Impact of an SVC device on voltage and transient stability in power systems

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ABSTRACT

The increasing complexity of modern electrical networks, driven by the expansion of transmission networks along with the increasing penetration of renewable-based generation, has intensified concerns regarding voltage control performance and rotor-angle stability. Flexible AC transmission system (FACTS) technology, particularly the shunt-connected static var compensator (SVC), offers effective solutions for enhancing system performance through dynamic reactive power support. This study examines the effect of SVC integration on voltage regulation performance as well as rotor-angle stability within electrical transmission networks. The study is conducted using MATLAB and the electrical network analysis toolbox (PSAT) on IEEE 5-bus, 14-bus, and 9-bus benchmark systems. Voltage stability performance is evaluated under transmission line outage conditions, while rotor-angle stability is assessed through critical clearing time (CCT) analysis during balanced three-phase faults. The simulation results demonstrate that the incorporation of an SVC considerably improves voltage profiles, reduces active and reactive power losses, and enhances system resilience under disturbed operating conditions. Furthermore, the SVC increases the critical clearing time and improves post-fault dynamic behavior, contributing to better preservation of generator synchronism. The presented results confirm that SVC-based compensation provides an effective and practical solution for strengthening both voltage control performance and rotor-angle stability reserves in power transmission systems.

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1. INTRODUCTION

The growing implementation of renewable generation together with the development of large interconnected transmission networks has created additional challenges for maintaining stable and secure electrical network operation [1]. Under these operating conditions, maintaining acceptable voltage levels and ensuring adequate dynamic performance represent essential requirements for modern transmission networks [2], [3]. Among the available flexible AC transmission system (FACTS) technologies, static var compensator (SVC) devices are frequently adopted because of their ability to provide fast and adjustable reactive power compensation [4], [5]. Their effectiveness in improving voltage profiles and supporting secure system operation has been reported in several studies [6]-[8]. Numerous studies have highlighted the capability of

FACTS compensator technology to reinforce voltage conditions and improve system stability during disturbances [9], [10]. Recent investigations have also explored advanced approaches for transient stability assessment and dynamic security enhancement in power systems [11]-[13]. Nevertheless, comprehensive evaluations addressing both voltage and rotor-angle stability within a unified simulation framework remain relatively limited, especially when several IEEE benchmark networks are investigated using MATLAB/PSAT tools [14]. Accordingly, this work explores the influence of SVC-based compensation on network behavior under normal and disturbed operating conditions. Voltage-related performance is examined using the IEEE 5-bus and 14-bus benchmark systems subjected to transmission-line contingencies, whereas dynamic stability is investigated on the IEEE 9-bus three-machine network through critical clearing time (CCT) analysis under balanced three-phase short-circuit events. The primary aims of this work are: i) to evaluate the effects of SVC deployment on voltage profiles together with power-flow distribution during contingency conditions; ii) to quantify improvements in transient performance through CCT evaluation; and iii) to examine the performance of SVC compensation for different IEEE benchmark networks implemented in the MATLAB/PSAT platform.

2. METHOD

2.1. Transient stability issues in power networks

Transient stability assesses a system dynamic performance to maintain generator synchronism after a major disturbance, such as a three-phase fault. The classical model describes generator dynamics using the swing equation, derived from Newton's second law [12], [13]. It relies on key assumptions [14]-[16]: constant mechanical input power, no damping, constant internal voltage behind transient reactance, balanced operation (positive-sequence only), constant-impedance loads, and neglect of saturation, saliency, and losses. Despite these simplifications, the model remains popular for its computational efficiency and ability to offer qualitative insights into system dynamics [17].

2.1.1. Swing equation

Generator electromechanical behavior during disturbances is commonly represented using the swing equation. The swing equation is expressed as (1).

$$2H\frac{d^2\delta}{dt^2} = P_m - P_e \tag{1}$$

Where δ is the rotor angle, H is the inertia constant, P_m is the mechanical input, and P_e is the electrical output power [2], [15]. With damping, it becomes (2).

$$2H\frac{d^2\delta}{dt^2} + D\frac{d\delta}{dt} = P_m - P_e \tag{2}$$

Where D is the damping coefficient [16]. This simplified model remains a standard tool for transient stability analysis.

2.1.2. Electrical power expression

The electrical power output of a generator is given by the nonlinear power-angle equation. This equation is presented in (3)

$$P_e = \frac{VE'}{X_{eq}}sin(\delta) \tag{3}$$

Where V and E' are the terminal voltage and internal EMF, and X_{eq} is the equivalent reactance [14], [15]. This relationship is key to assessing transient stability and system response during disturbances [17], [18].

2.1.3. Multi-machine model

In multi-generator power systems, rotor dynamics are described by a set of coupled swing equations. The electrical power output of each generator is determined from the network admittance matrix, as expressed in (4)-(6).

$$\frac{d\delta_i}{dt} = \omega_i - \omega_{syn} \tag{4}$$

$$\frac{d\omega_i}{dt} = \frac{\omega_{syn}}{2H_i}\left(P_{m_i} - P_{e_i}\right) \tag{5}$$

$$P_{e_i} = E_i{}^2 G_{ii} + \sum_{\substack{j=1 \\ j\neq i}}^{n} E_i E_j \left[B_{ij}\sin(\delta_i - \delta_j) + G_{ij}\cos(\delta_i - \delta_j)\right] \tag{6}$$

Here, E_i, G_{ij}, and B_{ij} are the internal voltages, conductance, and susceptance, respectively. This model captures dynamic interactions and supports transient stability analysis [13]-[15], [18].

2.2. Modeling of SVC

The proposed study focuses on shunt-connected FACTS devices, including SVC, TCR, and TSC. While their dynamic response is generally inferior to that of STATCOM-based solutions, they remain extensively investigated for maintaining acceptable voltage profiles under steady-state operating conditions [19], [20].

2.2.1. Modeling of static reactive power compensator SVC

SVC is modeled as a variable shunt admittance $y_{SVC} = jb_{SVC}$, assumed lossless and purely imaginary Figures 1(a) and 1(b) [21]. The susceptance can be capacitive or inductive, injecting or absorbing reactive power Q_{SVC}, accordingly, Figures 1(c) and 1(d). The relationship between B_{SVC} and the rated voltage is given by (7) and (8).

$$B_{SVC} = -U_n^2\, b_{SVC} = -U_n^2\, \frac{X_C[2(\pi-\alpha)+\sin 2\alpha]-\pi X_L}{\pi X_C X_L} \tag{7}$$

$$Q_{SVC} = -\left(\frac{U}{U_n}\right)^2 B_{SVC} \tag{8}$$

The negative sign indicates capacitive operation (power injection) or inductive (power absorption). Figure 1(d) illustrates Q_{SVC} as a function of nodal voltage [2], [22], [23].

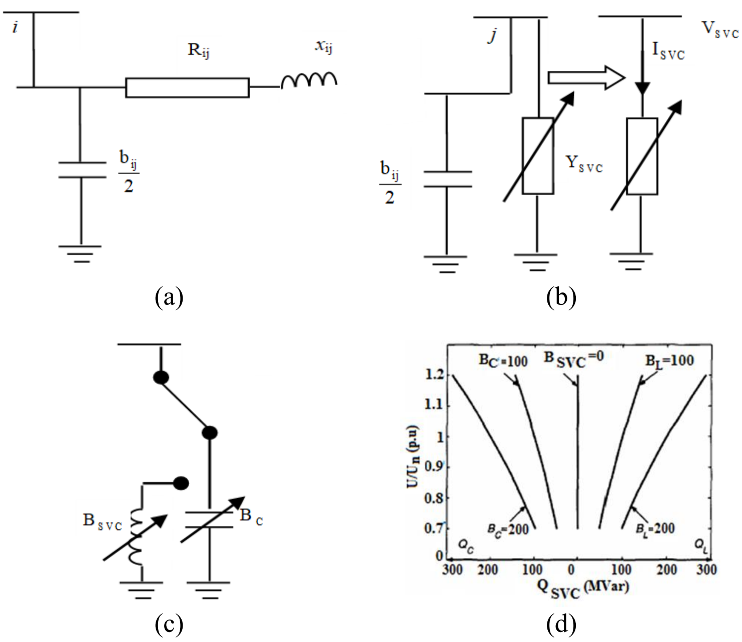


Figure 1. SVC modeling and reactive power variation: (a) placement at bus j, (b) SVC symbol, (c) SVC model, and (d) reactive power versus nodal voltage

2.2.2. Operational constraints and equation bounds

The model is formulated within a restricted operating domain. The reactive output of the static var compensator is bounded by its capability limits: $Q_{SVC}^{min} \leq Q_{SVC} \leq Q_{SVC}^{max}$. Voltage magnitudes are likewise maintained within acceptable ranges to preserve secure system operation. These constraints restrict the solution space and prevent non-physical responses, thereby improving the reliability of the computed responses.

3. RESULTS AND DISCUSSION

The SVC model is developed and simulated using the PSAT platform [24], and subsequently tested on extensively investigated IEEE benchmark networks to evaluate its influence on voltage regulation, power flow allocation, and transient stability. The IEEE 14-bus system is considered to examine voltage support performance, while the IEEE 5-bus configuration is used to analyze steady-state power flow characteristics. Furthermore, the IEEE 9-bus is employed to assess the critical clearing time (CCT) under fault scenarios [25]. These analyses are carried out in the context of recent advances in stability evaluation, encompassing both classical analytical techniques and emerging data-driven methodologies, particularly those leveraging machine learning frameworks [26]-[28].

3.1. Study of an IEEE 14-bus network

The system under consideration is a balanced three-phase overhead network comprising 14 buses. The selected base values for the analysis are 100 MVA for apparent power and 50 Hz for system frequency. The network configuration includes two generating units, sixteen transmission lines, eleven loads, three synchronous compensators, and one shunt capacitor. The overall system topology is illustrated in Figure 2(a).

3.1.1. Effect of the SVC on the faulty network

i. Loss of power lines

The outage of line (1–5) in the IEEE 14-bus system causes noticeable changes in the network operating conditions. The resulting variations in bus voltage magnitudes are presented in Figure 2(b). In addition, the disturbance alters the power flow distribution, as illustrated in Figures 3(a) and 3(b).

(a)

(b)

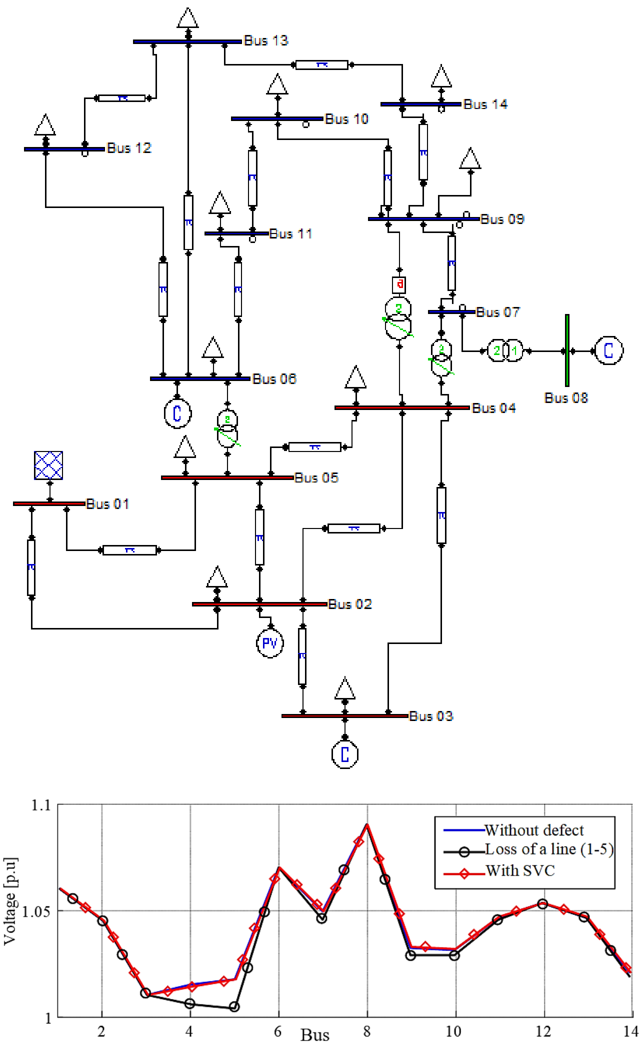
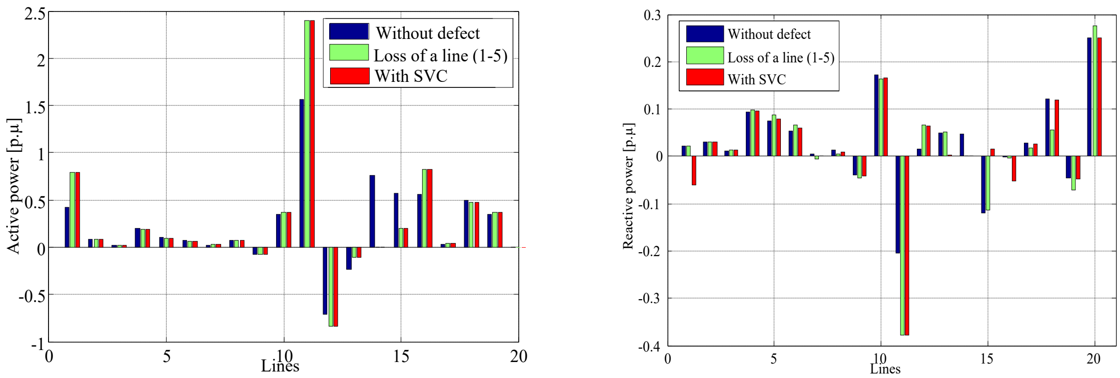


Figure 2. The IEEE 14-bus network: (a) diagram of the IEEE 14-bus system and (b) bus voltage magnitudes after installation of the SVC

3.2. Study of an IEEE 5-bus network (simulation under MATLAB environment)

The proposed approach is applied to the IEEE 5-bus test system Figure 4(a), which includes seven transmission lines, two generators, and four loads. The analysis is carried out using the MATLAB environment to ensure accurate numerical simulation. The power-flow study is first performed using the Newton-Raphson method without incorporating the SVC. For completeness, Figure 4(b) presents the IEEE 9-bus system used in this study for rotor-angle stability analysis, which is further detailed in section 3.3. A comparative assessment is subsequently conducted to evaluate the system behavior before and after the installation of the SVC.



(a) (b)

Figure 3. Variation of (a) active power and (b) reactive power flows in the network

(a)

(b)

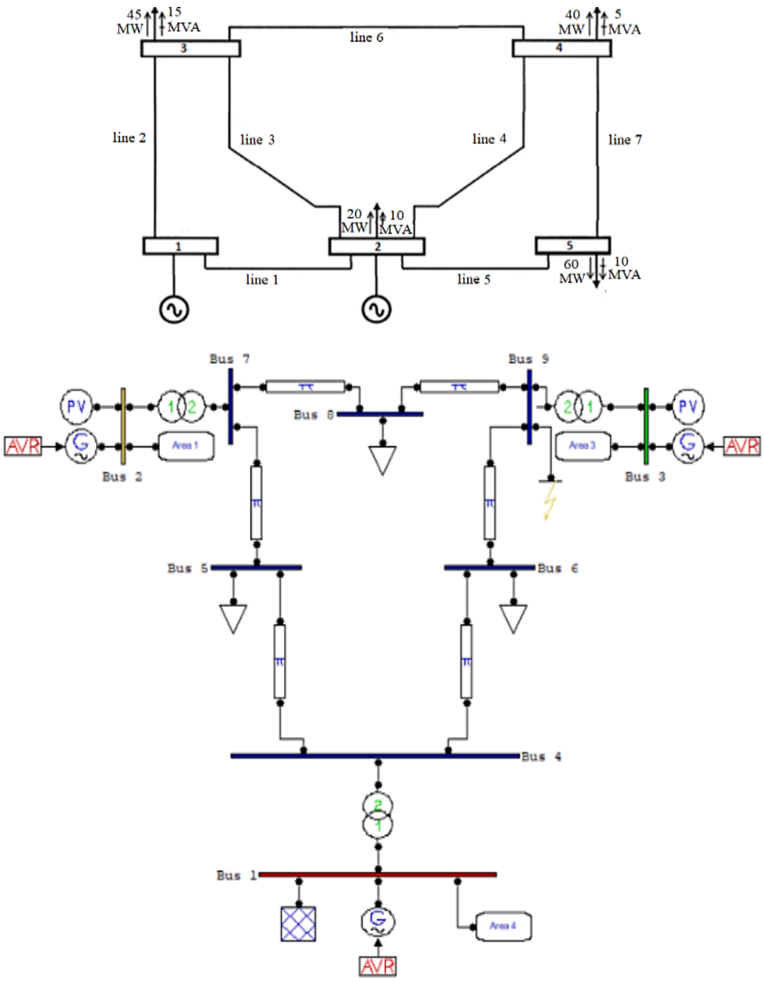


Figure 4. Test systems used in this study: (a) IEEE 5-bus system and (b) IEEE 9-bus system

3.2.1. Insertion of an SVC at bus 4

An SVC device is connected at bus 4 to evaluate its impact on system performance. The control variable, namely the firing angle α, is varied between 90° to 180° in order to assess its influence on bus voltage profiles and transmission line power losses. This parametric variation enables a detailed examination of the SVC's capability to provide dynamic reactive power support, thereby enhancing voltage regulation across the network. The corresponding effects on active and reactive power flows are presented in Figures 5(a) and 5(b), which highlight the sensitivity of system power distribution to the SVC operating point.

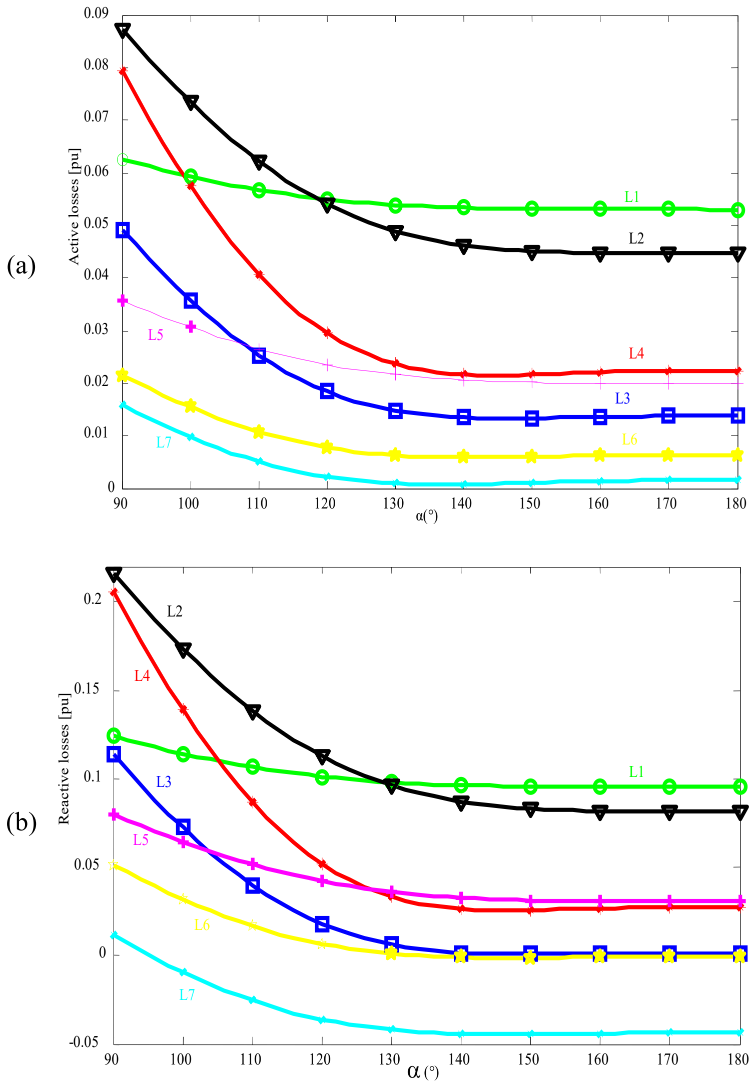


Figure 5. Variation of (a) active power losses and (b) reactive power losses with the firing angle α

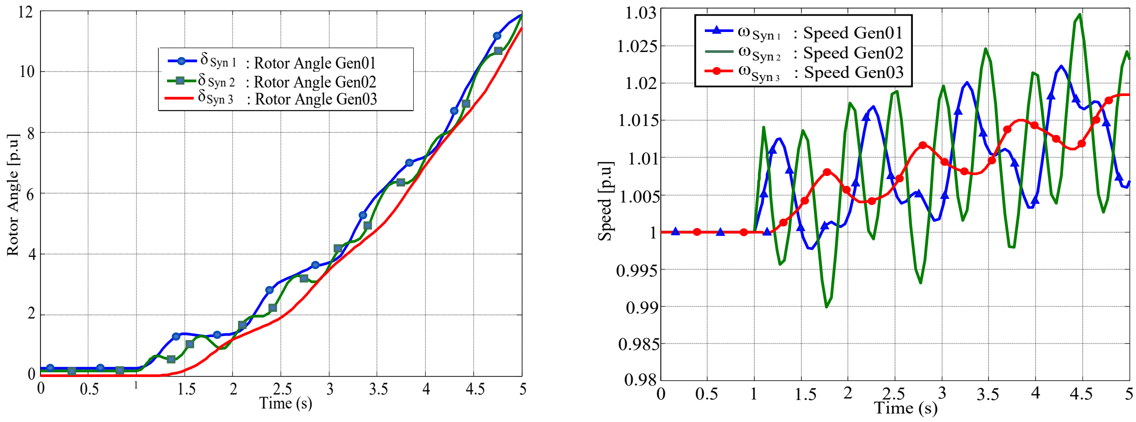
3.3. Study of an IEEE 9-bus network

3.3.1. Transient stability analysis

The IEEE 9-bus test system, widely used for transient stability studies under short-circuit faults, consists of three generating units connected to buses 1, 2, and 3 via step-up transformers. The generated power is transmitted to load buses 5, 6, and 8 through an interconnected transmission network forming a typical meshed configuration used in rotor-angle stability studies. All network and machine data, including transmission line parameters, loads, and generator characteristics, are expressed on a common 100 MVA base to ensure coherent steady-state and dynamic simulations. Rotor-angle stability assessment is performed under different disturbance conditions, with particular focus on fault response and critical clearing time assessment.

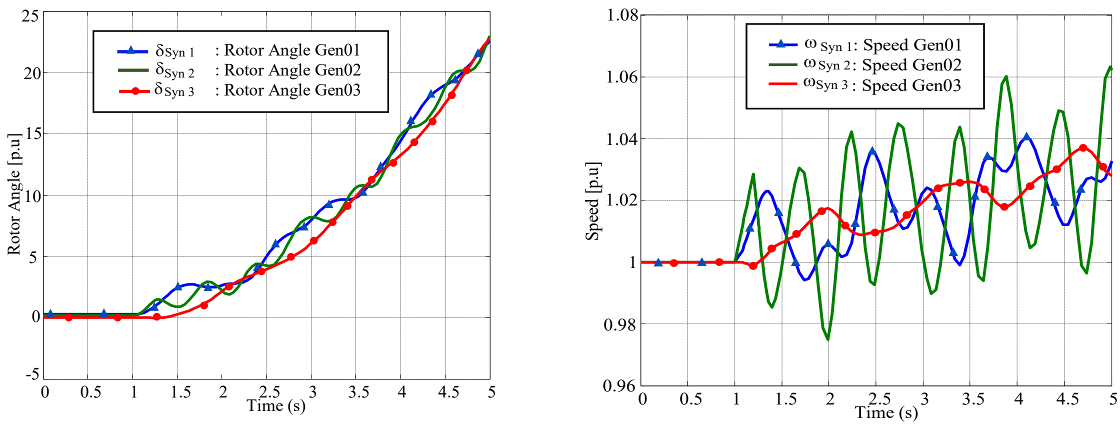
i. Three-phase fault at bus 3

A balanced three-phase fault is assumed to occur at T_0 = 0 s at bus 3. The fault is cleared after a variable clearing time Td, which is incremented in steps of 0.001 s. The procedure is repeated until the maximum stable clearing time is reached, beyond which the system loses transient stability. The maximum value of Td for which the system remains stable defines the CCT. The presented results are shown in Figures 6, 7, and 8.



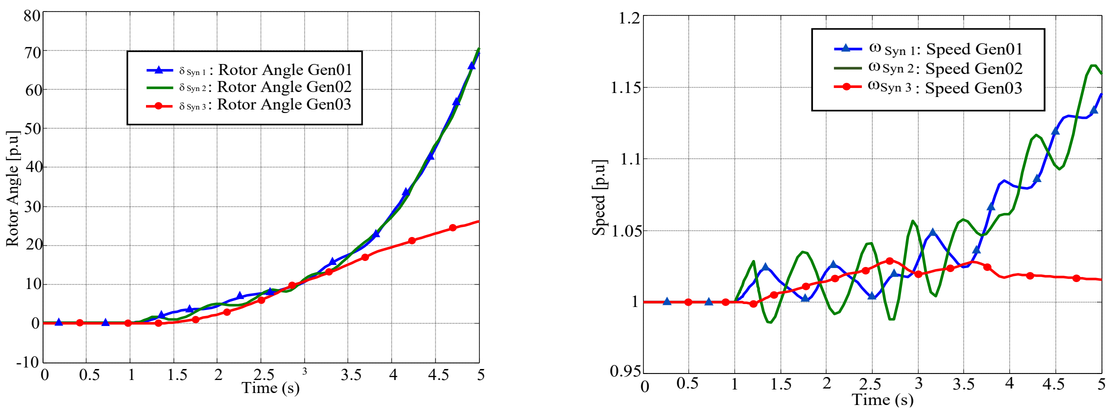
(a) (b)

Figure 6. Results for Td = 0.100 s: (a) rotor angles and (b) angular speeds



(a) (b)

Figure 7. Results for Td = 0.202 s: (a) rotor angles and (b) angular speeds



(a) (b)

Figure 8. Results for Td = 0.203 s: (a) rotor angles and (b) angular speeds

Based on this set of results, we observe that the system regains its stability for fault clearing times of Td = 0.100 s and Td = 0.202 s, as indicated in Figures 6 and 7. However, Figure 8 illustrates that loss of synchronism is observed for a fault clearing time of Td = 0.203 s. This allows us to conclude that the critical clearing time is 0.202 s.

ii. Balanced three-phase short-circuit faults applied at different buses

To examine the impact of fault position on critical clearing time (CCT), balanced three-phase short-circuit faults are applied successively at several buses of the network, as summarized in Table 1. According to Table 1, the CCT changes noticeably with the fault location. This behavior is associated with the different power flow redistributions and the resulting variations in the bus admittance matrix Y_{bus} during each fault condition. These variations modify the initial operating state of the network and consequently affect its transient response. Therefore, each fault location leads to a different transient stability margin.

Table 1. Critical clearing time for different fault locations

Bus fault	1	2	6	7	9
CCT (s)	0.224	0.163	0.295	0.179	0.185

3.4. Discussion

The IEEE 14-bus, 5-bus, and 9-bus systems were analyzed in PSAT to evaluate voltage regulation, power redistribution, and transient stability under contingency conditions. The outage of line (1-5) induces significant voltage depression and alters active/reactive power flows across the network. An SVC installed at critical locations (sending-end of the affected line and bus 4) provides fast reactive power compensation, effectively limiting voltage deviations, improving post-fault recovery, and reducing system losses. Firing-angle variation (90°-180°) demonstrates robust adaptive voltage support capability under different operating states. For transient stability, the critical clearing time of the 3-machine system was evaluated under severe fault conditions to assess rotor-angle stability and the system's ability to maintain synchronism. The results indicate that the CCT varies according to the fault location, with values ranging from 0.163 s to 0.295 s. This variation reflects the influence of fault location on the transient response and stability margin of the system.

4. CONCLUSION

Developed analysis provides a systematic assessment of the impact of static var compensators on voltage regulation and rotor-angle stability in transmission networks using standard IEEE benchmark systems (14-bus, 5-bus, and 9-bus). Time-domain simulations consistently demonstrate that SVC integration significantly enhances system resilience under a broad spectrum of contingencies. From a voltage stability perspective, fast-response shunt reactive compensation effectively mitigates voltage depressions and accelerates post-disturbance recovery, thereby increasing the available stability margin. Regarding transient stability, the analysis of the 9-bus system under severe fault conditions evaluates the critical clearing time for different fault locations. The results show that the critical clearing time varies according to the fault location, reflecting the influence of the disturbance location on the transient response and the ability of the system to maintain synchronism.

Regarding the voltage performance, simulation results obtained from the IEEE benchmark systems confirm the effectiveness of SVC compensation under different operating conditions. Voltage deviations are reduced during contingency events, while reactive support improves system recovery. Furthermore, the variation in CCT highlights the transient stability characteristics and the synchronizing behavior of the system. In general, the obtained results confirm the influence of fault location on transient system response and stability performance under disturbed operating conditions.

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This study was carried out without external financial support and was conducted solely using resources provided by the authors.

AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

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Hicham Zaimen		✓				✓		✓	✓	✓	✓	✓		
Hassen Belila	✓		✓	✓			✓			✓	✓		✓	✓

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

The authors declare that they have no competing financial or non-financial interests that could have influenced the work reported in the proposed analysis.

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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