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RESEARCH ARTICLE

Enhanced Transient Stability in Power Systems via Intelligent Control of SVCs Using Neural Networks

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Abstract

This paper investigates the application of Static VAR Compensators (SVCs) with neural network control to enhance power system grid stability, particularly in multi-source energy systems. SVCs, as Flexible alternating current Transmission Systems (FACTS) devices, are crucial for reactive power compensation and voltage regulation. The study models and simulates an SVC controlled by a neural network in MATLAB/Simulink, assessing its performance under three-phase fault conditions. The fault a 3-phase to-ground short circuit fault is introduced at location in close proximity to the wind energy. Results demonstrate that the proposed control scheme effectively reduces system oscillations and improves dynamic response, leading to faster fault recovery and enhanced overall grid stability. The superior dynamic performance of the SVC-based neural network controller confirms its potential for improving power system resilience.

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Keywords: Static VAR Compensators (SVCs); Neural network; Flexible Alternative Current Transmission Systems FACTS; MATLAB/ Simulink; Fault.

1. Introduction

Modern power grids experience unprecedented integration of renewable energy sources (RESs) and distributed generation (DG) because of global low-carbon energy system transitions. The transition to renewable energy sources and distributed generation delivers numerous environmental and economic benefits but produces complex operational obstacles because of how these sources produce energy in an irregular fashion. Electrical systems experience their most severe issues through voltage instability and increased power oscillations and damaged power quality which become worse during fast changes of load or when faults occur [1]. The wide adoption of Static VAR Compensators (SVCs) as one of the main components under Flexible Alternating Current Transmission System (FACTS) addresses both voltage regulation issues and reactive power requirements effectively. The devices use dynamic reactive power control to minimize voltage fluctuations while improving power factor together with strengthening power grid stability [2]. The standard operation of SVCs occurs through Proportional-Integral controller implementation providing basic control functionality under stable situations. PI controllers struggle to effectively manage power grid conditions and uncertain operating environments because of rising power grid non-linearity and complexity when renewable sources exceed specific thresholds [3].

Recent technological advancements in intelligent control methods achieve promising potential through the implementation of Artificial Neural Networks (ANNs). ANNs demonstrate three key characteristics which include modeling ability of complex non-linear relationships together with adaptive system dynamic response and operational data generalization without specific system models [4]. Power systems benefit from their successful application in fault detection and load forecasting and dynamic control applications because of the combination of fast response time and learning capability [5]. An ANN-based control strategy for SVCs serves to enhance voltage regulation as well as power system stability when grid conditions change due to fault disturbances. The ANN controller learns system behavior to automatically adjust reactive power compensation while changing the fixed parameter-based structure found in standard PI control [5]. A complete simulation framework in MATLAB/Simulink analyzes the proposed method alongside conventional PI-controlled SVCs when running simulations on three-phase faults. The controller's effectiveness will be evaluated by examining the quantitative performance metrics of overshooting as well as settling time and steady-state error.

2. Materials and Methods

2.1. SVC Modelling

The Static VAR Compensator operates as a shunt-connected FACTS device with the capability to manage voltage regulation through dynamic reactive power control functions. The fundamental structure of an SVC depends on thyristor-controlled reactors (TCRs), thyristor-switched capacitors (TSCs) and harmonic filters. The SVC functions by changing the system-connected equivalent susceptance value through the controlled thyristor firing angle modulation [6]. An SVC connected to a bus has the mathematical option to model as either a variable admittance device or a controlled reactive power source. The SVC injects reactive power Q_SVC and SVC current I_SVC to the system according to the following formula.

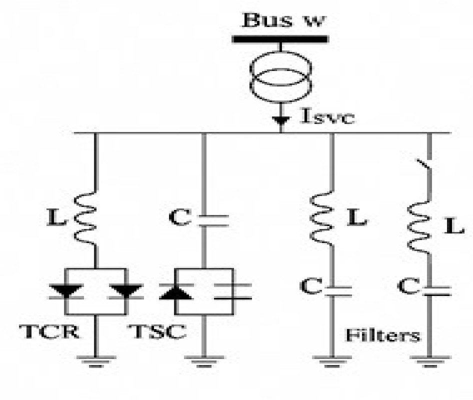

Fig. 1. SVC schematic diagram.

In addition to the equivalent circuit representation shown in Figure 2, the SVC enhances power system performance in several key areas [7]. These benefits encompass voltage regulation, power factor correction, improved dynamic and static security, increased system load ability, reactive power management, reduced power losses, and the mitigation of power oscillations.

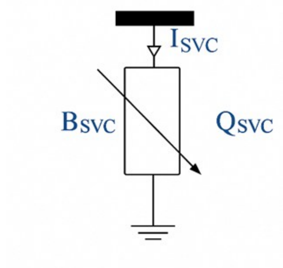

Fig. 2. Equivalent circuit of SVC.

The Static VAR Compensator (SVC) is commonly described as a shunt-connected device designed to either generate or absorb reactive power within a power system. A typical SVC configuration, as depicted in Figure 3 (left), consists of a capacitor bank in conjunction with a thyristor-controlled reactor. The equivalent single-phase circuit representation of this configuration is shown in Figure (right). Due to constraints imposed by the thyristor firing angle, the SVC effectively operates as a variable reactance [8], allowing for dynamic adjustment of reactive power. The reactive power injected at bus k and the corresponding injected current can be calculated using Equations (1) and (2), respectively, providing a quantitative understanding of the SVC's impact on the system.

$$V_K \, I_{SVC} = jB_{SVC} \tag{1}$$

$$Q_{SVC} = B_{SVC} \, V_K^2 \tag{2}$$

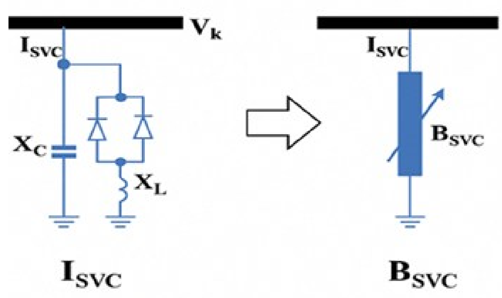

Fig. 3. Equivalent circuit of SVC.

Here, ISVC and QSVC denote the reactive current and reactive power, respectively, that the SVC injects into or absorbs from the power system [9]. The SVC's susceptance is given by BSVC, and Vk represents the voltage at the bus to which the SVC is connected [10].

As a shunt-connected device, the SVC's primary role is voltage regulation, a critical function for ensuring voltage stability, especially near the load end of transmission lines. While physically realized using a parallel combination of thyristor-controlled reactors and capacitor bank, the SVC's effective behavior is that of a variable shunt reactance. This variable reactance characteristic, illustrated in Figure 4, allows the SVC to control voltage by injecting or absorbing reactive power as needed [11].

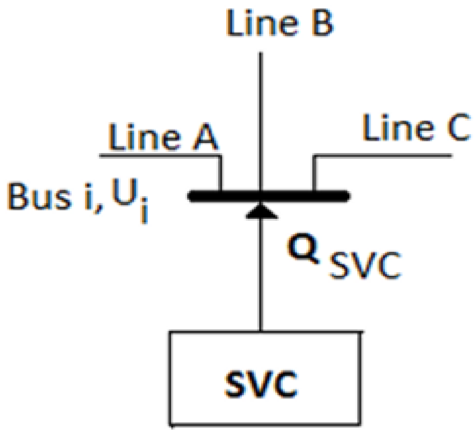

Fig. 4. SVC power injection model.

The amount of reactive power (QSVC) that the SVC can generate or absorb is governed by its available inductive and capacitive susceptance. This functionality allows the SVC to be implemented as a component that provides a specific bus with a defined quantity of reactive power, enabling voltage regulation and stability [12].

2.2. Static VAR Compensators (SVCs) based PI

In power systems, Static VAR Compensators (SVCs) play a vital role in reactive power compensation and voltage regulation Figure 5 illustrates the common practice of utilizing Proportional-Integral (PI) controllers to enable accurate and reliable control of these SVCs [13].

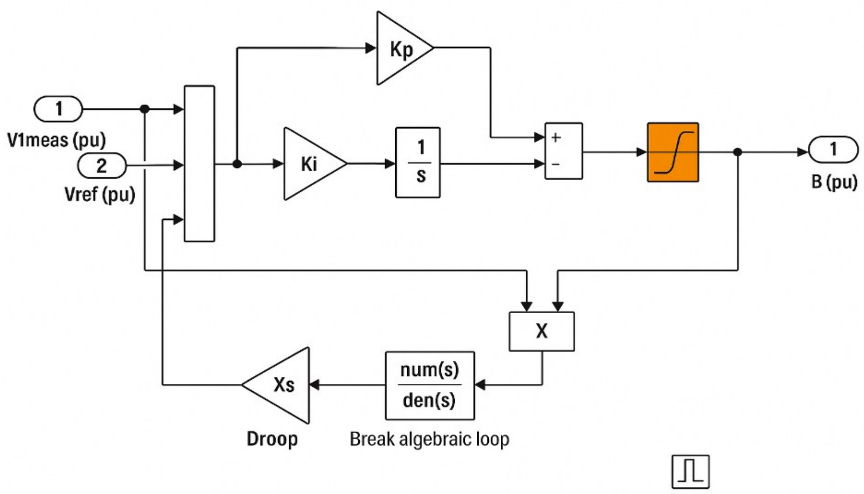

Fig. 5. SVC-Based PI controller.

2.2.1. SVC Operational

Static VAR Compensators (SVCs) are power electronic devices characterized by their ability to dynamically generate or absorb reactive power. This dynamic capability is crucial for their primary functions: regulating voltage levels and enhancing overall power system stability. Unlike static compensation methods, SVCs can continuously adjust their reactive power output to meet the changing demands of the system [14].

2.2.2. PI Controller Functionality within SVCs

A widely used feedback control method for SVCs is the Proportional-Integral (PI) controller, which consists of two key elements:

- Proportional (P) Element: This element generates a control signal that is directly proportional to the error signal, which represents the difference between the target voltage (typically a fixed value) and the actual system voltage. The benefit of the proportional element is its fast response to voltage deviations, providing immediate corrective action.

- Integral (I) Element: The integral element continuously integrates the error signal over time. The output of this element is based on the accumulated sum of past errors. The advantage of the integral element is its ability to eliminate steady-state errors, ensuring the system ultimately achieves and maintains the desired voltage level. Together, the proportional and integral elements provide both fast response and accurate tracking.

2.2.3. SVC Operation with a PI Controller

The PI controller of the System Voltage Controller stays active by tracking voltage levels at the selected power grid regulation point. The controller evaluates a pre-defined reference voltage known as the set point to compare it with the voltage measurement. The PI controller obtains its input from the calculated error value which results when measuring the voltage difference between target and actual conditions. A proportional control action within the PI controller operates instantly by changing the firing angle settings of TCR or TSC devices to control reactive power output of the SVC system. The integral component takes care of persistent steady-state error through continuous error signal integration that produces refined output corrections for reactive power adjustments [15]. The SVC achieves quick and effective voltage regulation through the coordinated operation of positional and integral controllers which work together to adjust the thyristor-controlled reactor or thyristor-switched capacitor firing angles.

2.2.4. Advantages of PI-Controlled SVCs

The precise voltage regulation function of SVC systems relies on PI controllers to deliver control at desired points throughout the power system. The system maintains operational boundaries for voltage stability through this control mechanism.
By using both proportional and integral control elements these systems respond quickly to voltage variations to produce immediate adjustments as well as sustain any remaining errors until they disappear. The integrated proportional and integral control system enables quick precise responses to disturbances in the power system.
The combination of PI controllers enables SVCs to enhance power quality through automatic reactive power adjustment resulting in diminished voltage dips and surges as well as minimized harmonic disturbance.
The integration of PI controllers makes SVCs indispensable components within current power systems. SVCs support voltage stability and play a leading role in preserving power quality through their operating mechanism. The combined proportional integral control system lets SVC components quickly respond to disturbances while keeping the desired voltage output levels [16].

2.3. Neural Network-Based Controller

To enhance SVC performance under dynamic grid conditions, this study proposes an Artificial Neural Network (ANN)-based controller. The neural network is trained to approximate the nonlinear mapping between the system's voltage error and the required reactive power adjustment.
The ANN structure includes:

- Input layer: voltage error e(t) = V_ref - V_meas
- Hidden layer(s): with sigmoid activation functions
- Output layer: control signal for SVC modulation

Training is conducted using the backpropagation algorithm. The loss function is defined as the mean squared error between the ANN output and the optimal reactive power control value. The weight updates follow the delta rule:

$\Delta w = -\eta * \partial E/\partial w$

where η is the learning rate and E is the error function. The ANN is trained offline using fault scenarios, and its performance is then tested in real-time simulations within Simulink.

2.4. Simulation Setup

In neural networks, the backpropagation algorithm employs the chain rule to efficiently determine the gradient of the loss function with respect to each weight. Rather than a single, direct computation, this process is carried out iteratively, calculating the gradient one layer at a time. While the mechanics of gradient calculation are outlined, the subsequent utilization of this gradient for weight adjustment is not explicitly detailed. The delta rule's calculation can be summarized in the following steps:

- The network receives input data, X, through its defined input channels.
- This input is then processed by a mathematical model that incorporates real-valued weights, represented by W.
- The initial values for these weights are typically assigned randomly.
- The algorithm proceeds by determining the output of each neuron throughout the network. This involves a forward pass, starting at the input layer, traversing any hidden layers, and culminating in the output layer. Subsequently, the algorithm quantifies the difference between the network's predicted outputs and the target or expected outputs. This difference, denoted as Error B, is calculated as follows:

$$Error\ B = Actual\ Output - Desired\ Output \tag{3}$$

To reduce this error, the algorithm adjusts the weights by propagating an error signal backwards through the network, from the output layer towards the hidden layers [17]. This process is visually represented in Figure 6.

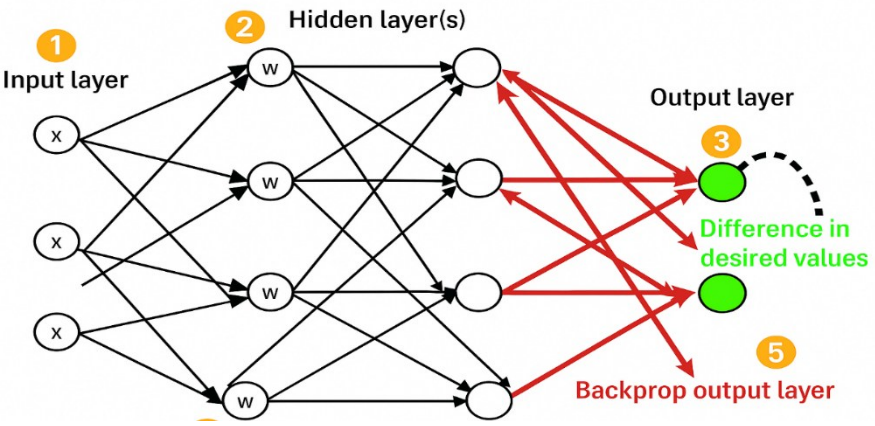

Fig. 6. Configuration (Back Propagation).

3. Results

The present study aims to conduct an analysis of a debate on the topic of Enhanced Transient Stability in Power Systems via Intelligent Control of SVCs Using Neural Networks. in Figure 7, the power system distribution included the FACTS- devices, SVC, which are controlled by a neural network controller. The model of the researched system is shown in Figure 8, using MATLAB/Simulink. To evaluate the performance of the system, a 3-phase-to-ground short circuit fault is introduced at the location in close proximity to the wind energy, the fault sites are situated at the wind bus (3). research was conducted to investigate the impact of SVC-based ANN on system situation and stability in the presence of disturbances.

3.1. Static VAR Compensators (SVCs) based ANN

Figure 7 illustrates a sophisticated approach to voltage regulation and reactive power compensation in electrical power systems, utilizing Static VAR Compensators (SVCs) in conjunction with Artificial Neural Networks (ANNs). SVCs, as dynamically controllable reactive power sources, are capable of either generating or absorbing reactive power as needed to maintain voltage stability and improve power quality in power grids. The integration with ANNs allows for intelligent and adaptive control of the SVCs, enhancing their performance under varying system conditions.

The diagram illustrates a neural network-based control system, likely for an SVC (or a STATCOM), detailing how the neural network integrates into the control of this power system component. The key components and their functions are:

- **Voltage Measurement (Vmeas):** Function: Measures the actual voltage at the control point in per-unit (pu).
- **Reference Voltage (Vref):** Function: Sets the desired target voltage level in per-unit (pu).
- **Error Calculation: Function:** Compares the measured voltage (Vmeas) to the reference voltage (Vref) to produce an error signal, representing the deviation from the desired voltage.
- **PI Controller: Function:** Processes the error signal using proportional (Kp) and integral (Ki) gains to generate a control output that minimizes the error and drives the system towards the target voltage.

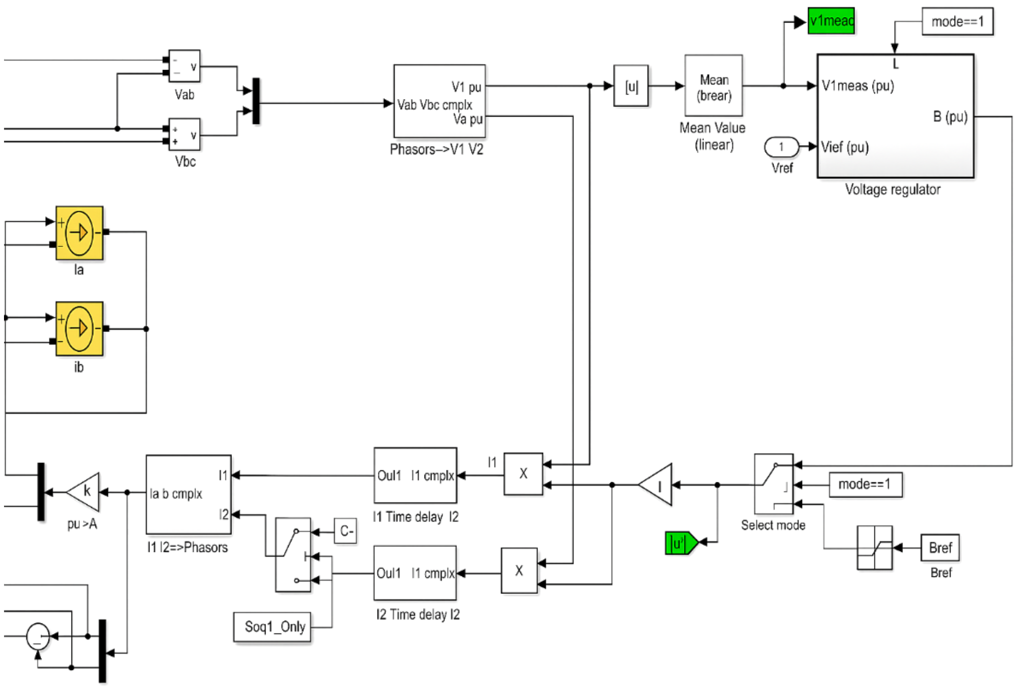

Fig. 7. Simulink/ Matlab SVC-based ANN.

Controlling the SVC voltage, as defined by the following relationship, dictates the energy exchange between the SVC and the power system.

$$Q_C = \frac{V_1^2}{X_{tr}} - \frac{V_1 V_s}{X_{tr}} cos(\theta_s - \theta_o) = \frac{V_1^2 - V_1 V_s}{X_{tr}} \quad (4)$$

The following parameters are relevant to the operation of the SVC:

Qc: Reactive power, representing the amount of reactive power generated or absorbed by the SVC. This is a key control variable.
Vs: SVC output terminal voltage, indicating the voltage level at the point where the SVC connects to the power grid.
Xtr: Leakage reactance, representing the reactance of the transformer used to connect the SVC to the power grid. This parameter affects the SVC's ability to control reactive power.
Figure 8 illustrates the temporal behavior of active and reactive power for the Static Var Compensator (SVC) Understanding how these quantities change over time is crucial for analyzing SVC performance. The fault 3-phase to-ground short circuit fault is introduced at location in close proximity to the wind energy.

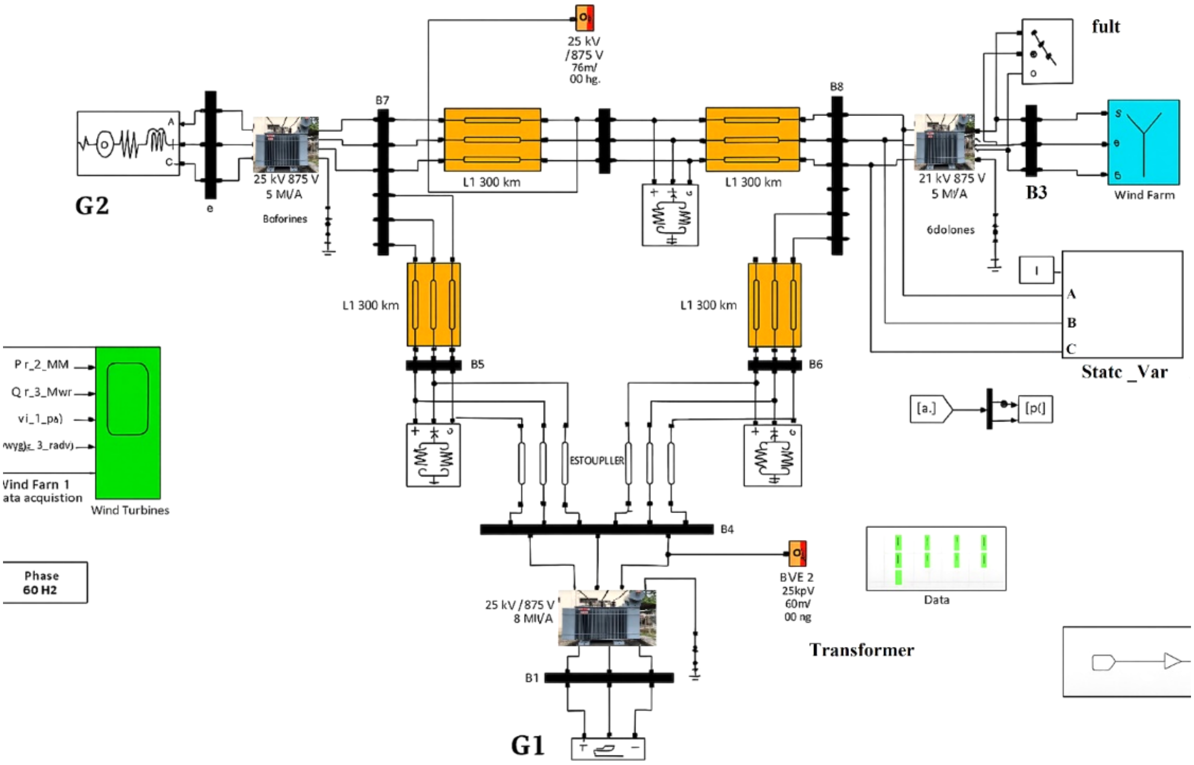

Fig. 8. Depicts the Simulink model representing the total system under study.

The time-domain response of voltage has been depicted alongside current and active power alongside reactive power in Table 1. as Generator 1 experiences a disturbance. The Table compares the system's behavior with and without the application of FACTS devices. When FACTS devices are removed the system first shows instability because the distance between the fault location and Generator 1 bus is extensive. The system displays a double problem during instability which combines both a rapid voltage escalation (termed overshoot) as well as continuous voltage fluctuations that create sustained oscillations before reaching a stable operating position. The deployment of FACTS devices helps stabilize the system because it shortens the simulation time needed to achieve a steady state to about half of the initial duration. FACTS devices display an effective capability to suppress power oscillations and enhance power system transient behavior.

TABLE 1: System Stability Comparison after Fault (Generator 1, with/without FACTS/SVC) - Bass ANN.

	Voltage (Pu)	Current (Pu)	Active power (Pu)	Reactive power (Pu)
No FACTS	1.14	1.35	1.37	1.38
SVC	1.1	1.28	1.29	1.25

The results presented in Table 1 demonstrate that the system's recovery to a stable operating condition (considering voltage, current, active power, and reactive power) after a fault is significantly quicker when an SVC, governed by an ANN, is implemented. Conversely, the system requires a longer stabilization time in the absence of FACTS devices. Table 2 demonstrates that the SVC-Bass ANN significantly accelerates system recovery after a fault. Voltage, current, active power, and reactive power all stabilize more rapidly compared to scenarios without FACTS devices. The prolonged stabilization time without FACTS highlights the critical role of the SVC-Bass ANN in enhancing power system resilience.

TABLE 2: Compression the rate of system stability after the fault in the state of (no FACTS, SVC) related to generator (2) bass ANN.

	Voltage (Pu)	Current (Pu)	Active power (Pu)	Reactive power (Pu)
No FACTS	1.33	1.40	1.38	1.32
SVC	1.23	1.33	1.25	1.24

3.2. Statistical Analysis and Performance Metrics

Controller performance was assessed using these metrics as in Table 3.

TABLE 3: Metrics used to evaluate the performance of the control unit.

Metric	Description
Overshoot (OS)	Max deviation above the reference voltage (pu)
Settling Time (Ts)	Time to stabilize within ±5% of reference (s)
Rise Time (Tr)	Time from 10% to 90% of final voltage (s)
Steady-State Error (Ess)	Final error between Vmeas and Vref

Average results for Generators 1 and 2 are summarized below in Table 4.

TABLE 4: Average results for Generators 1 and 2 are summarized.

Controller	Overshoot	Settling Time (s)	Rise Time (s)	Steady-State Error
No FACTS	0.14	2.8	1.6	0.03
SVC + PI	0.10	2.2	1.2	0.015
SVC + ANN	0.06	1.3	0.9	0.005

The ANN-based controller significantly outperformed the PI controller:

- Reduced overshoot by 40%.
- Improved settling time by approximately 40%, leading to faster recovery.
- Minimized steady-state error by 67%, enhancing voltage precision.

The ANN-controlled SVC demonstrated superior performance in all tested metrics, enabling quicker voltage regulation crucial for dynamic power systems with high renewable penetration. Its adaptability allows better response under varied conditions. Higher voltage instability and power oscillations without FACTS devices highlight the importance of advanced control.

4. Conclusion

This study showed that ANN-based controller for SVCs achieved better results for power system voltage regulation alongside transient stability performance. The proposed controller reached higher performance levels than PI controllers using the adaptation features of Artificial Neural Networks. Simulation outcomes demonstrated that an SVC controlled by ANN technology minimized voltage overshoot to 0.06 pu when compared to 0.10 pu, achieved a settling time decrease from 2.2 seconds to 1.3 seconds and reduced steady-state voltage error to 0.005 pu from 0.015 pu. Experimental tests confirmed that the neural network control method enhanced voltage accuracy by 67% and reduced both settling time by 40% and overshoot by 60% thus demonstrating its superior performance. System recovery after faults became more efficient when the SVC operated under ANN control. When utilized in a system lacking FACTS devices the ANN-based SVC accelerated steady-state recovery while decreasing both power and voltage oscillations mainly during faults affecting remote bus regions. Precise voltage and power stability became enhanced when Generator 1 operated under ANN control reaching 1.25 pu of reactive power while ordinary operations without FACTS settled at 1.38 pu. The research demonstrates that ANN controllers in SVC systems create an intelligent and resilient solution for voltage regulation in present-day power distribution systems. This method delivers optimal results when applied to renewable integration systems experiencing irregular load fluctuations. Research into forthcoming periods should analyze combinations between ANN and fuzzy logic and reinforcement learning to enhance system adaptability and resiliency against complex grid behaviors.

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