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Dynamic Stability and Damping Oscillation Control of Turbo Generator Using Facts Controllers

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ABSTRACT
Ensuring the stability of power systems during sudden disturbances remains a vital challenge, especially in large interconnected grids where electromechanical oscillations can threaten synchronized operation. This study explores the dynamic behavior of a synchronous turbo generator under such transient conditions, using advanced simulation techniques to assess the impact of three widely used FACTS controllers: the Static Var Compensator (SVC), Thyristor-Controlled Series Capacitor (TCSC), and Static Synchronous Compensator (STATCOM). A detailed nonlinear simulation framework was built in MATLAB to capture the generator's swing dynamics and evaluate its response under load disturbance. The system's performance was analyzed across essential parameters related to stability and damping. Among the three controllers, STATCOM emerged as the most effective. STATCOM was able to limit the initial deviation of the rotor angle more effectively, which is a critical factor in preventing loss of synchronism during disturbances. The TCSC also showed promising performance in damping ratio and settling time, while the SVC lagged behind with slower damping characteristics by damping ratio and longer settling time. Rotor angle stability margin was maximized with STATCOM, reducing the risk of cascading instability in multi-machine systems. These findings highlight the effectiveness of FACTS devices particularly STATCOM in enhancing the dynamic stability of generators during transient events. The study offers practical insights for power system operators and grid planners looking to strengthen grid resilience through advanced damping strategies, especially in the context of evolving smart grid infrastructures.

Keywords: *Turbo Generator, FACTS Controllers, Dynamic Stability, Damping Oscillation*

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I. INTRODUCTION

The stability of electrical power systems plays a critical role in guaranteeing a continuous and reliable electricity supply, particularly in today's evolving energy landscape marked by rising system complexity, growing load demand, and the widespread integration of renewable energy sources. A key aspect of power system stability is dynamic stability, which pertains to the system's ability to maintain synchronism and effectively damp out electromechanical oscillations after experiencing small disturbances such as minor load fluctuations or routine switching operations [1], [2]. As modern power systems increasingly shift toward decentralized and renewable-based architectures, preserving dynamic stability has become more challenging yet more essential than ever [3]. If left inadequately damped, electromechanical oscillations can persist in the power system, potentially causing sustained power swings, voltage instability, and, in severe cases, cascading failures that threaten overall grid reliability.

Conventional Power System Stabilizers (PSS) have played a crucial role in improving the damping of low-frequency oscillations by modulating the excitation of synchronous generators. This approach enhances system stability, especially after small disturbances or changes in load demand. However, conventional PSSs are typically designed with fixed parameters that are tuned for specific operating conditions [4]. As a result, their effectiveness can degrade significantly under varying grid scenarios, such as those introduced by high renewable energy penetration, dynamic load behaviors, and evolving grid topologies. These limitations highlight the need for more adaptive and intelligent stabilization strategies that can respond to real-time changes in system dynamics and maintain robust performance across a wide range of conditions [5], [6]. To overcome the inherent limitations of traditional power system components, Flexible AC Transmission System (FACTS) technologies have become vital tools in modern grid operations [7]. These devices enhance system performance by regulating power flow, stabilizing voltage levels, and significantly improving both transient and dynamic stability. Notably, devices such as the Static VAR Compensator (SVC), Thyristor Controlled Series Capacitor (TCSC), and Static Synchronous Compensator (STATCOM) have gained widespread application. Their appeal lies in their ability to provide real-time control, deliver rapid dynamic response, and adapt effectively to changing operating conditions, making them especially suitable for today's increasingly complex and renewable-integrated power systems [8],[9]. As modern power grids evolve with increasing levels of deregulation and renewable energy integration, the importance of FACTS (Flexible AC Transmission System) devices in ensuring adequate oscillation damping and dynamic stability has grown significantly. Recent research highlights that when these devices are coordinated and optimally tuned particularly using advanced computational methods or intelligent algorithms, they can effectively enhance the damping of both local and inter-area oscillations [7], [10].

Power system generators are naturally prone to electromechanical oscillations and transient instability, especially after sudden disturbances like load fluctuations, short circuits, or switching events. These disturbances, if not adequately managed, can disrupt the delicate balance of the grid. While conventional damping tools such as Power System Stabilizers (PSS) have been widely used, their effectiveness is often limited in today's increasingly nonlinear and fast-changing operating conditions. Inadequate damping of low-frequency oscillations can lead to a cascade of issues ranging from generator desynchronization to serious equipment damage and even large-scale blackouts. With modern power networks facing growing pressures from renewable energy integration, high load variability, and the push for reliability, it has become imperative to strengthen system damping. Flexible AC Transmission System (FACTS) devices, with their fast-acting, real-time control capabilities, offer a powerful solution for enhancing system stability and ensuring resilient, uninterrupted power delivery in this evolving energy landscape.

While most previous research has primarily focused on steady-state conditions or small-signal analysis of FACTS devices, there has been limited attention given to their dynamic behavior under identical nonlinear disturbances. This study addresses that gap by developing and simulating a dynamic damping control strategy for a turbo generator using FACTS controllers (SVC, TCSC, STATCOM) and evaluate their performance under disturbance conditions, offering valuable insights into the real-world performance of these controllers and the systems under study.

II. MATERIALS AND METHOD

The methodology approach for this study is describe by the modelling environment, system configuration, controller designs, and simulation procedures used to analyze and compare the performance of SVC, TCSC, and STATCOM in damping electromechanical oscillations of a single-machine infinite bus (SMIB) turbo generator under transient conditions.

1. System Modelling

A. Mathematical Modelling of the Turbo-Generator

A classical single machine infinite busSMIB configuration was used to represent a large-scale power generation unit connected to a strong grid (infinite bus). The generator's rotor dynamics was modeled using the classical second order swing equation for transient stability. [11]

$$\frac{d^2\delta}{dt^2} = \frac{\omega_b}{2H}\left(P_m - P_e - D\frac{d\delta}{dt}\right) \quad (1)$$

Where:

δ = is the rotor angle (rad)

ω_b = is the bae angular frequency (rad/s)

H = inertial constant (s)

D = is the damping factor (pu)

P_m = is the mechanical power input (pu)

P_e = is the electrical power output (pu)

The electrical output power P_e is given by;

$$P_e = \frac{EV}{X_{eq}}\sin(\delta) \quad (2)$$

B. Electrical Dynamics (Parks Transformation Model)

Using the two-axis d-q references frame model, the internal voltage equation in the rotor reference frame is represented as:[12].

$$\frac{d\psi_d}{dt} = v_d - R_s i_d + \omega_r \psi_q \quad (3)$$

$\frac{d\psi_q}{dt} = v_q - R_s i_q + \omega_r \psi_d$ (4)

Where;

ψ_d , ψ_q = flux linkages

v_d , v_q = stator voltages in d-q frame

i_d , i_q = stator currents

R_s = stator resistance

ω_r = rotor angular speed

2. FACTS Controller Modelling

A. Static VAR Compensator (SVC)

The SVC was modeled as a variable shunt susceptance, B_{SVC} that modifies the bus voltage magnitude to support reactive power [13] [14].

$Q_{SVC} = V^2 B_{SVC}$ (5)

$B_{SVC}(s) = \frac{K_{SVC}}{T_{SVC}\, s+1}\left(V_{ref} + V\right)$

Where:

K_{SVC} = proportional gain

T_{SVC} = time constant

V_{ref} = reference voltage

V = Bus Voltage

B. Thyristor Controlled Series Capacitor (TCS)

The TCSC was modeled as a variable capacitive reactance X_{tCSC} in series with the line.

$X'_{line} = X_l + X_{tcsc}(t)$ (6)

$X_{tcsc}(s) = \frac{K_{tcsc}}{T_{tcsc}S+1}\left(\delta_{ref} - \delta\right)$ (7)

Where:

K_{tcsc} = control gain

T_{tcsc} = TCSC controller time constant

δ_{ref} = rotor angle reference

C. STACOM

STACOM was modeled as a controlled voltage source injecting or absorbing reactive current to regulate voltage.

$I_{stat} = \frac{V_{conv} - V_{bus}}{jX_{stat}}$ (8)

$V_{conv}(s) = \frac{K_{stat}}{T_{stat}S+1}\left(V_{ref} - V\right)$ (9)

Where:

K_{stat} = STATCOM gain

T_{stat} = Time constant

V_{conv} = conventional voltage magnitude

3. Control Law Implementation

Al three FACTS devices were modeled as first order systems with PI-like response dynamics. The discrete time approximation in MATLAB is: [15].

$u(k+1) = u(k) + \frac{dt}{T}\left(-u(k) + k \cdot e(k)\right)$ (10)

Where:

$u(k)$ = control output

$e(k)$ =control error

k = controller gain

T = Time constant

dt = simulation time step

Each FACTS controller was modeled and integrated individually into the SMIB system to analyze its effectiveness.

III. RESULTS AND DISCUSSION

Table 1: Simulation Analysis Parameters

Controller/Turbo System	Parameters	Values/Units
SVC	Proportional Gain	50 (pu)
	Time Constant	0.05 seconds
TCSC	Proportional Gain	30 (pu)
	Time Constant	0.10 seconds
STATCOM	Proportional Gain	60 (pu)
	Time Constant	0.03 seconds
TurboGenerator	Rated Power	100 MVA
	Rated Line Voltage	13.8kV
	System Frequency	50 Hz
	Synchronous Speed	314.16 rad/s
	Inertia Constant	3.5 s
	Damping Coefficient	0.02(pu)

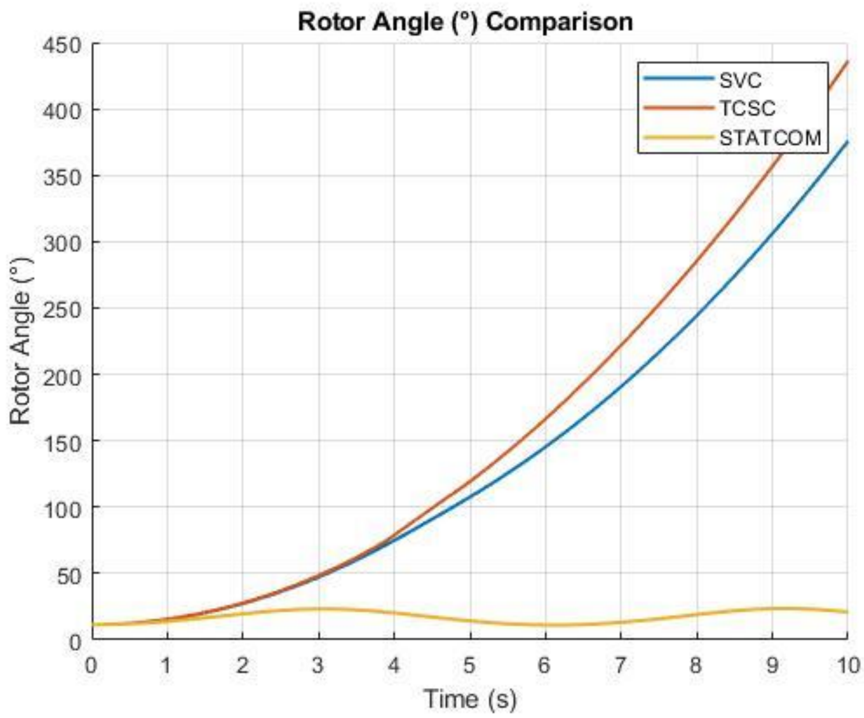

Figure 1: Rotor Angle Comparison

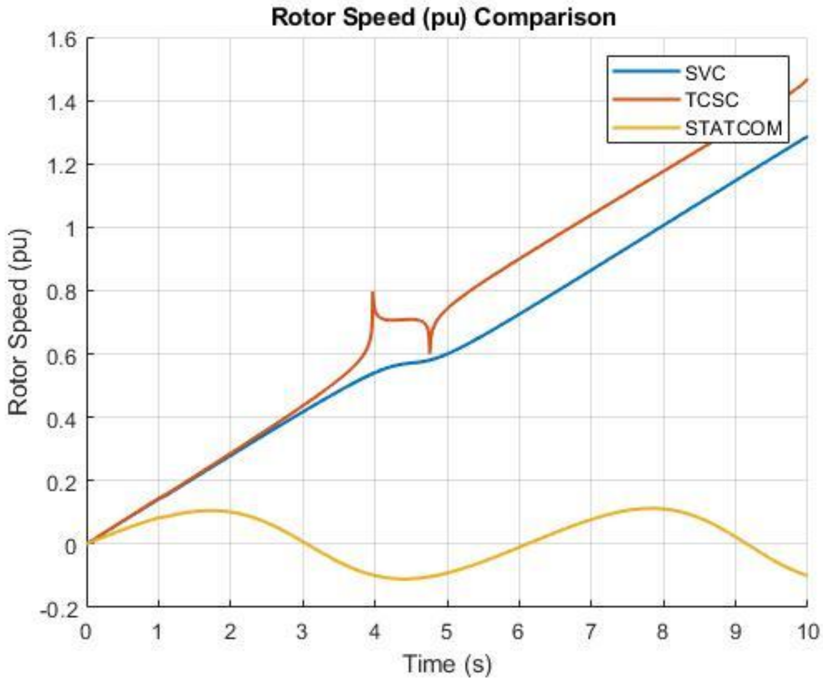

Figure 2: Rotor Speed Comparison

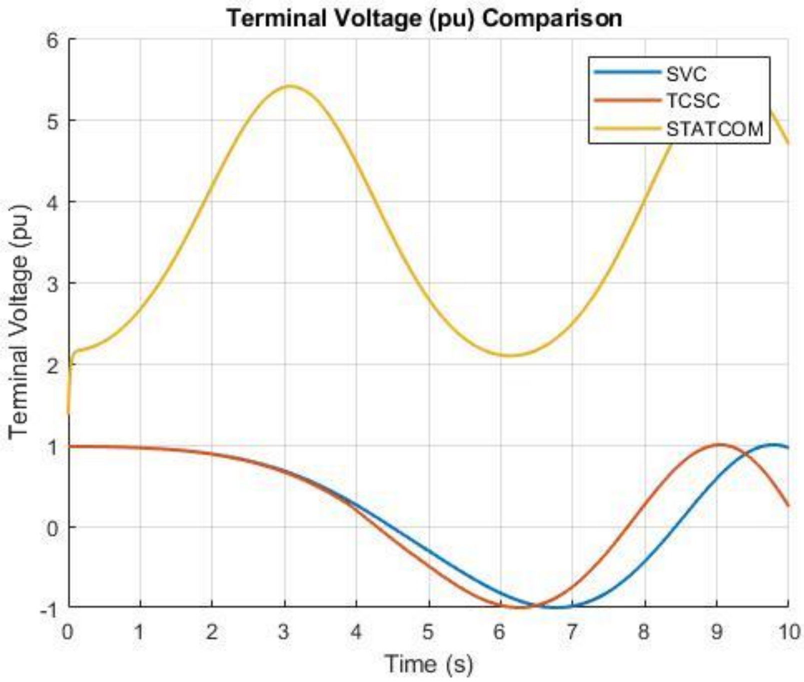

Figure 3: Terminal Voltage Comparison

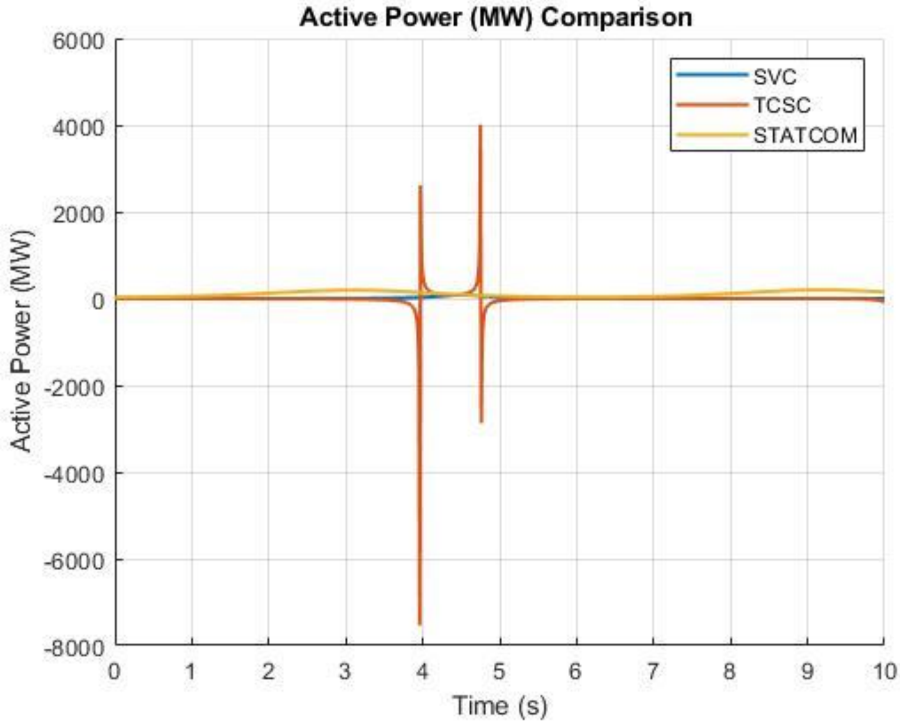

Figure 4: Active Power Comparison

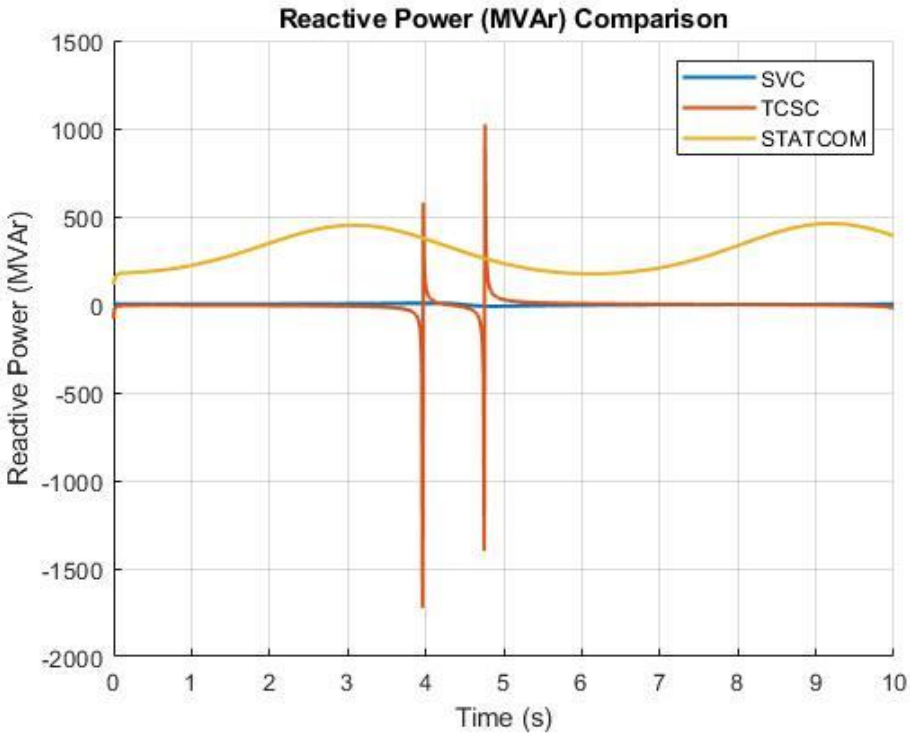

Figure 5: Reactive Power Comparison

IV. DISCUSSION

Fig. 1. shows Rotor angle deviation as a direct indicator of synchronism stability. The STATCOM demonstrated the lowest rotor angle deviation, indicating its superior capability in limiting rotor excursions through rapid voltage regulation. SVC followed, due to dynamic line reactance modulation, while TCSC showed the highest deviation, implying slower dynamic response due to its shunt nature and lower control bandwidth. Fig. 2. shows Rotor speed deviation which reflects how the generator's rotor accelerates or

decelerates during transients. STATCOM maintained the smallest deviation, suggesting effective damping and frequency regulation. SVC also limited speed deviations, while TCSC again performed weakest, correlating with its higher angular instability. Fig. 3. Shows maximum deviation from nominal voltage at generator terminal. SVC shows moderate improvement, TCSC shows better voltage support. While STATCOM shows best performance due to direct voltage regulation capability. Fig. 4. indicates how much real power the generator delivers under stress. TCSC achieved the highest output, due to its series compensation, which effectively reduces net line reactance and boosts power transfer. SVC and STATCOM are slightly lower, with STATCOM slightly lagging due to its reactive power focus rather than impedance control. Fig. 5. Shows Reactive power support which is critical for voltage control and system strength. TCSC provided the best, owing to its indirect modulation of power flow. SVC shows fairly, while STATCOM, despite its fast response, contributed effective considering its, possibly tighter voltage setpoint adherence reducing the need for reactive oversupply.

V. CONCLUSION

This study effectively models and simulates the nonlinear dynamic response of a turbo generator system subjected to external disturbances, with a focus on enhancing system damping using SVC, TCSC, and STATCOM controllers. The simulation results clearly demonstrate the impact of each controller;the findings suggest that STATCOM is better suited for high-performance dynamic stability enhancement in modern transmission networks. These results not only confirm the theoretical advantages of using FACTS devices for improving transient stability, but also offer valuable, real-world guidance for power utilities looking to make informed decisions about the most effective deployment of these technologies.

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