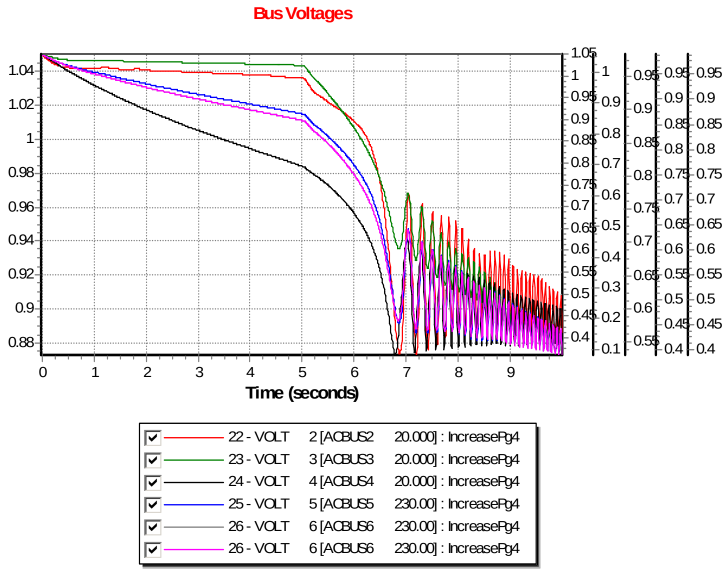


Figure 3-12: Bus Voltage when increasing Pg4

3.5 FULL LOF ON THE TWO-AREA SYSTEM WITH OEL AND ADDING SHUNT CAPACITOR AT LOF GENERATOR

From the previous simulations we can see that when LOF happens, the LOF generator mainly needs to absorb more reactive power. It means it changes from delivering Q to consuming Q. As we know, shunt capacitors can help to deal with this kind of situation because the capacitors can provide reactive power support and the system voltages may not decline as much. Since adding a shunt capacitor makes the generator initial reactive power output smaller, the generators do not need to produce that much of reactive power to support the LOF generator.

Let us add a shunt capacitor j0.46pu at generator 4 bus to see whether it can help the system to have more time before voltage collapse. From the simulation results, we can see that it actually helps the system to have more time before voltage collapse. It seems have the same effect as decreasing Pg4. The voltage declines are smaller (Figure 3-13) and the reactive power that generator 4 absorbs from the system is less due to the Q source which is the shunt capacitor (Figure 3-14).

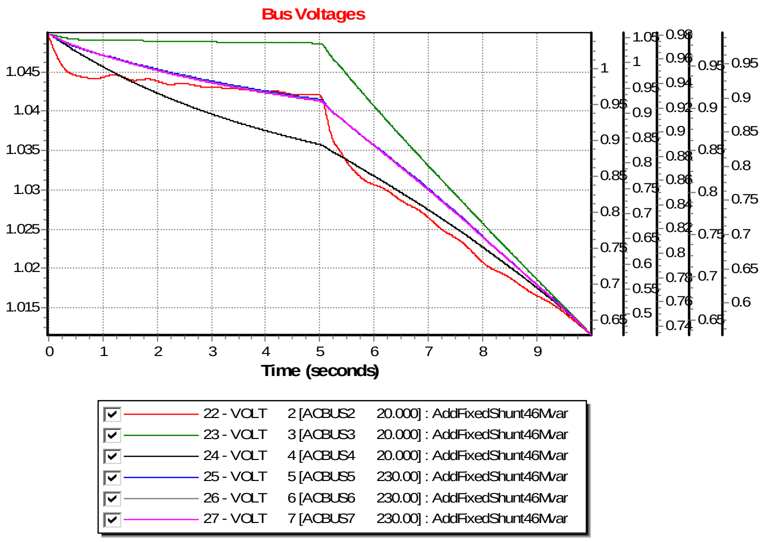


Figure 3-13: Bus Voltages with a shunt capacitor at bus 4

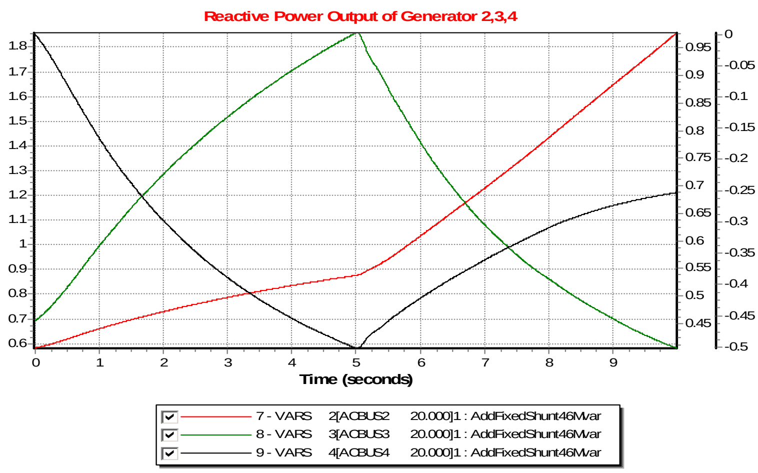


Figure 3-14: Reactive Power Output with a shunt capacitor at bus 4

3.6 PARTIAL LOF ON THE TWO-AREA SYSTEM WITHOUT OEL

So far, we have examined the sensitivities under a full LOF condition. Next we examine a partial LOF condition and how it impacts system performance. We will reduce Efd4 to 0.8pu (Figure 3-15).

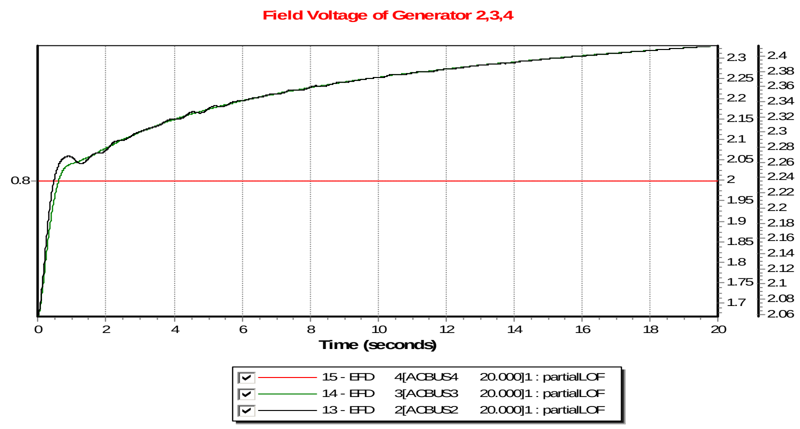


Figure 3-15: Field Voltage of Partial LOF

From the simulation results, we can see that the machine speed is still increasing and drawing large amount of reactive power from the rest of the power system (Figure 3-16).

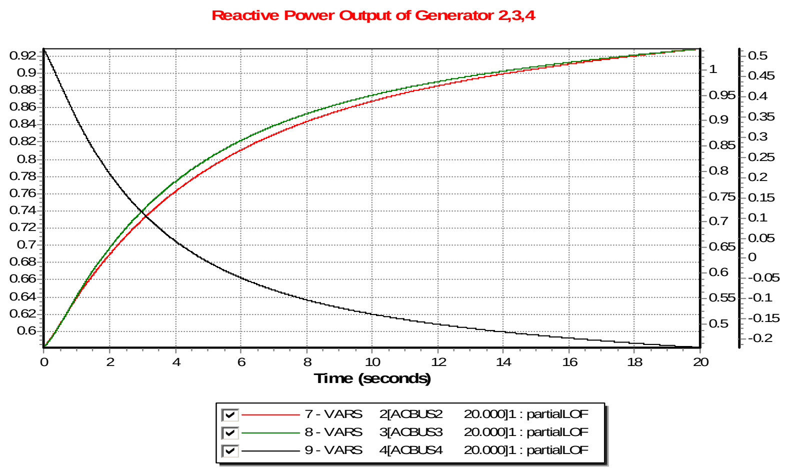


Figure 3-16: Reactive Power Output of Generator 2, 3, 4 of Partial LOF on Generator 4

However, the speed increases slowly compared to the full loss of field and the amount of reactive power absorbed by the machine is less. Even though the system looks more stable under partial LOF than full LOF, the voltages of the entire system still drop to some abnormal low value (Figure 3-17). If the LOF relay does not operate, eventually the system voltages will collapse.

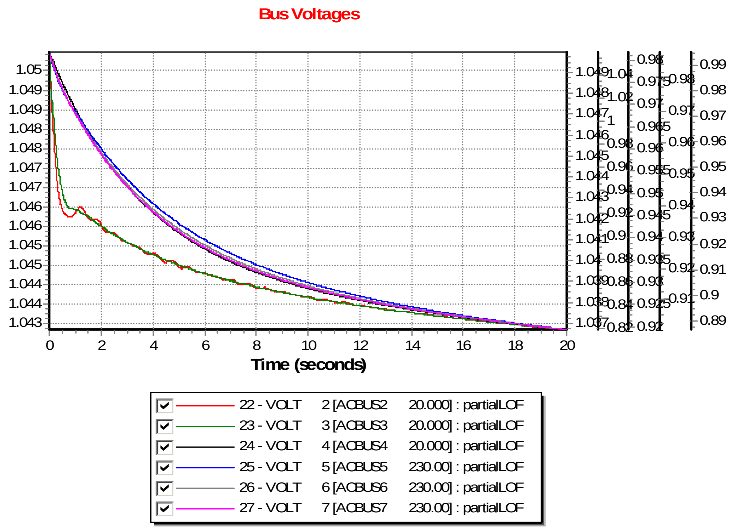


Figure 3-17: Bus Voltage under partial LOF on Generator 4

By comparing the full LOF and partial LOF simulations, we can see that system under partial LOF is more stable than the system under full LOF. This is as expected because when generator experiences a partial LOF, the amount of reactive power that the particular generator absorbs is less than under full LOF. Therefore, it does not depress the voltages of the rest of the system as much. The system voltages decline slowly, so the system will have more time before experiencing voltage collapse, which means LOF relays would have more time to correct the problem before voltage collapse happens.

3.7 TRIPPING THE LOF GENERATOR AT T=10 SECONDS

From all the above simulations we can see that if we left the LOF generator connect to the system, eventually the voltage may collapse depending on the current operating conditions. However, if we trip it before voltage collapse, a new question would be whether the system would recover to a stable state. Now, we will examine the response when the LOF generator is tripped at certain times under full LOF and partial LOF.

Under full LOF condition, when we trip the generator 4 at time t = 10 sec, we can see from the below simulation that the voltage can recover to a lower value (Figure 3-18), and the voltages will not collapse.

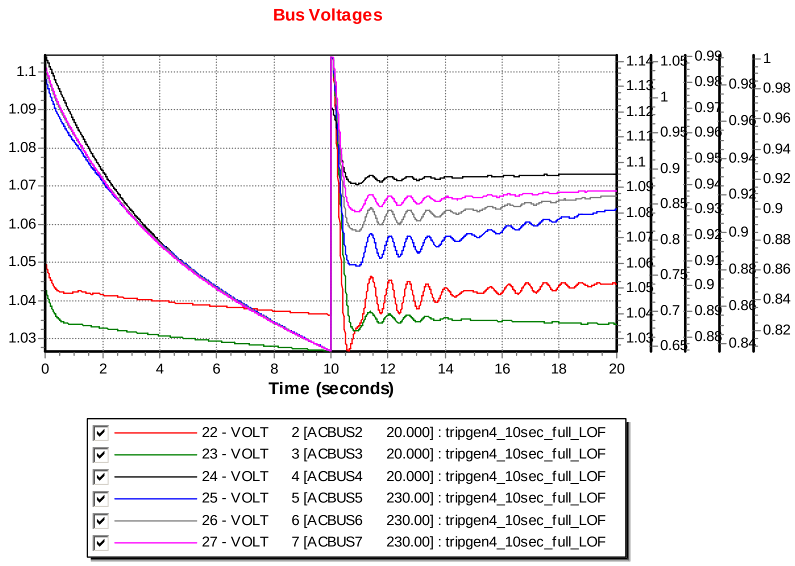


Figure 3-18: Bus Voltages when tripping the generator 4 at time t=10 seconds

Under partial LOF condition, when we trip the generator 4 at time t =10 sec, we can see that the voltage can recover to a lower value which means the system is stable (Figure 3-19).

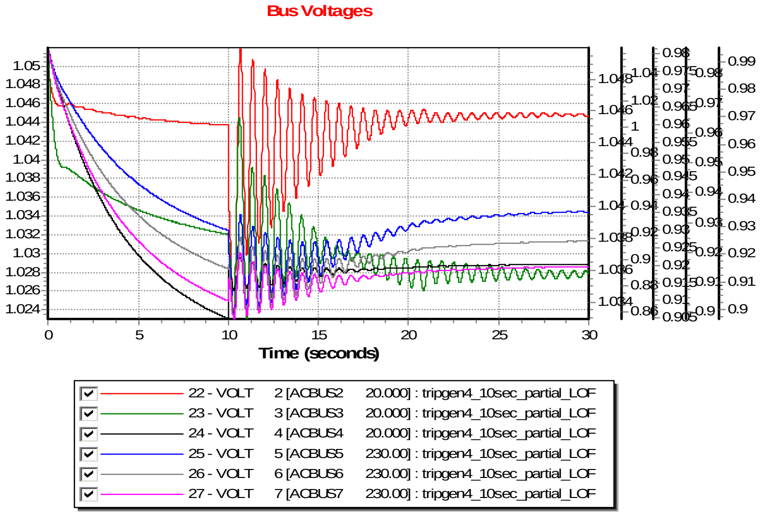


Figure 3-19: Bus Voltages when tripping generator 4 at time t = 10 seconds

3.8 CONCLUSIONS

From the PSS/E simulations performed, we can conclude that LOF conditions on a major generator can result in a local voltage collapse near the generator if the LOF generator is left connected to the system. The time that is available to trip the generator before voltage collapse depends on a few factors:

1) MW loading of the LOF generator (more MW implies less time before collapse).
2) MVAR support of neighboring system (more MVAR reserves implies more time before collapse).
3) Full or Partial loss of field on the generator (partial LOF implies more time than full LOF).
4) Field Overcurrent Limiter settings on neighboring generators (faster OEL settings imply less time before collapse).
5) Tripping time of the LOF generator.

In order to validate these observations, we will do some similar tests on a detailed eastern interconnection planning model in the next chapter.

CHAPTER 4 MODEL SIMULATION OF TVA LOF EVENTS

4.1 INTRODUCTION

From the two-area system LOF simulations, we know that the operating conditions of the system have a significant impact on how the full or partial LOF affects the system stability. Now, we will study how the Paradise LOF could impact TVA system stability if the LOF generator does not trip quickly enough. We will mainly focus on the November 29, 2007 case and try to duplicate the response after the partial LOF at PAF 3A which was recorded by the Cumberland PMU and area DFRs. Then for different of operating conditions near the Paradise 3 unit, we will study the response of the system due to LOF condition.

On November 29, 2007, the Paradise 3 unit was tripped due to a LOF condition on 3A machine. At the time of LOF, PAF 3 was generating just over 1000 MW. Over 25 seconds, the unit absorbed nearly 700 MVAR of reactive power. The LOF condition happens at time t = -4 sec. in the simulation time-plots. The simulations are carried out using a realistic 50,000 bus planning model of the eastern interconnection that is routinely used by TVA engineers. The simulations are carried out using the TSAT program.

4.2 PARTIAL LOF ON PAF 3A PLANT AND TRIP PAF 3 GENERATORS AT T=30 SECONDS

First, after simulating the TVA system under LOF conditions, we found out that the November 29, 2007 case was a partial LOF on the PAF 3A unit. The initial value of Efd of the PAF 3A unit is about 1.97pu. In TSAT, LOF happens at t=6sec in our simulations we decrease the Efd by 0.345pu and trip the generator at about t=30 sec in order to duplicate the November 29, 2007 case. From the simulation results, we can see that over about 25 sec., the PAF 3 units absorbed nearly 700 MVAR from the rest of the system which mainly from Davidson and Wilson (Figure 4-1). Large amount of reactive power flows from Davidson and Wilson to Montgomery, then from Montgomery to PAF units. It matches the PMU recordings well.

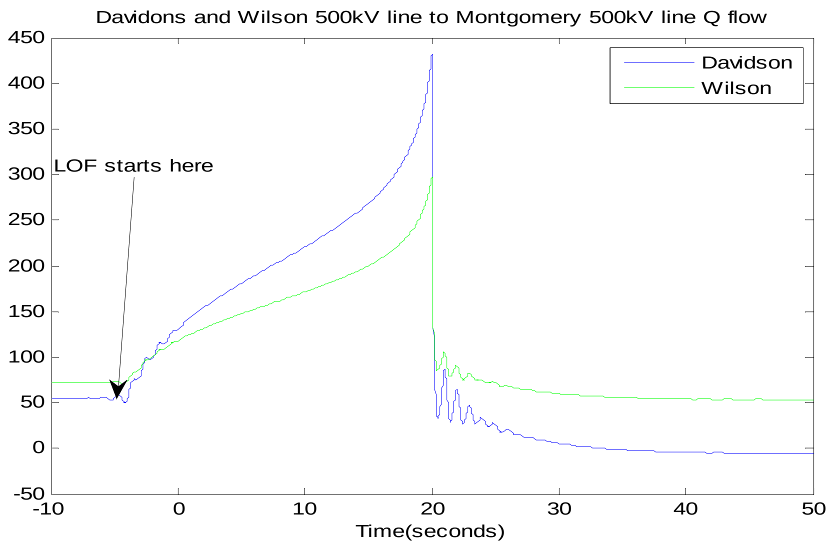


Figure 4-1: Davidson and Wilson to Montgomery Reactive Power Flow

Since Davidson and Wilson deliver large amount of reactive power to Montgomery, the bus voltages decline to abnormal low values (Figures 4-2). Specifically, we note that the Paradise 24 kV voltage has already declined to an abnormally low 0.75pu just prior to the PAF 3 tripping in the simulation (Figure 4-3). If the Paradise plant were not tripped from the system, the low voltage condition could spread to the 500 kV network and the system could have encountered a voltage collapse around Paradise and Montgomery 500 kV buses.

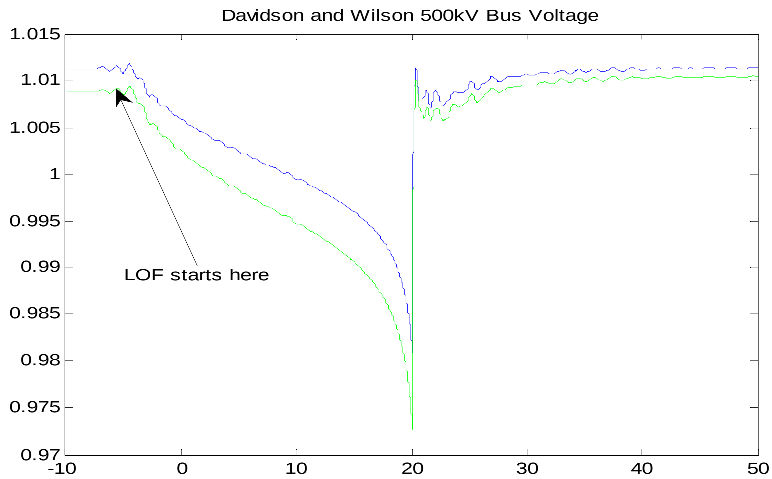


Figure 4-2: Davidson and Wilson 500kV Bus Voltage

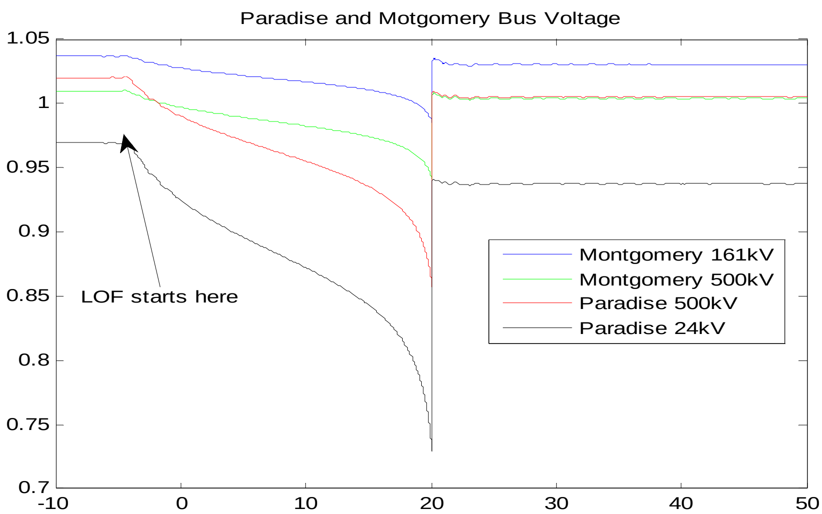
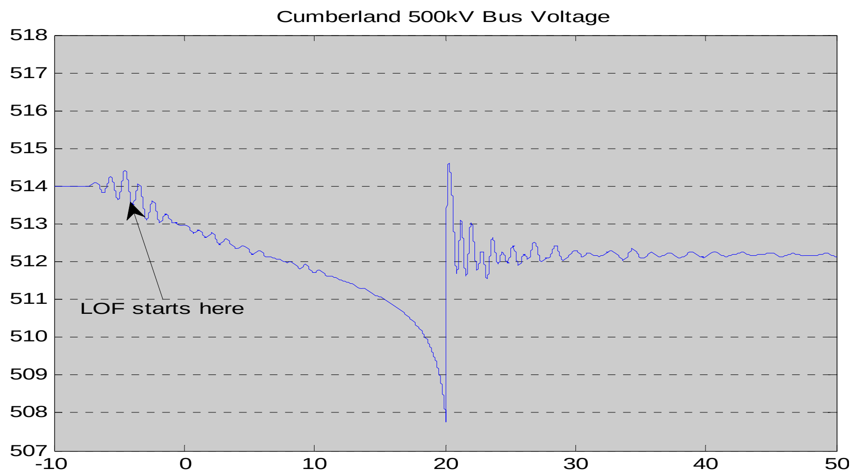


Figure 4-3: Montgomery and Paradise Bus Voltages

Comparing the PMU recording and TSAT simulation of Cumberland 500kV line bus voltage (Figure 4-4), we can see that the responses due to LOF are similar which means we have reasonably duplicated the November 29, 2007 case. The voltage drop of CUF 500kV line is about 6kV which matches the PMU recording.



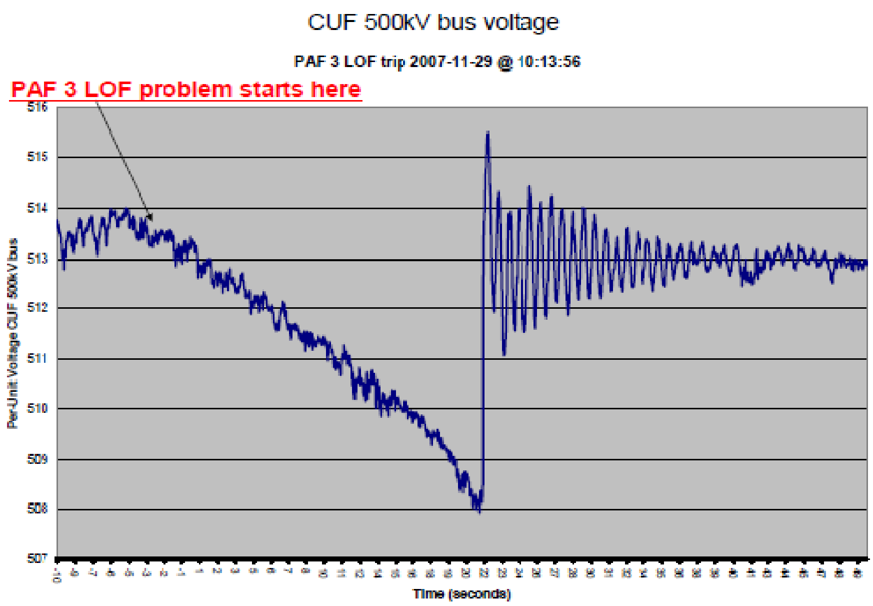


Figure 4-4: top-TSAT simulation of Cumberland 500kV line bus voltage vs. bottom-PMU recording

The CUF plant MW and MVAR simulated responses which damped out in about 25 sec (Figures 4-5 and 4-6) also match the PMU recording. However, there is about 300 MW generation difference, because the power-flow data we have used is somewhat different from the conditions during the November 29, 2007 event. Also, it appears that the planning model shows a somewhat better damped response of the local Cumberland plant mode whereas the actual PMU recording shows poorly damped MW oscillations.

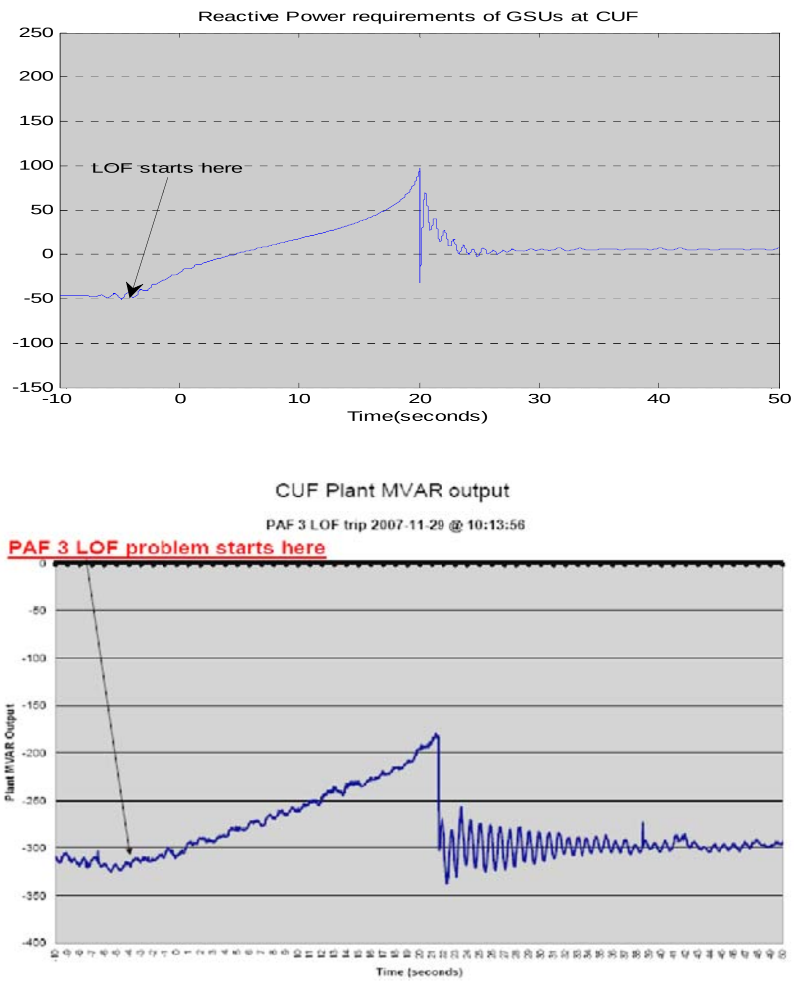


Figure 4-5: top-TSAT simulation of Cumberland plant Reactive Power Output vs. bottom-PMU recording

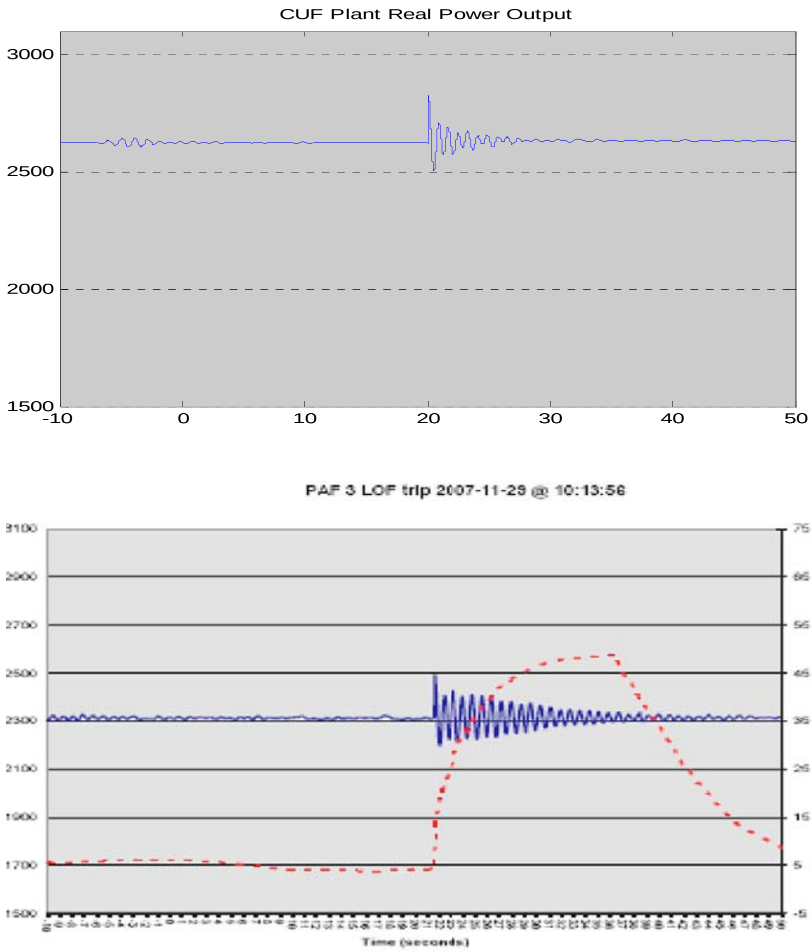


Figure 4-6: top-TSAT simulation of CUF plant Real Power Output vs. bottom-PMU recording

From the two-area studies, we know that after LOF happens, the system bus voltages will decline rapidly. If the LOF condition lasts too long, the system may not recover to normal operating condition which means voltage may collapse. So far, from the previous simulations we notice that the system is stable after we trip the generator. However, due to LOF condition, the nearby bus voltages decline to abnormal values. North Nashville and Springfield 161 kV line bus voltages decline to about 1.0 pu prior to the trip which matches the DFR recordings (Figure 4-7).

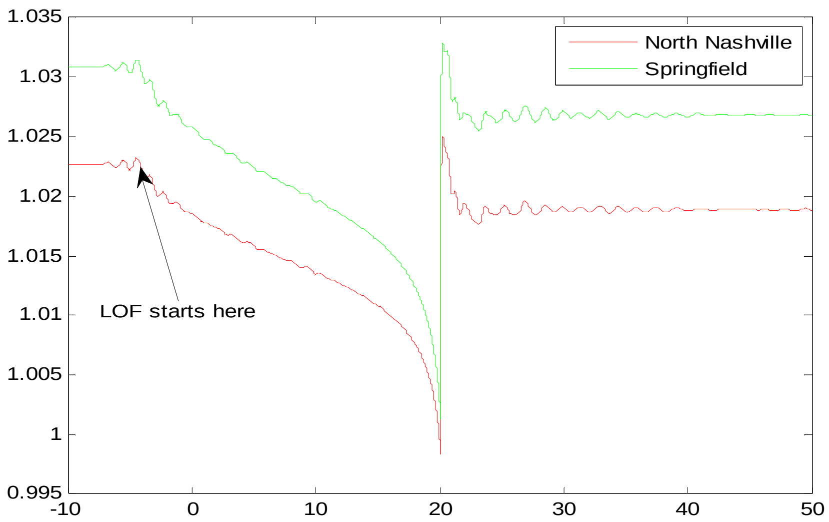


Figure 4-7: TSAT simulation of North Nashville and Springfield 161kV line Bus Voltage

There may be question about why it took the LOF relays so long to detect and correct this LOF problem. Since there is a malfunction on the MEL of the PAF 3 generators and the protection scheme of this plant is old which can refer back to the 60's. From Figure 4-8 and 4-9, we can see that the relays operate correctly from the impedance trajectories. The impedance trajectory of Paradise 3A plant (Figure 4-8) clearly shows that it enters the MHO circle at 22.7 seconds. With a preset time delay to operate the relay, it actually takes a long time to detect and correct the LOF problem. From Figure 4-9, we can see that the impedance trajectory never enters the MHO circle which is correct because there is no LOF problem at Paradise 3B plant.

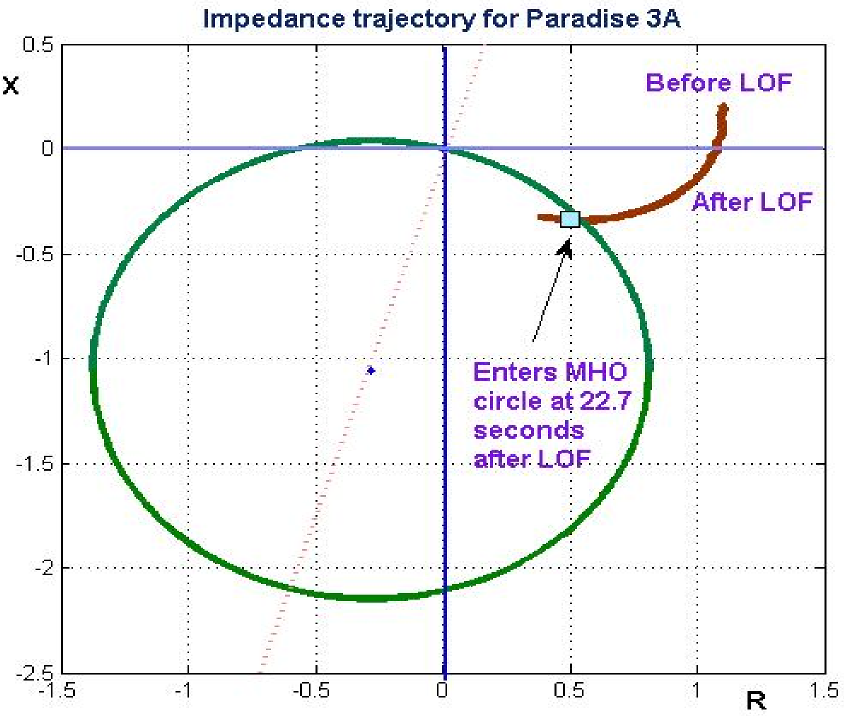


Figure 4-8: Impedance Trajectory for Paradise 3A Plant

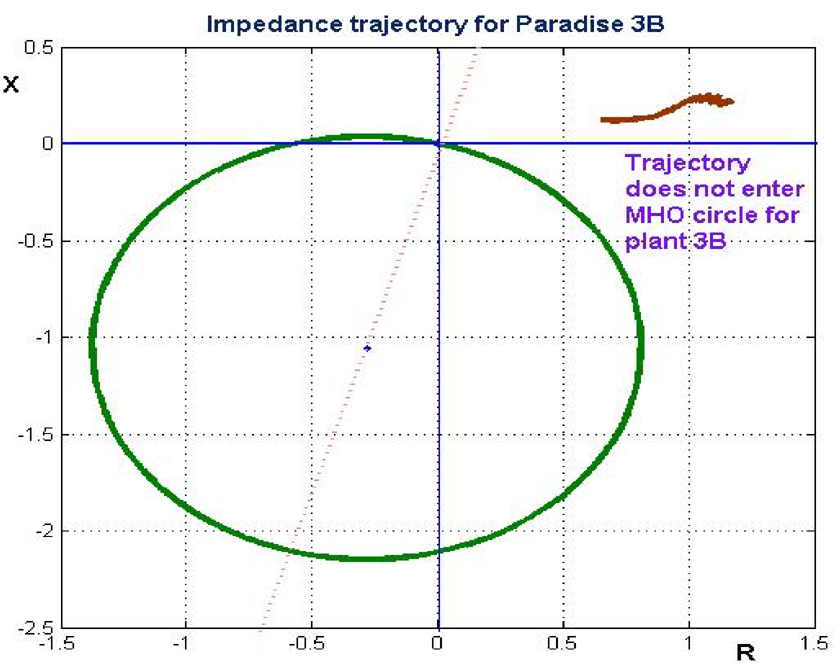


Figure 4-9: Impedance Trajectory for Paradise 3B Plant

From the above simulations, we can conclude that we have reasonably duplicated the November 29, 2007 LOF case because the TSAT simulations match well with available PMU and DFR recordings. Fortunately, LOF relays operated correctly for this event which tripped the LOF generator on time. If the LOF relay does not sense the LOF condition or operates more slowly, what may happen to the system need to be studied.

4.3 PARTIAL LOF ON PAF 3A PLANT WITHOUT TRIPPING PAF 3 GENERATORS

Now, under the same condition as above, suppose the generator relay did not trip the Paradise 3 generators. We will see that the system voltages will collapse at about 30.7 sec. In this simulation model, if the LOF tripping had been slowed by a few seconds beyond when the generator was actually tripped during the event, the LOF conditions could have resulted in a voltage collapse near the Paradise plant. The Cumberland plant reactive power output is even higher (Figure 4-10) which means the bus voltage of CUF 500kV line will be even lower (Figure 4-11).

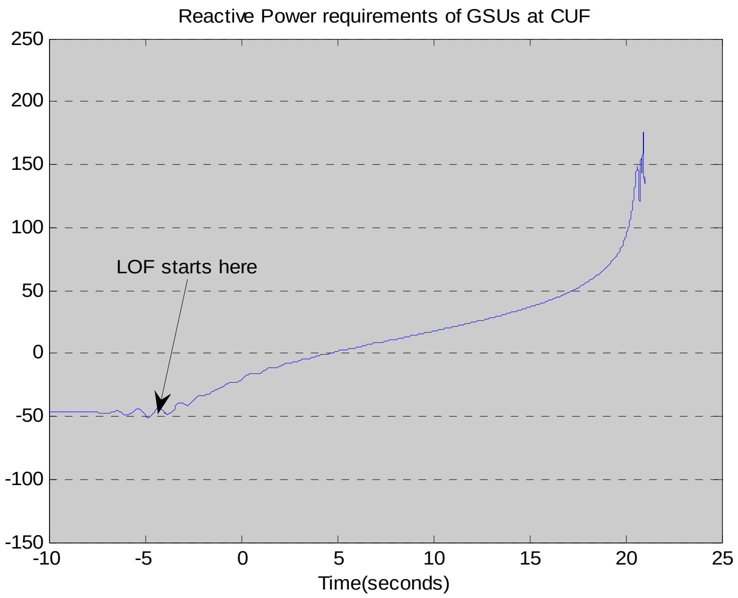


Figure 4-10: CUF plant Reactive Power Output without tripping the PAF 3A generator

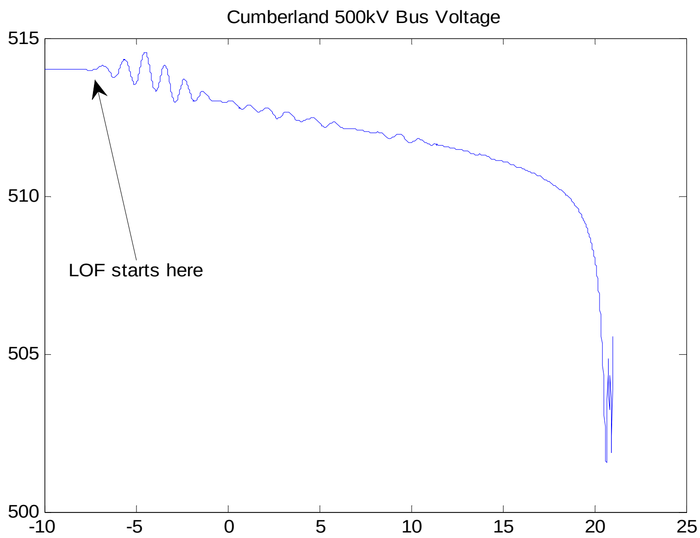


Figure 4-11: CUF 500kV line Bus Voltage without tripping PAF 3A generator

Since the LOF condition lasts longer, the nearby bus voltages will drop to even lower values (Figure 4-12). Specifically, the Paradise 24 kV voltage has collapsed to near 0.5pu in the TSAT simulation and the neighboring bus voltages also begin to collapse to abnormal values. At this point, the simulation tool TSAT fails to continue to solve the power-flow solutions. In reality, the behavior of loads and protection devices under such abnormally low voltages becomes unknown in our model based simulation. We can only conclude that the system conditions are nearing voltage collapse around Paradise bus.

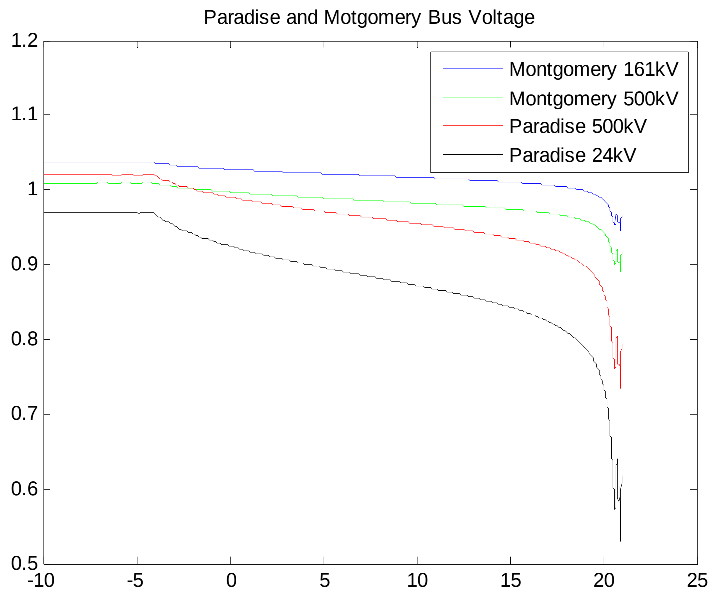


Figure 4-12: Montgomery and Paradise Bus Voltages

During the November 29, 2007 TVA event, if the PAF 3 plant was tripped by the relays at about +20 seconds in Figure 4-12. This TSAT model based simulation shows that if the PAF 3 tripping had been slowed by even a few seconds, the TVA system may have faced the danger of voltage collapse near the Paradise 500 kV part of the system.

This means that LOF condition on critical generators has to be detected as soon as possible in order to prevent damage to the generator itself and/or to the system stability. As we know, the time that available for the relay to operate correctly of the LOF problem is really important. Therefore, we will change the various operating conditions of the system to see how the system response changes under different conditions.

4.4 PARTIAL LOF ON PAF 3A PLANT---EFD DECREASES BY 1PU

First, we decrease Efd by 1pu which is a higher partial LOF. From the Two-Area system studies, we can obviously know that the system will collapse faster if we do not trip LOF generator soon enough. The CUF plant MVAR output is even higher during a small period of time which is about 5sec prior to the system oscillation (Figure 4-13).

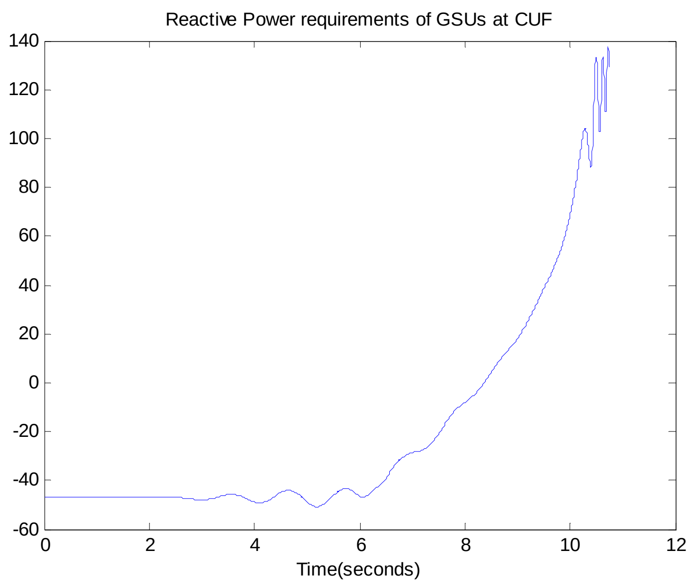


Figure 4-13: CUF plant Reactive Power Output without tripping the PAF 3A generator and decrease Efd by 1pu

Also, we can see that over this small period of time, the CUF 500kV line bus voltage also drops a lot (Figure 4-14). The major nearby bus voltages also drop to abnormal low value very shortly (Figure 4-15).

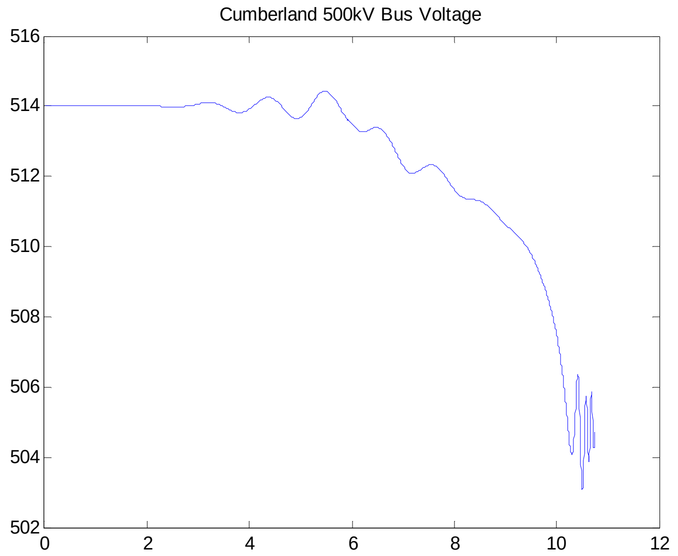


Figure 4-14: CUF 500kV line Bus Voltage without tripping the PAF 3A generator and decrease Efd by 1pu

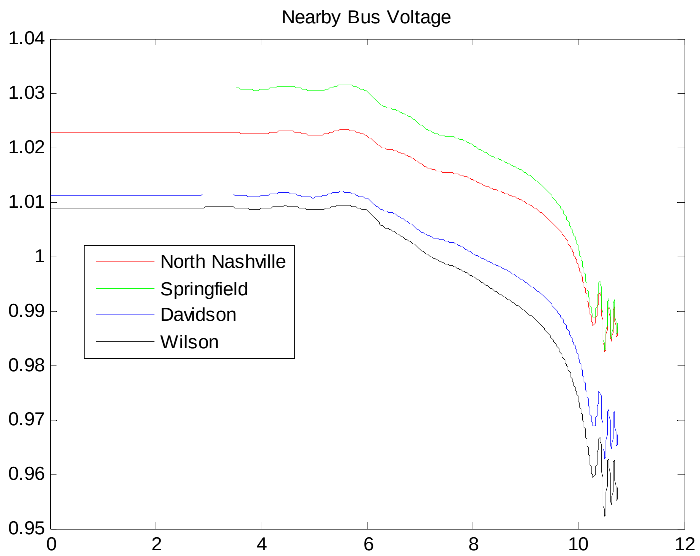


Figure 4-15: Major Nearby Bus Voltages

4.5 FULL LOF ON PAF 3A PLANT---EFD DECREASES BY 1.97PU

Compare the value of Efd we decreased, it is a really small amount. What the consequences are if full LOF happens at PAF 3A unit. From the two-area system simulations, we can know that the PAF 3 unit still draws large amount of reactive power from the system, but in a much less period of time which means the system voltage collapses more quickly.

From the simulation results, we can see that it only takes CUF 500kV line about 2 seconds to absorb the same amount of reactive power from the system (Figure 4-16), which means the bus voltage of CUF 500kV line will decline much faster than November 29,2007 case (Figure 4-17).

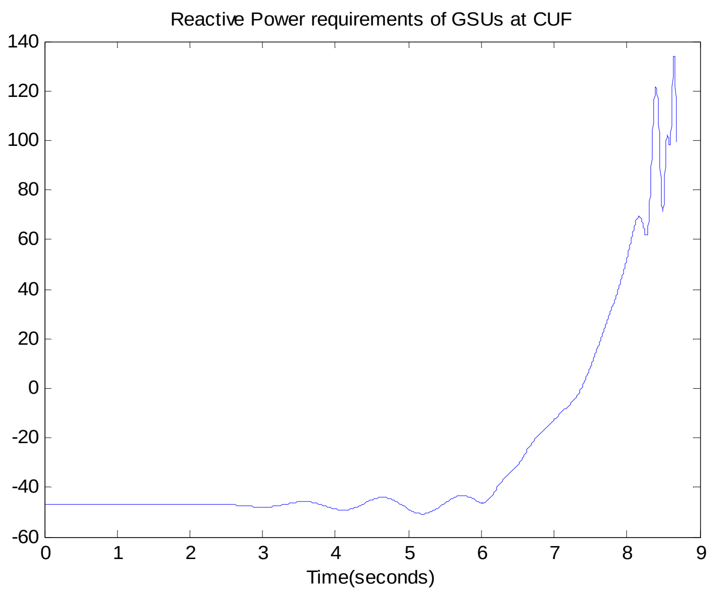


Figure 4-16: CUF 500kV line Reactive Power without tripping the PAF 3A generator and Full LOF

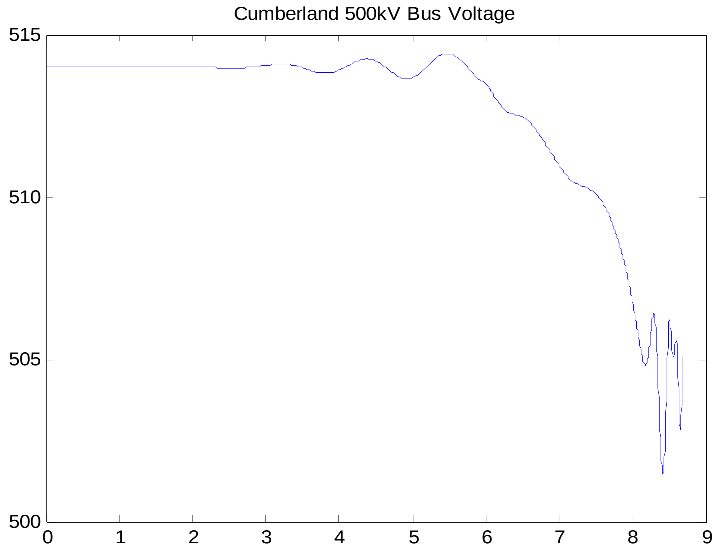


Figure 4-17: CUF 500kV line Bus Voltage under Full LOF

The major nearby bus voltages drop much faster than any other case before (Figure 4-18).

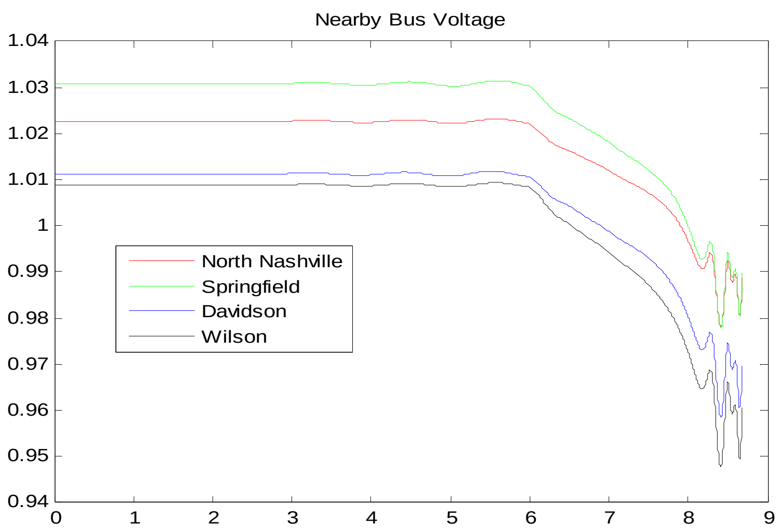


Figure 4-18: Nearby Bus Voltages under Full LOF

From the above simulations, we can see that partial or full LOF has a much different system responses. System under partial LOF has more time before system collapse than full LOF. Therefore, under LOF condition, it is better to first detect whether it is a partial or full LOF, then we will know how much time we probably have in order to correct the LOF problem.

There are some other factors that will affect the system responses due to LOF. As we seen in the Two-Area system, the schedules MW output of the LOF generator also affect the time that available before system collapse.

4.6 PARTIAL LOF ON PAF 3A PLANT WITH INITIAL MW GENERATION DECREASING

Since the MW output of PAF 3A plant is almost at its maximum capacity, so we will only decrease the scheduled MW output to see how the system responses to LOF. As we know, partial and full LOF has similar system responses, therefore, we will only examine this under partial LOF as the pervious TVA case (November 29, 2007).

We will decrease MW output of PAF 3A by 50% which means decrease it by 264.85 MW. From the simulation results, we can see that under the same partial LOF condition, the system response is much different. Even though partial LOF happens, the system is stable. The CUF 500kV line MVAR is decreasing (Figure 4-19) which implies the bus voltage is decreasing to a higher abnormal value than the previous case (Figure 4-20). CUF 500kV line bus voltage settles down to 512.8kV and stabilizes.

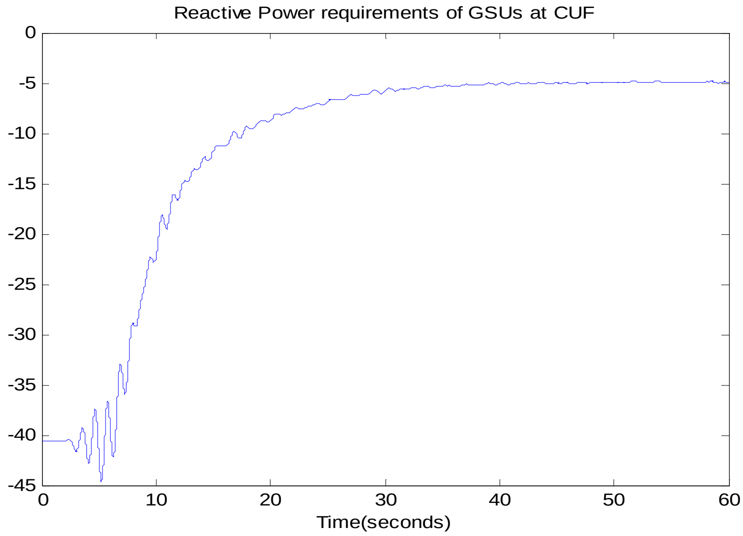


Figure 4-19: CUF 500kV Line Reactive Power

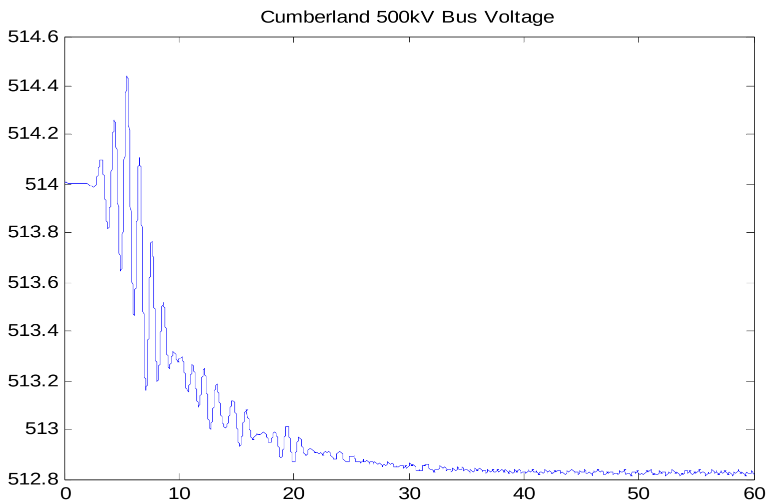


Figure 4-20: CUF 500kV Line Bus Voltage when changing Pg of PAF 3A under partial LOF condition

The Major nearby bus voltages also decrease to a higher abnormal value and then stabilize (Figure 4-21).

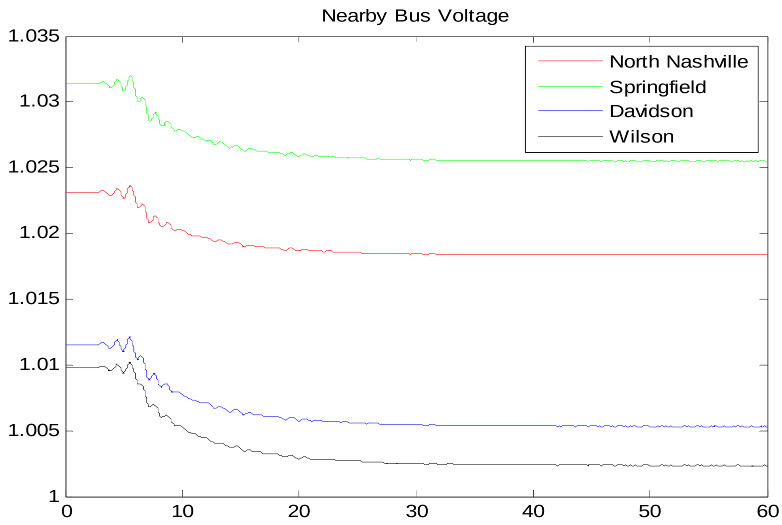


Figure 4-21: Nearby Bus Voltages when changing Pg of PAF 3A under partial LOF condition

From above simulations, we can see that decreasing the LOF plant's generation will give the LOF relay more time before the system collapses. But even though the system seems stable, the buses voltages are at lower than nominal values. For this specific generator loading, the protection may not have to interfere and the operators will have time to correct the problem.

4.7 Conclusions

From the simulation results, we can see that we successfully duplicate the November 29, 2007 Lof event using a detailed eastern interconnection planning model. We can see that the same key factors as we found in the two-area system study impact on the response of the system after LOF condition, such as:

1) MW loading of the LOF generator (more MW implies less time before collapse).
2) MVAR support of neighboring system (more MVAR reserves implies more time before collapse).
3) Full or Partial loss of field on the generator (partial LOF implies more time than full LOF).
4) Tripping time of the LOF generator.
5) Field Overcurrent Limiter settings on neighboring generators (faster OEL settings imply less time before collapse).

Therefore, full or partial LOF on a synchronous generator can harm both the LOF generator and the neighboring power system if it left connected to the system. This means that the LOF condition should be detected as quickly as possible and the LOF generator should be isolated from the system as soon as possible in order to prevent damage to the generator itself and to the rest of the power system.

CHAPTER 5 BACK-UP PROTECTION FOR LOF EVENTS BASED ON TERMINAL MEASUREMENTS

5.1 INTRODUCTION

From the studies we did about the three Loss of Field events at the Paradise Fossil plant, we recognized that if the LOF relay of the Paradise generator operated slowly or incorrectly, LOF condition can drag down the system voltage very fast and can jeopardize the stability of the rest of the power system. Even though the LOF relays operated correctly in all three events, the potential failure or slow operation of the LOF relays can still be problematic for the system stability. For that reason, we propose a back-up protection scheme for such a generator using synchrophasors, which could trip the generator under LOF condition by observing the reactive power flow measurements on the 500kV transmission line from Montgomery to Paradise.

Traditionally, the loss-of-field protection will use negative-offset mho elements, positive-offset mho elements or two-zone with positive/negative-offset mho elements. Since modern generators have large reactance, the positive/negative-offset, two-zone loss-of-field scheme (Figure 5-1) is typically used [3]. However, in Figure 5-2 [3], we can see that the relay characteristic is inside the capability curve which resulted in an unprotected region between relay characteristic and the capability curve of the generator. If a partial loss-of-field result in an impedance value that stays in that region long enough, the generator is not protected under this condition and may damage the generator and the system stability [3].

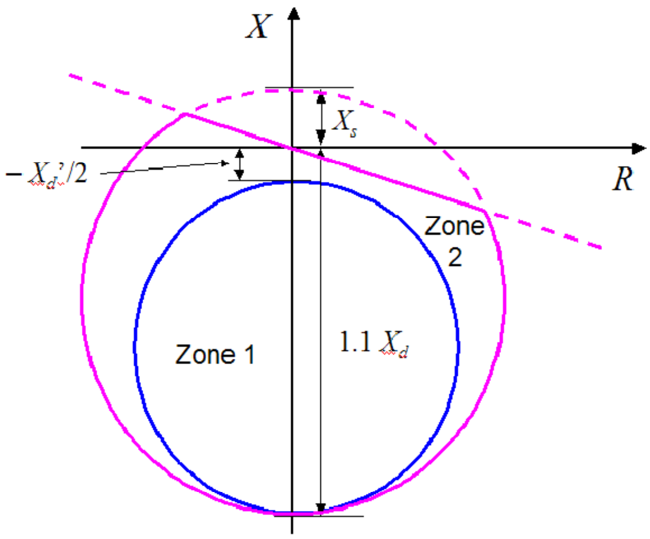


Figure 5-1: Two-zone LOF protection using positive- and negative-offset mho elements supervised by a directional element [3]

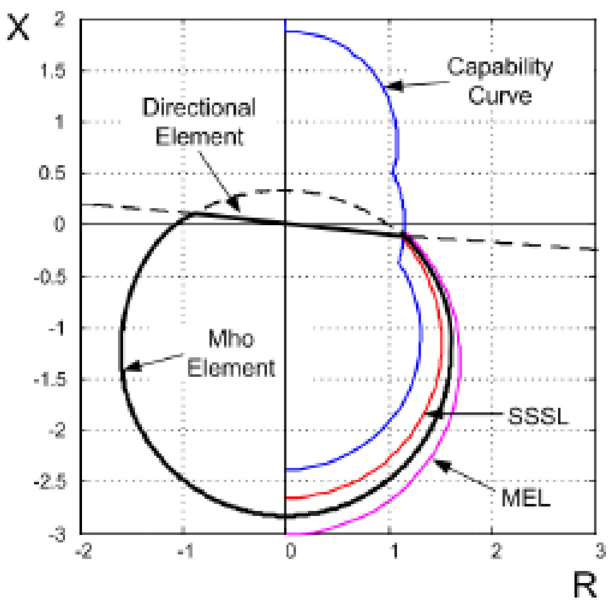


Figure 5-2: Impedance-plane representation of generator capability curve, MEL, SSSL, and LOF characteristic [3]

For the reason mentioned above, a P-Q curve based protection scheme will be introduced. The relay operating region is shown in Figure 5-3 [3]. Instead of using the true generator capability curve, we will use a setting which is found using P-Q and Q-V curve studies to approximate a new capability curve. We will use this curve to do the LOF protection for the generator.

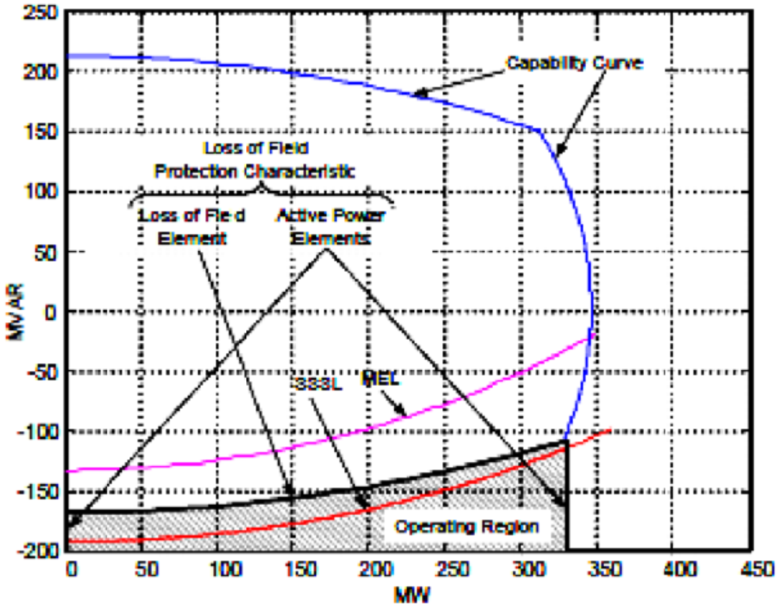


Figure 5-3: LOF element characteristic in the P-Q plane [3]

5.2 PROPOSED BACK-UP PROTECTION SCHEME [19]

Since TVA recently installed a PMU at Montgomery 500kV bus, we can monitor the real and reactive power-flows on the Montgomery to Paradise 500kV line to design the proposed back-up protection for the Paradise plant. The LOF is typically characterized by high MW flow out of the generator with large Q flow into the generator.

An inverse time-characteristic logic on the reverse Q flow into the plant (above a preset threshold) under high MW flow out of the plant is suggested.

We define real power flow (MW) from Montgomery to Paradise, and reactive power flow (MVAR) from Montgomery to Paradise. Both MW and MVAR flows on the Montgomery to Paradise 500kV line are available at Montgomery 500kV bus using PMU measurements. We want to look for high values of MW together with persistently large values of Q in real-time from synchrophasors to denote LOF condition and take appropriate action to prevent it. Reset logic is needed in order to prevent false tripping under stable system swings. Accordingly, tripping can be made slower under partial LOF conditions by encoding an inverse time characteristic on the trigger logic. The LOF back-up protection scheme is shown in Figure 5-4 below.

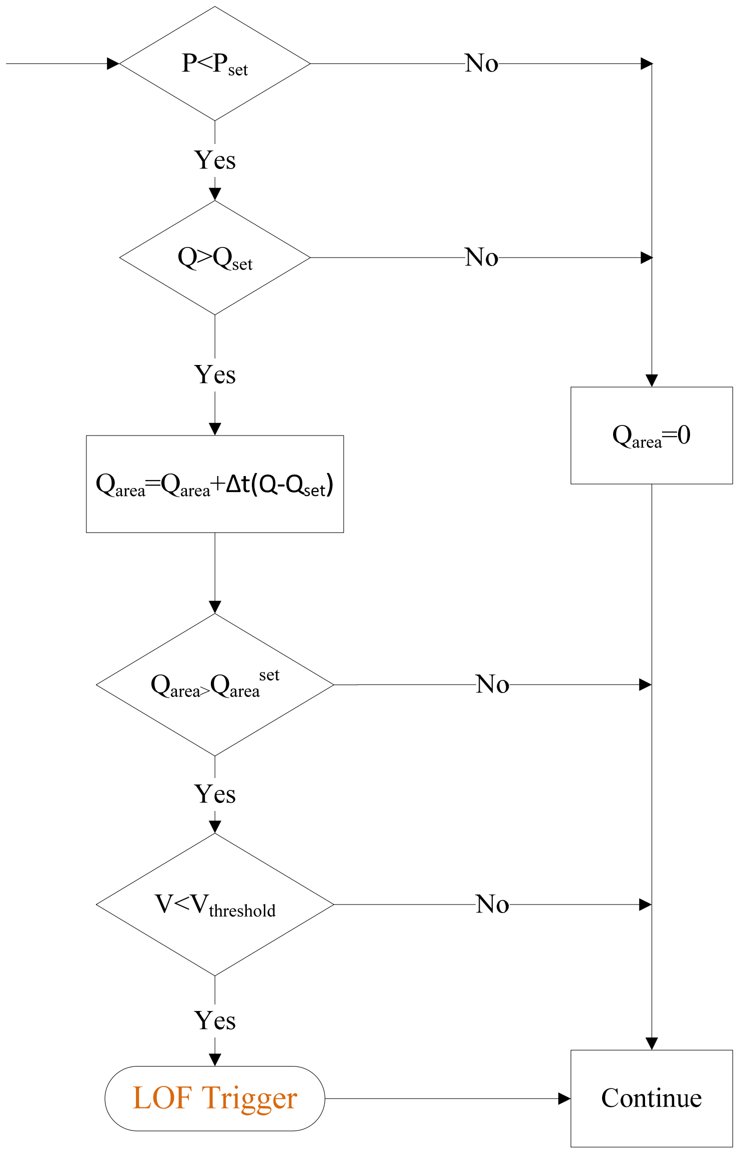


Figure 5-4: PMU Based Back-up Protection Scheme Logic

In order that the back-up protection scheme works correctly and quickly, several settings need to be tuned.

1) P_{set} = Min MW generation setting to enable LOF back-up protection (say 500 MW)
2) Q_{set} = Min reverse Q flow into plant to denote LOF conditions (say -200 MVAR)
3) Q_{area}^{set} = Min accumulated area of MVAR-seconds to issue LOF trigger (say 500 MVAR-sec.). The settings can be tuned to adjust the speed of the LOF trigger logic.
4) $V_{threshold}$ = Voltage threshold at Montgomery 500kV bus to issue LOF trigger

From the sensitivity studies we did for the TVA system on LOF conditions, we want to set a reasonable threshold in order to trigger the back-up protection at the right time. We can just set the Q threshold to be 200MVAR to denote LOF condition. With Q_{set} = 200 MVAR, Q_{area}^{set} can be chosen as say 500 MVAR-sec in order to trigger the back-up protection as discussed below.

Table 5-1: Accumulated Q Area for Montgomery to Paradise 500kV line

Scenario description	MVAR-sec
Partial LOF： Efd decreases by 0.345pu	1826.7
Partial LOF： Efd decreases by 0.345pu, no trip	2315.4
Partial LOF: Efd decreases by 1pu	587.46
Full LOF: Efd decreases by 1.97pu	542.89
Partial LOF: Decrease Pg of LOF Generator	0
Partial LOF: Decrease Load of LOF Generator	2472.5
Partial LOF: Increase Load of LOF Generator	2187.3

From Table 5-1, we can see that if the accumulated area is too small for any event, then it will not trigger the back-up protection. If the accumulated area is large enough, then we have to select the best value in order for the back-up protection working for all possible cases. Therefore, if we choose the threshold to be 90% of the smallest accumulated area among cases where we want to trigger the protection, then the threshold Q_{area}^{set} can be chosen as say 542.89*90%=488.6≈500MVAR-sec.

From Table 5-2, we can verify that the settings we chose works for all possible LOF conditions at the Paradise plant. With voltage threshold at Montgomery 500kV bus also included, the back-up protection scheme is triggered correctly in all cases.

Table 5-2: Accumulated Q Area and Trigger Logic

Scenario description	MVAR-sec	ALARM
Partial LOF： Efd decreases by 0.345pu	500.11	Trigger
Partial LOF： Efd decreases by 0.345pu, no trip	500.44	Trigger
Partial LOF: Efd decreases by 1pu	500.93	Trigger
Full LOF: Efd decreases by 1.97pu	502.14	Trigger
Partial LOF: Decrease Pg of LOF Generator	0	No
Partial LOF: Decrease Load of LOF Generator	500.25	Trigger
Partial LOF: Increase Load of LOF Generator	500.64	Trigger

Since we have a LOF protection relay at both the Paradise units, and then compare the back-up protection scheme we proposed to the actual LOF relay, we can see that our proposed back-up protection scheme works faster than the actual LOF relay in case of slow or malfunction of the relay. From Table 5-3 below, we can see that the time which takes our proposed back-up protection is much less than the time that the relay operates.

Table 5-3: Comparison of the response time of the proposed back-up protection vs. original LOF relay

	Time (s)	Time (s)
Scenario description	Proposed protection	acutal LOF relay
Partial LOF： Efd decreases by 0.345pu	14.7958	22.7
Partial LOF： Efd decreases by 0.345pu, no trip	14.8	22.7
Partial LOF: Efd decreases by 1pu	2.35	3.336
Full LOF: Efd decreases by 1.97pu	1.276	1.522
Partial LOF: Decrease Pg of LOF Generator	N/A	N/A
Partial LOF: Decrease Load of LOF Generator	15.6792	24.9609
Partial LOF: Increase Load of LOF Generator	11.5792	16.6754

Based on the above results, we can see that the settings recommended appears to be reasonable for the back-up protection of Montgomery to Paradise 500kV line for LOF condition at one of the Paradise 3 units. Also, the proposed back-up protection works much faster than the original LOF relay in case of slow or incorrect operation of the LOF relay. It is being implemented at TVA using the recommended settings we did now. Since all the settings can be tuned, there may be some other better settings than the recommended one depends on how well we want this back-up protection to be.

5.3 BACK-UP PROTECTION BASED ON TERMINAL MEASUREMENTS

5.3.1 METHODOLOGY

Since the traditional LOF relay protection schemes may not operate correctly as we mentioned in the introduction, we will propose a new back-up protection scheme which will be based on a kind of generator capability curve. Like in Figure 5-3, the relay operating zone depends on how we set the LOF element's characteristics. The relay will operate when the generator operating point in the P-Q curve falls inside the relay operating region, the scheme issues an alarm signal and initiates delayed generator tripping [3].

Our proposed back-up protection scheme will be similar to this scheme. Our proposed method is an extension of the PQ plane method in [3]. For our approach, the instability boundaries are determined in the context of system voltage stability rather than the local synchronous stability of the machine itself which was the approach in [3]. We will use the TSAT program to find the reactive power limit of the generator under LOF condition first. Then, the Q-V curve calculation will be performed to find the Q margin.

Compare the reactive power limit and the Q margin, we will have a rule of how to set the appropriate percentage of the Q margin to initiate generator tripping signal using least square estimation. A delay may also be included. The basic methodology will be based on several off-line studies. The back-up protection scheme is shown in Figure 5-5.

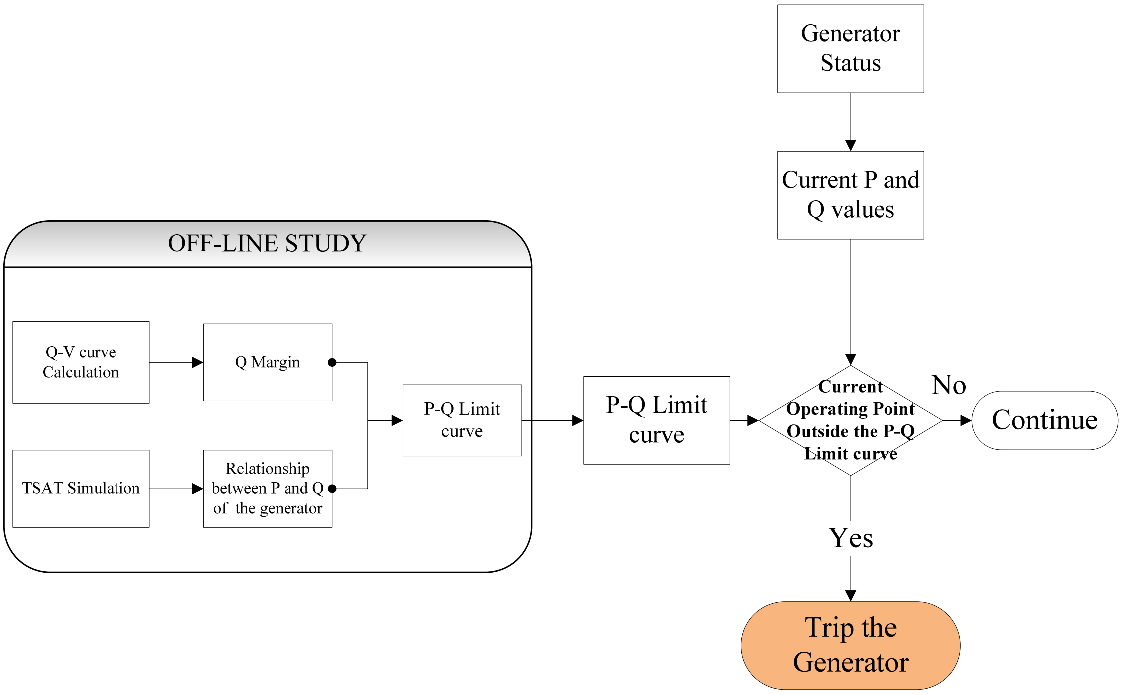


Figure 5-5: Back-up Protection Scheme based on terminal measurement

First, we will use the TSAT program to perform Q_G limit calculation. One minute simulation is done in TSAT. Under different real power output conditions of the generator, when LOF happens, the reactive power absorbed by the generator cannot be infinite. We want to find this limit first in order to set our proposed back-up protection scheme. The criteria we use is that when we perform the simulation under different LOF conditions at a specified real power output, the critical point we want is the reactive power should reach a steady-state value after the disturbance which we denote as the Q_G limit. It means if we further decrease the Efd a little bit, the reactive power output of the generator cannot reach a steady-state value during our one minute simulation.

Then, we will perform the Q-V curve study. Since the Paradise units are of cross-compound design, when we did the Q-V curve study, we put both units off-line. The MW and MVAR outputs will be treated as additional load to the existing load. Once we did this, the Q-V curve can be easily obtained by increasing the load at Paradise until the power-flow diverges. For the other generators we chose to study, we did not need to put all the units at one bus off-line because they are not cross-compound. For a particular generator, we just put the generator under study off-line. The MW and MVAR outputs at this generator will be added to the existing load. Once we did this, the Q-V curve can be easily obtained by increasing the load at this particular generator bus until the power-flow diverges. After obtaining the Q-V curve, the Q margin at certain studied bus can be obtained which will be the largest Q value that the power-flow can still be solved.

After the calculations are done, we will have the information about the reactive power limit of the generator after LOF at different real power output levels. Then compare the Q_G limit with the Q margin obtained in the first step, we will be able to set a reasonable threshold to denote severe LOF condition using least square estimation, which means the generator has to be tripped at this point.

5.3.2 Q_G LIMIT SETTING

Using the procedures we mentioned in section 5.3.1, we did TSAT and PSAT simulations in order to find the Q_G limit and Q margin under different real power output conditions. In order to find the Q_G limit at a specific real power output, we have to run several TSAT simulations. From Figure 5-6 which is the base case with Pg at 100% of the maximum power output, we can see that the Q_G limit can be set between 90 and 120MVAR. In the figure, the field voltage decreases from top to bottom. The way we set the Q_G limit is that after running the 60 seconds simulation, the Q_G settles down to a steady-state value. If we further decrease the field voltage, the Q_G will still be decreasing or become unstable which means at the end of the 60 seconds simulation, the Q_G does not settle down to a steady-state value or diverge. In this case, we choose the Q_G limit value to be 100MVAR which is the value in between. This Q_G limit value can be tuned depends on how well we want our back-up protection to be. Q_G limit value of other studied cases can be found use the same way we described above.

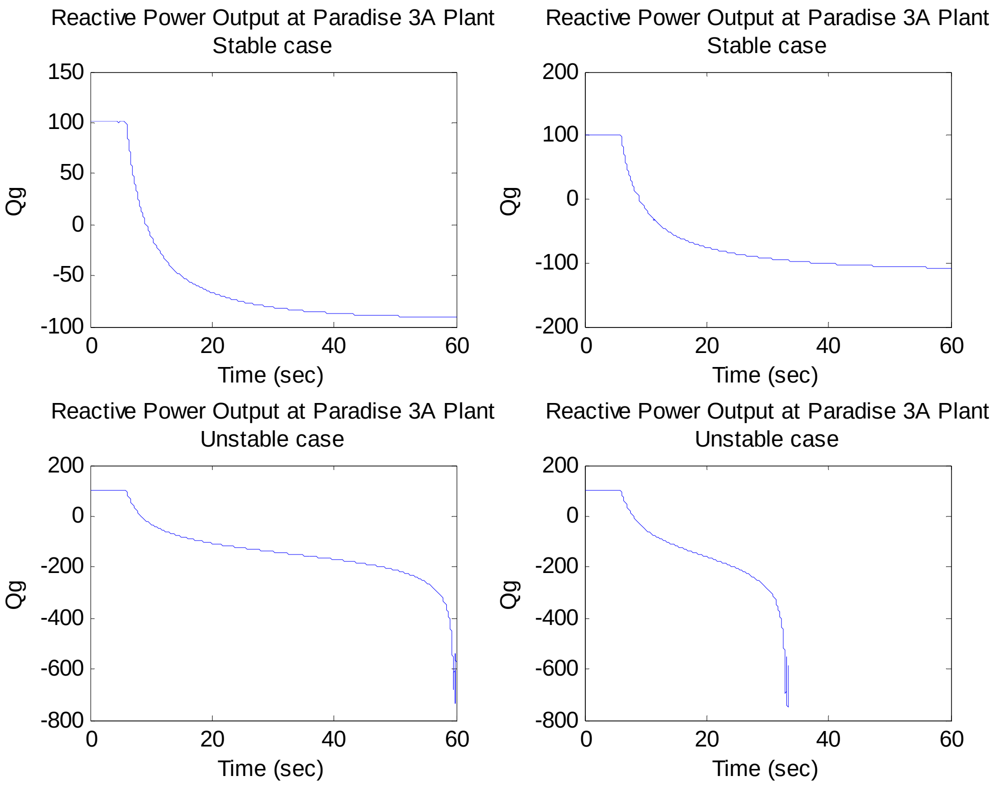


Figure 5-6: Q_G limit setting method

5.3.3 LOF ON PARADISE 3A PLANT UNDER DIFFERENT SYSTEM CONDITIONS

The maximum real power output at Paradise 3A plant is 529.7MW. From Table 5-4, we can see the actual Q_G limit and Q margin at the base case.

Table 5-4: Q_G limit and Q margin of the Base Case

P_G (%)	Q_G limit	Q margin	Q_G limit/Q margin
0	267	761	0.3509
20	238	745.76	0.3191
40	223	725.79	0.3073
60	170	710.99	0.2391
80	140	681.39	0.2055
100	100	648	0.1543

In order to use the least square estimation to set the appropriate back-up protection settings, we run several other LOF simulations under different system conditions which shown in Table 5-5 below. The contingencies can be seen in Appendix Table A-1.

Table 5-5: Results of Paradise 3A Plant LOF under different system conditions

Out-of-service	P_G(%)	Q_G limit	Q margin	Q_G limit/Q margin
44-71	0	267	693.78	0.3848
	20	220	680.14	0.3235
	40	190	651.96	0.2914
	60	156	629.28	0.2479
	80	124	612.13	0.2025
	100	95	558	0.1703
44-48	0	256	580.34	0.4411
	20	200	566.27	0.3532
	40	157	538.16	0.2917
	60	135	516.08	0.2616
	80	114	490.01	0.2326
	100	70	448	0.1563
44-48,48-581	0	263	473.5	0.5554
	20	200	457.23	0.4374
	40	150	437.4	0.3429
	60	122	413.96	0.2947
	80	86	387.59	0.2219
	100	40	288	0.1389
44-48,48-581	0	270	335.13	0.8057
365-378,40-48	20	180	332.01	0.5422
	40	152	321.14	0.4733
	60	120	307.06	0.3908
	80	73	299.62	0.2436
	100	28	168	0.1667

In order to see the actual relationship between the Q_G limit and Q margin at different real power output level, we plot all the studied cases results in the following Figure 5-7.

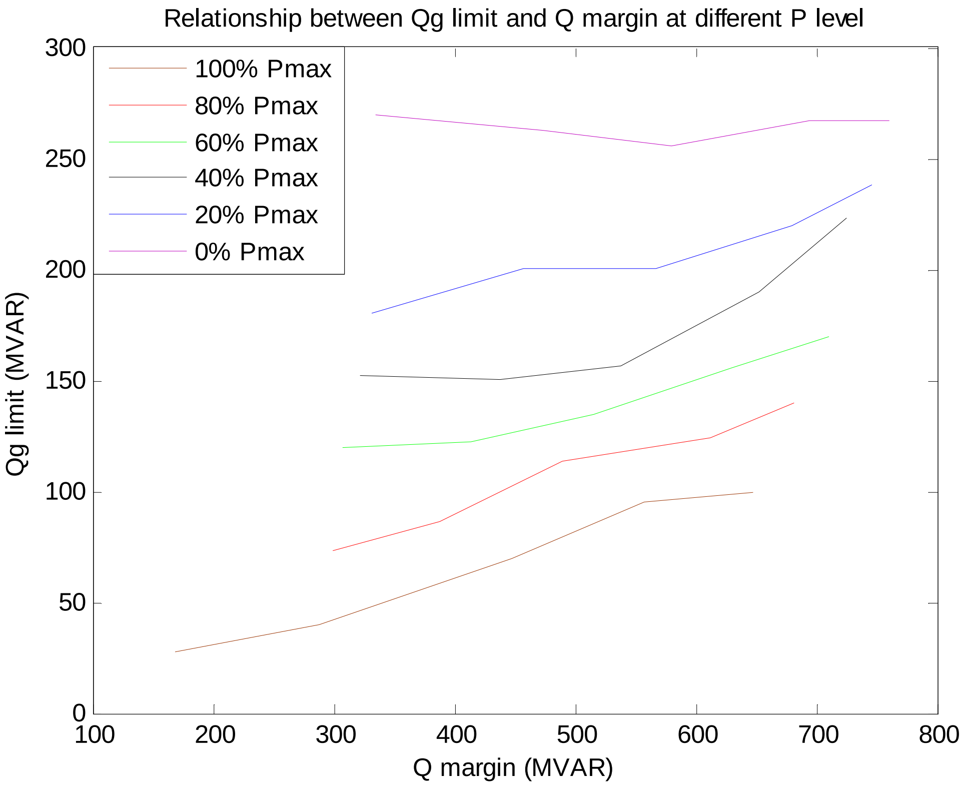


Figure 5-7: Relationship between Q_G limit and Q margin at different P levels

5.3.4 BACK-UP PROTECTION SETTING USING LEAST SQUARE ESTIMATION

From the previous section, we can see the Q_G limit and Q margin at various system conditions. The question becomes how we can set up our back-up protection in order to protect all possible cases we studied. We can use the least square estimation method [28]. If we assume that we have a PMU at the Paradise 500kV bus like the previous proposed back-up protection scheme, then we can monitor the real and reactive power flow at the Paradise 500kV bus. We can also perform the Q-V curve study on-line or off-line to obtain the Q margin. Once all these measurements are available, we can set up our equations to perform the least square estimation to obtain the coefficients we need. The problem will become to solve $aP_G + bQ_{margin} = Q_{G\_limit}$ for a and b.

In the least square estimation, the a and b constraints are the unknowns. The values of $P_G, Q_{margin}, Q_{G\_limit}$ are the known we obtained during our study in the previous section 5.3.3. Since we want to estimate the Q_{G_limit} to set up our protection, we will estimate a set of a and b at a specific real power level. The step size we chose to perform the estimation will be 20% of the maximum real power output at Paradise 3A plant. The total number of studied cases is 5, and then our H matrix will be 5x2. We have 6 different real power output levels, then we will have to estimate 6 sets of a and b at once which makes our H matrix to be 30x12.

The way of setting up the problem is shown below:

$$W = diag(ones(30,1))$$
$$h = zeros(5,2)$$
$$H = [\mathrm{H_1\ h\ h\ h\ h\ h;\ h\ H_2\ h\ h\ h\ h;\ h\ h\ H_3\ h\ h\ h;\ h\ h\ h\ H_4\ h\ h;\ h\ h\ h\ h\ H_5\ h;\ h\ h\ h\ h\ h\ H_6}]$$
$$\mathrm{z = [z1; z2; z3; z4; z5; z6]}$$

For example, H1=[529.7 648;529.7 558;529.7 448;529.7 288;529.7 168] and z1=[100;95;70;40;28] which are the Q_{G_limit} at Pg=100% of the maximum real power output.

Then we can obtain x which is the a and b by solving the equation (5.1) [28].

$$x = (H^T W H)^{-1} H^T W z \qquad (5.1)$$

The only problem remaining is the gain matrix $G = H^T W H$ will have a row and column of zeros which makes the matrix G singular which means G is not invertible. The problem happens because the 0 real power output we studied contained in H6 matrix. We can just put a small number rather than 0 to solve this kind of problem. We choose a value of 0.01MW to represent 0MW.

First, we will use equal weighted W matrix to set-up our back-up protection. After applying the least square estimation, we obtain the coefficients shown in Table 5-6.

Table 5-6: Proposed back-up Protection Setting

PG(%)	a	b
100	-0.00399	0.162834
80	0.05147	0.173205
60	0.230934	0.130374
40	0.386659	0.172886
20	1.292338	0.127075
0	26678.62	-0.00384

Then, we apply it to the base case to see how well it estimates the actual Q_{G_limit}.

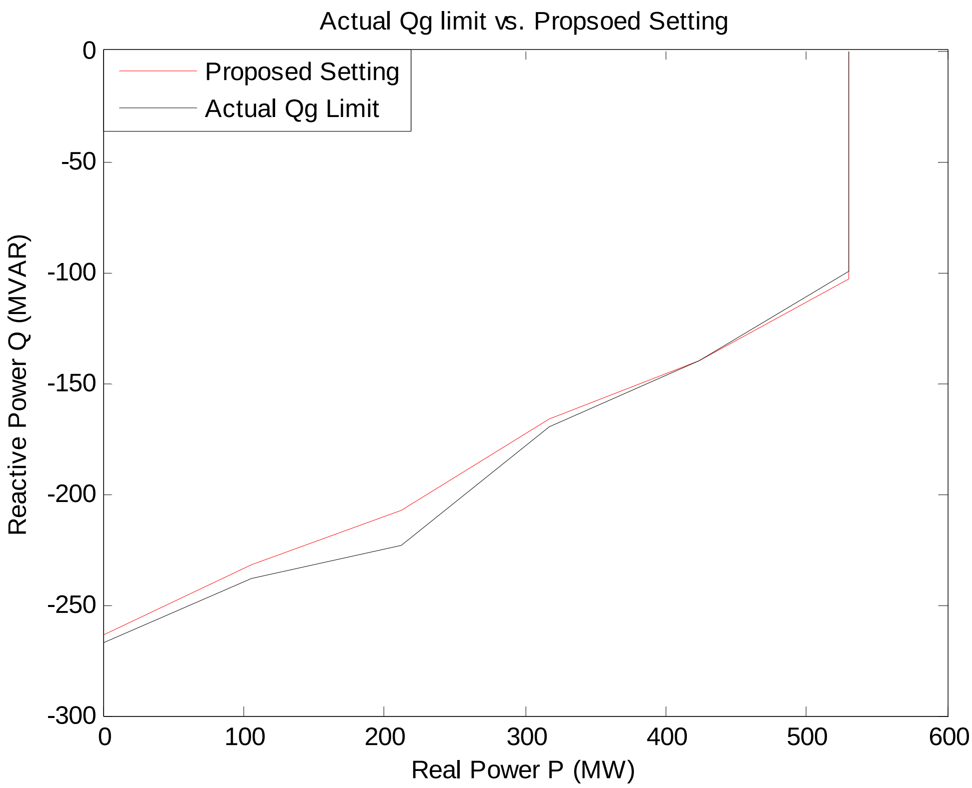


Figure 5-8: Actual Qg Limit vs. Proposed Setting

From Figure 5-8, we can see that our proposed back-up protection scheme will work for the base case under LOF condition. The setting well matched the actual Q_G limit which means the proposed method will detect the LOF condition and send correct tripping signal.

So far, the back-up protection scheme's setting seems working. In order to verify our methodology, we apply it to several other system conditions under LOF condition on the Paradise 3A plant. From the Figure 5-9 below, we can see that the back-up protection scheme works for the Paradise plant for different system conditions. The contingencies can be seen in Appendix Table A-1.

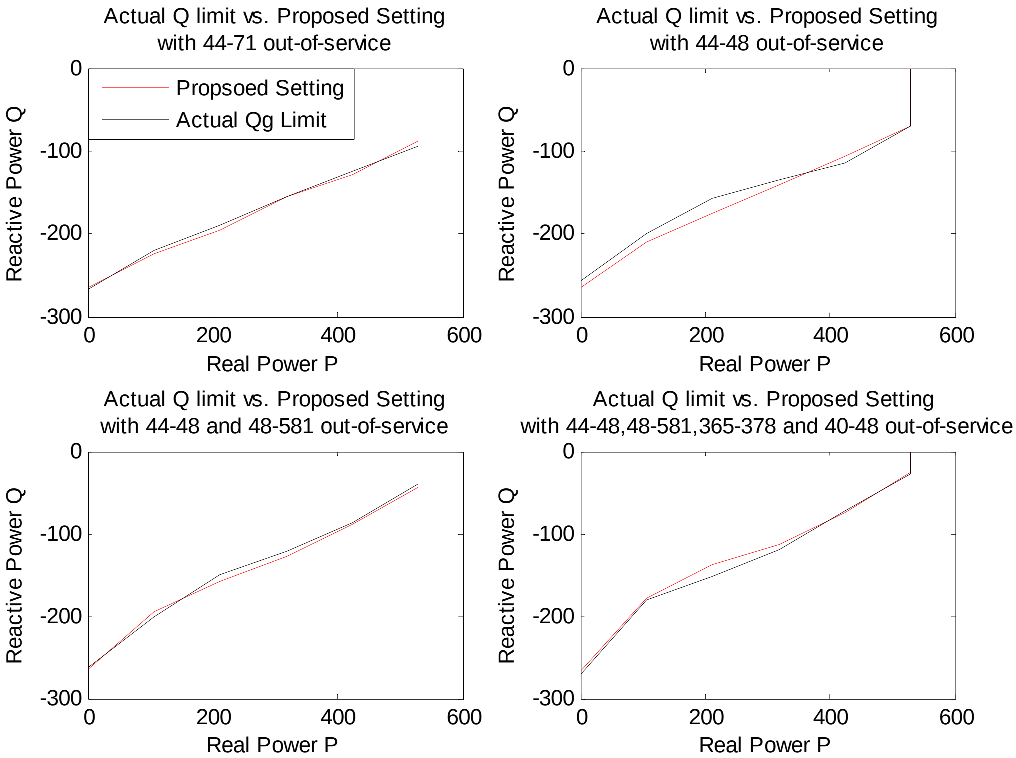


Figure 5-9: Actual Qg Limit vs. Proposed Setting for different system conditions

Since the least square estimation's results can be influenced by the weighted matrix W, next we will examine how weighted matrix W affects our results.

The minimum real power output at Paradise 3A plant is about 320MW which is about 60% of the maximum real power output. Then for the cases which real power output is less than 60% of Pg max, the weighted matrix W values will be half of the others. The new settings are shown in Table 5-7 below.

Table 5-7: Proposed back-up Protection Setting with unequal weighted matrix W

PG(%)	A	b
100	-0.00399	0.162834
80	0.05147	0.173205
60	0.230934	0.130374
40	0.386659	0.172886
20	1.292338	0.127075
0	26678.62	-0.00384

Compare Table 5-7 with Table 5-6, the values obtained are the same which means the results does not affect by the weighted matrix W.

We now have a setting for our back-up protection using the 5 different cases' result and the least square estimation. We apply the same setting that we obtained above and use it as the back-up protection setting to some other system conditions which have the Q margin in-between the maximum and minimum Q margins among the previous 5 cases. The Q_G limit and Q margin for the new test cases can be seen in Table 5-8.

Table 5-8: Results of Paradise 3A Plant LOF under different system conditions

Out-of-service	P_G(%)	Q_G limit	Q margin	Q_G limit/Q margin
40-48	0	265	639.19	0.4145
	20	205	612.2	0.3349
	40	170	590.35	0.288
	60	150	573.98	0.2613
	80	118	553.14	0.2133
	100	75	468	0.1603
365-378	0	268	724.93	0.3697
	20	220	709.71	0.31
	40	197	689.76	0.2856
	60	162	664.99	0.2436
	80	135	645.43	0.2092
	100	100	638	0.1567

From Figure 5-10, we can see that after applying the setting to the two new test cases, it still works well. It really demonstrates the effectiveness of using least square estimation to set up the back-up protection's setting.

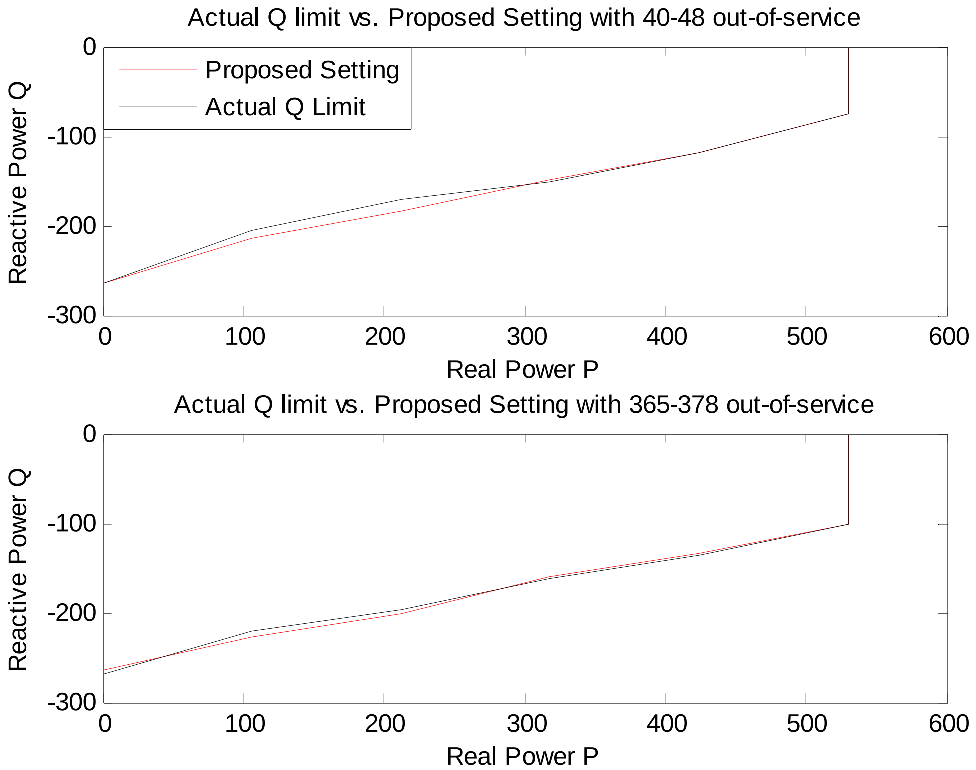


Figure 5-10: Actual Qg Limit vs. Proposed Setting for different system conditions

5.3.5 LOF ON SOME OTHER TVA GENERATORS

It seems that the proposed back-up protection works for the Paradise plan under different system conditions. Next, we apply our method to some other TVA generators in order to further verify our methodology. The proposed settings will still be used here. The same procedures we mentioned above also apply here.

Table 5-9: Results of Several TVA Generators under LOF condition

Generator	P_G(%)	Q_G limit	Q margin	Q_G limit/Q margin
Allen 4009	0	150	518.2	0.2895
	20	145	518.2	0.28
	40	135	518.2	0.2605
	60	110	508.2	0.2165
	80	90	508.2	0.1771
	100	70	503.2	0.1391
Shawnee 4176	0	115	326.6	0.3521
	20	97	326.58	0.297
	40	82	326.06	0.2515
	60	70	326.07	0.2147
	80	63	319.58	0.1971
	100	50	324.48	0.1541
Colbert 4050	0	120	431.15	0.2783
	20	115	430.74	0.267
	40	110	428.63	0.2566
	60	95	425.8	0.2231
	80	80	416.27	0.1922
	100	70	415.94	0.1683

From Figure 5-11, we can see that the proposed back-up protection seems not working for other TVA generators under LOF condition, especially when real power output is low. It because the setting we proposed is obtained using studies at Paradise Plant under different system conditions. The same methodology can be applied at other TVA generators to obtain different settings for different generator under different system conditions. But if we just want to provide a back-up protection under normal operating conditions, the settings we obtained can be classified as working because the minimum real power output at Allen 4009 generator is bigger than 50MW which the region under 50MW can be ignored.

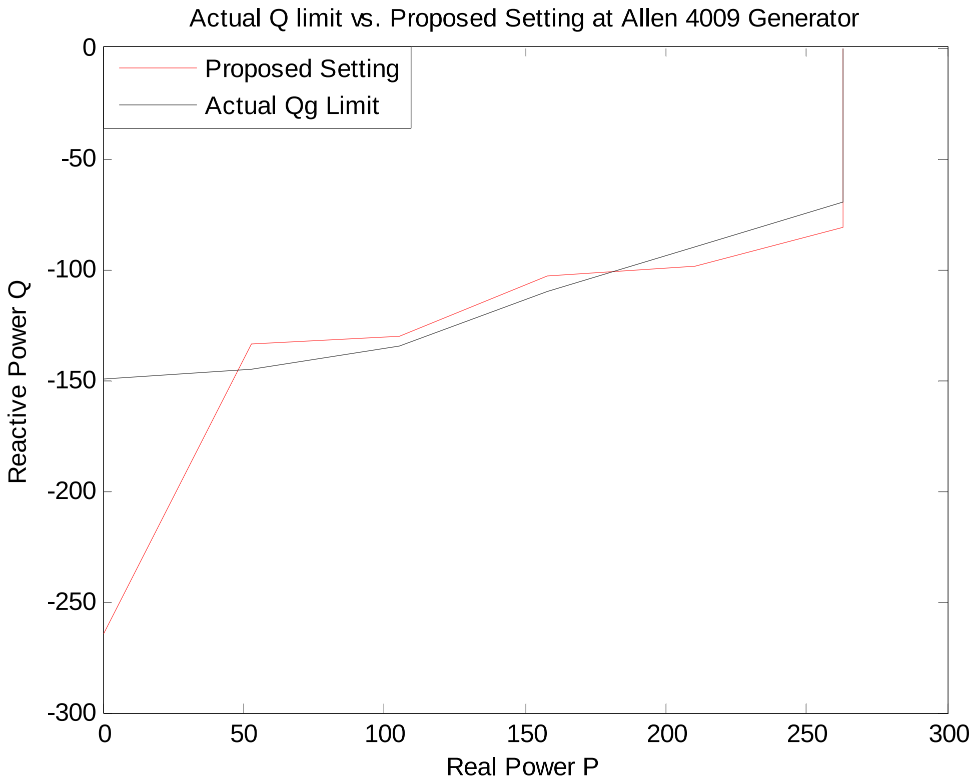


Figure 5-11: Actual Q limit vs. Proposed setting for Allen 4009 generators

The reason that at the low real power output, the actual limit does not match the proposed setting is at zero real power output, the proposed setting is mostly the same as the actual Q_G limit for Paradise plant. So if we use the actual Q_G limit at zero real power output for other TVA generators, the proposed setting seems still working. From Figure 5-12, we can verify the conclusion. But if we really want better settings for other TVA generators, we can use the same method as the Paradise plant which we can do more simulations under different system conditions, then obtain a particular set of settings for each generator.

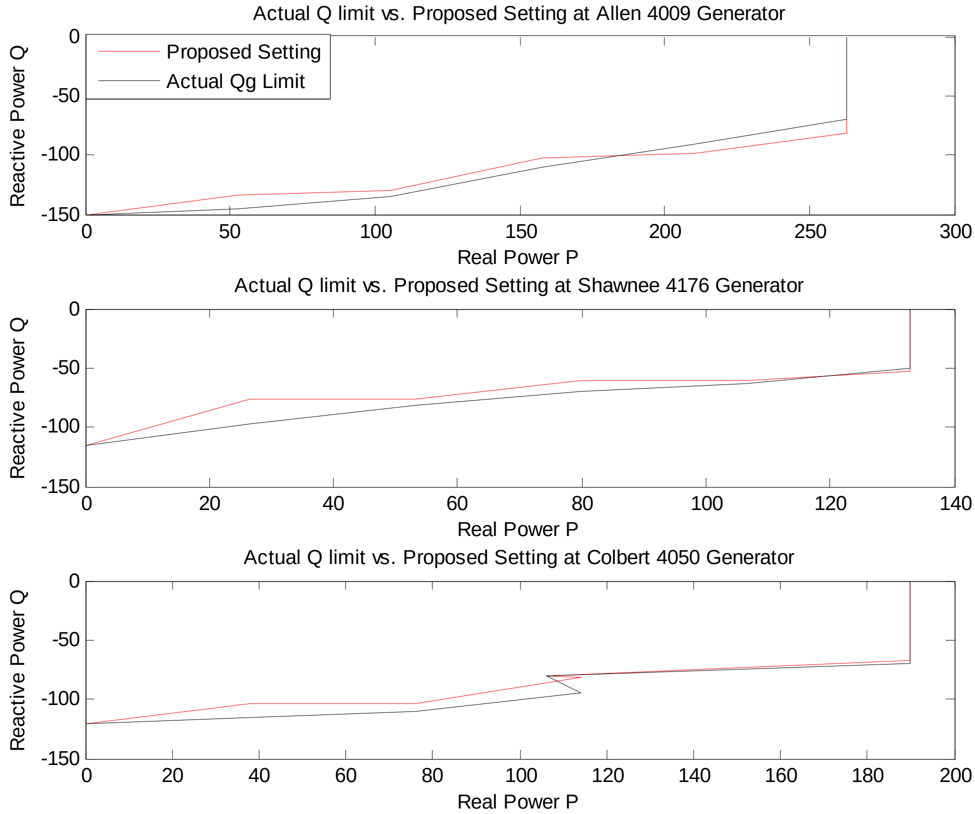


Figure 5-12: Actual Q limit vs. Proposed setting for other TVA generators

5.3.6 BACK-UP PROTECTION SETTING USING LEAST SQUARE ESTIMATION ON MONTGOMERY 500KV BUS SIDE

So far, we examine our methodology at the Paradise plant side. From section 5.3.4, we can see that the proposed method works if we monitor the real and reactive power at the Paradise 500kV bus side. The problem is we do not have PMU install at that bus now. We just assume we have a PMU, thus the real and reactive power information are available.

Table 5-10: Results of Paradise 3A Plant LOF under different system conditions

Out-of-service	P_G(%)	Q_G limit	Q margin	Q_G limit/Q margin
Base Case	0	267	1540	0.3509
	20	238	1530	0.3191
	40	223	1510	0.3073
	60	170	1480	0.2391
	80	140	1450	0.2055
	100	100	1420	0.1543
44-71	0	267	1370	0.3848
	20	220	1350	0.3235
	40	190	1320	0.2914
	60	156	1280	0.2479
	80	124	1240	0.2025
	100	95	1210	0.1703
44-48	0	256	1010	0.4411
	20	200	990	0.3532
	40	157	940	0.2917
	60	135	890	0.2616
	80	114	830	0.2326
	100	70	790	0.1563
44-48,48-581	0	263	580	0.5554
	20	200	570	0.4374
	40	150	550	0.3429
	60	122	530	0.2947
	80	86	490	0.2219
	100	40	460	0.1389
44-48,48-581	0	270	338	0.8057
365-378,40-48	20	180	338	0.5422
	40	152	335	0.4733
	60	120	330	0.3908
	80	73	310	0.2436
	100	28	300	0.1667

Since we have a PMU at the Montgomery 500kV bus side, like the proposed back-up protection scheme in the paper [19], we can apply the same methodology we proposed in section 5.3.4, and then we can implement the methodology because we have a PMU at Montgomery 500kV bus. The same method like in section 5.3.4 is applied; the results are shown in Table 5-10.

Then the settings can be obtained by applying the least square estimation shown in Table 5-11 below.

Table 5-11: Proposed back-up Protection Setting

PG(%)	a	b
100	0.020721	0.066536
80	0.139378	0.055946
60	0.317194	0.044113
40	0.5707	0.057444
20	1.58641	0.041373
0	26535.02	-0.00078

From Figure 5-13, we can see that if we apply the same method using the Q margin at the Montgomery 500kV bus side, the results are still as good as at Paradise side. It means that the method can be implemented at the Montgomery side now because we have a PMU at that 500kV bus.

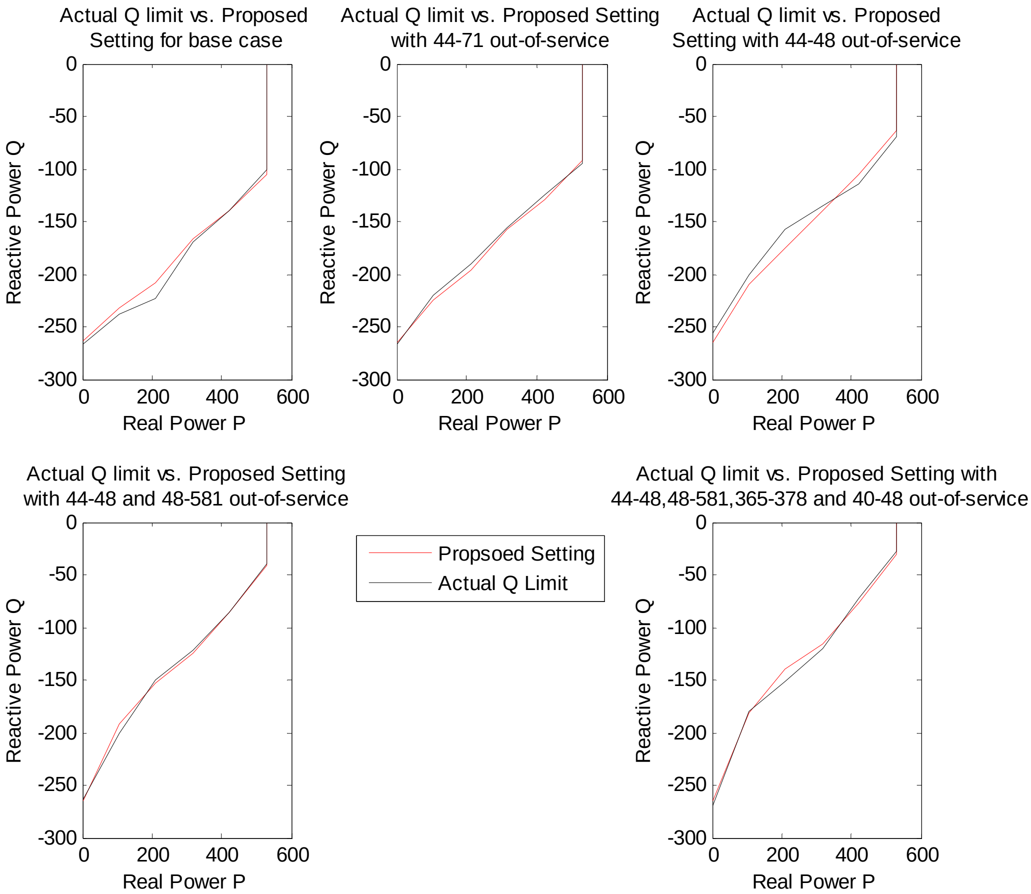


Figure 5-13: Actual Qg Limit vs. Proposed Setting at Paradise 3A Plant

The proposed method works at either Paradise side or Montgomery side. It gives us the freedom of where we want to implement this methodology. But the most important achievement is the back-up protection scheme using PMU measurements is a possibility. The remaining question is we have to coordinate our proposed settings with the actual P-Q curve because we do not know whether our setting is inside or outside of the actual P-Q curve at this point. Further research is still needed to solve this problem.

CHAPTER 6 LOF PROTECTION BASED ON INTERNAL MEASUREMENTS

6.1 INTRODUCTION

So far, we proposed a back-up protection scheme using terminal measurements. If the internal states of the generator can be measured, a protection scheme based on those measurements can still be possible. We will propose a protection scheme using off-line study about Q-V curve which will give us the Q margin at a particular bus and the two-axis model which will give us the absorbed Q by the generator in order to find the Efd threshold which would likely lead the system to voltage collapse. Once the Efd thresholds under different system conditions are obtained, we can use it to do the protection as we proposed next.

6.2 Q-V CURVE BASED PROTECTION SCHEME

From the operating stand point of view, we do not want to operate the generator at very low voltage level because it may operate at the under-excitation region of the P-Q curve which the generator will absorb reactive power from the system. Therefore, it will weaken the system because of the reactive power limitation. From the studies we did for the TVA LOF conditions, we can see that when LOF happens, the generator voltage declines. The speed of the voltage declines will depend on how severe the LOF condition is. In order to better protect the generator, we set the generator voltage limit at around 0.9pu for the studies we did below. A new back-up protection scheme will be proposed.

6.2.1 METHODOLOGY

The basic methodology will be based on several off-line studies. The back-up protection scheme is shown in Figure 6-1.

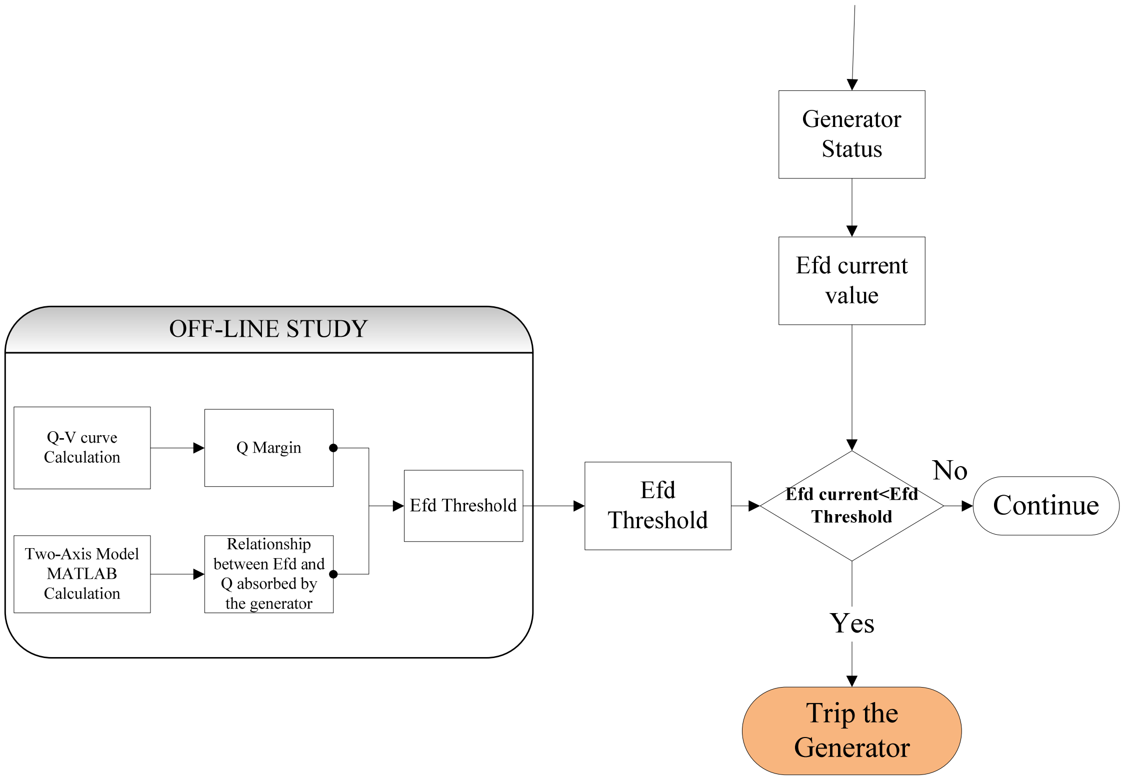


Figure 6-1: Q-V Curve based Efd Threshold Finding Back-up Protection Scheme

First, we will use the PSAT program to perform the Q-V curve calculation in order to find the Q_margin. Since the Paradise units are cross-compound, when we did the Q-V curve study, we put all the two units off-line. The MW and MVAR outputs will be treated as addition load to the existing load. Once we did this, the Q-V curve can be easily obtained by increasing the load at Paradise until the power-flow diverges. For the other generators we chose to study, we did not need to put all the units at one bus off-line because they are not cross-compound. For a particular generator, we just put the generator off-line. The MW and MVAR outputs at this generator will be added to the existing load. Once we did this, the Q-V curve can be easily obtained by increasing the load at this particular generator bus until the power-flow diverges. After obtaining the Q-V curve, the Q margin at certain studied bus can be obtained which will be the largest Q value that the power-flow can still be solved.

Second, we will calculate the reactive power absorbed by the generator using the two-axis model in MATLAB. The two-axis model equations are shown below.

$$\dot{\theta} = (\omega - 1)\omega_S \tag{6.1}$$

$$2H\dot{\omega} = P_m - P_e - K_D(\omega - 1) \tag{6.2}$$

$$T_{d0}^{`}\dot{E}_q^{`} = -E_q^{`} - (X_d - X_d^{`})I_d + E_{fd} \tag{6.3}$$

$$T_{q0}^{`}\dot{E}_d^{`} = -E_d^{`} + (X_q - X_q^{`})I_q \tag{6.4}$$

$$P_G - V_d I_d - V_q I_q = 0 \tag{6.5}$$

$$Q_G - V_q I_d + V_d I_q = 0 \tag{6.6}$$

where $P_e = P_G + (I_d^{\,2} + I_q^{\,2})R_S$ and V_d, V_q, I_d and I_q are the Park Transformation with the terminal voltage at $V\angle\delta = 0.9\angle\delta$.

From the equations (6.1)-(6.6), we can see that if the field voltage Efd is known, then we have 6 equations with 6 unknowns. The unknowns are θ, ω, $E_q^{`}$, $E_d^{`}$, P_m and Q_G.

Therefore, we can solve this set of differential-algebraic equations (6.7)-(6.12) to obtain the information we need about Q_G at certain P_G .

$$(\omega - 1)\omega_S = 0 \qquad (6.7)$$

$$P_m - P_e - K_D(\omega - 1) = 0 \qquad (6.8)$$

$$E_q^` - (X_d - X_d^`)I_d + E_{fd} = 0 \qquad (6.9)$$

$$-E_d^` + (X_q - X_q^`)I_q = 0 \qquad (6.10)$$

$$P_G - V_d I_d - V_q I_q = 0 \qquad (6.11)$$

$$Q_G - V_q I_d + V_d I_q = 0 \qquad (6.12)$$

where $V_d = E_d^` - R_s I_d + X_q^` I_q$, $V_q = E_q^` - R_s I_q - X_d^` I_d$, $V_d + jV_q = V\angle\delta$, $P_G = V_d I_d + V_q I_q$ and $Q_G = V_q I_d - V_d I_q$

Once the calculations are done, we will have the information about how much reactive power the generator needs to absorb from the system after LOF at a certain Efd value. Then compare the values with the Q margin obtained in the first step, we will be able to set a reasonable Q threshold which in this thesis to be X% of Q margin to denote severe LOF condition, which means the generator has to be tripped at this point. After obtaining the Q threshold, we can obtain the Efd threshold by comparing the Q threshold to the MATLAB calculations of Q_G at different levels of Efd.

In order to verify that out proposed method works, we used TSAT program to run some simulations in order to find the exact point corresponding to a particular field voltage Efd which the system voltage will collapse. Comparing the Efd threshold we obtained with the TSAT simulation results, we can show that the proposed method works for some of the cases we studied in this thesis.

First, we will examine our methodology under normal real power output condition which in most cases is the maximum real power output. Then, we will examine our methodology under different system condition which means at different real power output.

6.2.2 LOF ON PARADISE 3A PLANT AT PG=100%

As the procedures we mentioned above, we did the Q-V curve calculation first. From the Q-V curve shown in Figure 6-2, we can see that the Q_margin is about 648MVAR.

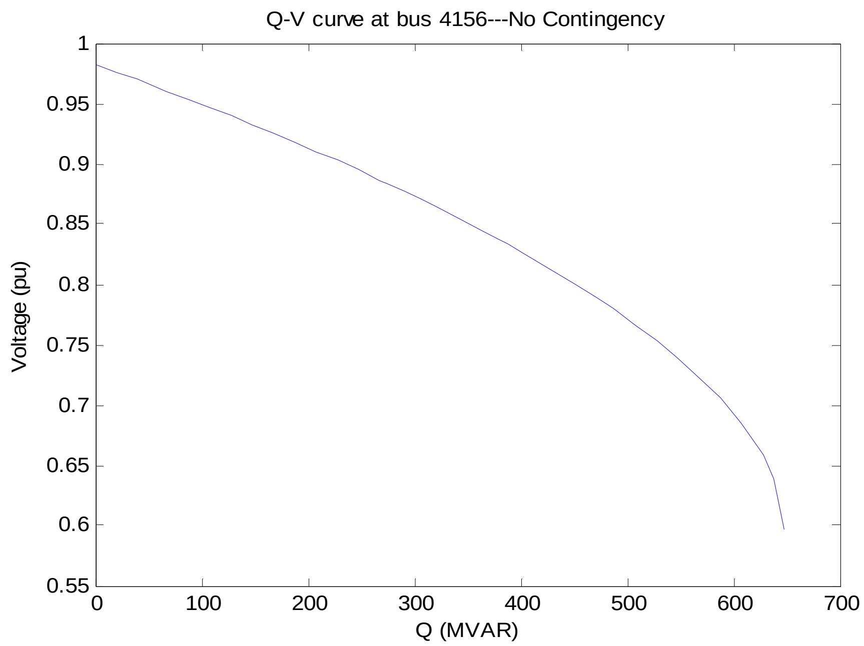


Figure 6-2: Q-V curve at bus 4156---Paradise at Pg=100%

Then the Q absorbed by the generator can be calculated in MATLAB which shown in Table 6-1 below. The question is how we can find the Efd threshold which is the value likely to lead the system to voltage collapse. We use TSAT program to run some simulations first in order to find the collapse point under LOF condition. The initial field voltage of Paradise 3A plant is about 1.97pu. After doing the test, we found out that the system voltage will collapse when the field voltage reduces to about 1.67pu, a reduction of -0.3pu.

Table 6-1: MATLAB Calculation of Q Absorbed by the Paradise 3A Plant

Efd reduction	Actual Efd	Q absorbed
-0.26	1.71	-106.3219
-0.27	1.7	-116.3981
-0.28	1.69	-121.0166
-0.29	1.68	-138.2883
-0.3	1.67	-150.3668

From results, we can see that if we set the Q threshold to be 20% of the Q_margin which is about 129.6MVAR, then we will be able to denote LOF condition which may lead the system to voltage collapse. It means we will be able to find the Efd threshold which in this case will be 1.68pu. The procedure here is a little bit different than we proposed because it is the first simulation and we do not know the Efd limit. The only way we can set proper Q threshold which will be some percentage of Q margin is to find the collapse point of Efd first in TSAT. Then we can set the Q threshold and find out the Efd threshold. In the later simulations, since we know we have to set the Q threshold to be 20% of Q margin, we will use it and verify the setting works for different system conditions.

6.2.3 LOF ON PARADISE 3A PLANT WITH MONTGOMERY-WILSON 500KV LINE OUT-OF-SERVICE AT PG=100%

With the Montgomery-Wilson 500kV line out-of-service, from the Q-V curve shown in Figure 6-3, we can see that the Q_margin is about 558MVAR. Since the Q-margin is smaller than the previous case, it is meaningful that the system voltage will collapse with a smaller reduction of field voltage because it does not have enough reactive power support from the system as before.

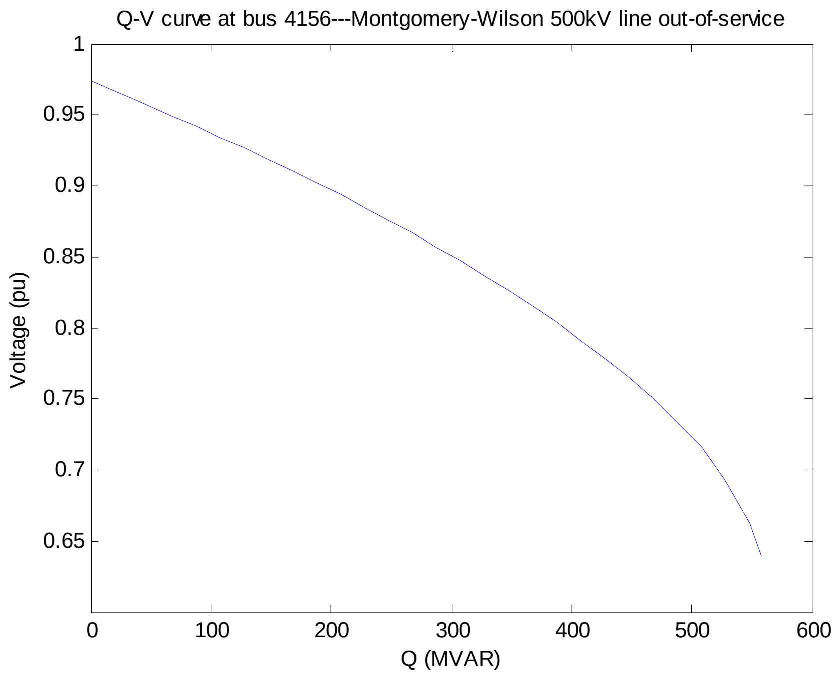


Figure 6-3: Q-V curve at bus 4156---Paradise with Montgomery-Wilson 500kV line out-of-service at Pg=100%

The Q absorbed by the generator can be calculated in MATLAB which shown in Table 6-2 below. From results, we can see that if we set the Q threshold to be 20% of the Q_margin which is about 111.6MVAR, then we will still be able to denote LOF condition which may lead the system to voltage collapse. The Efd threshold is about 1.71pu.

Table 6-2: MATLAB Calculation of Q Absorbed by the Paradise 3A Plant with Montgomery-Wilson 500kV line out-of-service

Efd reduction	Actual Efd	Q absorbed
-0.2	1.77	-58.1705
-0.24	1.73	-98.886
-0.25	1.72	-102.4202
-0.26	1.71	-112.4033

We can verify our results using TSAT simulation. After doing the TSAT simulation, we found out that the system voltage will collapse when the field voltage reduces to about 1.71pu, a reduction of -0.26pu which is the same as our Efd threshold.

6.2.4 LOF ON PARADISE 3A PLANT WITH SOME OTHER CONTINGENCIES AT PG=100%

So far, the Q threshold setting which to be 20% of the Q margin seems working. In order to verify our methodology, we apply it to several other contingencies for LOF on the Paradise 3A plant. From the table 6-3 below, we can see that the back-up protection scheme works for the Paradise plant. The contingencies can be seen in Appendix Table A-1.

Table 6-3: Results of Contingency Studies of Paradise 3A Plant LOF at Pg=100%

MATLAB Out-of-Service	Efd	Q_gen_in V(0.9pu)	Q_margin (MVAR)	20% of Q_margin	Efd (pu) Threshold	TSAT Efd
44-48			448	89.6	1.73	1.73
-0.21	1.76	-63.6514				
-0.22	1.75	-72.0393				
-0.23	1.74	-80.7082				
-0.24	1.73	-89.694				
40-48			468	93.6	1.72	1.71
-0.2	1.77	-55.1415				
-0.24	1.73	-89.2472				
-0.25	1.72	-98.5685				
-0.26	1.71	-108.301				
365-378			638	127.6	1.68	1.68
-0.27	1.7	-107.597				
-0.28	1.69	-117.585				
-0.29	1.68	-128.092				
-0.3	1.67	-139.222				
CUF 4067-1			648	129.6	1.68	1.67
-0.25	1.72	-93.315				
-0.29	1.69	-122.9				
-0.3	1.68	-133.823				
-0.31	1.67	-145.465				
-0.32	1.66	-158.007				
44-48,48-581			288	57.6	1.77	1.77
-0.15	1.82	-20.0942				
-0.18	1.79	-42.3682				
-0.19	1.78	-50.1619				
-0.2	1.77	-58.1705				
44-48,48-581			168	33.6	1.81	1.81
365-378 ,40-48						
-0.1	1.87	6.6224				
-0.14	1.83	-21.2673				
-0.15	1.82	-28.6125				
-0.16	1.81	-36.1329				

Compare the Efd threshold obtained by our methodology with the TSAT simulation results; we can see that they are match well with each other. Even though in some of the cases, the Efd threshold we obtained is a little bit different from the TSAT results that is acceptable. Near the Efd threshold we obtained, if the LOF condition persists long enough, the system may still be unstable. The other reason is the two-axis model we used to calculate the Q absorbed by the generator contains lots of model simplifications and model assumptions. Therefore, the settings we obtained need to be field tuned or on-line tuned in order that our proposed method works better in real-time.

6.2.5 LOF ON SOME OTHER TVA GENERATORS AT PG=100%

It seems that the proposed back-up protection works for the Paradise plan under different system conditions. Next, we apply our method to some other TVA generators in order to further verify our methodology. The Q threshold setting will still be 20% of the Q margin. The same procedures we mentioned above also apply here.

From Table 6-4, we can see that the proposed back-up protection is still working for other TVA generators under LOF condition. Even though, the Efd thresholds do not exactly match the TSAT results, it is acceptable for the same reason mentioned above.

Table 6-4: Results of LOF Studies of Several TVA Generators at Pg=100%

LOF MATLAB	Efd	Q_gen_in V (0.9pu)	Q_margin MVAR	20% of Q_margin	Efd (pu) Threshold	TSAT Efd
Allen 4009	2.39pu		503.2	100.64	1.59	1.57
-0.7	1.69	-47.3835				
-0.8	1.59	-111.263				
-0.81	1.58	-124.612				
-0.82	1.57	-151.155				
Gallatin 4081	2.26pu		514.07	102.814	1.46	1.43
-0.7	1.56	-51.2492				
-0.8	1.46	-110.121				
-0.82	1.44	-138.292				
-0.83	1.43	-153.398				
Shawnee 4176	1.733pu		324.48	64.896	1.133	1.113
-0.5	1.233	-41.6609				
-0.6	1.133	-78.3084				
-0.61	1.123	-86.7802				
-0.62	1.113	-98.3828				
Lagoon Creek 4288	2.54pu		183.7	36.74	1.67	1.65
-0.8	1.74	-22.372				
-0.86	1.68	-35.8595				
-0.87	1.67	-39.7675				
-0.88	1.65	-49.0432				
Colbert 4050	1.832pu		415.94	83.188	1.412	1.392
-0.41	1.422	-81.3013				
-0.42	1.412	-87.9222				
-0.43	1.402	-96.0591				
-0.44	1.392	-108				
Cumberland 4067-1	2.28pu	(1pu)	1727.35	345.47	1.78	1.77
-0.48	1.8	-272.161				
-0.49	1.79	-300.367				
-0.5	1.78	-349.643				
-0.51	1.77	-376.181				

6.2.6 LOF ON PARADISE AND OTHER TVA GENERATORS AT PG=80%

So far, the Q threshold setting which to be 20% of the Q margin seems working for Pg=100% of the maximum power output. In order to verify our methodology, we apply it to the Paradise 3A and some other TVA plants at Pg=80%. From Table 6-5 below, we can see that the back-up protection scheme still works for the TVA plants with a Q threshold setting to be 20% of the Q margin.

Table 6-5: Results of LOF Studies of Several TVA Generators at Pg=80%

LOF MATLAB	Efd	Q_gen_in V (0.9pu)	Q_margin MVAR	20% of Q_margin	Efd (pu) Threshold	TSAT Efd
Paradise 4156	1.7pu		681.39	136.278	1.36	1.34
	1.37	-130.582				
	1.36	-139.582				
	1.35	-149.065				
	1.34	-159.073				
Allen 4009	2.23pu		508.2	101.64	1.31	1.28
	1.32	-95.0644				
	1.31	-102.059				
	1.3	-110.164				
	1.29	-120.24				
Shawnee 4176	1.65pu		319.58	63.916	1.02	0.98
	1.03	-62.133				
	1.02	-65.6682				
	1.01	-69.5935				
	1	-74.0973				
Colbert 4050	1.66pu		416.27	83.254	1.17	1.16
	1.18	-79.1723				
	1.17	-84.2775				
	1.16	-90.1115				
	1.15	-97.1631				

6.2.7 LOF ON PARADISE AND OTHER TVA GENERATORS AT PG=60%

It seems that the Q threshold setting which to be 20% of the Q margin seems working for Pg=100% and Pg=80% of the maximum power output. In order to verify our methodology, we apply it to the Paradise 3A and some other TVA plants at Pg=60%.

Table 6-6: Results of LOF Studies of Several TVA Generators at Pg=60%

LOF MATLAB	Efd	Q_gen_in V (0.9pu)	Q_margin MVAR	25% of Q_margin	Efd (pu) Threshold	TSAT Efd
Paradise 4156	1.45pu		710.99	177.748	1.02	1.02
	1.05	-155.164				
	1.04	-163.213				
	1.03	-171.666				
	1.02	-180.605				
Allen 4009	2.1pu		508.2	127.05	0.97	1.01
	1	-104.044				
	0.99	-110.513				
	0.98	-118.19				
	0.97	-128.322				
Shawnee 4176	1.52pu		326.07	81.5175	0.74	0.73
	0.76	--75.678				
	0.75	-80.048				
	0.74	-85.77				
	0.73	-98.383				
Colbert 4050	1.49pu		425.8	106.45	0.85	0.83
	0.87	-98.162				
	0.86	--105.473				
	0.85	-121.72				
	0.84	-123.523				

From Table 6-6 above, we can see that the back-up protection scheme will not works for the TVA plants with a Q threshold setting to be 20% of the Q margin. The Q threshold setting needs to be adjust to 25% of the Q margin

6.2.8 LOF ON PARADISE AND OTHER TVA GENERATORS AT PG=40%

It seems that one Q threshold setting which to be X% of the Q margin seems working for certain Pg for all the studied generators. During the next study, it is not the case.

From Table 6-7, we can see that in order to find the correct Efd threshold for our protection scheme, we have to set the Q threshold to be different percentage of the Q margin for different generators. It seems that since the Paradise unit is cross-compound which makes it differ from the rest of the test generators. It may be reasonable to have different setting for it from other generators.

Table 6-7: Results of LOF Studies of Several TVA Generators at Pg=40%

LOF	Efd	Q_gen_in	Q_margin	35% of	Efd (pu)	TSAT
MATLAB		V (0.9pu)	MVAR	Q_margin	Threshold	Efd
Paradise 4156	1.23pu		725.79	254.026	0.65	0.64
	0.67	-232.546				
	0.66	-244.892				
	0.65	-260.921				
	0.64	-297.462				
				25%		
Allen 4009	1.99pu		518.2	129.37	0.65	0.61
	0.66	-123.565				
	0.65	-131.703				
	0.64	-149.967				
	0.63	-149.96				
Shawnee 4176	1.42pu		326.06	81.515	0.51	0.52
	0.54	--72.916				
	0.53	-75.546				
	0.52	-78.46				
	0.51	-81.809				
Colbert 4050	1.36pu		428.63	107.158	0.57	0.53
	0.59	--100.774				
	0.58	--106.119				
	0.57	-114.069				
	0.56	-122.886				

6.2.9 LOF ON PARADISE AND OTHER TVA GENERATORS AT PG=20%

From the results obtained in the previous section, we can see that one common setting may not work for all the generators. In this section, we will show that the proposed method may not work under low real power output.

Table 6-8: Results of LOF Studies of Several TVA Generators at Pg=20%

LOF	Efd	Q_gen_in	Q_margin	35% of	Efd (pu)	TSAT
MATLAB		V (0.9pu)	MVAR	Q_margin	Threshold	Efd
Paradise 4156	1.06pu		745.76	261.016	0.33	0.31
	0.34	-259.129				
	0.33	-270.216				
	0.32	-291.222				
	0.31	-297.543				
				28%		
Allen 4009	1.92pu		518.2	145.096	0.32	0.28
	0.34	-130.82				
	0.33	-136.509				
	0.32	-148.814				
	0.31	-149.977				
Shawnee 4176	1.36pu		326.58		0.3	0.48
Colbert 4050	1.28pu		430.74		N/A	0.21

From Table 6-8, we can see that in order to find the correct Efd threshold for our protection scheme, we have to set the Q threshold to be different percentage of the Q margin for different generators. Some of the generator cannot even find the Efd threshold correctly using the proposed method.

The remaining case will be Pg=0%. Obviously, the system should still be stable under full LOF condition. Therefore, the Efd threshold should be zero for all the tested generators.

6.2.10 CONCLUSION

From the studies we shown, we can see that using the internal measurements of the generator to do the LOF protection may be problematic because under low real power output, it cannot find the correct Efd threshold for us to do the protection. But for higher real power output such as 50% of the maximum output above, it works fine. Further research is needed to solve the problem under low real power output condition.

CHAPTER 7 CONCLUSIONS

From the simulations done on the detailed eastern interconnection planning model, we see that we successfully duplicate the November 29, 2007 TVA LOF event happened at the Paradise Fossil Plant. The impact of LOF protection at generators on the grid stability of the interconnected power system has been studied using both the two-area system and the detailed eastern interconnection planning model. We can conclude that LOF conditions on a major generator can result in a local voltage collapse near the generator if the LOF generator is left connected to the system. A few key factors will affect the time that available to trip the LOF generator before voltage collapse happens such as MW loading of the LOF generator, MVAR support of neighboring system, whether or not it is full LOF or partial LOF. Therefore, LOF condition should be detected as early as possible and the LOF relay should work as fast as possible in order to prevent potential damage to the generator and to the system stability.

We also provide two back-up protection schemes in order that the LOF relay does not function correctly. From the simulation results, we see that the terminal measurements based is better than the internal measurements based in some of the studied cases. The PMU based back-up protection scheme is now being implemented at TVA. We recommend further development and testing of the LOF back-up protection scheme for general power systems.

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CHAPTER 9 APPENDIX

Table A- 1: PSS/E Two-Area System Generator model "GENROE" and Parameters

T"do	8
T"qo	0.3
T'do	6
T'qo	0.5
H	4
D	0
Xd	1.2
Xq	1
X'd	0.3
X'q	0.3
X"d=X"q	0.25
Xl	0.15
s(1.0)	0
s(1.2)	0

Table A- 2: PSS/E Two-Area System Exciter model "SEXS" and Parameters

TA/TB	1
TB(>=0)	1
K	50
TE	0.1
EMIN	0
EMAX	4

Table A- 3: PSS/E Two-Area System Governor model "TGOV1" and Parameters

R	0.05
T1(>0)sec	20
V MAX	1
V MIN	0
T2 (sec)	1
T3(>0)sec	1
Dt	0

Table A- 4: Contingency Table

Out-Of-Service	
44-71	Montgomery-Wilson 500kV line
44-48	Montgomery-Davidson 500kV line
40-48	Cumberland-Montgomery 500kV line
365-378	Pin HOO-North Nashville 161kV line
CUF 4067-1	Cumberland 4067-1 Generator
48-581	Davidson-Pin HOO 500kV line