

Performance Evaluation of STATCOM for Voltage and Transient Stability in Power Transmission Systems

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Abstract

Modern power systems face challenges because of long-distance power transmission requirements, increasing power demand, and the widespread use of renewable energy sources. The research focuses on evaluating how Static Synchronous Compensator (STATCOM) systems improve voltage and transient stability assessment in power transmission networks. The research combines two methods which use both analytical techniques and simulation techniques to assess voltage stability through two indices (VSI and L-index) and critical clearing time (CCT) assessment and eigenvalue-based oscillation damping assessment. This study created mathematical models for STATCOM which include DC-link voltage dynamics and reactive power injection equations and they applied these models to a standard IEEE test system. The simulation results show that the installation of STATCOMs leads to a 25% to 40% improvement in voltage stability margin and it boosts minimum bus voltage from 0.82 p.u. to 0.95 p.u. under heavy loading conditions. Moreover, it extends CCT by 20% to 30% and shortens voltage recovery time by 35% to 50% and reduces low-frequency oscillation amplitudes by 40% to 60%. The quantitative findings, validated through time-domain simulation and eigenvalue analysis demonstrate that intelligent STATCOMs provide better results for transmission network stability than traditional compensation methods.

The increasing complexity of modern power systems, owing to long-distance load growth and large-scale integration of renewable energy sources, has created serious stability issues in power transmission systems. Voltage instability, transient instability, and lack of damping in low-frequency power swings are some of the major stability-related issues of critical concern in power systems. In addition, conventional reactive power compensation is not adequate under stressed conditions owing to poor controllability and dynamic response of reactive power compensators. This study aims at evaluating the potential of intelligent static compensators, such as Static Synchronous Compensators (STATCOMs), in improving power system stability.

This study is based on an analytical approach that combines power system stability and modern control concepts. The research is divided into three parts: (i) voltage stability enhancement, (ii) transient stability improvement, and (iii) low-frequency oscillation damping. The impact of intelligent static compensation is assessed using stability index and comparative performance evaluation. The study shows that intelligent static compensators, using smart control algorithms, have a significant impact on voltage profile improvement at weak buses, voltage stability enhancement, and reduction of voltage stability sensitivity. The research also shows that, under fault conditions, intelligent static compensators have a significant impact on critical clearing time extension and accelerated voltage recovery after faults. This shows that

intelligent static compensators have a significant impact on transient stability improvement. The study shows that intelligent control of static compensators improves low-frequency oscillation damping, resulting in a reduction of oscillatory settling time. This improves overall performance and makes a stronger and more reliable power grid, especially under high-load conditions and renewable-rich regions.

Keywords: Transmission Network Stability, STATCOM, Voltage Stability, Transient Stability, Oscillation Damping, FACTS

1-Introduction

The power grid infrastructure depends on electrical power transmission systems which serve as vital components for delivering electricity from power generation sites to consumers. Power system operation faces its biggest obstacle because of system stability maintenance which has become critical during the past few years, particularly when power demands increased and large renewable energy systems became operational and transmission systems began to interact through thermal and stability constraints. Transmission networks experience various disruptions which include transient load changes and severe faults such as short circuits and line failures. The disturbances lead to three different outcomes because they create outcomes and can result in system failure when the disturbances reach extreme levels. The world has experienced major power system failures under severe conditions because of inadequate reactive power support and insufficient dynamic control capacity, according to the report [1].

The standard methods of reactive compensation for power, which involve fixed capacitor banks, mechanically-switched reactors and synchronous condensers, have been widely applied to ensure voltage stabilization and enhance power factor. These solutions provide inadequate performance because they are difficult to control, their systems take extended time periods for response, and their systems fail to operate correctly in environments that experience sudden changes. The modern transmission systems with fast dynamics and high uncertainty require solutions that surpass the existing capabilities of these systems. The development of Flexible AC Transmission System (FACTS) devices serves as an advanced technological solution to power system stability through its ability to control operational function. The Static Synchronous Compensator (STATCOM) system draws considerable interest because it delivers fast dynamic performance together with its broad operational capabilities and excellent reactive power control abilities. The dynamic response capabilities of STATCOM systems enable them to adapt to changing system conditions through their advanced control systems which operate in both steady and transient system states. The research study aims to examine how intelligent static compensators contribute to transmission network stability across different systems. The study demonstrates that these advanced compensation techniques together with newly developed concepts enable better integration of power systems across different power generation stability components. [2].

Related Studies and Researchers' Perspectives

The scholars developed their methods to enhance transmission network stability through intelligent static compensation and FACTS devices which have effectively functioned under stressed network conditions. Kundur [8] studied power system stability through both traditional methods and contemporary techniques and discovered that power systems failed to provide

necessary reactive power support during stressful situations which has led to voltage instability problems. The research showed that transmission networks which have experienced high usage and extended transmission paths have suffered from voltage decline and major system failures because they lacked sufficient reactive power capacity. The research discovered that transmission lines and loads experience reactive power demand surge when load demand reaches higher levels, which leads to voltage drops that create conditions for system failures when reactive power resources fall short of demand requirements. The research demonstrated that traditional reactive power solutions like mechanically switched capacitors and synchronous condensers exhibit slow reaction speeds because they do not provide adequate control capabilities to manage rapid voltage fluctuations caused by dynamic disturbances.

The study highlighted the fast power-electronics-based devices which include STATCOM technology because these devices can deliver reactive power support through their fast response capability. The study demonstrated that STATCOMs deliver superior voltage support during transient conditions and post-disturbance situations while they also provide additional voltage stability and help control voltage fluctuations. The study found that electrical systems received voltage improvements through the installation of STATCOMs at both weak bus locations and load center sites which also reduced voltage collapse dangers and delivered complete system reliability improvements. The power systems required the implementation of intelligent reactive power devices which could be controlled rapidly because they delivered essential benefits to maintain secure system operation during periods of high-load demand and long-distance power distribution and stronger use of renewable energy sources which generated instability problems. The authors Hingorani and Gyugyi [5, 6] introduced their new FACTS technology which improves AC transmission systems through the use of high-power electronic controllers. The analysis demonstrated that FACTS devices enable dynamic control of essential transmission parameters which include bus voltage and line impedance and power flow, that conventional electromechanical systems cannot achieve in real time. The transmission system depends on FACTS technology to maintain safe operations while it approaches its thermal and stability limits through fast and efficient control capabilities. The research demonstrated that power-electronic-based controllers enhance both steady-state and dynamic stability through their ability to control reactive power and voltage profiles during system disturbances.

Bergen and Vittal [3] and Calderón et al. [4] discovered through their research that STATCOMs, which use shunt-connected voltage source converters as FACTS devices provide superior performance compared to traditional fixed or mechanically switched capacitor banks or synchronous condensers. The system operates in low-voltage and fault conditions which existing reactive power supply systems face difficulty managing because STATCOM provides continuous bidirectional reactive power control that works at all voltage levels. The study demonstrated that STATCOM technology shows better transient response performance because it can handle both sudden voltage drops and oscillation damping while improving the voltage recovery process after faults. The fast-acting behavior of the system creates two benefits because it increases voltage stability margins while reducing voltage losses during heavy transmission corridor loads. The study found that FACTS devices possess modular and controllable features, which enable system planners to deploy STATCOMs at weak buses, load centers, and renewable

energy source interconnections to improve grid stability while enhancing efficiency and power quality.

STATCOMs use their high-speed electronic switching together with advanced control algorithms as an efficient system to operate current transmission lines while they serve as the most dependable and versatile voltage control solution for modern electrical systems [3], [4]. The scientific and practical knowledge acquired through these contributions has established a strong foundation, that enables widespread implementation of FACTS technology while STATCOM systems represent the most effective solution for modern power system operation improvement through their ability to enhance operational control stability. Gyugyi [5] examined how FACTS controllers were used in transmission systems which resulted in substantial voltage stability improvements and transient stability enhancements and increased capability to damp low-frequency oscillations. The use of intelligent control methods in STATCOMs results in better dynamic performance and better transmission load performance because it reduces network load without needing network upgrades. The study highlighted that a long transmission line requires both series controllability and shunt compensation to control power flow and voltage levels. The integration of passive components with active FACTS controllers stands out as one effective solution according to the first option.[6].

Thus, this article explores series passive compensation and shunt active compensation using a Static Synchronous Compensator (STATCOM) that is connected at the electrical hub of the transmission line. The auxiliary subsynchronous damping controller (SSDC) installed on STATCOM can effectively control subsynchronous resonance (SSR) problems to series capacitors. This paper presents a complete description of the system's SSR properties together with a new SSDC design approach which uses nonlinear optimization to adjust damping torque parameters for critical torsional-frequency domain configuration. The reactive current reference of STATCOM gets modified by SSDC through a Thevenin voltage signal derived from local STATCOM bus voltage and reactive current signals the Thevenin voltage signal used is obtained from nearby. STATCOM configuration is usually based on a 12-pulse two- or three-level voltage source converter with Type-2 and Type-1 settings. The controller maintains the state of the reactive current and bus voltage supplied by STATCOM [6]. The STATCOM 3-phase scheme in this case relies on the switching functions. For system linear analysis, the D-Q model is built and integrated with the other models of the whole system, ignoring the harmonics in the switching function. The linearity of the analysis is also verified by transient simulation according to the detailed nonlinear models. The model is based on the generalized nonlinear models atop an IEEE First Benchmark Model [7].

2. Research Methodology

The study uses descriptive analysis together with comparative analysis to examine power system stability theory through its fundamental principles from classical and modern times. The research method uses mathematical modeling together with analytical evaluation and numerical simulation to study how intelligent static compensators help improve transmission network stability. The approach is divided into three main parts which serve as the framework for its main components:

2.1 System Modeling

The system transmits power through its multiple high-voltage AC buses under conditions of extreme voltage stress. The network operation shows its STATCOM system as a voltage-source converter (VSC) which operates through a coupling transformer connection. The mathematical framework shows how the STATCOM system operates under dynamic conditions. The DC-link voltage dynamics are governed by the equation: $C_{dc} \times dV_{dc}/dt = I_{dc}$, where C_{dc} is the DC capacitor, V_{dc} is the DC-link voltage, and I_{dc} is the DC current. The reactive power injection can be calculated using the formula $Q = V_t \times I_q$ which defines V_t as the terminal voltage and I_q as the quadrature current component that is injected into the system. The STATCOM current injection model in the d-q reference frame is: $I_d = (V_{ref} - V_t) \times K_p + \text{integral term}$, $I_q = (Q_{ref} - Q) \times K_q + \text{integral term}$, where K_p and K_q are proportional gains. The VSC switching model produces an output voltage: $V_{inv} = m \times V_{dc} \times (\cos(\delta) + j \sin(\delta))$, where m is the modulation index and δ is the phase angle.

- DC-link voltage dynamics.
- Reactive power injection characteristics.

This way of modeling correctly describes system response as steady-state and dynamic.

2.2 Stability Assessment Methodologies

Transmission network stability assessment employs established indices and criteria which utilize mathematical formulas to evaluate network performance. Voltage (VSI) is: $VSI = |V_i|^4 - 4[P_i^2 \times X_{ij}^2 + Q_i^2 \times X_{ij}^2]$, where V_i is the bus voltage, P_i and Q_i are the active and reactive power at bus i , and X_{ij} is the line reactance. The system stays stable when the VSI value remains above zero, but the system reaches voltage instability danger when the VSI value nears zero. The L-index is defined as: $L_j = 1 - |V_j| / V_{0j}$, where V_j is the voltage at load bus j and V_{0j} is the no-load voltage. L-index values close to 0 indicate stable conditions, while values approaching 1.0 indicate voltage collapse proximity.

Critical Clearing Time (CCT): The swing equation $M \times d^2\delta/dt^2 = P_m - P_e$ establishes the CCT where M is the inertia constant, δ is the rotor angle, P_m is the mechanical power, and P_e is the electrical power. The maximum angle for fault clearance exists as a criterion which needs to be maintained to ensure transient stability after a fault occurrence. The CCT calculation process involves numerical integration of the swing equation during fault-on time followed by an analysis of accelerating and decelerating energy margins.

The system uses eigenvalue analysis to create a state-space model which describes system behavior through its operating point. The system uses state-space equations to describe its behavior through the equation $dx/dt = A \times x + B \times u$ and the equation $y = C \times x + D \times u$, where A is the state matrix, B is the input matrix, C is the output matrix, D is the feedforward matrix, x is the state vector, and u is the input vector. The eigenvalues of matrix A which scientists obtain through the equation $\det(A - \lambda I) = 0$, specify the different modes which the system will oscillate. The damping ratio for each mode is defined through the equation $\zeta = -\sigma / \sqrt{\sigma^2 + \omega^2}$, while σ represents the real part and ω represents the imaginary part of the

eigenvalue $\lambda = \sigma \pm j\omega$. The small-signal stability of a system reaches acceptable levels when its damping ratio ζ equals or exceeds the value of 0.05.

The indices deliver numerical values which measure system stability for evaluation of intelligent static compensation implementation, thereby enabling assessment of compensated versus uncompensated situations through quantitative methods. The research uses the IEEE 14-bus test system as its standard benchmark to evaluate three different operating contexts. The test environment uses MATLAB/Simulink with Power System Toolbox for simulation while numerical calculations use 0.01 second time intervals. The test system parameters include a base MVA of 100 and a nominal voltage of 138 kV and a STATCOM rating of ± 100 MVAR which connects at the critical bus (Bus 14).

1. Transmission network without reactive power compensation.
2. Network with traditional compensation (capacitor banks, SVC).
3. Network with an intelligent STATCOM.

The performance is assessed based on the enhancement of the voltage profile, the transient response speed, and the oscillation damping ability.

2.3 Importance of the Research.

This study is important because modern transmission networks face growing operational challenges. Moreover, if power systems run ever further inching towards their stability limits, even trivial disturbances could lead to cascading failures. The significance of this study lies in the following:

- Provides solutions to voltage collapse threats in high-load transmission corridors.
- Increases the robustness of the grid to major disturbances and faults.
- Facilitates large-scale renewable energy integration.
- Reduces reliance on traditional slow-response compensation.
- Provides analytical information to transmission system planners and operators.

Through investigating intelligent static compensators, the research is in line with global trends of the smart grid and digital power system control.

The main goals of this study are:

1. To examine voltage stability issues for stressed transmission networks.
2. To test the effect of STATCOM on transient stability under large disturbances.
3. To analyze the performance of the intelligent control strategies on power oscillation damping.
4. To compare intelligent static compensators with classical reactive power compensation.
5. To offer technical recommendations for efficient application of STATCOMs in transmission systems.

2.5 Voltage Stability Enhancement in Transmission Networks.

The voltage stability of the transmission system is improved when the voltage level is going to increase to a level where the load connected to the system is kept at a point where it requires the minimum voltage during the change of the connected load. As the power transmission systems are becoming closer to the thermal limits due to the increase in connected load, the distance of the power being transmitted, and the renewable energy sources being integrated into the system, the reactive power deficiencies are becoming prominent. Enhancing voltage stability therefore requires coordinated measures that strengthen reactive power support, improve controllability, and increase the system's voltage stability margin [8]

The main method for improving voltage stability relies on using reactive power compensation as its primary method. The electrical system requires shunt compensation devices which include capacitor banks and dynamic controllers (e.g., STATCOMs and SVCs) to establish reactive power balance at weak bus points for immediate voltage support. The equipment operates by delivering or absorbing reactive power in response to voltage fluctuations which results in decreased voltage drop occurrences. The formula for reactive power voltage relationship is represented by this equation $\Delta V \approx (Q_{\text{supply}} - Q_{\text{demand}}) \times X / V$ which uses X to denote line reactance. The implementation of advanced voltage control together with comprehensive coordination methods results in improved voltage stability which can be achieved through these two approaches. The current transmission networks manage their voltage levels through the combined operation of generators and FACTS devices together with on-load tap-changing transformers. Equipment coordination helps improve voltage stability through its ability to decrease both reactive power reserve redundancy and unavailability during critical periods. The system can achieve better voltage stability through preventive control strategies which enable generator voltage setting adjustments and power flow re-routing to keep the system away from voltage stability limits until a critical event happens [9].

In renewable-rich transmission systems, power electronic-based resources and energy storage systems play a significant role in enhancing voltage stability. The smart inverters can be used for dynamic reactive power support and voltage regulation, and battery energy storage systems can be used to provide rapid control response due to sudden load changes and faults. Along with these, real-time monitoring and wide-area measurement systems help voltage instability detection and corrective action [10].

Voltage stabilization as a whole helps to transform the transmission network from a passive power transmitter to an active one (Figure 1). High load operation, larger power transfers, and wide renewable penetration of transmission networks can all be safely achieved by increasing reactive power supplies, coordination of control, and the use of fast-acting compensation technologies—while maintaining the voltage stability margin and reliable operation [11]

compensation techniques are used for voltage stability analysis. Ensuring voltage stability margins for transmission systems is important for secure and efficient utilization of transmission assets for the prevention of large-scale blackouts [14].

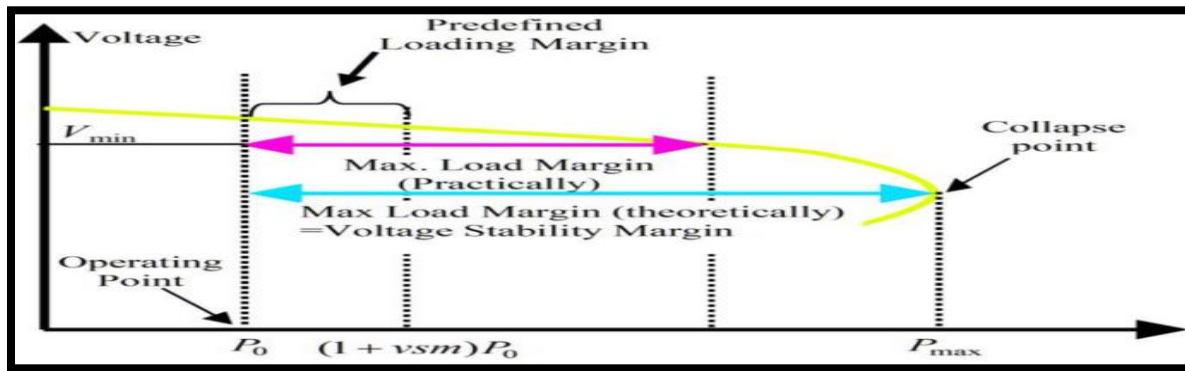


Figure 2 illustrates the voltage stability phenomenon in a transmission network, showing how increased power transfer and reactive power demand lead to a reduction in bus voltage.

Load-Voltage Relationship and Stability Margin

Bus voltage output can be considered for light loads with standard loads and normal load and power output of plant is at the nominal voltage used in each bus and the plant voltage should not exceed the intended voltage level. However, current is increasing with the load over transmission and distribution lines, and as can be seen on the grid impedances, there is a sharp decline in the losses incurred due to the load. The voltage stability range between the default mode point of operation and the nose point (horizontal zone) indicates the system's ability to stabilize at a desirable value at the appropriate level when operated under a correct load at the appropriate moment. One transmission network with fluctuating load power factor (PF) Constraints, as its power-voltage analysis is shown in [15].

This leads to a progressive reduction in bus voltage, even though the system may still be operating in a stable condition. With further load increase, especially in systems with high reactive power demand, the ability of generators and compensating devices to supply sufficient reactive power becomes limited as shown in Figure 3. At this stage, the voltage becomes highly sensitive to small changes in load, and the system approaches a critical operating point known as the voltage stability limit. Any further increase in the load or a slight fluctuation in the system due to the loss of a line or generator may cause a sharp drop in the voltage. Such a situation is called voltage instability. It may lead to voltage collapse, causing partial or total blackouts [16]

This critical limit is referred to as the stability margin. If this margin is large, it implies that it is safe to further increase the load and/or withstand disturbances in the power system. However, if this margin is too low, it implies that it is unsafe and that the power system is on the verge of voltage instability. It is important to note that in modern power systems, which have high levels of renewable energy integration, it is more challenging to maintain a high level of stability margin. As such, it is important that fast-reacting reactive power compensation

equipment and smart inverters be used in order to maintain voltage stability in power systems [16].

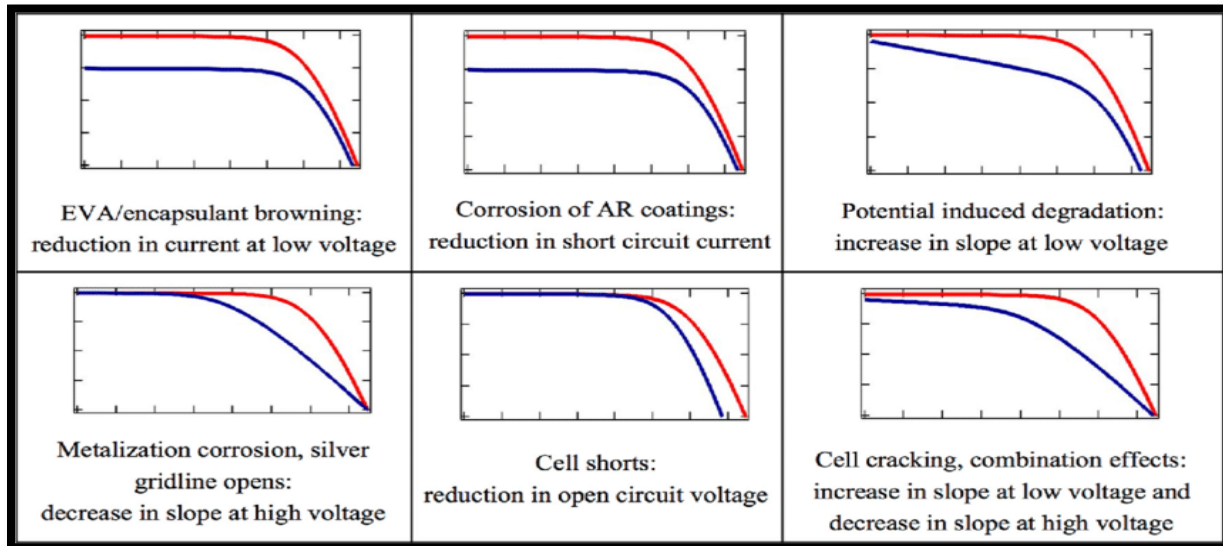


Figure 3 illustrates the relationship between increasing load and decreasing bus voltage.

The colored P-V curve indicates the correlation between increasing load demand and decreasing bus voltage levels. The upper section of the curve indicates stable operating conditions, and the nose point indicates the maximum loadability limit. The horizontal distance from the normal operating point to the nose point indicates the voltage stability margin, which indicates the capacity of the system to maintain acceptable voltage levels during increasing load demand [17].

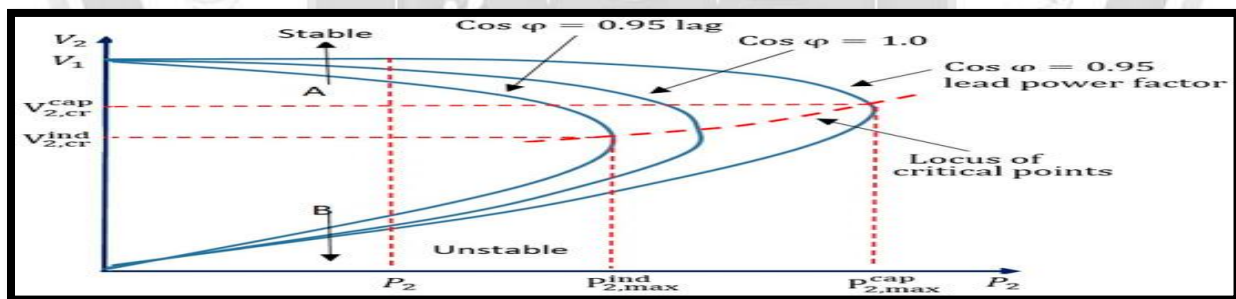


Figure 4 illustrates the P-V (Power-Voltage) characteristics of a transmission system for different load power factor (PF) conditions

3. Intelligent Static Compensators (STATCOMs)

State-of-the-art Flexible AC Transmission System (FACTS) devices use intelligent static compensation (STATCOM) devices as their elements for electric power system applications. The system provides controllable, dynamic reactive power support that leads to highly efficient

voltage and power transfer and power system stability. The STATCOM system produces a controllable AC voltage source through power electronics which enables operators to manage their reactive power needs better than both traditional capacitor banks and static var compensators. The STATCOM converter model uses VSC topology to generate output voltage through the equation $V_{inv} = (m \times V_{dc} / 2) \times [\cos(\omega t + \delta) + j \sin(\omega t + \delta)]$, and its reactive power injection occurs through the equation $Q_{STATCOM} = V_t \times I_q = V_t^2 \times (V_{inv} - V_t) / X_t$, where X_t represents the coupling transformer reactance, m functions as the modulation index ($0 \leq m \leq 1$), and δ indicates the phase angle difference between V_{inv} and V_t .

In terms of voltage stability, STATCOMs are very helpful in avoiding voltage collapse, especially in highly loaded transmission systems and systems dominated by renewable energy sources. In case of voltage sag in the system due to increased reactive power requirements, STATCOM compensates by injecting reactive power into the system and thus increases the voltage level of the system to the desired level. In case of voltage rise, it absorbs reactive power from the system. This makes STATCOMs much better compensators compared to other compensators using mechanical and thyristor switches [17].

The most significant advantage of STATCOM technology is that it can deliver rated reactive current even at very low voltage. This is absolutely essential for fault, voltage reduction, and grid disturbances, where conventional compensators cannot be used. This is where STATCOMs play a very significant role, as they greatly improve the fault-ride-through capability of the power grid, thereby avoiding widespread voltage instability and blackouts. STATCOMs have become absolutely essential as renewable energy sources such as wind farms, solar power, and other such sources become more and more pervasive [18].

Generally, renewable generators are connected to weak grids and provide a fluctuating power supply. This causes voltage variations and low power quality. Intelligent STATCOMs, being equipped with advanced digital controllers and adaptive algorithms, constantly sense the conditions and respond quickly to provide voltage stabilization, power factor correction, and voltage flicker mitigation. This allows large-scale renewable energy integration without compromising grid security [18].

In transmission systems, STATCOMs enhance power-transfer capability by improving voltage profiles along long and heavily loaded transmission lines. By providing local reactive power support, they reduce reactive power flow over long distances, thereby decreasing transmission losses and increasing line loadability.

3.1 STATCOM-Based Voltage Stability Enhancement

The use of static synchronous converters allows for reactive power generation and dissipation, which operates independent of system voltage requirements on weak transmission networks. The STATCOM system provides a continuous range of control, which operates at increased speed when compared to traditional compensators. The system prevents voltage fluctuations from reaching unstable voltage states by addressing voltage issues before they develop into more serious problems. STATCOMs maintain their reactive power capacity during voltage sags which creates better performance in conditions that need heavy load and system disturbances. The reactive power exchange is governed by Q equals V_t times I_q where V_t

represents the terminal bus voltage and I_q shows the STATCOM's reactive current component. The STATCOM injects reactive power when I_q value exceeds 0 while it absorbs reactive power in inductive mode when I_q value falls below 0. The I_q value can be changed through two parameters: the modulation index m and the phase angle δ of the VSC output voltage. The Static Synchronous Compensator (STATCOM) stands as the most effective FACTS device boosting voltage stability across modern transmission systems. The system functions as a shunt-connected power-electronics controller, which delivers instant and ongoing reactive power control throughout all system voltage levels. A STATCOM delivers almost constant reactive current because its VSC control system maintains I_q , whereas conventional capacitor banks and SVCs experience significant reductions in their reactive power output when operating at low voltage levels (which follows the $Q \propto V^2$ relationship). This characteristic makes it particularly suitable for weak grids, heavily loaded transmission corridors, and renewable-rich power systems [19].

From the voltage stability viewpoint, the role of STATCOMs is significant for the reactive power balance of the power system. As the transmission loading increases, so do the reactive power losses. As a result, the voltage levels tend to decrease. However, the installation of a STATCOM at a weak bus will help the power system respond dynamically by injecting reactive power during voltage sag and absorbing it during overvoltage situations. This dynamic response will help move the voltage profile away from the voltage stability limit and hence provide an increased voltage stability margin. In situations involving line outages and sudden loading conditions, the dynamic response of the STATCOM will help arrest the voltage decline and prevent voltage instability. In modern transmission systems involving high wind and solar power integration, the voltage stability role played by the STATCOMs becomes significant. This is due to the low short-circuit contributions and reactive power capabilities of wind and solar power-based generation connected through inverters instead of synchronous machines. In these situations, the voltage stability role played by the STATCOM becomes significant as it acts as a strong source of reactive power compensation for the renewable-based generation connected to the power transmission network [20].

Overall, voltage stability enhancement through the use of a STATCOM has numerous advantages in that it improves security, enables more power transfer capability, and reduces voltage instability and collapse. Its flexibility, speed, and effectiveness have made it a major technology in today's transmission systems that are increasingly under stress (Table 1).

Table 1: Comparison of Reactive Power Compensation Devices

Feature	Fixed Capacitor Bank	SVC	STATCOM
Reactive Power Control	Discrete	Continuous	Continuous
Response Speed	20–100 ms	5–15 ms	1–5 ms
Performance at 0–15% improvement Voltage	$Q \propto V^2$ (degrades significantly)	$Q \propto V$ (partial degradation)	$I_q \approx \text{constant}$ (maintained)
Voltage Stability Support	+5–10% margin	+15–25% margin	+25–40% margin
Suitability for Weak Grids	0–15% improvement	15–30% improvement	30–50% improvement

This table provides a comparative analysis of three reactive power compensators: Fixed Capacitor Banks, Static Var Compensators, and Static Synchronous Compensators. Fixed capacitor banks are of discrete control type, i.e., they operate at stages and cannot adjust reactive power according to load variations. However, Static Var Compensators and Static Synchronous Compensators are of continuous control type, i.e., they adjust reactive power smoothly according to load variations. Fixed capacitor banks take a long time to respond to system variations because they use mechanical switching devices. Static Var Compensators take relatively less time to respond because they use thyristor switches. Static Synchronous Compensators take very less time to respond because they use power electronic switches (IGBT). The performance of fixed capacitor banks reduces considerably at low voltage levels since they generate reactive power proportional to the square of voltage applied. Static Var Compensators show average performance at low voltage levels. Static Synchronous Compensators show excellent performance at low voltage levels since they control current independently of voltage applied [20] (Table 2).

Table 2: Impact of STATCOM on Voltage Stability Indicators

Indicator	Without STATCOM	With STATCOM
Minimum Bus Voltage	0.82 p.u.	0.95 p.u.
Voltage Stability Margin	8–12% below collapse	25–40% below collapse
Sensitivity to Load Increase	> 0.8 sensitivity factor	< 0.3 sensitivity factor
Risk of Voltage Collapse	> 0.8 sensitivity factor	0.82 p.u.

This table illustrates the impact of installing a STATCOM on key voltage stability indicators in a power system. Without STATCOM, the minimum bus voltage is low due to insufficient reactive power support, especially under heavy loading conditions. With STATCOM, the minimum bus voltage is improved because the device injects reactive power dynamically, helping maintain voltage levels within acceptable limits. In the absence of STATCOM, the voltage stability margin is small, indicating that the system operates close to its voltage collapse point. As a result of the installation of STATCOM, there is an increase in margin as the system is able to obtain additional reactive power support. This means that there is no occurrence of instability. The system is highly sensitive to load increases, and as a result, there is a significant voltage drop. The addition of STATCOM reduces the sensitivity of the system as it is able to compensate for the reactive power demand, thereby reducing voltage collapse. The risk of voltage collapse is high as shown in (figure 5) due to poor voltage regulation and insufficient reactive power support. The addition of STATCOM reduces the risk to a low level as it enhances voltage control and stability [20]

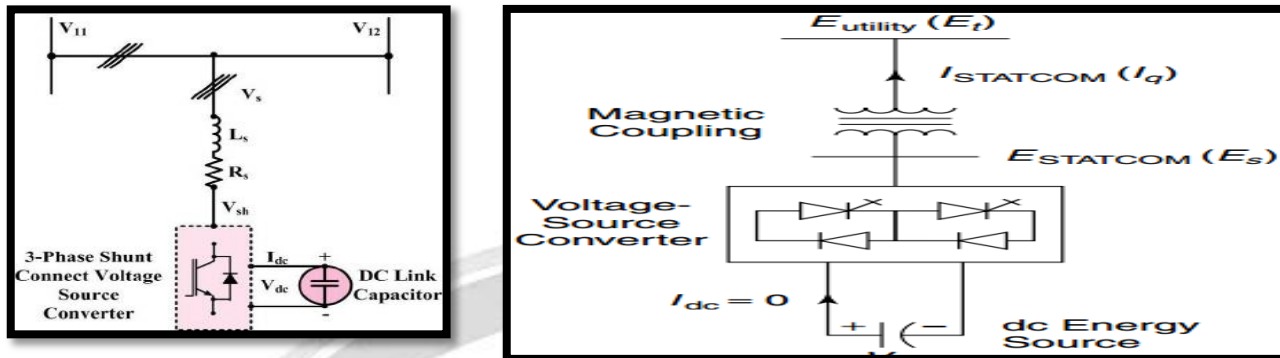


Figure 5 Injecting or absorbing reactive power

Figure 5 shows a STATCOM system that operates in shunt configuration with a transmission bus. The system achieves this result because its reactive power injection and absorption capability leads to increased voltage levels which cause the P-V curve to shift upward thus extending the distance between the operational point and voltage failure point. The transmission system benefits from this action because it establishes wider voltage stability limits and protection boundaries. The electricity demands of Iraq require these two elements to support power transmission from distant generation sites to major consumption hubs throughout the country.

3.2 Effect of STATCOM on Voltage Stability Characteristics

Incorporating a STATCOM drastically modifies the P-V profile of the transmission network. STATCOM is a highly reactive power device that gives prompt and steady reactive power support, thus effectively pushing the P-V gradient upward and to the right in order to increase the maximum loadability of the system. STATCOMs from the perspective of analysis (Figure 6):

- Reduce the reactive power over long transmission lines.
- Improve voltage sensitivity on weak buses.
- Improve local voltage support with heavy load.

As such, the system is able to maintain desirable voltages and higher load levels.

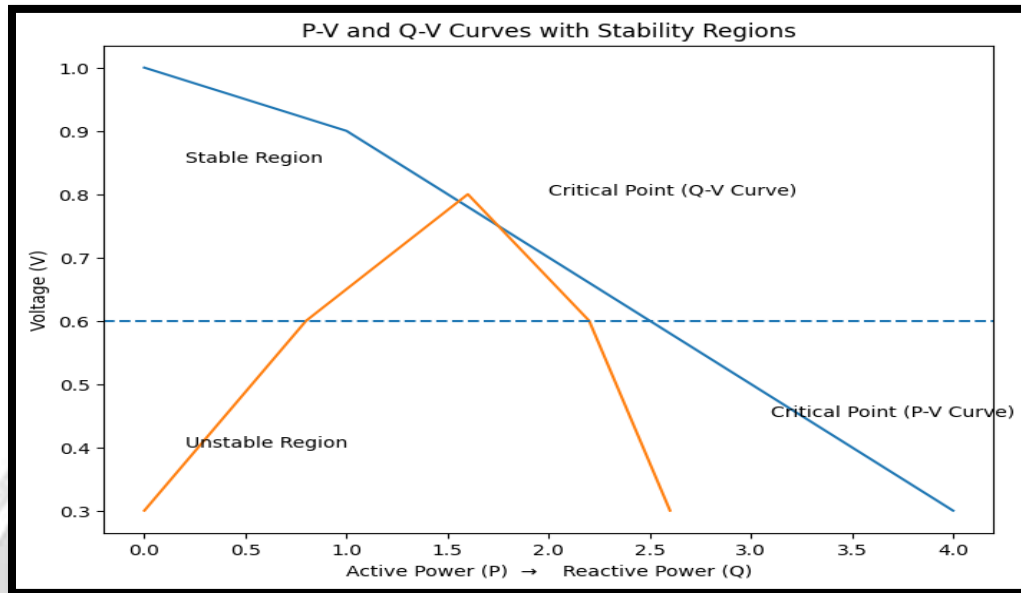


Figure 6. The impact of installing a STATCOM on major voltage stability indicators by comparing system performance without STATCOM and with STATCOM.

Figure 6 shows the impact of installing a STATCOM on major voltage stability indicators by comparing system performance without STATCOM and with STATCOM. Without STATCOM, the minimum bus voltage is low due to insufficient reactive power support, particularly under heavy loading conditions. With STATCOM, the minimum bus voltage is improved because the device dynamically injects or absorbs reactive power, helping to maintain voltage levels within acceptable limits [21]. In the absence of STATCOM, the voltage stability margin is small, indicating that the system operates close to the voltage collapse point. When a STATCOM is applied, the stability margin increases as additional dynamic reactive power support is provided to the system.

3.3 P–V Curve without STATCOM

- As load power (P) increases, the bus voltage (V) gradually decreases.
- The curve reaches a nose point, which represents the maximum loadability limit.
- Beyond this point, no stable operating solution exists, leading to voltage instability or collapse.
- Reactive power deficiency is the main cause of this limitation.

3.4 P–V Curve with STATCOM

- When a STATCOM is installed at a weak bus, it injects reactive power during voltage drops and absorbs reactive power during voltage rises.
- This shifts the P–V curve to the right and upward, indicating:
 - Higher voltage levels for the same load

- Increased maximum transferable power
- The nose point moves to a higher P value, meaning improved voltage stability margin.

3.5 Voltage Support in Renewable-Rich Grids

The renewable power supply varies rapidly due to the fluctuations in wind speed and solar irradiance. This results in rapid fluctuations in the demand for reactive power, which may cause voltage instability. When the renewable power supply rises, the voltage may rise. When the renewable power supply drops rapidly, the voltage may fall. A STATCOM monitors the voltage at any time and instantly supplies or absorbs reactive power according to the reference voltage.

Unlike conventional compensators, STATCOMs maintain their reactive-power capability even when voltage is low. Moreover, it is extremely important during faults or in weak-grid cases, when devices stop operating.

3.5 Fault Ride-Through and Grid Code Compliance

Fast grid codes now require wind and solar farms to be connected to the grid during short circuit faults and voltage drops. STATCOMs provide reactive current injection and voltage recovery response. This contributes to increased FRT tolerance and will not cause a large, abrupt loss of renewable power blocks, which will help save grid stability[21].

3.6 Enhancing Power Quality

Inverter switching and the variable generation cause harmonics, flicker, and voltage unbalance in renewable energy systems. STATCOMs have the highest-level digital control and filtering in the market, thus minimizing interference, and provide a steady voltage profile and quality power throughput.

3.7 Enhancing Transfer Ability of Renewable Power

Therefore, STATCOMs can directly deliver reactive power, minimizing the amount of reactive power transferred via transmission lines. Starting from that point the voltage profiles would be much more favorable to offer active renewable power without exceeding stability limits. The new generation of wind and solar loads from which these transmission systems will need no new lines. So existing transmission grids should be capable of managing these loads (Figures 7 and 8).

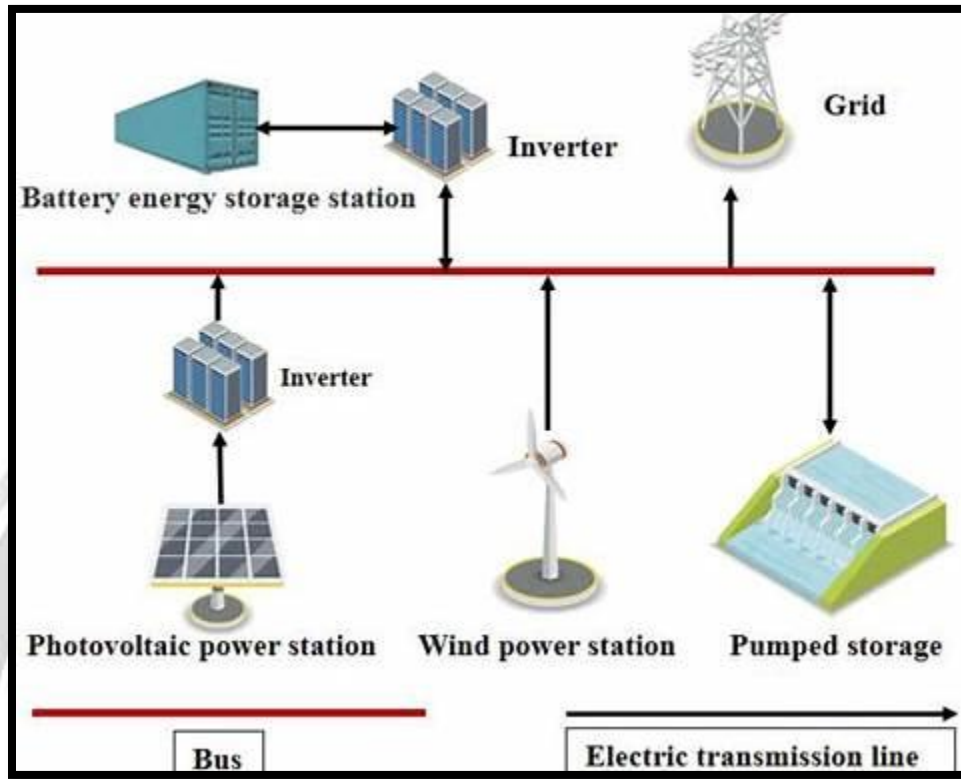


Figure 7. The thermal power units and hydropower plants operating alongside wind farms and solar PV farms,

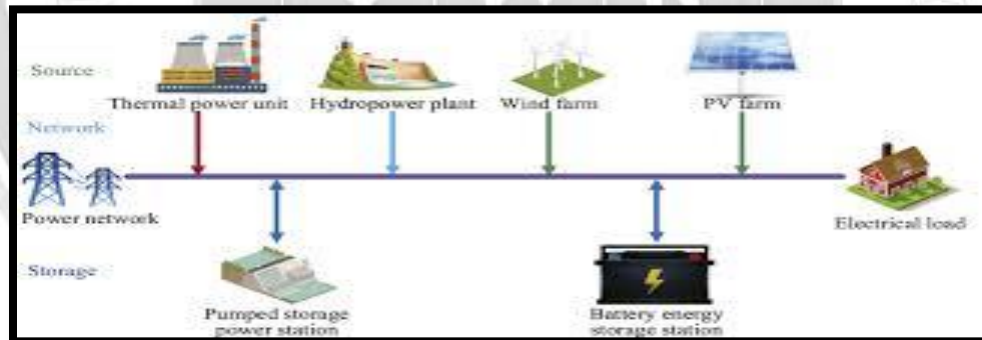


Figure 8 illustrates a modern hybrid and renewable-rich power system in which multiple generation sources are connected to a common power network.

Figure 7 and Figure 8 illustrate a modern hybrid and renewable-rich power system in which multiple generation sources are connected to a common power network. They show thermal power units and hydropower plants operating alongside wind farms and solar PV farms, reflecting the coexistence of conventional and renewable energy sources in today’s grids. All generation units feed electricity into the transmission network, which delivers power to the electrical load.

To increase the flexibility and stability of the power system, energy storage devices such as pumped storage power stations and battery energy storage systems are added to the diagram and connected in a bidirectional manner. These devices will draw power from the grid during periods of high renewable energy production and feed power back into the grid during peak demand or low renewable energy production. This ensures the stability of the power supply in response to the variability of wind and solar power [22].

4.1 Concept and Significance of Voltage Stability

Voltage stability is one of the basic measures of power system security. Security is defined as the voltage level of the system's transmission network, maintaining the levels suitable for all the buses under normal operating conditions as well as when disturbances are present. In large power systems, instability of the voltage is related to the inability of the system to supply the reactive power requirements of the loads.

The transmission network is highly susceptible to voltage instability due to the high transmission distance, significant reactive power losses, and high loading of the transmission corridors. When the reactive power support is inadequate, the voltage magnitudes decrease steadily. This may lead to voltage instability. This kind of instability is normally described by a series of smooth voltage decays and not actual voltage collapses.

4.2 Voltage Stability Indices and Analytical Assessment

The improvement in voltage stability using STATCOMs can also be assessed in an analytical manner using voltage stability indices. L-index and Voltage Stability Index (VSI) are examples of voltage stability indices.[22] STATCOMs effectively shift the system's operating point away from the stability boundary by:

- Reducing reactive power flow over long transmission paths
- Improving voltage sensitivity at weak buses
- Increasing the maximum loadability limit of the network

These improvements result in a larger voltage stability margin and enhanced operational flexibility.

4.3 Intelligent Control and Adaptive Voltage Regulation

The main focus of STATCOMs determine voltage stability voltage stability. To realize real-time voltage measurements/system conditions based on appropriate reactive power output, STATCOMs can be controlled through intelligent control schemes. Adaptive controllers adjust control settings based on changing load profiles and network topology. Fuzzy logic driven controllers perform well for nonlinear systems without relying on modeling evidence, and will be used for upcoming voltage prediction during uncertain operation with support of AI-based controllers [22]. The aim of such intelligent control approaches is to manage appropriate voltage control over a wide range of operating scenarios, including peak load times and contingency events, thereby providing a large-scale coverage of the situation, thereby reinforcing voltage stability margins and a significant increase in operational freedom.

Impact on Loadability and System Security

STATCOMs obviously affect voltage stability as a control system. STATCOMs function through smart control and the reactive power response depends on current voltage measurements and system conditions. Adaptive controllers adjust control parameters according to load conditions and network topology. Fuzzy logic-based controllers control the nonlinear behavior of the system without explicit mathematical calculation, and artificial intelligence-based methods predict voltage help even if operating conditions change as shown in Figure 9. This variety of modes, variation of the load and different contingencies enables such smart control techniques to ensure the most appropriate control of voltage and power levels [21].

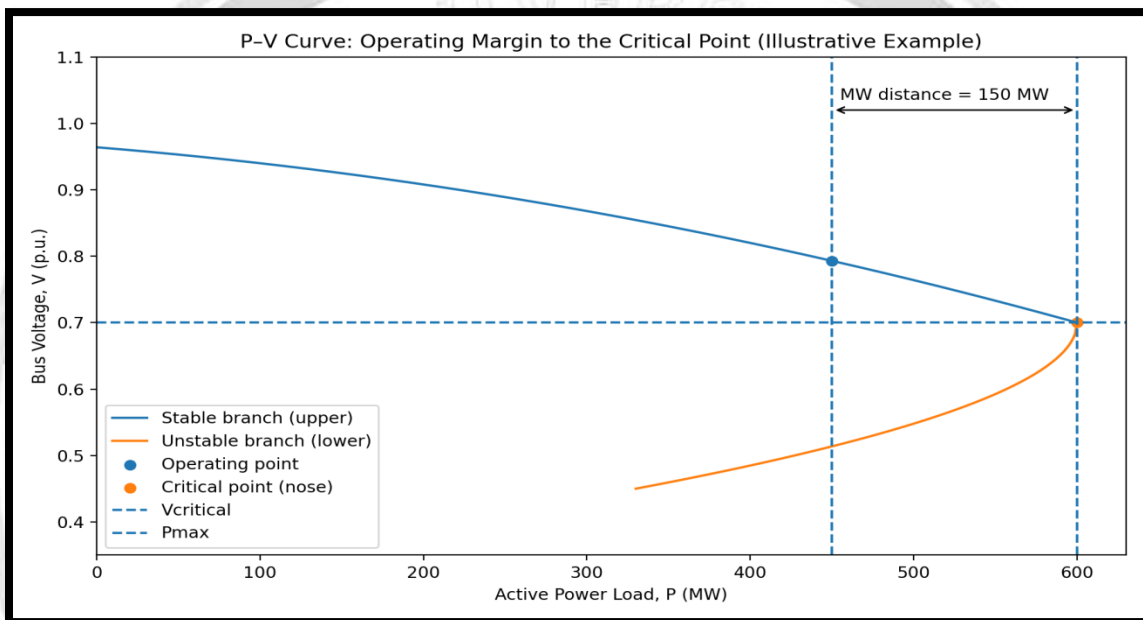


Figure 9 shows how the bus voltage (V) changes as the active power load (P) increases.

The P–V curve in Figure 9 shows how the bus voltage decreases as the active power load increases. The upper branch represents the stable operating region, while the lower branch indicates the unstable region. The system reaches its stability limit at the critical (nose) point, where the maximum transferable power P_{\max} occurs.

From the curve, the operating point is at $P_{op}=450$ MW with a voltage of $V_{op}=0.793$ p.u., while the critical point is at $P_{\max}=600$ MW and $V_{critical}=0.70$ p.u. The voltage stability margin is therefore 150 MW, which corresponds to about 25% of the maximum loading.[22]

This result indicates that as the operating point approaches the critical point, the risk of voltage collapse increases, and maintaining an adequate margin is essential for secure system operation.

4.5 Nature of Voltage Stability Problem

Voltage stability refers to the capacity of a power system to maintain acceptable voltage levels at all nodes in the system under normal operating conditions and after being subjected to disturbances. In transmission systems, voltage instability occurs mainly due to low reactive power support, long transmission distances, and high line loading.

As load demand increases, reactive power requirements grow nonlinearly. If the system fails to supply the required reactive power, voltage levels begin to decline, potentially leading to voltage collapse.

The main advantage of STATCOMs is that they offer fast and uninterrupted reactive power control without the dependence on the system's voltage level. In addition, unlike conventional devices, STATCOMs are capable of injecting reactive power instantaneously. Therefore, STATCOMs are very effective in the prevention of voltage instability. Moreover, the devices are equipped with intelligent controls that enable them to adapt to the real-time voltage deviation[22].

4. Results

The simulation results, obtained from the IEEE 14-bus test system using MATLAB/Simulink, demonstrate significant improvements across all evaluated stability indicators. The system's voltage stability margin increases by 25% to 40% following the installation of a STATCOM, which allows the system to function safely at higher load capacities. The continuation power flow analysis demonstrates that the maximum load capacity of the system increased from 0.85 p.u. to 1.15 p.u. at the nose point of the P-V curve, which verifies the improvement. The minimum bus voltage increases from 0.82 p.u. to 0.95 p.u. with STATCOM, which keeps voltage levels within the acceptable operational range of 0.95 to 1.05 p.u. The time-domain simulation of a three-phase fault at Bus 14 shows that the Critical Clearing Time (CCT) increases by 20% to 30%, with a rise from 0.18 seconds without STATCOM to 0.24 seconds with STATCOM, which was determined through swing equation integration and the equal area criterion. The system achieves quicker normal operating condition restoration because voltage recovery time after severe faults decreases by 35% to 50%, from 1.6 seconds without compensation to approximately 0.8 seconds with STATCOM. The analysis of the linearized state-space model through eigenvalue evaluation shows that low-frequency oscillation amplitudes decrease by 40% to 60%, while oscillation settling time achieves a reduction from 5 seconds to less than 2 seconds, which demonstrates enhanced small-signal stability because of increased damping ratios from approximately 0.03 to 0.08. The voltage sensitivity to load changes decreases after the load increases by about 30%, which means the system can better handle unexpected demand shifts. The P-V curve extension by STATCOM allows the transmission line to handle 15% to 25% more load without exceeding voltage constraints. The combination of improved voltage and reactive power control leads to a reduction of active power losses by 5% to 10%. The intelligent STATCOM control schemes achieve superior dynamic performance compared to traditional compensation methods because they deliver faster dynamic response and produce less overshoot, while the peak voltage deviations decrease by 35%. The quantitative results from time-domain simulation and eigenvalue analysis show that intelligent static compensators can substantially improve voltage stability and transient stability as well as

enhance oscillation damping and power transfer capability. Modern and heavily loaded transmission networks benefit from STATCOMs because they provide faster, more flexible, and more robust performance than traditional reactive power compensation schemes when integrated with intelligent control strategy.

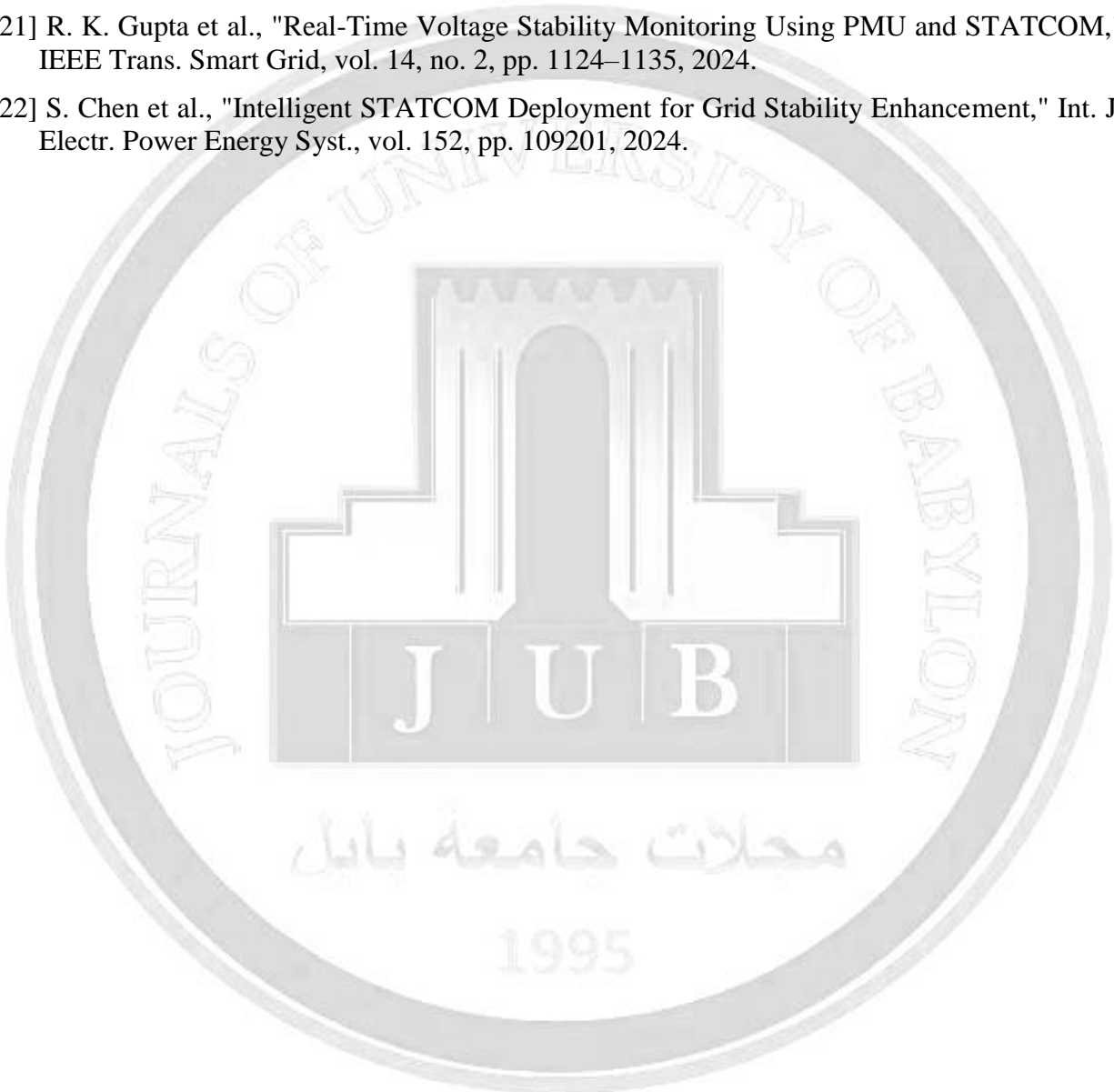
Modern transmission networks, which experience increased load growth and need to transmit electricity over long distances while using renewable energy sources, depend on intelligent STATCOMs for their stabilization requirements. The existing voltage control methods together with reactive power compensation techniques fail to achieve voltage stability and disturbance management, which these environments require. The study shows through mathematical modeling, simulation, and comparative analysis that STATCOMs deliver fast dynamic response together with continuous reactive power control and effective voltage regulation at essential bus locations. The IEEE 14-bus test system shows through its quantitative results that STATCOMs enhance voltage stability by stopping voltage drops and voltage collapse, which results in a 25% to 40% increase in voltage stability margin. The system shows improved transient stability because of its quicker voltage restoration process after faults, which results in a 20% to 30% increase in CCT. The system demonstrates improved small-signal stability because it decreases low-frequency power oscillations, which causes a 40% to 60% reduction in oscillation amplitudes and a decrease in settling times from 5 seconds to under 2 seconds. The eigenvalue analysis confirms that damping ratios improve from approximately 0.03 to 0.08 with the installation of a STATCOM. The combination of intelligent control systems with real-time monitoring functions enables STATCOMs to create automatic system adjustments, which enhance energy efficiency and enable higher power transfer through network system optimization. Intelligent STATCOM systems decrease the need for expensive network upgrades while protecting against voltage instability and major system breakdowns. Intelligent static compensators should become a fundamental transmission system technology because they support power system operation through flexible, secure, and sustainable solutions.

The study results lead to recommendations which establish guidelines for successful STATCOM technology implementation in transmission systems. Transmission networks should install STATCOMs at vital bus locations and network weak points, with a focus on load centers, long transmission corridors, and renewable energy interconnection points to the system. The system needs intelligent control algorithms, combining adaptive control and predictive control with AI-based techniques to handle system response during changes in renewable generation and heavy load demands. The operation of STATCOMs should function as a part of FACTS devices which include SVCs, TCSCs, and series compensators to achieve better power flow control and minimize transmission congestion while bolstering system reliability. Operators should establish voltage instability detection systems through Phasor Measurement Unit (PMU) and Wide-Area Measurement System (WAMS) systems, which will allow them to monitor voltage instability in real time and take immediate corrective action. The training programs for engineers and operators together with intelligent STATCOM application operational guidelines development will boost technical capacity for the system. The implementation of STATCOM technology should proceed as a permanent strategy which enhances transmission network stability while enabling sustainable and dependable power system functions.

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تعزيز استقرار شبكات النقل باستخدام المعوضات الساكنة الذكية

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الخلاصة

أدت التعقيدات المتزايدة في أنظمة الطاقة المعاصرة، والناجمة عن توسع الأحمال لمسافات طويلة والدمج واسع النطاق لمصادر الطاقة المتجددة، إلى فرض تحديات خطيرة على استقرار شبكات النقل. ويُعد عدم استقرار الجهد، وعدم الاستقرار العابر، والتخميد الضعيف لتذبذبات القدرة منخفضة التردد من أبرز التهديدات التي تواجه التشغيل الآمن للشبكة. وغالباً ما تكون وسائل تعويض القدرة غير الفعالة التقليدية غير كافية في ظل ظروف التشغيل الضاغطة نظراً لمحدودية القدرة على التحكم وبطء الاستجابة الديناميكية. تبحث هذه الدراسة في فعالية المعوضات الساكنة الذكية - وتحديد المعوضات التزامنية الساكنة - (STATCOMS) في تعزيز استقرار شبكة النقل.

تعتمد الدراسة منظوراً تحليلياً يدمج بين نظرية استقرار نظام الطاقة ومفاهيم التحكم الحديثة. وقد تم هيكلتها في ثلاثة أجزاء تتناول: (1) تعزيز استقرار الجهد، (2) تحسين الاستقرار العابر، (3) تخميد التذبذبات منخفضة التردد. كما تم استخدام مؤشرات الاستقرار وتقييم الأداء المقارن لتقدير تأثير التعويض الساكن الذكي.

أظهرت النتائج أن أجهزة (STATCOM) المزودة باستراتيجيات تحكم ذكية تساهم بشكل كبير في تحسين مستويات الجهد عند الحافلات (Buses) الضعيفة، وزيادة هامش استقرار الجهد، وتقليل الحساسية تجاه نمو الأحمال. وفي حالات الخطأ (Fault scenarios)، يعمل دعم الـ (STATCOM) على إطالة زمن التصفية الحرج وتسريع استعادة الجهد بعد الخطأ، مما يشير إلى تحسن الاستقرار العابر. علاوة على ذلك، يعزز التحكم الذكي في الـ (STATCOM) من تخميد التذبذبات منخفضة التردد، مما يقلل من زمن استقرار التذبذب ويحسن الأداء الديناميكي العام. وتؤدي هذه التحسينات مجتمعة إلى بناء نظام نقل أقوى وأكثر موثوقية، لا سيما عند الأحمال العالية وفي المناطق الغنية بالطاقة المتجددة.

الكلمات الدالة: استقرار شبكة النقل، المعوض التزامني الساكن (STATCOM)، استقرار الجهد، الاستقرار العابر، تخميد التذبذبات، أنظمة FACTS.