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Hybrid Learning Algorithm for Power System Stability: Fuzzy-Neural Control Approach

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Abstract

With the aim of enhancing the small signal stability of electric power systems, the present paper evaluated and compared some power system stabilizers (PSSs). The dilemma of small signal instability is avoided by equipping the generator's automatic voltage regulator (AVR) with a backup controller known as a PSS. Conventional PSS operates with acceptable efficiency when designed to suit specific operating conditions, but there are limitations and drawbacks that arise when disturbances lead to fluctuation in system parameters. Strengthening the design methodology for PSS in the face of these limitations is achieved by adopting artificial intelligence. This research presents a fuzzy, neural system-based approach to the development of PSS. The Adaptive Network Based Fuzzy Inference System (ANFIS) is used to design the Fuzzy Neural Power Systems stabilizer (FNPSS) . ANFIS eliminates the disadvantages of using fuzzy logic and neural networks independently in PSS design. The single machine infinite bus (SMIB) power system was used as a case study to evaluate the effectiveness of the proposed methodology. Additionally, the study includes root locus scheme for loop of voltage regulation by utilizing proportional Integral controller, P-I controller, a widely used traditional linear design technique, for comparison. The simulation results confirm the effectiveness of the method, demonstrating the superiority of the ANFIS design method over other PSS designs. MATLAB, along with Control System Toolbox and SIMULINK, is used for simulation and design.

Keywords
Fuzzy Logic Controller (FLC), Adaptive Neuro Fuzzy Inference System (ANFIS), P-I Controller , Power System Stabilizer (PSS), Root Locus.

I. INTRODUCTION

Synchronous generators operate in a power system under a range of operational conditions as well as disturbances. They include, among other things, oscillations of active power (swings in electromechanical operation of the power system). Real power oscillations, which could arise if the generator is not adequately dampened could lead to a blackout in a power system or generator failure [1–3] . An extra regulation loop is used by the alternator's excitation-control system to positively moderate such oscillations. This loop is called the PSS. Damping system oscillations improves the dynamic performance related to the power system. With regard to power systems, power oscillation damping controllers commonly fall into two categories: FACTS and PSS controller [4, 5]. In order to enhance power systems' performance and functionality both throughout abnormal and normal operations, PSS is extensively utilized in electric power industry. It could reduce the power system's low-frequency oscillation, raise system positive damping, and boost the steady-state stability margin [6, 7]. The world's main transmission networks are nearly all operating near their stability limits due to the massive growth in demand for power. Fast excitation control is important in these types of systems. For the next reasons, designing efficient excitation controllers for every operating condition is still a challenging challenge:

- Wide range of potential operating conditions.

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- Many different types of disturbances could happen in different areas of power systems.
- Plant parameter variation brought on by modifications to the power network configuration.

Fast excitation control is important in these types of systems. The terminal voltage is intended to be regulated by the excitation controllers. Additionally, improving the system's overall stability are AVRs. For the purpose of designing PSS for various power system models, numerous design techniques and algorithms were put forth over time.

It is helpful to add additional stabilizing signals at low frequency oscillations and raise the synchronous machine's damping torque for lessening such instability effect as well as enhancing the system stability performance [6, 8]. The linearized power system model around the nominal operating point serves as the basis for the parameters of a traditional PSS. Since power systems are extremely non-linear, the performance regarding a typical PSS designed using a linearized power system model cannot be guaranteed in a practical operational environment [9–11].

Intelligent control methods have been enhanced by the development of digital computers. Many previous studies have adopted fuzzy logic in the design of FLPSSs without the need for an accurate mathematical model of the controlled system. Although FLPSSs show an improvement in performance compared to Conventional Power System Stabilizer, CPSSs. The problem of accurately specifying the system parameters and the mechanism of selecting membership functions remains a fault-tolerant problem. Adopting hybrid techniques that rely on adopting fuzzy digital rules in training the neural network by adopting the Neural Fuzzy Inference System (ANFIS) is considered a promising technology [12–14]. The proposed method can adaptively calibrate membership functions and rules to increase system performance.

This paper is organized into five sections. In Section II. , a brief review of the SMIB and AVR model is discussed. In Section III. , Conventional Power System Stabilizer, CPSS design techniques and Artificial Intelligence Power System Stabilizer, AI-PSS Design are discussed. Section IV. presents the simulation results while Section V. provides a conclusion of this work.

II. MODELING OF POWER SYSTEM

A. Synchronous Generator Model

A single machine linked to infinite bus (SMIB) via a transmission line was chosen for stability analysis. The system consists of synchronous generator that supplies electrical power (Pe) to infinite bus, a power grid, through a transmission line.

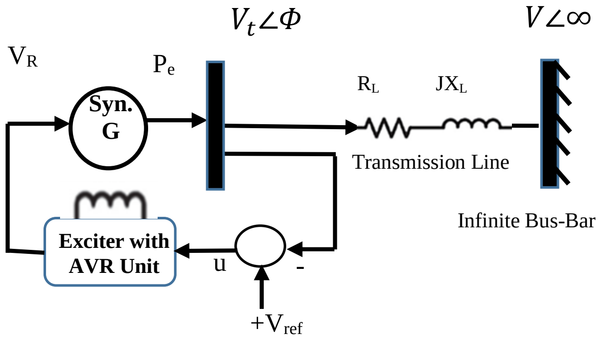


Fig. 1. Schematic diagram for (SMIB) model.

One piece of machinery utilized in generators is the Exciter AVR [15]. The test system's schematic diagram is displayed in Fig. 1. The reference for system data is [16].

For keeping generator terminal voltage V_{term} at the intended value V_{ref}, voltage regulator regulates input u to excitation system, which supplies field voltage. The following is how we view the state-space representation regarding the aforementioned system [1]:

One input variable, three output variables, and three state variables are present, where:
Output variables $y = [\omega \quad \delta \quad V_{term}]^T$
Input variable $u = V_{ref}$
The state variables $x = [x_1 \quad x_2 \quad x_3]^T = [\omega \quad \delta \quad V_{term}]^T$
Where, ω= angular frequency in radian/sec, δ= rotor angle in radian , V_{term}= terminal voltage and $()^T$ is transpose of a matrix $(\cdot)$.

In the state space form, the linearized equations could be rewritten in the following way

$$\dot{X} = AX + BU \tag{1}$$

$$Y = CX + DU \tag{2}$$

The system dynamics are represented by the matrices B, A, D, and C, which can be ascertained by considering the particular features of the power system. In the state-space equations, the matrices A and B are dependent on various system parameters and operating conditions. These parameters and conditions include the system configuration, generator characteristics, network topology, load conditions, and control settings.

The specific values of matrices A and B can be derived by considering the specific system model and the corresponding equations that describe the dynamics of the power system as shown in Fig. 2. Where

$$A = \begin{bmatrix} \frac{-K_D}{2H} & \frac{-K_1}{2H} & \frac{-K_2}{2H} \\ \omega_o & 0 & 0 \\ 0 & \frac{K_3K_4}{t_3} & \frac{-1}{t_3} \end{bmatrix} \tag{3}$$

$$B = \begin{bmatrix} 0 \\ 0 \\ \frac{1}{t_3} \end{bmatrix} \tag{4}$$

B. Power System Stabilizer Structure

The primary aspect of our design problem is PSS structure. The voltage regulator receives a stable output from the PSS, which receives input from filter outputs of rotor speed variables. Because of the unstable operating conditions, PSS functions as damper to oscillation related to synchronous machine rotor. It accomplishes this by providing the voltage regulator a stabilized output after receiving the rotor speed as input (along with rotor's swings). To offer the best damping for stable operation, a PSS is adjusted using a variety of techniques. They are adjusted around what we will attempt to define as a steady state operating point. The PSS is a straightforward component of synchronous generator excitation system that offers an extra dampening torque during a period of generator speed variation [17].

Fig. 3 shows the physical components of the PSS that are required to achieve the desired outcome, which are:

Washout filter, a high pass filter with a dc gain of 0, receives the output (ω) after being sent back through a sign inverter. In the case when the steady state is reached, this is offered to eliminate PSS path. We use the filter as a transfer function model regarding the following in our simulation:

$$W(s) = \frac{10s}{(10s+1)} \tag{5}$$

Torsional Filter, the high frequency oscillations caused by the alternator's torsional interactions are eliminated by this block. We use the filter's transfer function model as the basis for simulation.

$$T(s) = \frac{1}{(1+0.06s+0.0017s^2)} \tag{6}$$

III. CONTROL STRATEGIES ADOPTED IN PSS DESIGN

While reducing oscillations is PSS's primary goal, it could also significantly impact the transient stability regarding the power system. VAR output swings due to PSS damping oscillations through controlling generator field voltage. In order to ensure that the resulting gain margin related to the Volt/VAR swing is adequate, PSS gain is carefully selected. Wash-Out Filter's time constant could be changed to enable frequency shaping regarding the input signal in order to lessen the swing [18]. Once more, throughout loading/unloading or generation loss, in the case when significant variations in speed and frequency might act through PSS and cause the system to become unstable, a control enhancement might be required. The dampening effect of PSS for all other system events will be maintained, whereas such limits can be reduced thanks to a new limit logic. We have two design aspects in the model for control of single-machine excitation system, which are AVR&PSS.

Three strategies were adopted in designing the PSS:

1. Root-Locus approach (Lead-Lead compensator), as traditional technique.
2. Fuzz Logic PSS Design (FLPSS), based on Artificial Intelligence
3. ANFIS to design Fuzzy Neural Power Systems Stabilizer (FNPSS), as adaptive control.

Now go over the approach in depth, going over the steps that were taken, the outcomes that were attained, and, lastly, a quick summary related to the drawbacks and benefits of each approach.

A. Sequential Stages for Optimal AVR/PSS: A Root Locus Approach

The design regarding the PSS and VR with the use of root-locus methods—which are typically taught first in a control systems course—was the first project in sequence. The procedure was laid out in multiple tasks:

Stage1: Simulate the reaction of open-loop system in state of 1-p.u. step input for a duration of 10 seconds. recur the simulation with the presence of PSS-loop open and the system controlled by a relative VR with various gain KP (10, 20,..., 50).

Stage2: innovate a root-locus scheme for loop of voltage regulation by utilizing proportional controller Locate the gain Ku at which the delicately damped swing mode be unstable.

Stage3: Choosing the specifications required for modern high-gain VRs requires the application a PI controller by:

$$KV(s) = K_{PI}(s) = K_P + \frac{K_I}{(s)} \tag{7}$$

Plot the Scheme of closed-loop response of V_{term} during a 1-p.u. V_{ref} step input,

Choose the range of $0 \leq K_P \leq Ku$ and $0.1 \leq K_I \leq 10$ within

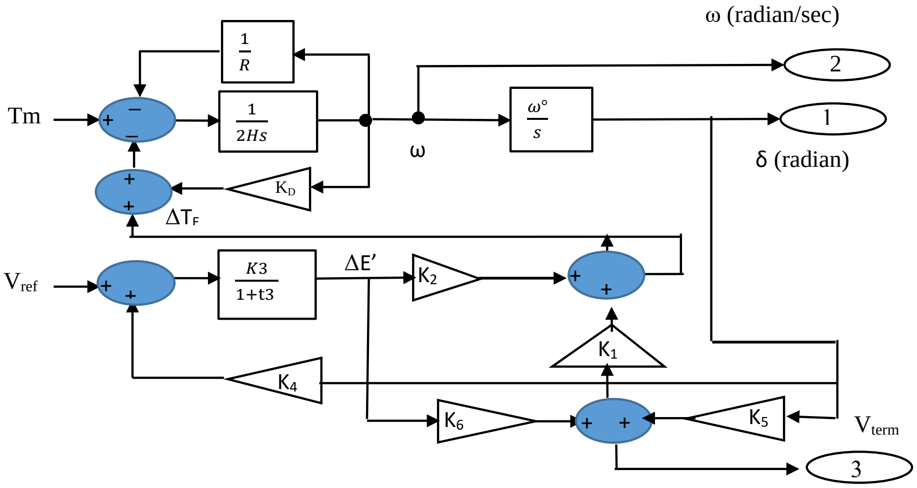


Fig. 2. Block diagram of SMIB system

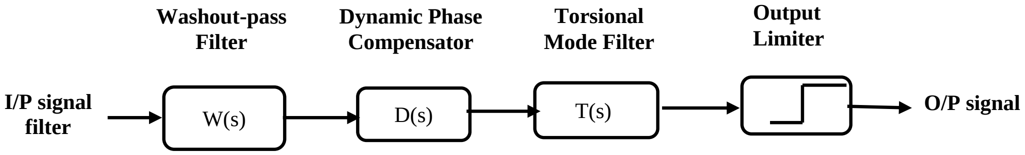


Fig. 3. Block Diagram of PSS

specific value to reach $t_r \leq 0.5$ and $MP \leq 10\%$

Stage4: Lock up the voltage regulation loop through KPI(s), then execute a root-locus analysis of PSS loop based on $\frac{V_{ref}}{\dot{\omega}}$. arguably that torsional filter's output, D(s) adopted to be a proportional gain control.

Determine the departure's angle of ϕdep of the root-locus section leaving the swing form with the positive imaginary aspect [19].

Stage5: According to ϕdep, determining the structure of a second-order phase-lead compensator

$$D(s) = K(K_\alpha \frac{s+z_1}{s+P_1})(K_\alpha \frac{s+z_2}{s+P_2}) \tag{8}$$

Based on the phase-lead characteristics [19] , set $\phi dep = 180°$

Stage6: Apply D (s) to simulate the closed-loop response V_{term} to a 1-p.u. step input. With a guarantee that rise time and the overshoot have been still satisfied (i.e.$t_r \leq 0.5$,$MP \leq 10\%$).

B. Sequential AI-PSS Design

The low frequency oscillation problem is addressed in the previous section by means of a traditional PSS. As previously noted, such PSS offer an additional dampening signal to reduce the aforementioned oscillations and improve the system's overall stability. However, the transfer functions regarding highly linearized models around a certain operational point are used in such traditional PSS. As a result, such systems cannot function satisfactorily under a variety of operational conditions . AI-based solutions were created for addressing such problem. Those consist of genetic algorithms (GA), NN, and fuzzy logic (FL). In the case when made adaptive, FL-based controllers have a significant deal of potential to reduce local mode oscillations. The NN is used to tune for adaptability [20].

1) Fuzz Logic Power System Stabilizer (FLPSS

The purpose of PSS is to enhance the efficiency of synchronous generator. Yet, in the case when combined with traditional PSS, it performs poorly under a range of loading conditions. Consequently, FLPSS becomes necessary. The basic steps of fuzzy inference system, such as the fuzzy inference, defuzzification, and inferencing processes, are introduced in this part along with the concepts of fuzzy system logic. Input signals that best describe the system's dynamic performance are chosen for FLPSS controller design. In FLPSS uses a Mamedani approach, which consists of two input components and one output component. The generator rotor angular speed deviation (ω) and change in speed deviation ($\dot{\omega}$) are the inputs

TABLE I.
RULES ADOPTED FOR THE FLC

	Change in speed ($\dot{\omega}$)					
speed(ω)	**U**	**NL**	**NM**	**Ze**	**PM**	**PL**
	PL	Ze	PM	PM	PL	PL
	PM	NM	Ze	PM	PM	PL
	Ze	NM	NM	Ze	PM	PM
	NM	NL	NM	NM	Ze	PM
	NL	NL	NL	NM	NM	Ze

to the FLC, and voltage (VPSS) is the output. Five linguistic fuzzy subsets are bring to service for each input-output variable such as negative low (NL), negative medium (NM), zero (Ze), positive low (PL) and positive medium (PM) [21]. each membership function for error ,change of error and the output are shown in Fig. 4 . by two inputs (ω ,$\dot{\omega}$) twenty five rules were generated, which identify the correlation between the FLC's output and input. Each subset is associated with a triangular membership function to form a set of five membership functions for each fuzzy variable. Table I exhibit the rules of FLC. since the exciter required a non-fuzzy signal, then the result is achieved by utilize the centroid defuzzification technique [22, 23].

2) *Adaptive Network based Fuzzy Inference System (ANFIS)*

The principles regarding ANFIS system were presented in this section, followed by an explanation of the process the ANFIS uses for optimizing the system settings. The FIS rule base is used for describing the relation between the input and output parameters even when system uncertainty exists. ANN are used for training data and determine the optimal parameters for the FIS membership functions in order to obtain the appropriate membership functions and fuzzy rules. This allows ANFIS to combine the advantages of both ANN and FIS rule bases. ANFIS utilizes either back-propagation alone or a combination of least squares estimation and back-propagation for estimating the membership function parameters [24] . The mathematical information processing systems known as ANNs are based on the same principles as the operation of human brain, wherein synapses in ANN correspond to weighted links as well as neurons in biological neural systems link to nodes. The way the membership function parameters and FIS rules are estimated distinguishes the ANFIS model structure from the FIS structure. ANFIS structure appears as it is depicted in the Fig. 5.

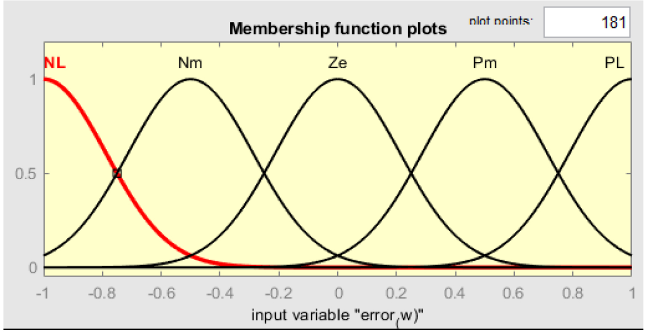


Fig. 4. MFs of the inputs and output.

There are two steps in its design process

Step1: FLPSS, or training data, is used to construct the system's input-output data pair. The precise relation between the ANFIS-PSS's output and input is ascertained using this training set. Next, an FIS is developed. The MF parameters regarding FIS are often modified by a combination of a least squares approach permutation or solely a back propagation algorithm [25]. Here, Gaussian MFs were applied. The network is trained once the number of MFs, number of training epochs, MF types, and expected training error are selected.

Step2: The FIS model is preserved if it is valid. The Takagi-Sugeno type FIS model and two inputs, rotor acceleration ($\dot{\omega}$) and rotor speed (ω), are employed in this research. The inputs are membership type Gaussian. For covering the entire range of respective inputs, a total of five MFs are needed. With regard to the output function, this results in the appearance of 25 rules that show a linear relation with the inputs. Fig. 6 shows the created ANFIS program's flowchart.

IV. SIMULATION RESULTS

Based on the SIMULINK model, we can build the PSS and optimize the voltage regulator by adopting a variety of design strategies that we discuss in the following:

The feedback control system block diagram implemented in Simulink is shown in Fig. 7 The reason for adopting a negative sign for the inverter is: Cancellation: It can be used to cancel a specific unwanted signal component. If there is noise or interference of a specific polarity, reversing the signal and adding it to the original signal can eliminate that component.

According to stage1, Open-loop step response and the responses for the system controlled by a relative VR with various gain KP are displayed in Fig. 8. The open loop response is slow and indicates a steady-state error of approximately 25% at 0.747 p.u. The increase of Kp is reflected in the development of the closed-loop performance accompanied by the worsening of the oscillation mode damping.

Apply what we mentioned in the stage3, PI voltage regulator is utilized, Ki and Kp are setting to get the following results: tolerance=0.09 of the end value (unit step), $5 \leq K_p \leq 50$,

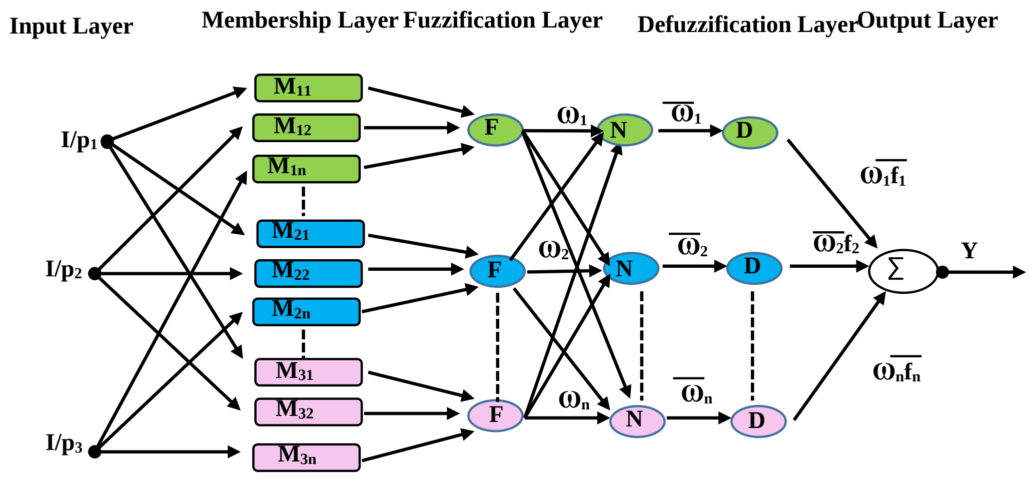


Fig. 5. ANFIS structure for time series evaluation

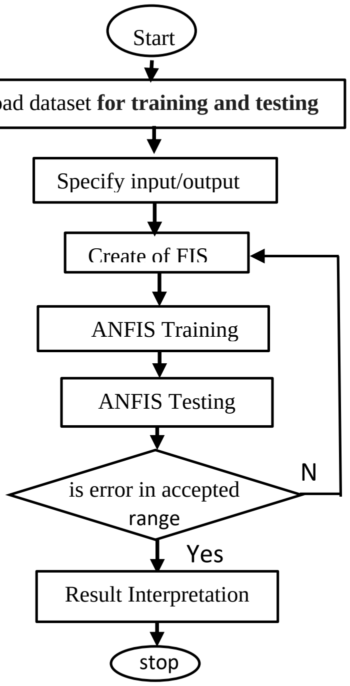


Fig. 6. Flowchart of the developed ANFIS program

and $0.10 \leq K_i \leq 10$ The step response for a 1pu step input and various values of Ki is displayed in Fig. 9.

design Ki=0.6 and Kp=15, which step response is offered with the yellow curve as shown in Fig. 9. From observing the curve it is clear that, 5.6 sec as settling time, 0.345 sec as rise time finally 6% as ultimate overshoot that will agree with the necessities.

It is evident from Fig. 9, swing mode causes steady state error and oscillation. Consequently, a PSS is added to the feedback path for lessening oscillation. For this reason, the root locus method must be used for designing a PSS. The machine speed is fed through a washout filter and many banks of torsional filters for determining the speed input signal to a PSS. With a dc gain of zero, washout filter is a high-pass filter.

With the aforementioned Ki and Kp, we close VR loop and simulate the response of the system to a step input. The steady state error = 0 is displayed in the curves. Thus, AVR is inserted, allowing the system to follow the step input. However, because of AVR's PI controller, the swing mode—that is, the dominant complex poles—becomes unstable, introducing oscillations into output Vterm. For lessening oscillations, we must include a feedback loop that feeds PSS loop with the rotor angular speed swing (ω). The complex dominant pole is determined by drawing as well as analyzing the root locus of close loop AVR and PSS. The root locus map of a closed loop AVR with PSS is displayed in Fig. 10. The dominant complex poles are located at $-0.8040 \pm 8.3279i$.

With the use of MATLAB, calculate the departure angle from poles; the result is = 63.1099°, as mentioned in stage4. By implementing the stage5, the parameters and order of the phase lead compensator are selected based on the value of the departure angle.

In this case, adding an angle of 117° is required, and a single lead compensator cannot accomplish this. Consequently, a transfer function with the form of 2 lead compensators in

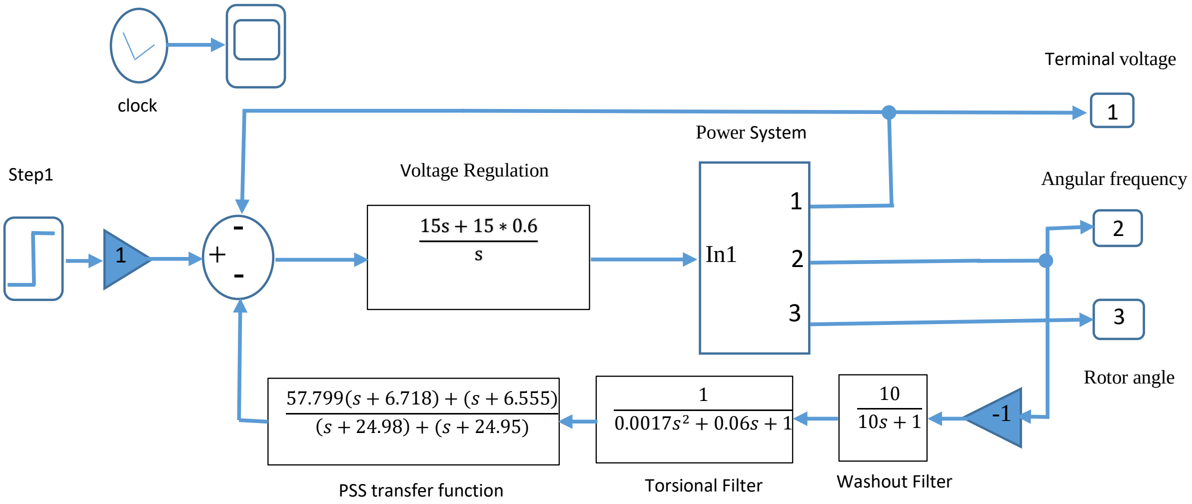


Fig. 7. Simulink model for power system control

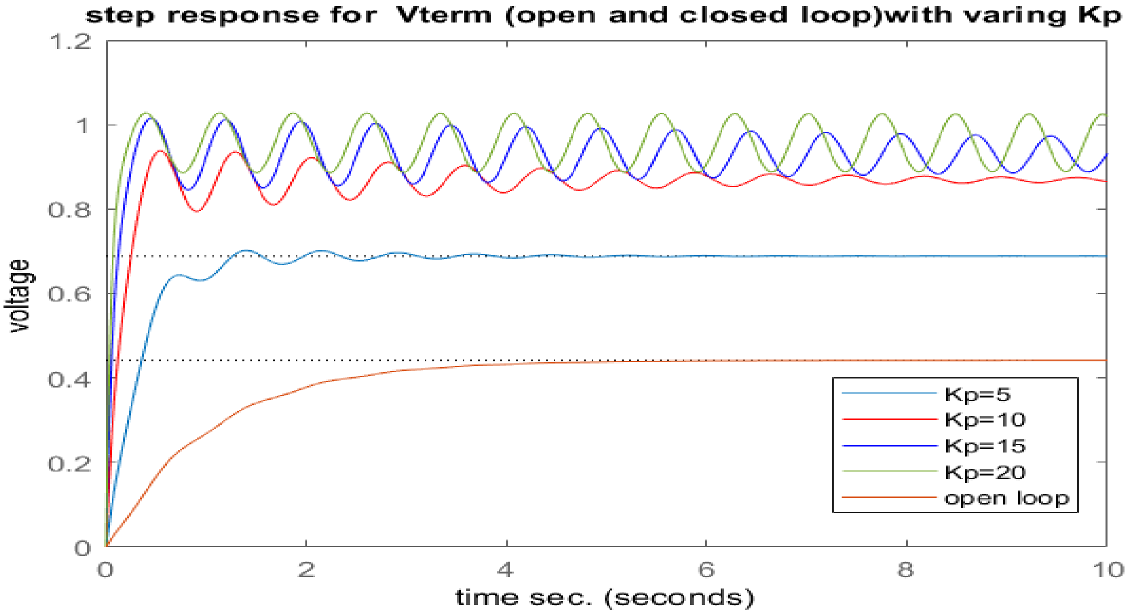


Fig. 8. V_{term} responses to step in V_{ref}, open loop, and closed loop for Kp = 5; 10; 15; 20

series, each one adding an angle of 58.5°, is employed. Based to Control System Designer tools, we design Single-Input, Single-Output (SISO) controllers for feedback systems modeled in MATLAB. According to equation (8), the final transfer function of lead - lead compensator PSS block is

$$D(s) = 57.799\frac{(s+6.718)+(s+6.555)}{(s+24.98)+(s+24.95)} \tag{9}$$

Ultimately, SMIB system's root locus and response are redrawn and studied with the use of such PSS; Fig. 12 displays

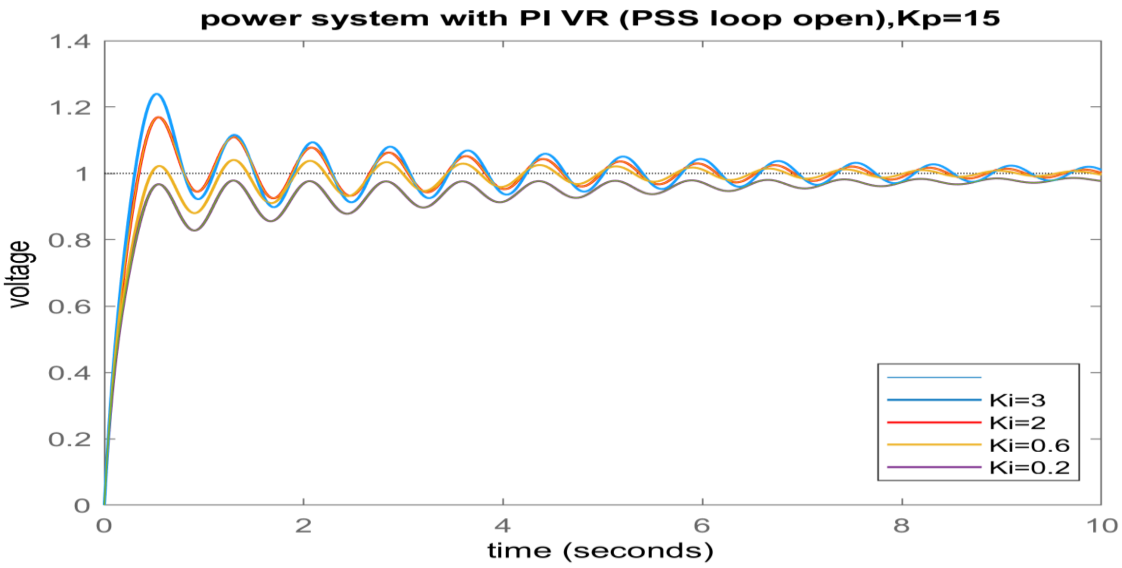


Fig. 9. Power System with PI VR (PSS Loop open), KP=15

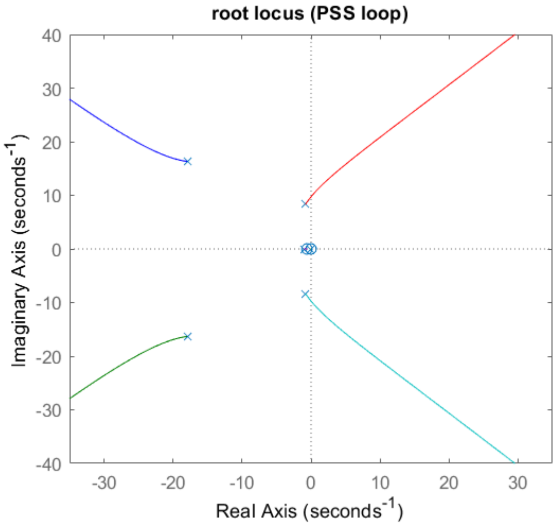


Fig. 10. Uncompensated system root locus.

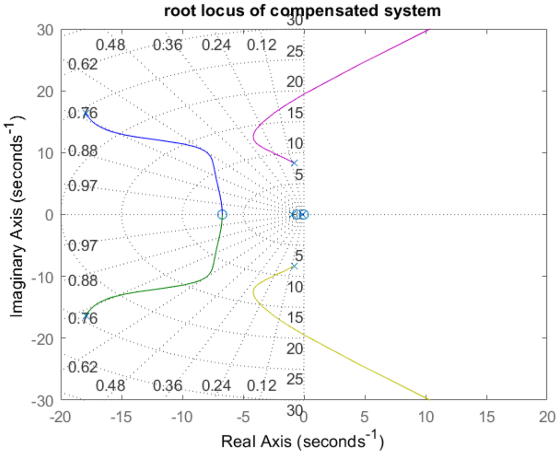


Fig. 11. Final compensated system root locus

the final compensated system root locus plot. Fig. 12 display the compensated PSS vs uncompensated PSS.

According to step1 and 2 in steps ANFIS design process, the neural network has five layers as referred in Fig. 13

Input Layer, the first layer receives the raw input data. The second layer represents the input membership functions (MFs) which is Gaussian. The third layer represents the AND function. The fourth layer represents the normalized firing strength as given in the sugeno model and, the five layer represents the combination of the rules and their weighted average to find the final output using Sugeno defuzzification technique.

The training for the rule base has been started with 100 epochs for improved dependability with the use of back-propagation approach since ANFIS combines the learning benefits of ANN and the advantages of FIS rule base. The

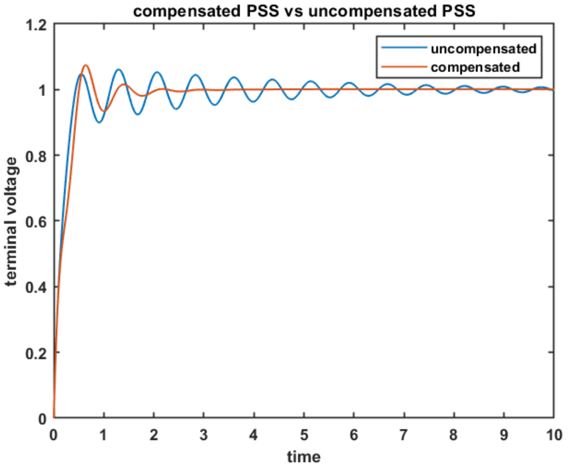
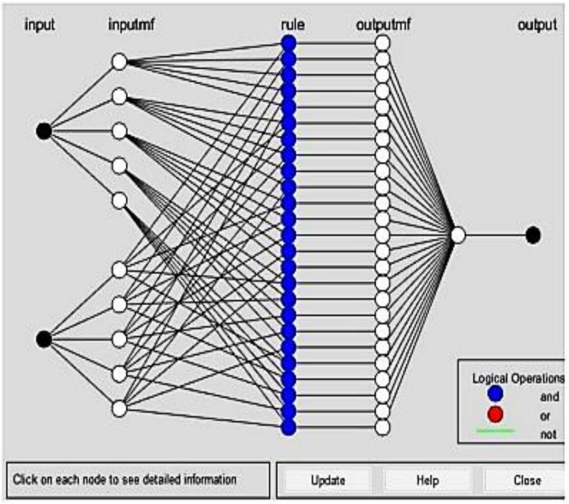


Fig. 12. compensated PSS vs uncompensated PSS

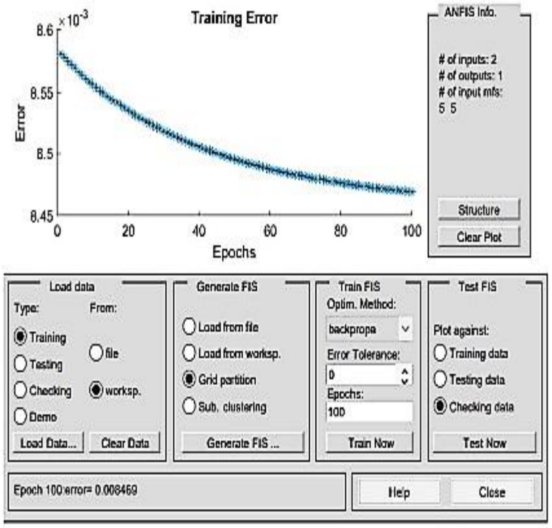


Click on each node to see detailed information

Fig. 13. Structure of Neural Network

error is as shown in Fig. 14. Lastly, the output data is used to test the trained model as Fig. 15:

The trained data (red stars) nearly exactly matches the output (blue circles), as can be seen in the figure16. We may utilize such exported trained FIS model in the fuzzy logic controller block (PSS). To simulate PSS, the fuzzy controller employed the offline-trained FIS. Fig. 16. The simulation results of rise time, max. overshoot and settling times confirm the quality of the design specifications. The effectiveness of the proposed design, FNPSS compared to the CPSS in terms of speed deviation and terminal voltages are shown in Figs. (17,18) respectively.



# of inputs: 2
# of outputs: 1
# of input mfs:
5 5

Type: ● Training ○ Testing ○ Checking ○ Demo
From: ○ file ● worksp.

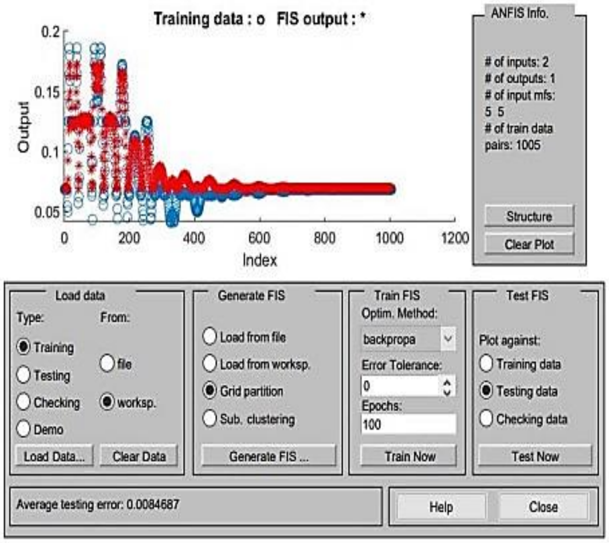
○ Load from file
○ Load from worksp.
● Grid partition
○ Sub. clustering

Optim. Method: backpropa
Error Tolerance: 0
Epochs: 100

Plot against: ○ Training data ○ Testing data ● Checking data

Epoch 100:error= 0.008469

Fig. 14. The training of ANFIS showing the training error



# of inputs: 2
# of outputs: 1
# of input mfs:
5 5
# of train data pairs: 1005

Type: ● Training ○ Testing ○ Checking ○ Demo
From: ○ file ● worksp.

○ Load from file
○ Load from worksp.
● Grid partition
○ Sub. clustering

Optim. Method: backpropa
Error Tolerance: 0
Epochs: 100

Plot against: ○ Training data ● Testing data ○ Checking data

Average testing error: 0.0084687

Fig. 15. Comparison between trained and test data

V. CONCLUSION

thorough comprehension regarding the dynamics of single machine infinite bus system is necessary for the ideal design of PSS. We see the issue as a feedback control problem because we attempted to construct PSS in the project based on control system concepts. This research examines the effectiveness of several PSS design methods. It was discovered that :

1. A generator with no PSS exhibits significant speed and

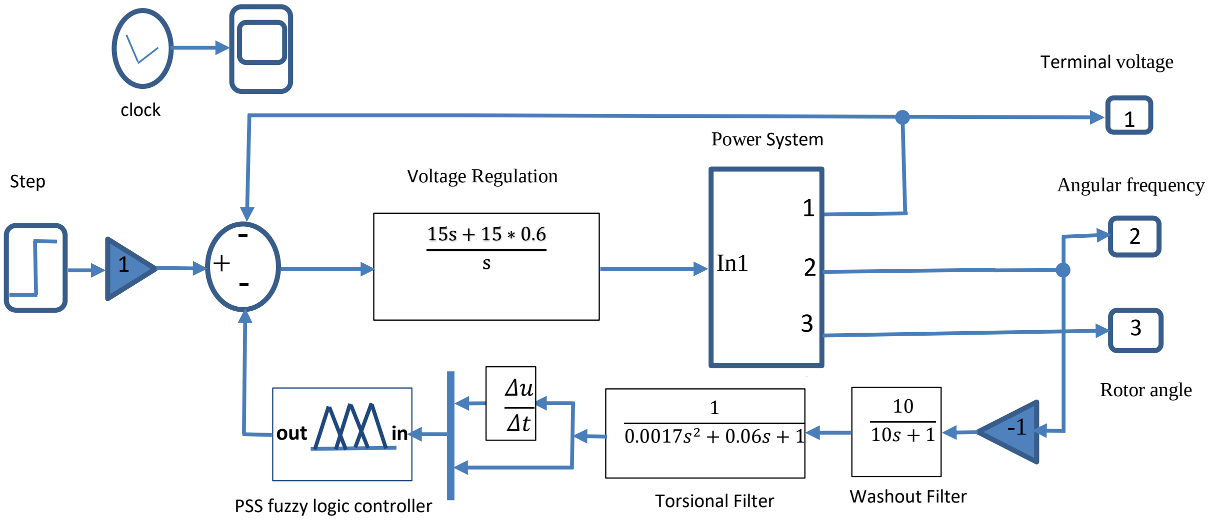


Fig. 16. SIMULINK implementation of the fuzzy controller

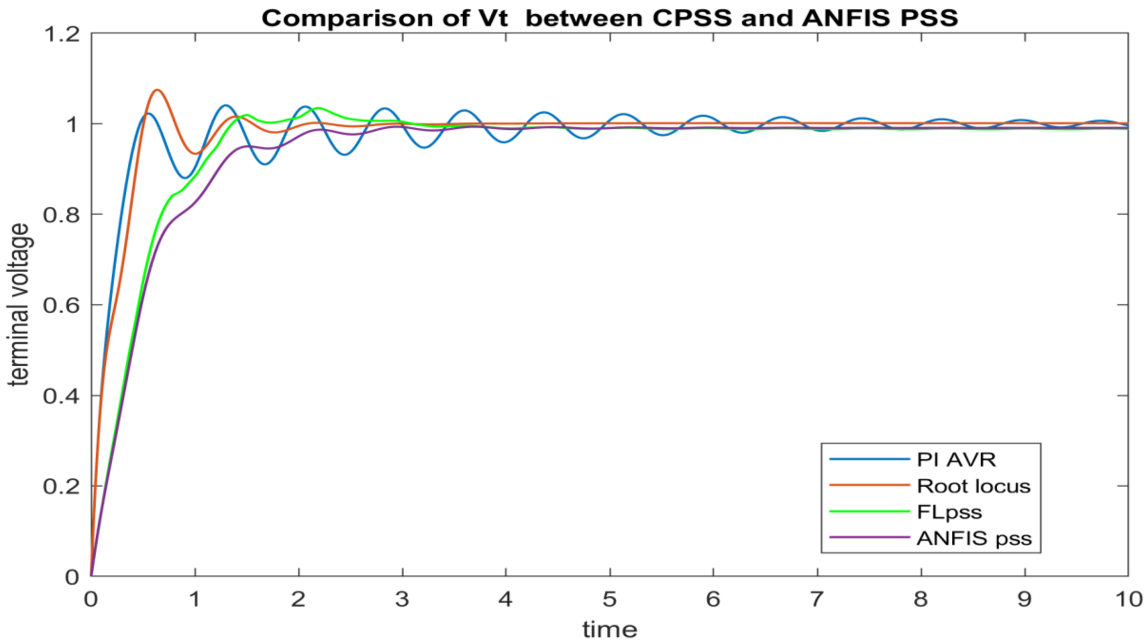


Fig. 17. Comparison of v_{term} between (CPSS and ANFIS)

voltage oscillation.

2. Under different operating conditions, the traditional PSS design approach cannot ensure good performance.

3. Fuzzy logic controller has the potential to improve sys-

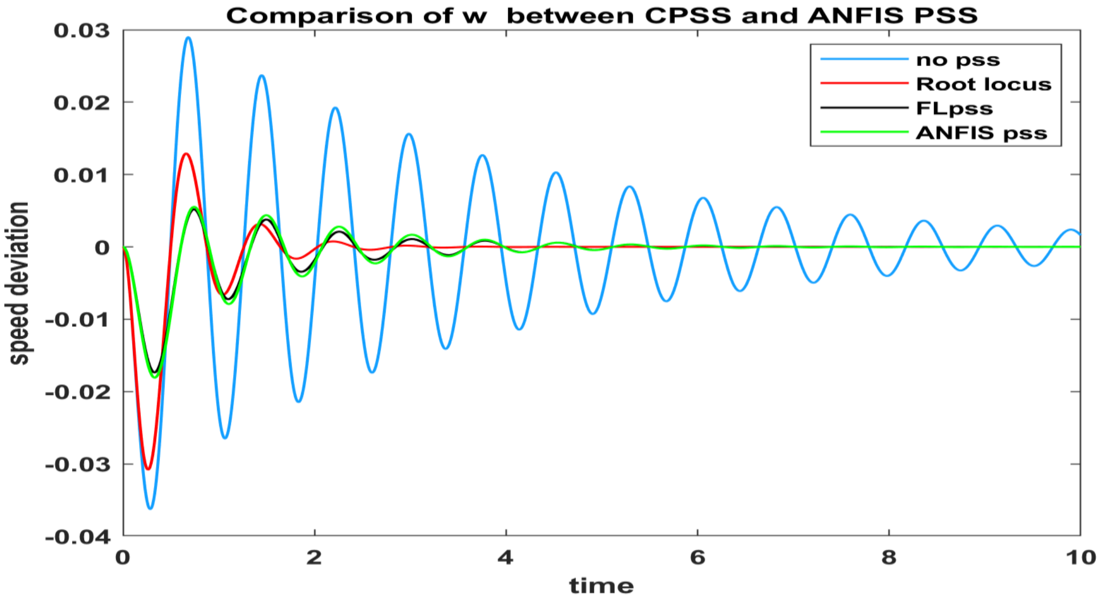


Fig. 18. Comparison of ω between (CPSS and ANFIS)

tem performance, but there are no set standards for choosing its MFs. But the adaptive PSS that has been designed could get over the aforementioned challenges.

According to simulation data, in the case when operating conditions vary, ANFIS-PSS guarantees optimal performance with regard to setting time and overshoot. As a result, it is suitable for use in contemporary power system applications.

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CONFLICT OF INTEREST

The authors have no conflict of relevant interest to this article.

APPENDIX

TABLE II.
APPENDIX 1

Parameter	Value
Infinite bus voltage, V	1
Inertia constant, H	2.37
Rated speed, ω°	314.1593 rad/sec
Mechanical Torque, Tm	1
Term regulation, R	2.4 Hz/MW
Damping factor,D	0
K1	1.0751
K2	1.2578
K3	0.3072
K4	1.7124
K5	0.0477
K6	0.477
t3	0.4

REFERENCES

[1] M. R. Salimian and M. R. Aghamohammadi, “A three stages decision tree-based intelligent blackout predictor for power systems using brittleness indices,” *IEEE Transactions on Smart Grid*, vol. 9, no. 5, pp. 5123–5131, 2017.

[2] Y. Zhang, Y. Xu, and Z. Y. Dong, "Robust ensemble data analytics for incomplete pmu measurements-based power system stability assessment," *IEEE Transactions on Power Systems*, vol. 33, no. 1, pp. 1124–1126, 2017.

[3] S. Amini, F. Pasqualetti, and H. Mohsenian-Rad, "Dynamic load altering attacks against power system stability: Attack models and protection schemes," *IEEE Transactions on Smart Grid*, vol. 9, no. 4, pp. 2862–2872, 2016.

[4] M. Abido and Y. Abdel-Magid, "Power system stability enhancement via coordinated design of pss and facts-based stabilizers," *Final Report of a Project Funded by FKUPM*, 2002.

[5] M. Eslami, H. Shareef, and A. Mohamed, "Application of pss and facts devices for intensification of power system stability," *International Review of Electrical Engineering (IREE)*, vol. 5, no. 2, pp. 552–570, 2010.

[6] G. Shahgholian, "Review of power system stabilizer: Application, modeling, analysis and control strategy," *International Journal on Technical and Physical Problems of Engineering*, vol. 5, no. 3, pp. 41–52, 2013.

[7] W. Peres, "Multi-band power oscillation damping controller for power system supported by static var compensator," *Electrical Engineering*, vol. 101, no. 3, pp. 943–967, 2019.

[8] D. Mondal, A. Chakrabarti, and A. Sengupta, *Power system small signal stability analysis and control*. Academic Press, 2020.

[9] J. Liu, Y. Zhang, K. Meng, Z. Y. Dong, Y. Xu, and S. Han, "Real-time emergency load shedding for power system transient stability control: A risk-averse deep learning method," *Applied Energy*, vol. 307, p. 118221, 2022.

[10] N. O. Kalu, O. Oyeleke, S. Thomas, and O. O. Oshiga, "Artificial intelligence techniques for power system stabilization," in *2021 1st International Conference on Multidisciplinary Engineering and Applied Science (ICMEAS)*, pp. 1–5, IEEE, 2021.

[11] F. Jamsheed and S. J. Iqbal, "An improved neuro-adaptive-optimal control for oscillation damping in wind-integrated power systems," *Optimal Control Applications and Methods*, vol. 44, no. 2, pp. 885–904, 2023.

[12] N. Singh, M. Jain, and N. Arora, "Economic lot sizing for unreliable production system with shortages," *International Journal of Mathematics in Operational Research*, vol. 7, no. 4, pp. 464–483, 2015.

[13] P. Aengchuan and B. Phruksaphanrat, "Comparison of fuzzy inference system (fis), fis with artificial neural networks (fis+ ann) and fis with adaptive neuro-fuzzy inference system (fis+ anfis) for inventory control," *Journal of Intelligent Manufacturing*, vol. 29, pp. 905–923, 2018.

[14] H. Tozan and Ö. Vayvay, "Fuzzy and neuro-fuzzy forecasting approaches to whiplash effect in supply chains," *Journal of Naval Sciences and Engineering*, vol. 4, no. 1, pp. 27–42, 2008.

[15] M. Htay and K. Win, "Design and construction of automatic voltage regulator for diesel engine type stand-alone synchronous generator," *World academy of science, engineering and technology*, vol. 42, pp. 652–658, 2008.

[16] P. Kundur, "Power system stability," *Power system stability and control*, vol. 10, pp. 7–1, 2007.

[17] M. Balasubbareddy, G. Murthy, and K. S. Kumar, "Performance evaluation of different structures of power system stabilizers," *International Journal of Electrical and Computer Engineering (IJECE)*, vol. 11, no. 1, pp. 114–123, 2021.

[18] G. N. Baltas, N. B. Lai, L. Marin, A. Tarrasó, and P. Rodriguez, "Grid-forming power converters tuned through artificial intelligence to damp subsynchronous interactions in electrical grids," *IEEE access*, vol. 8, pp. 93369–93379, 2020.

[19] A. K. Swain, A. K. S. R. Swain, and A. Mohapatra, *Design of power system stabilizer*. PhD thesis, 2012.

[20] K. Y. Yap, C. R. Sarimuthu, and J. M.-Y. Lim, "Artificial intelligence based mppt techniques for solar power system: A review," *Journal of Modern Power Systems and Clean Energy*, vol. 8, no. 6, pp. 1043–1059, 2020.

[21] L. H. Hassan, M. Moghavvemi, H. A. Almurib, and O. Steinmayer, "Current state of neural networks applications in power system monitoring and control," *International Journal of Electrical Power & Energy Systems*, vol. 51, pp. 134–144, 2013.

[22] M. Ahmed and N. K. Roy, "Design of a power system stabilizer using adaptive-neuro fuzzy logic for a multi-machine system having dynamic loads," in *2016 5th International Conference on Informatics, Electronics and Vision (ICIEV)*, pp. 402–407, IEEE, 2016.

[23] I. F Jasim, "Fuzzy neural design of power systems stabilizers," *journal of kerbala university*, vol. 5, no. 3, pp. 333–345, 2009.

[24] R. Shukla, P. Kumar, D. K. Vishwakarma, R. Ali, R. Kumar, and A. Kuriqi, “Modeling of stage-discharge using back propagation ann-, anfis-, and wann-based computing techniques,” *Theoretical and Applied Climatology*, pp. 1–23, 2021.

[25] F. Jamsheed and S. J. Iqbal, “A minimal architecture neuro adaptive predictive control scheme for power system stabilizer,” *International Journal of Electrical Power & Energy Systems*, vol. 137, p. 107750, 2022.