Enhancement of Power System Security by the Intelligent Control of a Static Synchronous Series Compensator

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ABSTRACT

Improving and maintaining the stability of a power system is a major focus of modern technology and research. However, due to financial issues, environmental concerns, and health risks associated with electric and magnetic fields, the growth of the current transmission system is constrained. Transmission line problems can be resolved by the effective use of reactive power compensation based on Flexible AC Transmission (FACT) devices. The effectiveness of these devices in regulating active and reactive powers as well as dampening oscillations in the transient phase of the power system is examined using a Static Synchronous Series Compensator (SSSC) with Artificial Neural Network (ANN) control. When compared to the traditional Proportional Integral (PI) controller, the suggested ANN controller offers better dynamic performance. For the suggested test system, this study utilized modeling and simulation using the MATLAB/Simulink software. The observations show that by using ANN in disturbed situations, power oscillations are quickly damped and power flow is enhanced.

Keywords-FACT; SSSC; PI; fuzzy damping of oscillations; ANN; power handling capacity

I. INTRODUCTION

The need for electrical power in the modern world has grown dramatically during the past few decades. Power producing facilities are usually functioning at their utmost capacity to meet the growing demand and transmission lines are likewise approaching their thermal limitations. As a result, power systems appear to be less protected, and they are constantly exposed to voltage instabilities, which have caused several significant network breakdowns throughout the world.

In [1], using MATLAB/Simulink, it was shown that SSSC with POD and ANN has a greater potential for damping network oscillations. Additionally, the real power of the system is increased by SSSC-POD with ANNs, increasing the network's load capacity. In [2], a comparison of STATCOM with the traditional PI controller and a fuzzy-based controller is conducted. The results suggest that the system's dynamic performance is improved by the coordinated function of POD and PSS. Designing an SSSC with the addition of RBFN to the sliding mode technology improves power flow and controls DC voltage in transmission network [3]. Using PI and ANN control techniques with a pod controller, the article compares the efficacy of SSSC in transmission networks. In comparison to the PI controller, the suggested ANN controller may deliver high dynamic performance [4-6]. The components of the SSSC intelligent fuzzy control have been developed in detail to ensure smooth reactive power regulation in [7]. To synchronise the voltage control of the SSSC and increase stability, fuzzy logic was used in [8, 9]. In [10], and in order to synchronise the control of the SSSC a performance comparison between the PI and the RBFN controllers was conducted. The outcome showed that the SSSC controller based on RBFN is superior to the PI controller. For enhancing STATCOM performance during abrupt, significant disruptions, the usage of a super-capacitor with STATCOM is suggested in [11]. The control of damping of SSSC used in power systems is examined in this [12, 13]. The effectiveness of SSSC, STATCOM, and UPFC for reducing oscillations and stabilising the power system is examined in [14]. The location of SSSC in the test system is determined using the analytical hierarchy approach [15].

Many researchers have studied the SSSC performance under steady state and abnormal system conditions. In this study, when compared to the PI controller, the suggested ANN controller has a higher dynamic performance. For the given test system, this study suggests modeling and simulation with the MATLAB/Simulink software. In comparison with the PI controller, the results show that using ANN under abnormal situations rapidly damps power oscillation and increases power flow. The PI based SSSC performance deteriorates under changing system conditions, therefore an intelligent controller for SSSC is required. The main contributions of the current paper are:

- Verification of the conventional PI based SSSC performance under steady state as well as disturbing conditions.
- An ANN-based SSSC is designed with two input variables like change in voltage and rate of change in voltage signal for damping the oscillations in fault condition. The local mode of oscillations is analyzed.
- Performance comparison of the SSSC controller for inter area oscillation
- The multimachine model of the sample system is utilized to verify the role of the proposed SSSC controller in MATLAB environment.

II. OVERVIEW OF THE SSSC

The way a series compensator with a voltage source converter able to inject voltage in a transmission line so that the P and Q of the transmission line can be easily managed with help of coupling transformer can be seen in [16].

III. CONTROL SYSTEM OF THE SSSC

Figure 2 represents the SSSC control system. The current I is synchronized by a Phase-Locked Loop (PLL). The result from PLL (θ = ωt) is utilized to calculate the components of the AC 3Φ voltages and currents named as V_d, V_q or I_d, I_q. The q component of the AC voltages V_1, V_2 and Vdc is monitored by a measuring system. The AC and DC voltage regulators calculate the two converter voltage components (V_{dcnv} and V_{qcnv}) necessary to produce the V_{dcref} and V_{qref}, i. e. the desired DC voltage and the injected voltage respectively.

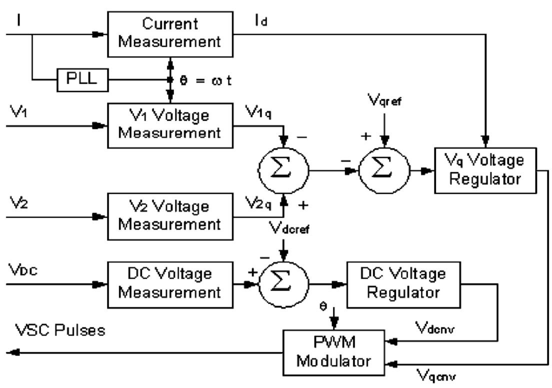

Fig. 1. Single-line diagram of the SSSC control system.

IV. MATHEMATICAL MODELING OF THE SSSC

The two bus transmission line shown in Figure 2 has three components: line's resistance (r), it's reactance X, and voltage injection V_c. Figure 3 shows the vector representation of a transmission line.

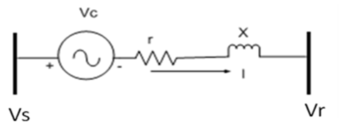

Fig. 2. Equivalent circuit.

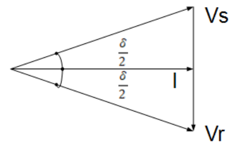

Fig. 3. Phasor diagram.

Equation (1) indicates the transmission line voltage drop:

$$IX - Vc = 2Vsin\frac{\delta}{2} \quad (1)$$

The current equation is:

$$I = \frac{Vc}{X} + \frac{2Vsin\frac{\delta}{2}}{X} \quad (2)$$

Equation (3) gives the active power. The imaginary power of the line is given by (4) and (5) provides the current in the compensator:

$$P = VIcos\frac{\delta}{2} = \frac{VVc}{X}cos\frac{\delta}{2} + \frac{V^2}{X}sin\delta \quad (3)$$

$$Q = VIcos\frac{\delta}{2} = \frac{VVc}{X}cos\frac{\delta}{2} + \frac{V^2}{X}(1 - cos\delta \quad (4)$$

$$I = \frac{2Vsin\frac{\delta}{2}}{X(1-Kse)} \quad (5)$$

Power flow can be controlled by changing the injection voltage.

V. TEST POWER SYSTEM MODEL

A SSSC multi-machine test system can be seen in Figure 4. Between buses B1 and B2, a 100 MVA SSSC is attached. There are two important load centers at bus B3 and two power production substations that make up the electrical grid. The first power generating substation (M1) has a 1000 MVA rating, while the second (M2) has a 5000 MVA rating. To simulate the load of about 5000 MW, a dynamic load model is employed. M1 is coupled to the load by lines L1 and L2. In order to construct a three-phase fault, L1 and L2 are 150 km and 700 km long, respectively.

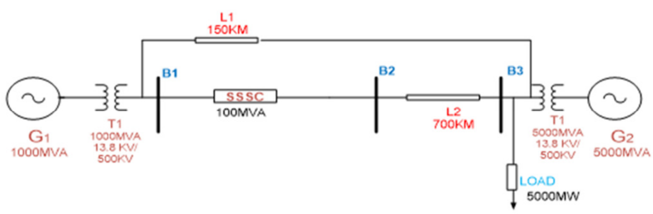

Fig. 4. The test system.

VI. SSSC NEURAL NETWORK CONTROLLER MODELING

An ANN is a versatile tool for creating learning algorithms and decision-making processes that allow for precise regulation of activities in a variety of applications. The ANN approach, which selects what to do for a certain testing input based on the trained data provided, fundamentally relies on the past information provided [16]. The feed forward model is the most fundamental kind of ANN. The following are the basic processes involved in NN controller modeling:

- Step 1: Examine the i/p for the ANN controller.
- Step 2: Decide the ANN type.
- STEP 3: Examine the required output for the ANN controller.

The structure of the suggested ANN controller and the ANN controller simulation block developed after successful development and training are shown in Figures 5 and 6.

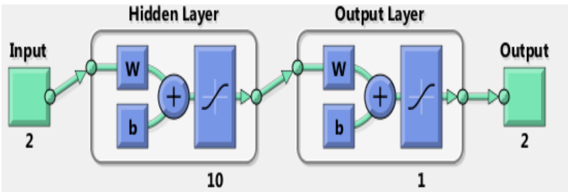

Fig. 5. Structure of developed ANN controller.

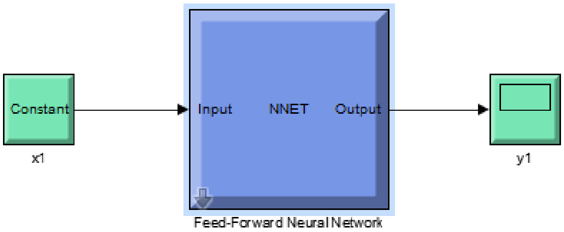

Fig. 6. Simulation block of the ANN controller.

The Simulink model of the ANN controller is shown in Figure 7. It has three layers, namely input, hidden, and output layer. The PI controller of the SSSC controller may be replaced with this ANN with the same input. The Output of the ANN V_{qref} is given to the SSSC.

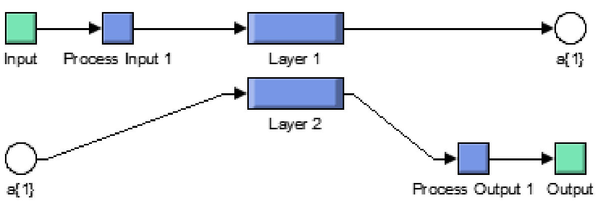

Fig. 7. Internal architecture of the ANN controller.

VII. SIMULATION RESULTS

The suggested SSSC with the ANN controller was successfully simulated in MATLAB/Simulink. Under various system conditions of a multi-machine power system, the PI controller and the ANN controller were compared and their performance was evaluated.

A. System Response without SSSC for Various Fault Transient Durations

The simulation response for a 3 phase fault at bus B3 for fault durations of 0.32 sec, 0.34 sec, and 0.4 sec are shown in Figure 8. The results indicate that as the fault duration increases, the real power variations, the variation in rotor angle, and system oscillations also increase, along with settling time and first peak.

(a)

(b)

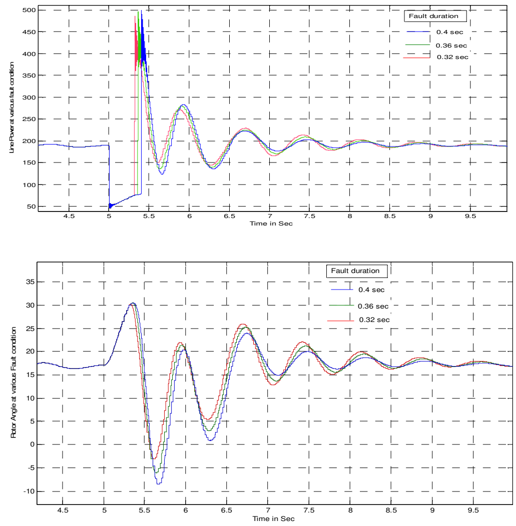

Fig. 8. System without SSSC. Various fault durations. (a) Real power control, (b) rotor angle response.

B. System Response with PI-based SSSC

1) System Response for Various Fault Transient Durations

Figure 9 shows the plot for power flow in MW and the rotor angle with a PI controller having two input variables. For comparison, a 3Φ fault is generated between B2 and B3 bus for various transient durations of 0.32 sec, 0.322 sec and 0.323 sec using the three phase fault generator. PI control is used to suppress the rotor angle δ during fault conditions. The system's transient stability is maintained by the PI-based SSSC. The inter area oscillations caused by the three-phase fault are shown in Figure 9(c). The findings show that using the PI-based SSSC, the speed deviation difference is quite minor. The response indicates that the oscillations increased with increase in fault duration.

2) System Response for Various Load Conditions

System response with various load conditions at the receiving end is shown in Figure 10. From the result, it can be concluded that the line power is more for 6000 MW load as compared to 6800 MW load.

(a)
(b)
(c)

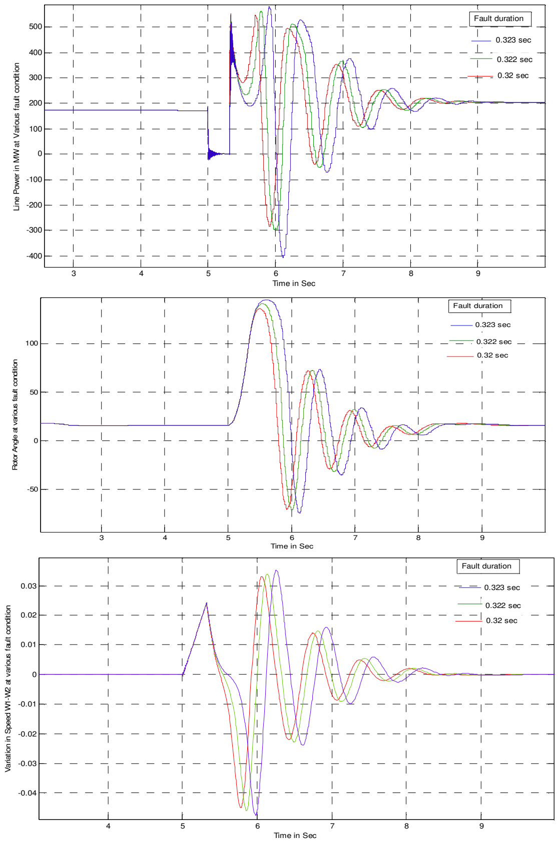

Fig. 9. PI SSSC. Various fault transient durations. (a) Real power control, (b) rotor angle response, (c) speed deviation (W1-W2) rad/sec.

(a)
(b)
(c)

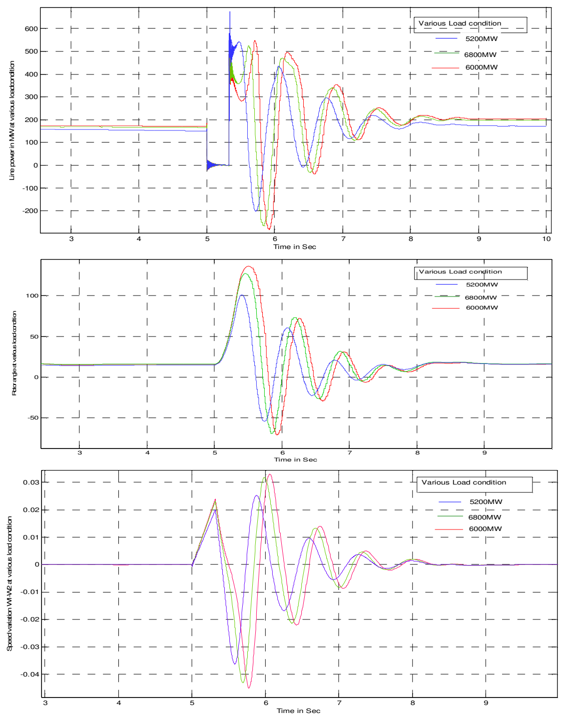

Fig. 10. PI SSSC. Various load conditions. (a) Real power control, (b) rotor angle response, (c) speed deviation (W1-W2) rad/sec.

(a)
(b)
(c)

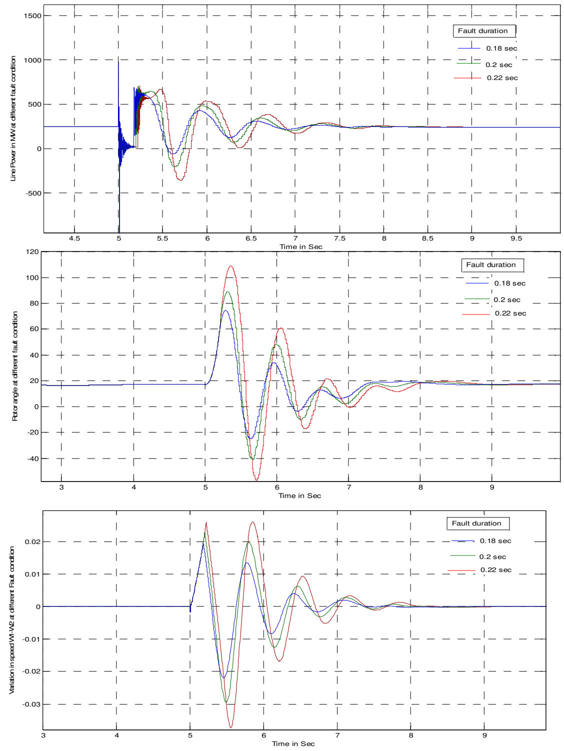

Fig. 11. ANN SSSC. Various fault transient durations. (a) Real power control, (b) rotor angle response, (c) speed deviation (W1-W2) rad/sec.

(a)
(b)
(c)

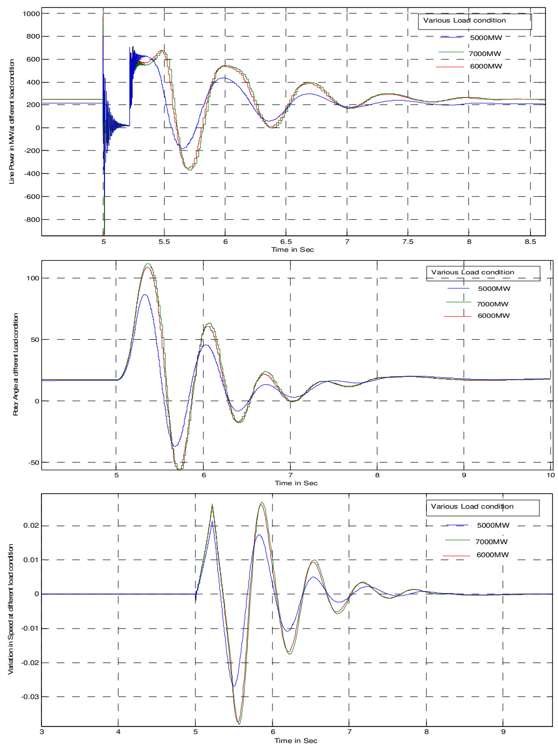

Fig. 12. ANN SSSC. Various load conditions. (a) Real power control, (b) rotor angle response, (c) speed deviation (W1-W2) rad/sec.

C. System Response with the ANN-based SSSC

1) System Response for Various Fault Transient Durations

The simulation results of the system with the ANN-based SSSC are shown in Figure 11.

2) System Response at Various Load Conditions

Under various load conditions, the results of the SSSC with ANN for a three phase fault of 0.22 sec duration are shown in Figure 12. The results show that the system is more stable for 5000 MW applied load. The difference in system performance parameters at 7000 MW and 8000 MW applied load is quite minor.

D. ANN-PI Control System Response Comparison

1) Power Flow

Figure 13 illustrates the comparative response of PI and ANN controller line power with respect to time, with a fault introduced between buses B2 and B3 for duration 0.22 sec. We can draw the conclusion that the ANN control of the SSSC enhances power flow. Compared with the PI control, the actual power improves by over 10% with ANN control.

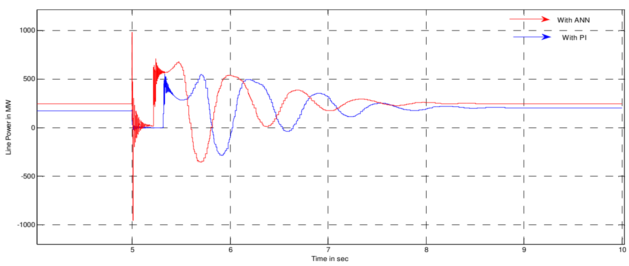

Fig. 13. Damping response. Red: ANN controller, Blue: PI controller.

2) Rotor Angle Response

The deviation graph of the rotor angle with PI controlled and ANN controlled SSSC with fault induced for a duration of 0.22 sec is shown in Figure 14. The rotor angle is decreased by ANN control during fault conditions.

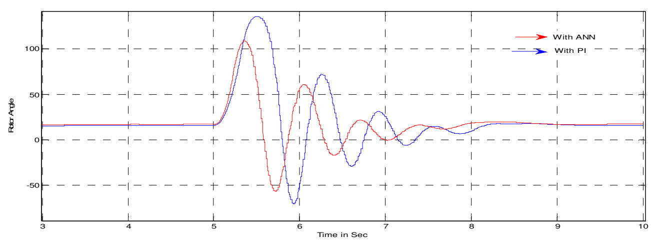

Fig. 14. Rotor angle variation. Red: ANN controller, Blue: PI controller.

3) Speed Deviation

The simulation's output, given in Figure 15, depicts the inter-area oscillations ($\Delta w1 - \Delta w2$), that occur during a three-phase failure at the receiving end between buses B2 and B3. The findings show that when compared to PI controller, the suggested ANN controller performs better dynamically and damps quicker the oscillations under abnormal conditions.

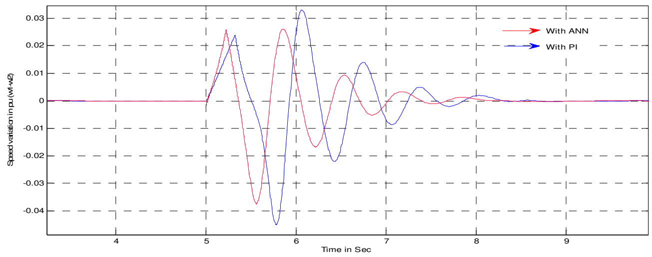

Fig. 15. Speed deviation. Red: ANN controller, Blue: PI controller.

VIII. DISCUSSION

The comparative response of the PI and ANN controllers displayed line power against time, with a fault caused between buses B2 and B3 for duration 0.22 sec. The ANN control of the SSSC improves power flow. In comparison to PI control, the ANN control enhances real power by more than 10%. Considering the inter-area oscillations ($\Delta w1 - \Delta w2$), the findings show that the suggested ANN controlled SSSC outperforms the PI controller. The simulation result summary with respect to rotor angle, indicating the increased damping performance of the designed ANN controller over the PI based-controller is shown in Table I.

TABLE I. COMPARATIVE PERFORMANCE OF ANN BASED SSSC AND PI BASED SSSC WITH RESPECT TO ROTOR ANGLE

Controller	First peak for 0.22 sec fault duration	Settling time of response	No. of oscillations
PI based	136 deg	8.3 sec	4
ANN based	108 deg	8 sec	3

Table I indicates that the ANN-based SSSC significantly improved the damping performance during sudden large disturbance, thus improving power system security.

IX. CONCLUSION

As the performance of the PI-based SSSC degrades with changing system conditions, an intelligent controller for SSSC is necessary. There are very few articles that discuss ANN-based SSSC. The current research describes the standard PI-based SSSC performance in both steady-state and abnormal conditions. For damping oscillations under fault conditions, an ANN-based SSSC is constructed with two input variables: voltage change and voltage rate of change. The local mode of oscillations is investigated. The multimachine model of the sample system is used to validate the function of the proposed SSSC controller in MATLAB. The ANN and PI controller designs for the system's SSSC are presented. Under various system conditions, comparative performance of the controllers is shown in terms of the line's ability to handle power, rotor angle deviation, bus voltage, terminal voltage, and inter-area oscillations. The proposed ANN controller provides higher dynamic performance when compared to the PI controller. The findings demonstrate that, in contrast to the PI controller, the use of ANN-based control in abnormal conditions immediately dampens power oscillations and improves power flow.

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