01 Jan 2007

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***Abstract*—Steady state analysis cannot provide the details of how system evolves in cascading failure. Dynamic response of generator plays an important role in power system operation and blackout events. In this paper, classical generator and detail generator models are integrated into system model for cascading dynamic simulations.. The cascading scenarios are compared using both steady state and dynamic simulations. Classical models are simpler; however, the detailed generator model is more accurate. Generator performance of speed deviation and angle deviations as well as the bus voltage profile are investigated for various scenarios. The IEEE 118-bus, 20-generator test case is used as the test system.**

***Index Terms*—Blackout, generator modeling, power system dynamic performance, transient stability.**

I. INTRODUCTION

CASCADING failures have traditionally been considered as low probability high consequence events. In August 1996, a blackout resulting from cascading failures took place in the Western Electric Coordinating Council grid resulting loss of 30,390 MW load and affecting more than 7 million people in 11 states [1]. The August 14, 2003 cascading blackout, the largest ever blackout in North America, resulted in 62,000MW of load shedding and 531 generator tripping [2]. There were also several other major blackouts in the world, namely, the August 28, 2003 blackout in London; the September 23, 2003 blackout in Sweden and Denmark; the September 28, 2003 blackout in Italy and the May 24, 2005 blackout in Russia [3].

These recent cascading failures in power systems around the world underscore the need for researchers to investigate the cascading failure process and identify probability distribution of potential blackouts [4],[5]. There is no systematic method for analyzing the risk of cascading failures for a given operating condition because large scale power grids are too complex and there are seemingly inexhaustible numbers of scenarios to search [6]. Instead of looking at the overall risk of cascading failures in power systems, this paper deals with individual blackout scenarios from both a steady state and a dynamic perspective. The IEEE 118-bus, 20-generator mid-western US power grid system is selected as the test system. Simulations are carried out to compare blackout scenarios based on system representation and modeling. It is quite obvious that steady state analysis such as power flow studies is preferred by engineers because of the relative ease of setting up different cases and the fast execution times for each simulation run. However, sometimes steady state analysis does not provide the complete picture of how the system evolves in a cascading failure scenario. Therefore, the emphasis of this study will be to investigate the system dynamically with simple classical representation of synchronous machines versus with machines represented in more details which includes voltage and frequency control properties of generators.

Existing cascading failure scenario analysis mostly focuses on steady state analysis. The steady state cascading cases are simulated from an initial equilibrium state using static power flow methods [6]. With the most highly overloaded single line tripped at each step, the steady state analysis of the 118 bus test system identified eight cascading line outage contingency scenarios which will finally lead to a system blackout [7].

Although generator controls play an important role in power system operation, dynamic stability analysis is seldom applied at present for reasons of modeling difficulties and complexities encountered with large power systems. In the advanced stages of a blackout, uncontrollable system separation, angle instability and voltage collapse can occur. The conclusion can be reached that the 14 August 2003 North American blackout resulted from system overloading that led to voltage deterioration in the power system with key generators in critical areas forced offline by automatic protection devices [2]. It is necessary to study transient stability scenarios in more detail with adequate representation of synchronous generators and other dynamic elements in the 118 bus test system.

The simulation software EUROSTAG [8], [9] is used in this study. EUROSTAG is developed for the simulation of power system dynamics. It can simulate transient stability, mid-term and long-term stability using a single power system model.

This paper is structured as follows: first, steady state simulation of cascading failures is introduced. Then the necessity of dynamic simulation considering generator models is discussed. The classical generator and detailed generator models are then compared and both models are used for dynamic simulations to produce cascading failures. Next, the steady state simulation results are compared and analyzed for the same cases considering generator dynamics when using the classical generator model and the detailed model. Finally we

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draw conclusions and propose relevant future work.

II. Cascading Failures Identified from Steady State Simulations

A cascading failure in power systems is a process, in which an initial disturbance or component outage increases the stress on other system components, and then a series of critical components are subsequently tripped either as a direct consequence or due to hidden failures. The domino effect will finally lead to islanding and result in the loss of a substantial amount of load. In this paper only the line trip is considered as the probable contingency.

The line trip event is simulated by modifying the network admittance matrix in steady state power flow calculation. The extent of overloading as compared to the maximum transmission capacity is used as a criterion for deciding further outages in the system. Overloaded lines are then removed one-by-one until the power flow fails to converge – which is considered to be a blackout state. Those line trip sequences of eight critical initiating contingencies that each eventually lead to a blackout as presented in [7] are repeated in Table I. The tripped line is defined with bus numbers in the table. The first line is tripped at 0.5s and subsequent lines are tripped at 2s, 4s, 6s, 8s and 10s.

TABLE I
EIGHT MAIN CONTINGENCY

Case no.	1st Line	2nd Line	3rd line	4th line	5th line	6th line	7th line
1	48-49	47-46	45-49	34-43			
2	64-65	62-67	66-62	56-58	54-56	54-55	56-57
3	69-70	74-75	70-75	72-24			
4	4-5	5-11	7-12	3-5	16-17	14-15	
5	34-37	35-36	43-44				
6	5-8	14-15	16-17				
7	37-38	15-33	19-34	43-44			
8	47-69	47-49	46-48	45-49			

III. The 118 Bus Test System Model

The cascading failure simulations of the 118 bus test system based on the steady state power flow method is not accurate enough to capture the details of a blackout, because it doesn't consider the dynamics of power system such as generator trip, load shedding and other dynamic elements. The dynamic response of system controllers plays a key role in system stability and blackout events. With detailed generator model representation, automatic control of voltage and frequency often shape the system trajectory following a series of events. Generator active and reactive power control capabilities can limit the effect of a critical disturbance; however in some cases, these controls can exacerbate the effect. Therefore it is important to investigate generator performance and identify proper controls when dealing with cascading blackout scenarios.

In this study, the generator behavior is investigated in detail but load tap changing transformers are replaced by fixed transformers since the concern is with transient stability. All loads are assumed to be constant impedance static loads.

The EUROSTAG dynamic simulation program is designed for systems with 5000~10,000 state variables (typically 1000-2000 nodes and a few hundred machines). Models are drawn interactively in EUROSTAG using a block diagram representation. It also has extended and flexible modeling capabilities for the graphical input facilities. The new model is defined at the user level and coding with graphical macro language, which is obviously much easier than FORTRAN or C coding efforts [9].

A synchronous generator can be modeled as a full model or a simplified model for different purpose. The full machine model has two rotor windings in each axis whereas the simplified machine model only has a field winding in the d axis. The electrical parts of two axis full generator can be described as follows:

$$\begin{bmatrix} \dot{\varphi}_d \\ \dot{\varphi}_q \\ \dot{\varphi}_0 \\ \dot{\varphi}_{fd} \\ \dot{\varphi}_{d1} \\ \dot{\varphi}_{q1} \\ \dot{\varphi}_{q2} \end{bmatrix} = \begin{bmatrix} R_s I_d + \omega_r \varphi_q + V_d \\ R_s I_q - \omega_r \varphi_d + V_q \\ R_s I_o + V_0 \\ -R_{fd} I_{fd} + V_{fd} \\ -R_{1d} I_{1d} + V_{1d} \\ -R_{1q} I_{1q} + V_{1q} \\ -R_{2q} I_{2q} + V_{2q} \end{bmatrix} \tag{1}$$

Where φ_d , φ_q , φ_0 are dq0 axis flux linkage, and φ_{fd} , φ_{d1} , φ_{q1} , φ_{q2} are field and amortisseur circuit flux linkage; ω_r is the rotor speed, R_s is the armature resistance, and R_{fd} , R_{1d} , R_{1q} , R_{2q} are rotor circuit resistance, I_d, I_q, I_0 are stator currents in dq0 axis, $I_{fd}, I_{1d}, I_{1q}, I_{2q}$ are field and amortisseur circuit current. V_d, V_q, V_0 are stator voltage in dq0 axis, $V_{fd}, V_{1d}, V_{1q}, V_{2q}$ are field and rotor circuit voltage.

Equation (2)-(3) describes the mechanical characteristics:

$$\dot{\delta} = \omega_r - \omega_s \tag{2}$$

$$\frac{2H}{\omega_s}\dot{\omega}_r = T_m - (\varphi_d I_q - \varphi_q I_d) \tag{3}$$

Where δ is the power angle of generator, ω_r is rotor speed, ω_s is the rated synchronous speed, H is inertia constant, T_m is the mechanical torque applied to the shaft.

The simplified one-axis generator model neglects the amortisseur effects and the reduced order equations are also discussed in [10-11].

The synchronous generators in the IEEE 118-bus 20-generator test system are given typical external parameters of fossil steam units for different rated MVA capacity [12]. IEEE recommended excitation, PSS and governor models are used. These IEEE models [13] accompanied by the typical parameters are integrated with the full generator to represent the detailed generator. The detailed model is depicted as Fig. 1.

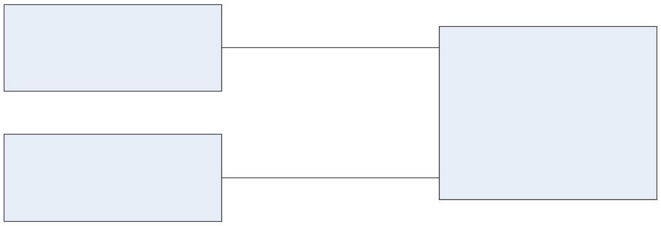

Fig. 1. Detailed generator model

To get the classical generator model, the simplified single-axis generator should be assuming that the mechanical torque CM is constant and excitation voltage EFD is constant.

IV. DYNAMIC PERFORMANCE WITH CLASSICAL GEN MODEL

The dynamic performance of the 118 bus test system with classical generator model is reported in this section. The generators speed deviations and power angle deviations from the reference generator at bus 69 are calculated to evaluate system dynamic performance. The voltage profiles are also provided. The simulation results are also compared with steady state power flow solutions.

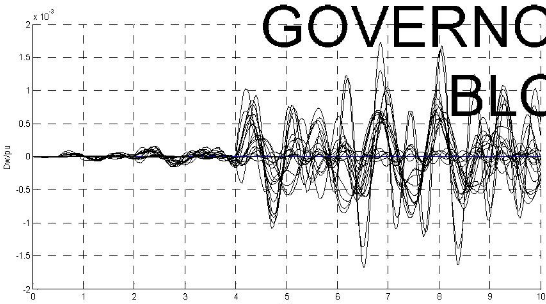

Fig. 2. Generators speed deviation for Case 1

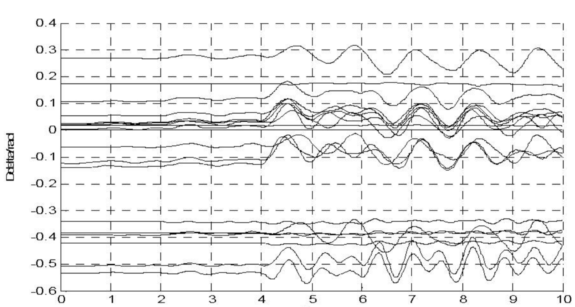

Fig. 3. Generators angle deviation for Case 1

For Case no. 1, the power flow solution will diverge when the fourth line is tripped. All 20 generators dynamic performances of speed deviation and angle deviation are shown in Fig. 2 and Fig. 3. As seen, all generators appear to be stable and the power grid operates as normal even after multiple line outages. However, steady state calculation reveals that the power flow will diverge after the four critical lines are tripped. The voltages at bus 43, 44, 45, 46, 48, and 69 are plotted in Fig. 4. Because some buses are separated from the grid and there is no generator in this islanded network, these bus voltages absolutely can not be maintained and will finally drop to zero. These zero bus voltages can also explain why the power flow solution diverges.

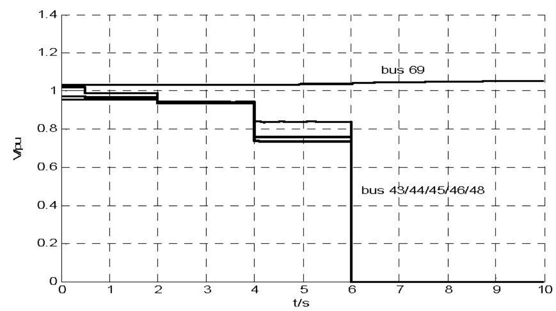

Fig. 4. Bus voltage for Case 1

For Case 3, some areas become weak with fewer line connected to generation area after disturbance. Bus voltage drop to emergency levels and power flows do not converge either. Voltage of bus 24, 70 and 74 are plotted in Fig. 5.

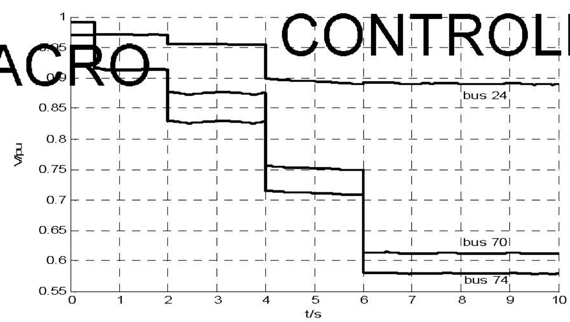

Fig.. 5. Bus voltage for Case 3

Based on the above simulation results, we can draw the conclusion that some cascading sequences found in the steady state simulations do not cause an instability problem and the grid could continue to operate, albeit in an alert state

Among the eight main contingency, six cases namely Cases 1, 2, 3, 5, 7 and 8 can maintain generator stability, but some bus voltages will drop to a very low level and steady state simulation will stop.

The preceding comparisons between steady state and dynamic simulations with classical generator model shows that only static power flow calculation is not enough to simulate the complex cascading failure. Some regular failures could be looked upon as catastrophic failures.

Generator transient stability maybe a more serious problem than power flow divergence problem because fewer cascading line trips may lead the system to instability. For Case 4, Generator 2 at bus 10 will lose first swing stability after tripping of the 5th line at 8s as shown in Fig.6, while the power flow solution will diverge when the 6th line is tripped at 10s.

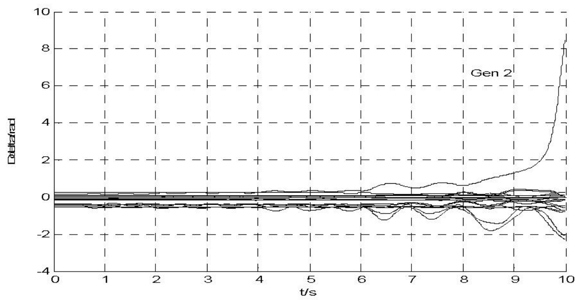

Fig. 6. Classical generator angle deviation for Case 4

For the last case of eight main cascading contingency, Case 6, power flow solution diverges and some generators will lose synchronism when the 3rd line is tripped at 4s. It is hard to justify if this failure is part of a cascading failure scenario or simply a regular instability problem. Further research on system dynamic performance should be carried out in this case.

V. Dynamic performance with detailed Gen model

In this section, system dynamic performance is simulated in the same conditions as previous section and classical generator model is replaced with detailed generator model. System dynamic performances with detailed generator model are compared with those with classical generator model. The stability problem is also compared with steady state power flow solutions.

Among the six cases namely Cases 1, 2, 3, 5, 7 and 8, which produce stable operation with the classical generator model, all cases except Case 2 will yield the same results with a detailed generator model. Thus Case 2 is simulated and analyzed more closely with detailed generator model. The simulation results are shown as Fig. 7 and Fig. 8. Generator 11 and 12 will lose synchronism after the 7th line is tripped at 12s. However, all generators with classical model are first swing stable for the same trip sequence. Thus, even with AVR and PSS controllers, Case 2 shows that the generators will lose synchronism earlier than the case when the generators are represented with a classical model.

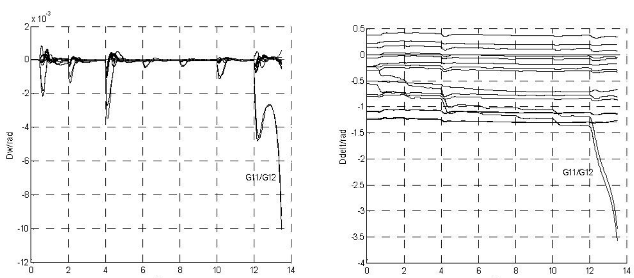

Fig. 7. Detailed generator dynamic performance for Case 4

Fig. 8 shows a comparison of bus voltage profiles between the two simulation runs of classical generator versus detailed generator. As obvious, the case with detailed generator representation provides better voltage support because of the presence of voltage regulation.

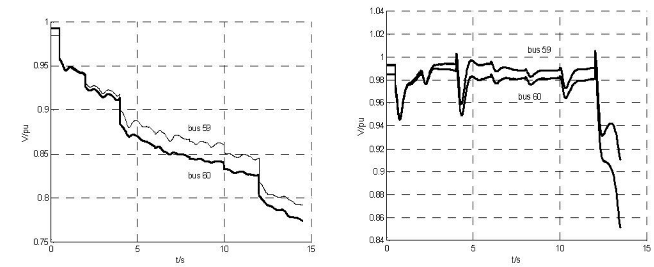

Fig. 8. Bus voltage comparison for Case 2 with classical and detailed generator

For Case 4, the system with classical generators will lose stability after the 5th line trip at 8s as shown in Fig. 6, but the same system will lose stability after the 6th line trip at 10s when detailed generator models are used. Generator dynamic performances with detailed models are shown in Fig. 9. Compared to the case with classical generator models, as seen in Fig. 6, Generator 2 will lose its first swing stability with the tripping of the 5th line. However, all generators with detailed models will be stable after the same number of line tripping.

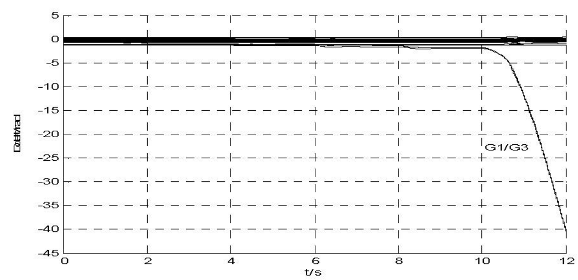

Fig. 9. Detailed generator angle deviation for Case 4

For Case 6, Generators 1 and 3 will lose first swing stability with both classical generator and detailed generators on the 3rd line trip at 4s. Steady state power flows will also diverge at the 3rd line trip. Bus voltages are maintained at a decent level with the detailed generator model, while the bus voltages will decline to an unacceptable level with the classical model.

Based on the simulation results of Cases 4 and 6, it can be concluded that some generators will lose synchronism during the cascading line trip disturbance. If they are small generators with low inertia, they should be tripped so that simulations can continue.

The dynamic simulation results with both classical and detailed generator model is compared with the steady state simulation. The summary is shown as in Table II.

VI. Conclusion

In the steady state simulation strategy, several cascading line trip cases which lead to local area voltage decline and leading to power flow divergence have little effect on generator dynamic performance. For those cases, simple load shedding will help power flow reach convergence again. Therefore, they should not be considered as truly representative of cascading failure based blackout. On the other hand, dynamic performance simulations provide a more realistic cascading failure scenario. Both strategies of generator representation – classical and detailed model provide a better insight into why a blackout happens.

For certain serious cascading disturbance cases, the detailed generator representation does not seem to help in stability improvement and generators appear to lose synchronism at the same time as in the case with classical model representation. This sort of instability usually occurs due to a small generating unit accelerating or decelerating too fast after a disturbance. In those anomalous cases, these generators could be tripped so as to reach the true blackout resulting from cascading failures.

In general, classical generator modeling results in voltage decline in some areas of the system because classical generators are not equipped to maintain bus voltages. To future investigate the cascading blackout, voltage collapse should be considered in dynamic simulations as well. The detailed generator model is preferred for the next step in the research.

VII. Future work

Future work will focus on continuing some of the dynamic simulations with emphasis on generator trips and voltage stability. A theoretical framework will be established which will help provide answers as to why the performance differs with different models used.

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Appendix

The appendix shows the 118-bus 20-generator test system.

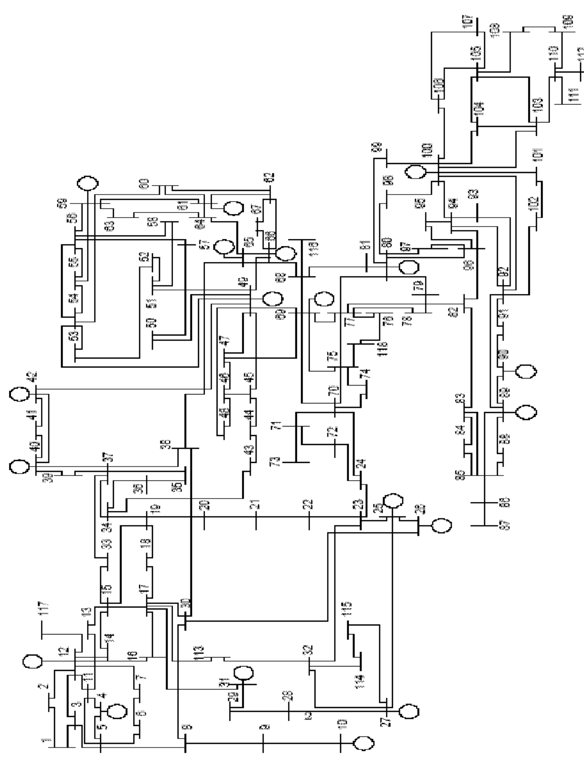

Figure 1: IEEE 118 bus test system

TABLE II
SIMULATION RESULTS COMPARISON

Case no.	Simulation divergence time for Steady state	Simulation with classical generator	Simulation with detailed generator
1	4th line	Stable	Stable
2	7th line	Stable	Unstable on 7th line
3	4th line	Stable	Stable
4	6th line	Unstable on 5th line	Unstable on 6th line
5	3rd line	Stable	Stable
6	3rd line	Unstable on 3rd line	Unstable on 3rd line
7	4th line	Stable	Stable
8	4th line	Stable	Stable