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Transient Stability Analysis of the Transmission System Considering the Initial Steady State Results

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Abstract- **In modern power systems, nonlinear power system stability under normal conditions depends on the magnitude of disturbances and the initial conditions. In other words, after a disturbance occurs in the power system, the system stability is determined by the observation of voltage, frequency and rotor angle. Transient stability examines the impact of disturbances on power systems considering the operating conditions. The analysis of the dynamic behavior of power systems for the transient stability gives information about the ability of a power system to sustain synchronism during and after the disturbances. In this paper, the transient stability of the IEEE-9-bus modified test system is analyzed with Matpower and PowerWorld software under a 3-phase balanced short-circuit.**

Keywords: **analysis of transient stability, power system stability, transmission systems, power system dynamic stability, dynamic machine models**

I. INTRODUCTION

The transient, dynamic, and steady-state stability analyses are performed considering the structure of the electrical power system and electrical power devices. The structure of the electrical power system is basically classified into three categories: generation, transmission, and distribution. Each of these power system parts operates at different voltage levels, namely extra high voltages, high voltages, medium voltages and low voltages [1].

Voltage, rotor angle and frequency of electrical power units are dynamically examined to understand the system time domain stability during the period of the disturbance [2]. The dynamic behavior of synchronous machines or time domain stability in power systems gives information about the rotor angle stability and the synchronism ability after being subjected to large and small disturbances, such as drops in bus voltages or load changes [3]. The analysis of the voltage stability in the power system is assessed by comparing each of the buses' pre-fault voltages with the voltages that are calculated or observed after the disturbances are cleared [4].

An imbalance between the load and the generation of the power system makes the system frequency unstable, and the stability of frequency refers to the ability to restore the system frequency in order to decrease the loss of load with operating in an acceptable state of equilibrium [3]. Under small or large disturbances, the power system's transient stability refers to the ability to reach an acceptable operating condition, which can be a new equilibrium state or the initial steady state after the disturbances have disappeared [5].

While power flow analysis gives information about the power system equilibrium point and is used for the calculation of the transfer capacity limits before large disturbances occur and are cleared, results cannot be obtained by the load flow analysis during the interconnecting transient. That's why transient stability analysis with time domain simulation is necessary to observe the system's transient response during large disturbances [7].

When large disturbances, such as line tripping, occur in a power system, the faults are cleared and fixed in a short period of time by fast protection systems included in the power system in order to provide system reliability and security [8].

During these large disturbances, the dynamic parameters of devices are used to analyze the system's transient stability, which depends on the system's devices, such as synchronous generator, exciter, governor, voltage-source converter, and load model [9].

In this paper, the IEEE 9-bus test system is modified and analyzed using time domain dynamic simulation and steady state load flow simulation. In the network, there are three different synchronous generators, which are used with different controller devices, such as exciters and governors.

The aim of this paper is to analyze the transient stability of the system when some of the generators are deactivated under the same fault which impacts the network in a specific period of time. Before analyzing the transient stability, power flow analysis is made for each case to indicate the steady state results.

The proposed IEEE 9 test system is analyzed using Matpower and PowerWorld software, which are available online in [10] and [11]. The same fault analysis is performed for different cases to see the behavior of synchronous generators, and to observe the system's general transient response. After the transient behaviors of the synchronous generators are simulated, the frequency of the power system is controlled by changing the governor parameter using PowerWorld, and MATLAB software.

II. DYNAMIC MODELS OF POWER SYSTEM COMPONENTS

In this section, a generator, an exciter, and a governor are described with their dynamic model parameters.

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A. *Dynamic Model of the Synchronous Generator*

The following standard parameters in Table I are used for the dynamic analysis of the synchronous generator.

TABLE I
THE PARAMETERS OF THE SYNCHRONOUS GENERATOR

Inductive reactance's and resistances		Unit
r_a	Armature resistance	p.u.
x_d, x_q	Unsaturated d, and q axis synchronous reactance	p.u.
x'_d, x'_q	Unsaturated d, and q axis transient reactance	p.u.
x''_d, x''_q	Unsaturated d and q axis subtransient reactance.	p.u.
x_l or x_p	Leakage reactance	p.u
Field circuit time constants		
T'_{d0}, T'_{q0}	d axis transient open circuit time constant	S
T'_{q0}	q axis transient open circuit time constant	S
T''_{d0}	d axis subtransient open circuit time constant	S
T''_{q0}	q axis subtransient open circuit time constant	S
Inertia of generator		
H(s)	Inertia constant	S

In the synchronous generator, the winding model four, which is a 6th-order model including leakage reactance, is used with these parameters. Stator and network transients are not considered in the model [12].

The 6th order of the synchronous generator equations is specified in [13] as follows:

$$E'_d T'_{d0}=[-E'_d+(X_q-X'_q)\{I_q-\frac{X'_q-X''_q}{(X'_q-X_{lk,s})^2}*(\psi_{2q}+(X'_q-X_{lk,s})I_q+E'_d)\}] \quad (1)$$

$$E'_q*T'_{d0}=[-E'_q+(X_d-X'_d)\{I_d-\frac{X'_d-X''_d}{(X'_d-X_{lk,s})^2}*(\psi_{1q}+(X'_d-X_{lk,s})I_d+E'_q)\}] \quad (2)$$

$$\psi_{1q}=\frac{1}{T''_{d0}}[-\psi_{1d}+E'_q-(X'_d-X_{lk,s})I_d] \quad (3)$$

$$\psi_{1d}=\frac{1}{T''_{q0}}[-\psi_{1q}+E'_d-(X'_q-X_{lk,s})I_q \quad (4)$$

$$\Delta\omega_r=\frac{1}{2H}[P_m-P_e-D\Delta\omega_r] \quad (5)$$

$$\dot{\delta}=(\omega_r-\omega_{syn})=\Delta\omega_r \quad (6)$$

The equations of the dynamic system analysis are specified separately for d-axis and q-axis that are accomplished by Park's transformation [14].

B. *Dynamic Model of the Exciter*

The exciter is a generating unit that protects the synchronous generator during a fault and helps to achieve the stabilization of the power system. The exciter system controls the field current of the synchronous generator according to the required terminal voltage of the alternator [15].

TABLE II
THE PARAMETERS OF THE EXCITER

Parameters of Exciter		Unit
K_a	Regulator gain (continuous acting regulator)	p.u.
V_{RMAX}	Maximum regulator output	p.u.
V_{RMIN}	Minimum regulator output	p.u.
K_e	Exciter self-excitation	p.u.
K_f	Regulator stabilizing circuit gain	p.u
E_1	Field voltage value,1	p.u.
$SE(E_1)$	Saturation factor at E1	p.u.
E_2	Field voltage value,2	p.u.
$SE(E_2)$	Saturation factor at E2	*p.u.*
T_r	Regulator input filter time constant	S
T_d	Regulator time constant	S
T_f	Regulator stabilizing circuit time constant	S
T_e	Exciter time constant	S

The parameters of the IEEE type1 exciter system are described for the time domain system analysis while the system is operating under large short circuit disturbances [17].

The equations of the exciter type are listed in [14] as follows:

$$\dot{E}_{FD}*T_E=(-[K_E+S_E(E_{FD})]E_{FD}+V_R) \quad (1)$$

$$\dot{V}_2*T_F=\frac{K_F}{T_F}E_{FD}-V_2 \quad (2)$$

$$\dot{V}_1*T_R=V_T-V_1 \quad (3)$$

$$V_{ERR}=V_{REF}-V_1 \quad (4)$$

$$V_F=\frac{K_F}{T_F}E_{FD}-V_2 \quad (5)$$

$$F_R=\frac{1}{T_A}[-V_R+K_A(V_{ERR}+V_S-V_F)] \quad (6)$$

$$V_r=\begin{cases} V_{r,max} & \text{if } V_R>V_{R,max} \\ \dot{V}_R=0 & \text{if } V_R=V_{R,max} \text{ and } F_R>0 \\ V_{r,min} & \text{if } V_r<V_{r,min} \\ \dot{V}_R=0 & \text{if } V_R=V_{R,max} \text{ and } F_R<0 \\ \int F_R & \text{else} \end{cases} \quad (7)$$

C. *Dynamic Model of the Governor*

The turbine governor is the main controller of the synchronous generator that makes the system real power and frequency more stable while the power system is affected by disturbances. A governor is a control model that provides necessary mechanical power input to the synchronous generator [18]. The following parameters of the governor are used for the dynamic analysis of the power system.

TABLE III
THE PARAMETERS OF THE GOVERNOR

P_{max}	Maximum turbine output	p.u
R	Turbine steady-state regulation setting or droop	p.u
T_1	Control time constant	S
T_2	Hydro reset time constant	S
T_3	Servo time constant	S
T_4	Steam valve bowl time constant	S
T_5	Steam reheat time constant	S
F	Shaft output ahead of reheater	p.u

The used governor model is specified by the following governor block diagram. Detailed information about the model can be found in [19].

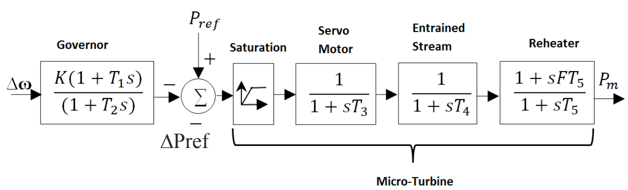

Fig. 1. Block diagram of the micro turbine and governor combination.

In this governor model, the input is the differences between the reference speed setting of the governor and the speed measurement, whereas the output signals equal the desired power [19].

III. THE SIMULATION RESULTS OF THE NETWORK

A. Power Flow Simulation of the IEEE- 9 Bus model

In this section, the power flow simulation of the IEEE 9-bus system is analyzed using the MATLAB™'s Matpower Package m-file software, and in the second section, the transient dynamic analysis of the system is simulated under different fault effects using PowerWorld software.

The dynamic models and parameters of the IEEE 9-bus system for the synchronous generator, exciter and governor are used according to the real data presented in [10] and [11].

Power flow results of the system using the Newton-Raphson Method are obtained as in Fig. 2.

```
How many?                    How much?              P (MW)
---------------------        -------------------   --------
Buses                  9     Total Gen Capacity      820.0
Generators             3     On-line Capacity        820.0
Committed Gens         3     Generation (actual)     325.7
Loads                  3     Load                    315.0
  Fixed                3       Fixed                 315.0
  Dispatchable         0       Dispatchable           -0.0
Shunts                 0     Shunt (inj)             -0.0
Branches               8     Losses (I^2 * Z)        10.68
Transformers           0     Branch Charging (inj)     -
Inter-ties             0     Total Inter-tie Flow      0.0
```

Fig. 2. The power flow results of the system using Matpower

The results of different power flow analyses are obtained as in the following table.

TABLE IV
THE RESULTS OF THE DIFFERENT STATUS OF POWER FLOW ANALYSIS

Generator Data					Losses (Branches)	
Gen	Bus	Status	Pg (MW)	Qg (MVAr)	Pg (MW)	Qg (MVAr)
All the generators active						
1	1	1	77.68	2.44		
2	2	1	163.00	78.95		
3	3	1	85.00	11.05	10.68	85.15
The second generator is deactivated						
1	1	1	244.02	103.01		
3	3	1	85.00	30.75	14.02	121.28
The third generator is deactivated						
1	1	1	170.16	39.00		
2	2	1	163.00	114.32	18.16	136..92

The printed output results of the Matpower simulation are obtained using the Matpower options that enable different solution algorithms.

B. The Dynamic Simulation Results of the IEEE- 9 Bus System

For the dynamic transient simulation of the network, the PowerWorld software is used. The network system is edited according to the power flow data for Bus 9, generator case 3.

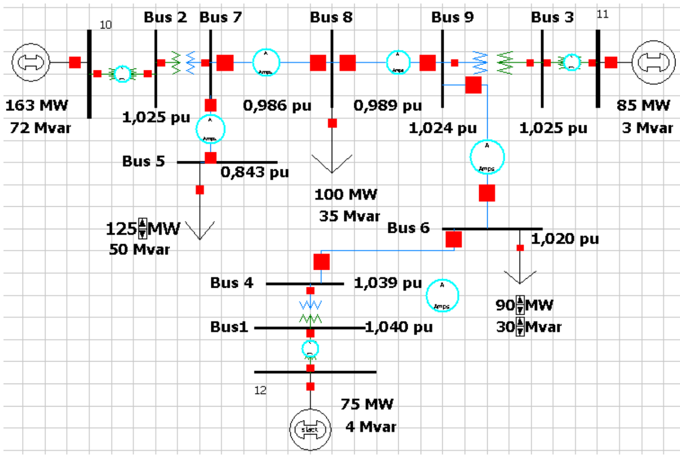

Fig. 3. Modified the IEEE 9-bustest system.

In the network, the first synchronous generator, which is connected with the defined slack bus (Bus 1), operates in each internal fault case, and the behavior of the synchronous generators under the faults are analyzed.

A different governor and a different exciter system with their parameters are used for each synchronous generator device.

The line parameters, which are taken from [10], are changed depending on the bus numbers of the power system network. The first generator is connected to Bus 1, the second generator is connected to Bus 2 and the third synchronous generator is connected to Bus 3.

TABLE V
THE LINE PARAMETERS

Line No.	From Bus	To Bus	X (p.u)	Flow Limit (MW)
1	1	4	0,0576	250
2	4	6	0,092	250
3	6	9	0,17	150
4	3	9	0,0586	300
5	9	8	0,1008	150
6	8	7	0,072	250
7	7	2	0,0625	250
8	7	5	0,161	250

In this case, the three-phase short circuit fault, which is described as a large disturbance, is examined for different operating conditions to analyze the generator's transient stability. The created fault is the same for each situation. The fault occurs in Bus 3 with the following fault information.

TABLE VI
THE FAULT INFORMATION

	Fault Location	Time (Cycles)	Time (Seconds)
1	Bus 3 – Apply Fault	15	0,3
2	Bus 3 – Clear Fault	22,5	0,45
3	Bus 3 – Apply Fault	22,5	0,6
4	Bus 3 – Clear Fault	30	0,75

In this case, the dynamic transient response of the synchronous generator is obtained as in the following Fig. 4.

In the first case, when the fault occurs in Bus 3, the speed

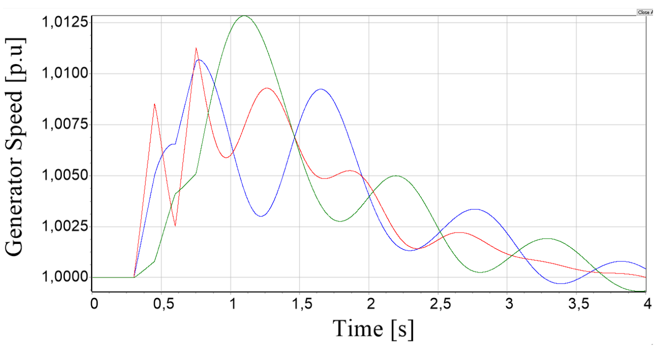

Fig. 4. The speed of the synchronous generators- all the synchronous generators are active in the system.

of the generator which is connected to Bus 3 is decreasing, and the speeds of other generators are increasing to support the system during the fault.

In the second case, the fault is also created in Bus 3 with the same fault information, and the second synchronous generator is deactivated from the network in this time.

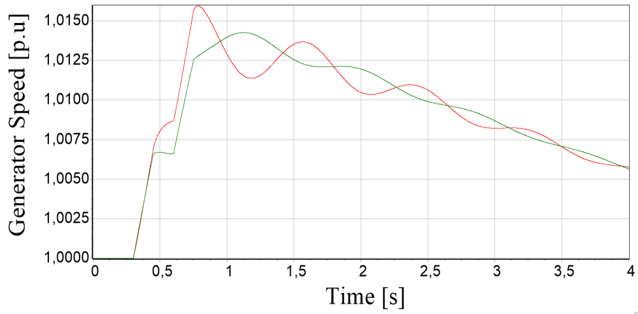

Fig. 5. The speed of the synchronous generator - the second synchronous generator is deactivated.

When the fault occurs in the same bus, the speeds of the synchronous generators in the second case decrease more slowly than the speeds of the first case synchronous generators. At the end of the time measured, the speeds of the synchronous generators in the second case are still higher than the speeds of the first case synchronous generator.

In the third case, the fault is located on the same bus (Bus 3) with the same fault information, and the third synchronous generator is deactivated from the network in this time.

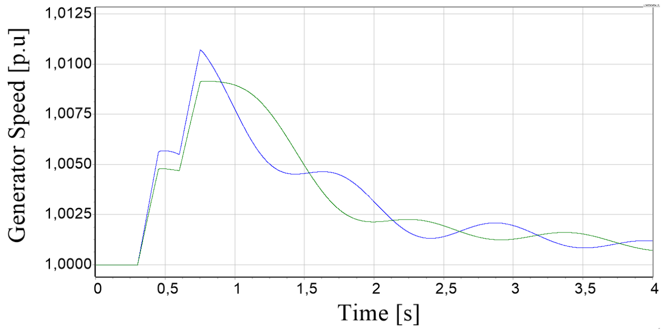

Fig. 6. The speed of the synchronous generators- the third synchronous generator is deactivated in the system.

While the fault occurs in Bus 3, the speeds of the synchronous generators in the third case fall more sharply than the speeds of the second case synchronous generators. Also, while the maximum speed of the synchronous generator in the second case is 1.0160, the maximum speed of the synchronous generator in the third case is 1.0105.

In the last case, the fault also occurs in Bus 3 with the same fault information, and the second and the third synchronous generator are deactivated from the network. Before the simulation, the total reactive power losses are calculated at 166.52 MVAr using the Matpower package software, and during the simulation PowerWorld creates an error which disables dynamic simulation.

In the second case, at the end of the simulation time, the speed of the first synchronous generator, which is connected to the slack bus, is higher than the speeds of the first and the third case synchronous generators. Due to the imbalance between the generation and the load of the power system, the frequency is also unstable. The frequency of the power system is analyzed by observing the transient frequency of Bus 3.

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The results are obtained with the same fault events. In the first case, the frequency of Bus 3 is obtained as in the following Fig. 7.

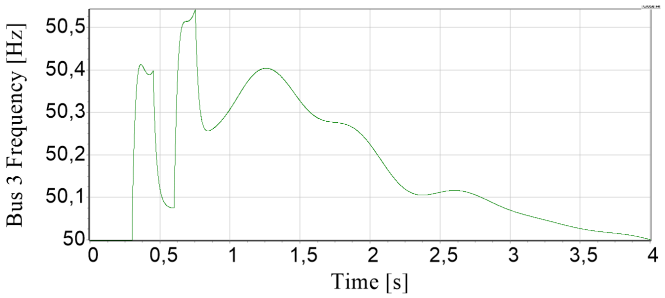

Fig. 7. The frequency of the third bus - all the synchronous generators are active in the system.

In the second case, the transient frequency behavior of Bus 3 is obtained as in the following Fig. 8.

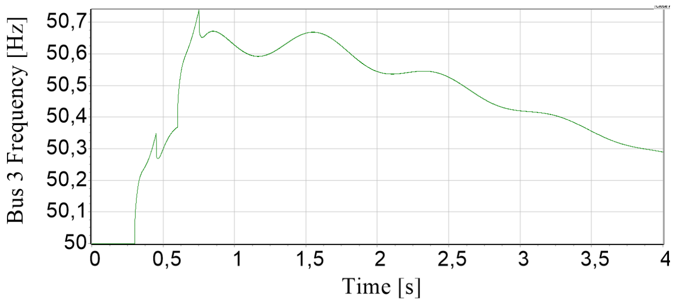

Fig. 8. The frequency of the third bus - the second synchronous generator is deactivated.

In the last case, when the third synchronous generator is deactivated from the network, the frequency fluctuations of Bus 3 during the fault is observed as in the following Fig. 9.

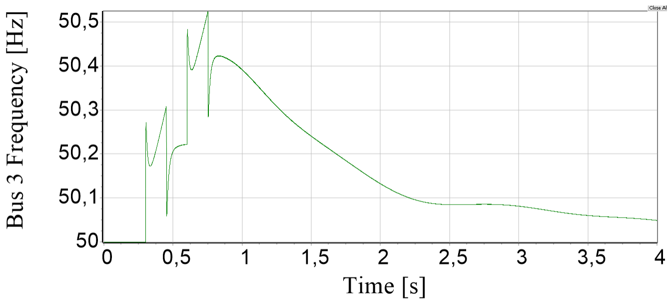

Fig. 9. The frequency of the third bus - the second synchronous generator is deactivated.

The results show that the largest fluctuation in the frequency of Bus 3 occurs during the second case when the second synchronous generator is deactivated from the network. The parameters of the first governor model are examined to control the frequency of Bus 3 during the fault. The examination is done considering the second fault event, in which Bus 3 has the frequency of 50.3 Hz in the steady state. The transfer function of the micro turbine model can be written as in the following equation.

$$\frac{Pm}{\Delta Pref}=\frac{1+sFT_5}{1+s(T_3+T_4+T_5)+s^2(T_3T_4+T_3T_5+T_4T_5)+s^3(T_3T_4T_5)} \quad (8)$$

As it can be seen in the transfer function, the output power of the micro turbine and governor combination is increased by decreasing T3, T4, and increasing F. When the transfer function is increased, the frequency of the power system is more stable after the fault is cleared. In other words, the mechanical power input to the synchronous generators are increased by increasing the output power of the micro turbine and governor combination.

In this case, the reheater parameters of the first governor are examined to observe the change of frequency in Bus 3. The steam reheat time constant of the governor model, which is specified as T5, is set from 5 to 10 seconds, and the results are obtained for the second case as in the following Fig. 10.

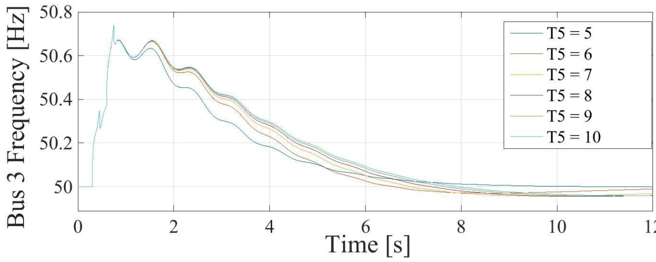

Fig. 10. The frequency of the third bus – The steam reheat time constant of the first synchronous generator is changed.

The results show that when the steam reheat time constant of the first synchronous generator is set to 10 seconds, which is defined as the maximum value in the simulation, the amplitude of the frequency response is higher than the others in the first 5 seconds. On the contrary, after the fault is cleared, the frequency of the bus is more stable, and close to the steady state frequency response when the steam reheat time constant is decreased.

IV. CONCLUSION

In this paper, the transient analysis of the IEEE-9 bus modified test system is performed. The dynamic model of the generator, exciter and governor are used according to the defined model in [17]. After the power flow simulation has been calculated using the Newton-Raphson Method under different operating conditions, the transient stability of the system is tested with the same fault. Simulation results show that the fault location in the power system has a great influence on the speed of the synchronous generator. When some synchronous generators are deactivated before the fault occurs, the transient stability of the network is critically affected depending on the distance of the fault. The frequency of the bus, in which the faults are created, is controlled by tuning the steam reheat time constant. The results show that when the steam reheat time constant, which is specified as T5 in the reheater of the micro turbine model, is decreased, the frequency of the power system is more stable after the fault is cleared. . As it can be seen in Fig. 4, and Fig. 10, the more a power system is balanced with supplied power and power losses depending on the short circuit distances, the less time it takes the network to reach transient stability. As a result, the parameters of the models and the output power has a great impact to the power system stability.

APPENDIX

This Appendix provides the data about the synchronous machines, governors and exciters which are used in this paper.

TABLE VII
THE SYNCHRONOUS GENERATOR DYNAMIC ANALYSIS DATA OF THE IEEE-9 BUS MODIFIED TEST SYSTEM

Unit Number	1	2	3
Rated Power (MVA)	512	270	125
Rated Voltage (kV)	24	18	15.5
Rated pf	0.9	0.85	0.85
H (s)	2.6312	4.1296	4.768
D	2.000	2.000	2
ra (p.u)	0.004	0.0016	0.004
Xd (p.u)	1.700	1.700	1.220
Xq (p.u)	1.650	1.620	1.160
X'd (p.u)	0.270	0.256	0.174
X'q (p.u)	0.470	0.245	0.250
X''d ; X1 or Xp (p.u)	0.200	0.185	0.134
T'do (s)	3.800	4.800	8.970
T'qo(s)	0.480	0.500	0.500
T''do (s)	0.010	0.010	0.033
T''qo(s)	0.0007	0.007	0.070
S(1.0)	0.090	0.125	0.1060
S(1.2)	0.400	0.450	0.432

TABLE VIII
THE EXCITER DYNAMIC ANALYSIS DATA OF THE IEEE-9 BUS MODIFIED TEST SYSTEM

Unit Number	1	2	3
Rated Power (MVA)	512	270	125
Rated Voltage (kV)	24	18	15.5
Tr (s)	0.000	0.000	0.060
Ka (p.u)	200	30	25
Ta (s)	0.395	0.400	0.200
Vrmax, Vrmin (p.u)	± 3.840	± 4.590	± 1.000
Ke (p.u)	1.000	-0.020	-0.0601
Te (s)	0.000	0.560	0.6758
Kf (p.u)	0.0635	0.050	0.108
Tf (s)	1.000	1.300	0.350
E1 (p.u)	2.880	2.5875	2.4975
SE (E1)	0.000	0.7298	0.0949
E2 (p.u)	3.840	3.450	3.330
SE (E2)	0.000	1.3496	0.37026

TABLE IX
THE GOVERNOR DYNAMIC ANALYSIS DATA OF THE IEEE-9 BUS MODIFIED TEST SYSTEM

Unit Number	1	2	3
Rated Power (MVA)	512	270	125
Rated Voltage (kV)	24	18	15.5
Pmax (p.u)	0.8984	0.8518	1.056
R (p.u)	0.00976	0.01852	0.040
T1 (s)	0.150	0.100	0.083
T2 (s)	0.050	0.000	0.000
T3 (s)	0.300	0.259	0.200
T4 (s)	0.260	0.100	0.050
T5 (s)	8.000	10.000	5.000
F	0.270	0.272	0.280

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