J. Electrical Systems 20-11s (2024): 1408-1416

Sapana Arun Bhande[1*]
Dr. Vinod Kumar Chandrakar[2]
Dr. Sonali N. Dhurvey[3]

Radial Basis Function Network-Based Static Synchronous Series Compensator For Power System Security Enhancement

ABSTRACT

Power system oscillation presents a substantial risk to the stability of power systems. The impact of oscillation damping significantly influences the safety of contemporary power systems. This research explores the enhancements in power security by improving transient stability and damping oscillation by using a Radial Basis Function Network (RBFN)-based Static Synchronous Series Compensator (SSSC). A comparison between two controllers, the conventional PI controller and the RBFN, reveals that the neural network based controller demonstrates superior dynamic performance over the typical proportional integral (PI) controller. RBFN controller is design to achieve, during disturbances promptly reduces power oscillations and enhances power flow control as compared to the PI controller. The proposed controller is designed with two signals, reference voltage and measured voltage at SSSC location. The training data developed with difference between reference voltage and measured voltage signals at SSSC location. The validation of results done in MATLAB environment.

Keyword- *FACTS; SSSC; PI; RBFN; Capacity for handling power; Oscillations Damping*

I. INTRODUCTION

In the upcoming era of utility deregulation and power wheeling, there will be an increased requirement for transmission systems to exhibit greater flexibility and agility in controlling power flow. Electric power system stability refers to the grid's capability to restore equilibrium and return to regular functioning after experiencing any physical disruption. The most critical factor in establishing secure and dependable operation is power system stability. Because of technological complexity and innovation, power demand is increasing. Because of this ongoing need, linked power networks exist via long transmission lines. To accommodate rising demand, such power systems are run close to their full capacity. Ensuring the safe functioning of power systems poses a significant challenge when faced with various disruptions, whether minor or major, in power networks. These disturbances have the potential to amplify undesirable oscillations within the power system, which, if left unchecked, can lead to significant stability issues [1]. The results obtained from MATLAB/Simulink analysis indicate that employing SSSC with POD and ANN holds greater promise in mitigating network oscillations. Moreover, integrating SSSC with POD and ANN enhances the actual power of the system, thereby increasing network capacity [2].Control of DC voltage in transmission line and power flow improvement is possible by sliding mode technique of SSSC with RBFN [3]. Through the utilization of PI and intelligent control methodologies, the study examines the effectiveness of SSSC within transmission networks. The introduction of a neural network (NN) controller is suggested to potentially offer superior dynamic performance compared to the conventional PI controller [4-6, 8]. Fuzzy logic was employed to improve the stability margin and manage voltage in the SSSC system, aiming to enhance its overall performance [7, 14, 17]. The analytical hierarchy technique is employed to identify the most suitable location for integrating SSSC within the test system [18].Comparative study of conventional PI and ANN for inter area oscillation [23].

Many researches documented SSSC performance under a variety of load circumstances, including static and disturbed system. [2,4,6]. In this, The findings indicate that employing RBF instead of the PI controller effectively mitigates power oscillations and enhances power flow during abnormal scenarios. Moreover, the effectiveness of SSSCs equipped with a PI-based controller diminishes when subjected to fluctuating system conditions, highlighting the need for an intelligent SSSC controller.

There are very few studies on RBF-based SSSC as compare to multi layer feed forward network with single and multi machine test system. This work is tested in moderate size of power system. The proposed controller is designed using two signals: the reference voltage and the measured voltage at the SSSC location. The training data is generated based on the difference between these reference and measured voltage signals at the SSSC location. The multilayer feed forward network need more data for training, whereas RBFN need less training data and less layer to achieve improve system security. The RBFN based network results are more effective in nonlinear system as compared to multi layer feed forward network, the following significant contributions in this paper

- Performance of traditional PI-based SSSCs in both steady and faulted conditions.
- The comparative performance of RBF-based SSSC controller with traditional PI controller for inter-area oscillation.
- SSSC controller is validated through MATLAB using a Multimachine model of the sample system.
- In order to mitigate oscillations during fault conditions, an RBF-based SSSC utilizes dual input parameters: voltage deviation and the rate of voltage deviation. The research investigates the local oscillation mode of oscillations.

[1*] Research Scholar, G H Raisoni College of Engineering, Nagpur, pbcoe.sbhande@gmail.com
[2] Professor in Electrical Engineering, G H Raisoni College of Engineering, Nagpur, v12k5c63@gmail.com
[3] Assistant Professor, Priyadarshini College of Engineering, Nagpur, sonal.nd2014@gmail.com

II. OVERVIEW & MODELING OF SSSC

The SSSC is crucial for regulating both active and reactive power by utilizing a coupling transformer, in the line as illustrated in Figure (1) [20]

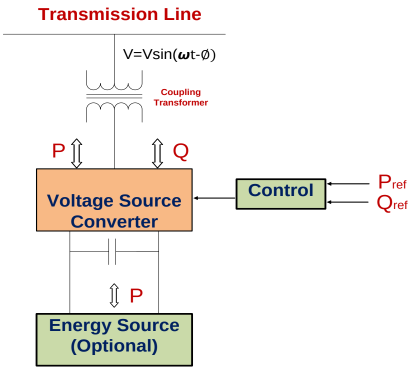

Fig.1. Circuit Diagram of SSSC

Figure 2 comprises the two bus transmission line with r, X and Vc where r is the line's resistance, X is the reactance and Vc is the voltage injection. The vector representation of the same is shown in figure 3[20]

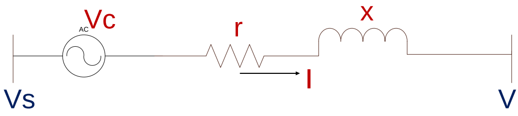

Fig. 2. Equivalent Circuit with injected voltage Vc

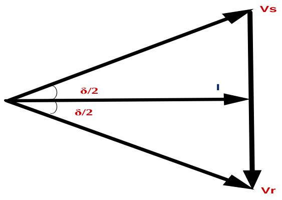

Fig. 3. Vectror diagram

Equation (1) illustrates the voltage drop in transmission line.

$$IX - Vc = 2V\sin\frac{\boldsymbol{\delta}}{\mathbf{2}} \tag{1}$$

The current equation is as

$$I = \frac{Vc}{X} + \frac{2V\sin\frac{\delta}{2}}{X} \tag{2}$$

Equation (3) gives the Active power

$$P = VI\cos\frac{\delta}{2} = \frac{VVc}{X}\cos\frac{\delta}{2} + \frac{V^2}{X}\sin\delta \tag{3}$$

Equation (4) illustrate the reactive power equation of line

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

The equation (5) provides the current in the compensator.

$$I = \frac{2V\sin\frac{\delta}{2}}{X(1-Kse)} \tag{5}$$

The adjustment of injection voltage enables the control of power flow. [20]

III. TEST NETWORK

To assess power network performance during transient conditions, a multi-machine test system with an SSSC is employed, depicted in Figure 4. The test network encompasses two generators, one load, two transformers, two lines, and three buses. The system is simulated using MATLAB/Simulink, with the following parameters: Generator G1 has a capacity of 1000 MVA, while G2 has a capacity of 5000 MVA, and the load is 5000 MW. Additionally, the system features a 1000 MVA and a 5000 MVA transformer, along with a VSC-based 100 MVA SSSC.

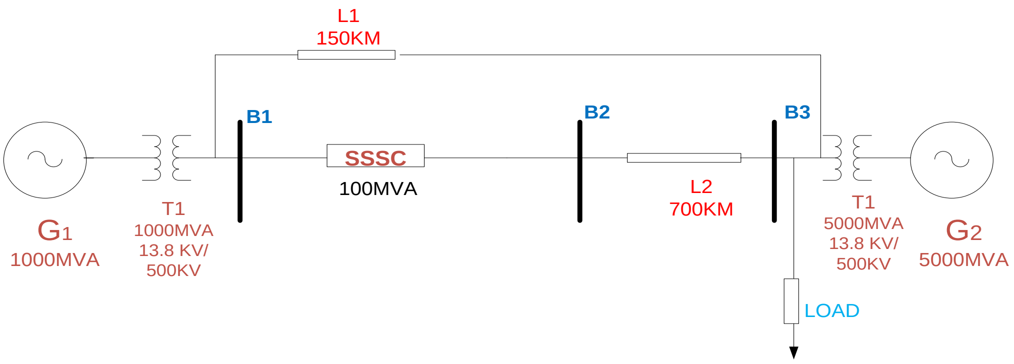

Fig. 4. Test system

IV. SSSC -RBFN CONTROLLER MODELING

A Radial Basis Function Network (RBFN) represents a variant of artificial neural networks that employs radial basis functions to activate its neurons. It's structured into three layers: input, hidden, and output. Input information is received by the input layer and then transmitted to the neurons within the hidden layer. Inside the hidden layer, radial basis functions are strategically positioned across the input space. Each neuron calculates its output by evaluating the distance between the input vector and its center. The output layer consolidates the outputs of the hidden layer neurons to produce the network's final output.

The processes involved in RBF controller modeling are:

Initialization: The centers of the radial basis functions are usually initialized using clustering algorithms like K-means.

Training: During the training process, the weights of both the hidden and output layers are adjusted iteratively to reduce the difference between the network's predictions and the expected outcomes. This adjustment aims to achieve the desired results with minimal error. To evaluate and quantify the accuracy of the model, various statistical metrics such as mean square error (MSE) and root mean square error (RMSE) are commonly used. These metrics can be mathematically represented and calculated by Equations (6) and (7).

i) Mean square error (MSE) is a non-negative value that reflects the average of the squared differences between the predicted and actual values. It serves as an indicator of a model's prediction accuracy, with smaller MSE values signifying better model performance. To compute MSE, the difference between predicted and actual values for each data point is squared, these squared differences are then summed, and the total is divided by the number of data points. [24].

$$\mathrm{MSE} = \frac{1}{n}\sum_{i=1}^{n}(\mathrm{Actual}_i - \mathrm{Predicted}_i)^2 \tag{6}$$

ii) Root mean square error (RMSE) measures a model's accuracy by taking the square root of the average of the squared differences between the predicted and actual values..

$$\mathrm{RMSE} = \frac{1}{n}\sum_{i=1}^{n}((\mathrm{Actual}_i - \mathrm{Predicted}_i)^2)^{0.5} \tag{7}$$

Prediction: Once trained, the RBFN can predict fresh input data by sending it through the network and computing the output using the learnt weights. A schematic structure of RBF model as shown figure 6[24] where x is the input vector $\boldsymbol{\omega}$ is weight vector and Z is the RBF Function. The PI based SSSC is replaced with this RBF network. The Output of RBF Vqref is given to SSSC.[24]

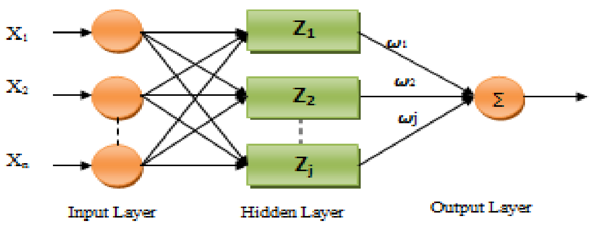

Fig. 6. A schematic structure of RBF model.

An RBF controller designed for an SSSC utilizes radial basis functions to estimate the control action required for regulating power flow within a transmission line. Parameters including centers, widths, weights, and output weights are adjusted through training to attain optimal performance.

In the context of an SSSC, the RBF controller takes as input system variables voltage error signal obtained between the measured voltage Vq_mes and Reference Voltage Vq_ref. The RBF controller uses radial basis functions to transform this voltage Vq into a hidden layer representation. During the training phase, the parameters of the radial basis functions (centres and widths) are changed using techniques such as gradient descent to reduce the difference between the measured voltage Vq_mes and the reference voltage Vq_ref. Once trained, the RBF controller can generate the appropriate control signals Vq_conv for the SSSC based on the current system conditions. Through constant adaptation of the SSSC's output voltage using input variables and the acquired mapping, RBF controller efficiently manages power flow and enhances system stability. Generated error samples between reference voltage and measured voltage at the device location. Mainly 70% of the data is used for training the neural network, 20% used for target and 10% for testing. Data generated for different location of SSSC in the sample power system.

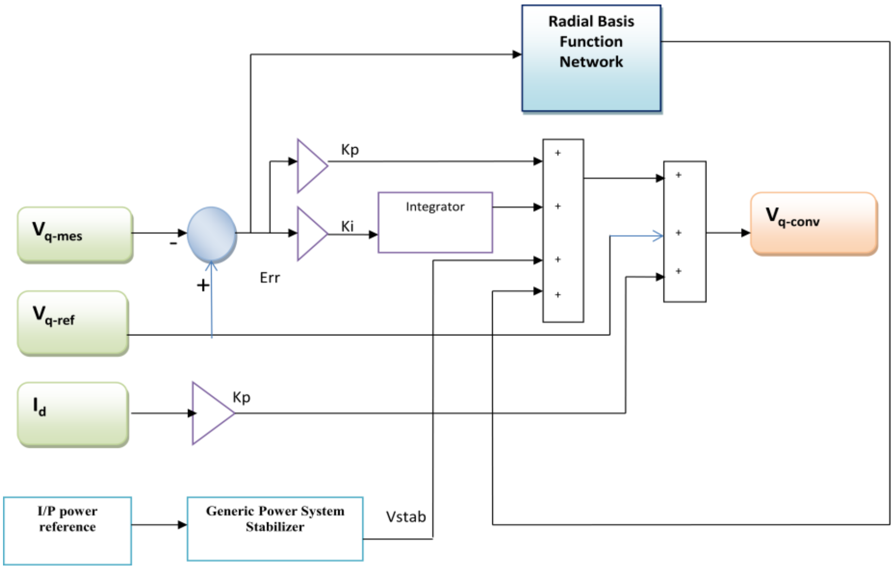

Fig. 7. Control network of a SSSC with RBFN

After training the network, The accuracy plot shown in fig. 8 shows the mean squared error (MSE) over a series of epochs for a static synchronous series compensator (SSSC) model with a radial basis function network (RBFN). The plot includes the training, validation, and test performance, with specific highlights on the best validation performance. The best validation performance is reached at an MSE of 1.5864e-05 at epoch 0. The graph includes separate curves for training, validation, and test data, showing how the model performed on each dataset over 6 epochs. Generated error samples between reference voltage and measured voltage at the device location. Mainly 70% of the data is used for training the neural network, 20% used for target and 10% for testing. Data generated for different location of SSSC in the sample power system

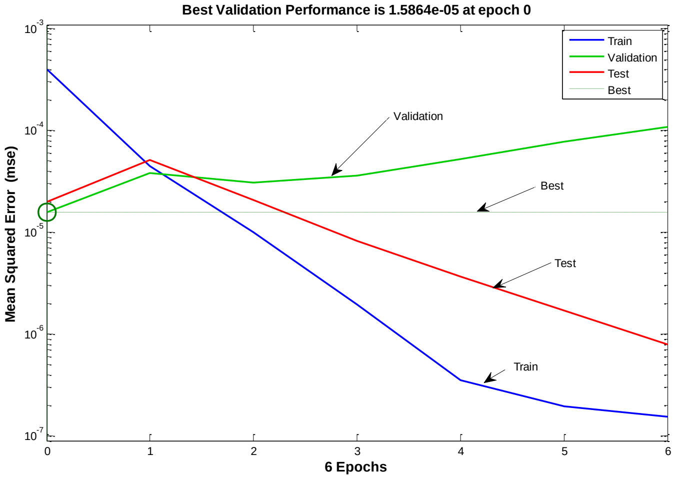

Fig. 8. Accuracy plot

V. SIMULATION RESPONE

Simulation performance is evaluated using 3-phase faults with durations of 0.18s, 0.2s, and 0.22s near bus B3, indicating a transitory situation. Several characteristics, such real power, rotor speed, rotor angle, and bus voltage is measured. Transient situations or disruptions can cause imbalanced network parameters and oscillations. To avoid such failures, balancing device can be connected. The SSSC with RBF controller is connected between bus B1 and B2 to support the network under disturbance situations and the test system was successfully simulated. In a proposed system, the output of the PI and RBF controllers is evaluated and compared under various conditions. The outcomes obtained from MATLAB Simulink simulations are presented for analysis.

Figure 9 shows the system response of RBF based SSSC which implies the Simulation response of real power, rotor angle, speed deviation and bus voltage for 3 $\boldsymbol{\Phi}$ fault at bus B3 for duration 0.18s, 0.2s, and 0.22s. After simulation of system with RBFN based SSSC, figure 9(a) shows another crucial feature of RBF based SSSC that is power damping, Power oscillation increases as the fault duration increase. Settling time and first peak of rotor angle also increases as shown in figure 9(b). The simulation's output in figure 9(c) which depicts the inter-area oscillations (Δw1− Δw2), the inter-area oscillation decreases as fault duration decreases.

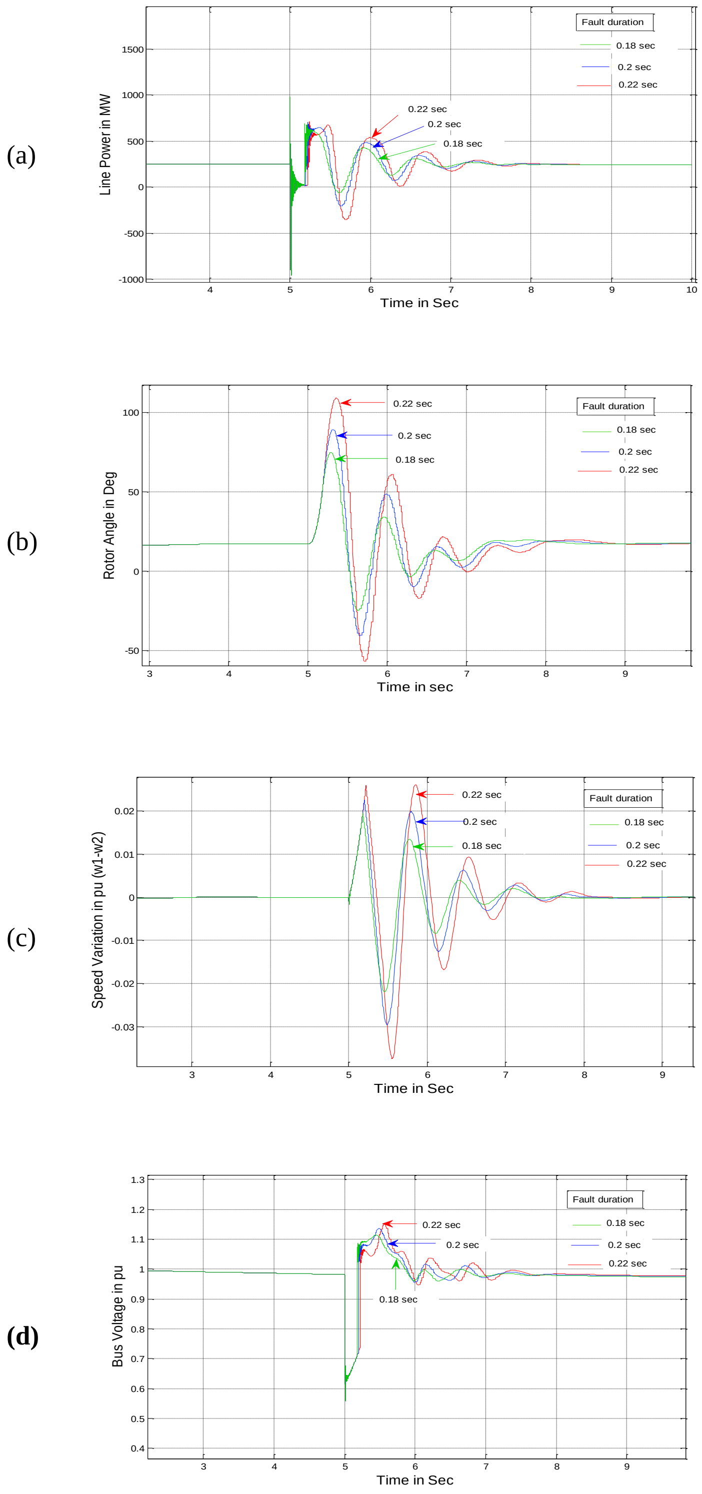

Fig. 9. RBF SSSC with various fault duration (a) Real power flow (b) Rotor Angle (c) Speed deviation (d) bus voltage

Figure 10 demonstrates the system response of an RBF-based SSSC, indicating the simulation response of actual power, rotor angle, speed deviation, and bus voltage under various load conditions at receiving end. Increased load makes the system more unstable. The oscillation is more when the load of 7000 MW is applied as compared to load of 6000MW. The variation in system performance metrics between 6000MW and 6500MW is fairly modest. When the load above 7000MW is applied, then the system goes in unstable condition.

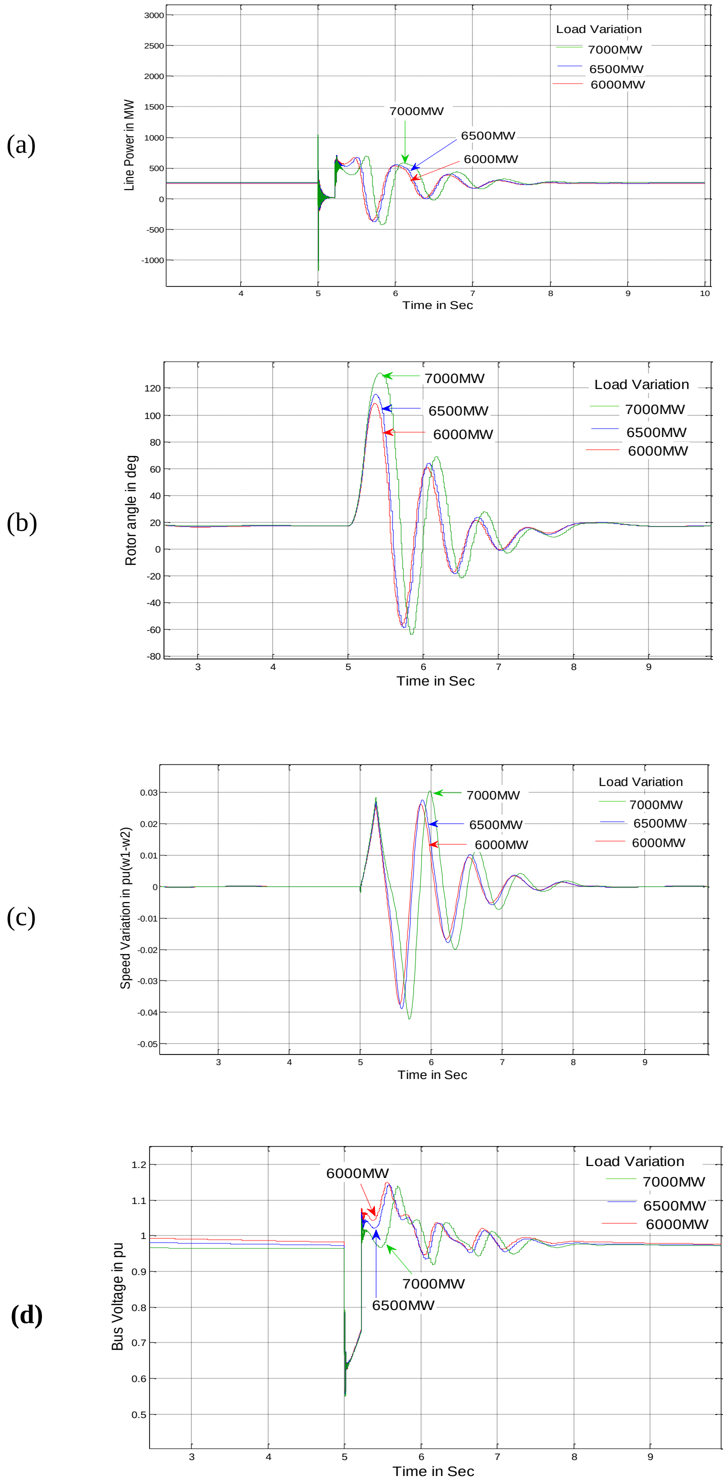

Fig. 10. RBF SSSC with various load condition (a) Real power flow (b) Rotor Angle (c) Speed deviation (d) bus voltage

Figure 11 compares the performance of PI-based SSSC with RBF-based SSSC in terms of actual power, rotor speed, rotor angle, and bus voltage when a 3 Φ fault occurs at bus B3 lasting 0.22 seconds. The network using PI-based SSSC exhibits greater oscillations and requires more time to stabilize than RBF-based SSSC. The connected RBF based SSSC boost the true power nearly by 10% than suggested PI controller as shown in figure 11(a). The inclusion of an RBF-based SSSC demonstrates a more effective suppression of rotor angle δ and oscillation when contrasted with a PI-based

SSSC, as illustrated in Figure 11(b). The simulation outcomes depicted in Figure 11(c) illustrate the inter-area oscillations ($\Delta\boldsymbol{\omega}1$ - $\Delta\boldsymbol{\omega}2$) triggered by a $3\boldsymbol{\Phi}$ failure. Connecting RBF to SSSC gives more remarkable results since less settling time required to damp out rotor speed oscillations. Hence the system with RBF based SSSC helps to increase stability margin during transient time.

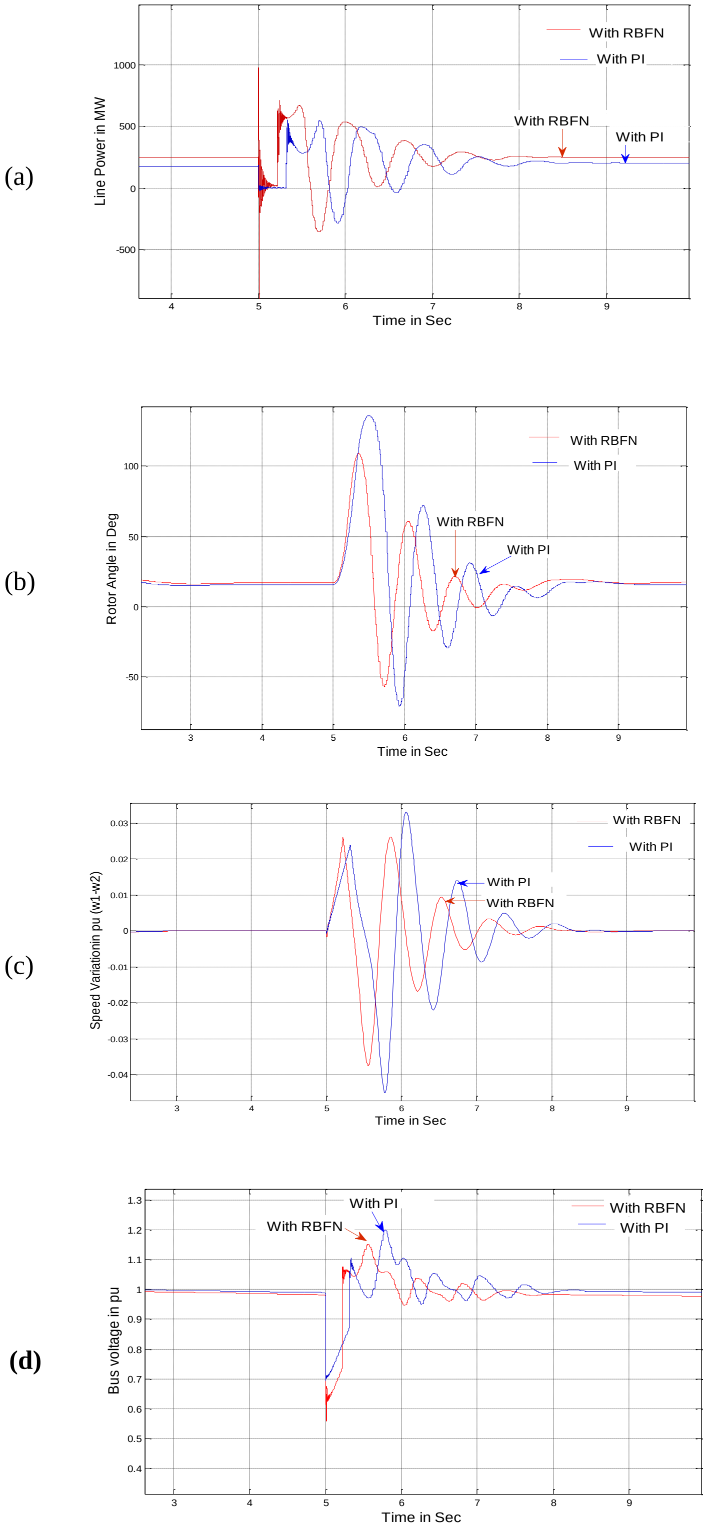

Fig. 11. Comparative response of RBF SSSC with PI based SSSC (a) Real power flow (b) Rotor Angle (c) Speed deviation (d) bus voltage

VI. DISCUSSION

System performance is evaluated in MATLAB during various transient conditions 1. Three-phase faults with various durations of 0.18s, 0.2s, and 0.22s near bus B3 2.with various load condition of 6000MW, 6500MW and 7000MW and

3. The comparative response of RBF based SSSC with PI based SSSC with fault duration of 0.22s at bus B3. The other responses such as real power, rotor speed, rotor angle and bus voltage is measured. The proposed controller increase the stability margin even after fault duration increases . In case of load variation, the system is stable for large MW load. A comparison of PI and RBFN controllers reveals line power flow, highlighting a failure between buses B2 and B3 for 0.22 seconds. The implementation of RBF control on the SSSC enhances power flow, exhibiting a more than 10% increase in real power compared to PI control. The injected voltage on the line tested for 10% to 20% rise, which increases the power flow. Table 1 presents simulation results of generator rotor angle, demonstrating the comparative damping performance of the RBFN controller versus the PI-based controller of the SSSC. The first peak of rotor angle significantly reduces from 140 deg to 107 deg. and number of oscillations also reduces with ANN based SSSC. The settling time of rotor angle also reduces with intelligent controller.

The result shows that RBFN based SSSC greatly enhanced damping performance during sudden disturbances and increases power system security.

TABLE I : ROTOR ANGLE RESPONSE WITH RBF BASED SSSC AND PI BASED SSSC

Type of controller	First peak when fault duration is 0.22Sec	Response settling time	Number of oscillation
PI based	140 deg	8.35 Sec	4
RBFN based	107 deg	8 Sec	3

VII. CONCLUSION

The RBFN based SSSC is design to improve transient stability of the sample power system. The design objective is to maximize power flow while minimizing oscillations under major disturbances in a multi-machine system. The results indicate the proposed RBFN based SSSC controller is significantly improved the stability margin of power system as compared to a PI based SSSC. The RBFN based SSSC increases actual power handling by neatly 10% compared to the PI controller and damp out rotor speed oscillations in less time. The simulation results indicates that the proposed objectives of RBFN based SSSC is achieved. This work is tested in moderate size of power system whereas it can be tested with more number of buses may be implemented. With this proposed SSSC performance can be tested for congestion management.

REFERENCES

[1] L. Wang, Q.-S. Vo, and A. V. Prokhorov, “Stability Improvement of a Multimachine Power System Connected With a Large-Scale Hybrid Wind-Photovoltaic Farm Using a Super capacitor,” IEEE Trans. Ind. Appl., vol. 54, no. 1, pp. 50–60, Jan. 2018.

[2] S. N. Dhurvey, V. K. Chandrakar, “Improvement of Power System Performance using Fuzzy Logic Based Interline Power Flow Controller,” *Journal of Power and Energy Engineering*, vol. 4 no. 4, pp 67-77, April 2016, https://doi.org/10.4236/jpee.2016.44007.

[3] Lionel Leroy Sonfack, Godpromesse Kenné, Andrew Muluh Fombu, “A New Static Synchronous Series Compensator Control Strategy Based on RBF Neuro-Sliding Mode Technique for Power Flow Control and DC Voltage Regulation,” *Taylor & Francis,Electric Power Components and Systems*, vol. 46, no. 4, 2018, https://doi.org/10.1080/15325008.2018.1445795.

[4] Dr. M Vasavi Uma Maheswari, P Mahesh, “Compare The effectiveness of SSSC in Transmission network using PI and ANN control with POD Controller,” *International Journal for Modern Trends in Science and Technology, vol. 8, no. 9,* pp 231-236, 2022, https://doi. : https://doi.org/10.46501/IJMTST0809047.

[5] V.K.Chandrakar, A.G.Kothari, “Comparision of RBFN and Fuzzy based STATCOM Controller for Transient Stability improvement,” *International Aegean Conference on Electrical Machines and Power Electronics IEEE*, 2007, https://doi.org/10.1109/ACEMP.2007.4510556

[6] V.K. Chandrakar and A.G .Kothari, “MFFN based Static Synchronous Series Compensator (SSSC) for Transient Stability improvement,” *International Conference on Intelligent System Applications to Power Systems, ISAP Kaohsiung,* November pp 4 -8, 2007.

[7] V.K.Chandrakar, A.G.Kothari “Fuzzy Logic based Static Synchronous Series Compensator(SSSC) for Transient Stability Improvement,” *IEEE International Conference on Electric Utility Deregulation, Restructuring and Power Technologies Hong Kong,* (DRPT2004), April 2004, pp 240-245, https://doi.org/10.1109/DRPT.2004.1338500.

[8] V.K.Chandrakar, A.G.Kothari, “RBFN based Static Synchronous Series Compensator (SSSC) for Transient Stability improvement,” *IEEE 9th International Conference on Control, Automation, Robotics and Vision, Singapore,* 2006, https://doi.org/10.1109/ICARCV.2006.345227.

[9] Prajakta Vaidya, V. K. Chandrakar, “Exploring the Enhanced Performance of a Static Synchronous Compensator with a Super-Capacitor in Power Networks,” *Engineering, Technology & Applied Science Research*, vol. 12, no. 6, 2022, pp 9703-9708, https://doi.org/10.48084/etasr.5317.

[10] Vedashree P. Rajderkar, Vinod K. Chandrakar, “Design Coordination of a Fuzzy-based Unified Power Flow Controller with Hybrid Energy Storage for Enriching Power System Dynamics,” *Engineering, Technology & Applied Science Research*, vol. 13, no. 1, 2023, pp 10027-10032, https://doi.org/10.48084/etasr.5508.

[11] S. V. Chandrakar, J. B. Helonde, R. M. Mohril, V. K. Chandrakar, “Fuzzy Based SVC with coordinated POD for Damping of Oscillation of Power System*,” WSEAS Transactions on Power System*, vol 5, July 2010, pp 253-261.

[12] S. N. Dhurvey, V. K. Chandrakar, “Performance Comparison of PI and Fuzzy Logic Based IPFC on Damping of Power System Oscillation,” *International Journal of Power Systems*, vol 2, 2017, pp 94-104.

[13] S. N. Dhurvey, V. K. Chandrakar, “Damping Of Power System Oscillations With Coordinated Tuning Of UPFC and POD,” *Asian Power & energy System*, IASTED, pp 270-275.

[14] H.F. Wang, “Design of SSSC Damping Controller to Improve Power System Oscillation Stability,” *Africon. 5th Africon Conference in Africa IEEE*, 1999, pp 499-500, https://doi.org/10.1109/AFRCON.1999.820931.

[15] Ishwar Lal Yadav, Satayadharma Bharti,“Stability Enhancement for Transmission Lines using Neural Network in Static Synchronous Series Compensator,” *International Journal of Scientific Engineering and Technology*, vol.4 no.6, pp: 365-369, 2015.

[16] Saidi Amara, Hadj Abdallah Hsan, “Power system stability improvement by FACTS devices: a comparison between STATCOM, SSSC and UPFC,” *IEEE, First International Conference on Renewable Energies and Vehicular Technology*, 2012, pp 360-365, https://doi.org/10.1109/REVET.2012.6195297.

[17] Kalyan K. Sen, “SSSC - Static Synchronous Series Compensator: Theory, Modelling, and Applications*,” IEEE Transactions on Power Delivery*, vol. 13, no. 1, pp 241-246 January 1998, https://doi.org/10.1109/61.660884.

[18] K. Padma,K. Vaisakh, “Application of AHP Method for Optimal Location of SSSC Device under Different Operating Conditions, *“International Conference on Intelligent Control Power and Instrumentation (ICICPI), IEEE* 2016, pp 210-214, https://doi.org/10.1109/ICICPI.2016.7859704.

[19] Narain G. Hingorani, Laszlo Gyugyi, “*Understanding FACTS- Concepts and technology of flexible AC transmission system*,” by IEEE press, Standard publishers distributors

[20] Sapana A Bhande, Vinod K Chandrakar. "Static Synchronous Series Compensator (SSSC) to Improve Power System Security*," International Conference on Electronics and Renewable Systems (ICEARS)*, 2022 https://doi.org/10.1109/ICEARS53579.2022.9752146.

[21] V K Chandrakar, AG Kothari, “Optimal location for line compensation by shunt connected FACTS controller,” *The Fifth International Conference on Power Electronics and Drive Systems*, IEEE, vol 1, pp 151-156 https://doi.org/10.1109/PEDS.2003.1282736.

[22] V K Chandrakar, SN Dhurvey, SC Suke, “Performance comparison of SVC with POD and PSS for damping of power system oscillations,” *3rd International Conference on Emerging Trends Engineering and Technology, IEEE*, 2010, pp 247-252, https://doi.org/10.1109/ICETET.2010.136.

[23] Sapana Bhande, V K Chandrakar, “Enhancement of Power System Security by the Intelligent Control of a Static Synchronous Series Compensator,” *Engineering, Technology & Applied Science Research* Vol. 13, No. 5, 2023, pp 11953-11958 https://doi.org/10.48084/etasr.6150

[24] Alireza Zendehboudi, R. Saidur,, I.M. Mahbubul, S.H. Hosseini, “Data-driven methods for estimating the effective thermal conductivity of nanofluids: A comprehensive review,” *International Journal of Heat and Mass Transfer*, Vol 131, 2019, pp 1211–1231, https://doi.org/10.1016/j.ijheatmasstransfer.2018.11.053

[25] R. H. Adware, V. Chandrakar, "Comprehensive Analysis of STATCOM with SVC for Power Quality Improvement in Multi Machine Power System”, *International Conference on Power Electronics & IoT Applications in Renewable Energy and its Control (PARC)*, Mathura, India, 2022, pp. 1-5, doi: 10.1109/PARC52418.2022.9726566.

[26] P. Jagtap, V. Chandrakar, "Comparative Study of UPFC Controllers to Improve Transient and Dynamic Stability of Power System,” *IEEE 4th International Conference on Computing, Power and Communication Technologies (GUCON), Kuala Lumpur, Malaysia*, 2021, pp. 1-7, doi: 10.1109/GUCON50781.2021.9573804.

[27] Vedashree P. Rajderkar, Vinod K. Chandrakar, “Security Enhancement through the Allocation of a Unified Power Flow Controller (UPFC) in a Power Network for Congestion Management,” *Engineering, Technology & Applied Science Research*, Vol. 13, No. 4, 2023, pp 11490-11496, https://doi.org/10.48084/etasr.6075

[28] Akshay N. Deshmukh, Vinod K. Chandrakar, “Analysis and mitigation of power quality (PQ) issues in 0.3MW solar photovoltaic system (SPV) connected to grid with MPPT tracker and controlled load using PSCAD software,” Engineering Review, Vol. 44, No. 1, 2024 pp 99-113

[29] R. H. Adware, V. Chandrakar, “A Hybrid STATCOM Approach to Enhance the Grid Power Quality associated with a Wind Farm,”Engineering, Technology & Applied Science Research, Vol 13 No 4, 2023 https://doi.org/10.48084/etasr.6125

[30] R. L. Kapse, V. K. Chandrakar, "ANN Based Static Var Compensator For Improved Power System Security," *Third International Conference on Artificial Intelligence and Smart Energy (ICAIS)*, Coimbatore, India, 2023, pp. 652-657, doi: 10.1109/ICAIS56108.2023.10073700.

[31] Prashant Jagtap, V.K. Chandrakar “Advanced UPFC Controllers to Improve Transient and Dynamic Stabilty of Power System,” *International Conference on Advances in Mechanical Engineering*, 2024, doi:10.1088/1742-6596/2763/1/012003