

TRANSIENT STABILITY ENHANCEMENT OF A TYPICAL 2×30 MW THERMAL POWER PLANT AND VALIDATION THROUGH IEEE 9-BUS TEST SYSTEM - A CASE STUDY

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Abstract: *Now-a-days, the per-capita consumption which dictates the development of any nation has been increased because of the sophisticated life. Because of the industrial growth, the power system network becomes more complex and widespread. The quality and reliability of the electrical power are the key factors in such a complex power system. In grid connected operation, the stability plays a major role to ensure the reliable power to the customers. In this paper, an attempt has been made to analyze the transient stability of a typical 2×30 MW thermal power plant using Electrical Transient Analyzer Program (ETAP) software. Power flow response of the typical system has been studied and the voltage limit violation and overloading conditions were also analyzed. Stability of the system for various cases in the presence of the controllers namely governor, exciter and power system stabilizer (PSS) has also been studied. The simulation responses have been analyzed based on critical clearing time (t_{cc}) and critical clearing angle (δ_{cc}) and an optimal combination of these controllers for the best transient stability response has also been identified. In addition, the stability behavior has been validated using the standard IEEE 9-bus test system. Simulation response of the typical 2×30 MW thermal power plant and IEEE 9-bus system show that the stability of any system can be improved by the optimal combination of controllers as identified in this paper. The detailed description of the transient stability study and the simulation response of both the systems have been furnished in this paper.*

Keywords: *Electrical Transient Analyzer Program (ETAP), Exciter, Governor, IEEE 9-bus system, Power System Stabilizer (PSS), Thermal power plant, Transient stability enhancement.*

I. Introduction

Electric power consumption is an important deciding factor for the development of any country and the generated power should be of high quality and more reliable [1], [2]-[4]. The power plants should be

operated with high reliability as well as economical for electrical power generation and thermal applications [5]. The complexity of the power system network is increased due to the distributed generation and grid interconnection [3], [6]. Since the electric power system is wide spread, it is continuously subjected to various disturbances, which may lead to instability [5]. Due to the industrial growth, the power transfer capacity of the existing system needs to be increased after being analyzed and the power balance should be maintained between the source and the load to ensure the stable operation of a power system [7], [8]. The power system studies are needed to analyze the performance of the power system at both planning and running stages [9]-[12]. The successful operation of a power system mainly depends on its ability to provide reliable power to the load [13]-[15]. To facilitate the reliable power, the power system components should be designed properly and the power system studies such as power flow, short circuit and stability study have to be performed in advance for different operating scenario [5]. A continual and comprehensive analysis of a power system is needed to know the status of the power system at present and in future by taking into account the future expansion [5]. In recent years, the electrical engineers have been focusing on analyzing the power system using software tools. Due to the recent advances in electrical engineering and computational techniques, many software tools have been developed for performing power system studies [5], [16]-[19].

In this paper, the power flow and transient stability of the typical 2×30 MW thermal power plant have been analyzed using ETAP. Since ETAP is the most effective and user friendly tool to perform the power system studies [20], [21], it has been chosen in this

paper to simulate the typical 2×30 MW thermal power plant. Violation of bus voltage limits and overloading conditions of the components have been ensured by load flow analysis. It is found from the stability responses that the stability has been enhanced by using various controllers namely exciter, governor and Power System Stabilizer (PSS). Later, the transient responses are validated by performing the stability analysis on the standard IEEE- 9 bus test system. The sections in this paper are organized as follows. Section II presents the complete description of both the systems considered for analysis (i.e.) the typical 2×30 MW thermal power plant and IEEE 9-bus system. Section III describes about the transient stability analysis. The simulation results of the systems are furnished and discussed in section IV. The major

findings based on the simulation results are highlighted in section V.

II. System Description

Thermal power plants play an important role in supplying reliable power out of total power generation. Therefore, a typical 2×30 MW thermal power plant is considered in this paper and its responses are analyzed. The complete description about the major components of the typical 2×30 MW thermal power plant and IEEE 9-bus test system are presented in this section. The single line diagram of the typical 2×30 MW thermal power plant having all the major components is shown in Figure 1. The electrical ratings of the major components of the typical 2×30 MW thermal power plant are furnished in Appendix 1.

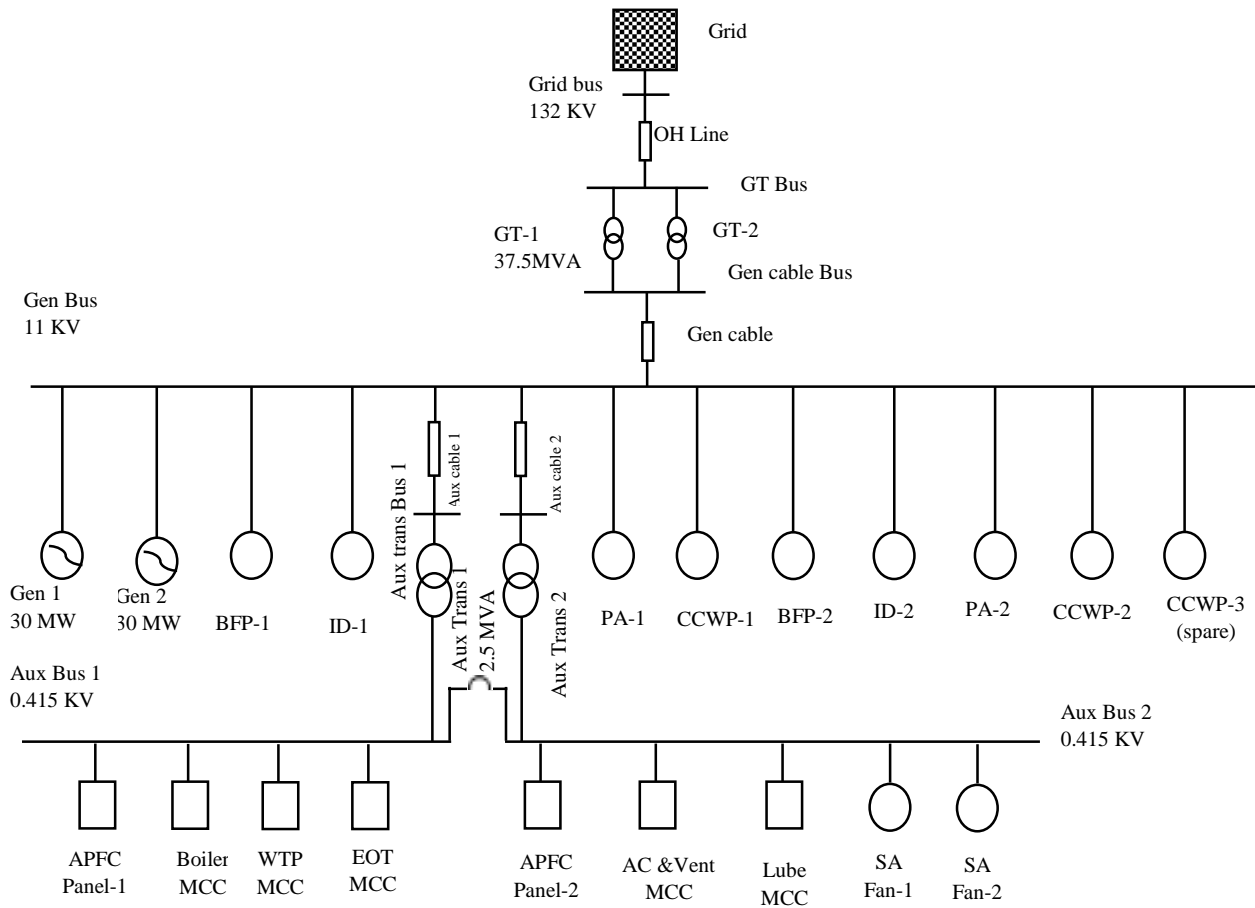


Fig. 1. Single line diagram of the typical 2×30 MW thermal power plant

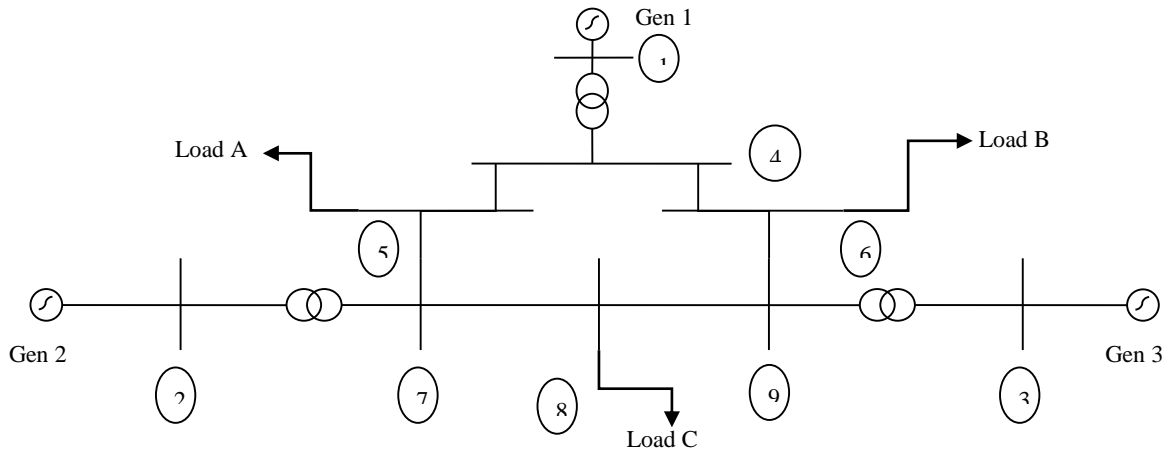


Fig. 2. Single line diagram of IEEE 9-bus test system

Table 1 Major components of typical 2×30 MW thermal power plant

S.No.	Name of the component	Quantity
1	Steam turbine generator	2
2	Generation transformer (GT)	2
3	Auxiliary transformer	2
4	HT motors	8
5	LT motors	2
6	Power cables	3
7	APFC panel	2
8	Boiler MCC	1
9	Water Treatment Plant (WTP) MCC	1
10	Electrical Overhead Travelling (EOT) MCC	1
11	AC and Ventilation MCC	1
12	Lube MCC	1

The typical 2×30 MW thermal power plant consists of 8 main buses namely Grid bus, GT bus, Gen cable bus, Gen bus, Aux Trans bus-1, Aux Trans bus-2, Aux bus-1 and Aux bus-2. 75 MVA of power is being evacuated from the system to the grid at 132 KV through Lychee Aluminum Conductor Steel Reinforced (ACSR) conductor. Cross Linked Polyethylene (XLPE) armoured cable is used to supply the power to the auxiliary equipments.

The IEEE 9-bus test system considered for validating the responses has 3 generators, 3 GT, 3 Lumped loads and 9 buses [22], [23]. The IEEE 9-bus test system has a total generation of 519.5 MW and a connected load of 335.445 MVA. It has 6 transmission lines which connects the 3 generators and 3 lumped loads. The single line diagram of the IEEE 9- bus test

system is shown in Figure 2. The line parameters and the generator data are furnished in Appendix 2.

III. Model Description of Controllers

The modern day electrical power system has realized the drastic growth and become more complex. In order to manage the effective power delivery in such a complex system, proper modeling and control of the power system are essential [24], [25]. The electrical power system is characterized with many control functions viz., voltage control, power system stabilizer control and governor control loops as shown in Figure 3. The frequency, f , generated power, P_g , terminal voltage of the generator, V_g and the actual power output, P_{actual} are the input signals for various control loops. The model description of controllers namely governor, exciter and power system stabilizer are briefed as below.

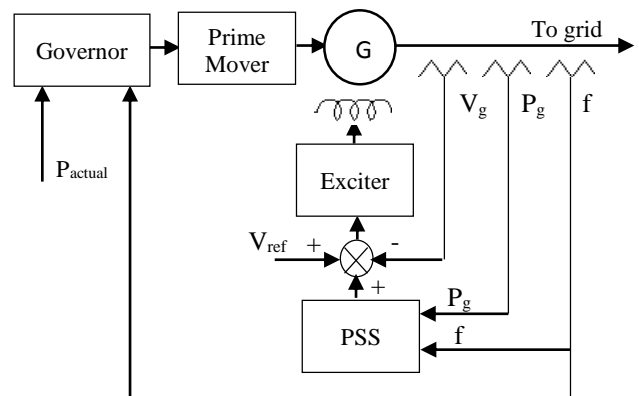


Fig. 3. Control functions in Power System

In a practical situation, frequent load deviation cause for the considerable speed deviation from the

desired speed. The speed governor mechanism can control the power and frequency of the system [26]. Various governor control techniques were analyzed for the governor control of the power plants [27]–[29]. General block diagram of the governor control system of steam power plant has been shown in Figure 4. ST Governor is used in this paper for the analysis.

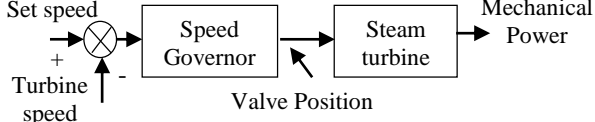


Fig. 4. Governor control system of thermal plant

The voltage fluctuation is also another issue caused by the frequent load disturbances in the power system [30]. In order to maintain the quality of the output voltage of the synchronous generator, various components of the excitation system namely amplifier, exciter and generator have to be modeled properly. The dynamic simulation model of the excitation control system is shown in Figure 5. In this paper, Type-1 exciter has been used for analyzing the performance of thermal power plant.

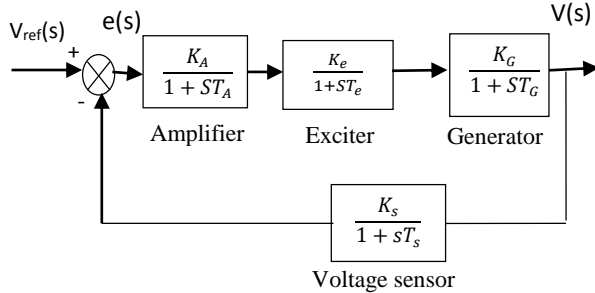


Fig. 5. Dynamic simulation model of Excitation Control system

Power System Stabilizer (PSS) provides an additional input to the voltage regulator in order to damp out the power system oscillations [26]. However the PSS can also have more impact on the transient stability of the power system. Various control schemes are proposed for the PSS using soft computing techniques [31]–[34]. The components of the PSS are modeled and the overall transfer function model of PSS has been presented in Figure 6 [35].

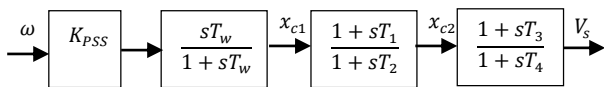


Fig. 6. Transfer function model of PSS

The controller gain of PSS (K_{PSS}), time constants of lead block (T_1 and T_2) and time constants of lag

block (T_3 and T_4) are tuned based on the system oscillation. In this paper, the transient stability of the typical thermal power plant has been analyzed by using PSS1A stabilizer in ETAP.

IV. Transient stability Analysis

Now-a-days the power system becomes more stressed because of the increase in demand that cause for more transient events and hence affect the system stability. Therefore, it is indeed necessary to assess the stability of a power system [4], [10], [13], [22], [36]–[40]. It is required to avoid huge financial losses as well in such transient conditions [16], [41]. Since the power flow analysis supplies the solutions which are the initial conditions to perform transient stability study, the power flow analysis of the typical 2×30 MW thermal power plant is studied in this paper [2], [3]. The under voltage problem causes the overheating of motor which may damage the equipment [1], [5]. The load growth and decrease in power factor leads to increased system loss and reduced system capacity which makes the power flow analysis as an essential step in operational condition [1], [3], [5]. In ETAP, the load flow analysis module calculates the bus voltages, currents and power flows in the entire radial and loop connected systems [36]. The load flow analysis is generally carried out to ensure that the bus voltages are within the limit and the power components such as transformers and transmission lines are not overloaded. In this paper, the NR method is chosen as the technique to obtain power flow solutions.

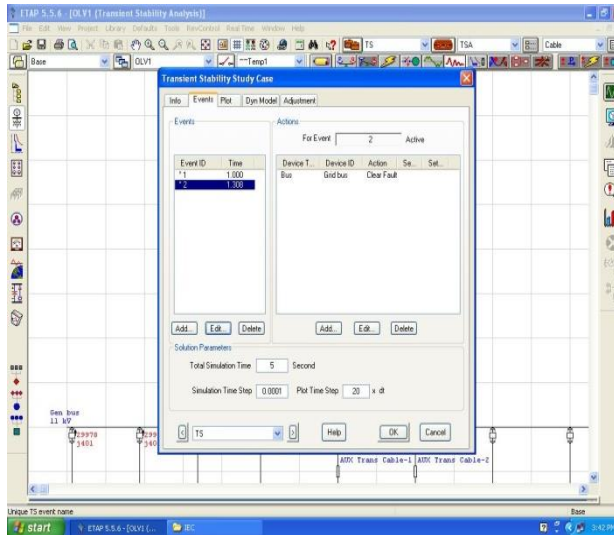
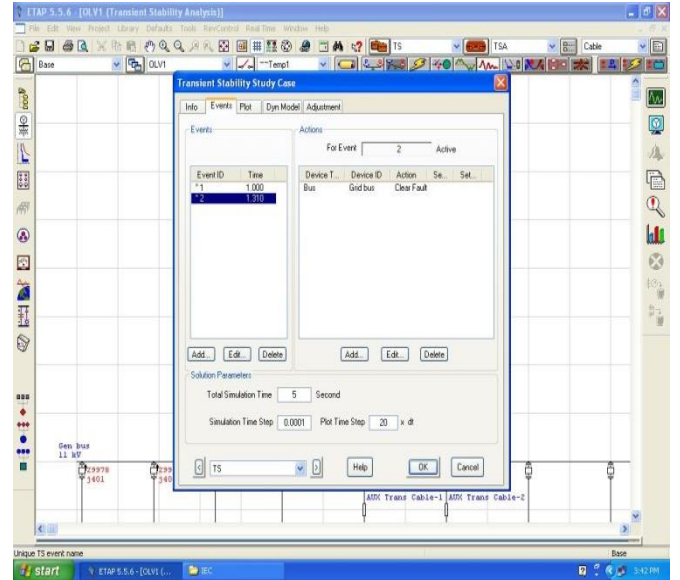
Power system stability is an ability of the electric power system to be in steady state under normal operation to regain a state of operating equilibrium after being subjected to a disturbance [26]. It is used to determine the nature of relaying scheme, circuit breaker selection, design of protection system and assess the transfer capability between the systems [11], [23], [38], [42]. The critical clearing time (t_{cc}) is the main criteria for the assessment of transient stability. The rotor angle oscillations are expected to be within 180 degrees to ensure the stable operation [11], [42]. The various parameters affecting the transient stability are presented in [40], [43]–[46].

In this paper, the transient stability analysis has been performed for a three phase fault on the generator bus of the typical 2×30 MW thermal power plant by simulating the single line diagram for a period of 5 second. The stability of the typical plant has been analyzed for various cases based on the controllers as given in Table 2.

Table 2 System condition for various cases

Case	System condition
Case-1	Without exciter and governor
Case-2	With Type 1 exciter
Case-3	With ST governor
Case-4	With Type 1 exciter and ST governor
Case-5	With ST governor, Type 1 exciter and PSS 1A

The transient stability of the system is assessed based on t_{cc} and δ_{cc} , when the system is subjected to disturbances. In ETAP, the t_{cc} and δ_{cc} is obtained by arbitrarily creating the events for the fault occurrence and fault clearing at different point of time within a total simulation time of 5 seconds. Initially, the three phase fault is created on Gen bus at 1 second by creating an event in the study case tool bar of ETAP and the same is cleared at 1.290 second (290 ms after the fault occurrence) as shown in Figure 7. An another event is created to have a three phase fault on Gen bus at 1 second by the same procedure and the fault is cleared during 1.292 second (292 ms after the fault occurrence) as shown in Figure 8. The transient stability responses of the typical 2×30 MW thermal power plant for various cases have been analyzed with respect to t_{cc} as in section IV. Then, the transient stability responses of the standard IEEE 9- bus test system for the above cases have also been analyzed and the responses are validated.

**Fig. 7. Transient stability study case window for the fault clearing at 1.290 second****Fig. 8. Transient stability study case window for the fault clearing at 1.292 second**

V. Results and Discussion

In this paper, the power flow and transient stability of the typical 2×30 MW thermal power plant is being analyzed using ETAP. The contribution of governor, exciter and PSS for the transient stability enhancement is also verified. The transient stability responses are also being validated using the standard IEEE 9-bus test system. The simulation responses of both these systems are presented in this section in two phases viz., transient response and steady state response. The load flow analysis is performed for the typical 2×30 MW thermal power plant using ETAP software by NR method and the solution is found to converge within 2 iterations. The load flow solution of the typical 2×30 MW thermal power plant has been shown in single line diagram as in Figure 9. The load flow results and the generation, load and loss details are furnished in Tables 3 and 4 respectively.

Based on the load flow results, it is found that all the bus voltages are within the limit ($\pm 2\%$) and hence the system does not require any voltage compensating devices. It is also clear from the results that none of the components in the system are overloaded. After ensuring that the bus voltages are not violated the limit and the generator, transformer and transmission lines are not overloaded, the transient stability of the typical 2×30 MW thermal power plant is assessed as given below.

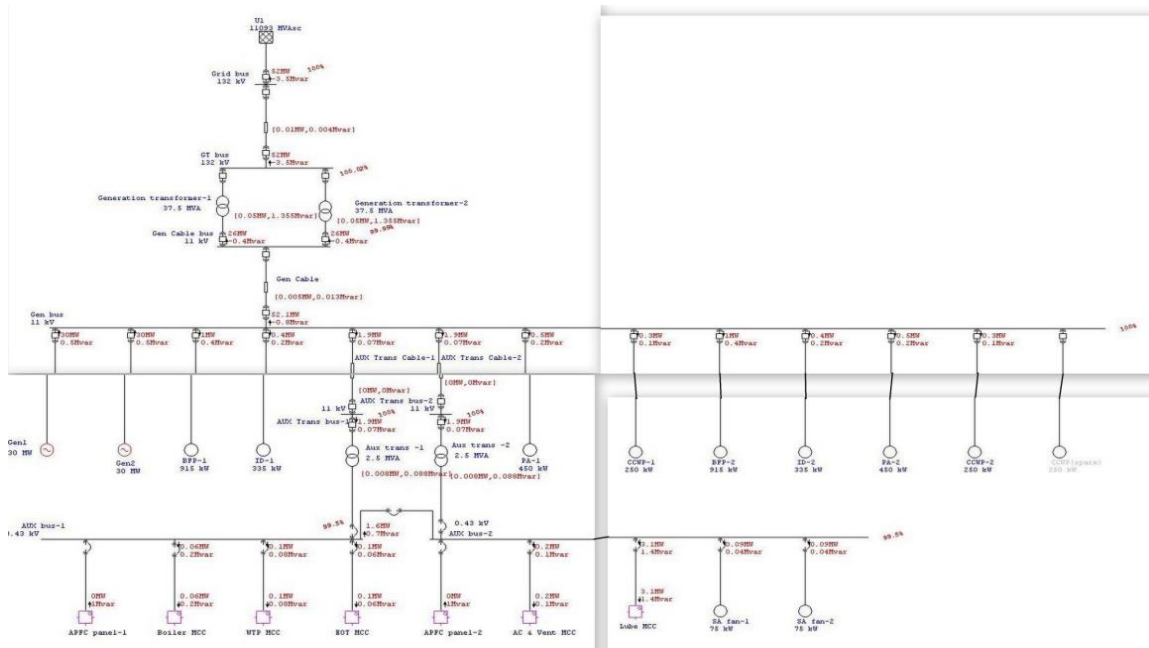


Fig. 9. Load flow results of the typical 2x30 MW thermal power plant

Table 3 Power flow result ('-' indicates power drawn)

Bus Name	Voltage			Generation		Load	
	KV	% Mag	Angle	MW	Mvar	MW	Mvar
Grid bus	132	100	0	52	-3.5	0	0
GT bus	132	100.02	0	52	-3.5	0	0
Gen cable bus	11	99.99	3	52	-0.8	0	0
Gen bus	11	100	3	60	1	8.2	1.94
Aux trans bus-1	11	99.99	0.4	0	0	1.9	0.07
Aux trans bus-1	11	99.99	0.4	0	0	1.9	0.07
Aux bus-1	0.43	99.5	0.4	0	1	0.26	0.34
Aux bus-2	0.43	99.5	0.4	0	1	3.48	1.58

Table 4 Generation, Load and Losses of various components ('-' indicates power drawn)

Type	Component	Power		PF		Voltage Drop (%)
		MW	MVar	%	Lag/Lead	
Generation	Grid	51.957	-3.518	99.77	Lead	-
	Generator	60	1.097	99.98	Lag	-
	APFC Panel	0	2	0	Lead	-
Load	In-house loads	-7.912	-3.692	90.62	Lag	-
Losses	Aux Trans-1	0.008	0.088	-	-	0.5
	Aux Trans-2	0.008	0.088	-	-	0.5
	Aux Trans Cable-1	0	0	-	-	0
	Aux Trans Cable-2	0	0	-	-	0
	Gen Cable	0.005	0.013	-	-	0.01
	OH Line	0.01	0.004	-	-	0.02
	GT-1	0.05	1.355	-	-	0.03
	GT-2	0.05	1.355	-	-	0.03
Total Losses		0.131	2.902	-	-	-

The transient stability of the typical 2×30 MW thermal power plant is assessed based on t_{cc} and δ_{cc} for various test cases as given in Table 2. In ETAP, the t_{cc} and δ_{cc} is obtained by arbitrarily creating the events for fault occurrence and fault clearing. The relative power angle curve of the generator-1 for the fault clearing at 1.290 second (290 ms) and 1.292 second (292 ms) are shown in Figures 10 and 11 respectively.

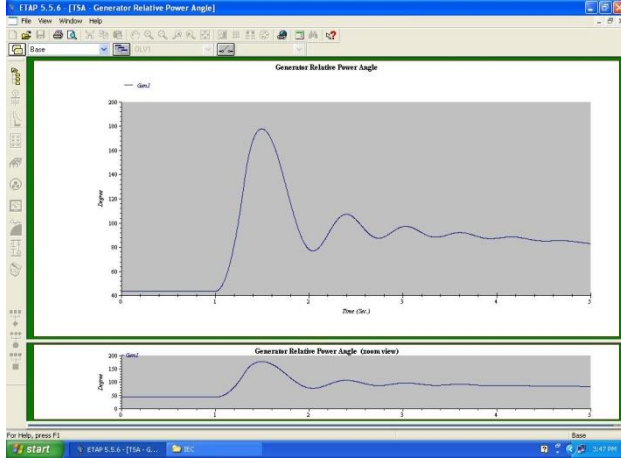


Fig. 10. Power angle curve for the fault clearing at 1.290 second

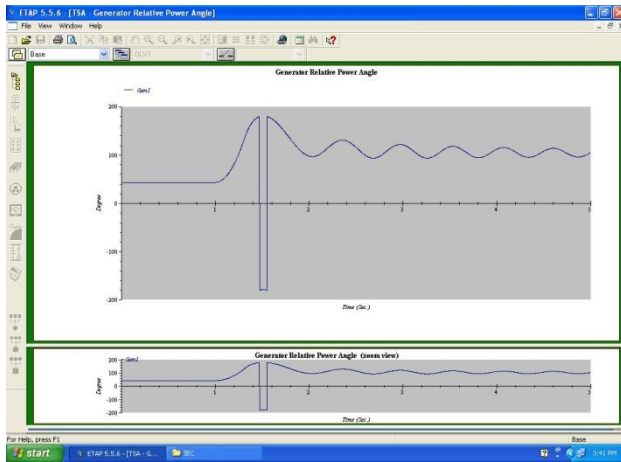


Fig. 11. Power angle curve for the fault clearing at 1.292 second

The power angle curve obtained through simulation when the fault is cleared at 1.290 ms, shows that the power angle of the generator does not exceeded the limit of 180°. Hence, the generator is identified as stable. The power angle curve of the generator-1 when the fault is cleared at 1.292 second shows that the power angle of the generator exceed the 180° and hence it is unstable. The stability of the typical 2×30 MW thermal power plant has been further analyzed for various cases as mentioned in Section III by the above procedure and the t_{cc} and δ_{cc} values are shown in Table-5. It is understood from the

responses that the t_{cc} increases when the controllers namely governor, exciter and PSS are used together (Case-5) and hence the stability of the system has been improved.

Table 5 t_{cc} and δ_{cc} of the typical 2×30 MW thermal power plant

Study case	t_{cc} (ms)	δ_{cc} (degrees)
Case-1	290	176.71
Case-2	296	175.85
Case-3	296	179.17
Case-4	304	179.3
Case-5	304	179.24

The stability behavior of the typical 2×30 MW thermal power plant against various cases is validated using IEEE 9-bus test system. The responses of the standard IEEE 9- bus test system for these cases are shown in Table-6. It is witnessed from the responses that t_{cc} can be improved when all the controllers namely governor, exciter and PSS are present in the system. It confirms the simulation results obtained for the typical 2×30 MW thermal power plant.

Table 6 t_{cc} and δ_{cc} of IEEE 9-bus test system

Study case	t_{cc} (ms)	δ_{cc} (degrees)
Case-1	450	167.57
Case-2	494	175.83
Case-3	470	173.78
Case-4	518	178.8
Case-5	526	178.41

VI. Conclusion

In this paper, the load flow study and transient stability study of the typical 2×30 MW thermal power plant has been performed. Based on the load flow result, it is found that none of the components in the system are over loaded. It is also identified that all the bus voltages are well within the limit and hence the voltage compensating devices are not required for the system. The transient stability of the system with various combinations of the controllers namely governor, exciter and PSS has been studied and the responses are analyzed based on t_{cc} and δ_{cc} . Based on the transient stability responses, it is found that the stability of the typical 2×30 MW thermal power plant is improved in the presence of governor, exciter and PSS. Hence it is identified as the optimal combination of controller for transient stability enhancement. The stability responses of various test cases have been confirmed by analyzing the simulation results of IEEE 9-bus test system. It is validated from the analysis that the stability of any system can be enhanced by using the optimal combination of controllers as identified in this paper.

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APPENDIX 1

Table A 1.1 Electrical rating of Components in the typical 2×30 MW thermal power plant

Sl. No	Component Name	Voltage (KV)	Capacity (KW/HP)
1	BFP - 1,2	11	915
2	ID Fan - 1,2	11	385
3	PA Fan- 1,2	11	450
4	CCWP-1,2,3	11	250
5	SA Fan	0.415	250

Table A 1.2 Generator data of the typical 2×30 MW thermal power plant

Parameters	Gen 1	Gen 2
H	4.36	4.36
X_d (p.u.)	1.745	1.745
X_d' (p.u.)	0.203	0.203
X_d'' (p.u.)	0.159	0.159
T_{d0} (sec)	4.902	4.902
T_{q0} (sec)	0.017	0.017

APPENDIX 2

Table A 2.1 Generator data of IEEE9-bus test system

Parameters	Gen 1	Gen 2	Gen 3
H	23.64	6.4	3.01
X_d (p.u.)	0.146	0.8958	1.3125
X_d' (p.u.)	0.0608	0.1198	0.1813
X_q (p.u.)	0.0969	0.8645	1.2578
X_q' (p.u.)	0.0969	0.1969	0.25
T_{d0} (sec)	8.96	6.0	5.89
T_{q0} (sec)	0.31	0.535	0.6

NOMENCLATURE

MCC	-	Motor Control Center
WTP	-	Water Treatment Plant
MOV	-	Motor Operated Valve
AHS	-	Ash Handling System
FHS	-	Fuel Handling System
EOT	-	Electrical Overhead Travelling
ACDB	-	AC Distribution Board
APFC	-	Automatic Power Factor Correction
BFP	-	Boiler Feed Pump
GT	-	Generator Transformer
IA	-	Induced Air
PA	-	Primary Air
AHU	-	Ash Handling Unit
LT	-	Low Tension
HT	-	High Tension
t_{cc}	-	Critical clearing time
δ_{cc}	-	Critical clearing angle
K_A, T_A	-	Amplifier Gain and Time constant
K_e, T_e	-	Exciter Gain and Time constant
K_G, T_G	-	Generator Gain and Time constant
K_S, T_S	-	Sensor Gain and Time constant
V_{ref}	-	Reference voltage
V	-	Actual terminal voltage of generator