POWER SYSTEM SECURITY ENHANCEMENT BY NARX ANN MODEL BASED STATIC SYNCHRONOUS SERIES COMPENSATOR

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Abstract:

Ensuring the security of power systems has become an increasingly complex challenge due to the growing intricacies and dynamic nature of modern grids. This paper introduces a novel approach to strengthening power system security by integrating a Nonlinear Autoregressive with Exogenous Inputs (NARX) Artificial Neural Network (ANN) model with a Static Synchronous Series Compensator (SSSC). The NARX ANN model is applied to forecast key system parameters, facilitating real-time and adaptive control of the SSSC. A comparative performance between a conventional Proportional-Integral (PI) controller and the NARX-based SSSC shows that the NN controller outperforms the PI controller in respect of dynamic performance. The NARX controller is designed to quickly mitigate power oscillations and improve power flow control during disturbances, surpassing the conventional PI controller's capabilities. The proposed controller uses two input signals—reference voltage and measured voltage at the SSSC location. The training data is generated from the difference between these two signals. The model's results were validated using MATLAB simulation.

1 Introduction

In the future, with the rise of energy market deregulation and electricity wheeling, there will be a heightened demand for transmission systems to demonstrate increased flexibility and responsiveness in managing power flow. Stability in electric power systems refers to the grid's ability to regain balance and return to normal operations following any physical disturbances. The cornerstone of ensuring secure and reliable operations is maintaining system stability. Due to technological advancements and innovation, the demand for power continues to rise, resulting in interconnected power networks stretching over long transmission lines. As demand grows, these power systems often operate near their maximum capacity, making it increasingly challenging to ensure the safe operation of the grid when faced with disturbances of varying magnitudes. Such disturbances can lead to undesirable oscillations, which, if left unmanaged, may cause severe stability issues [1]. A nonlinear dynamic model of a multi-machine power system integrated with an fuzzy based IPFC to enhance the damping of power system oscillations and improve transient stability and effectiveness is compared with PI controller. [2]. Techniques such as sliding mode control of SSSC with RBFN allow for the regulation of DC voltage [3]. This study evaluates the performance of SSSC within transmission networks using both PI and advanced intelligent control techniques. Introducing a neural network (NN) controller has been proposed to offer superior dynamic performance compared to traditional

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PI controllers [4], [6], [8]. Fuzzy logic is employed to improve the stability margin and control voltage in SSSC systems, boosting overall performance [7]. This study explores the damping control capability of (SSSC) implemented in power systems. A linearized model of the SSSC integrated within the power network is developed, and approaches for designing its damping controller are proposed [14]. SSSChas been developed using the EMIT simulation package. Its functionality is tested by connecting it in series with a basic transmission line, which can be readily swapped with the utility's more intricate existing power system network [17]. An analytical hierarchy process is utilized to determine the optimal location for SSSC integration within the test system [18]. Study examines the optimal placement of shunt FACTS devices in transmission lines to maximize benefits under normal operating conditions. The analysis is carried out using three different line models: the line impedance model, the reactance model, and the pi (π) model [21]. There is also a comparative study on PI and ANN controllers for managing inter-area oscillations [23]. The performance of the IPFC is evaluated using the Modified Phillips-Heffron Model, comparing PI controllers with Fuzzy Logic Controllers and Multilayer Feedforward Network (MFFN) controllers [25]. Numerous studies have examined the performance of SSSCs under various load conditions, including both steady-state and disturbed scenarios. These studies reveal that using a NARX controller in place of the traditional PI controller significantly reduces power oscillations and improves power flow during abnormal conditions. Additionally, the effectiveness of SSSCs with PI-based controllers tends to decrease under changing system conditions, emphasizing the need for a more advanced, intelligent controller for the SSSC.

This study is conducted on a moderately sized power system. The proposed controller is developed using two key signals: the reference voltage and the measured voltage at the SSSC location. The training data is generated by calculating the difference between these reference and measured voltage signals at the SSSC's position. The NARX ANN-based SSSC network proves to be more effective in handling nonlinear systems, and the paper presents several notable contributions in this regard.

- Dynamic power flow control is achieved by leveraging real-time data from the power system, allowing the NARX ANN to anticipate power flow variations and modify the SSSC's output to ensure optimal flow and system stability.
- In addition, NARX ANN aids in damping inter-area oscillations by forecasting voltage and current fluctuations, enabling the SSSC to inject the appropriate compensating voltage.
- For stability enhancement, NARX models can foresee potential instabilities, such as voltage collapse or frequency deviations, and adjust the SSSC's voltage injection to take preventive action.
- Furthermore, the NARX ANN can be trained to detect fault patterns or disturbances and modify the SSSC's output to address these issues effectively.

1.1 Modelling of SSSC

The SSSC is used to enhance the stability by dynamically controlling power flow in the transmission line. It enhances voltage regulation and can mitigate oscillations, especially during disturbances or fluctuating system conditions [20].

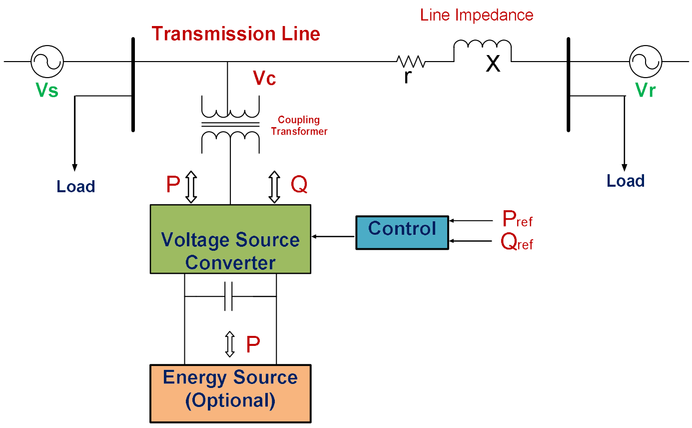


Figure.1. Circuit Diagram of SSSC

The SSSC (Static Synchronous Series Compensator) can regulate the active power flow P by adjusting the line reactance X, using the equation (1) for power flow:

$$P = \frac{VsVr}{X'} Sin\delta \tag{1}$$

Where:

- P is the active power transmitted between two buses,
- Vs and Vr are the voltages at the sending and receiving ends, respectively,
- X′ is the line's effective reactance after compensation by the SSSC, and
- δ is the phase angle between Vs and Vr

The SSSC injects a controllable series voltage (Vc) into the transmission line, altering the reactance X′. This change in reactance affects the active power flow: a reduction in reactance X′ increases power flow, while an increase in reactance reduces it.

Additionally, the SSSC influences reactive power Q in the transmission line. The equation (2) is for reactive power

$$Q = \frac{V^2}{X'} - \frac{V^2}{X} \tag{2}$$

Where:

- X is the original line reactance,
- X′ is the effective reactance after SSSC compensation, and
- V is the voltage magnitude (in kV or per unit) at the point where power flow control is being applied.

The SSSC adjusts the injected voltage to either raise or lower the effective reactance, thus increasing or decreasing the reactive power flow.

1.2 Test Network

A multi-machine test system, including an SSSC, is used to evaluate the power network's performance during transient conditions, as shown in Figure 2. The system is with Generator G1 has a capacity of 1000 MVA, and Generator G2 has a capacity of 5000 MVA, while the load demand is 5000 MW. The system also includes a 1000 MVA and a 5000 MVA transformer, as well as a 100 MVA VSC-based SSSC.

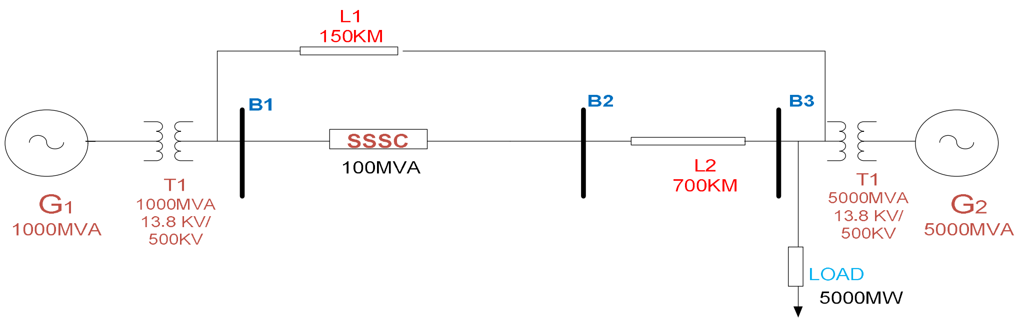


Figure 2. Test system

2 NARX ANN Controller Modelling

In this configuration, the NARX neural network is employed to model and forecast the nonlinear dynamic behavior of SSSC. The NARX model learns the system's response to different inputs (such as voltage) and generates predictions that help adjust the SSSC's control actions.

Key components of the NARX-ANN-based SSSC include:

- Inputs (Exogenous Inputs): These are variables like line current, bus voltage, power flow, and other measurable power system parameters, which influence the SSSC's control decisions.
- Outputs (Controlled Outputs): The primary output predicted or controlled by the NARX ANN could be the compensation voltage injected by the SSSC, power flow, or system stability indicators.
- Time Delays: The NARX network utilizes past values of both input variables (such as previous voltage and current) and output variables (like previously injected voltages) to predict the system's future behavior.

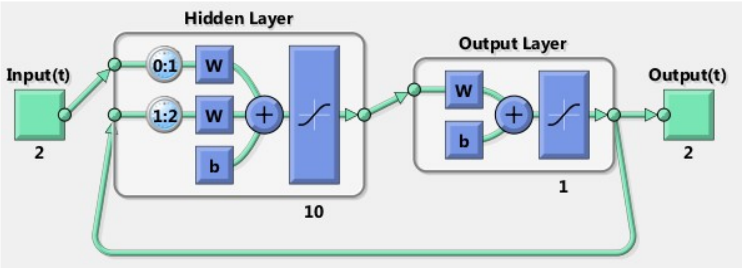


Figure 3. Structure of developed NARX controller

The NARX ANN is trained using back propagation through time, with the objective of minimizing prediction errors. The network is trained to predict the output based on both exogenous inputs (e.g., bus voltages, line currents) and past outputs. Once trained, the model is validated with unseen data and tested in real-time simulation or physical experiments to ensure its robustness in real-world conditions.

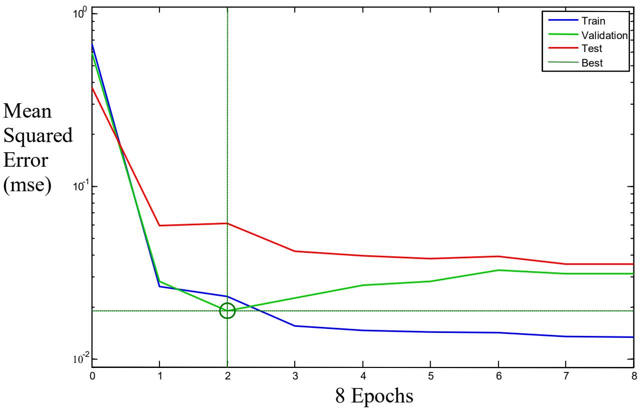


Figure 4. Accuracy plot

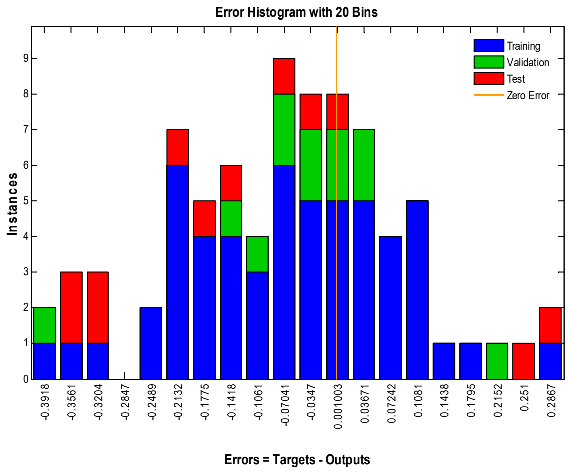


Figure 5. Histogram plot

The accuracy plot shown in Figure 4 illustrates the training, validation, and testing performance of a NARX NN model over several epochs. The MSE is shown on a logarithmic scale to accommodate a broad range of values. According to the graph, the optimal validation performance is achieved at epoch 2, where the MSE reaches 0.019047. After epoch 2, a rise in both validation and test errors suggests the model may be overfitting.

The histogram in Figure 5 displays the error distribution for the NARX NN model. This error histogram provides a visual representation of how accurately the NARX model is predicting outputs relative to the true target values for all datasets. The majority of the errors are clustered around zero, which indicates that the model's predictions are generally close to the actual target values, reflecting good performance.

The figure 6 illustrates a control system for a SSSC that uses a NARX neural network. The system's main objective is to control the output voltage Vq−conv, which allows the SSSC to regulate power flow by injecting a series voltage into the line. The measured voltage Vq−mes is compared with the reference voltage Vq−ref to generate an error signal. This error is then processed through a PI controller, which includes both proportional (Kp) and integral (Ki) components. Additionally, the direct-axis current Id is managed by a proportional gain (Kp) control. The NARX neural network helps predict the control actions by learning from the system's past behavior. The outputs from the PI controller, the NARX neural network, and the power system stabilizer are combined to generate the adjusted output voltage Vq−conv, which in turn controls the SSSC's voltage regulation.

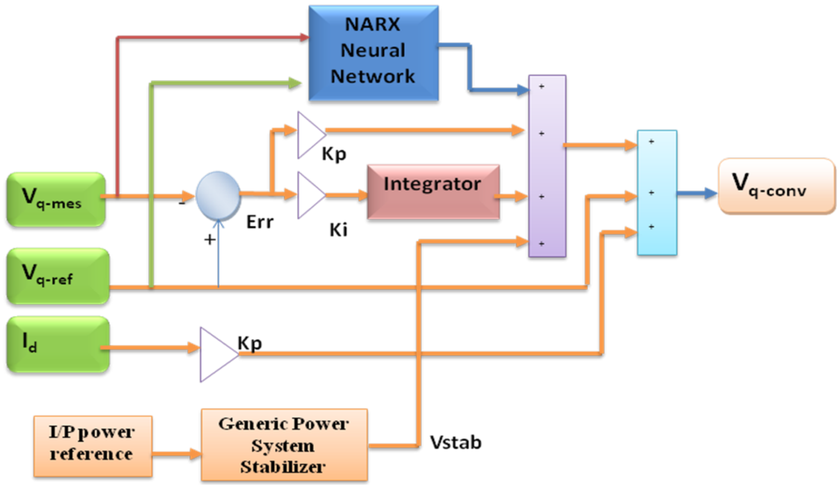


Figure 6. Control network of a SSSC with NARX

3 NARX with SSSC

The flowchart shown in figure 7 illustrates an intelligent control framework combining a NARX Artificial Neural Network (ANN) with a Static Synchronous Series Compensator (SSSC) to enhance power system performance. Real-time power system inputs such as voltages, currents, and power flow are first preprocessed to remove noise and normalize data. The cleaned data is then fed into a NARX-ANN, which uses past outputs and exogenous inputs to predict future system behavior. These predictions are evaluated against stability criteria to generate appropriate control signals. The SSSC control algorithm uses these signals to determine the voltage to inject into the transmission line, improving system stability and power flow. The resulting system response is fed back into the loop for continuous learning and real-time adaptation.

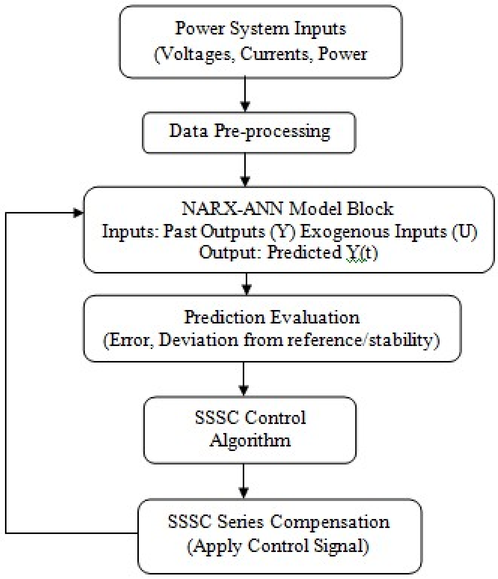
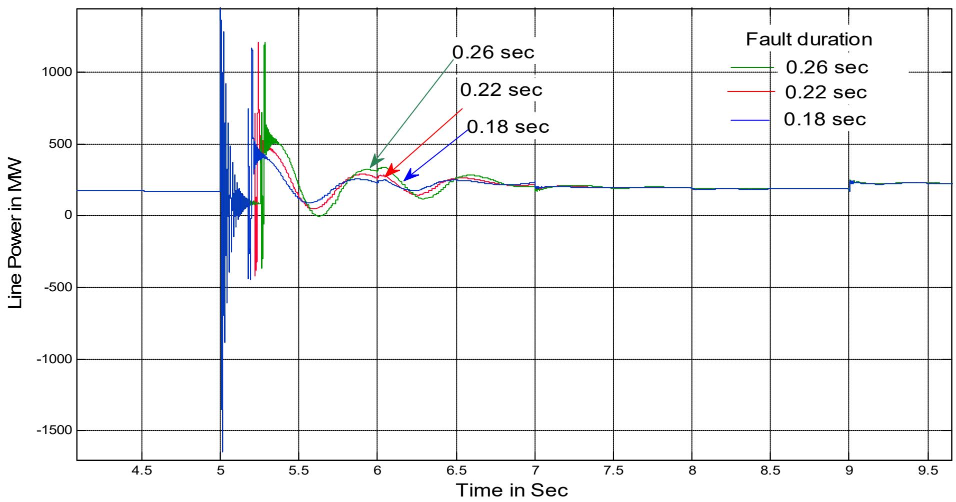


Figure 7. Flowchart for NARX with SSSC

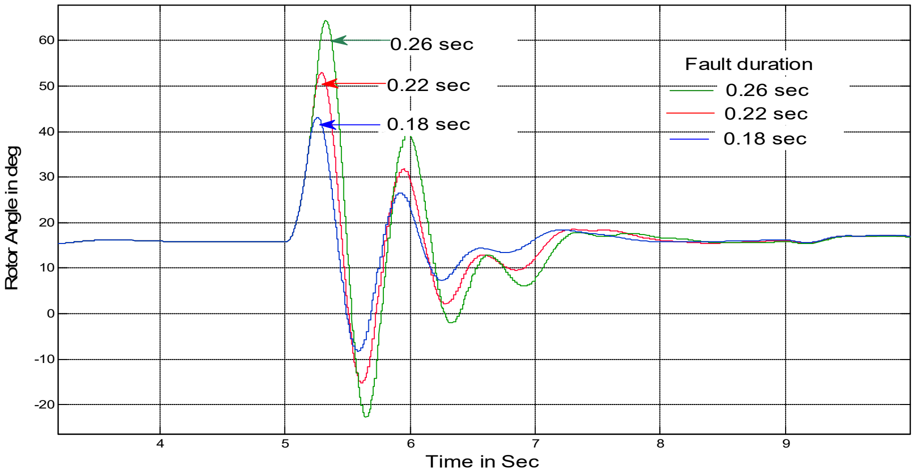
4 Simulation Response

The simulation performance is evaluated by applying 3-phase faults with durations of 0.18s, 0.22s, and 0.26s near bus B3, reflecting a transient condition. Parameters such as real power, rotor speed, rotor angle, and bus voltage are recorded. Transient disturbances can cause imbalances in the network and trigger oscillations. To address these issues, balancing devices can be introduced. An SSSC equipped with a NARX controller is connected between buses B1 and B2 to assist in stabilizing the network during disturbance events and the test system was successfully modelled. In this proposed setup, the outputs of both PI and NARX controllers are analysed and compared under various conditions. The findings from MATLAB Simulink simulations are presented for further examination.

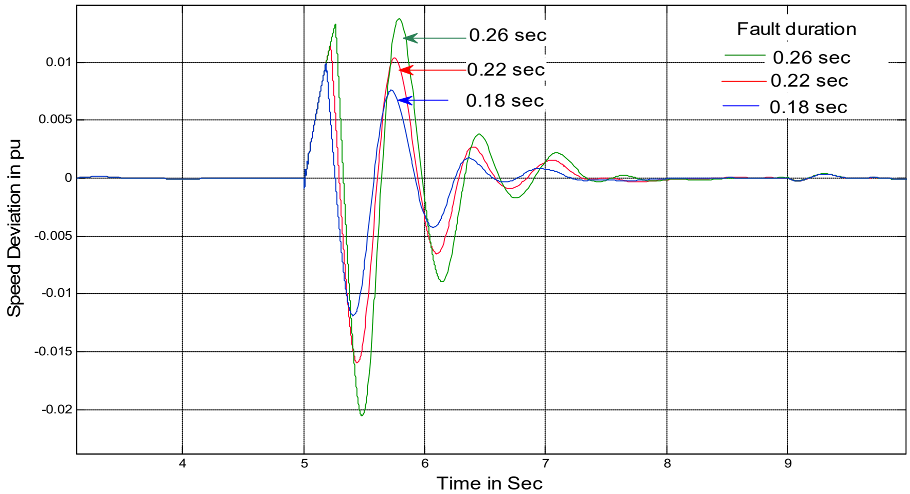
The NARX-based SSSC proves to be an effective solution for stabilizing the system under fault conditions. As seen in Figure 7, the severity of disturbances depends on the fault duration, with longer faults causing more pronounced oscillations in line power, rotor angle, speed deviation, and bus voltage. Figure 8(a) shows the response of the line power to faults at different durations. The system experiences significant oscillations immediately after the fault, especially at 0.26s. The magnitude of the disturbance is initially higher with longer fault durations, but the system stabilizes eventually as the SSSC controller works to mitigate the effect of the fault. Figure 8(b) displays transient oscillations following the fault. For longer fault durations (0.26s), the rotor angle shows larger deviations, peaking around 60 degrees before stabilizing. Faults of shorter durations (0.18s) result in smaller deviations in the rotor angle, indicating better stability. Figure 8(d) illustrates the system's voltage response to faults. Initially, a drop is observed right after the fault, especially for the longest fault duration (0.26s). The system voltage shows oscillatory behaviour before stabilizing. For shorter fault durations, the voltage dip is smaller and the recovery is quicker. The NARX-based SSSC works effectively to restore and maintain the voltage within acceptable limits after the transient period.



(a)



(b)



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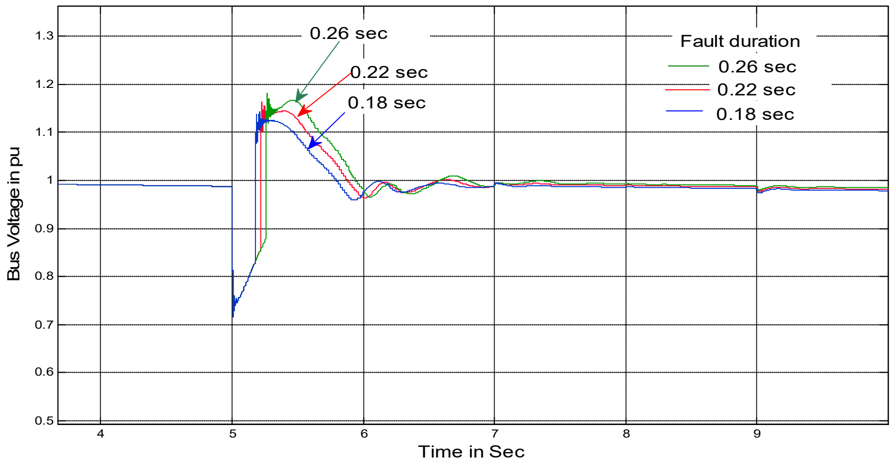
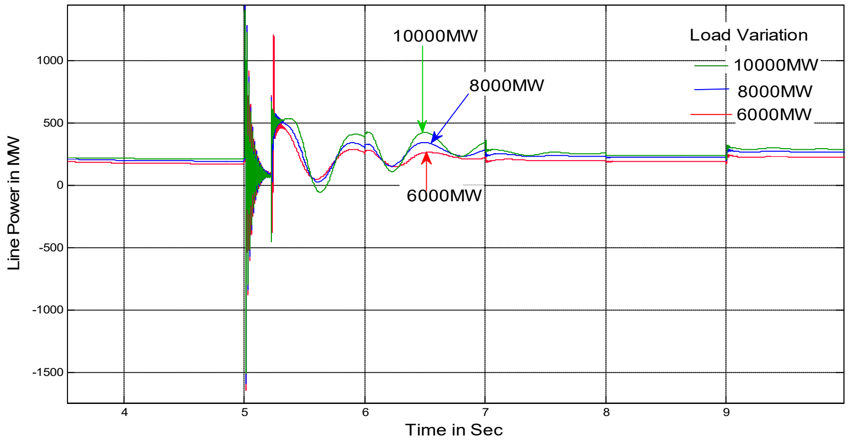


(d)

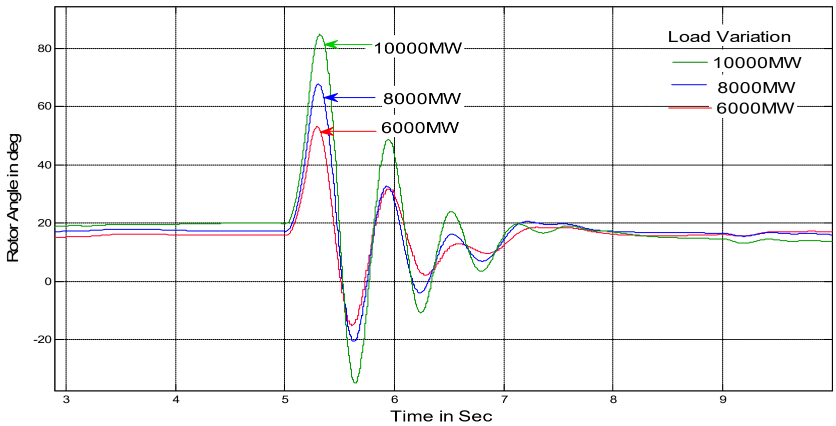
Figure 8. NARX based SSSC with various fault duration (a) Real power flow (b) Rotor Angle (c) Speed deviation (d) bus voltage

Figure 9(a) illustrates how the power transferred over the line responds to load changes over time. The system with a higher load experiences larger deviations, indicating a higher instability risk. However, over time, the oscillations diminish, and the system returns to a more stable operating point. In Figure 9(b), we see that the rotor angle exhibits significant deviations following a disturbance. Over time, these oscillations gradually reduce, leading to system stabilization. The NARX-based Static Synchronous Series Compensator (SSSC) plays a crucial role in damping these oscillations, restoring the system to stability more efficiently than in a system without such compensation. Figure 9(c) focuses on the speed deviations of the rotor. The system experiences more considerable speed deviations for higher loads following the disturbance. However, with the NARX-based SSSC, these oscillations are damped more effectively, allowing the system to return to its nominal speed more quickly, indicating improved dynamic performance and overall stability. Lastly, Figure 9(d) illustrates the bus voltage behaviour after the disturbance. Similar to the other variables, the bus voltage experiences oscillations, particularly in the case of higher load conditions. Over time, the system stabilizes, and the voltage returns to its nominal value. The NARX-based SSSC helps regulate the bus voltage by controlling the reactive power flow, ensuring that the voltage levels stabilize and remain within acceptable limits.

In summary, the NARX-based SSSC enhances the stability of the power system by damping oscillations in power transfer, rotor angle, speed deviation, and bus voltage, leading to improved dynamic performance and faster recovery after disturbances.



(a)



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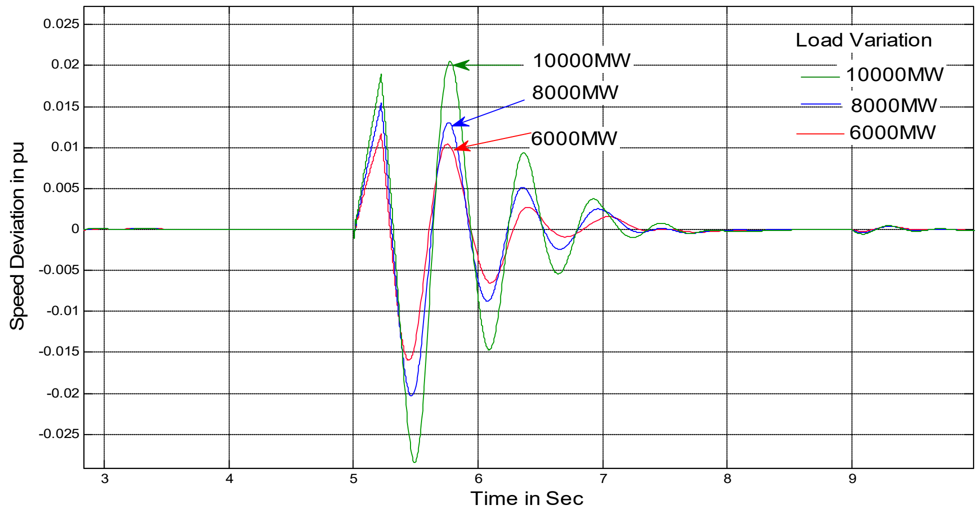

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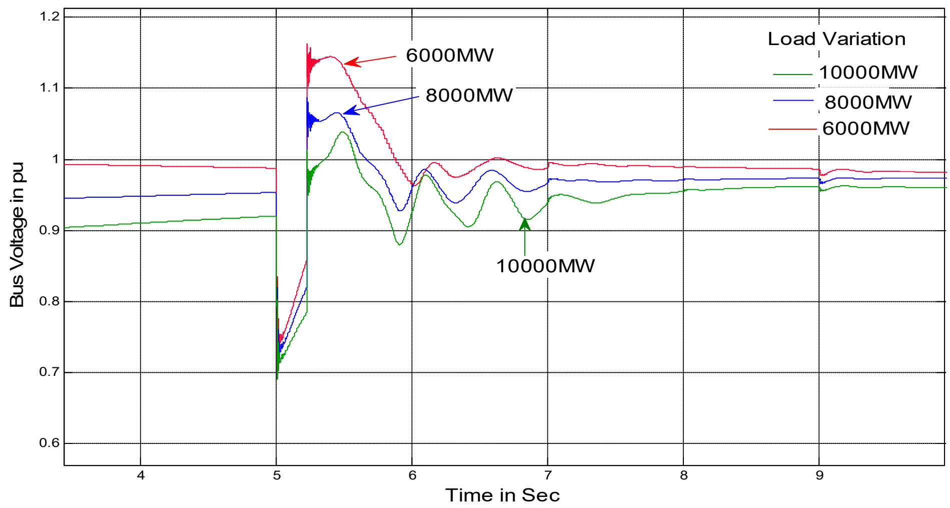
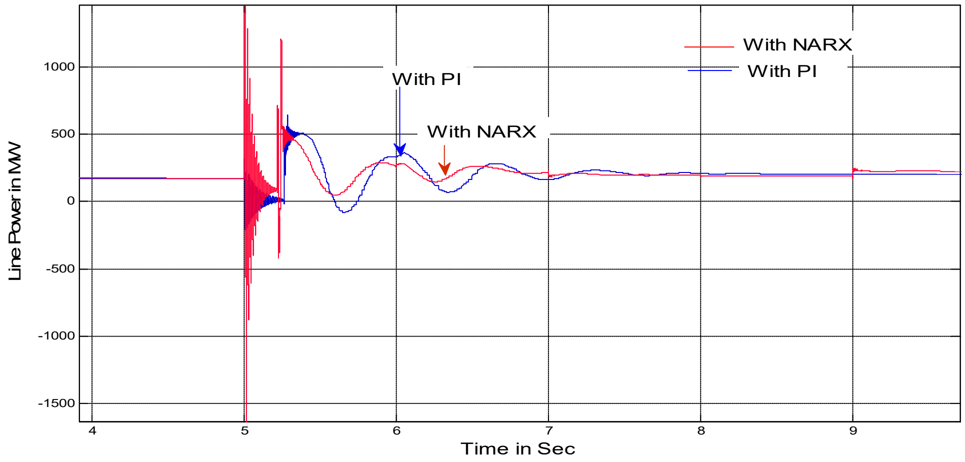


(d)

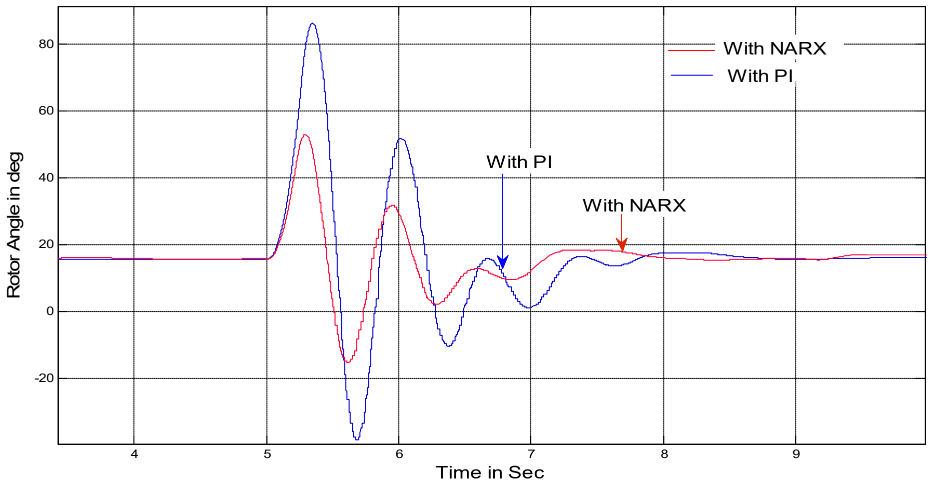
Figure 9. NARX based SSSC with various load condition (a) Real power flow (b) Rotor Angle (c) Speed deviation (d) bus voltage

Figure 10(a) depicts the power transfer over the line and the system's response to a disturbance. The NARX controller efficiently damps the power transfer oscillations faster than the conventional PI controller. In Figure 10(b), the rotor angle response is shown, highlighting the system’s behaviour following a disturbance. The NARX-based controller enables faster damping of rotor angle oscillations and stabilizes more rapidly after an initial overshoot, reducing the risk of instability associated with larger deviations. Figure 10(c) presents the system's speed fluctuations after a disturbance. Both controllers eventually restore the speed to its nominal value, but the NARX controller offers a quicker response and enhanced dynamic performance, effectively minimizing oscillations compared to the PI controller. Lastly, Figure 10(d) shows the voltage response, where the NARX controller ensures a faster return to nominal voltage levels, enhancing voltage stability during high-load conditions or disturbances.



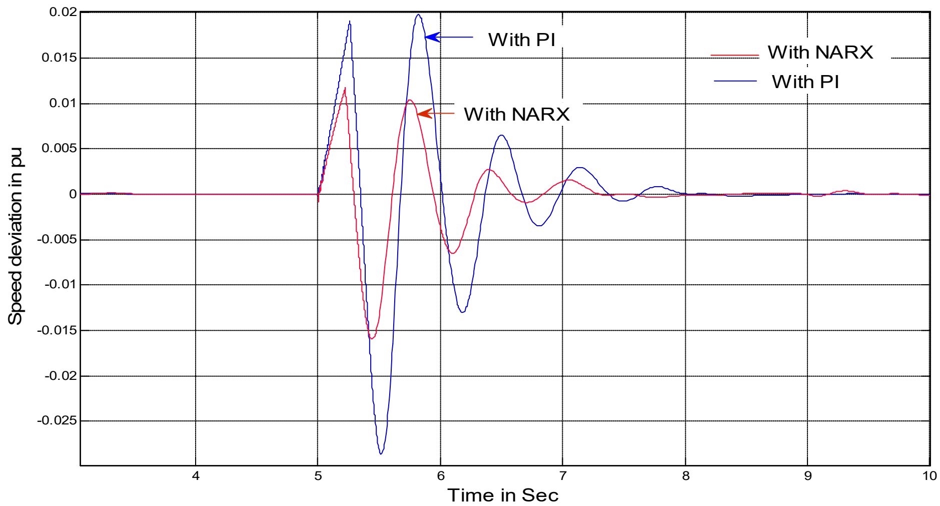
Line Power in MW
1000
500
0
-500
-1000
-1500
4
5
6
7
8
9
Time in Sec
With PI
With NARX
With NARX
With PI

(a)



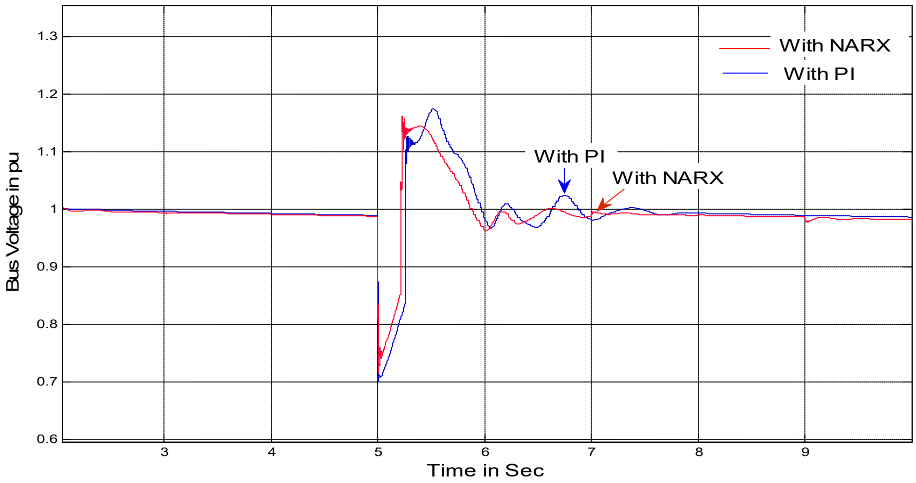
Rotor Angle in deg
80
60
40
20
0
-20
4
5
6
7
8
9
Time in Sec
With NARX
With PI
With PI
With NARX

(b)



Speed deviation in pu
0.02
0.015
0.01
0.005
0
-0.005
-0.01
-0.015
-0.02
-0.025
4
5
6
7
8
9
10
Time in Sec
With PI
With NARX
With NARX
With PI

(c)



(d)

Figure 10. Comparative response of NARX Based SSSC with PI based SSSC (a) Real power flow (b) Rotor Angle (c) Speed deviation (d) bus voltage

5 Discussion

The simulation evaluates power system performance by introducing 3-phase faults near bus B3 with durations of 0.18s, 0.22s, and 0.26s, simulating transient disturbances. Parameters such as real power, rotor speed, rotor angle, and bus voltage are recorded. Transient faults lead to network imbalances and oscillations, which can be mitigated using balancing devices. In this case, a SSSC equipped with a NARX controller is placed between buses B1 and B2 to help stabilize the network during disturbances.

The simulation results specify that the NARX-based SSSC effectively stabilizes the system during faults, with fault duration influencing the severity of disturbances. For longer fault durations (0.26s), larger oscillations in power, rotor angle, speed, and voltage are observed, but the system eventually stabilizes as the SSSC mitigates the disturbances. The rotor angle and voltage show more pronounced deviations with longer faults, but they stabilize as the controller works to restore normal conditions. Load variations are also studied, with higher loads causing greater instability, but the NARX-based SSSC effectively dampens oscillations, improving stability and dynamic performance.

The comparison between the PI and NARX controllers shows that the NARX controller offers faster damping of oscillations in power, rotor angle, speed, and voltage, leading to quicker system stabilization and enhanced performance, especially during disturbances or high-load conditions. Overall, the NARX-based SSSC proves to be a more effective solution for maintaining system stability compared to the conventional PI controller. The application of NARX control to the SSSC improves power flow, resulting in an over 10% increase in real power compared to the PI controller. The line's injected voltage was tested with a rise of 10% to 20%, leading to an increase in power flow. Table 1 provides simulation data for the generator's rotor angle, highlighting the improved damping performance of the NARX controller in comparison to the PI-based SSSC. The first peak of the rotor angle decreases significantly from 86 degrees to 53 degrees, and the number of oscillations is also reduced with the NARX-based SSSC. Additionally, the rotor angle's settling time is shorter with the intelligent controller.

The results indicate that the NARX-based SSSC significantly improves damping performance during sudden disturbances and enhances the security of the power system.

Table I : Rotor angle response with NARX based SSSC and PI based SSSC

Type of controller	First peak when fault duration is 0.22Sec	Settling time	No. of oscillation
PI based	86 deg	8 Sec	4
NARX based	53 deg	7.2 Sec	3

6 Conclusion

The NARX-based SSSC is designed to improve the transitory stability of the sample power system. The main goal of the design is to maximize power flow while minimizing oscillations during major disturbances in a multi-machine system. The results show that the NARX-based SSSC controller significantly improves the stability margin of the power system compared to the PI-based SSSC. It increases actual power transfer by nearly 10% and reduces rotor speed oscillations more quickly. Additionally, the NARX-based SSSC greatly enhances damping performance during sudden disturbances and improves the security of the power system. The simulation confirms that the proposed objectives for the NARX-based SSSC are successfully achieved. Although this work is tested on a moderately sized power system, it can be extended to larger systems with more buses, and the proposed SSSC can also be evaluated for congestion management.

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