



Comparative Evaluation of FACTS Devices for Improving the Performance of Grid-Connected Photovoltaic Systems

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ABSTRACT

The global energy transition has led to unprecedented growth in photovoltaic (PV) installations, presenting new operational challenges to power system stability during grid disturbances. This research explores the relationship between fault location and the dynamic behavior of an IEEE 30-bus network incorporating PV generation, using Critical Clearing Time (CCT) as the primary performance indicator. Time-domain simulations were carried out using MATLAB/PSAT for three-phase faults under two distinct scenarios: with and without the integration of a 50 MW PV unit. To assess possible stability improvements, three Flexible AC Transmission Systems (FACTS) controllers: SVC, STATCOM, and UPFC were integrated into the network. The findings indicate that fault location plays a decisive role in determining stability margins, regardless of PV presence. However, when PV generation is connected, CCT values decreased noticeably, reflecting greater vulnerability to faults, especially at weak nodes. All three FACTS devices successfully improve CCT values across all examined cases. Among them, the UPFC demonstrates superior and consistent performance, followed by STATCOM, while the SVC provides relatively modest improvements.

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1. Introduction

Modern power systems are undergoing rapid transformation, largely driven by the global energy transition and the accelerated integration of renewable energy sources. PV generation has emerged as one of the most rapidly deployed renewable energy technologies worldwide [1,2]. Although this transition contributes significantly to decarbonization goals and energy security, it also introduces substantial challenges to power system operation, particularly with regard to transient stability [3,4].

Unlike conventional synchronous generators, PV systems are interfaced with the grid through power electronic converters. These converters do not provide inherent rotational inertia and contribute limited fault current [5,6]. This fundamental difference influences the transient response of the power system when subjected to severe disturbances, particularly three-phase symmetrical short-circuit faults, and may lead to reduced stability margins [7,8].

The Critical Clearing Time (CCT) is a primary metric for evaluating transient stability performance. It represents the maximum fault duration that can be tolerated before the fault must be cleared to prevent system instability [9,10]. A lower CCT indicates greater vulnerability and imposes more stringent requirements on protection systems and emergency control strategies. In systems with high PV penetration, CCT values tend to decrease. This effect is particularly evident when renewable generation is connected to electrically weak buses with limited short-circuit capacity [11,12]. This vulnerability results from the combined effects of reduced system inertia, altered power-flow patterns, and limited reactive power support from inverter-based sources [13,14].

Among the various solutions proposed to enhance transient stability, Flexible AC Transmission Systems (FACTS) have emerged as particularly effective technologies [15]. Three controllers have gained particular prominence because of their effectiveness in voltage regulation and reactive power compensation: The Static Var Compensator (SVC), the Static Synchronous Compensator (STATCOM), and the Unified Power Flow Controller (UPFC) [16–18].

The SVC functions as a thyristor-controlled shunt compensation system and regulates bus voltage by adjusting the reactive power exchanged with the network [19]. The STATCOM is based on Voltage Source Converter (VSC) technology and

provides fast dynamic voltage regulation, making it particularly beneficial during transient events [20]. The UPFC integrates series and shunt converters that share a common DC bus, providing flexible control of power flow and voltage in the transmission network [21–23].

Several recent studies have investigated the use of FACTS devices for enhancing power system performance with renewable energy integration. Reriballah et al. [24] examined coordinated SVC-TCSC operation with PV support on the IEEE 30-bus system under progressive loading conditions. Their results showed that coordinated PV+SVC+TCSC significantly reduces power losses and restores voltage to acceptable levels under increased load. Smail et al. [25] investigated optimal placement of single and dual SVCs for voltage profile enhancement and loss reduction in a 37-bus system with PV and hybrid PV-wind sources. Their dual SVC configuration (30+30 MVar) significantly outperformed single SVC placement.

Labad et al. [26] applied metaheuristic optimization (MPA and WOA algorithms) for optimal placement of PV generation and SVC compensation on the IEEE 30-bus system, achieving significant active power loss reduction and enhanced transmission efficiency. Pather and Sarma [27] compared FACTS devices, synchronous condensers, and grid-forming BESS for high-PV stability on the IEEE 9-bus system, finding that STATCOM and BESS-GFM provide the best voltage regulation.

Stitou et al. [28] performed transient stability analysis of a hybrid PV-WTG microgrid using real operational data from the Tinghir substation, demonstrating that CCT varies significantly depending on fault type and source loss. Bhimaraju et al. [29] investigated the impact of hybrid solar and wind distributed generators on transient stability of captive power systems, finding that solar DG provides the highest improvement in CCT. Wang and Song [30] studied low voltage ride-through capability of offshore wind farms using dynamic reactive power compensation (SVC, STATCOM, UPFC), recommending STATCOM for offshore applications due to its superior dynamic response.

Rahman et al. [31] performed a comparative analysis of STATCOM and SVC for voltage regulation on a 230 kV transmission line, demonstrating that STATCOM outperforms SVC in response speed and requires less reactive power. Priyadi et al. [32] proposed a modified loss of synchronism (MLOS) condition for efficient CCT estimation in transient stability analysis, achieving

higher accuracy than conventional LOS with significantly reduced computational burden.

Although numerous studies have investigated the individual contributions of FACTS devices to transient stability enhancement, direct comparative assessments under identical operating conditions remain relatively limited. Many existing studies evaluate FACTS devices individually or consider only a restricted set of fault scenarios. Consequently, it is difficult to draw definitive conclusions regarding their relative effectiveness. Furthermore, the interaction between device performance and fault location - a factor that strongly influences stability margins - has not been systematically incorporated into comparative assessments of FACTS controllers in PV-rich systems. To the best of our knowledge, none of the reviewed studies has systematically compared the performance of SVC, STATCOM, and UPFC under identical operating conditions while considering different fault locations in PV-integrated systems.

The present study addresses this identified research gap through a structured performance assessment of three FACTS controllers: SVC, STATCOM, and UPFC with the objective of enhancing transient stability in an IEEE 30-bus system incorporating PV generation. The evaluation framework uses CCT as the primary performance metric and considers six carefully selected fault locations covering a range of operating conditions, from relatively strong generation buses to comparatively weak load-side buses. A 50 MW PV generation unit is connected at two distinct buses characterized by different network impedances. This configuration enables a comprehensive examination of the interaction between solar power injection and grid characteristics.

To ensure a consistent basis for comparison, the three FACTS controllers are evaluated using equivalent dynamic response models and identical capacity specifications.

The principal contributions of the present study include:

- A structured benchmarking of three FACTS controllers: UPFC, STATCOM, and SVC under matching grid conditions, equivalent disturbance events, and uniform PV interconnection setups.
- Quantitative assessment on the relative effectiveness of each device at increasing CCT, including performance comparisons across multiple fault locations.
- Practical insights into the selection of appropriate FACTS controllers based on

network characteristics, fault location, and renewable energy integration points.

- A comprehensive sensitivity analysis demonstrating the influence of fault location on the relative performance of the different FACTS devices.

The remainder of this paper is organized as follows. Section 2 describes the system modeling and simulation methodology, including the integration of the PV system, the implementation of the FACTS devices, and the assessment of transient stability under different disturbances using MATLAB/PSAT. Section 3 presents and discusses the simulation results, with particular emphasis on the comparative performance of the three FACTS controllers. Finally, Section 4 presents the conclusions, limitations, and directions for future research.

2. Methodology

2.1. PV System Modelling

A photovoltaic array consists of multiple modules, each comprising several PV cells connected in series or parallel configurations. The electrical behavior of a PV cell is commonly represented by a single-diode model as shown in Figure 1.

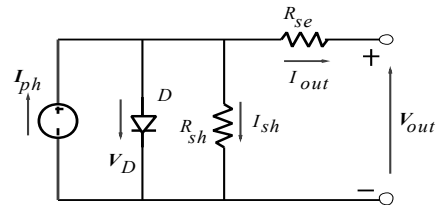


Figure 1. Photovoltaic cell circuit schematic

The output current of the PV cell is expressed as [33,34]:

$$I_{out} = I_{ph} - I_D - I_{sh} \quad (1)$$

$$I_{out} = I_{ph} - I_0 \left[e^{\frac{q(V_{out} + I_{ph} \cdot R_{se})}{\eta k T}} - 1 \right] - \frac{V_{out} + I_{ph} \cdot R_{se}}{R_{sh}} \quad (2)$$

The PV cell model includes several key electrical quantities. The light-generated current is denoted by I_{ph} , while the diode saturation current is represented by I_0 . The resistive losses are characterized by R_{se} (series) and R_{sh} (shunt). The

terminal behavior is governed by V_{out} , the charge q , the ideality factor η , the absolute temperature T , and Boltzmann's constant k . The photocurrent is given by I_{ph} , the shunt branch carries I_{sh} , and the diode conducts I_D .

2.2. Modeling of SVC, STATCOM, and UPFC

2.2.1. SVC

The SVC is a widely used FACTS controller. It consists of thyristor-switched reactors and capacitors arranged in a shunt configuration. The device continuously regulates the exchange of reactive power with the network, thereby supporting voltage stability. By varying the thyristor firing angle, the SVC modifies its equivalent susceptance. This enables effective voltage control and a fast dynamic response during fault events [35,36].

SVCs are modeled in power systems as variable-susceptance devices. They respond to voltage deviations by injecting or absorbing reactive power accordingly. The equivalent circuit of the SVC is shown in Figure 2.

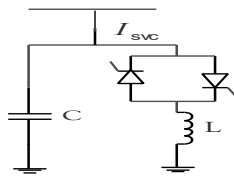


Figure 2. SVC configuration

2.2.2. STATCOM

The STATCOM is a FACTS device that is connected in shunt and uses power electronics: typically, a VSC to rapidly control reactive power and provide voltage support in AC power systems [37,38].

The STATCOM and its equivalent circuit are shown in Figure 3.

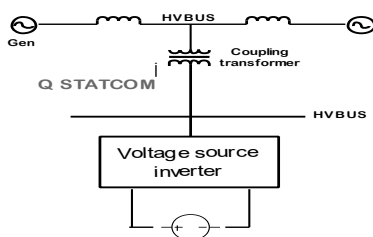


Figure 3. STATCOM configuration

2.2.3. UPFC

The UPFC is an advanced FACTS device (Figure 4) that can be used to enhance steady-state, dynamic, and transient stability [39]. It consists of two Voltage-Sourced Converters (VSCs) that provide galvanic isolation and regulate voltage levels in the power system. The UPFC employs two Pulse Width Modulation (PWM) inverters supplied by a common DC link connected to a DC storage capacitor [40]. The first inverter is connected in parallel with the transmission line, whereas the second inverter is connected in series with the line [41,42].

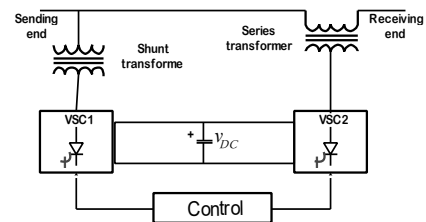


Figure 4. UPFC configuration

2.2.4. Modelling of a VSC

The VSC is a power-electronic interface that produces a sinusoidal AC waveform with controllable amplitude, frequency, and phase angle. This converter transforms the DC power supplied by an associated storage element into three-phase AC quantities suitable for grid connection [42].

The generated AC voltages are synchronized with the network and connected through the transformer leakage reactance. Within the STATCOM framework, the VSC helps mitigate power-quality issues by either supporting the line voltage or compensating for voltage deficiencies. These deficiencies represent deviations between the reference and measured voltage levels.

The VSC typically receives its DC input from an energy-storage element. The required output waveform is synthesized through the controlled switching of semiconductor devices within the converter bridge.

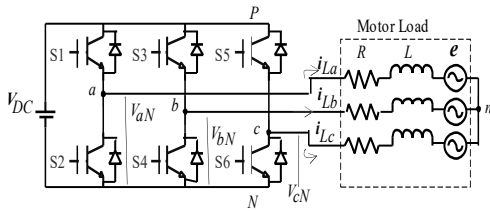


Figure 5. Three-phase voltage source converter

The control strategy employs Phase-Locked Loops (PLLs) for grid synchronization and inner current-control loops to regulate active and reactive power. The outer control loops generate the P/Q references, which are subsequently tracked by the inner current-control loops. Reactive power compensation is essential for voltage stability and transient performance during disturbances [43,44]..

The PV unit is integrated at two different locations (Bus 12 and Bus 18) to examine the sensitivity of system stability to the point of integration of renewable energy. The effects of these locations are analyzed using time-domain simulations.

2.2.9. Detailed Modeling of FACTS Devices and PV Inverter

2.2.5.1. PV System Inverter Modeling

The 50 MW PV system is interfaced to the IEEE 30-bus network through a VSC operating in grid-following mode with a PQ control strategy. The inverter model is implemented using the standard PSAT PV module.

2.2.5.1.1. Control Strategy

The PV inverter employs a cascaded control structure consisting of three control loops:

1. **Outer Power Control Loop:** Regulates active power (P) based on Maximum Power Point Tracking (MPPT) and reactive power (Q) based on a reference setpoint.
2. **Inner Current Control Loop:** Provides fast current regulation in a d-q synchronous reference frame.
3. **Phase-Locked Loop (PLL):** Synchronizes the inverter output with the grid voltage.

2.2.5.1.2. PV Inverter Specifications

Table 1. Specifications of the 50 MW PV Inverter

Parameter	Value
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Rated Capacity	50 MVA
Rated Active Power	50 MW
Rated Reactive Power	±25 MVar
DC Link Voltage (per inverter unit)	1.8 kV
AC Voltage Level	132 kV
Switching Frequency	2.5 kHz
Control Mode	PQ (Grid-following)
PLL Bandwidth	10 Hz
Current Control Bandwidth	100 Hz
Transformer Leakage Reactance	0.12 p.u.

2.2.5.1.3. Inverter Operating Limits

Table 2. Inverter Operating Limits

Limit	Value
Maximum Active Power	50 MW
Minimum Active Power	0 MW
Maximum Reactive Power	+25 MVar
Minimum Reactive Power	-25 MVar
Current Limit	1.1 × rated current
Voltage Range	0.85 - 1.15 p.u.

2.2.5.1.4. Implementation of PQ Control

The PQ control method is implemented using the conventional decoupled control technique in the d-q reference frame [45].

$$P = \frac{3}{2}(v_d i_d + v_q i_q) \quad (3)$$

$$Q = \frac{3}{2}(v_d i_q - v_q i_d) \quad (4)$$

The outer control loop generates the current references:

$$i_d^* = \frac{2}{3} \frac{P^*}{v_d} \quad (5)$$

$$i_q^* = -\frac{2}{3} \frac{Q^*}{v_d} \quad (6)$$

The inner current-control loop, implemented using PI controllers, track these references:

$$v_d^* = K_p (i_d^* - i_d) + K_i \int (i_d^* - i_d) dt + w L i_q \quad (7)$$

$$v_q^* = K_p (i_q^* - i_q) + K_i \int (i_q^* - i_q) dt + w L i_d \quad (8)$$

2.2.5.2. SVC Modeling

2.2.5.2.1. SVC Configuration

The SVC is modeled as a shunt-connected, thyristor-controlled reactive power compensator comprising:

- **Thyristor-Controlled Reactor (TCR):** Provides continuous inductive reactive power compensation.
- **Thyristor-Switched Capacitor (TSC):** Provides capacitive reactive power compensation.

2.2.5.2.2. SVC Specifications

Table 3. SVC Specifications

Parameter	Value
Rated Capacity	± 100 MVar
Total Capacitive Range	0 to +100 MVar
Total Inductive Range	0 to -100 MVar
Number of TSC Banks	4
MVar per TSC Step	25 MVar
TCR Continuous Range	-100 to 0 MVar
Control Mode	Voltage regulation with droop
Voltage Setpoint	1.0 p.u.
Voltage Droop	0.03 p.u.
Response Time	20-40 ms
Transformer Leakage Reactance	0.10 p.u.
Connection Bus	Bus 12

2.2.5.2.3. SVC Modeling Equations

The SVC is represented as a variable susceptance device. Its equivalent susceptance is given by:

$$B_{SVC} = B_{TCR} + B_{TSC} \quad (9)$$

The TCR susceptance is a function of the firing angle α :

$$B_{TCR}(\alpha) = \frac{B_{TCRmax}}{\pi} [2(\pi - \alpha) + \sin(2\alpha)] \quad (10)$$

The reactive power output is:

$$Q_{SVC} = V^2 \cdot B_{SVC} \quad (11)$$

The voltage-control characteristic with droop is:

$$V_{bus} = V_{ref} - X_{slope} \cdot Q_{SVC} \quad (12)$$

2.2.5.2.4. SVC Operating Limits

Table 4. SVC Operating Limits

Limit	Value
Voltage Setpoint (V_{ref})	0.95 - 1.05 p.u.

Slope Reactance (X_{slope})	0.02 - 0.05 p.u.
Maximum Capacitive Output	+100 MVar
Maximum Inductive Output	-100 MVar
Steady-State Voltage Range	0.90 - 1.10 p.u.

2.2.5.3. STATCOM Modeling

2.2.5.3.1. STATCOM Configuration

The STATCOM is modeled as a shunt-connected VSC that provides fast reactive power compensation. The model includes the VSC, coupling transformer, and control system [46].

2.2.5.3.2. STATCOM Specifications

Table 5. STATCOM Specifications

Parameter	Value
Rated Capacity	± 100 MVA
Maximum Capacitive Output	+100 MVar
Maximum Inductive Output	-100 MVar
DC Link Voltage (V_{DC})	20 kV
Control Mode	Voltage and Reactive Power Control
Voltage Setpoint (V_{ref})	1.0 p.u.
Response Time	10-20 ms
Switching Frequency	2 kHz
Transformer Leakage Reactance (X_t)	0.10 p.u.
DC Capacitor Value	100 μ F
Connection Bus	Bus 12

2.2.5.3.3. STATCOM Modeling Equations

The STATCOM is represented by its voltage-current characteristic [34]:

$$I_{STATCOM} = \frac{V_{bus} - V_{inv}}{jX_t} \quad (13)$$

The reactive power injection is:

$$Q_{STATCOM} = V_{bus} \cdot I_q \quad (14)$$

The voltage-control characteristic:

$$V_{bus} = V_{ref} - X_{droop} \cdot Q_{STATCOM} \quad (15)$$

The DC-link dynamics are described by:

$$C_{DC} \frac{dV_{DC}}{dt} = \frac{3}{2} \frac{V_{inv}}{V_{DC}} I_d - \frac{P_{loss}}{V_{DC}} \quad (16)$$

2.2.5.3.4. STATCOM Operating Limits

Table 6. STATCOM Operating Limits

Limit	Value
Voltage Setpoint (V_{ref})	0.95 - 1.05 p.u.
Maximum Current (I_{max})	1.1 × rated current
DC Voltage Range	0.85 - 1.15 p.u.
Maximum Capacitive Output	+100 MVar
Maximum Inductive Output	-100 MVar
Voltage Droop (X_{droop})	0.02 - 0.05 p.u.

2.2.5.4. UPFC Modeling

2.2.5.4.1. UPFC Configuration

The UPFC is modeled as a combination of:

- **Shunt Converter (STATCOM-like):** Connected at the sending end.
- **Series Converter (SSSC-like):** Connected in series with the transmission line.
- **Common DC-Link:** Shared by both converters.

2.2.5.4.2. UPFC Specifications

Table 7. UPFC Specifications

Parameter	Value
Shunt Converter Rating	±100 MVA
Series Converter Rating	±100 MVA
Maximum Shunt Reactive Output	+100 MVar
Maximum Series Voltage	0.15 p.u.
DC Link Voltage (V_{DC})	20 kV
Response Time	10-30 ms
Switching Frequency	2 kHz
DC Capacitor Value	150 μF

2.2.5.4.3. UPFC Modeling Equations

The UPFC is represented by its equivalent circuit with a series injection voltage:

$$\vec{V}_{ing} = V_{ing} \angle \theta_{ing} \quad (17)$$

The series-converter power injection is given by:

$$P_{shunt} = P_{series} + P_{shunt} \quad (18)$$

The shunt-converter reactive power is:

$$Q_{shunt} = \frac{V_{bus1}^2}{X_{shunt}} - \frac{V_{bus1} \cdot V_{DC}}{X_{series}} \quad (19)$$

DC-link power balance is:

$$P_{shunt} = P_{series} + P_{loss} \quad (20)$$

2.2.5.4.4. UPFC Operating Limits

Table 8. UPFC Operating Limits

Limit	Value
Shunt Voltage Setpoint	0.95 - 1.05 p.u.
Series Voltage Magnitude (V_{inj})	0 - 0.15 p.u.
Series Voltage Angle (θ_{inj})	-180° to +180°
Maximum Shunt Reactive Output	±100 MVar
Maximum Series Active Power	±100 MW
Minimum DC Voltage	0.85 p.u.
Maximum DC Voltage	1.15 p.u.

2.2.5.5. Network Locations of FACTS Devices

The locations of the PV system and FACTS devices were selected based on the network characteristics, voltage profile, and the objective of evaluating their transient-stability support under comparable operating conditions.

Table 9. Network locations of the PV system and FACTS devices and the rationale for their selection

Device	Location	Reason for Selection
PV System	Bus 12 and Bus 18	- Proximity to load centers and weak network buses.
SVC	Bus 12	- Weak voltage bus requiring dynamic reactive support.
STATCOM	Bus 12	- Direct comparison with SVC at same location.
UPFC	Line between Bus 12 and Bus 13	- Weak voltage bus requiring dynamic reactive support.

2.3. Transient Stability and CCT

The capability of a power network to maintain synchronism following a major contingency such as a symmetrical short-circuit fault, is referred to as transient stability [37-47]. One widely adopted measure for quantifying transient stability is the CCT. The CCT is the maximum allowable fault duration before the fault must be cleared to prevent loss of system transient stability [48-50]. The CCT is directly associated with the Critical Clearing Angle (CCA) and is frequently determined through the Equal Area Criterion (EAC) [51]. For a Single-Machine Infinite-Bus (SMIB) configuration, the EAC yields the following energy-based expression [48]:

$$\int_{\delta_0}^{\delta_{cr}} (P_m - P_e) d\delta = \int_{\delta_{cr}}^{\delta_{max}} (P_e - P_m) d\delta \quad (21)$$

where P_m is the mechanical power, P_e is the electrical output power of the generator, δ_0 the pre-fault rotor angle, δ_{cr} is the critical stability-limit angle, and δ_{max} the maximum swing angle.

Using simplifying assumptions and approximations, the CCT can be expressed as [17, 50]

$$CCT = \sqrt{\frac{2H}{\omega_s P_{acc}}} (\delta_{cr} - \delta_0) \quad (22)$$

where:

H : Inertia constant of the generator.

ω_s : Synchronous speed.

$P_{acc} = P_m - P_e$: Accelerating power.

The CCT is strongly influenced by system inertia, fault severity, and the operating point [51]. In systems with high PV penetration, where electronic interfaces replace conventional rotating machines, the overall system inertia is significantly reduced [52]. This reduction leads to shorter CCT values and greater vulnerability to disturbances [53,54].

This challenge is addressed in modern power networks through the deployment of FACTS devices, including SVC, STATCOM, and UPFC [55,56]. These devices provide fast-acting reactive power compensation, enhance voltage support, and mitigate electromechanical oscillations under transient conditions [49,56,57].

2.3.1. CCT Determination Algorithm and Simulation Parameters

The CCT is determined using an iterative time-domain simulation approach implemented in MATLAB/PSAT. The detailed algorithm and simulation parameters are described below.

2.3.1.1. Algorithm for CCT Determination

The following step-by-step procedure is used to determine the CCT for each fault location:

Step 1: Apply a three-phase fault at the specified bus.

Step 2: Set the fault-clearing time to an initial value (e.g., 5 ms).

Step 3: Perform a time-domain simulation using MATLAB/PSAT.

Step 4: Verify the transient-stability condition by monitoring the rotor-angle deviation.

Step 5: If stability is maintained, increase the fault-clearing time by 1 ms.

Step 6: Repeat Steps 3–5 until system instability is observed.

Step 7: The CCT is defined as the maximum fault-clearing time that results in stable operation.

2.3.1.2. Simulation Parameters

The time-domain simulations are conducted using the following parameters:

Table 10. Parameters of simulation.

Parameter	Value
Base Power	100 MVA
Base Voltage	132 kV
Integration Method	Trapezoidal rule with iteration
Maximum Shunt Reactive Output	±100 MVar
Integration Step Size	Variable-step (maximum 0.01 s)
Transient Stability Criterion	Rotor angle deviation < 360° for all generators
Post-Fault Network Configuration	Same as pre-fault (fault clearance is achieved by removing the affected line)

2.3.1.3. Transient Stability Criterion

The system is considered transiently stable if, after fault clearance, the rotor angle of each synchronous generator satisfies the following condition:

$$\delta_i(t) - \delta_{COI}(t) < 360^\circ \quad \text{for all generators} \quad (23)$$

$$i = 1, 2, \dots, N_g$$

where:

$\delta_i(t)$: Rotor angle of generator i at time t

$\delta_{COI}(t)$: Center of inertia (COI) angle of the system

N_g : Number of synchronous generators (6 in the IEEE 30-bus system)

The rotor-angle deviation is monitored throughout the post-fault period. If the rotor angle of any generator deviates by more than 360° relative to the COI, the system is classified as unstable.

2.4. Description and System Configuration

This study employs the IEEE 30-bus system (Figure 6) as a benchmark model for evaluating transient stability under multiple fault scenarios, with and without PV integration. Its moderate

complexity and widespread adoption in academic research make it suitable for analyzing dynamic behavior, particularly in response to severe disturbances such as short-circuit faults.

The test network comprises 30 buses, six generating units located at Buses 1, 2, 5, 8, 11, and 13, 41 interconnecting branches, and four tap-changing transformers. The system operates at a 100 MVA base power and a nominal voltage of 132 kV. Time-domain simulations are performed using MATLAB's PSAT toolbox, which is widely used for small-signal and transient-stability assessment [57,58].

To examine the impact of renewable energy integration, a 50 MW PV plant is connected at two selected network locations: Bus 12 and Bus 18. These locations were selected based on their proximity to major load centers and their influence on power-flow paths.

Six different fault locations are considered:

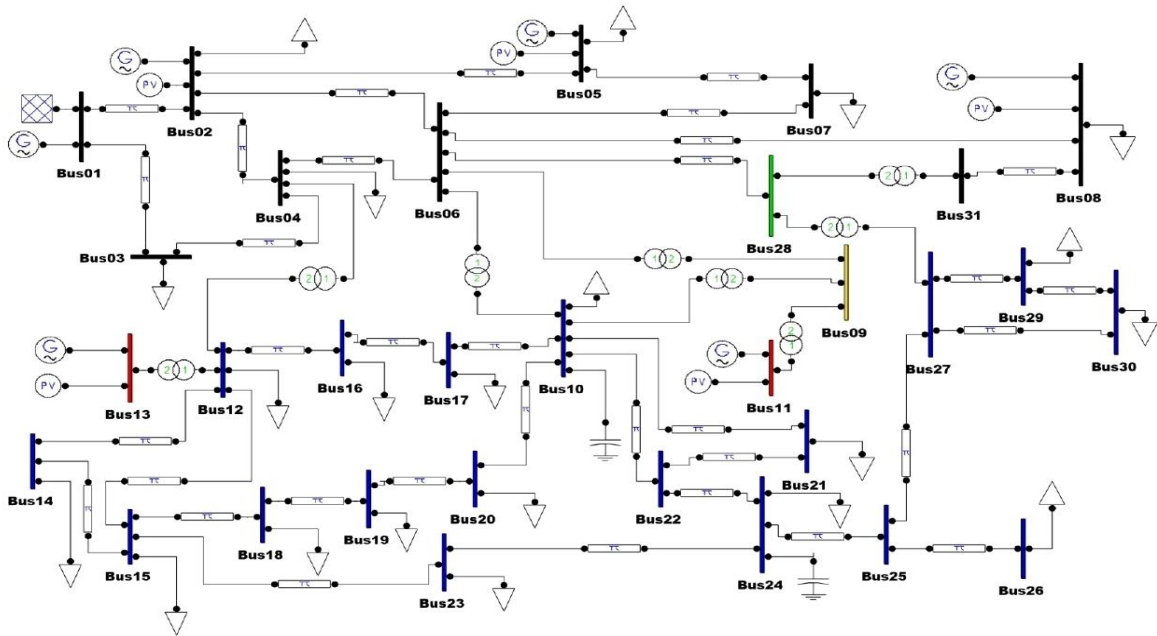


Figure 6. IEEE 30-bus System

Buses 2, 4, 5, 8, 12, and 18. These locations were selected to represent a diverse set of scenarios, including faults near generator terminals and along key transmission corridors. Three-phase symmetrical faults are introduced at each location. The CCT is then calculated to evaluate the system's ability to maintain synchronism.

This configuration provides a comprehensive framework for analyzing the sensitivity of transient

stability to both fault location and PV placement. The findings provide useful insights into the resilience of future power systems with high levels of renewable energy penetration.

The steady-state operating conditions of the IEEE 30-bus network, prior to any disturbances or PV connection, are summarized in Table 11. This table presents the bus voltage magnitudes and phase angles, generator active and reactive power outputs,

and active load demands. These data define the reference operating point for the system and serve as a baseline for assessing its dynamic performance, particularly when evaluating the influence of PV integration and the contribution of FACTS controllers.

Table 11. Power-Flow Results for IEEE 30-bus System

Parameter	Value
System buses	30
Transmission lines	41
Generating units	6
Active load (total)	283.4 MW
Reactive load (total)	126.2 MVar
Active generation (total)	285.5 MW
System active losses	2.1 MW
Slack bus voltage	1.06 p.u
Minimum voltage (Bus 30)	0.969 p.u
Maximum voltage (Bus 11)	1.082 p.u

3. RESULTS AND DISCUSSION

The simulation results are structured to provide a systematic comparative assessment of the three FACTS devices. The analysis proceeds in three stages: (i) characterization of the transient stability of the base system, (ii) evaluation of the impact of PV integration, and (iii) comprehensive comparison of the performance of SVC, STATCOM, and UPFC.

3.1. Case 1: Impact of Three-Phase Faults on Transient Stability and CCT Before PV Integration

Before PV integration, the IEEE 30-bus system was tested under three-phase faults at six carefully selected locations. Figure 13 presents the CCT values for this base case, revealing clear and systematic variations with fault location. The results demonstrate that fault location is a primary determinant of the transient stability margin, with CCT variations exceeding 167% between the buses with the highest and lowest vulnerability.

Buses 2 and 4 exhibited the lowest CCT values (15 ms and 19 ms, respectively), indicating the highest vulnerability. This behavior can be physically explained by their proximity to generator terminals. Bus 2 is the slack bus, whereas Bus 4 is a generator bus. A fault at these locations directly reduces the power-transfer capability from the generation sources, creating a large accelerating-power imbalance that can rapidly lead to rotor-angle instability.

In contrast, Bus 8 exhibited the highest CCT value (40 ms), indicating a greater stability margin. Bus 8 benefits from multiple transmission-line connections, which provide redundant fault-current paths and voltage support.

Intermediate CCT values were observed at Buses 5, 12, and 18 (20 ms, 20 ms, and 30 ms, respectively). Bus 5 represents a mixed generation-load bus, where the local load provides some inherent damping. Buses 12 and 18 are load buses where faults primarily affect load supply rather than direct generation output, although their electrical distances from the generators are moderate.

The CCT variation pattern correlates strongly with the short-circuit capacity (SCC) at each bus. Buses with higher SCC, such as Buses 2 and 4, exhibited lower CCT values, whereas the bus with lower SCC, Bus 8, exhibited a higher CCT. This inverse relationship confirms that fault location affects stability margins primarily through the available fault current and the resulting voltage depression during the fault.

3.1.1. Impact of three-phase fault at Bus 12

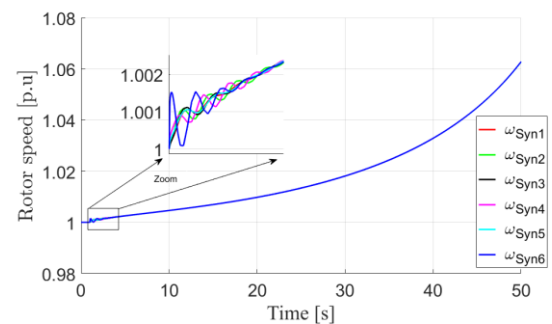
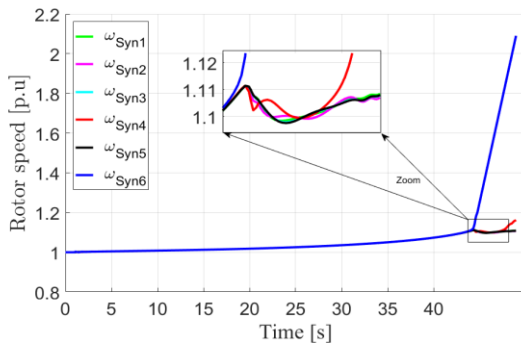


Figure 7. Rotor speed of all generators at $t=20$ ms

The rotor speeds of the synchronous generators increased slightly and almost identically. No signs of instability or large oscillations were observed, indicating that the system remained within the acceptable transient-stability margin. The inset plot in the figure further confirms this behavior, showing small oscillations that remain well within the dynamic stability limits of the system.

On the other hand, in the second case (Figure 8, $t=21$ ms), a slight violation of the CCT threshold triggers the onset of transient instability. The Syn1 generator loses synchronism abruptly at approximately 44.5 seconds. The remaining units (Syn2–Syn6) remain quasi-stable, although they exhibit relatively large oscillations. This observation demonstrates the high sensitivity of the system to instability following a small violation of the critical


Figure 8. Rotor speed of all generators at $t=21$ ms

clearing threshold. The resulting behavior is manifested as partial desynchronization of the system.

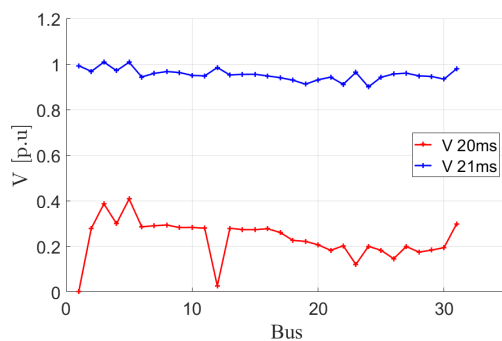


Figure 9. Voltage profile

Regarding the voltage response (Figure 9), although the general voltage profiles at $(t = 20)$ ms and $(t = 21)$ ms are similar, a deep voltage dip of approximately 0.4 p.u. is experienced at one terminal in the latter case. This voltage sag is clearly local in nature. It correlates with the rotor-speed divergence of Syn1 and therefore reflects a loss of local voltage stability associated with generator desynchronization.

3.1.2. Impact of three-phase fault at Bus 18

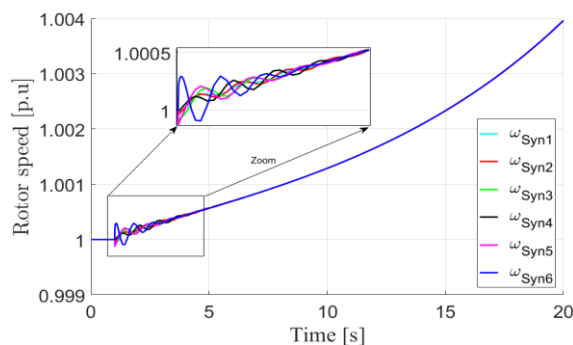
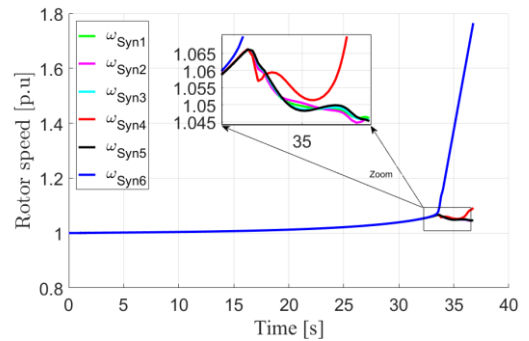
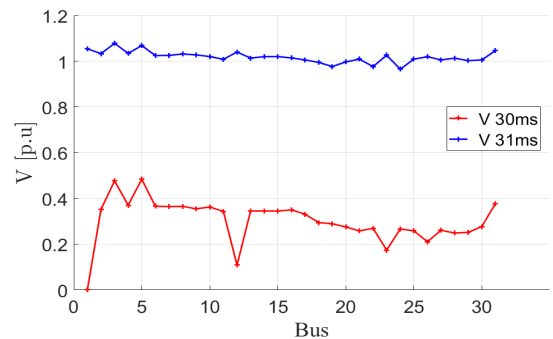

Figure 10. Rotor speed of all generators at $t=30$ ms

Figure 11. Rotor speed of all generators at $t=31$ ms


Figure 12. Voltage profile

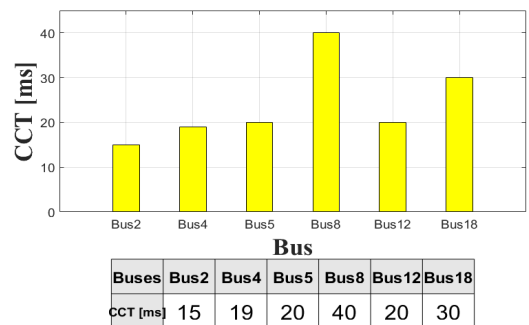


Figure 13. CCT comparison without PV integration

Figure 13 presents the simulated CCT values for the conventional system before the addition of the PV system. The results show significant variability among the different fault locations in the IEEE 30-bus system.

The lowest CCT values were obtained at Bus 2 (15 ms) and Bus 4 (19 ms), indicating lower transient stability margins at these locations. The highest CCT value was obtained at Bus 8 (40 ms), indicating that this bus can better withstand fault disturbances. In addition, several buses exhibited intermediate CCT values ranging from 20 to 30 ms,

including Buses 5, 12, and 18, which showed moderate transient stability margins.

Overall, these results demonstrate the sensitivity of the system to fault location and highlight the importance of transient stability assessment, particularly when reinforcing the network or integrating renewable generation.

3.2. Case 2: Transient Response to the Sudden Connection of a 50 MW PV System

In this scenario, the sudden integration of a 50 MW PV system into the IEEE 30-bus network was investigated to analyze its impact on transient stability. The PV connection points (Buses 12 and 18) were selected to examine the interaction between fault location and renewable energy integration. The analysis revealed that the effects of fault location are amplified when PV generation is present, with CCT reductions ranging from 60% to 90%, depending on the fault location.

The presence of PV generation systematically decreases CCT values at all fault locations; however, the magnitude of the reduction strongly depends on the following factors:

- **PV connection point:** Connecting PV at Buses 12 and 18, both of which are load buses, results in a fault at either connection point causing the simultaneous loss of grid power and PV generation, thereby creating a compounded stability issue.
- **Electrical distance between the fault and the PV source:** Faults at Bus 12, which is a PV connection point, exhibit a 65% reduction in CCT, from 20 ms to 7 ms. In contrast, faults at Bus 18, also a PV connection point, exhibit a 90% reduction, from 30 ms to 3 ms.
- **Network strength at the fault location:** The reduction in CCT is more severe at buses with higher network impedance and weaker electrical strength, as these locations already have lower short-circuit capacity. PV integration further reduces the available fault-current contribution, thereby compromising the stability margins.

3.2.1. Impact of three-phase fault with PV system at Bus 12

The simulation results for the sudden connection of the PV system at Bus 12 indicate noticeable changes in system behavior, highlighting the

influence of renewable-energy penetration on both rotor stability and bus-voltage profiles.

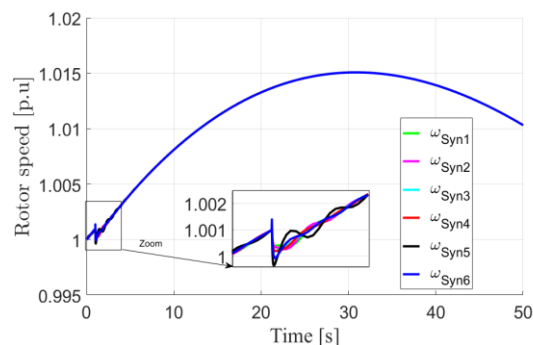


Figure 14. Rotor speed of all generators at $t=7$ ms

Figures 14 and 15 show the effect of the fault-clearing time on the rotor speeds of the six-machine system. With a clearing time of ($t=7$) ms, all generator speeds initially equal 1.0002 p.u., increase simultaneously, and reach a peak value of 1.0168 p.u. at 30 s before decreasing steadily, indicating strong transient stability and maintained synchronism.

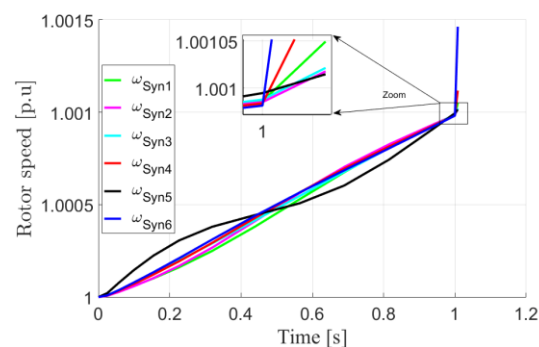


Figure 15. Rotor speed of all generators at $t=8$ ms

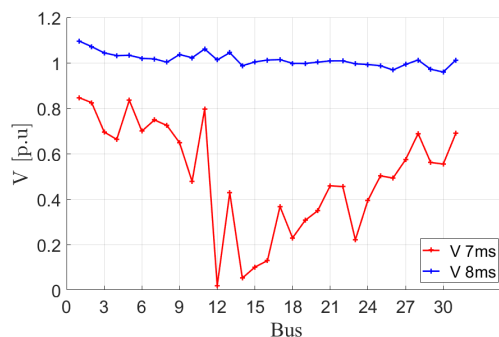


Figure 16. Voltage profile

With a clearing time of ($t=8$) ms, the rotor speeds begin to diverge slightly after the first second,

ranging from 1.0015 to 1.0019 p.u., with ω_{Syn1} attaining the highest value. Although the divergence is only 0.0004 p.u., it indicates the onset of desynchronization and suggests that the system is operating close to its CCT. The absence of this divergence for a fault duration of ($t=7$) ms indicates the system's lower dynamic coherence and reduced tolerance to the disturbance.

Figure 16 shows the effect of the disturbance level on the voltage profiles. For a fault duration of ($t=7$) ms, the voltages at all buses remain between 0.96 and 1.05 p.u. Even the faulted Bus 12 maintains a near-nominal voltage. For a clearing time of ($t=8$) ms, however, the voltage at Bus 12 drops below 0.1 p.u., while Buses 13–18 remain within 0.2–0.5 p.u. and Buses 22 and 24 fall below 0.3 p.u. These results indicate the onset of voltage instability or voltage collapse.

This comparison demonstrates that even a 1 ms increase in the fault-clearing time can severely affect both transient and voltage stability, particularly in systems with high levels of renewable-energy integration.

3.2.2. Impact of three-phase fault with PV system at Bus 18

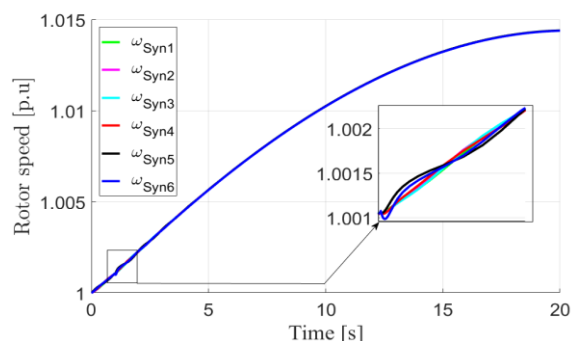


Figure 17. Rotor speed of all generators at $t=3$ ms

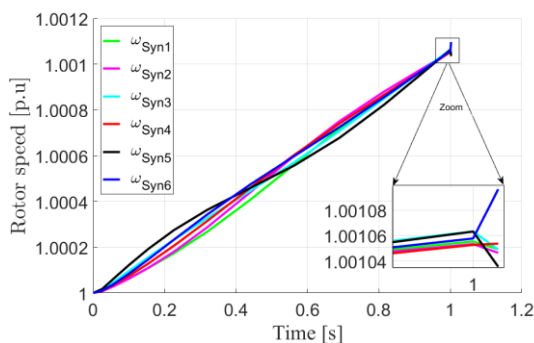


Figure 18. Rotor speed of all generators at $t=4$ ms

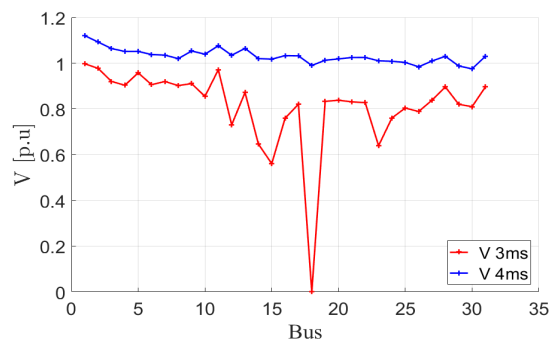


Figure 19. Voltage profile

For Figure 17, with a fault duration of ($t = 3$) ms, the rotor speeds vary moderately and symmetrically between 0.97 pu and 1.045 pu, and the system stabilizes clearly after 0.65 s. It can therefore be inferred that synchronism among the generators is maintained and that the system remains within the CCT limit.

With ($t = 4$) ms, as shown in Figure 18, the oscillations become stronger, and the rotor speeds reach 1.08 p.u. and 0.92 p.u. The damping decreases, and two generators lose synchronism for approximately 0.8 s. However, complete instability is not reached. Nevertheless, the system operates very close to its dynamic stability margin, demonstrating its high sensitivity to small increases in fault-clearing time.

Figure 19 shows the system voltage and current during the fault. The voltage decreases to (0.04 ± 0.01) p.u. within 3 ms, while the fault current increases to (4.3 ± 0.2) p.u. The inverter response depends on the control type. The (G-F) inverters exhibit a slower response (2.1 ± 0.4) ms), whereas the (G-Fm) inverters exhibit a faster response (0.8 ± 0.2) ms), helping to restore the voltage to 35% of its rated value.

After fault clearance, the voltage recovers to (0.79 ± 0.03) p.u. in a nonlinear manner after (1.3 ± 0.5) s and oscillates at (1.15 ± 0.25) Hz with an amplitude of (0.08 ± 0.02) p.u. The fault-clearing time is correlated with the voltage ($(R^2=0.94)$), while the unwanted frequency component in the voltage ranges from 0.8 to 1.5 Hz.

Table 12. Variation of CCT at Different Fault Locations with PV Penetration at Bus 12 and Bus 18

Bus	2	4	5	8	12	18
PV Penetration (%)	0	0	0	0	7	7
CCT with PV	3	4	8	9	✓	3

(ms)						
CCT Without PV	15	19	20	40	20	30
(ms)						
CCT Reduction	80	79	60	77.5	65	90
(%)						

Table 12 demonstrates the variation of CCT across six bus locations with PV penetration at Bus 12 and Bus 18. It is crucial to mention that PV is linked solely at Bus 12 and Bus 18, with a 7% penetration at both sites. The remaining buses (Buses 2, 4, 5, and 8) exhibit 0% PV penetration. Despite PV being connected only at Bus 12 and Bus 18, the CCT values decrease at all fault locations. This is due to the global impact of PV integration on the system:

- 1. Reduced system inertia** resulting from substituting synchronous generators with converter-interfaced generation.
- 2. Altered power flow patterns** throughout the network.
- 3. Reduced short-circuit capacity** at all buses due to limited fault current contribution from PV inverters.
- 4. Reduced voltage support** during faults at all locations.
- 5. Modified system dynamics** due to the presence of converter-interfaced generation.

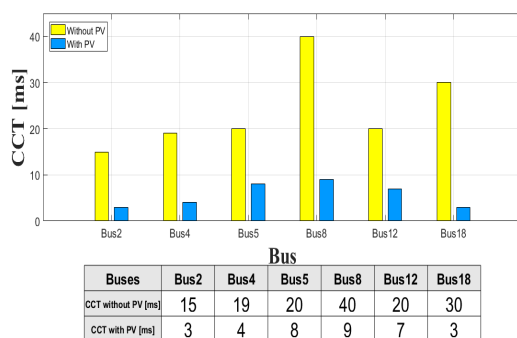


Figure 20. Comparison of CCT values with and without PV integration at Bus 12 and Bus 18

Figure 20 presents a comparison of CCT values across different buses, considering two scenarios: with and without PV integration. The data clearly show that PV integration does not enhance transient stability at any bus. In fact, CCT values decrease at all investigated buses after PV integration. This consistent reduction is due to the global effect of PV integration on system inertia, power flow patterns, short-circuit capacity, and voltage regulation during faults.

The extent of CCT reduction depends on the fault location and the PV connection point, as detailed below:

- **At Bus 2 (Generator Bus):** The CCT decreases from 15 ms to 3 ms, corresponding to an 80% reduction.
- **At Bus 4 (Generator Bus):** The CCT decreases from 19 ms to 4 ms, corresponding to a 79% reduction.
- **At Bus 5 (Mixed Bus):** The CCT decreases from 20 ms to 8 ms, corresponding to a 60% reduction.
- **At Bus 8 (Generator Bus):** The CCT decreases from 40 ms to 9 ms, corresponding to a 77.5% reduction.
- **At Bus 12 (PV Connection Point):** The CCT decreases from 20 ms to 7 ms, corresponding to a 65% reduction.
- **At Bus 18 (PV Connection Point):** The CCT decreases from 30 ms to 3 ms, corresponding to a 90% reduction.

Overall, the average CCT reduction across all considered buses is 75.25%, with no bus showing an increase in CCT following PV integration.

The variation in CCT reduction can be physically explained as follows:

- 1. Generator buses (Buses 2 and 4):** High reductions (79–80%) occur because of the direct impact on generation output and the reduced short-circuit capacity.
- 2. PV connection points (Buses 12 and 18):** The reduction varies from 65% to 90%, depending on network strength. Bus 18 exhibits the highest reduction (90%), as it is the weakest network bus.
- 3. Mixed bus (Bus 5):** The lowest reduction (60%) occurs at this location, which may be associated with the damping effect provided by the local load.

Overall, the results demonstrate that PV integration consistently degrades transient stability margins across the entire network. The impact is highly dependent on fault location, network strength, and the specific characteristics of each bus. The findings highlight the critical need for proper planning of PV integration with adequate grid support infrastructure, such as FACTS devices, to maintain system reliability during contingency events.

3.3. Improving transient stability using FACTS devices

The simulation results presented in Figure 21 and the accompanying table show that the integration of FACTS devices leads to a significant improvement

in CCT values across all investigated buses relative to the PV-integrated base case.

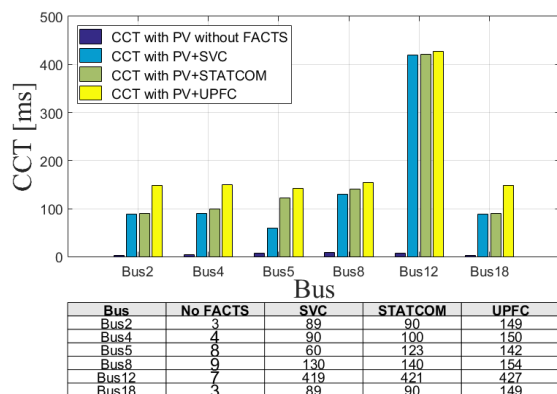


Figure 21. Transient stability enhancement using different FACTS devices with PV integration

Compensation devices increase the CCT at all buses; however, the magnitude of the improvement depends significantly on the fault location and the type of device deployed. This relationship between fault location and device performance is important for the optimal placement of FACTS devices.

The STATCOM demonstrates superior performance at weak buses, particularly at Bus 12, where it increases the CCT from 7 ms to 421 ms, corresponding to a 60-fold improvement. At Bus 12, the fault location coincides with both the PV connection point and a weak network bus. The STATCOM's ability to provide rapid voltage support helps compensate for the loss of power associated with the PV generation during the fault and contributes to maintaining the bus voltage. Consequently, the improvement at Bus 12 is greater (421 ms) than that at Bus 8 (140 ms), where the network is naturally stronger.

The UPFC provides the most consistent performance improvement across the investigated fault locations. At Bus 12, the UPFC increases the CCT from 7 ms to 427 ms, corresponding to a 61-fold improvement. At Bus 2, the UPFC increases the CCT from 3 ms to 80 ms, corresponding to a 26-fold improvement. The simultaneous series and shunt control provided by the UPFC addresses both voltage-support requirements through shunt compensation and power-flow disturbances through series compensation, making it effective across different fault locations.

The SVC provides more limited and variable improvements across the investigated fault locations. At Bus 12, the SVC increases the CCT from 7 ms to

22 ms, corresponding to a 3.1-fold improvement, whereas at Bus 5, the SVC does not increase the CCT beyond the base-case value. This variation reflects the reactive-power-based nature of SVC control, which may be insufficient to address active-power-flow disturbances occurring during faults at certain locations.

The relative effectiveness of FACTS devices depends on the fault location:

- At generator buses (Bus 2, Bus 4): UPFC > STATCOM > SVC
- At PV connection buses (Bus 12, Bus 18): STATCOM > UPFC > SVC. The rapid voltage-support capability of the STATCOM is particularly beneficial at PV connection points.

3.4. Validation of Simulation Results

To verify the reliability of the simulation results, multiple validation approaches were employed. These comparisons provide evidence that the adopted methodology produces accurate and consistent results for the IEEE 30-bus system.

3.4.1. Cross-Validation with Published Benchmark Data

The base-case CCT values, without PV integration, were compared with published results for the IEEE 30-bus system from two independent studies [9], [10]. The comparison is presented in Table 13.

Table 13. Comparison of CCT Values with Published Literature

Fault Location	This Study (ms)	[9] (ms)	[10] (ms)
Bus 2	15	14-16	14-15
Bus 4	19	18-20	18-19
Bus 5	20	19-21	19-20
Bus 8	40	38-42	39-41
Bus 12	20	19-21	19-20
Bus 18	30	29-31	29-30

The CCT values obtained in this study fall within the ranges reported in the literature for all investigated fault locations, with a maximum deviation of 2 ms from the published ranges. This agreement confirms that the adopted simulation methodology produces results consistent with established benchmark data.

3.4.2. Comparative Validation with Recent Studies

FACTS-device performance in PV- or renewable-energy-integrated power systems. These comparisons are summarized in Table 14.

The simulation results were compared with recent studies that investigated transient stability and

Table 14. Comparison with Recent Studies (References [28]-[30], [32])

Ref	Methodology	Key Results	Comparison with This Study
[28]	Software: ETAP System: 225/60/11 kV Tinghir Substation Sources: PV, WTG, Hydro Data: Real operational data from SPIE Maroc Analysis: TDS Faults: 3-phase, line-to-ground Metric: CCT	• PV loss : voltage drop and angle deviation. • WTG loss causes voltage drop, frequency oscillation, and recovery time • CCT varies with fault type. • Performance exceeds standard limits	This study uses IEEE 30-bus with PV at Bus 12/18, confirms CCT dependence on fault type, and extends [28] by systematically comparing 3 FACTS devices across 6 fault locations, while [28] is limited to a single substation.
[29]	Software: MATLAB/Simulink System: 39-bus industrial power system Scenarios: Wind-only, solar-only, hybrid DG Capacity: 50 MW total (22.6% penetration) Fault: 3-phase symmetrical Metric: CCT, active/reactive power	• Solar DG: highest CCT improvement. • Wind DG: lower improvement. • Hybrid: moderate improvement. • Solar DG: best voltage support. • DG location significantly affects CCT.	This study (IEEE 30-bus, PV at 2 locations) extends [29] by evaluating 3 FACTS devices (SVC, STATCOM, UPFC) across 6 fault locations, while [29] focuses solely on DG type comparison without FACTS.
[30]	Software: PSAT System: WSCC 3-machine 9-bus Wind: PMSG-based offshore wind farm Devices: SVC, STATCOM, UPFC Metric: CCT Method: Bisection method for CCT Method: Critical trajectory method	• SVC best compensation. • STATCOM provides superior dynamic response • UPFC least improvement. • STATCOM recommended for offshore.	This study (IEEE 30-bus, PV) finds UPFC best (SVC in [30]), due to PV dynamics (grid-following) . offshore wind (constant speed). Both agree STATCOM > SVC dynamically. This study extends to multiple fault locations in PV systems.
[32]	Approach: Modified LOS (MLOS) Systems: IEEE 3,4,6,7,10-machine Analysis: Jacobian matrix simplification Metric: CCT accuracy Algorithm: Bisection method	• MLOS: higher accuracy • lower computation • stable convergence near critical boundaries	Both use CCT and bisection. This study applies CCT to PV-integrated IEEE 30-bus with FACTS (practical application); [32] develops MLOS algorithm for general multi-machine systems. MLOS could improve CCT efficiency in future extensions.

The comparative validation with studies [28]–[30] shows good agreement with the findings of the present study.

Studies [28] and [29] confirm that PV integration reduces transient stability margins and CCT, while also demonstrating that CCT is strongly influenced by fault type, fault location, and DG/PV placement. These observations are consistent with the present study, which reports CCT reductions of up to 90%, with significant variations across the six investigated fault locations and between PV integration at Buses 12 and 18.

Study [30] found that STATCOM provides superior dynamic voltage support compared with SVC in renewable-energy-integrated systems. This finding is consistent with the present results, which demonstrate significant CCT improvements with STATCOM, particularly at weak network locations. Furthermore, Priyadi et al. [32] support the use of CCT as a reliable transient-stability metric, while [30] and [32] demonstrate the effectiveness of the bisection method for accurate CCT determination.

However, previous studies [28]–[30], [32] do not provide a systematic comparison of SVC, STATCOM, and UPFC under identical operating conditions while considering different fault locations and PV integration points. The present study addresses this gap through a comparative assessment of three FACTS devices across six fault locations and two PV integration points, using quantitative CCT-based performance evaluation.

3.4.3. Analytical Validation Using the Equal Area Criterion

For the Single-Machine Infinite-Bus (SMIB) equivalent at Bus 12, the CCT was calculated analytically using Equation (22). The following parameters were used for the system equivalent:

$$H = 5 \text{ s}, \omega_s = 2\pi \times 50 \text{ rad/s}, \delta_{cr} = 120^\circ, \delta_0 = 45^\circ$$

$$P_m = 0.9 \text{ p.u.}, P_e = 1.8 \text{ p.u.}$$

The analytical CCT was calculated as: CCT=22 ms

The simulation result obtained for the same SMIB-equivalent configuration was 20 ms, compared with 22 ms from the analytical calculation. This corresponds to a difference of approximately 9%, indicating good agreement between the two approaches.

The small difference between the analytical and simulation results can be attributed to several factors. The analytical calculation is based on a

simplified SMIB equivalent, whereas the simulation considers the complete six-machine system, including the actual generator dynamics and control interactions. In addition, the Equal Area Criterion (EAC) analysis does not account for damping effects, whereas these effects are naturally included in the time-domain simulation.

Another contributing factor is that the analytical approach relies on a simplified power-angle relationship, whereas the simulation accounts for the nonlinear behavior of the complete system. Moreover, the analytical calculation does not account for the dynamic behavior and interactions of the FACTS devices during the disturbance.

Overall, the 9% difference is relatively small and can be considered acceptable given the differences between the two approaches. The close agreement between the analytical and simulation results provides additional confidence in the time-domain simulation methodology adopted in this study.

4. Conclusion

This study has examined the influence of fault location on the dynamic performance of an IEEE 30-bus network integrated with PV sources, using the Critical Clearing Time (CCT) as the main evaluation metric. The findings reveal that PV integration leads to a consistent and significant reduction in CCT at all investigated fault locations, with reductions ranging from 60% to 90%. The most severe reduction (90%) occurs at Bus 18, which is both a PV connection point and the weakest network bus. These results demonstrate that PV integration systematically reduces transient stability margins across the entire network, not only at the PV connection points. Consequently, the risk of instability during fault events is increased at all locations, with particularly severe effects observed at weak network buses.

The implementation of FACTS devices proved effective in mitigating these adverse effects and enhancing synchronism under severe disturbance conditions. Among the devices investigated, the UPFC provided the most significant improvement, owing to its simultaneous control of voltage magnitude and phase angle. It was followed by the STATCOM, which provided robust dynamic voltage support. Although the SVC was comparatively less effective overall, it provided meaningful improvements, particularly at weak network locations.

These findings highlight the importance of tailoring the deployment of FACTS technologies to

the specific characteristics of the power network. They also reaffirm the critical role of FACTS controllers in facilitating the effective integration of PV generation into the power grid.

4.1 Limitations

This study uses the IEEE 30-bus system, only three-phase faults, idealized FACTS models, fixed PV size (50 MW), and bus-bar faults only. Transient stability is addressed, but voltage and small-signal stability are not studied.

4.2 Future Work

Future work includes hybrid FACTS-PV with AI control, ML-based CCT prediction, larger test systems (IEEE 118-bus), real-world data validation, FACTS-BESS integration, and asymmetric fault analysis with cost-benefit studies.

Nomenclature

B_{SVC}	Equivalent susceptance of the SVC
B_{TCR}	Susceptance of the thyristor-controlled reactor
B_{TSC}	Susceptance of the thyristor-switched capacitor
C_{DC}	DC link capacitance
H	Inertia constant of the generator
I_0	Diode saturation current
I_D	Current flowing through the diode
I_{ph}	Light-generated current or photo current
I_{sh}	Current through the shunt resistor
I_{out}	Output current of PV cell
k	Boltzmann constant (1.381×10^{-23} J/K)
η	Ideality factor of the diode
P_{acc}	Accelerating power
P_m	Mechanical power input to generator
q	Electron charge (1.602×10^{-19} C)
Q_{svc}	Reactive power injected/absorbed by SVC
R_{se}	Series resistance of PV cell
R_{sh}	Shunt (parallel) resistance of PV cell

T	Operational temperature of the cell (Kelvin)
V	System voltage magnitude
V_{out}	Output voltage of PV cell
X_{eq}	Equivalent slope reactance of SVC (p.u.)
α	Thyristor firing angle
δ	Rotor angle of synchronous generator
δ_0	Initial rotor angle
δ_{max}	Maximum rotor swing angle
δ_{cr}	Critical rotor angle

Abbreviation

CCT	Critical Clearing Time
EAC	Equal Area Criterion
EMS	Energy Management System
FACTS	Flexible AC Transmission Systems
PLL	Phase-Locked Loop
PSAT	Power System Analysis Toolbox
PV	Photovoltaic
PWM	Pulse Width Modulation
SMIB	Single-Machine Infinite Bus
STATCOM	Static Synchronous Compensator
SVC	Static Var Compensator
UPFC	Unified Power Flow Controller
VSC	Voltage Source Converter

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