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Artificial Neural Network Based Static Var Compensator Analysis in Fault Condition

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ABSTRACT
This thesis presents an in-depth study on the implementation of Artificial Neural Networks (ANN) to enhance the performance of Static VAR Compensators (SVCs) for voltage stability control in modern power systems, particularly under fault conditions. As the complexity of power grids increases due to the integration of renewable energy sources and growing interconnectivity, traditional control techniques face challenges in providing fast and adaptive responses to disturbances. This research proposes an ANN-based control strategy for SVCs to achieve more efficient reactive power compensation and voltage regulation. A detailed simulation model of a multi-machine power system was developed in MATLAB/Simulink. The ANN controller was trained offline using the Levenberg-Marquardt backpropagation algorithm to predict optimal susceptance values for the SVC. Simulation results were analyzed and compared with systems using conventional PI controllers and systems without SVCs. The findings indicate that the ANN-based SVC significantly improves voltage stability, enhances transient performance, and ensures quicker voltage recovery during single line-to-ground faults. Additionally, the ANN controller exhibits better adaptability to dynamic system conditions. This study demonstrates the potential of intelligent control methods like ANNs to replace conventional strategies in flexible AC transmission systems (FACTS), contributing to more robust and reliable power grid operations.

Keywords**: Artificial Neural Network (ANN), Static VAR Compensator (SVC), Fault Analysis, Power System Stability, Reactive Power Compensation**

1. INTRODUCTION

The integration of renewable energy sources (RES) and the increasing adoption of electric vehicles (EVs) have introduced several power quality challenges in modern power systems. The widespread installation of RES, particularly solar PV and wind power systems, has led to a reduction in system inertia, making power grids more vulnerable to disturbances and uncertainties [1][5]. As systems become more complex, the need for reliable and stable power systems has increased in recent years. The stability and reliability of power systems depend on the power quality of the system. Power quality can be maintained by regulating either voltage, frequency, or rotor angle in power systems. For many years, researchers have been studying voltage stability improvement to enhance stability, reliability, reduce losses, and support integration of RES and EVs in the system[6]. Flexible AC transmission system (FACTS) devices have played a crucial role in improving voltage profiles in power systems to date. These devices can provide reactive power compensation, control power flow, and enhance voltage stability[6].

1.1 Power System Stability

Power system stability is defined as the ability of an electric power system, for a given initial operating condition, to regain a state of operating equilibrium after being subjected to a physical disturbance, with most system variables bounded so that practically the entire system remains intact. Power system stability can be categorized into three distinct phenomena: 1) rotor angle stability, 2) voltage stability, and 3) frequency stability[6][19].

The capacity of synchronous generators within an interconnected power system to maintain synchronization following major disruptions, such as unexpected load shedding or line disconnections due to faults, is crucial for rotor angle stability. Frequency instability occurs when there is an imbalance between the total power production and consumer demand. In recent years, voltage instability has been identified as the primary cause of numerous widespread power outages globally[20].

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1.2 Flexible AC Transmission System

Existing Knowledge Various methods, including the use of Flexible AC Transmission Systems (FACTS) devices, have been implemented to enhance voltage stability in power systems. Knowledge Gap Conventional methods for controlling FACTS devices, such as Static Var Compensators (SVC), are increasingly inadequate for meeting the demands of modern power systems. Conventional Static VAR Compensators (SVCs) exhibit several limitations in power system applications[6][8]. While traditional SVCs are effective for managing reactive power and regulating voltage, they possess constraints in their response speed and control precision. These systems typically employ thyristor-controlled reactors and fixed capacitors, resulting in decreased reaction times compared to more contemporary technologies. This reduced responsiveness can be problematic in power systems with rapidly changing conditions, particularly given the increasing integration of renewable energy sources that induce voltage fluctuations.

1.3 Research Gaps

Analyzing research papers on modern power system problems reveals that Artificial Neural Network (ANN) based Static Var Compensators (SVCs) are considered a promising solution. However, several research gaps have been identified. Firstly, the complexity of the systems developed often hinders their applicability in real-time scenarios. Secondly, the research paper had been using ANN in facts devices for generating the waveforms and give the calculated result not for controlling purposes. Also, the research paper has considered the secondary distribution system where the voltage level. Despite the potential of ANN-based SVCs, there is a notable lack of research specifically addressing their integration for comprehensive voltage profile improvement across diverse power system scenarios. This gap is particularly significant given the increasing integration of renewable energy sources and the growing variability in power demand. Addressing this research gap is crucial for enhancing the overall reliability and efficiency of power systems. The key question that emerges is how to optimize an ANN-based static var compensator to effectively improve voltage profiles in power systems, considering a wide range of operational conditions and disturbances.

1.4 Objective

This study aims to develop and validate an ANN-based SVC model to enhance voltage stability and power quality in electrical power systems. This study focuses on developing and validating an Artificial Neural Network (ANN)-based Static Var Compensator (SVC) model to improve voltage stability and power quality in electrical power systems. The integration of ANN technology with SVC systems represents a significant advancement in power system control and optimization. By leveraging the learning capabilities of neural networks, the proposed model aims to adapt more effectively to dynamic system conditions and provide more precise and responsive voltage regulation. The research encompasses several key aspects, including the design of the ANN architecture, training methodologies, and integration with existing SVC control systems. The model is expected to enhance the SVC's ability to mitigate voltage fluctuations, and improve overall system stability. Validation of the model will likely involve extensive simulations under various operating conditions and potential field tests to demonstrate its effectiveness in real-world scenarios. The successful implementation of this ANN-based SVC model could lead to more efficient and reliable power systems, potentially reducing operational costs and improving the quality of electricity supply to consumers.

2. METHODOLOGY

This research adopts an Artificial Neural Network (ANN)-based approach to enhance the control of Static VAR Compensators (SVCs) for maintaining voltage stability in a multi-machine power system under fault conditions. The entire modeling, training, and testing processes were carried out using MATLAB/Simulink and the Deep Learning Toolbox.

2.1 System Modeling

A multi-machine power system model was developed in MATLAB Simulink consisting of two 735 kV voltage sources, two step-down transformers (735/16 kV), and two 20 MW loads connected via four buses. Key components included programmable voltage sources, busbars, transformers, RLC loads, fault blocks (to simulate various fault conditions), relays, and SVCs. The SVC model included four major units: voltage measurement, voltage regulator, distribution system, and firing unit.

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2.2 SVC Control Design

The voltage measurement unit used a Phase-Locked Loop (PLL) and Fourier-based averaging to measure the root-mean-square voltage. The voltage regulator employed a PI controller with droop control logic to generate an error signal, which was passed to the neural network. The distribution unit computed the required susceptance BsvcB_{svc}Bsvc from the ANN output and derived the thyristor firing angle. This angle was sent to the firing unit to control the Thyristor-Controlled Reactor (TCR) and Thyristor-Switched Capacitor (TSC) for reactive power compensation.

2.3 ANN Design and Training

A feedforward neural network with one hidden layer (10 neurons) was developed using the feedforwardnet function. The hidden layer used the hyperbolic tangent sigmoid activation function (tansig), while the output layer used a linear activation function (purelin). Synthetic training data were generated, normalized using mapminmax, and split into training (70%), validation (15%), and testing (15%) datasets.

Offline training was conducted using the Levenberg-Marquardt backpropagation algorithm, with performance measured using mean squared error (MSE). The ANN was trained to predict the optimal susceptance value BsvcB_{svc}Bsvc based on the input error signal between measured and reference voltages. Post-training, the network was integrated into the SVC model to replace the PI controller.

2.4 Implementation and Integration

Once trained, the ANN was embedded in the SVC's voltage regulation block to provide real-time predictions of BsvcB_{svc}Bsvc. The ANN-based control dynamically adjusted the SVC's reactive power output during fault and non-fault conditions. The system's performance under a single line-to-ground fault was analyzed and compared against traditional PI-based control.

2.5 Evaluation

Comparative simulations were run to assess system response with:

- No SVC
- SVC with conventional PI control
- SVC with ANN-based control

The ANN-based controller showed improved voltage stability, faster voltage recovery, and better adaptability under varying fault conditions.

3. RESULT AND DISCUSSION

In the previous chapter, we discussed the methods for creating an SVC – ANN model in MATLAB Simulink. The two source voltages of 735 kV were connected by a transmission line through three-phase step-up transformers. The system comprises two output voltages of transformers at 735/16 kV, respectively, in each area, connected by a transmission line. The loads in each area, having 20 MW, were selected such that real power flows on the transmission line from area 1 to 2. The active and reactive power absorbed by the load are functions of the system voltage. The system has four buses, where the voltage (pu), current (pu), and reactive power are observed. The SVC rating is approximately 100MVA.

Without SVC and Under Normal Operating Conditions

The system operates with minimal real power transfer and low reactive power availability. The voltage at all buses remained close to 1.0 pu, as depicted in Fig4.1, indicating an electrically stable system but with a limited capability to handle sudden load changes or disturbances. Owing to the absence of reactive power compensation shown in Fig4.3, there were minor fluctuations in the current flow, as shown in Fig4.2, which could lead to instability under varying loads. The lack of an SVC meant that the system could not dynamically regulate the voltage, leading to poor transient stability.

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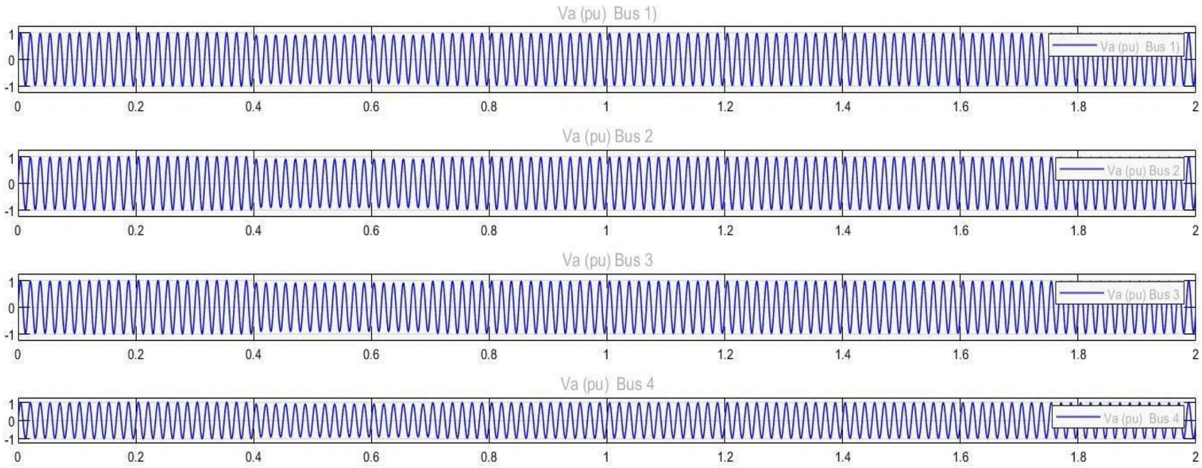

Fig 4.1 Voltage at each bus without SVC connected and without fault

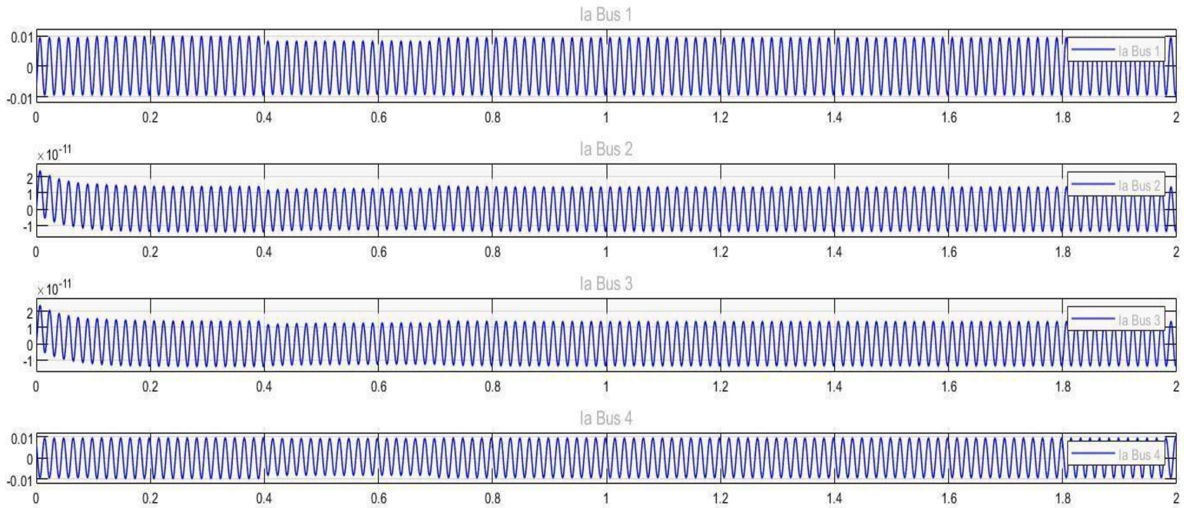

Fig 4.2 Current at each bus without SVC connected and without fault

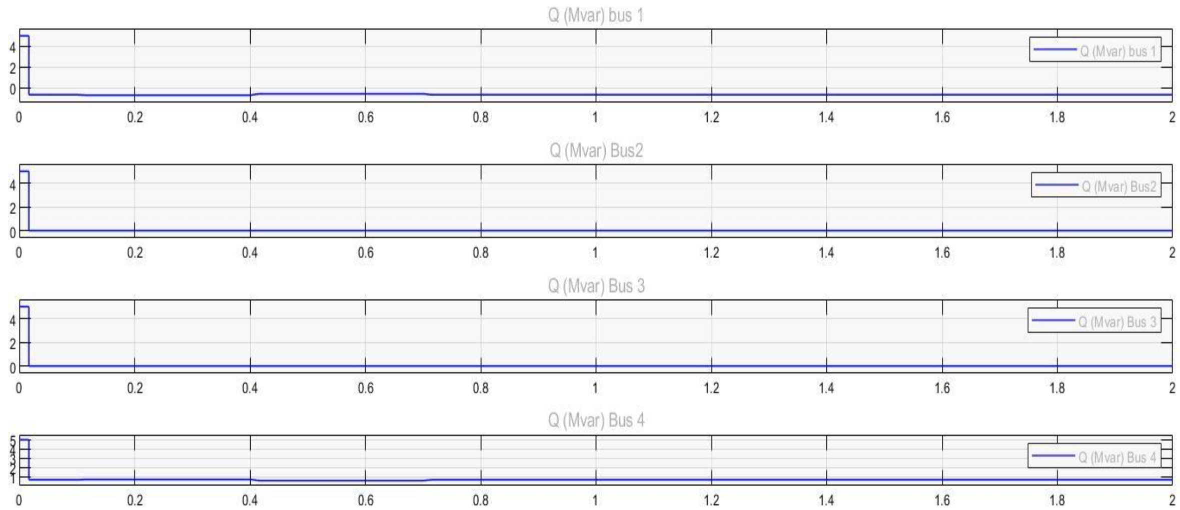

Fig 4.3 Reactive power at each bus without SVC connected and without fault

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Key Observations:

- Voltage stability was maintained at 1.0 pu in the absence of reactive support.
- Minor power oscillations were observed owing to insufficient damping.
- The system demonstrates an inadequate capacity to compensate for potential disturbances.

The voltage stability maintained at 1.0 per unit (pu) in the absence of reactive support indicates that the power system operates at its nominal voltage level under normal conditions. This suggests that the system has sufficient voltage regulation mechanisms to maintain steady-state voltage levels without additional reactive power compensation. However, the observation of minor power oscillations owing to insufficient damping reveals a potential weakness in the dynamic performance of the system. These oscillations can be attributed to inadequate damping torque in generators or insufficient damping control in power system stabilizers.

The inadequate capacity of the system to compensate further highlights its vulnerability to disturbances and changes in operating conditions. This limitation may manifest in various ways, such as difficulty in maintaining voltage levels during sudden load changes, reduced ability to handle reactive power imbalances, and increased risk of voltage collapse under stressed conditions. To address these issues, system operators may need to consider implementing additional reactive power sources, enhancing generator excitation systems, or deploying advanced control strategies to improve the overall stability and resilience of the system.

1.1.2 With SVC and Under Normal Operating Conditions

The ANN-based SVC was installed near Bus 3, allowing for dynamic reactive power injection into the system. With the SVC in operation, the voltage remained stable at all buses, and the system demonstrated an improved power transfer capability, as shown in Fig6.4. The SVC supplied reactive power whenever required, ensuring smooth power flow and enhanced voltage regulation. The current and reactive power flows were optimized, thereby reducing the overall system losses, as shown in Figs6.5 and 6.6, respectively.

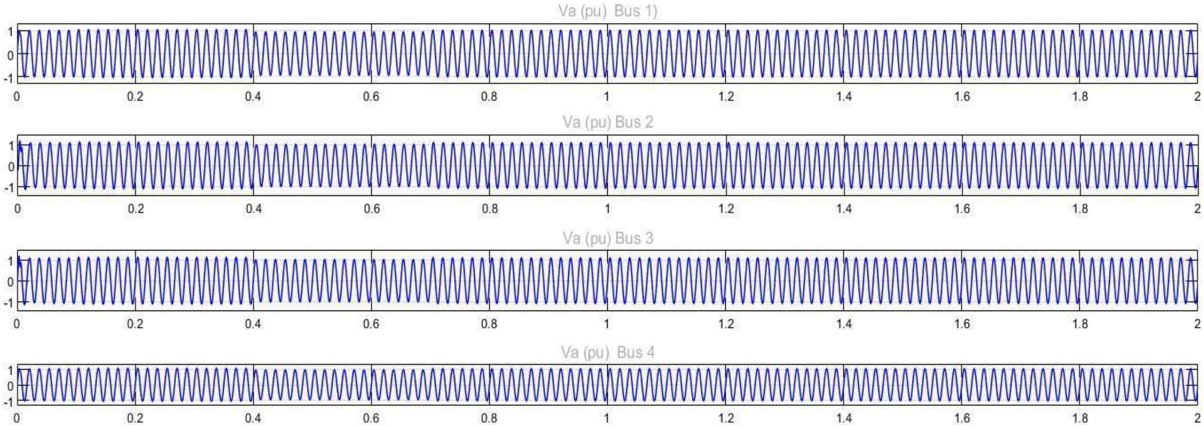

Fig 4.4 Voltage at each bus with SVC connected and without fault

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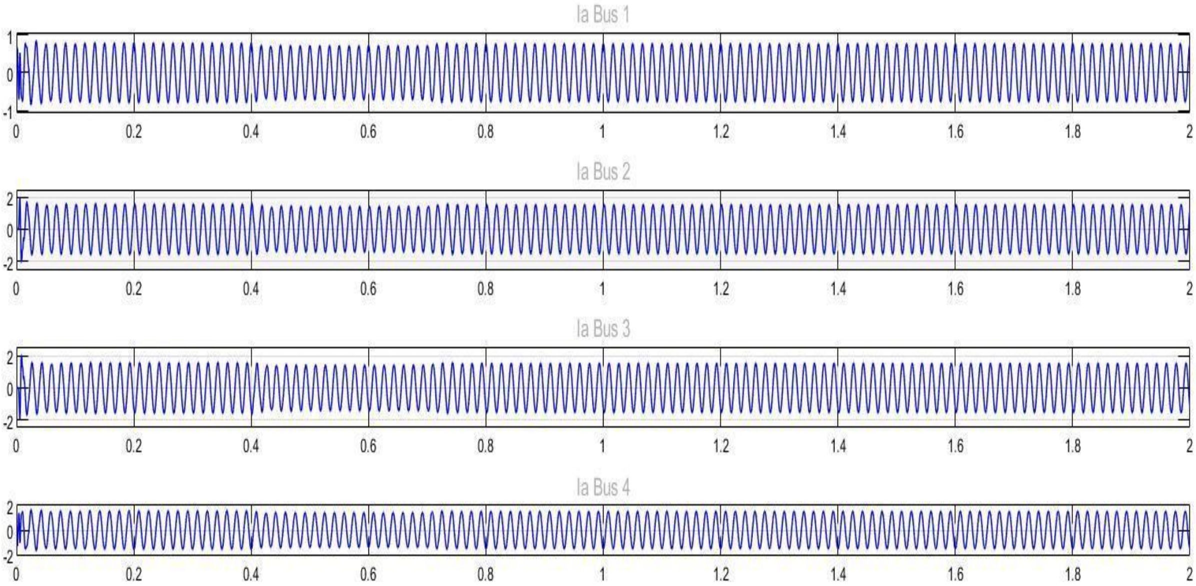

Fig. 4.5 Current at each bus with SVC connected and without fault

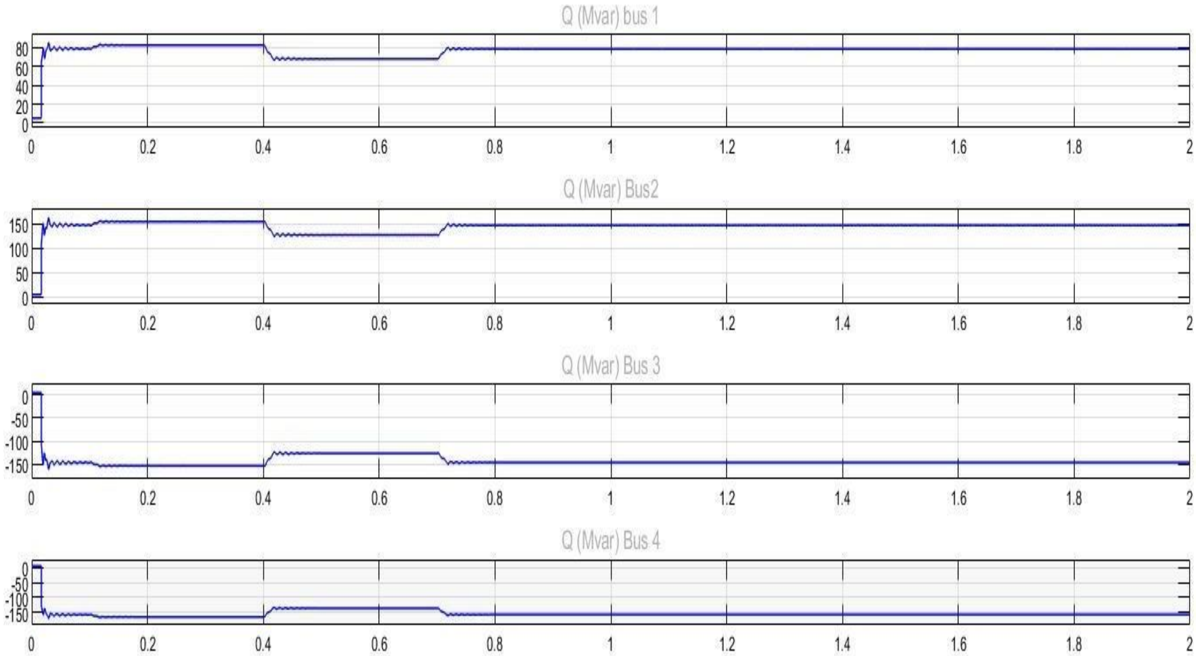

Fig 4.6 Reactive power at each bus with SVC connected and without fault Key

Observations:

- Improved voltage stability owing to reactive power support.
- Enhanced transient response and improved fault-handling capability.
- Reduced voltage oscillations and improved power quality were observed.

The tests showed that the controller reacted quickly and accurately to provide the correct amount of power support, which helped prevent voltage drops and large-scale system failures. Using this controller, the power system requires less overall power support. This leads to better power efficiency and improved electricity transmission. Overall, the new controller proved to be very effective in maintaining the stability of the power system and improving its performance.

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With SVC and Under Line-to-Ground (LG) Fault

A single-phase LG fault was introduced at Bus 3 for a short duration (0.5s - 1s). Without the SVC, the fault caused a voltage dip at Bus 3, affecting power stability. With the SVC, the system recovered quickly, and the voltage at the affected bus returned to 1.0 pu after fault clearance. The reactive power injection by the SVC compensated for the fault, preventing excessive voltage fluctuations.

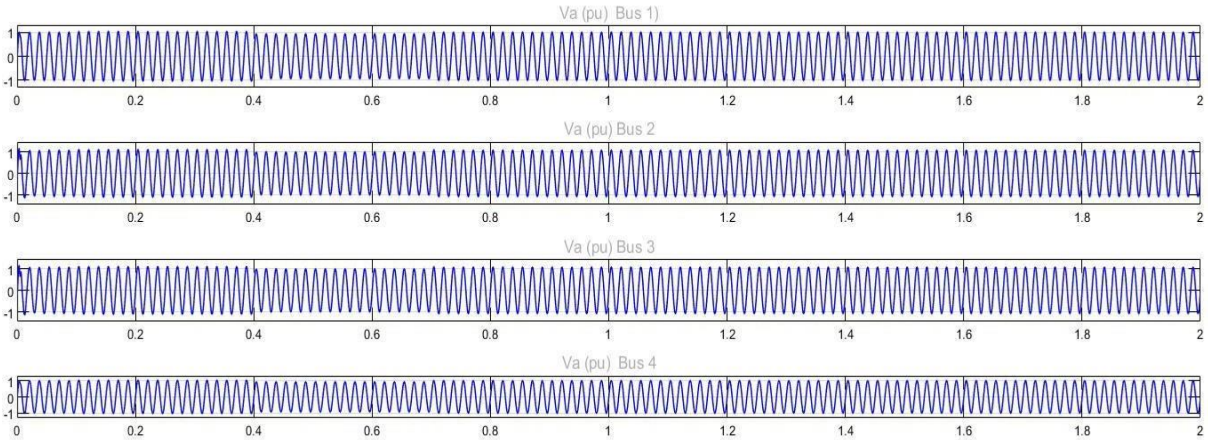

Fig 4.7 Voltage at each bus with SVC connected and with LG fault

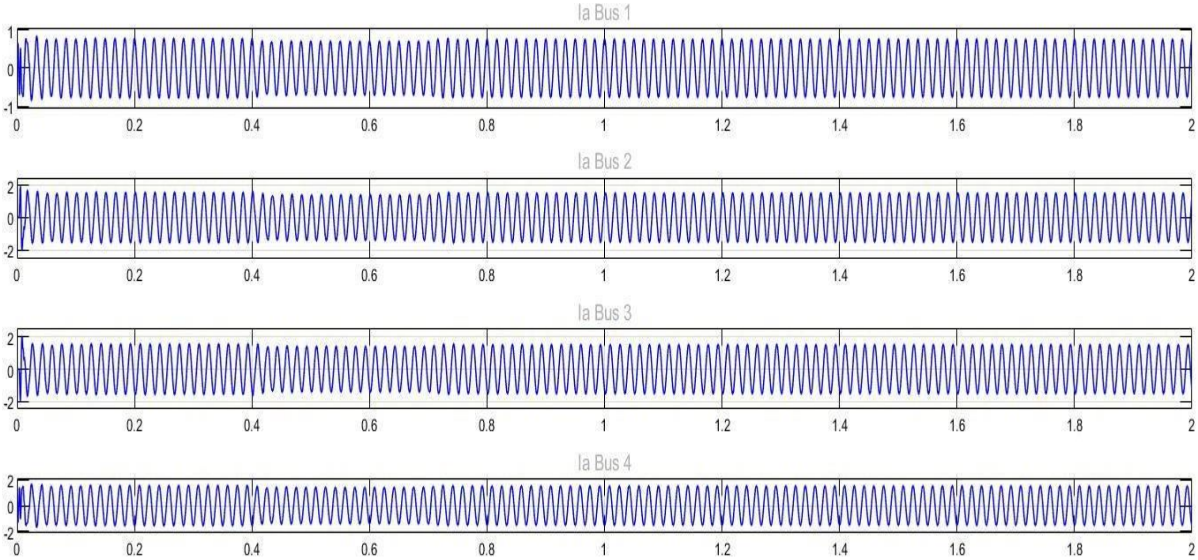

Fig 4.8 Current at each bus with SVC connected and with LG fault

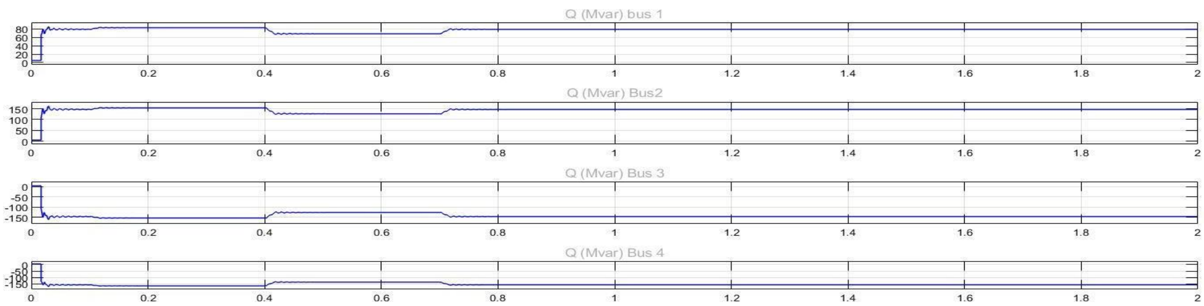

Fig 4.9 Reactive Power at each bus with SVC connected and with LG fault Key

Observations:

- The ANN-based SVC successfully mitigated voltage dips during the LG fault.
- The power system recovered quickly with minimal disturbance.
- Improved reactive power control prevents system instability.

The effectiveness of the SVC in mitigating the impacts of the LG fault is clearly illustrated in Figs 4.7, 4.8, and 4.9, which depict the voltage, current, and reactive power at each bus, respectively, with the SVC connected during fault conditions. These figures visually demonstrate the improved performance of the system with the SVC. The key observations from this scenario highlight the success of the Artificial Neural Network (ANN)-based SVC in mitigating voltage dips during the LG fault. The rapid recovery of the power system with minimal disturbances underscores the efficacy of the SVC in maintaining system stability. Furthermore, the enhanced reactive power control provided by the SVC played a crucial role in preventing more severe consequences that could have resulted from faults. In conclusion, the implementation of ANN-based SVC demonstrated significant improvements in power system stability and performance under various operating conditions. The comparative analysis between the scenarios with and without the SVC clearly illustrates the effectiveness of the device in enhancing voltage regulation, reducing power oscillations, and improving the resilience of the system to faults. Under normal operating conditions, the SVC provides dynamic reactive power support, optimizing the power flow and reducing system losses. During the Line-to- Ground fault, the SVC's rapid response mitigated voltage dips and facilitated quick system recovery. These results underscore the potential of ANN-based SVC technology in addressing the challenges of modern power systems, particularly in maintaining stability and improving the overall system efficiency. Future research could focus on further optimizing the ANN controller and exploring its application in more complex power-system configurations.

4. CONCLUSION

This thesis addresses the pressing challenge of voltage stability in modern power systems, which are increasingly complex due to growing interconnectivity and renewable energy integration. While conventional FACTS devices such as Static VAR Compensators (SVCs) offer reactive power support, their effectiveness is limited under dynamic and fault-prone conditions. To overcome these limitations, this study proposes the integration of Artificial Neural Networks (ANNs) with SVCs to achieve faster, intelligent, and more adaptive voltage control. The ANN-based controller was trained to determine optimal susceptance values for SVCs in response to voltage deviations, using the Levenberg-Marquardt backpropagation algorithm. Simulations conducted in MATLAB/Simulink under various fault conditions—including short circuits and sudden load changes—demonstrated that ANN-enhanced SVCs provide faster voltage recovery, reduced oscillations, and overall improved system stability compared to conventional PI-controlled systems. The results highlight the ANN’s ability to dynamically respond to disturbances, enhancing both the speed and accuracy of reactive power compensation. Additionally, the ANN-based approach shows promise for improving grid resilience and facilitating the integration of renewable energy sources. In summary, this research presents a novel and effective method for voltage stability control. It emphasizes the potential of AI-driven solutions in modernizing power grid operations and paves the way for future research in intelligent power system control strategies.

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