Dynamic IEEE Test Systems for Transient Analysis

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***Abstract*— Transient stability analysis is performed to assess the power system's condition after a severe contingency and is carried out using simulations. To adequately assess the system's transient stability, the correct dynamic models for the machines (i.e., generators, condensers, and motors) along with their dynamic parameters must be defined. The IEEE test systems contain the data required for steady-state studies. However, neither the dynamic model of the machines nor their specific parameters have been established for transient studies. As a result, there is a demand for test bed systems suitable for transient analysis. This paper defines dynamic machine models along with their parameters for each IEEE test bed system, thus producing full dynamic models for all test systems. It is important to mention that the parameters of the proposed dynamic models are based on typical data. The test systems are subjected to large disturbances and a case study for each test system, which examines the frequency, angle, and voltage stability is presented. Further, the proposed dynamic IEEE test systems, implemented in PowerWorld, are available online.**

***Index Terms*— Dynamic machine models, exciters, governors, IEEE test systems, transient stability analysis.**

I. Nomenclature

Rated MVA	Machine-rated MVA; base MVA for impedances
Rated kV	Machine-rated terminal voltage in kV; base kV for impedances
H	Inertia constant in s
D	Machine load damping coefficient
r_a	Armature resistance in p.u.
x_d	Unsaturated *d* axis synchronous reactance in p.u.
x_q	Unsaturated *q* axis synchronous reactance in p.u.
x'_d	Unsaturated *d* axis transient reactance in p.u.
x'_q	Unsaturated *q* axis transient reactance in p.u.
x''_d	Unsaturated *d* axis subtransient reactance in p.u.
x''_q	Unsaturated *q* axis subtransient reactance in p.u.
x_l or x_p	Leakage or Potier reactance in p.u.
T'_{d0}	*d* axis transient open circuit time constant in s
T'_{q0}	*q* axis transient open circuit time constant in s
T''_{d0}	*d* axis subtransient open circuit time constant in s
T''_{q0}	*q* axis subtransient open circuit time constant in s
$S(1.0)$	Machine saturation at 1.0 p.u. voltage in p.u.
$S(1.2)$	Machine saturation at 1.2 p.u. voltage in p.u.
T_r	Regulator input filter time constant in s
K_a	Regulator gain (continuous acting regulator) in p.u.
T_a	Regulator time constant in s
V_{Rmax}	Maximum regulator output, starting at full load field voltage in p.u.
V_{Rmin}	Minimum regulator output, starting at full load field voltage in p.u.
K_e	Exciter self-excitation at full load field voltage in p.u.
T_e	Exciter time constant in s
K_f	Regulator stabilizing circuit gain in p.u.
T_f	Regulator stabilizing circuit time constant in s
E_1	Field voltage value,1 in p.u.
$SE(E_1)$	Saturation factor at E_1
E_2	Field voltage value,2 in p.u.
$SE(E_2)$	Saturation factor at E_2
P_{max}	Maximum turbine output in p.u.
R	Turbine steady-state regulation setting or droop in p.u.
T_1	Control time constant (governor delay) in s
T_2	Hydro reset time constant in s
T_3	Servo time constant in s
T_4	Steam valve bowl time constant in s
T_5	Steam reheat time constant in s
F	Shaft output ahead of reheater in p.u.

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II. Introduction

ELECTRIC power systems are being operated close to their stability limits in an attempt by the electric utilities to satisfy the ever-increasing electricity demand and to remain competitive in the deregulated electricity market. Therefore, power systems are vulnerable to severe contingencies that can propagate to a large portion of the power system leading in many cases to power system instabilities. More specifically, the power system becomes transient unstable when it fails to retain the synchronism of the electric machines after the occurrence of a severe disturbance. In such a case, the synchronism between a synchronous generator or a group of generators with the rest of the power system is lost, leading to a partial or complete blackout unless appropriate protection and/or control measures are taken [1].

The stability of the power system can be categorized into the angle and voltage stability [2]. In the case of the angle stability, the power system should be able to maintain synchronism between the generators and the rest of the system after a severe disturbance, while in the voltage stability the system voltage level after the disturbance should be preserved as in the steady state. In any of the two cases, the loss of stability could lead to devastating consequences.

In order to prevent such situations, power system operators assess the stability condition of the power system by examining several scenarios offline. The transient analysis that is usually used in the power system control center enhances the situational awareness of the power system operators by providing a visualization of the generator rotor angles, bus voltages, and system frequency during a large contingency based on the current operating condition of the power system. Therefore, operators can plan a set of remedial measures to maintain the stability of the system.

In general, for running transient stability analysis both the type and the parameters of the dynamic model for the power system components should be available. On one hand, each electric utility has its own dynamic parameters and models for its power system. On the other hand, the several IEEE test bed systems available for steady state analysis, whose topology and power flow data can be found in [3], are lacking of dynamic models.

In the literature, a few test bed systems that can be used in transient analysis were proposed [4]-[6]. However, since the IEEE test bed systems are widely used by the research community, there are several cases where researchers are forced to choose dynamic models and their parameters for the IEEE systems in order to build their own dynamic systems [7]-[8]. In this case, there is a lack of consistency and uniformity among the different dynamic test systems. Furthermore, there is a common desire among the research community for dynamic test bed systems that can be used for assessing methodologies based on dynamic simulations.

In this paper, the IEEE test bed systems available in the literature for steady-state studies (14, 30, 39, 57, and 118 bus systems) are extended and modified to consider dynamic data for time-domain simulations. The dynamic parameters for a sixth order full machine model (i.e., machine, exciter, and governor) are defined for each generator in the IEEE test systems. Dynamic parameters are also determined for the condensers and motors. It is to be noted that the dynamic parameters are based on typical dynamic models provided in [9]. Particularly in [9], the dynamic parameters for fossil fuel generators are according to their rated power. For each generator the dynamic parameters for its exciter and governor are also available. Therefore, knowing the rated power of each generator in the IEEE test systems (available from their steady state data) the appropriate dynamic model from [9] is selected (including the exciter and the governor). The same procedure is followed for choosing dynamic parameters for the condensers and the motors in the IEEE test systems.

The aim of Section IV of this paper is to test the proposed dynamic test bed systems under transient conditions. As it is aforementioned, there are no default responses of the IEEE systems for specific contingencies; hence, the validation of the proposed dynamic models and parameters accommodated to the test bed systems cannot be performed. A criterion for the reliability of the proposed dynamic models and parameters is to show that the dynamic behavior of the IEEE dynamic models is reasonable and is similar to dynamic responses of real systems.

The proposed modified IEEE test systems are implemented in the PowerWorld software [10]. Using the transient analysis of the software, the transient behavior of each dynamic system can be obtained. In particular, a single case study for each test system is examined and the transient analysis results are presented in Section IV. The paper concludes in Section V. It is of course possible to run the test systems in other software that support dynamic analysis.

III. Dynamic Models and Parameters for IEEE Systems

In this Section, the dynamic models and parameters for each generator, condenser, and motor in the IEEE 14 bus system are provided based on real data [9]. The full dynamic data for the IEEE 30, 39, 57, and 118 bus systems are available online in open access (*www.kios.ucy.ac.cy/testsystems*). In the case of the generators, both the associated exciter and governor parameters are given, while in the case of the condensers and motors only exciter parameters are given. The excitation and governor system models used for the implementation of the IEEE dynamic test systems in the Powerworld software were the IEEE Type1 excitation model (exciter IEEET1) and WSCC Type G governor model (governor BPA_GG) respectively. The block diagrams of both models are presented in Figs. 1 and 2. It is important to mention that the IEEE Type1 excitation model corresponds to the Type DC1A excitation system model of the IEEE Standard 421.5 (2005) [12], which is the currently accepted IEEE standard for excitation system models for power system stability studies.

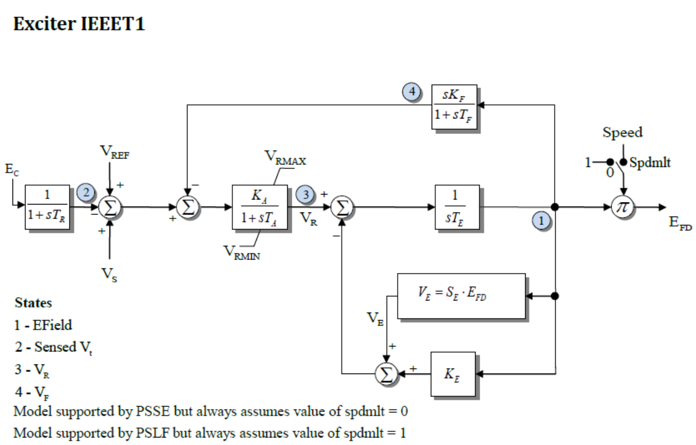

Fig. 1. Block diagram of the IEEET1 excitation system model [11]

It is important to notice that the rated voltage of the machines (generators, motors, and condensers), as indicated in

[9], is much smaller than the voltage levels of the IEEE test systems. In order to comply with the voltage levels of the generators as provided in [9], and thus build more realistic dynamic test bed systems, the machines are connected through an ideal transformer. Thus, it is necessary to add an additional bus having the same voltage level as the machine models given in [9].

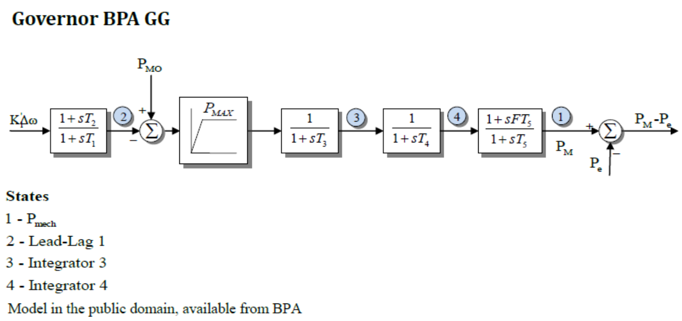

Fig. 2. Block diagram of the WSCC Type G governor [11]

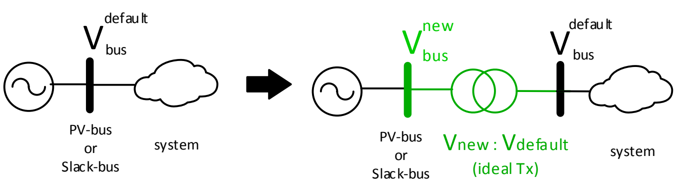

Fig. 3. Extension and modification of an existing system

Performing this modification (Fig. 3), the IEEE test systems topology is effectively not changed, and at the same time, there is no change in the operating conditions of the systems since the power flows are not affected. This can be concluded by comparing the total power losses of the systems before and after the modification, as shown in the case studies. The data of the transmission lines, existing transformers, voltage levels and other steady-state data are considered the same as those presented in [3]. Due to this modification, hereafter the IEEE test bed systems will be called as "modified IEEE systems". In order to better illustrate the modification to the IEEE dynamic test systems, the IEEE 14-bus test system before and after the modification is shown in Figs. 4 and 5 respectively.

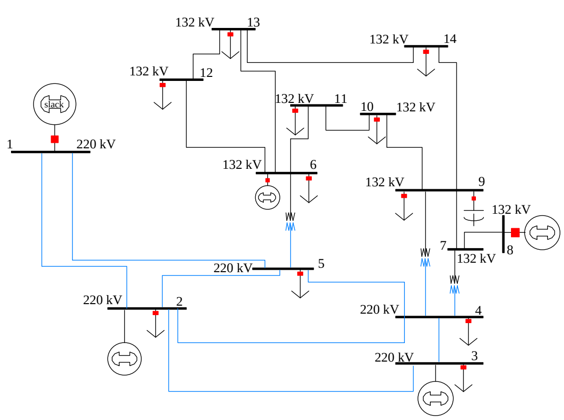

Fig. 4. IEEE 14-bus test system-default topology

The IEEE 14-bus modified test system consists of 5 synchronous machines with IEEE type-1 exciters, 3 of which are synchronous compensators used only for reactive power support. There are 19 buses, 17 transmission lines, 8 transformers and 11 constant impedance loads. The total load demand is 259 MW and 73.5 MVAr.

In the default topology of the IEEE 14-bus test system (Fig. 4), the generators and the condensers are connected to high voltage buses (132 kV or 220 kV) [3]. In the case of the IEEE 14-bus modified test system (Fig. 5), the generators and the condensers with their dynamic models are attached to the new buses added to the extended system, as explained earlier. Tables I to III provide the system data for the IEEE 14-bus modified test system. The numbers shown in the Tables for the bus numbers correspond to the default test system and the modified system (in parenthesis) respectively.

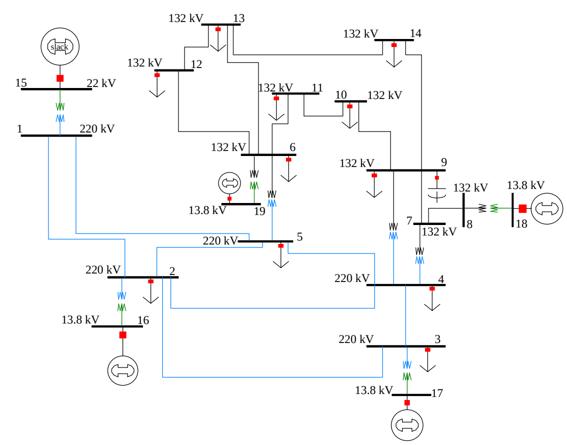

Fig. 5. IEEE 14-bus modified test system

TABLE I
IEEE 14-BUS MODIFIED TEST SYSTEM MACHINE DATA

Type	GENROU	GENROU	GENROU	GENROU
Operation	Sync. Gen.	Sync. Gen.	Condenser	Condenser
Default Unit no. (New Unit no.)	1(15)	2(16)	3(17)	6(19), 8(18)
Rated power (MVA)	448	100	40	25
Rated voltage (kV)	22	13.8	13.8	13.8
H (s)	2.656	4.985	1.520	1.200
D	2.000	2.000	0.000	0.000
r_a (p.u)	0.0043	0.0035	0.000	0.0025
x_d (p.u)	1.670	1.180	2.373	1.769
x_q (p.u)	1.600	1.050	1.172	0.855
x'_d (p.u)	0.265	0.220	0.343	0.304
x'_q (p.u)	0.460	0.380	1.172	0.5795
x''_d (p.u)	0.205	0.145	0.231	0.2035
x''_q (p.u)	0.205	0.145	0.231	0.2035
x_l or x_p (p.u)	0.150	0.075	0.132	0.1045
T'_{d0} (s)	0.5871	1.100	11.600	8.000
T'_{q0} (s)	0.1351	0.1086	0.159	0.008
T''_{d0} (s)	0.0248	0.0277	0.058	0.0525
T''_{q0} (s)	0.0267	0.0351	0.201	0.0151
$S(1.0)$	0.091	0.0933	0.295	0.304
$S(1.2)$	0.400	0.4044	0.776	0.666

TABLE II
IEEE 14-BUS MODIFIED TEST SYSTEM EXCITER DATA

Type	IEEET1	IEEET1	IEEET1	IEEET1
Default Unit no. (New Unit no.)	1(15)	2(16)	3(17)	6(19), 8(18)
Rated power (MVA)	448	100	40	25
Rated voltage (kV)	22	13.8	13.8	13.8
T_r (s)	0.000	0.060	0.000	0.000
K_a (p.u)	50	25	400	400
T_a (s)	0.060	0.200	0.050	0.050
V_{Rmax} (p.u)	1.000	1.000	6.630	4.407
V_{Rmin} (p.u)	-1.000	-1.000	-6.630	-4.407
K_e (p.u)	-0.0465	-0.0582	-0.170	-0.170
T_e (s)	0.520	0.6544	0.950	0.950
K_f (p.u)	0.0832	0.105	0.040	0.040
T_f (s)	1.000	0.350	1.000	1.000
E_1 (p.u)	3.240	2.5785	6.375	4.2375
$SE(E_1)$	0.072	0.0889	0.2174	0.2174
E_2 (p.u)	4.320	3.438	8.500	5.650
$SE(E_2)$	0.2821	0.3468	0.9388	0.9386

TABLE III
IEEE 14-BUS MODIFIED TEST SYSTEM GOVERNOR DATA

Type	BPA_GG	BPA_GG
Default Unit no. (New Unit no.)	1(15)	2(16)
Rated power (MVA)	448	100
Rated voltage (kV)	22	13.8
P_{max} (p.u)	0.870	1.050
R (p.u)	0.011	0.050
T_1 (s)	0.100	0.090
T_2 (s)	0.000	0.000
T_3 (s)	0.300	0.200
T_4 (s)	0.050	0.300
T_5 (s)	10.000	0.000
F	0.250	1.000

IV. CASE STUDIES

In this Section the proposed IEEE 14, 30, 39, 57 and 118 modified dynamic test systems are tested in order to evaluate their behavior after large disturbances. For each case study, the angle, frequency, and voltage stability are examined. Thus, a depiction of the generator rotor angle, bus voltage, and system frequency during transient conditions is obtained. More specifically, for evaluating the proposed dynamic governor models and their parameters, the system frequency is obtained for two cases. In the first case, generators are equipped with governor models, while in the second case no governor models were considered (for both cases machine and exciter dynamic models are available). Moreover, to evaluate the proposed exciter models and their parameters, voltage magnitudes and angles for selected buses are presented for the case where system generators are equipped with exciter models and without exciter models (for both cases machine and governor dynamic models are available). Finally, the rotor angle for selected generators (with full machine models) is obtained to check their dynamic response during contingencies. It is important to mention that a comparison between the total power losses of each system before and after the modification (in steady state operation) is also performed to verify that the power flows are not affected. This is shown in Tables IV to VIII.

A. *IEEE 14-Bus Modified Test System*

In order to assess the stability condition of the IEEE 14-bus modified test system during transient analysis, a single load event is considered. At time t = 1 s, the value of loads at buses 3, 4 and 9 is increased by 20% (total step change of 34.3 MW). The IEEE 14-bus modified test system response under this event is given in Figs. 6-11.

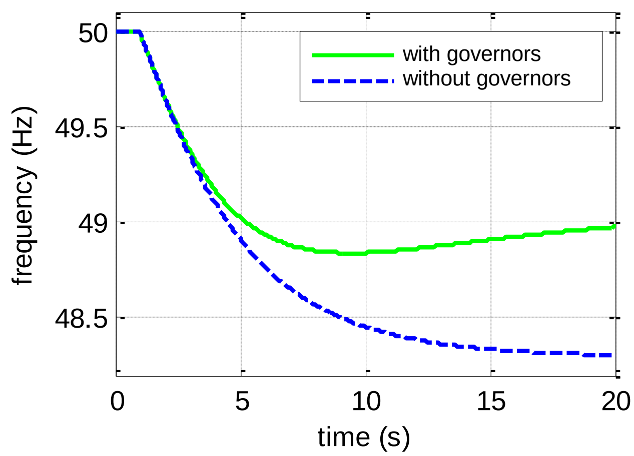

Fig. 6. System frequency in the IEEE 14-bus modified test system with and without governor models

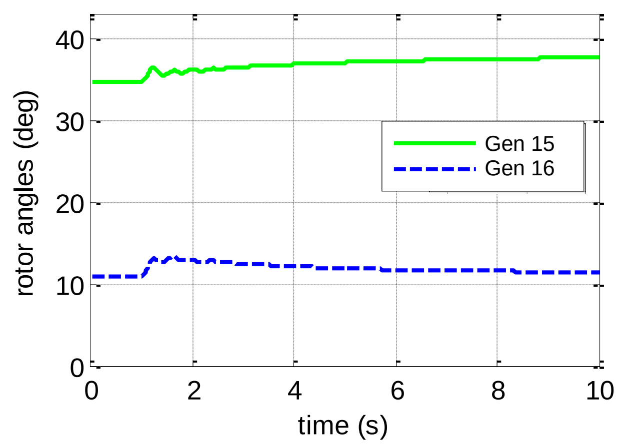

Fig. 7. Generator rotor angle for the machines in the IEEE 14-bus modified test system

TABLE IV
REAL POWER LOSSES IN IEEE 14-BUS SYSTEM

Losses in default topology (MW)	Modified topology (MW)
15.2	15.2

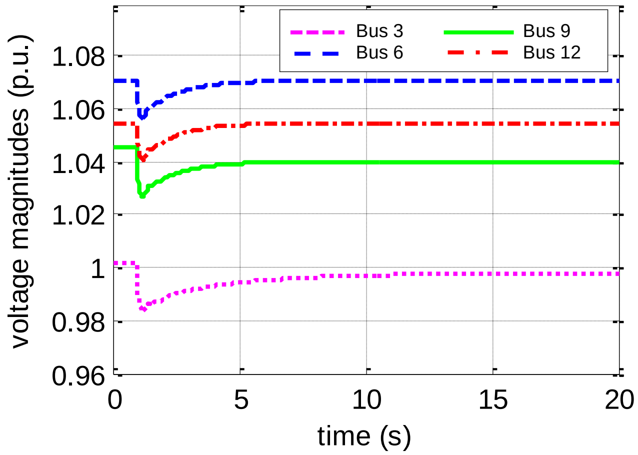

Fig. 8. Voltage magnitudes for selected buses in the IEEE 14-bus modified test system with exciter models

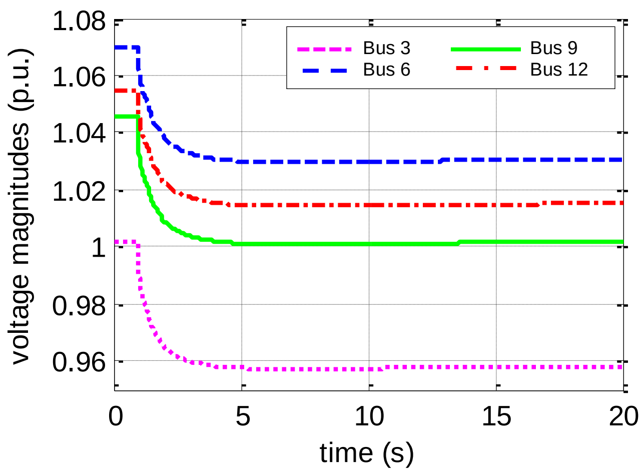

Fig. 9. Voltage magnitudes for selected buses in the IEEE 14-bus modified test system without exciter models

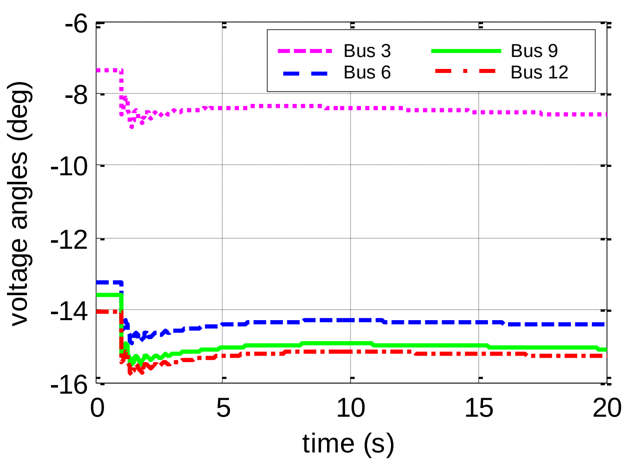

Fig. 10. Voltage angles for selected buses in the IEEE 14-bus modified test system with exciter models

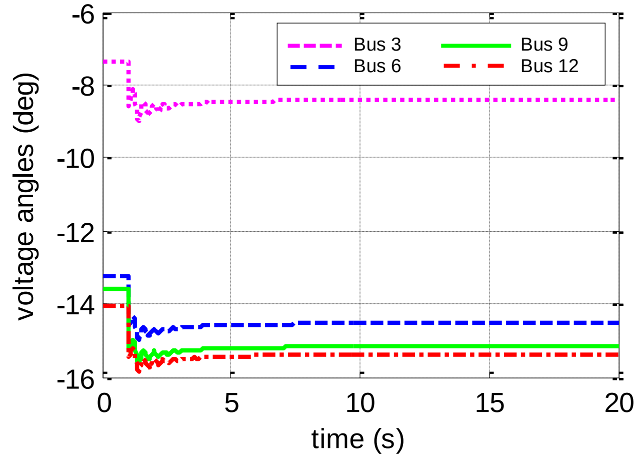

Fig. 11. Voltage angles for selected buses in the IEEE 14-bus modified test system without exciter models

B. IEEE 30-Bus Modified Test System

The IEEE 30-bus modified test system has 6 synchronous machines with IEEE type-1 exciters (4 of which are synchronous compensators), 36 buses, 37 transmission lines, 10 transformers and 21 constant impedance loads (with a total consumption of 283.4 MW and 126.2 MVAr).

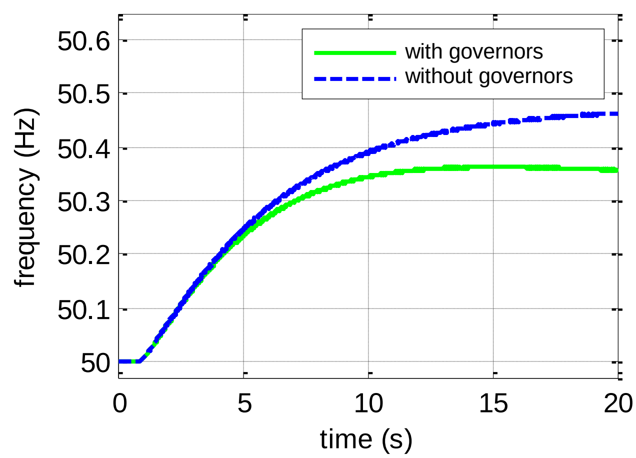

Fig. 12. System frequency in the IEEE 30-bus modified test system with and without governor models

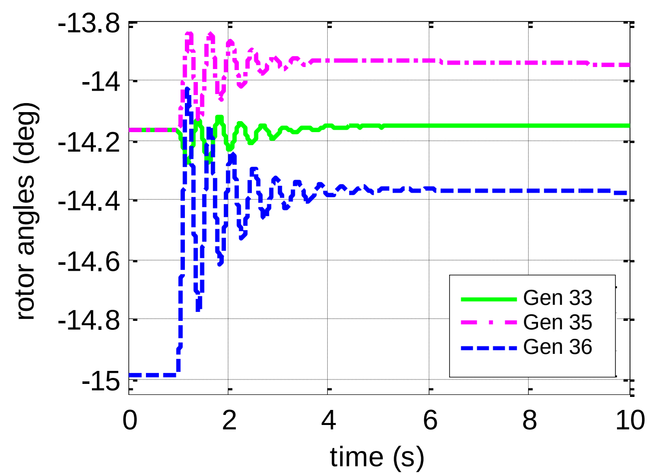

Fig. 13. Generator rotor angle for selected machines in the IEEE 30-bus modified test system

At time $t = 1$ s, both ends of the transmission lines connecting buses 14-12 and 14-15 are opened and thus bus 14 is isolated from the rest of the power system. The ability of the IEEE 30-bus modified test system to return to stable condition and maintain its synchronism is evaluated in Figs. 12-17.

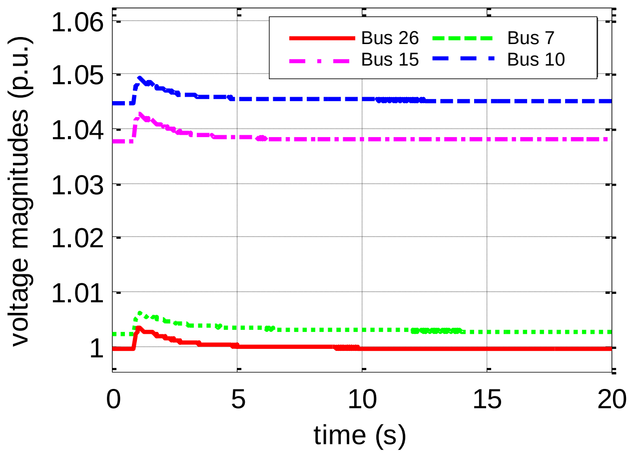

Fig. 14. Voltage magnitudes for selected buses in the IEEE 30-bus modified test system with exciter models

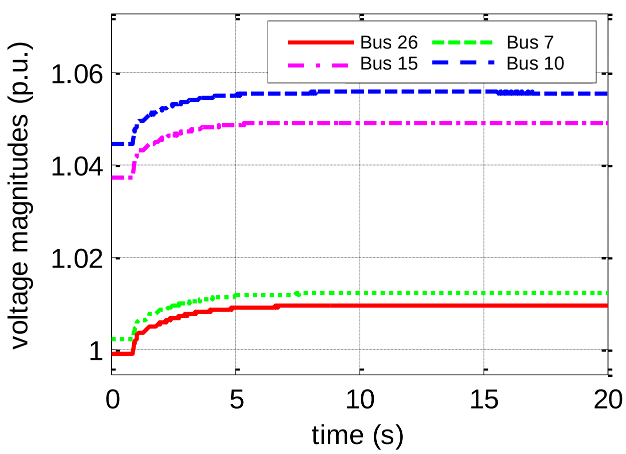

Fig. 15. Voltage magnitudes for selected buses in the IEEE 30-bus modified test system without exciter models

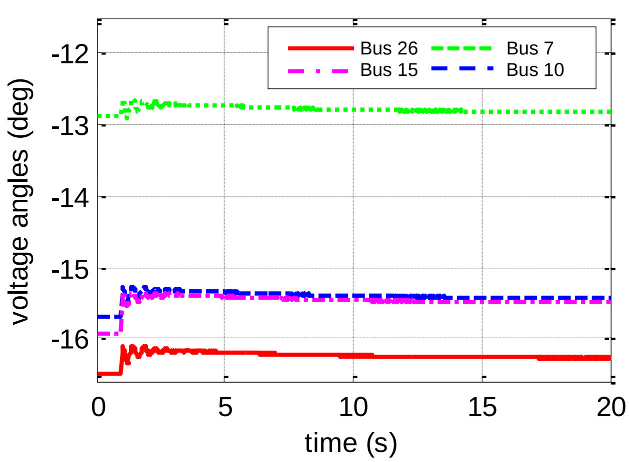

Fig. 16. Voltage angles for selected buses in the IEEE 30-bus modified test system with exciter models

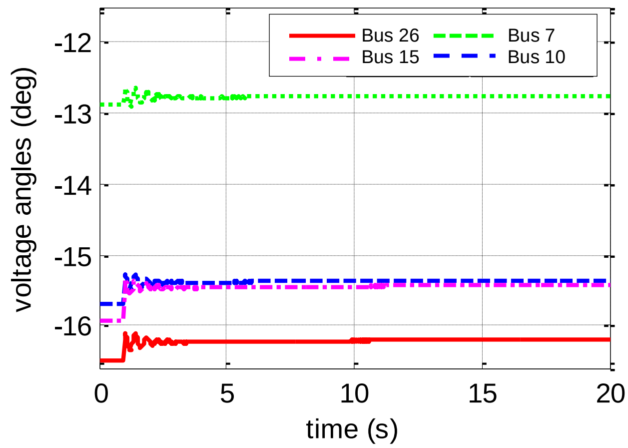

Fig. 17. Voltage angles for selected buses in the IEEE 30-bus modified test system without exciter models

TABLE V
REAL POWER LOSSES IN IEEE 30-BUS SYSTEM

Losses in default topology (MW)	Modified topology (MW)
17.5	17.5

C. IEEE 39-Bus Modified Test System

The IEEE 39-bus modified test system contains 49 buses, 32 transmission lines, 24 transformers and 10 generators. It has 19 constant impedance loads totaling 6097.1 MW and 1408.9 MVAr. All the generators are equipped with an IEEE type-1 exciter and a simple turbine governor, except generator 39 which is an aggregation of a large number of generators and is considered not to have a governor. The behavior of the IEEE 39-bus modified test system during transient analysis is evaluated by considering a single load event. At time $t = 1$ s, the value of loads at buses 3, 4, 7, 8, 25 and 39 is increased by 10% (total step change of 290.58 MW). Figures 18-23 show the response of the corresponding system during the event.

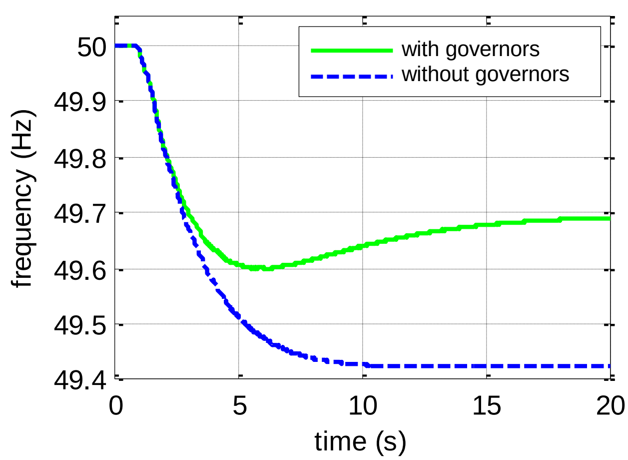

Fig. 18. System frequency in the IEEE 39-bus modified test system with and without governor models

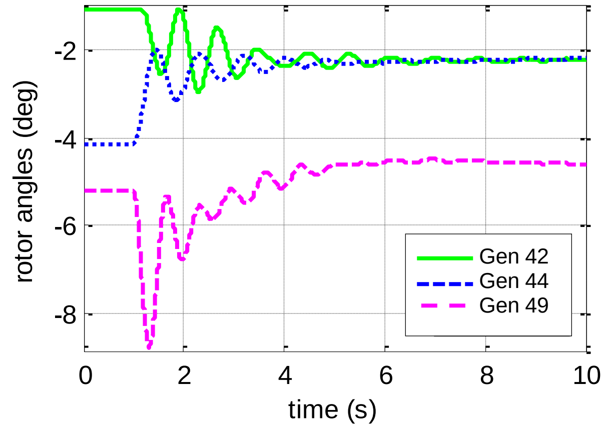

Fig. 19. Generator rotor angle for selected machines in the IEEE 39-bus modified test system

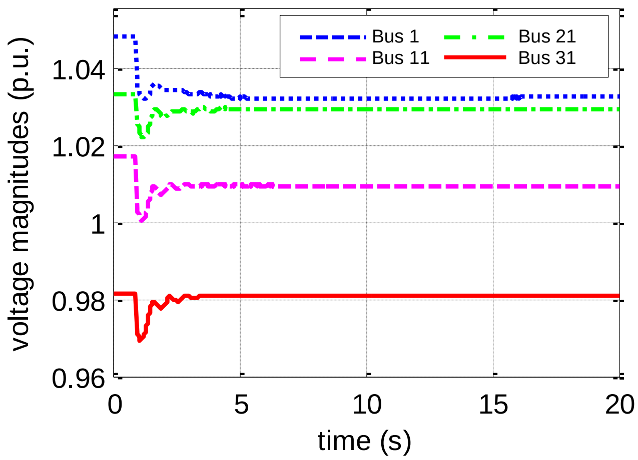

Fig. 20. Voltage magnitudes for selected buses in the IEEE 39-bus modified test system with exciter models

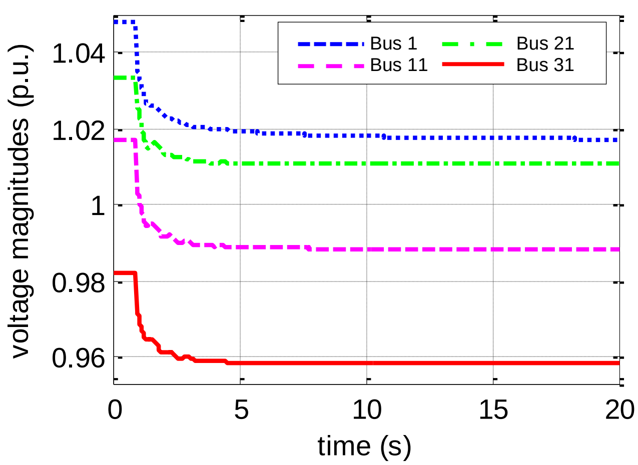

Fig. 21. Voltage magnitudes for selected buses in the IEEE 39-bus modified test system without exciter models

TABLE VI
REAL POWER LOSSES IN IEEE 39-BUS SYSTEM

Losses in default topology (MW)	Modified topology (MW)
42.8	42.8

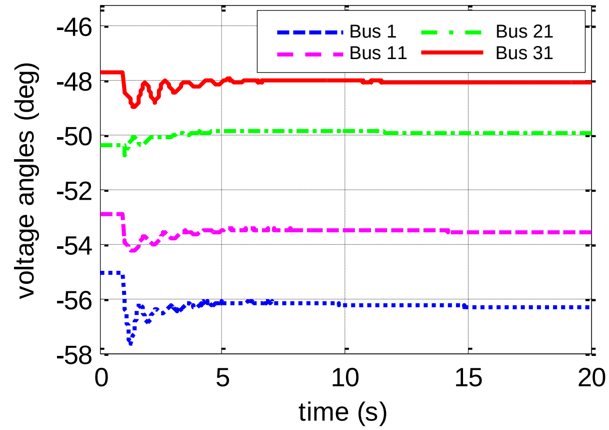

Fig. 22. Voltage angles for selected buses in the IEEE 39-bus modified test system with exciter models

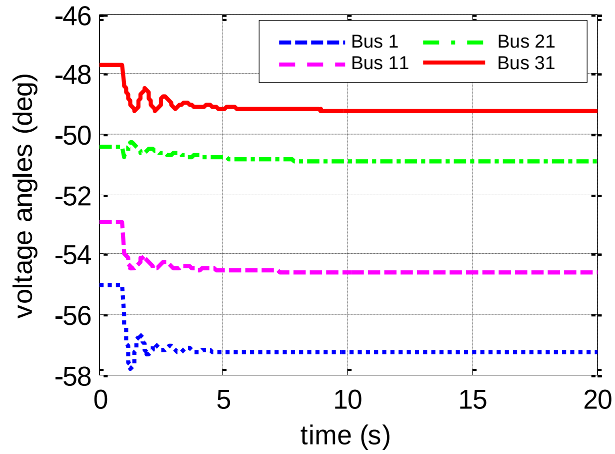

Fig. 23. Voltage angles for selected buses in the IEEE 39-bus modified test system without exciter models

In addition, the stability condition of the IEEE 39-bus modified test system during transient analysis is further assessed by considering a worst case scenario. At time t = 1 s, a balanced three phase fault is applied at bus 39 and is cleared at t=1.2 s. As shown in Fig. 24, if the system generators are not equipped with governor models, then the system will collapse.

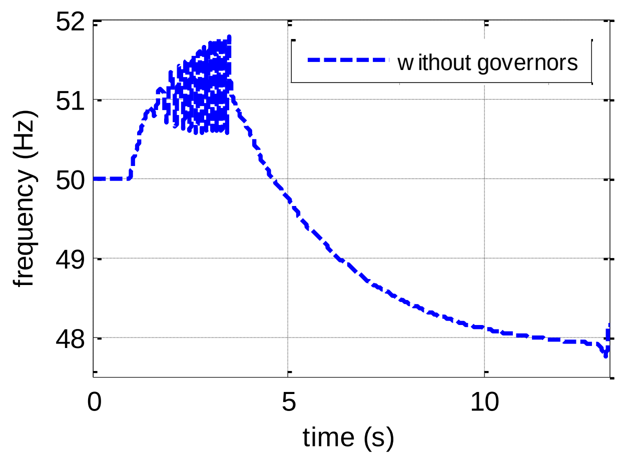

Fig. 24. System frequency in the IEEE 39-bus modified test system without governor models

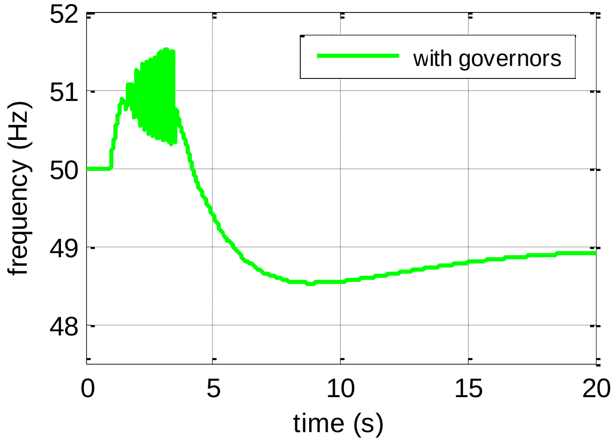

Fig. 25. System frequency in the IEEE 39-bus modified test system with governor models

In particular, when the speed limits of a generator are violated (in this case the speed drops below 48 Hz or exceeds 52 Hz), auxiliary corrective measures are applied (e.g., under/over frequency control), and the corresponding generator is tripped. Consequently, since the system generators are not equipped with any governor models, a sequence of generator trips ensues leading to system collapse. However, if the system generators are equipped with governor models, a generator trip through an under/over frequency control scheme does not lead to more generator trips, since the governors maintain the speed of each generator close to the nominal speed. As a result, the system can withstand the fault and it can maintain its synchronism, as shown in Fig. 25.

D. IEEE 57-Bus Modified Test System

The IEEE 57-bus modified test system has 7 synchronous machines with IEEE type-1 exciters (3 of which are synchronous compensators), 64 buses, 65 transmission lines, 22 transformers and 42 constant impedance loads (with a total of 1250.8 MW and 336.4 MVAr). The stability condition of the IEEE 57-bus modified test system is assessed through a single load event. At time $t = 1$ s, the value of loads at buses 1, 2, 12, 16 and 17 is increased by 10% (total step change of 52 MW). The IEEE 57-bus modified test system response under this event is given in Figs 26-31.

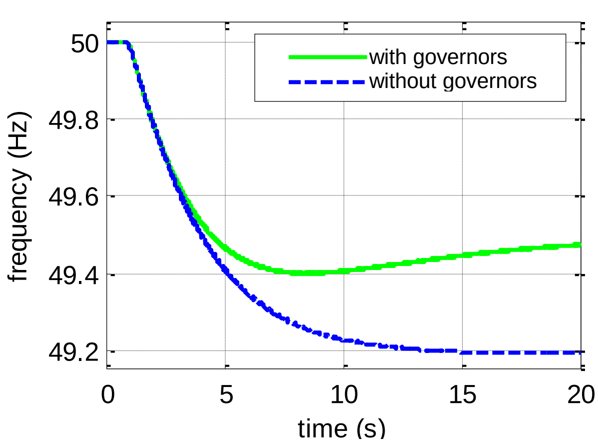

Fig. 26. System frequency in the IEEE 57-bus modified test system with and without governor models

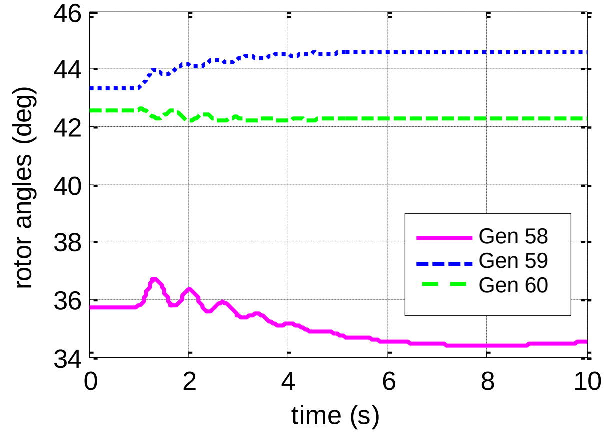

Fig. 27. Generator rotor angle for selected machines in the IEEE 57-bus modified test system

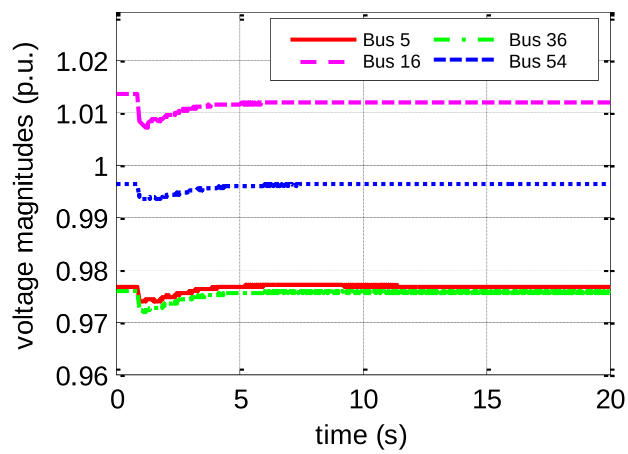

Fig. 28. Voltage magnitudes for selected buses in the IEEE 57-bus modified test system with exciter models

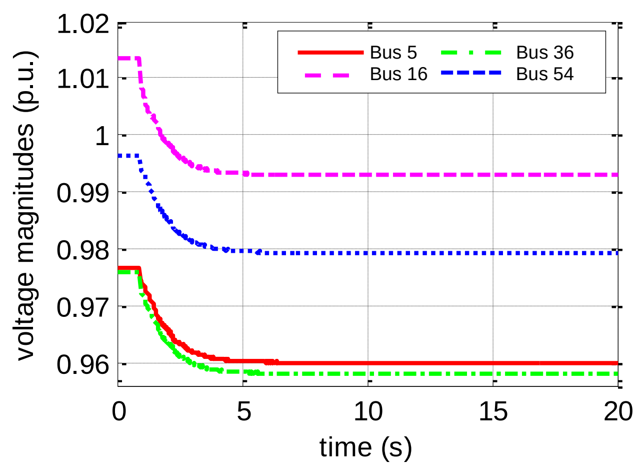

Fig. 29. Voltage magnitudes for selected buses in the IEEE 57-bus modified test system without exciter models

TABLE VII
REAL POWER LOSSES IN IEEE 57-BUS SYSTEM

Losses in default topology (MW)	Modified topology (MW)
27.9	27.9

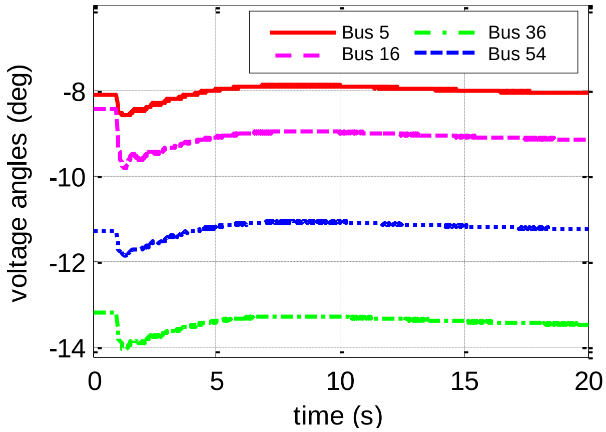

Fig. 30. Voltage angles for selected buses in the IEEE 57-bus modified test system with exciter models

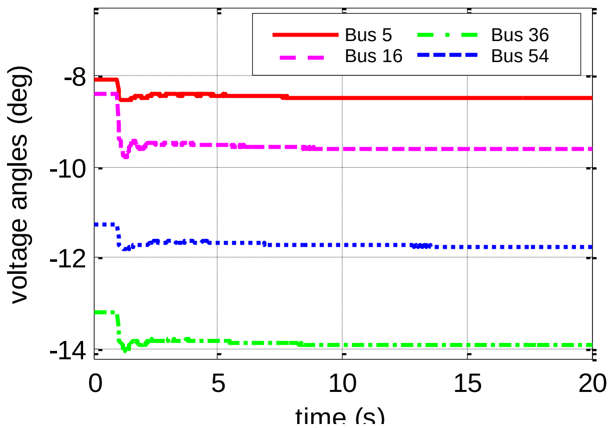

Fig. 31. Voltage angles for selected buses in the IEEE 57-bus modified test system without exciter models

E. IEEE 118-Bus Modified Test System

The IEEE 118-bus modified test system consists of 54 synchronous machines with IEEE type-1 exciters, 20 of which are synchronous compensators used only for reactive power support and 15 of which are motors. There are 172 buses, 185 transmission lines, 76 transformers and 91 constant impedance loads, which consume in total 3668 MW and 1438 MVAr. To evaluate the behavior of the IEEE 118-bus modified test system during transient analysis, a switch event is considered.

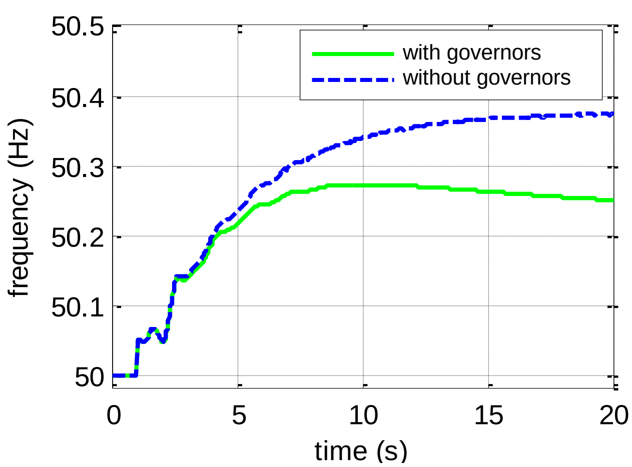

Fig. 32. System frequency in the IEEE 118-bus modified test system with and without governor models

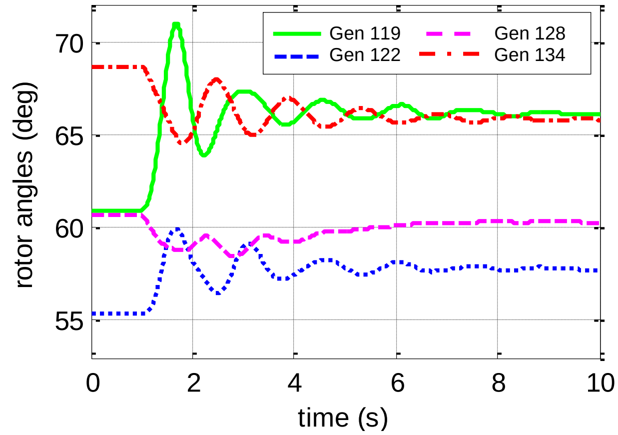

Fig. 33. Generator rotor angle for selected machines in the IEEE 118-bus modified test system

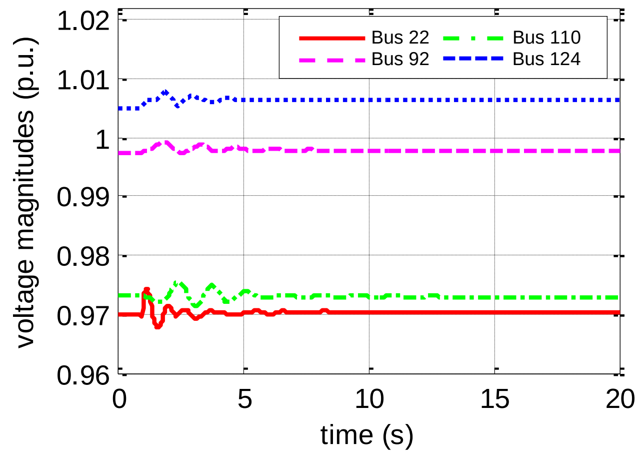

Fig. 34. Voltage magnitudes for selected buses in the IEEE 118-bus modified test system with exciter models

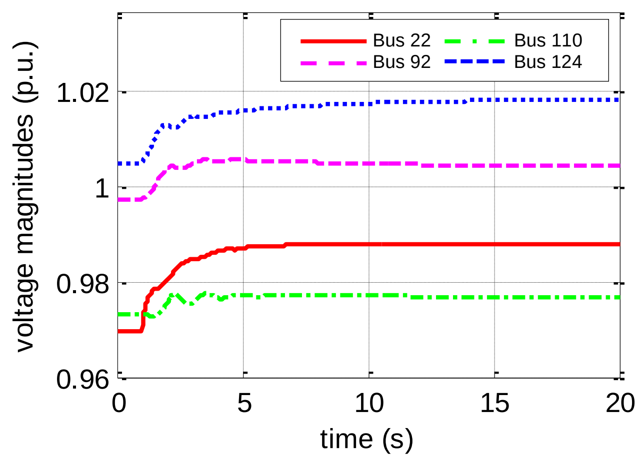

Fig. 35. Voltage magnitudes for selected buses in the IEEE 118-bus modified test system without exciter models

At time $t = 1$ s, both ends of transmission lines connecting buses 13-11, 13-15, 14-12 and 14-15 are opened (bus 13 and 14 are isolated) creating a transient instability into the system. The ability of this system to return to stable condition and maintain its synchronism is evaluated in Figs. 32-37.

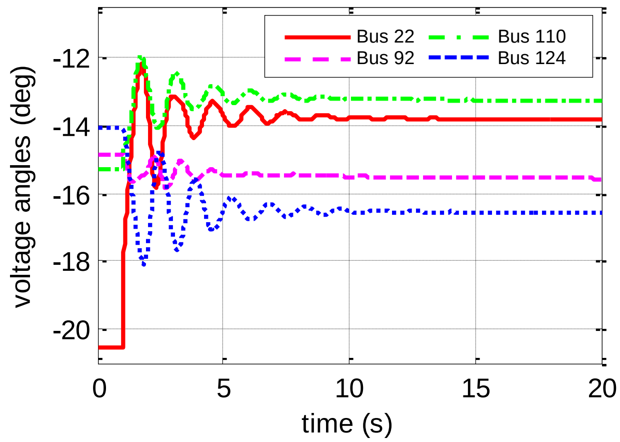

Fig. 36. Voltage angles for selected buses in the IEEE 118-bus modified test system with exciter models

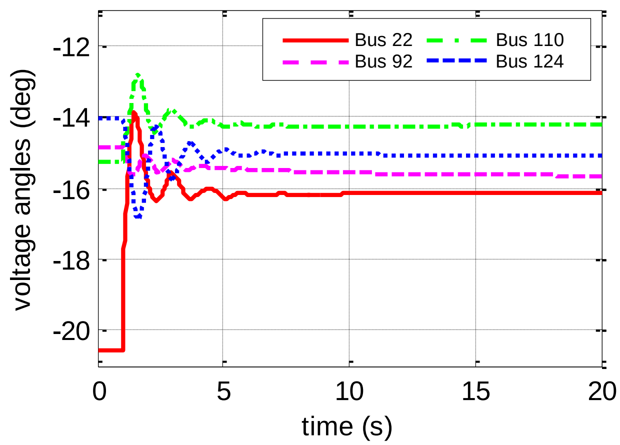

Fig. 37. Voltage angles for selected buses in the IEEE 118-bus modified test system without exciter models

TABLE VIII
REAL POWER LOSSES IN IEEE 118-BUS SYSTEM

Losses in default topology (MW)	Modified topology (MW)
122.3	122.3

V. CONCLUSIONS

In this paper the dynamic models and the dynamic parameters for sixth order full machine models (i.e., machine, exciter, and governor) as well as for the condensers and motors contained in the IEEE 14, 30, 39, 57, and 118 bus systems are defined based on typical data provided in [9]. The topology of the proposed dynamic IEEE test bed systems was slightly altered from the default one by adding new buses with a lower voltage level for the generators, condensers, and motors, in order to be compliant with the rated voltage level of the dynamic models provided in [9]. The procedure followed in this paper for including dynamic models into a system can be generalized for several systems, assuming that the rated power of the generators, motors, and condensers are known. The dynamic test systems complement the existing steady state systems. Based on the simulation results, it can be concluded that the dynamic models with the proposed typical parameters are reliable since the dynamic response of the IEEE modified test systems follows the expected behavior of actual systems under contingencies. It is shown that the proposed governor models play a crucial role in the maintenance of the system frequency, even under severe faults. Moreover, the voltage magnitudes of the buses for all the test systems are preserved close to their pre-fault values in the presence of the proposed exciter models. In the case of the rotor angle stability, it is obvious that the generators maintain synchronism between them after the occurrence of a fault.

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