# Simulation and Performance Analysis of a Synchronous Generator Excitation System: Case of the IEEE ST1A

Achiza Mushagalusa Josué[1]; Ramazani Mukamba Joseph[2]; Assani Pataule Grâce[3]

[1,2,3]Faculty of Engineering, Université Mapon
[1,2,3]Kindu, Democratic Republic of the Congo

Publication Date: 2026/01/07

**Abstract: This paper presents a simulation-based performance analysis of the IEEE ST1A static excitation system for a synchronous generator. This system plays a crucial role in ensuring optimal generator operation by regulating the output voltage and maintaining network stability under disturbances. The main objective is to evaluate the stability, speed, accuracy, and damping characteristics of the voltage regulator. The methodology is based on MATLAB/SIMULINK simulations, enabling a detailed analysis of the ST1A model's dynamic behavior under various fault conditions, including single-phase, two-phase, and three-phase faults within an IEEE 9-bus network. The results show that the ST1A system provides fast and precise voltage regulation, minimizing oscillations and enhancing overall system robustness. However, its ability to damp low-frequency electromechanical oscillations is limited. The integration of a multi-band Power System Stabilizer (PSS4B) proves essential to significantly improve damping, reduce settling times, and enhance transient stability. The coordinated ST1A–PSS4B configuration thus represents an effective solution for reliable voltage control and stability enhancement.**

***Keywords:*** *Synchronous Generator, Excitation System, IEEE ST1A Model, Automatic Voltage Regulator (AVR), Voltage Stability, Transient Response, MATLAB/SIMULINK Simulation, Reactive Power, Power System Stabilizer (PSS), Dynamic Performance.*

**How to Cite:** Achiza Mushagalusa Josué; Ramazani Mukamba Joseph; Assani Pataule Grâce (2025) Simulation and Performance Analysis of a Synchronous Generator Excitation System: Case of the IEEE ST1A. *International Journal of Innovative Science and Research Technology*,10(12), 2639-2652. https://doi.org/10.38124/ijisrt/25dec1400

## I. INTRODUCTION

The excitation system of a synchronous generator is a critical component for ensuring its optimal operation, as it directly governs the rotor magnetic flux, regulates the terminal voltage, manages reactive power exchange, and plays a decisive role in maintaining overall system stability, particularly during transient disturbances and load variations, as demonstrated in [1],[2]. In modern interconnected power systems characterized by increasing penetration of dynamic loads and renewable energy sources, accurate voltage regulation and fast dynamic response have become essential requirements for reliable and high-quality power supply. Consequently, advanced excitation systems are required to enable synchronous generators to operate close to their stability limits while preserving system reliability and power quality, as highlighted in [3],[4].

Among the reference models used for the analysis and simulation of excitation systems, the standardized models defined in the IEEE Std 421 family provide widely recognized and validated representations for power system stability studies, as formalized in [5]. Within this framework, the IEEE ST1A model corresponds to a static excitation system in which the exciter is supplied directly from the generator terminals through a transformer and a controlled rectifier. Owing to its simplified structure and well-defined parameters, such as the regulator gain $K_A$, the time constant $T_A$, compensation networks, and limiter devices. The ST1A model is particularly suitable for dynamic and transient stability investigations, as discussed in [4],[6].

Excitation systems are commonly classified into DC, AC, and static categories, as defined in [5],[4]. The DC1A model employs a DC exciter with a field rheostat, while the AC5A model represents brushless excitation using a rotating rectifier and stabilizing feedback. In contrast, the ST1A model relies on a stationary rectifier, typically configured as a full bridge, resulting in a high initial response and negligible exciter time constants. This configuration enables rapid field voltage buildup, which is essential for effective voltage support during disturbances, as emphasized in [7]. The associated voltage regulator combines a series compensator, an optional stabilizing feedback loop, and an amplifier characterized by $K_A$ and $T_A$, allowing adequate stability to be achieved through appropriate parameter tuning.

ISSN No: -2456-2165 https://doi.org/10.38124/ijisrt/25dec1400

Several comparative studies have highlighted the superior dynamic performance of static excitation systems relative to rotating DC and AC schemes. Performance evaluations under severe disturbances, such as three-phase short-circuit faults, indicate that static systems, including ST1A and ST2A, exhibit improved transient stability margins, longer critical clearing times, and faster voltage recovery, as reported in [6]. These advantages are largely attributed to the absence of rotating components and the direct utilization of terminal voltage for excitation, a conclusion consistent with the survey presented in [7]. Furthermore, investigations into transient voltage behavior have demonstrated that the fast regulation characteristics of the ST1A model can significantly mitigate voltage oscillations following disturbances, thereby enhancing overall system stability, as shown in [4].

The tuning of excitation system parameters has been identified as a determining factor in achieving satisfactory transient performance. Sensitivity analyses indicate that improper selection of $K_A$ and $T_A$ can severely degrade the dynamic response of the ST1A model, despite its inherently fast static structure, as evidenced in [4]. Consequently, simulation and experiment-based studies emphasize the importance of accurate modeling and systematic parameter adjustment when evaluating voltage stability, regulation quality, and robustness under fault and overload conditions, as discussed in [8]. In this context, key performance indicators such as critical clearing time and settling time are widely adopted to quantitatively assess excitation system robustness, as proposed in [6].

Beyond conventional linear control approaches, recent research has increasingly focused on advanced and hybrid control strategies to further enhance excitation system performance. The integration of Particle Swarm Optimization with advanced controllers, including Model Predictive Control, has been shown to significantly reduce settling time and oscillatory behavior compared to classical PID-based designs, as demonstrated in [9]. To improve robustness with respect to operating point and load variations, nonlinear modifications of automatic voltage regulators have also been proposed. In particular, the introduction of corrective terms based on the ratio Vt/Vq into the ST1A regulator structure enhances phase compensation robustness and reduces sensitivity to load changes, as presented in [10].

Modern excitation systems increasingly rely on digital control platforms integrating protective limiters to ensure safe operation. Over-excitation limiters and under-excitation limiters enable the short-term exploitation of generator overload capability while preventing thermal damage and loss of stability. Their critical role in maintaining generator integrity while preserving dynamic voltage support during abnormal operating conditions is highlighted in [11].

Numerous studies have highlighted the importance of simulation and experimental analysis of excitation systems as essential tools for assessing voltage stability, regulation quality, and system robustness under fault and overload conditions, as demonstrated in [8]. A comprehensive performance evaluation of several synchronous generator excitation systems, including IEEE DC1A, DC2A, AC4A, AC5A, ST1A, and ST2A, has been conducted in [6], where transient stability is assessed through a three-phase fault applied to a generator connected to an infinite bus. Using indicators such as settling time, critical clearing time, and voltage overshoot, the study concludes that the IEEE ST2A static excitation system exhibits the fastest recovery and the most stable post-fault response; however, the reliance on a third-order machine model and a single-machine framework limits the representativeness of the results for real interconnected power systems. Comparative investigations such as [12] further report superior dynamic speed and stability of the ST7B model compared to ST1A, although the absence of detailed parameter disclosure reduces the credibility and reproducibility of the findings. More broadly, despite the widely acknowledged advantages of static excitation systems, significant divergences persist in the literature regarding modeling and control approaches: while some works emphasize detailed nonlinear modeling to achieve optimal control performance, others advocate model-free or fractional-order strategies to reduce modeling complexity and enhance robustness in multi machine environments, as proposed in [13]. In addition, a fundamental limitation of self-excited static systems such as IEEE ST1A, namely their strong dependence on terminal voltage, which can severely reduce forcing capability during nearby faults, is clearly emphasized in [7]. Finally, broader comparative assessments, including [12], confirm the potential advantages of alternative static models such as ST7B in terms of speed and damping, while also underscoring the recurring issue of incomplete parameter transparency that limits the generality of such conclusions.

The objective of this study is to evaluate the performance of the ST1A excitation system of a synchronous generator in terms of stability, response speed, accuracy, and damping. The aim is to optimize the quality and reliability of the output voltage, enhance the transient behavior of the machine, and ensure the stability of the power system under disturbances such as ground faults. The analysis is conducted through simulations using MATLAB/SIMULINK.

The paper is organized as follows. Section II details the methodology and modeling . Section III describes the result and discussion. Finally, the conclusions are given in Section IV.

## II. METHODOLOGY AND MODELING

This section details the modeling approaches used for the ST1A excitation system and the synchronous generator, as well as the simulation setup.

### ➢ *Overview of Synchronous Generator Excitation Systems*

The required performance of an excitation system is primarily influenced by the characteristics of the synchronous generator and its supply circuit . The excitation system of a synchronous generator is intrinsically linked to the performance and stability of the power system to which it

ISSN No: -2456-2165 https://doi.org/10.38124/ijisrt/25dec1400

is connected. This point outlines the requirements of an excitation system, its key components (AVR, MVR, de-excitation, over-excitation and under-excitation limiters "OEL, UEL, Volts/Hertz, PSS"), and the different existing types (DC, AC, and static "ST"). These elements are essential to ensure the stable and protected operation of the generator. Over-excitation (OEL) and under-excitation (UEL) limiters are critical advanced protection functions.

➢ *Components of an Excitation System*

A synchronous generator excitation system is a fundamental assembly of components, including the exciter, voltage regulator, sensors and load compensators, the power system stabilizer (PSS), as well as various limiters and protective circuits, which serve to precisely control and regulate the generator's output voltage as shown in Fig.1 These elements work together to maintain grid stability, prevent power oscillations, manage reactive power, and protect equipment against limit violations or faults, thereby ensuring safe, reliable operation and optimal power quality[14].

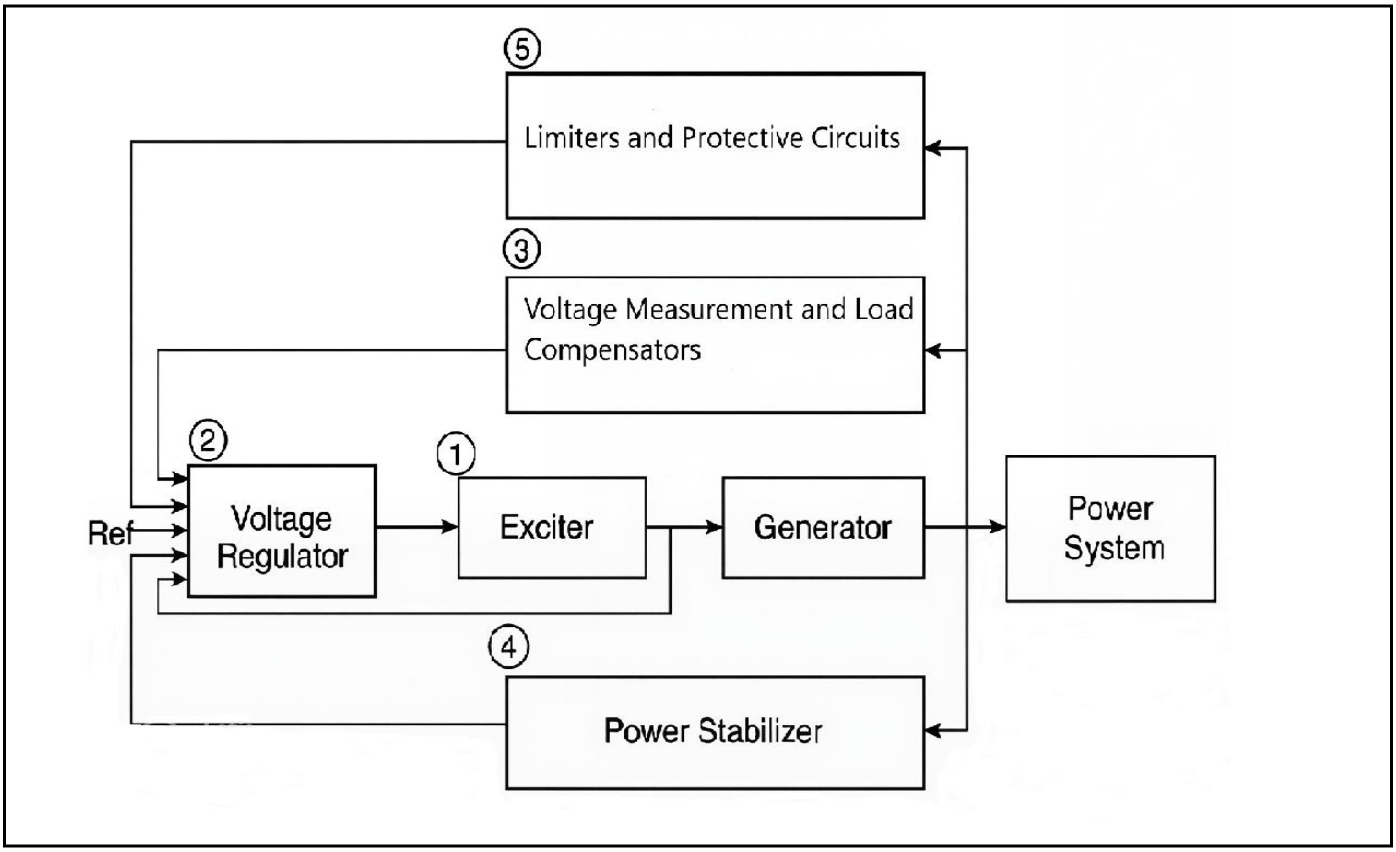


Fig 1 Functional Diagram of a Synchronous Generator Excitation System

➢ *Direct Current (DC) Excitation Systems*

They employ a direct current (DC) source to supply the rotor excitation winding, a crucial component for generating the magnetic field necessary for electrical power production. These systems rely on a DC machine, called an exciter, which is mechanically coupled either to a prime mover[12] or to the shaft of the synchronous generator. Two types of exciters can be distinguished: self-excited, where the exciter derives its excitation current from the main generator (or synchronous generator), and separately excited, where an independent source powers the exciter. In the latter case, the main exciter field current is provided by a pilot exciter, typically consisting of a permanent magnet DC generator [12],[15] offering greater operational flexibility.

Fig. 2 illustrates a classic self-excited DC excitation system for a synchronous generator. In this setup, the field winding draws its energy from the generator's own output, yielding a simple and cost-effective design. The closed-loop control circuit uses a rheostat for manual field adjustment and a voltage regulator with an amplifier to maintain constant output voltage under load variations. Power is supplied to the rotor via slip rings reliable but maintenance-prone components. This traditional configuration, though robust, is increasingly replaced by brushless excitation systems offering faster response and lower maintenance.

➢ *Alternating Current Excitation Systems (AC Excitation Systems)*

Unlike DC excitation systems that use a direct current source, AC excitation systems utilize an alternating current source. This alternating current is typically generated by a small synchronous generator, called an exciter, which is mechanically coupled to the shaft of the main generator. The exciter can be either self-excited or separately excited.

ISSN No: -2456-2165 https://doi.org/10.38124/ijisrt/25dec1400

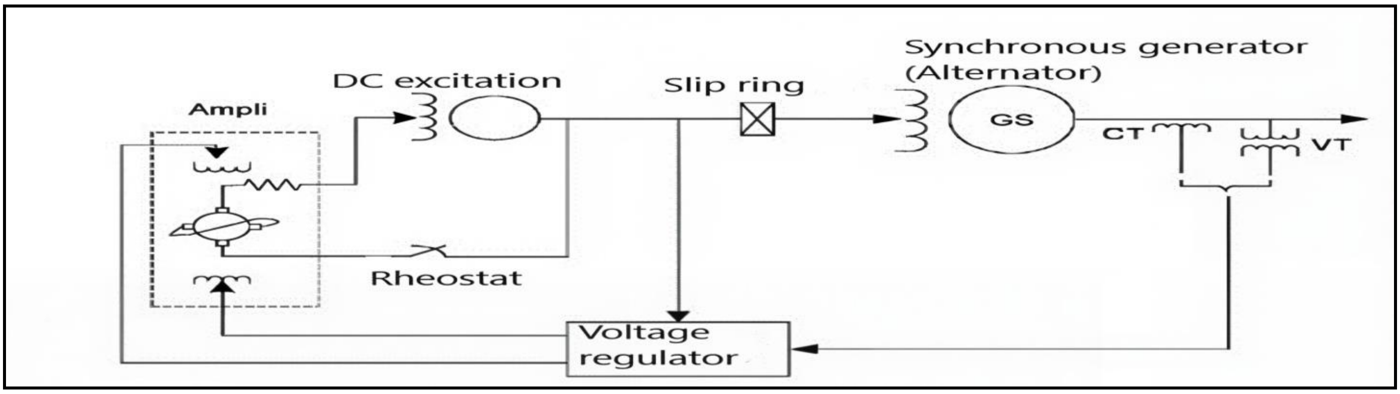

Fig 2 Functional Diagram of a Self-Excited DC Excitation System

The alternating current produced by the exciter is then rectified using a diode or thyristor bridge to obtain a direct current output. Two main types of AC excitation systems can be distinguished:

- *Static Systems:*

The rectification of the alternating current is carried out using a diode bridge (Fig.3a) or a static thyristor bridge (Fig.3b). Fig.3 presents two functional diagrams of a synchronous generator (SG) excitation system, which regulates the generator's output voltage. Both systems rely on voltage $V_T$ and current $C_T$ measurements, comparing them with an AC reference, while an AC regulator controls a rectifier that supplies the field circuit. The main distinction lies in the type and placement of the rectifier. In the first diagram, an uncontrolled rectifier delivers AC excitation power to the rotor via slip rings. In contrast, the second, more modern design employs a controlled rectifier mounted directly on the rotor, eliminating the need for power slip rings. Only the control signals pass through slip rings, thereby enhancing system reliability and overall performance. These systems are compact and offer high responsiveness, but they can be sensitive to disturbances in the electrical network.

- *Systems with Rotating Exciter (AC Brushless Excitation):*

The exciter is a small synchronous generator whose rotor rotates together with that of the main generator. Fig.4 illustrates the functional architecture of a Pilot Exciter type excitation system for a synchronous generator. This cascaded configuration employs a three-phase AC source to supply the pilot exciter, whose output subsequently energizes the main generator field. The alternating current produced by the exciter is rectified through rotating diodes or thyristors mounted on the rotor. Regulation is achieved on two hierarchical levels: the AS unit governs the pilot exciter, while the GS unit supervised by a central regulator with manual control capability regulates the main generator using feedback from current ($C_T$) and voltage ($V_T$) transformers. Such systems are known for their robustness and reliability, although they are typically bulkier than static excitation systems. They provide accurate and stable dynamic control of the generator's output voltage.

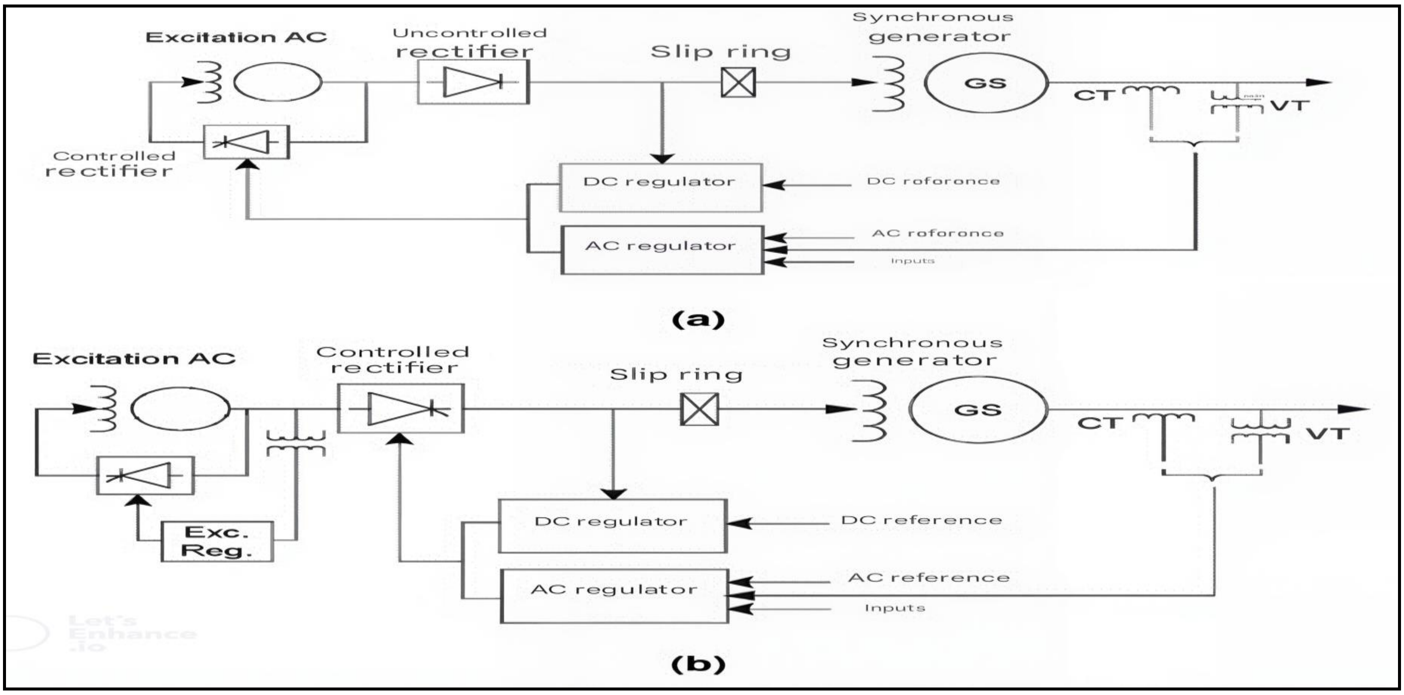

Fig 3 Functional Diagrams of an AC Excitation System with an Uncontrolled Rectifier (a) and with a Controlled Rectifier (b)

ISSN No: -2456-2165 https://doi.org/10.38124/ijisrt/25dec1400

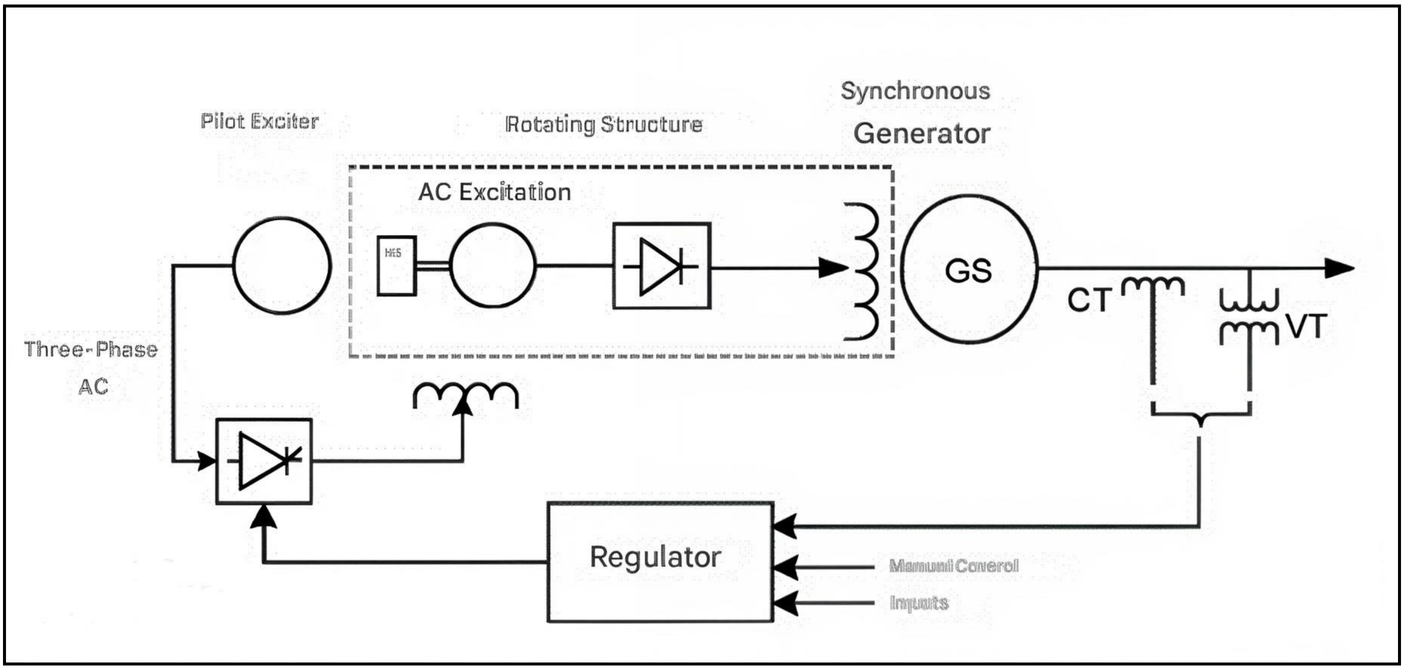

Fig 4 Functional Diagram of an AC Excitation system with Controlled Rectifier

➢ *Static Excitation Systems (ST)*

Unlike traditional systems that use a rotating machine (exciter), static excitation systems directly convert alternating current (AC) into direct current (DC) using power electronic components. This DC current is then injected into the rotor field winding, creating the magnetic field required for electrical energy generation. The power supply for static excitation systems can be derived either from the electrical grid or from the terminals of the generator itself [6].

Fig.5 illustrates a modern static excitation system used for synchronous generators. This configuration typically comprises a power transformer, a thyristor-controlled rectifier bridge, a voltage regulator, and various protection circuits. The process begins by sampling the generator's three-phase AC voltage through potential transformers (VTs). The voltage regulator compares this measured signal with a reference value to determine the required excitation power. A corresponding control signal is then applied to the rectifier, which converts the AC power supplied by the excitation transformer into a regulated DC current.

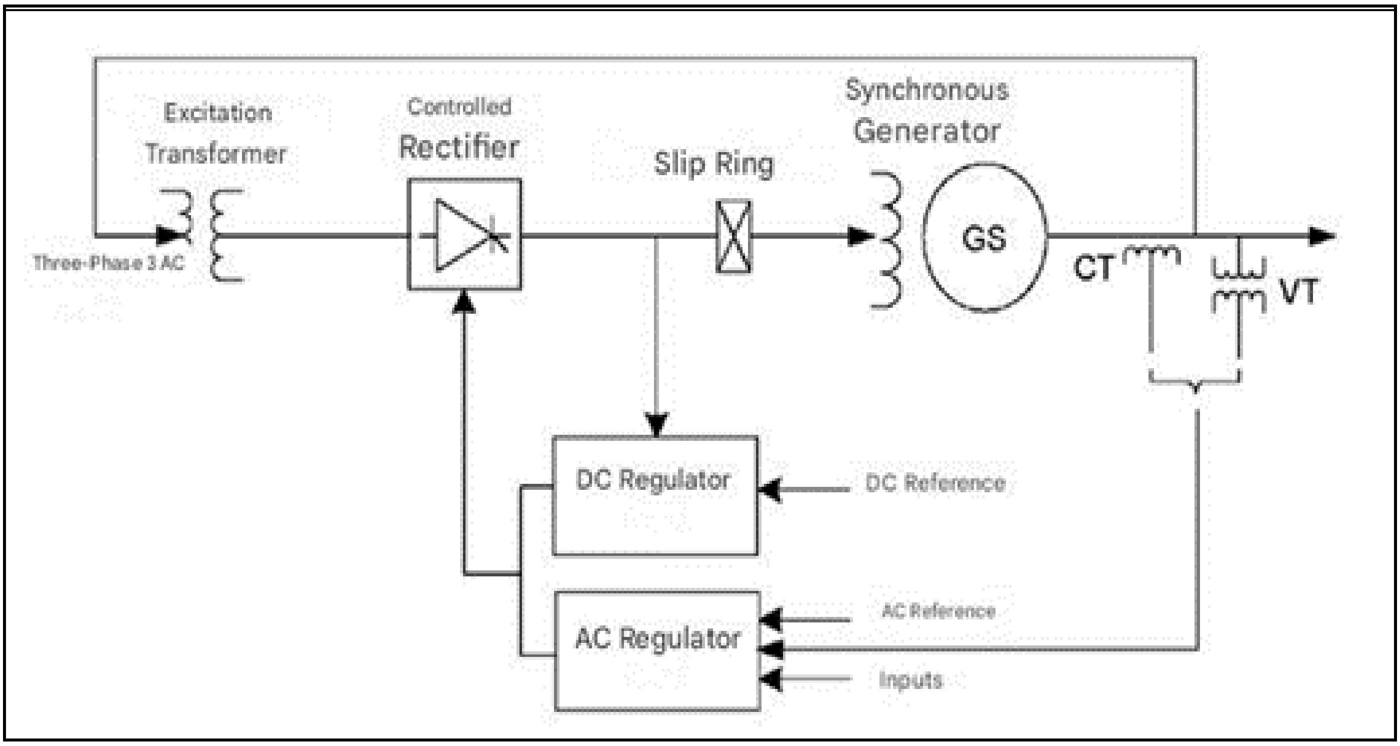

Fig 5 Functional Diagram of a Voltage-Source Controlled Rectifier ST Excitation System

ISSN No: -2456-2165 https://doi.org/10.38124/ijisrt/25dec1400

This current is delivered to the rotor through slip rings, allowing precise control of the generator's output voltage. Additionally, a DC regulation loop often supplied by current transformers (CTs) enhances the system's stability and protection. The main advantages of this architecture include high dynamic response, compact design, low maintenance requirements, and improved reliability compared with conventional excitation systems, thereby enabling accurate and dependable voltage regulation within the power grid [12], [16].

➢ *Excitation System Control and Protection Circuits*

The control of an excitation system goes beyond simple voltage regulation, combining regulation, limitation, and protection functions to ensure reliable performance as shown in Fig. 6. The main control loop starts from the measurement of the generator terminal voltage and acts on the magnetic field via the excitation power source. Two types of voltage regulators are used: the Automatic Voltage Regulator (AVR), a closed-loop electronic system providing precise, fast, and secure regulation, and the Manual Voltage Regulator (MVR), a simpler, robust, and cost-effective backup solution. The system also includes voltage sensors for feedback and load compensators to maintain stable voltage at a distance by managing reactive power.

Safety and stability are reinforced by specialized limiters and protective devices, including the field current limiter, over-excitation limiter (OEL), under-excitation limiter (UEL), Volts/Hertz flux limiter, and the Power System Stabilizer (PSS) to damp network oscillations. Relays and a de-excitation circuit provide rapid shutdown of the excitation current in case of faults. This integrated approach of regulation, limitation, and protection, powered by the excitation source and connected to the grid through the power transformer, ensures stable, efficient, and secure electricity generation.

➢ *Modeling of the ST1A Excitation System*

The ST1A model comprises several functional blocks, each with its own mathematical representation and parameters. This includes the modeling of the amplifier with its limiting functions, the stabilizing circuit, different types of limits (windup and non-windup), the lead-lag compensator, and the gating functions, such as the low-voltage gate (LV Gate) and high-voltage gate (HV Gate). These elements are integrated to form the detailed overall model of the excitation system as shown in Fig.7. The IEEE model of the static excitation system type ST1A conforms to the IEEE® 421 standard[5].

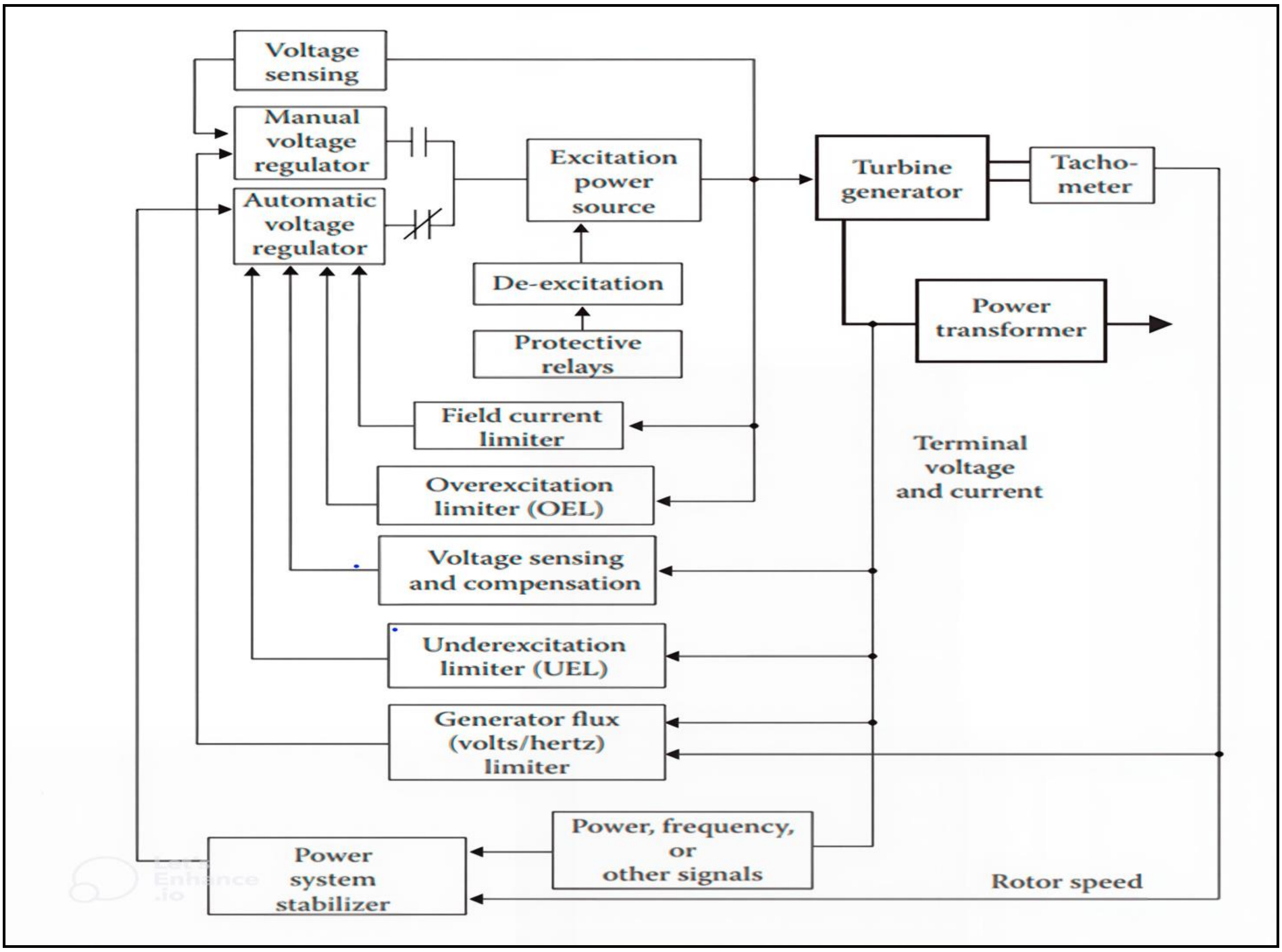


Fig 6 Functional Diagram of an Excitation System with Protection Circuits and Limiters

ISSN No: -2456-2165 https://doi.org/10.38124/ijisrt/25dec1400

➤ *Modeling of the ST1A Excitation System*

The ST1A model comprises several functional blocks, each with its own mathematical representation and parameters. This includes the modeling of the amplifier with its limiting functions, the stabilizing circuit, different types of limits (windup and non-windup), the lead-lag compensator, and the gating functions, such as the low-voltage gate (LV Gate) and high-voltage gate (HV Gate). These elements are integrated to form the detailed overall model of the excitation system as shown in Fig.7. The IEEE model of the static excitation system type ST1A conforms to the IEEE® 421 standard[5].

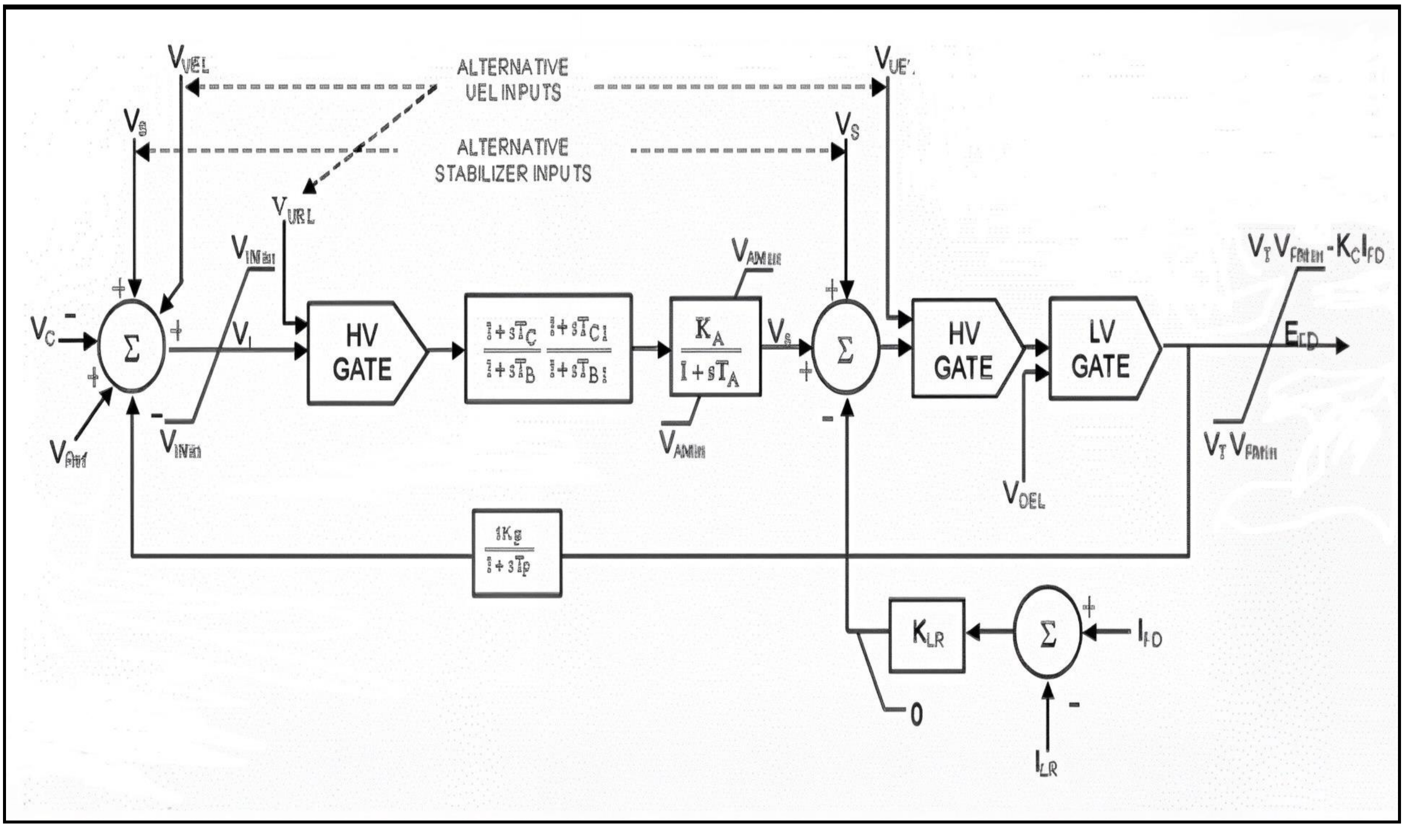


Fig 7 IEEE Model of the Type ST1A Static Excitation System

➤ *Description of the System Used for Simulation*

The simulated system employs a 9-bus IEEE network as shown in Fig.8, a standard configuration widely used for power system stability studies. This network is modeled in MATLAB/SIMULINK, with specific schemes for generation at buses 1 and 3. The parameters of the synchronous generators at buses 2 and 3, the hydro turbine (HTG) and PID controller, as well as the network transformers and lines, are detailed in Tables 1,2,3,4,5,6 and 7. The ST1A excitation system is modeled using the parameters specified in Table 1. A Multi-Band Power System Stabilizer (PSS4B) is employed, with its parameters provided in Table 4, for simulations that include a power stabilizer.

## III. RESULTS AND DISCUSSION

This section presents the simulation results and their interpretation, analyzing the dynamic behavior of the ST1A excitation system and the synchronous generator under various network fault conditions. The tests include single-phase, two-phase, and three-phase ground faults.

➤ *Performance Tests and Scenarios*

The simulations were carried out by considering several scenarios to evaluate the impact of the components:

- Without the lead-lag compensator (where TB = TC = 0 s) and without the addition of the Power System Stabilizer (Multi-Band PSS).
- Without the lead-lag compensator but with the presence of a PSS4B.
- With the lead-lag compensator (TB = 1 s, TC = 11.2 s) but without the PSS4B (Vstab = 0 pu).

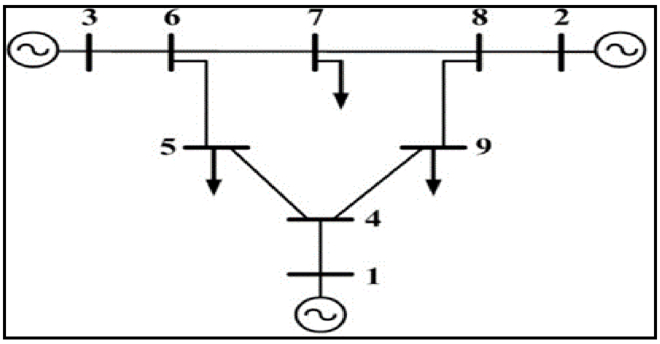


Fig 8 Single-Line Diagram of the IEEE 9-Bus Network

ISSN No: -2456-2165 https://doi.org/10.38124/ijisrt/25dec1400

Table 1 Multi-Band PSS Parameters at Buses 2 and 3

| Parameter | Value |
|---|---|
| Global Gain | 1 |
| $F_I$ (Hz) | 1.25 |
| $K_H$ | 160 |
| $V_{Hmax}$ | 0.15 |
| $F_L$ (Hz) | 0.2 |
| $K_I$ | 40 |
| $V_{Lmax}$ | 0.075 |
| $V_{Smax}$ | 0.15 |
| $K_L$ | 30 |
| $F_H$ (Hz) | 12 |
| $V_{Imax}$ | 0.15 |

Table 2 Parameters of the Transformers at Buses 2 and 3

| Parameter | Value |
|---|---|
| Winding Connection | $Y_g$–$Y_g$ |
| $U_{1N}$ (kV) | 13.5 |
| $U_{2N}$ (kV) | 230 |
| $R_m$ (pu) | 500 |
| $S_N$ (MVA) | 500 |
| $R_1$ (pu) | $10^{-6}$ |
| $R_2$ (pu) | $10^{-6}$ |
| $L_m$ (pu) | 500 |
| f (Hz) | 60 |
| $L_1$ (pu) | 0.0235 |
| $L_2$ (pu) | 0.0586 |

Table 3 Transformer Parameters at Bus 4

| Parameter | Value |
|---|---|
| Winding Connection | $Y_g$–$Y_g$ |
| $U_{1N}$ (kV) | 16.5 |
| $U_{2N}$ (kV) | 230 |
| $R_m$ (pu) | 500 |
| $S_N$ (MVA) | 500 |
| $R_1$ (pu) | $10^{-6}$ |
| $R_2$ (pu) | $10^{-6}$ |
| $L_m$ (pu) | 500 |
| f (Hz) | 60 |
| $L_1$ (pu) | 0.0235 |
| $L_2$ (pu) | 0.0586 |

Table 4 Parameters of the Different Lines

| Line | Rpu (pu) | Lpu (pu) | Ypu (pu) |
|---|---|---|---|
| 4–5 | 0.010 | 0.085 | 0.088 |
| 4–6 | 0.017 | 0.092 | 0.079 |
| 5–7 | 0.032 | 0.153 | 0.088 |
| 6–9 | 0.039 | 0.170 | 0.179 |
| 7–8 | 0.0085 | 0.072 | 0.0745 |
| 8–9 | 0.0119 | 0.1008 | 0.1045 |

Table 5 Parameters at Buses 2 and 3

| Parameter | Value |
|---|---|
| $K_A$ | 210 |
| $T_A$ (s) | 0.001 |
| $T_R$ | 0.020 |
| $T_C$ | 0.000 |
| $T_B$ | 0.000 |

ISSN No: -2456-2165 https://doi.org/10.38124/ijisrt/25dec1400

| | |
|---|---|
| $T_{B1}$ | 0.000 |
| $T_{C1}$ | 0.000 |
| $V_{RMAX}$ (pu) | 6.430 |
| $V_{RMIN}$ (pu) | -6.000 |
| $K_C$ (pu) | 0.038 |
| $K_F$ (pu) | 0.001 |
| $T_F$ (s) | 1.000 |
| $K_{LR}$ (pu) | 4.540 |
| $I_{LR}$ (pu) | 4.400 |

Table 6 Synchronous Generator Parameters at Bus 2

| **Parameter** | **Value** |
|---|---|
| $S_N$ (MVA) | 200 |
| $X_d$ (pu) | 1.305 |
| $X_q$ (pu) | 0.474 |
| $T_d'$ (s) | 1.01 |
| $R_S$ (pu) | $0.8544 \times 10^{-3}$ |
| $U_N$ (kV) | 13.5 |
| $X_d'$ (pu) | 0.296 |
| $X_q''$ (pu) | 0.243 |
| $T_q''$ (s) | 0.053 |
| H (s) | 3.2 |
| f (Hz) | 60 |
| $X_d''$ (pu) | 0.252 |
| $X_l$ (pu) | 0.18 |
| $T_{q0}''$ (s) | 0.1 |
| Number of poles | 4 |

Table 7 Parameters of the HTG (Hydraulic Turbine and PID Governor)

| **Parameter** | **Value** |
|---|---|
| $K_A$ | 10/3 |
| $g_{max}$ (pu) | 0.97518 |
| $R_p$ | 0.05 |
| $K_d$ | 0 |
| $T\omega$ (s) | 2.67 |
| $T_a$ (s) | 0.007 |
| $v_{gmin}$ (pu/s) | -0.1 |
| $K_p$ | 1.163 |
| Td (s) | 0.01 |
| Pmo (pu) | 0.751606 |
| $g_{min}$ (pu) | 0.01 |
| $v_{gmax}$ (pu/s) | 0.1 |
| $K_i$ | 0.105 |
| $\beta$ (beta) | 0 |

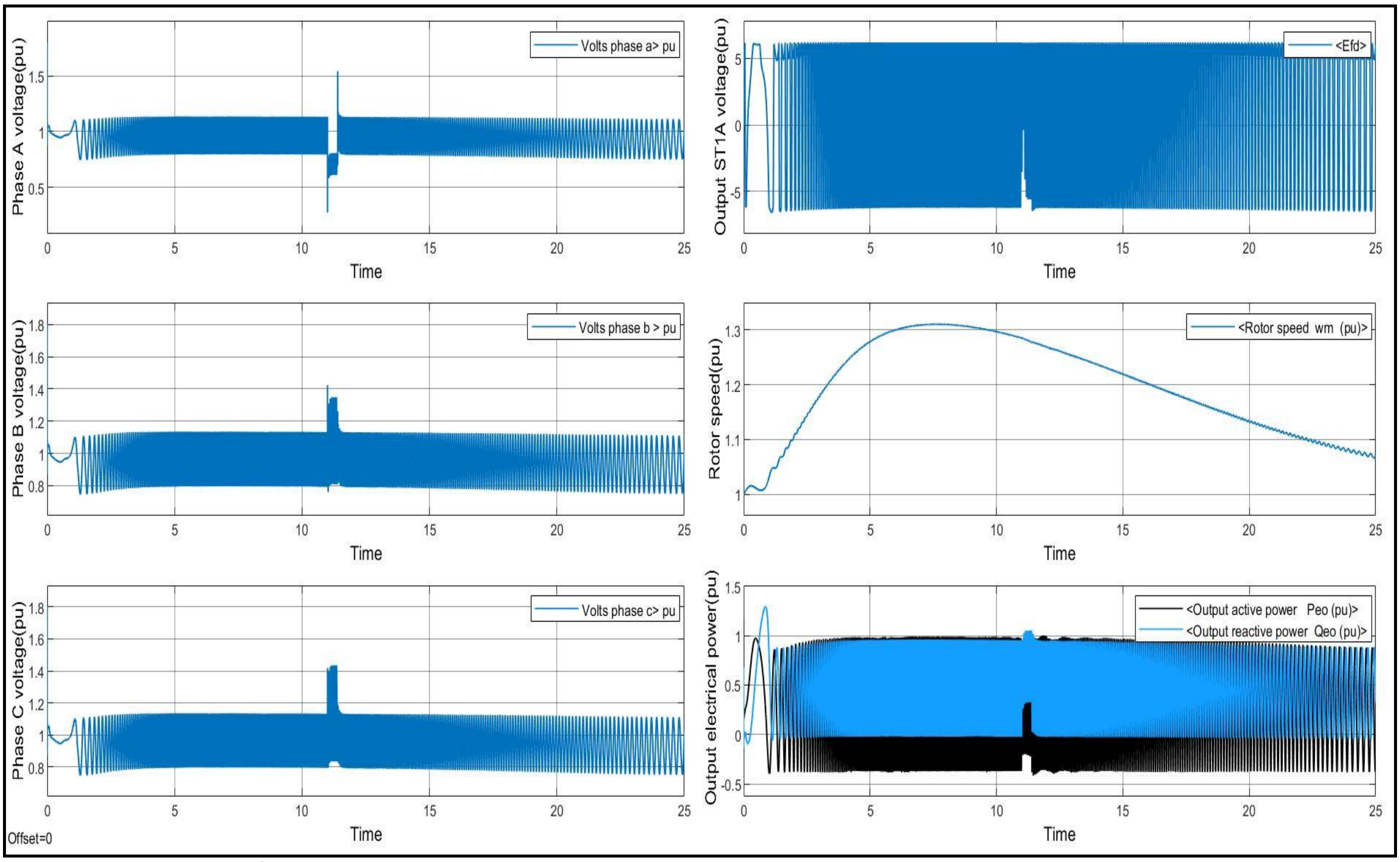


Fig 9 Output Signals of the Generator and the ST1A, and the Rotational Speed Without the Lead-Lag Compensator ($T_B = T_C = 0$ s) and Without the Multi-Band PSS [Single-Phase Short Circuit, Fault Duration = 400 ms)]

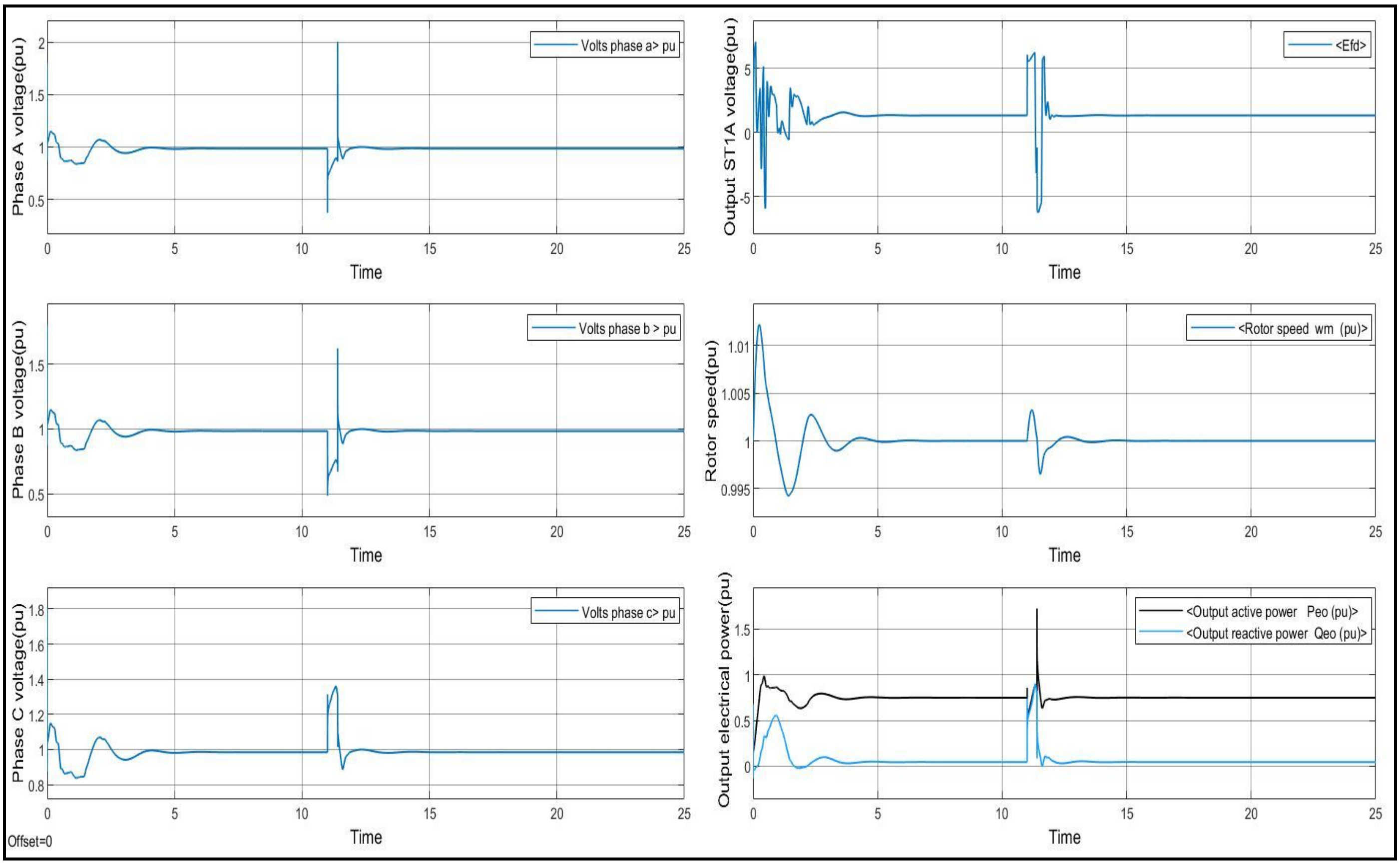


Fig 10 Output Signals of the Generator and the ST1A, and the Rotational Speed with the Lead-Lag Compensator ($T_B$ = 1 s, $T_C$ = 11.2 s) and Without the PSS4B ($V_{stab}$ = 0 pu) [Single-Phase Short Circuit, Fault Duration = 400 ms].

ISSN No: -2456-2165 https://doi.org/10.38124/ijisrt/25dec1400

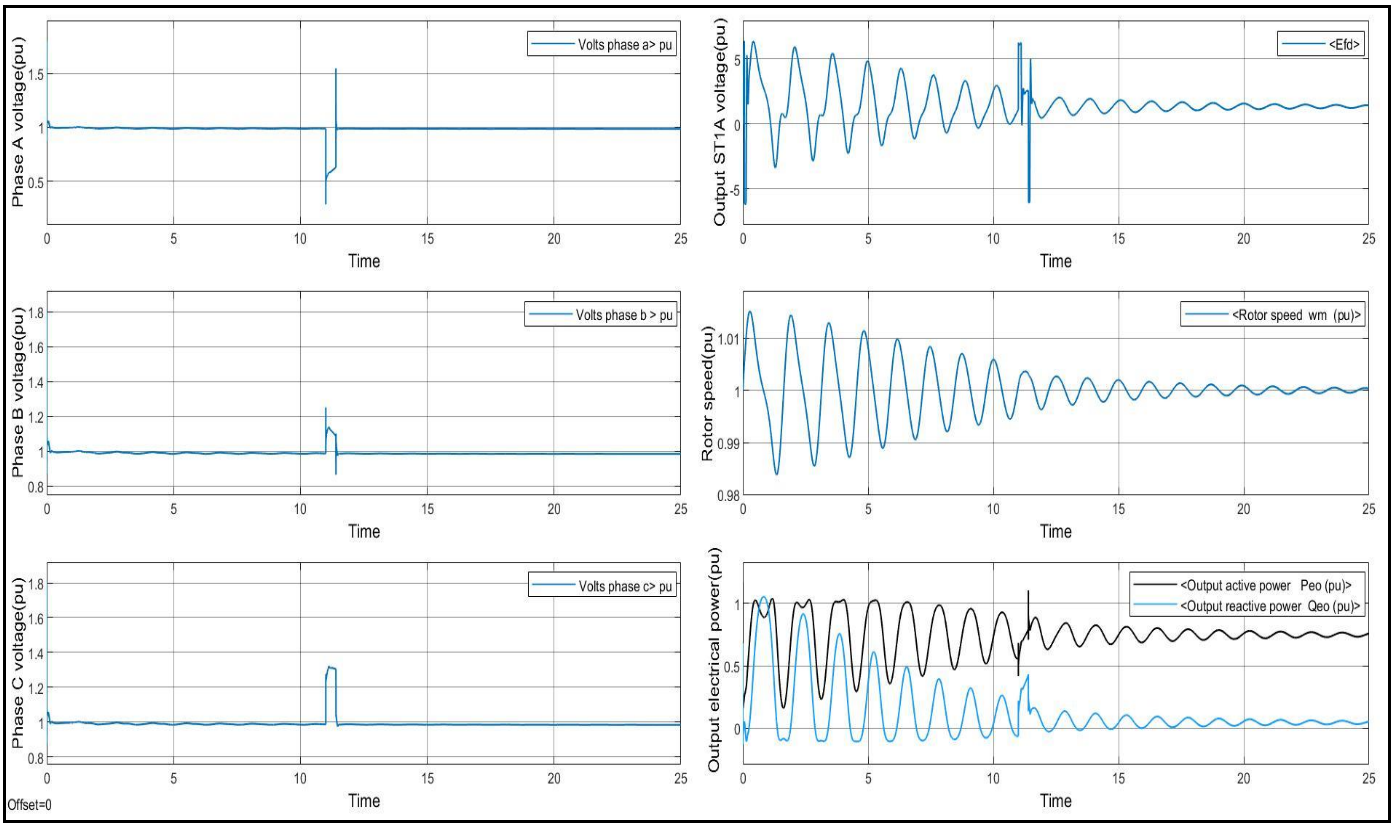


Fig 11 Output Signals of the Generator and the ST1A, and the Rotational Speed with the Lead-Lag Compensator ($T_B$ = 1 s, $T_C$ = 11.2 s) and Without the PSS4B ($V_{stab}$ = 0 pu) [Single-Phase Short Circuit, Fault Duration = 400 ms].

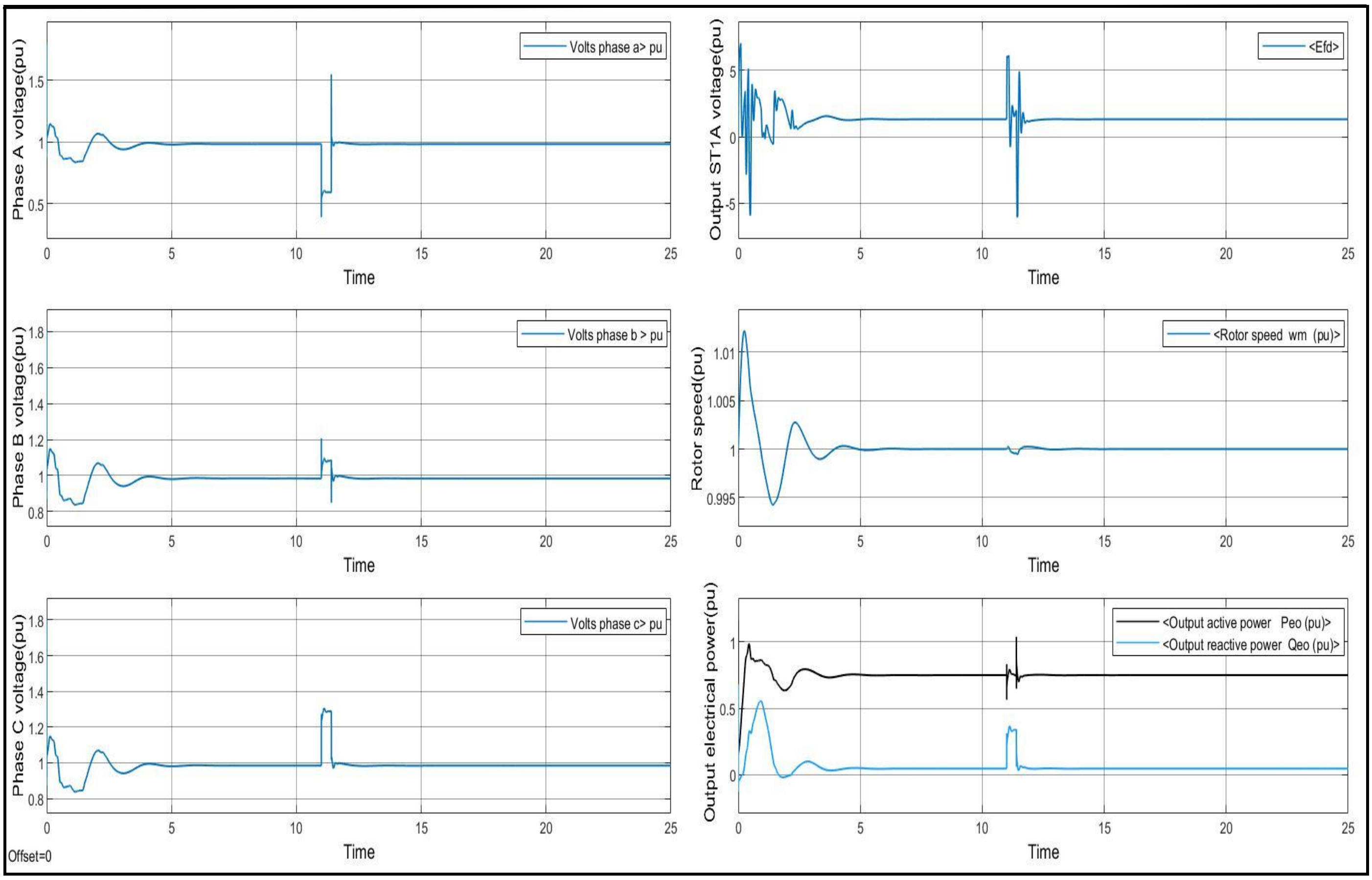


Fig 12 Output Signals of the Generator and the ST1A, and the Rotational Speed Without the Lead-Lag Compensator ($T_B$ = $T_C$ = 0 s) and with the Presence of a PSS4B [Two-Phase Short Circuit, Fault Duration = 400 ms].

ISSN No: -2456-2165 https://doi.org/10.38124/ijisrt/25dec1400

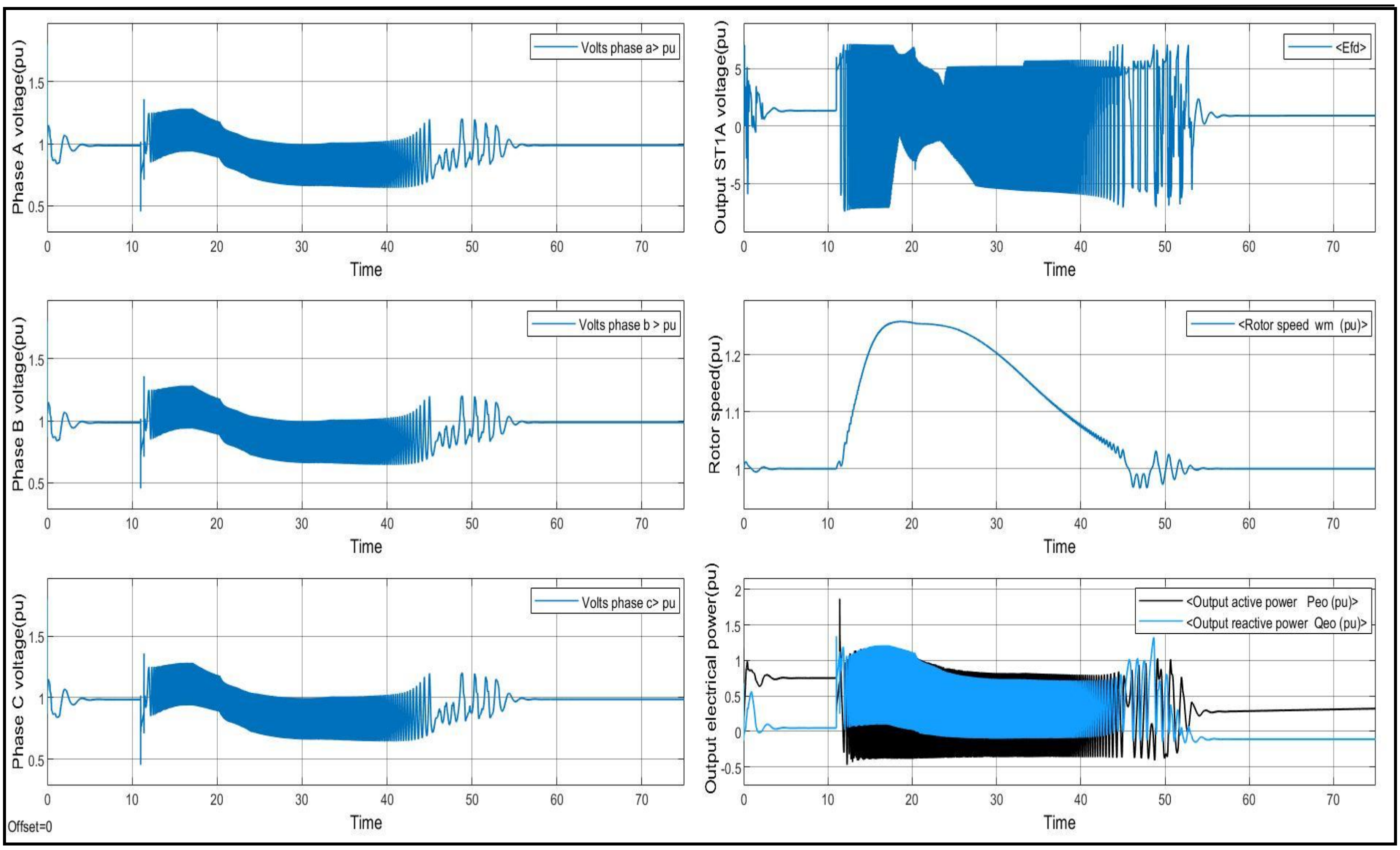


Fig13 Output Signals of the Generator and the ST1A, and the Rotational Speed Without the Lead-Lag Compensator ($T_B = T_C = 0$ s) and with the Presence of a PSS4B [Three-Phase Short Circuit, Fault Duration = 400 ms].

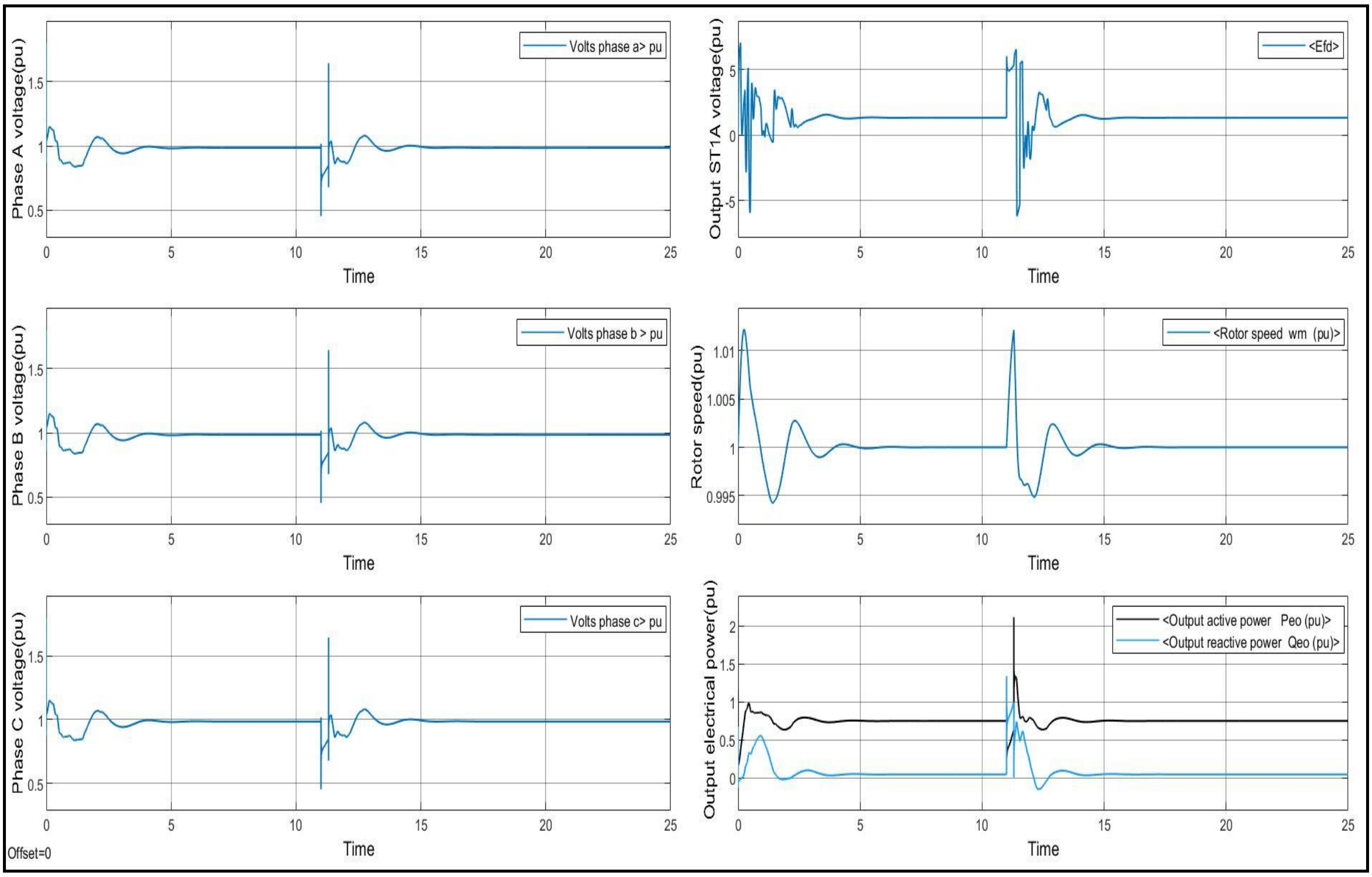


Fig 14 Output Signals of the Generator and the ST1A, and the Rotational Speed Without the Lead-Lag Compensator ($T_B = T_C = 0$ s) and with the Presence of a PSS4B [Three-Phase Short Circuit, Fault Duration = 300 ms].

ISSN No: -2456-2165 https://doi.org/10.38124/ijisrt/25dec1400

➢ *Discussion of Results*

The simulation results provide a comprehensive assessment of the dynamic performance of the IEEE ST1A excitation system under various fault scenarios and control configurations. The analysis highlights the respective roles of the voltage regulator, the lead–lag compensator, and the Power System Stabilizer (PSS) in ensuring voltage regulation, damping electromechanical oscillations, and maintaining overall system stability.

As illustrated in Fig. 9, the response of the system using the IEEE-recommended ST1A parameters, typically associated with a PSS2A, reveals a clear lack of dynamic stability. Severe oscillations are observed in terminal voltage as well as in active and reactive power, indicating poor damping of electromechanical modes. Although the rotor speed remains close to its reference value, the persistence of large oscillations in electrical variables demonstrates that the excitation system, when inadequately coordinated with an effective stabilizer, is unable to ensure acceptable transient performance. This result emphasizes that parameter sets recommended for specific stabilizer configurations may lead to instability when applied outside their intended context.

The system behavior under fault conditions with the PSS4B enabled and the lead–lag compensator deactivated ($T_B = T_C = 0$ s) is depicted in Fig. 10 and Fig. 12 for single-phase and two-phase short circuits of 400 ms duration, respectively. In the case of a single-phase fault (Fig. 10), the phase voltages experience only short-lived deviations, which are rapidly corrected by the ST1A voltage regulator. The exciter output voltage exhibits an initial oscillatory response that is quickly damped, while the rotor speed promptly returns to its nominal value after minor fluctuations. Similarly, active and reactive power responses show transient variations of limited amplitude, followed by fast stabilization. These results confirm the high responsiveness of the ST1A regulator and the strong damping capability introduced by the PSS4B.

Comparable observations are made for the two-phase short circuit presented in Fig. 12. Despite the severity of the disturbance, the PSS4B effectively suppresses electromechanical oscillations and ensures smooth recovery of both electrical and mechanical variables. Notably, this satisfactory dynamic behavior is achieved even in the absence of the lead–lag compensator, demonstrating that the PSS4B alone provides sufficient damping of low-frequency modes when properly tuned. These findings underline the critical contribution of the PSS4B to transient stability enhancement and confirm that additional phase compensation is not mandatory under these operating conditions.

The influence of the lead–lag compensator acting alone is examined in Fig. 11, which corresponds to a 400 ms single-phase short circuit with the compensator enabled ($T_B = 1$ s, $T_C = 11.2$ s) and the PSS4B deactivated. Although the system remains stable, the responses are characterized by lightly damped oscillations in rotor speed and electrical power. The ST1A regulator succeeds in restoring the phase voltages with a moderate overshoot; however, the absence of a dedicated stabilizer leads to prolonged electromechanical oscillations lasting several seconds. This behavior highlights the limited damping capability of the lead–lag compensator when used as the sole auxiliary control and clearly demonstrates the necessity of a PSS to effectively attenuate low-frequency oscillatory modes.

The response of the system to a severe three-phase fault of 400 ms duration is shown in Fig. 13. With the PSS4B active and the lead–lag compensator disabled, the system avoids instability but exhibits poor damping characteristics. Rotor speed and active/reactive power oscillations decay slowly, resulting in long settling times and significant overshoot. Moreover, the dynamic response becomes increasingly sluggish as the fault duration increases, revealing a strong sensitivity of system performance to disturbance severity. The low damping ratio and extended settling time indicate suboptimal excitation system performance under these conditions, thereby justifying the need for complementary compensation strategies to enhance robustness.

This observation is further supported by the results in Fig. 14, which illustrate the system response to a 300 ms three-phase short circuit with the ST1A excitation system coordinated with the PSS4B. In this case, oscillations in rotor speed and power are significantly attenuated, transient overshoots are reduced, and the system returns more rapidly to a stable operating point. These results clearly demonstrate the effectiveness of the PSS4B in improving damping performance and strengthening system resilience under severe disturbances.

Overall, the simulation results confirm that the IEEE ST1A excitation system provides fast and accurate voltage regulation under a wide range of fault conditions. While the ST1A regulator alone ensures rapid voltage recovery and limits excessive reactive power excursions, it does not guarantee sufficient damping of electromechanical oscillations. The lead–lag compensator contributes only marginally to stability enhancement when used in isolation. In contrast, the integration of a properly tuned PSS4B significantly improves damping, shortens settling times, and enhances transient stability. Consequently, the coordinated ST1A–PSS4B configuration emerges as a robust and high-performance solution for improving voltage quality, electromechanical stability, and overall power system reliability under disturbed operating conditions.

## IV. CONCLUSION

This paper presented a simulation-based evaluation of the IEEE ST1A static excitation system applied to a synchronous generator in the IEEE 9-bus network. The study analyzed dynamic performance under various fault conditions, emphasizing voltage regulation, transient stability, and overall system robustness. Results show that the ST1A provides fast and accurate voltage control, ensuring rapid recovery of terminal voltage and effective reactive power management during disturbances.

ISSN No: -2456-2165 https://doi.org/10.38124/ijisrt/25dec1400

However, the ST1A alone is insufficient to damp low-frequency electromechanical oscillations, particularly under severe faults. The use of a lead–lag compensator offers only limited improvement, highlighting the need for additional stabilizing mechanisms to maintain satisfactory transient behavior.

The coordinated integration of a multi-band Power System Stabilizer (PSS4B) with the ST1A significantly enhances system performance. This configuration effectively suppresses oscillations, reduces overshoot and settling time, and improves transient stability margins, confirming the critical role of the PSS in complementing the excitation system. Overall, the ST1A–PSS4B combination provides a robust and high-performance solution for synchronous generator control, with potential for further improvements through adaptive tuning and multi-machine studies.

## REFERENCES


[1]. M. B. Idris and A. J. Elzubia, ‘The Effect of Excitation System on Synchronous Generator Transient Stability’, IJIREEICE, vol. 4, no. 8, pp. 84–87, Aug. 2016, doi: 10.17148/IJIREEICE.2016.4817.

[2]. D. Jiang et al., ‘Research on excitation system of synchronous generator’, J. Phys. Conf. Ser., vol. 1607, no. 1, p. 012040, Aug. 2020, doi: 10.1088/1742-6596/1607/1/012040.

[3]. P. Sankhwar, ‘Excitation System, Proportional and Integral Controls of a Synchronous Generator for Reducing Adverse Impacts to Power System from Voltage Fluctuations’, SSRN Electron. J., 2025, doi: 10.2139/ssrn.5168281.

[4]. H. Zimmer, M. W. Asmah, and J. Hanson, ‘Influences of Excitation Systems on the Dynamic Voltage Behavior of Power Systems’.

[5]. ‘IEEE Std 421.1-2007, IEEE Standard Definitions for Excitation Systems for Synchronous Machines’.

[6]. A. Al-Zahrani and S. K. Ramdas, ‘Performance Evaluation of Excitation Systems in Stability Enhancement of Power Systems’, Eur. J. Eng. Technol. Res., vol. 7, no. 5, pp. 82–93, Oct. 2022, doi: 10.24018/ejeng.2022.7.5.2820.

[7]. J. K. Noland, S. Nuzzo, A. Tessarolo, and E. F. Alves, ‘Excitation System Technologies for Wound-Field Synchronous Machines: Survey of Solutions and Evolving Trends’, IEEE Access, vol. 7, pp. 109699–109718, 2019, doi: 10.1109/ACCESS.2019.2933493.

[8]. X. Shen and Y. Wei, ‘Research on Performance Test of Generator Excitation System’, in Proceedings of the 2017 7th International Conference on Manufacturing Science and Engineering (ICMSE 2017), Zhuhai, China: Atlantis Press, 2017. doi: 10.2991/icmse-17.2017.71.

[9]. P. Kambala, K. P. Yadav, M. Thakur, and S. Deshmukh, ‘Optimized Controllers for Efficient Excitation in Power Generation Systems: Design and Performance Analysis’, J. Mines Met. Fuels, pp. 3551–3561, Nov. 2025, doi: 10.18311/jmmf/2025/49937.

[10]. A. Kumar, ‘Nonlinear AVR for power system stabilisers robust phase compensation design’, IET Gener. Transm. Distrib., vol. 14, no. 21, pp. 4927–4935, Nov. 2020, doi: 10.1049/iet-gtd.2020.0092.

[11]. M. Prajapati, J. Patel, D. H. Chandwani, and M. V. Patel, ‘Digital Excitation System for Synchronous Generator’.

[12]. S. Tsegaye and K. A. Fante, ‘Analysis of Synchronous Machine Excitation Systems: Comparative Study’, Int. J. Energy Power Eng., vol. 10, no. 12, 2016.

[13]. A. Fathollahi and B. Andresen, ‘Enhancing Transient Stability in Multi-Machine Power Systems through a Model-Free Fractional-Order Excitation Stabilizer’, Fractal Fract., vol. 8, no. 7, p. 419, July 2024, doi: 10.3390/fractalfract8070419.

[14]. R. Kumari and A. Kumar, ‘Power System Stabilizer Design for Nonlinear AVR Using Local Measurements’.

[15]. Ravina B. Binnar and Walchand College of Engineering, ‘Analysis of Static Excitation System Models for Synchronous Machine’, Int. J. Eng. Res., vol. V9, no. 09, p. IJERTV9IS090027, Sept. 2020, doi: 10.17577/IJERTV9IS090027.

[16]. A. Kutsyk, M. Semeniuk, M. Korkosz, and G. Podskarbi, ‘Diagnosis of the Static Excitation Systems of Synchronous Generators with the Use of Hardware-In-the-Loop Technologies’, Energies, vol. 14, no. 21, p. 6937, Oct. 2021, doi: 10.3390/en14216937.