European Journal of Engineering and Technology Research
ISSN: 2736-576X

Performance Evaluation of Excitation Systems in Stability Enhancement of Power Systems

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***Abstract* — This paper involves the characterization and the performance evaluation of various types of synchronous generator excitation systems in the transient stability enhancement of power systems. The Investigations are carried out by modelling the typical DC, AC and static excitation systems represented by IEEE types DC1A, DC2A, AC4A, AC5A, ST1A and ST2A attached with a generator connected to the infinite bus. The performance evaluation of these excitation systems is performed in terms of their response ratio and ceiling voltage together with the system settling time and the critical clearing time following a sudden three-phase short-circuit in the system. Each excitation system together with its power system stabilizer is considered in the analysis. 4th order Runge Kutta method is utilized for transient stability analysis of the power system with the 3rd order model for synchronous generator representation. The investigations reveal that the IEEE ST2A Excitation System is better than the other types of excitation systems.**

***Keywords* — Excitation System, Modeling, Power System Stabilizer, Simulation, Stability.**

I. INTRODUCTION

The basic function of an excitation system is to provide a continuous direct current to the field winding of a synchronous machine. Based on the power supply employed as the source of excitation, synchronous machine excitation systems may be divided into three major classes. These are DC excitation, AC excitation, and static excitation systems. DC excitation system makes use of DC generators as a source of excitation power. It can be either self-excited or separately excited. When it is independently activated, the exciter field current is supplied by a pilot exciter consisting of a permanent magnet generator. AC excitation systems use alternators as a source of generator excitation power. The AC output of the exciter is converted by either regulated or diode rectifiers to provide the direct current required by the generator field. Depending on the rectifier design, mechanism of exciter output regulation, and source of excitation for the exciter, AC excitation systems can take many different forms. Stationary and rotating AC rectifier systems are currently commonly utilized in AC excitation systems. The DC output of a stationary rectifier is delivered to the generator's field winding via slip rings. Rotating rectifiers, on the other hand, do not require slip rings or brushes. As the exciter and rectifiers' armature rotate with the generator field, the DC supply is delivered directly to the generator field. Brushless systems were developed to eliminate the problems associated with brushes when high field currents are delivered to large generators. Static excitation systems receive power from the generator via auxiliary windings or a step-down transformer [1]. In such systems, the generator serves as a source of power, implying that the generator is self-excited.

In 1968, the IEEE Excitation Modeling Subcommittee introduced guidelines for the excitation systems in use at that time, which would include a standard nomenclature and criteria for those models [2]. New models were launched in 1981 which reflected facilities improvements and improved quality standards. In 1992, the IEEE Excitation Device Board updated these versions again, in which new control functions are given for the requirements. The excitation system consists of an integrated voltage regulator, exciter, measuring devices, as well as a power system stabilizer and safety mechanism. The excitation systems generally utilize the linear controllers such as proportional (P), proportional integral (PI) or proportional integral & derivative (PID) controller in their operations. Nonlinear regulation can take the form of artificial neural networks or adaptive control. Such systems are more complex than linear control structures but with more research these have the potential to improve the regulation of the excitation systems [3]. In addition, the excitation systems regulate the voltage of the generators making them an important factor in the stability of the system. [4]. The control parameters of the excitation mechanism have a major impact on the overall power system's dynamic responses and efficiency [1]-[3]. Many of the recently developed excitation systems in use consists of digital controllers and electronic power switching devices. The brushless synchronous generator digital voltage control system has powerful static and dynamic features. This control system can also be used for static excitation system without software and hardware adjustments [5]. Stabilizing circuit excitation systems are employed to boost the excitation system's efficiency. Special stabilizing signals are used by the Power System Stabilizer (PSS) to control both excitation process and improvement of power system stability. The basic PSS input signals are shaft speed, frequency, and power. By means of excitation force, the stabilizer dampens rotor oscillations.

This Paper deals with the performance evaluation of typical synchronous generator excitation systems in the transient stability enhancement of power systems. The response ratio and ceiling voltage of the excitation systems together with the system settling time and the critical clearing time are considered for the comparative evaluation of the excitation systems. The system modeling aspects are discussed in the following section followed by the test system and simulation results in Section III and finally conclusion in Section IV.

Submitted on May 10, 2022.
Published on October 24, 2022.
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II. System Modelling

The effectiveness of various excitation systems in damping the transient stability oscillations is investigated on a synchronous generator connected to the infinite bus through a transformer and transmission line. The modeling of various system components is discussed in this Section. [13]-[15].

A. Synchronous Generator Model

Synchronous generator is represented by the third order model, the differential equations of which are given by (1), (2) and (3).

$$\frac{d\delta}{dt} = \omega_b(S_m - S_{m0}) \tag{1}$$

$$\frac{dE'_d}{dt} = \frac{1}{T'_{qo}}\left[i_q\left(x_q - x'_q\right) - E'_d\right] \tag{2}$$

$$\frac{dE'_q}{dt} = \frac{1}{T'_{do}}\left[i_d\left(x_d - x'_d\right) + E_{fd} - E'_q\right] \tag{3}$$

The equivalent impedance (Ze) between the generator and the infinite bus is given by (4).

$$Z_e = R_e + jx_e \tag{4}$$

(5) and (6) are the algebraic equations representing the model.

$$V_d = \acute{E}_d - \acute{x}_q i_q = R_e i_d + x_e i_q - E_b \sin\delta \tag{5}$$

$$V_q = \acute{E}_q + \acute{x}_d i_d = R_e i_q - x_e i_d - E_b \cos\delta \tag{6}$$

The variables id and iq are obtained by solving the system of (5) and (6).

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} \acute{x}_d + x_e & -R_e \\ -R_e & -(\acute{x}_q + x_e) \end{bmatrix}^{-1} \begin{bmatrix} E_b\cos(\delta) - \acute{E}_q \\ -E_b\sin(\delta) - \acute{E}_d \end{bmatrix} \tag{7}$$

B. Transformer Model

Transformers are represented by the series impedance model as shown in Fig. 1.

C. Transmission Line Model

Transmission lines are assumed to be short and hence represented by the series impedance model as shown in Fig. 2.

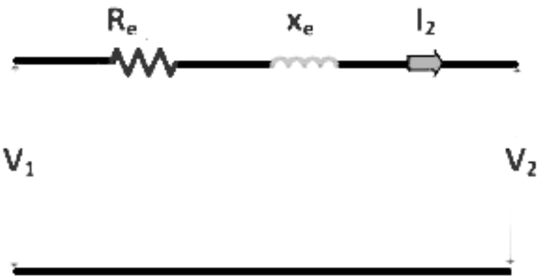


Fig. 1. Transformer Model.

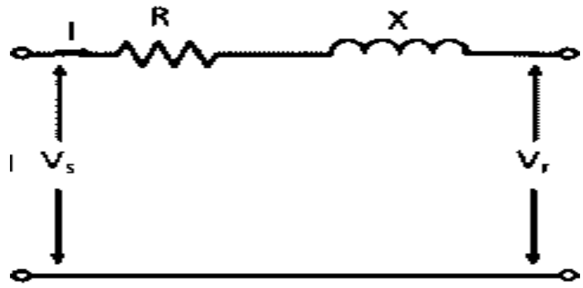


Fig. 2. Transmission line model.

D. Load Model

Loads in the system are modelled as constant admittances, which are computed from the real and reactive power load demands as (8).

$$Y_L = \frac{P_D - jQ_D}{|V|^2} \tag{8}$$

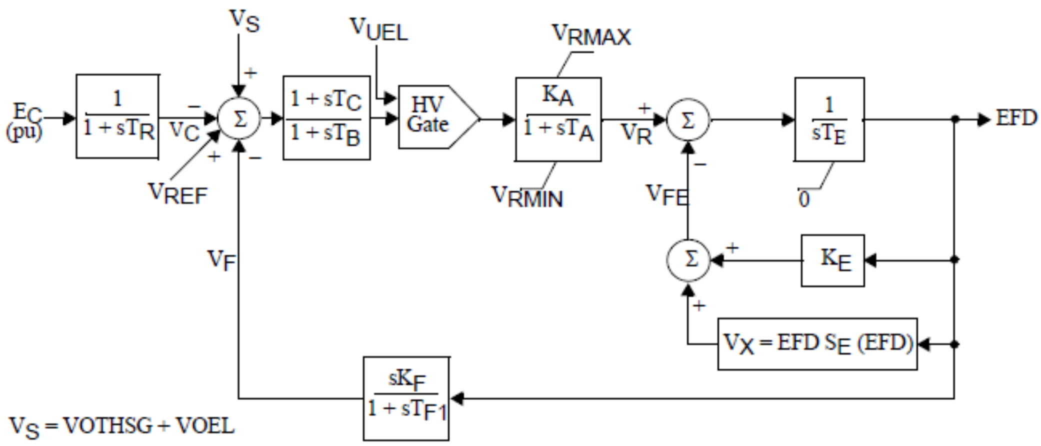


Fig. 3. IEEE DC1A excitation system.

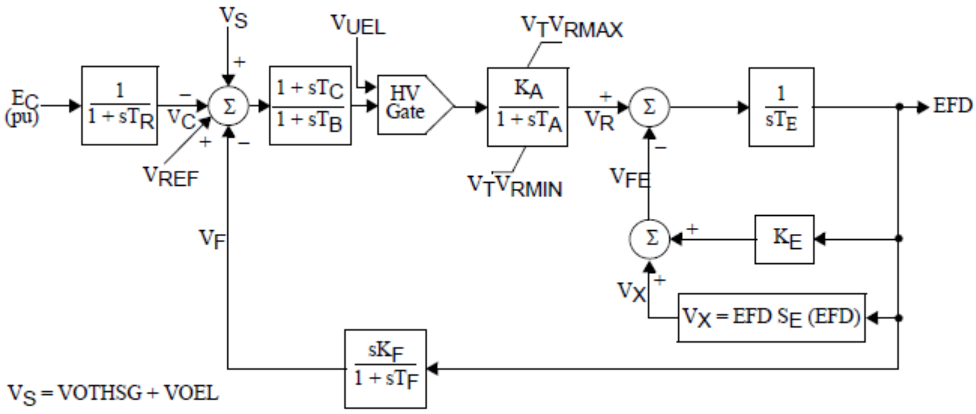


Fig. 4. IEEE DC2A excitation system.

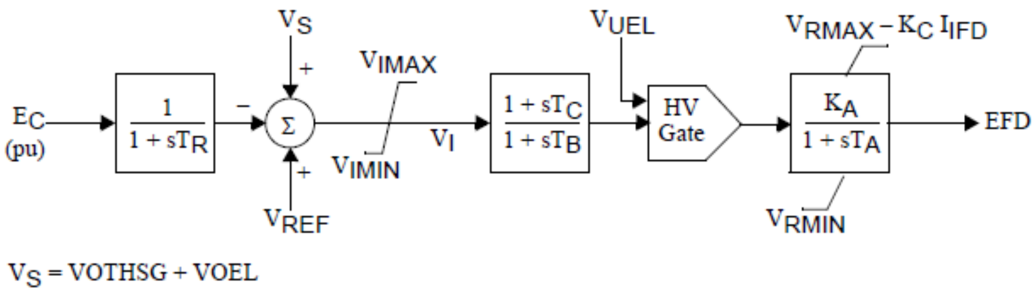


Fig. 5. IEEE AC4A excitation system.

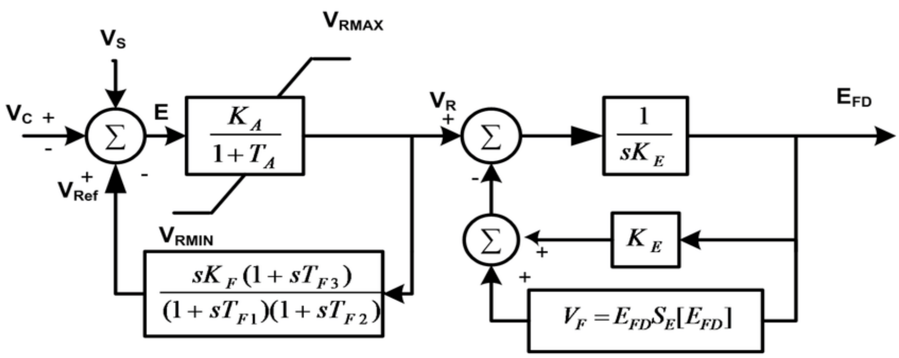


Fig. 6. IEEE AC5A excitation system.

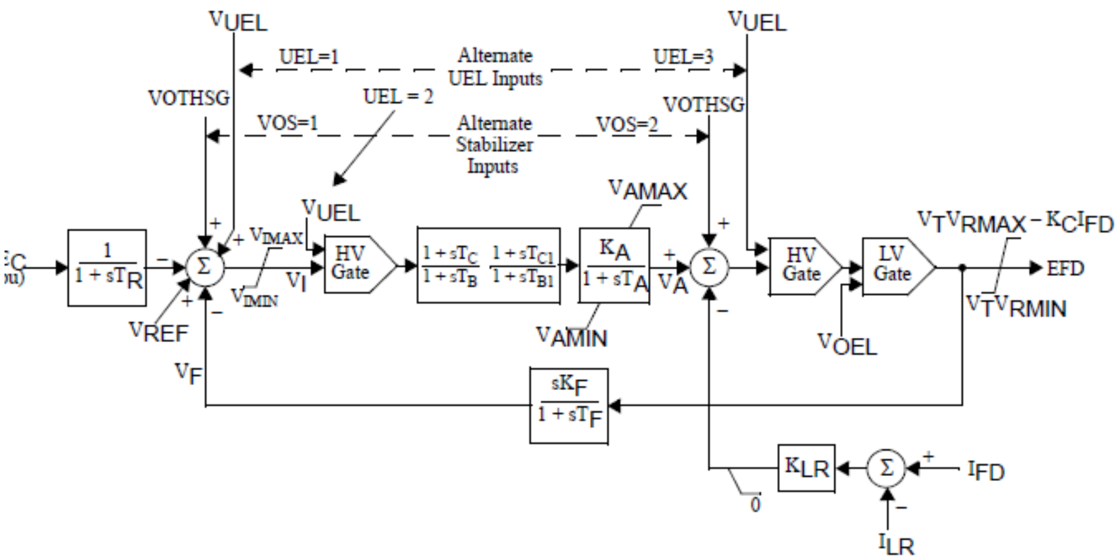


Fig. 7. IEEE ST1A excitation system.

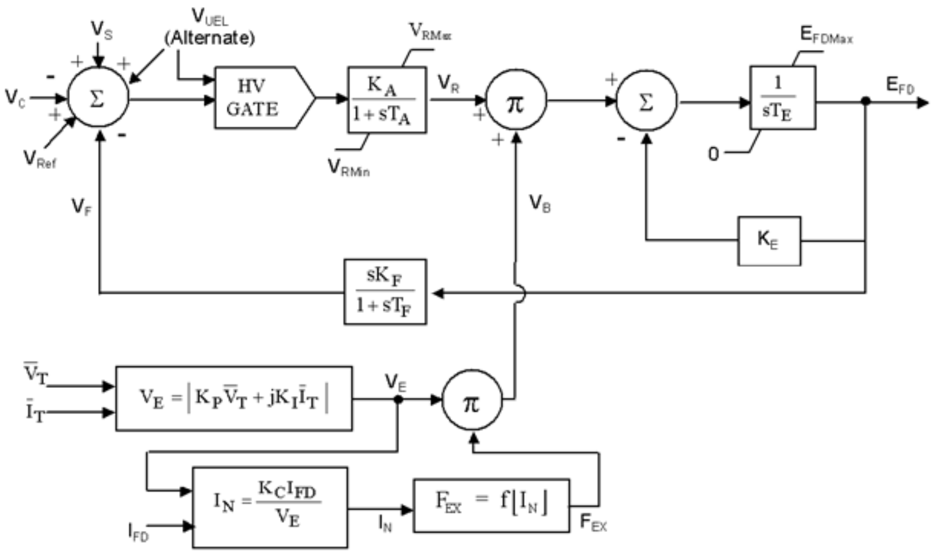


Fig. 8. IEEE ST2A excitation system.

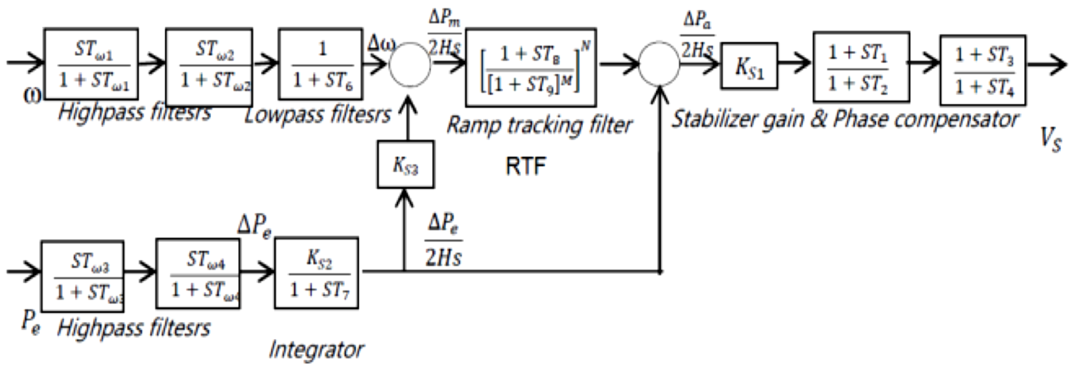


Fig. 9. IEEE PSS2A power system stabilizer.

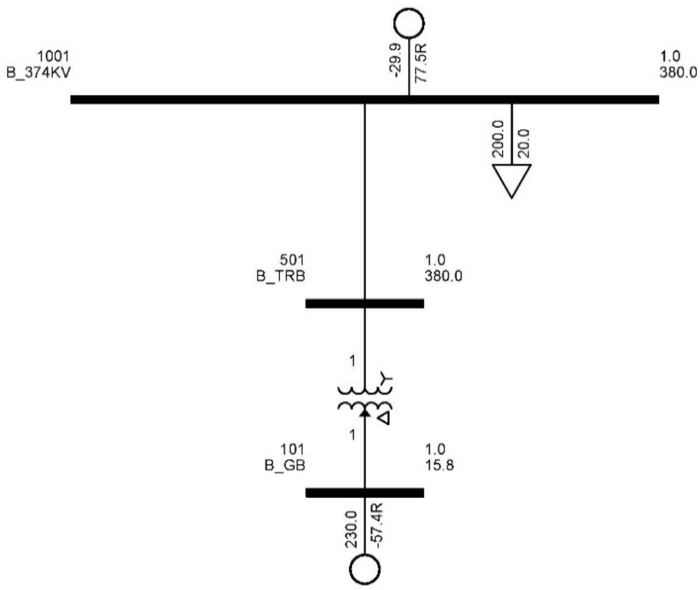


Fig. 10. System Single Line Diagram.

E. Excitation System Models

In this paper, typical excitations systems represented by IEEE models DC1A, DC2A, AC4A, AC5A, ST1A and ST2A are considered for performance evaluation in the transient stability enhancement of power systems. The block diagram representations of these excitation systems are given in Fig. 3 to Fig. 9 respectively. The description of the gain and time constant parameters in these models is given in Appendix [6]-[15].

F. Power System Stabilizer Model

Each excitation system is assumed to receive an additional input from IEEE PSS2A power system stabilizer, the block diagram of which is shown in Fig. 9 [15].

The PSS input signals are the rotor angular velocity (ω) and the electrical power output (Pe) of the synchronous generator. The two wash-out filters with time constants TW1 and TW2 respectively remove the steady-state components of the signals. The blocks with time constants T6 and T7 are the filter circuits. The block with time constant Ks2 is used to adjust the scale of the two inputs. The ramp tracking filter is a low pass filter that filters out all high frequency components. The gain of the stabilizer is determined by KS1, and the lead-lag stages with non-windup limiters [10],[16].

III. Test System And Simulation Results

The effectiveness of various excitation systems in enhancing the transient stability of synchronous generators connected to the large power grid is evaluated based on the response of the excitation systems following a three-phase short-circuit on the power grid and its consequent removal. The exciter ceiling voltage is the highest value that an exciter voltage output can attain within the specified conditions. The nominal response of the excitation system is the rate at which the excitation system output voltage rises divided by the rated field voltage. The system settling time and the critical clearing time also are considered in the comparative evaluation of excitation systems. The system single-line diagram is shown in Fig. 10. The major system data is given in Table I. The data corresponding to various excitation systems are given in the appendix.

To get dynamic voltage capability of the excitation systems, a three-phase short-circuit fault is applied at the time instant t = 2.0 seconds at Bus-1001 in Fig. 10. The fault is removed after 60 ms. The transient stability analysis of the system shown in Fig. 11, with the generators provided with the respective excitation systems and the associated power system stabilizers, is performed after converting the system differential equations into discretized equations using the fourth order Runge Kutta method [16].

Fig. 11 to Fig. 16 show the variation of power output, terminal voltage, field voltage, and rotor speed of the generator corresponding to this disturbance. These figures correspond to the generator with the attached IEEE DC1A, IEEE DC2A, IEEE AC4A, IEEE AC5A, IEEE ST1A and IEEE ST2A excitation systems respectively.

TABLE I: System Data

No	Network Part	Description	Value
1	Generator	Nominal Power P_n (MVA)	230
		line-to-line voltage V_n (KV_{rms})	15.75
		Frequency f_n (Hz)	60
		x_d (p.u)	2.00
		x'_d (p.u)	0.214
		x_q (p.u)	1.88
		x'_q (p.u)	0.310
		H (s)	3.00
		T'_{do} (s)	9.600
		T'_{qo} (s)	1.200
		r_e (p.u)	0.005
		x_e (p.u)	0.072
2	Transformer	Nominal Power P_n (MVA)	250
		line-to-line voltage V_n (KV_{rms}) Primary Winding(Δ)	15.75
		line-to-line voltage V_n (KV_{rms}) Secondsondary Winding (Y)	347
		R_e (pu)	0.0098
		X_e (pu)	0.277
3	Transmission Line	OHTL Length (Km)	50
		R(Ω/km)	0.05
		X(Ω/km)	0.480
4	Base Load	Active Power / Phase (MW)	200
		Reactive Power / Phase (MVAR)	20

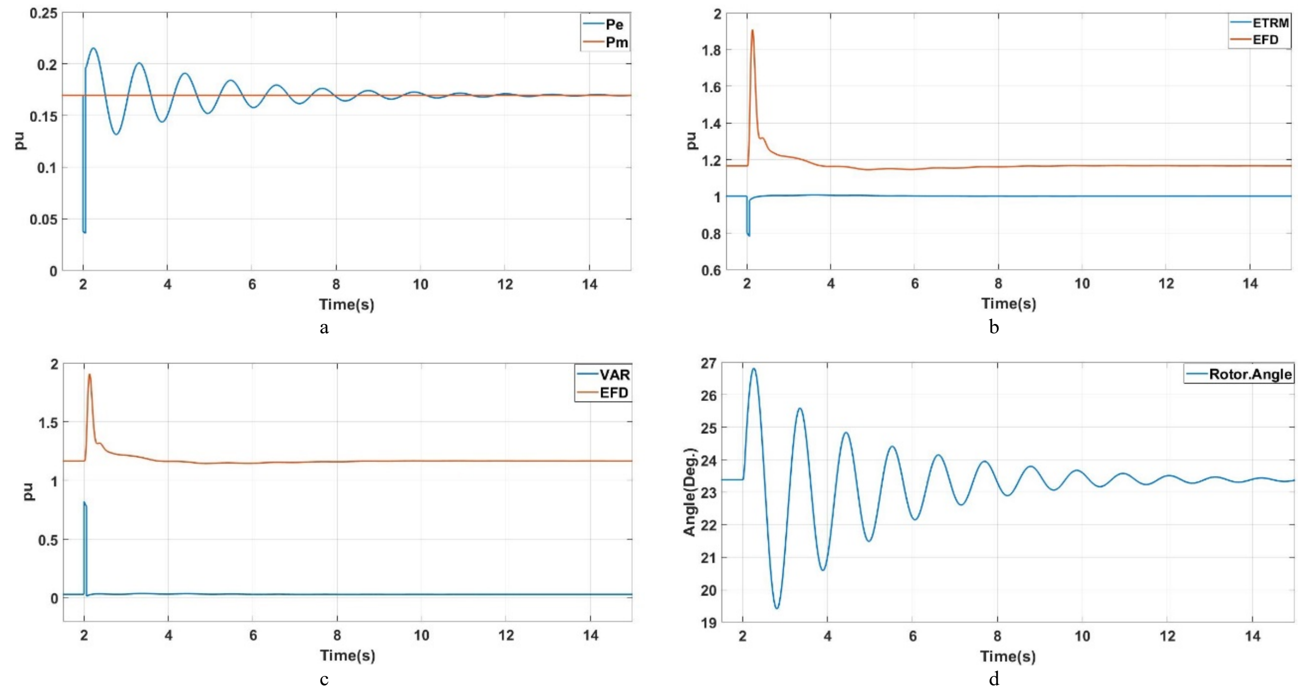
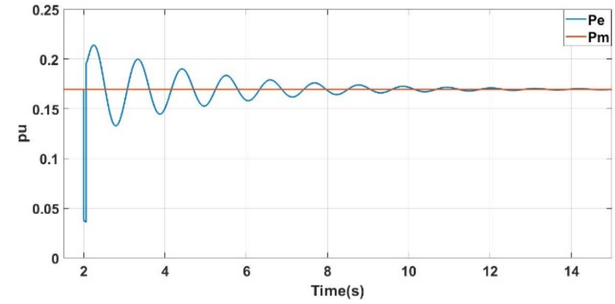


Fig. 11. a) Variation of synchronous generator power output with IEEE DC1A excitation system following a 60ms short-circuit fault at Bus-1001; b) Variation of synchronous generator voltage output with IEEE DC1A excitation system following a 60ms short-circuit fault at Bus-1001; c) Variation of synchronous generator reactive power and exciter voltage output with IEEE DC1A excitation system following a 60ms short-circuit fault at Bus-1001; d) Variation of synchronous generator rotor angle with IEEE DC1A excitation system following a 60ms short-circuit fault at Bus-1001.



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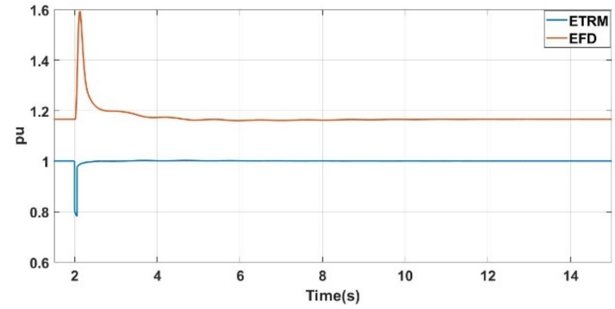

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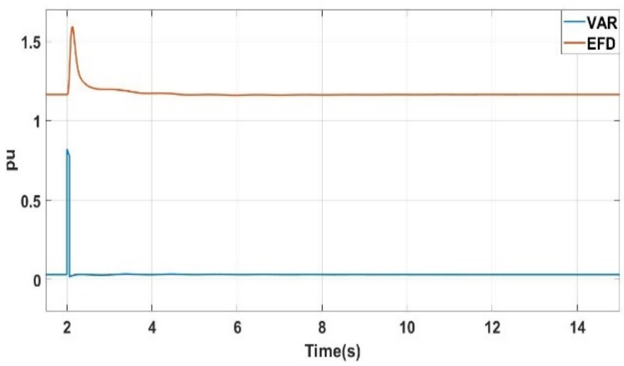

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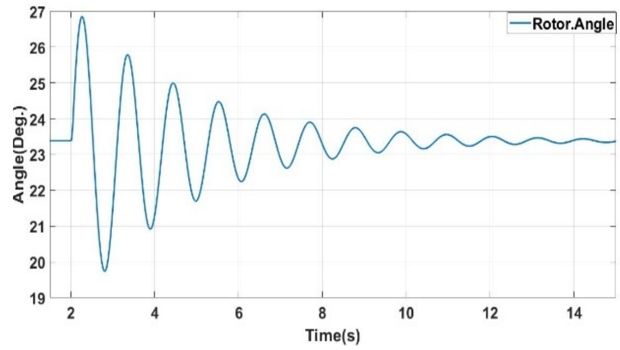

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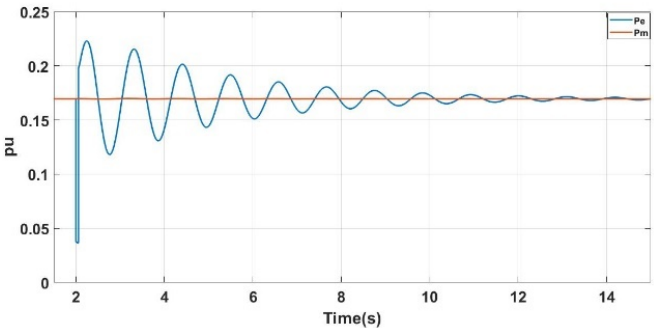
Fig. 12. a) Variation of synchronous generator power output with IEEE DC2A excitation system following a 60ms short-circuit fault at Bus-1001; b) Variation of synchronous generator voltage output with IEEE DC2A excitation system following a 60ms short-circuit fault at Bus-1001; c) Variation of synchronous generator reactive power and exciter voltage output with IEEE DC2A excitation system following a 60ms short-circuit fault at Bus-1001; d) Variation of synchronous generator rotor angle with IEEE DC2A excitation system following a 60ms short-circuit fault at Bus-1001.



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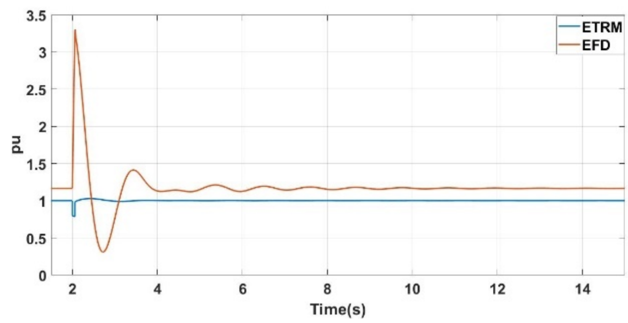

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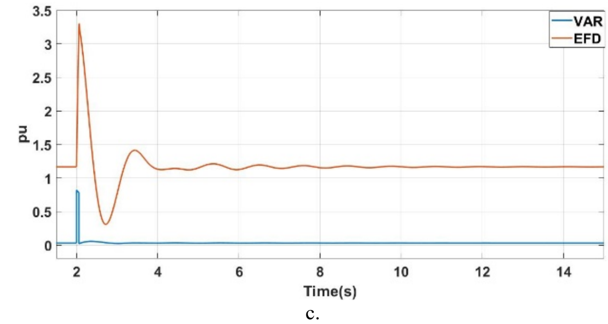

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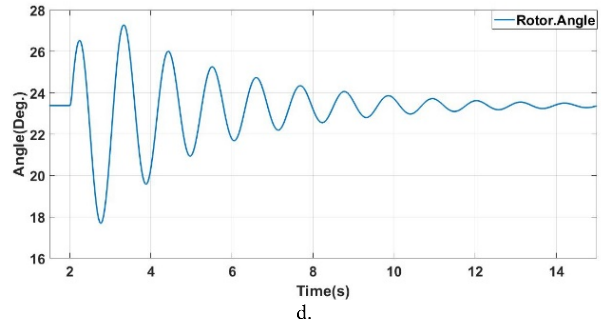

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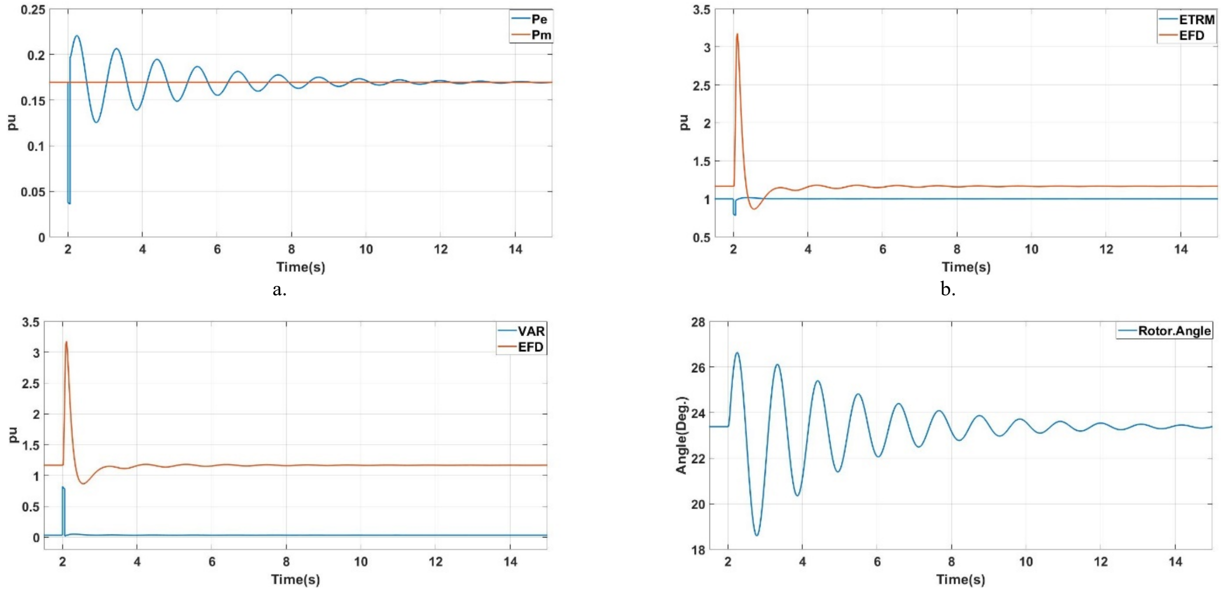
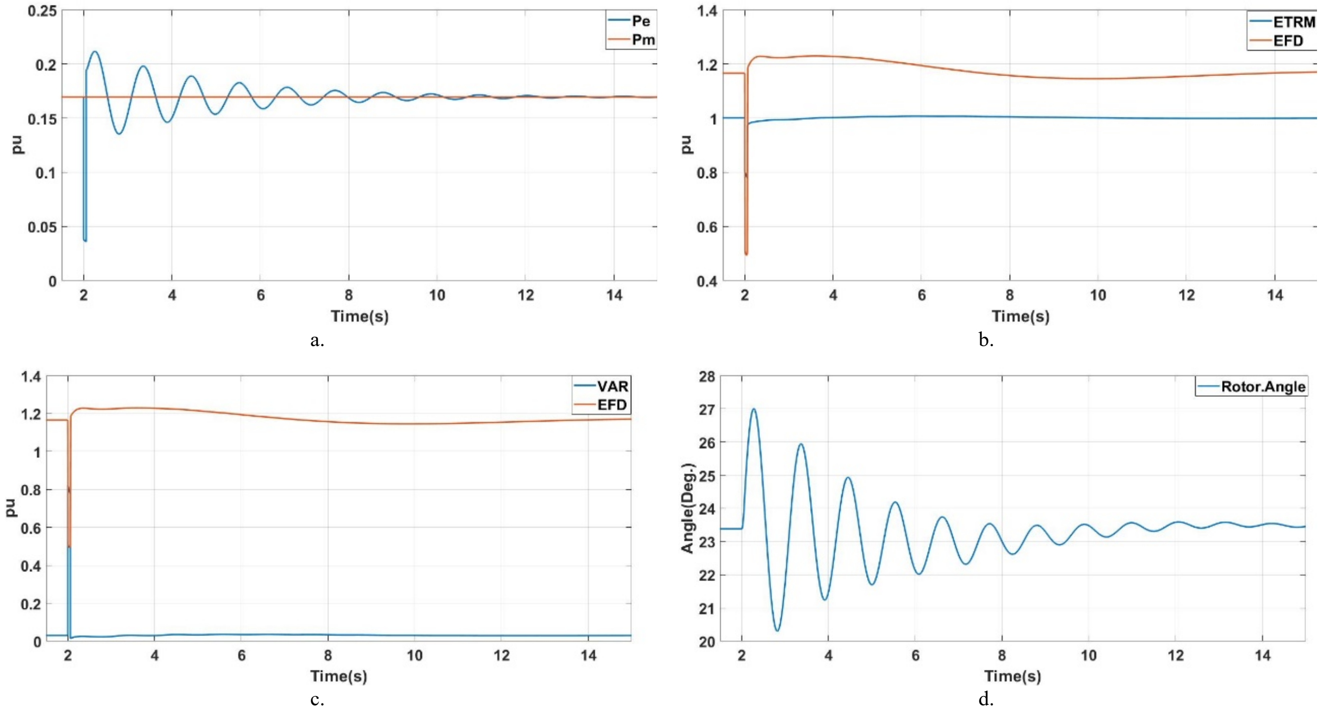
Fig. 13. a) Variation of synchronous generator output with IEEE AC4A excitation system following a 60ms short-circuit fault at Bus-1001; b) Variation of synchronous generator voltage output with IEEE AC4A excitation system following a 60ms short-circuit fault at Bus-1001; c) Variation of synchronous generator reactive power and exciter voltage output with IEEE AC4A excitation system following a 60ms short-circuit fault at Bus-1001; d) Variation of synchronous generator rotor angle with IEEE AC4A excitation system following a 60ms short-circuit fault at Bus-1001.



a. b. c. d.

Fig. 14. a) Variation of synchronous generator power output with IEEE AC5A excitation system following a 60ms short-circuit fault at Bus-1001; b) Variation of synchronous generator voltage output with IEEE AC5A excitation system following a 60ms short-circuit fault at Bus-1001; c) Variation of synchronous generator reactive power and exciter voltage output with IEEE AC5A excitation system following a 60ms short-circuit fault at Bus-1001; d) Variation of synchronous generator rotor angle with IEEE AC5A excitation system following a 60ms short-circuit fault at Bus-1001.



a. b. c. d.

Fig.15. a) Variation of synchronous generator output with IEEE ST1A excitation system following a 60ms short-circuit fault at Bus-1001; b) Variation of synchronous generator voltage output with IEEE ST1A excitation system following a 60ms short-circuit fault at Bus-1001; c) Variation of synchronous generator reactive power and exciter voltage output with IEEE ST1A excitation system following a 60ms short-circuit fault at Bus-1001; d) Variation of synchronous generator rotor angle with IEEE ST1A excitation system following a 60ms short-circuit fault at Bus-1001.

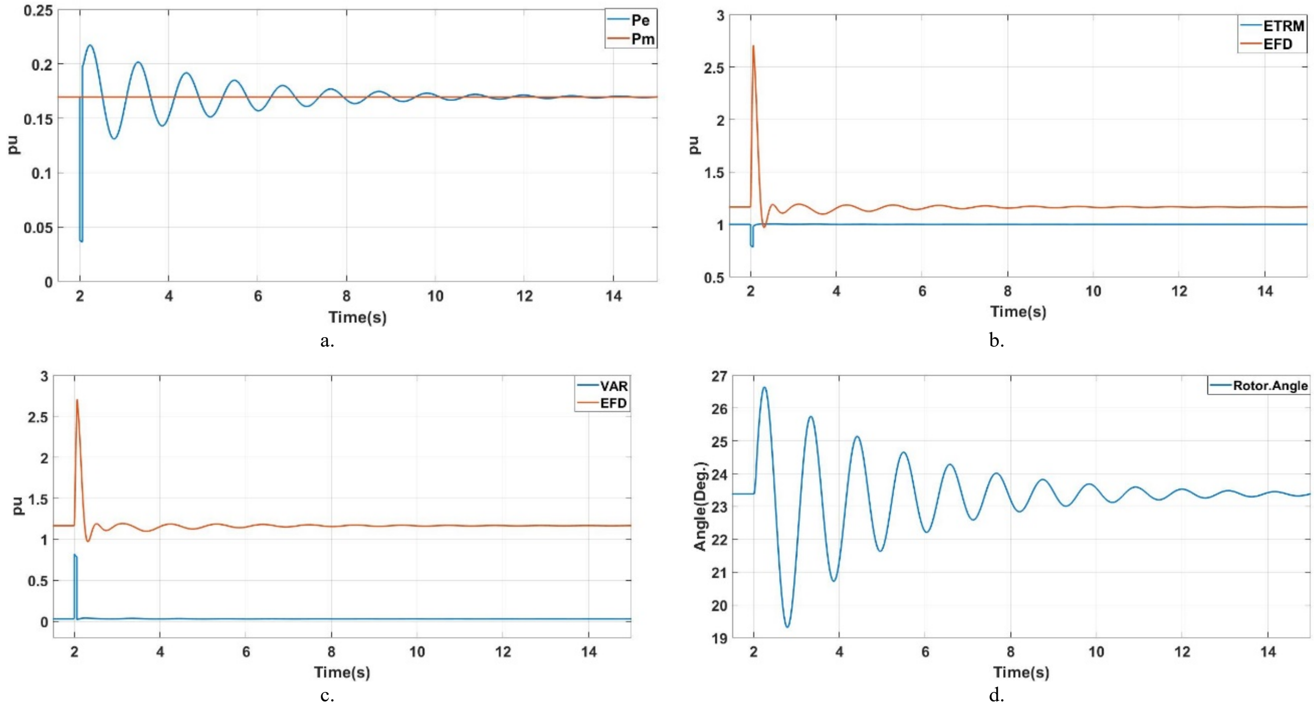


Fig. 16. a) Variation of synchronous generator power output with IEEE ST2A excitation system following a 60ms short-circuit fault at Bus-1001; b) Variation of synchronous generator voltage output with IEEE ST2A excitation system following a 60ms short-circuit fault at Bus-1001; c) Variation of synchronous generator reactive power and exciter voltage output with IEEE ST2A excitation system following a 60ms short-circuit fault at Bus-1001; d) Variation of synchronous generator rotor angle with IEEE ST2A excitation system following a 60ms short-circuit fault at Bus-1001.

TABLE II: OUTPUT OF SYNCHRONOUS GENERATOR WITH DC EXCITATION SYSTEMS FOLLOWING A 60MS SHORT-CIRCUIT FAULT AT BUS-1001

No	Output of Synchronous Generator	Ref.Value(pu)	Peak Value (pu)		Peak Time (Seconds)		Settling Time (Seconds)	
			IEEE DC1A	IEEE DC2A	IEEE DC1A	IEEE DC2A	IEEE DC1A	IEEE DC2A
1	Active Power (Pe)	0.169	0.036	0.036	2.06	2.06	9.94	9.938
2	Mech.Power(Pm)	0.169	0.169	0.169	0	0	0	0
3	Terminal voltage (ETRM)	1	0.782	0.781	2.06	2.06	4	2.327
4	Field Voltage (EFD)	1.16	1.91	1.593	2.129	2.129	6.237	3.745
5	Rotor Angle (Tan.delta)	23.4 (deg)	26.820 (deg)	26.85 (deg)	2.27	2.269	13.239	13.16
6	Reactive Power (VAR)	0.03	0.823	0.823	2	2	2.06	2.06

TABLE III: OUTPUT OF SYNCHRONOUS GENERATOR WITH AC EXCITATION SYSTEM FOLLOWING A 60MS SHORT-CIRCUIT FAULT AT BUS-1001

No	Output of Synchronous generator	Ref.Value(pu)	Peak Value (pu)		Peak Time (Seconds)		Settling Time (Seconds)	
			IEEE AC4A	IEEE AC5A	IEEE AC4A	IEEE AC5A	IEEE AC4A	IEEE AC5A
1	Active Power (Pe)	0.169	0.036	0.036	2.06	2.06	12.043	10.461
2	Mech.Power(Pm)	0.169	0.169	0.169	0	0	0	0
3	Terminal Voltage (ETRM)	1	0.781	0.783	2.06	2.06	3.396	2.804
4	Field Voltage (EFD)	1.16	3.303	3.177	2.069	2.11	5.951	3.824
5	Rotor Angle (Tan.delta)	23.4 (deg)	27.283 (deg)	26.635 (deg)	3.329	3.329	14.294	13.157
6	Reactive Power (VAR)	0.03	0.823	0.823	2	2	2.581	2.361

TABLE IV: OUTPUT OF SYNCHRONOUS GENERATOR WITH STATIC EXCITATION SYSTEM FOLLOWING A 60 MS SHORT-CIRCUIT FAULT AT BUS-1001

No	Output of Synchronous generator	Ref.Value(pu)	Peak Value (pu)		Peak Time (Seconds)		Settling Time (Seconds)	
			IEEE ST1A	IEEE ST2A	IEEE ST1A	IEEE ST2A	IEEE ST1A	IEEE ST2A
1	Active Power (Pe)	0.169	0.0357	0.0363	2.06	2.06	9.92	09.438
2	Mech.Power(Pm)	0.169	0.169	0.169	0	0	0	0
3	Terminal voltage (ETRM)	1	0.779	0.785	2.06	2.06	8.187	2.126
4	Field Voltage (EFD)	1.16	0.493	2.709	2.03	2.07	12.364	4.906
5	Rotor Angle (Tan.delta)	23.4 (deg)	27.001 (deg)	26.645 (deg)	2.28	2.26	14.366	12.202
6	Reactive Power (VAR)	0.03	0.823	0.823	2	2	2.071	2.06

Table II to Table IV show the comparison of generator outputs corresponding to these types of DC, AC and static systems respectively. The observations from these results related to the variations in the exciter output and generator power outputs are as follows:

- The performance of IEEE DC2A excitation system is better than that of IEEE DC1A excitation system.
- The performance of IEEE AC5A excitation system is better than that of IEEE AC4A excitation system.
- The performance of IEEE ST2A excitation system is better than that of IEEE ST1A excitation system.

IV. Discussion

In the paper, a single machine infinite bus system is utilized to evaluate the effect of various excitation systems on the generator terminal voltage and the power output following the application of a three-phase short-circuit fault and its removal. For the dynamic performance evaluation, the variations in the exciter output voltage and the variations in the generator rotor angle following the application of the three-phase fault is utilized. The instant of fault removal is extended in incremental steps up to the critical clearing time (CCT) until the system becomes unstable. Fig. 17 and Fig. 18 show the variation of the generator rotor angle and the exciter output voltage corresponding to the application of a three-phase solid short-circuit at Bus-1001 in Fig. 11, at the instant t = 0.0 second and its removal after 400 ms, 600 ms, 700 ms, 730 ms and 750 ms respectively. The effects of various excitation systems represented by the IEEE excitation system models DC1A, DC2A, AC4A, AC5A, ST1A and ST2A are shown in these figures. From these figures corresponding to the rotor angle and exciter output voltage variations, the exciter ceiling voltage, exciter response ratio and the system settling time corresponding to these excitation systems are obtained as given in Table V. Furthermore, the performance parameters; ceiling voltage, response ratio, settling time and CCT are also given in the Table V for each fault duration.

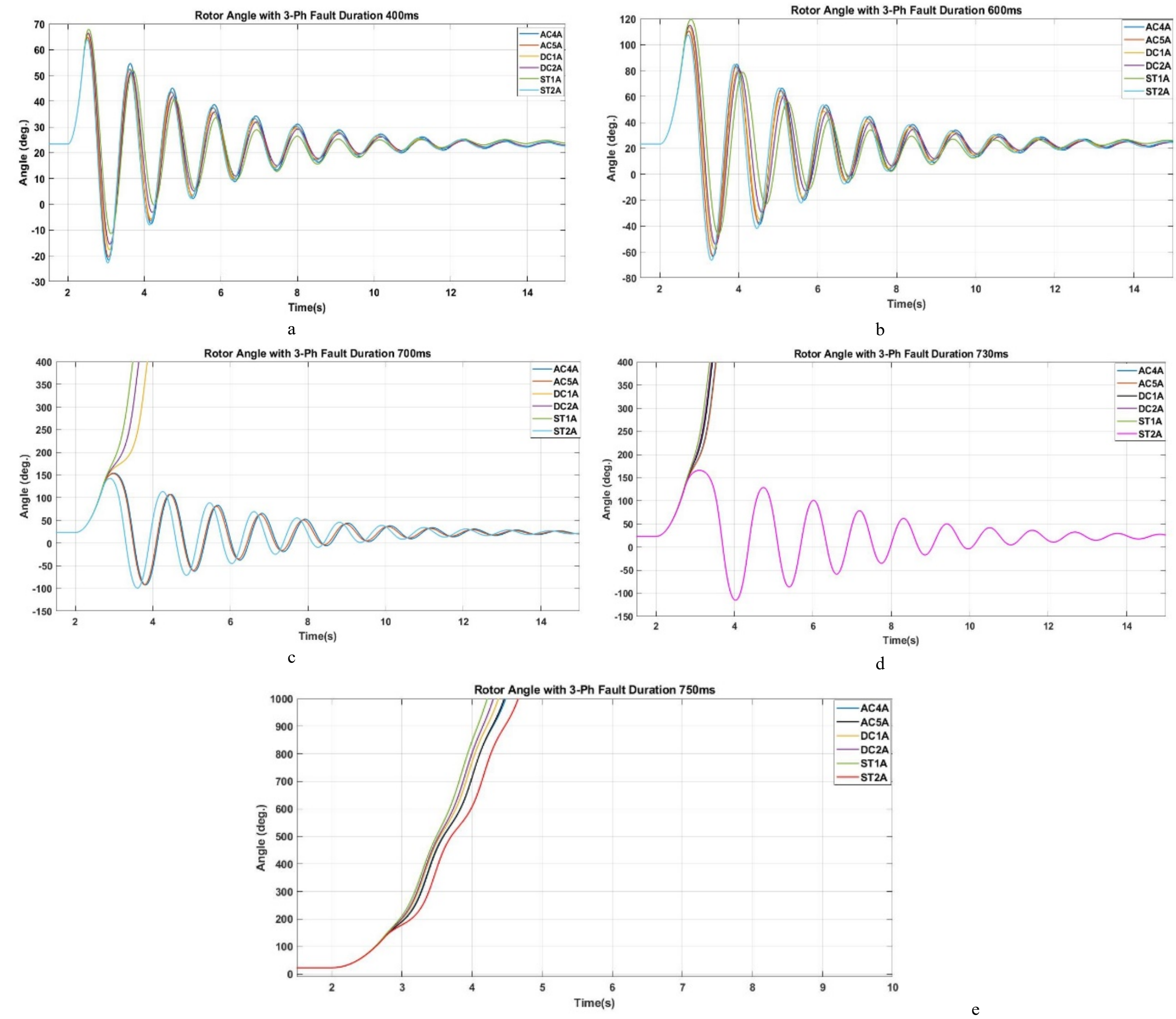
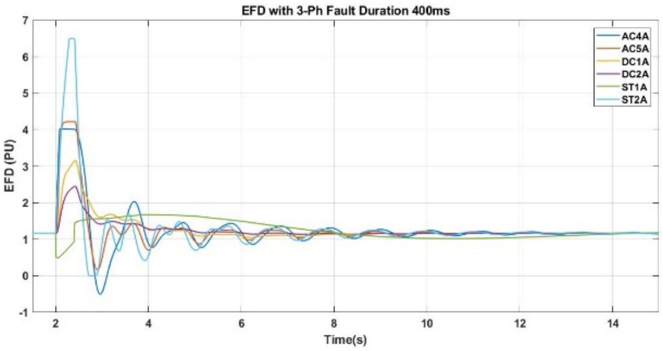


Fig. 17. a) Variation of synchronous generator rotor angle with 400 ms fault duration; b) Variation of synchronous generator rotor angle with 600 ms fault duration; c) Variation of synchronous generator rotor angle with 700 ms fault duration; d) Variation of synchronous generator rotor angle with 730 ms fault duration; e) Variation of synchronous generator rotor angle with 750ms fault duration.



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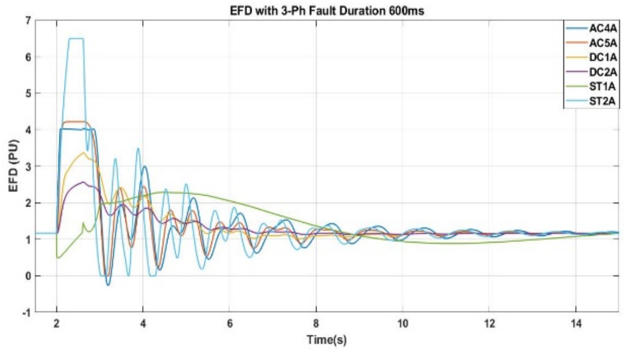

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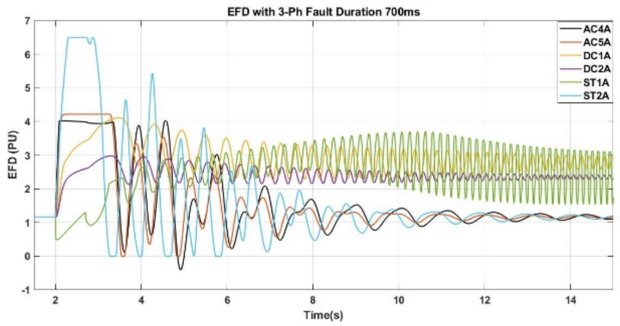

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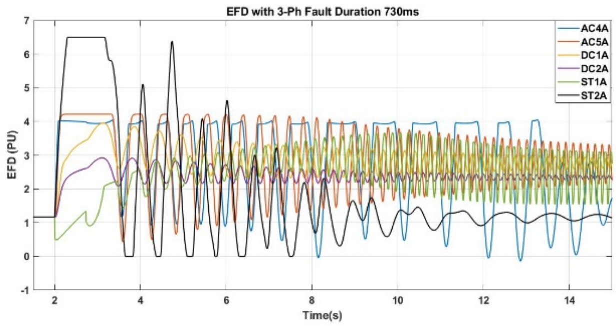
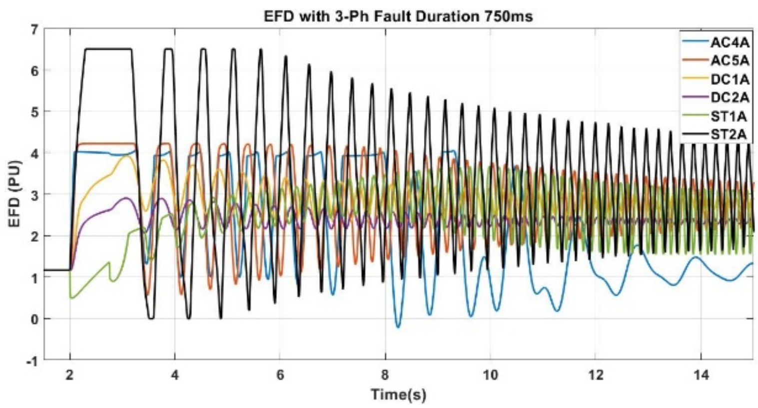


d.



e.

Fig. 18. a) Variation of synchronous generator exciter output voltage with 400 ms fault duration; b) Variation of synchronous generator exciter output voltage with 600 ms fault duration; c) Variation of synchronous generator exciter output voltage with 700 ms fault duration; d) Variation of synchronous generator exciter output voltage with 730 ms fault duration; e) Variation of synchronous generator exciter output voltage with 750 ms fault duration.

TABLE V: PERFORMANCE COMPARISON OF EXCITATION SYSTEMS UNDER THE MAXIMUM THREE PHASE SHORT CIRCUIT DURATIONS

No	Excitation Type	Maximum SC/CCT (ms)	Ceiling Voltage (pu)	Response Ratio	Settling Time (s)
1	IEEE DC1A	690	3.928	0.296	14.567
2	IEEE DC2A	680	2.881	0.403	14.589
3	IEEE AC4A	710	4.062	0.286	14.71
4	IEEE AC5A	709	4.219	0.275	14.808
5	IEEE ST1A	660	2.784	0.417	13.729
6	IEEE ST2A	730	6.5	0.178	13.486

The settling time of the system shows the steadiness with bounded response time from the table, it can be seen that the steady state condition of the system is achieved with bounded response time for the IEEE ST2A system. Further, CCT response is observed to be better for this system. Hence it can be observed that the system gives more stable response with IEEE ST2A excitation system when compared to other excitation systems. Hence it is inferred that the IEEE ST2A excitation system is better than the other excitation systems discussed in this paper.

V. CONCLUSION

This Paper has dealt with the simulation of the some of the typical DC, AC, and static excitation systems to investigate their effectiveness in the transient stability enhancement of synchronous generators connected to a power grid. Various types of excitation systems considered for performance comparison include those represented by the IEEE DC1A, DC2A, AC4A, AC5A, ST1A and ST2A models. The performance of these excitation systems has been compared based on the time domain simulations of single machine connected to infinite bus, the machine being provided with various DC, AC and static excitation systems respectively.

Their effectiveness in the improvement of system stability against short circuit faults has been evaluated based on the ceiling voltage, response ratio, settling time and critical clearing time. The performance evaluation has shown that the IEEE ST2A excitation system is better than the other type of excitation systems.

APPENDIX

A. Major Symbols

E'_d	D−axis transient voltage
E'_q	Q−axis transient voltage
i_d	d- axis components of the armature current for each phase
i_q	q- axis components of the armature current for each phase
v_d	d- axis components of the armature voltage for each phase
v_q	q- axis components of the armature voltage for each phase
x'_d	D−axis transient resistance
x'_q	Q−axis transient resistance
E_{FD1}	Exciter voltage for SE1 [pu]
E_{FD2}	Exciter voltage for SE2 [pu]
I_r	The current at the receiving stage
I_s	The current at the sending stage
K_A	Regulator gain [pu]
K_E	Exciter constant related to field [pu]
K_F	Rate feedback gain [pu]
R_s	Stator winding resistance
$S_E [E_{FD}]$	Exciter saturation function value at the corresponding exciter voltage, E_{FD} [pu]
$S_E [E_{FD1}]$	Saturation at E_{FD1} [pu]
$S_E [E_{FD2}]$	Saturation at E_{FD2} [pu]
T_A	Regulator time constant [s]
T_B	Lag time constant [s]
T_C	Lead time constant [s]
T_E	Exciter time constant [s]
T_F	Rate feedback time constant [s]
V_C	Output of terminal voltage transducer and load compensation elements [pu]
V_F	Excitation system stabilizer output [pu]
V_{FE}	Signal proportional to exciter field current [pu]
V_r	The voltage at the receiving stage
V_R	Voltage regulator output [pu]
V_{REF}	Voltage regulator reference (determined to satisfy initial conditions) [pu]
V_{RMAX}, V_{RMIN}	Maximum and minimum regulator outputs [pu]
V_s	The voltage at the sending stage
V_S	Alternate inputs. Combined power system stabilizer and possibly discontinuous control output after any limits or switching, as summed with terminal voltage and reference signals [pu]
V_{UEL}	Under-excitation limiter input [pu]
V_X	Signal proportional to exciter saturation [pu]

TABLE A1: IEEE DC1A EXCITATION SYSTEM DATA

No.	Description	Value
1	T_R (Seconds)	0.025
2	KA	50.000
3	T_A(Seconds)	0.100
4	VR_{MAX}	6.000
5	VR_{MIN}	-6.000
6	K_E	1.000
7	T_E (Seconds)	0.041
8	K_F	0.010
9	T_{F1} (Seconds)	1.000
10	T_{F2} (Seconds)	0.100
11	T_{F3} (Seconds)	0.100
12	E1	4.000
13	S_E (E_1)	0.400
14	E2	5.000
15	S_E (E_2)	0.500

TABLE A2: DC2A EXCITATION SYSTEM DATA

No.	Description	Value
1	T_R(Seconds)	0.010
2	K_A	50.000
3	T_A(Seconds)	0.060
4	T_B(Seconds)	1.000
5	T_C(Seconds)	1.000
6	VR_{MAX}	3.000
7	VR_{MIN}	-2.500
8	K_E	0.000
9	T_E(Seconds)	0.500
10	K_F(Seconds)	0.110
11	T_F(Seconds)	1.000
12	E_1	2.470
13	Efd_1 S_E (E_1)	0.035
14	E1	3.500
15	Efd_2 S_E (E_2)	0.500

TABLE A3: AC4A EXCITATION SYSTEM DATA

No.	Description	Value
1	T_R (Seconds)	0.1
2	K_A	10.01
3	T_A (Seconds)	0.060
4	T_B (Seconds)	0.1
5	T_C (Seconds)	0.2
6	VR_{MAX} (v)	9.99
7	VR_{MIN} (v)	-9.99
8	K_E	1
9	T_E (Seconds)	0.080
10	K_F	0.11
11	T_F (Seconds)	1.000
12	E_1 (v)	2.470
13	SE(E_1) (v)	0.035
14	E1 (v)	3.500
15	SE(E_2) (v)	0.500

TABLE A4: AC5A EXCITATION SYSTEM DATA

No.	Description	Value
1	T_R (Seconds)	0.025
2	VI_{MAX} (pu)	1.000
3	VI_{MIN} (pu)	0.060
4	T_C (Seconds)	1.000
5	T_B (Seconds)	1.000
6	K_A	3.000
7	T_A (Seconds)	-2.500
8	VR_{MAX} (pu)	1.800
9	VR_{MIN} (pu)	0.080
10	K_C	0.110

TABLE A5: ST1A EXCITATION SYSTEM DATA

No.	Description	Value
1	T_R (Seconds)	0.1000
2	VI_{MAX}	0.200
3	VI_{MIN}	-0.200
4	T_C (Seconds)	0.0100
5	T_B (Seconds)	10.00
6	T_{C1} (Seconds)	0.010
7	T_{B1} (Seconds)	0.100
8	K_A	51.00
9	T_A (Seconds)	0.0100
10	VA_{MAX}	4.600
11	VA_{MIN}	-4.600
12	VR_{MAX}	3.400
13	VR_{MIN}	-3.400
14	K_C	0.0100
15	KF	0.100
16	TF (Seconds)	0.3100
17	K_{LR}	1.000
18	I_{LR}	2.000

TABLE A6: IEEE ST2A EXCITATION SYSTEM DATA

No.	Description	Value
1	T_R (Seconds)	0.1000
2	VI_{MAX}	0.200
3	VI_{MIN}	-0.200
4	T_C (Seconds)	0.0100
5	T_B (Seconds)	10.00
6	T_{C1} (Seconds)	0.010
7	T_{B1} (Seconds)	0.100
8	K_A	51.00
9	T_A (Seconds)	0.0100
10	VA_{MAX}	4.600
11	VA_{MIN}	-4.600
12	VR_{MAX}	3.400
13	VR_{MIN}	-3.400
14	K_C	0.0100
15	KF	0.100
16	TF (Seconds)	0.3100
17	K_{LR}	1.000
18	I_{LR}	2.000

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