Neural Network Based Efficient Power System Stabilizer for Power Oscillation Damping

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***Abstract*—Destructive power oscillations are frequently caused by the complexity and vulnerability of modern power systems to disruptions like generator failures, transmission line faults, and sudden load changes. The stability and dependability of the system are seriously threatened by these oscillations, which are manifested in variations in rotor angle and speed. In order to efficiently suppress such oscillations, this paper suggests a novel power system stabilizer (PSS) based on convolutional neural networks (CNNs). To take advantage of CNN's strengths in pattern recognition, the CNN model is trained using three essential system parameters—active power, reactive power, and terminal voltage—converted into image formats. In both multi-machine and single-machine infinite bus settings, the trained network dynamically predicts the best PSS parameters suited to changing operating conditions. Extensive time-domain simulations verify that the suggested CNN-based PSS is effective at stabilizing contemporary, disruptive power networks by providing better damping performance and flexibility when compared to traditional techniques.**

Index Terms—**Power system stabilizer, Power oscillation, Multi-machine system, Deep neural network, Convolutional neural network.**

I. Introduction

Significant complexity and uncertainty have been introduced by the fast evolution of modern power systems marked by renewable integration, smart grids, and extensive interconnections. Maintaining system stability, especially against rotor angle oscillations, is progressively difficult owing to disturbances including generator outages, transmission faults, and sudden load variations . Key parameters including active power, reactive power, and terminal voltage affect rotor angle behavior; where imbalances often produce harmful power oscillations and potential loss of synchronism . When a system's natural damping is inadequate, rotor angle instability results from deviations in rotor speed and angle, so endangering general network stability . Emphasizing rotor angle stability—a critical factor affected by synchronous generator dynamics—fig. 1 shows power system stability classification [1,2,3].

The rotor angle dynamics can be described using the well-known swing equation, formulated as [4,5]:

$$M\frac{d^2\delta}{dt^2} = P_{mech} - P_{elec}$$

In which δ is the rotor angle and M is the angular momentum. Stability depends on δ to oscillate within allowed limits; else, continuous deviations cause instability. Widely used to reduce such oscillations by supplying auxiliary control signals are conventional power system stabilizers (CPSS). CPSS, based on linearized models and fixed parameters, finds difficulty handling the non-linear, time-varying dynamics of modern grids. Notwithstanding their success. This calls for clever, flexible stabilizing structures [6,7,8].

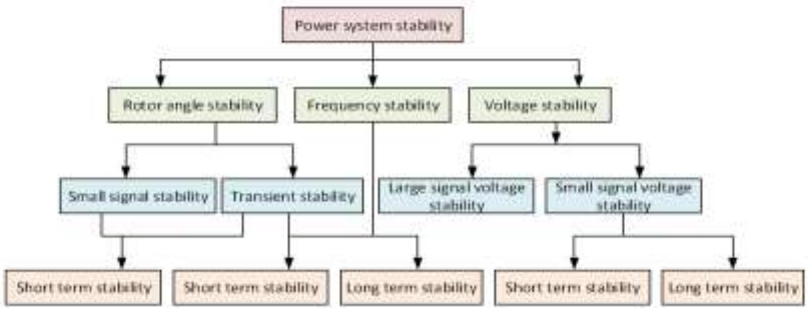


Fig. 1. Classification of power system stability

II. Problem statement

Conventional CPSS suffers in both efficiently damping oscillations and grid condition adaptation. Their linear assumptions and fixed-parameter character impede performance in complex, renewable-rich settings. Although recent studies investigate neural networks for adaptive PSS design, issues including hyperparameter tuning, computational efficiency, and scalability remain underresellled.

III. Research Motivation

The Historical blackouts stress the need of strong damping systems. For example, transmission failures caused Sri Lanka's 2021 blackout to affect 21 million people . Major worldwide blackouts resulting from system instability are compiled in Table 1 and Fig. 2. The growing complexity of linked grids increases vulnerability, which drives the need of adaptive PSS solutions driven by artificial intelligence [9,10,11].

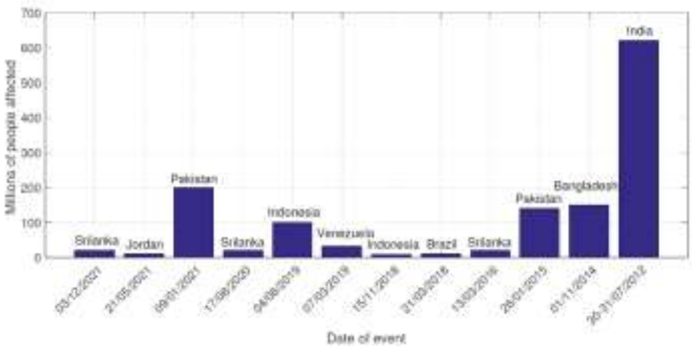


Fig. 2. Major blackouts worldwide

Summary of Major Global Blackouts

Date	Population Affected (Millions)	Country
03/12/2021	21	Sri Lanka
09/01/2021	200	Pakistan
30-31/07/2012	620	India

IV. Literature review

In order to handle rotor angle instability and oscillations, modern power systems require adaptive and effective damping mechanisms. Three main areas comprise the body of existing literature on Power System Stabilizer (PSS) design: Even though they worked well in early power grids, classical control-based PSSs have trouble handling the non-linear and dynamic behavior of modern systems. Although they have demonstrated improvements in damping, methods such as H_∞ control , μ -synthesis , and robust decentralized designs frequently call for exact system models and might not adjust well to system changes. Though issues like model uncertainties and limited scalability still exist, recent comparative studies of metaheuristic-tuned PSSs, like STO, GWO, and PSO, highlight improved stability under varying conditions . To fine-tune PSS parameters, optimization algorithms like PSO, GA, WOA, and CSA have been used extensively . These techniques increase system stability across a range of test systems by optimizing damping performance and eigenvalue placement [12,13,14]. However, particularly when used in large-scale or multi-machine environments, they frequently face computational burdens and convergence limitations . Because of their capacity for adaptive and non-linear learning, artificial intelligence (AI) approaches—in particular, neural networks and fuzzy logic systems—have shown great promise as remedies. Superior damping has been demonstrated by ANN-BESS integrated controllers , adaptive neural PSSs , and LSTM-based PSS designs . But there is still room for improvement in areas like higher computational demands, overfitting risks, and a lack of research on hyperparameter optimization . Even with significant improvements, current control, optimization, and AI-based PSS methods still struggle with computational efficiency, robustness, and adaptability when dealing with the complexity of the modern grid. This emphasizes the necessity of a new, flexible PSS framework that can react quickly to changing grid circumstances [15,16,17].

V. Objectives

The objectives of this research are:

- Develop a CNN-based PSS framework to obtain optimal stabilizer parameters.
- Apply the proposed PSS to single-machine and multi-machine systems.
- Validate performance across various disturbances and operating conditions.
- Benchmark against conventional PSS methods.

VI. SYSTEM UNDER STUDY

The studied system comprises a Single Machine Infinite Bus (SMIB) model integrated with an IEEE Type-I high-gain excitation system. Accurate modeling of system dynamics is essential for analyzing stability and designing effective controllers. Fig. 3 shows the SMIB configuration, while Fig. 4 illustrates its transfer function representation [18,19,20].

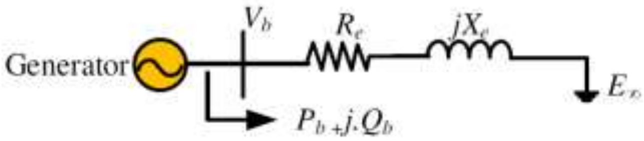


Fig. 3. Single-line diagram of the SMIB system

Designed respectively by $\frac{K_3}{1+sK_3T'_{do}}$, $\frac{K_A}{1+sT_A}$, and $\frac{1}{1+sT_R}$. Key elements are the generator, exciter, and measuring transducer. Ignoring stator resistance ($R_s = 0$), the generator links to the infinite bus via transmission impedance $(R_e + jX_e)$. Disturbances produce deviations in speed (ω) and rotor angle (δ . Integrated as described below is a Power System Stabilizer (PSS) to help to reduce oscillations.

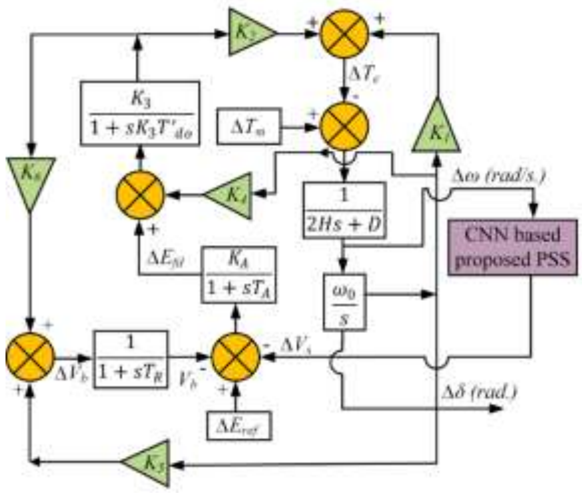


Fig. 4. Transfer function model of the SMIB system

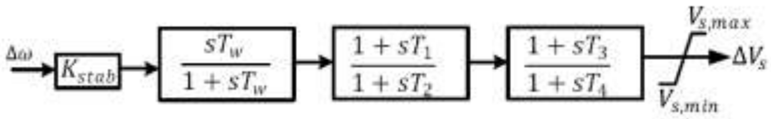


Fig. 5. Structure of the conventional PSS

Conventional Power System Stabilizer (CPSS):

Showed in Fig. 5, the CPSS structure consists in a lead-lag compensator, washout filter, and stabilizing gain . It damps low-frequency oscillations by injecting a supplementary signal into the excitation system . While effective for smaller systems, CPSS performance declines in complex grids due to fixed parameters and limited adaptability.

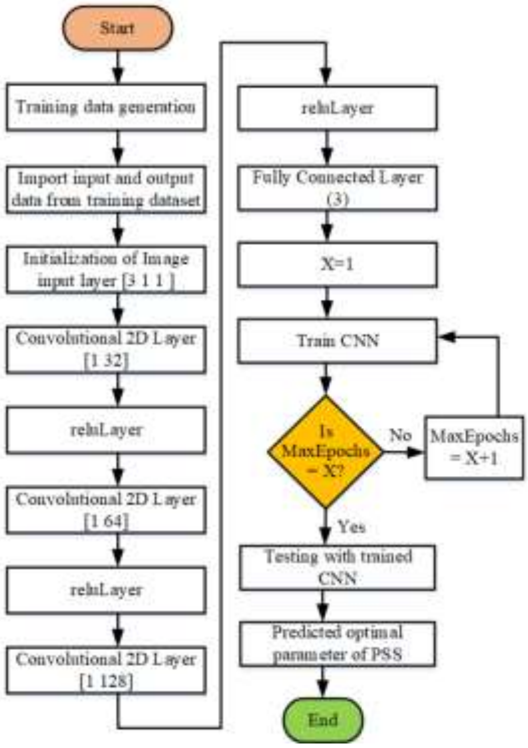


Fig. 6. Flowchart of CNN-based PSS algorithm

CNN-Based Power System Stabilizer:

A Convolutional Neural Network (CNN)-based PSS is proposed to overcomes CPSS constraints, so improving adaptability and damping efficiency. Figures 6 show the CNN architecture; its operational flow is shown in Figure 7. CNN input consists in terminal voltage (V_b), reactive power (Q_b), and active power (P_b . The network forecasts ideal stabilizer parameters: gain ($K_{stab,CNN}$), lead-lag time constants ($T_{1,CNN}$, $T_{2,CNN}$), so improving real-time damping capability .

The proposed CNN-PSS has a transfer function like:

$$G(s) = K_{stab,CNN}\left(\frac{sT_w}{1+sT_w}\right)\left(\frac{1+sT_{1,CNN}}{1+sT_{2,CNN}}\right)^2$$

The SMIB system model, CPSS framework, and proposed CNN-based stabilizer were presented in this part. Using the pattern recognition of deep learning, the CNN-PSS dynamically adjusts stabilizer parameters to provide better damping under different environments. Later parts examine its performance relative to more traditional approaches.

VII. RESULT AND DISCUSSION

Performance in SMIB System:

Two different operational environments are used to evaluate the proposed CNN-based PSS against MBPSS, delta-ω PSS, and CPSS. Figure 8 and Fig. 9 show responses for rotor speed (ω) and rotor angle deviation ($\Delta\delta$). CNN-PSS achieves minimal overshoot and faster settling (2.85 s) in Case I (P_b =0.95 pu, Q_b =0.98 pu) by means of tuned parameters; $K_{stab,CNN}$ =55.0690, $T_{1,CNN}$ =0.3189, and $T_{2,CNN}$ =0.0725.

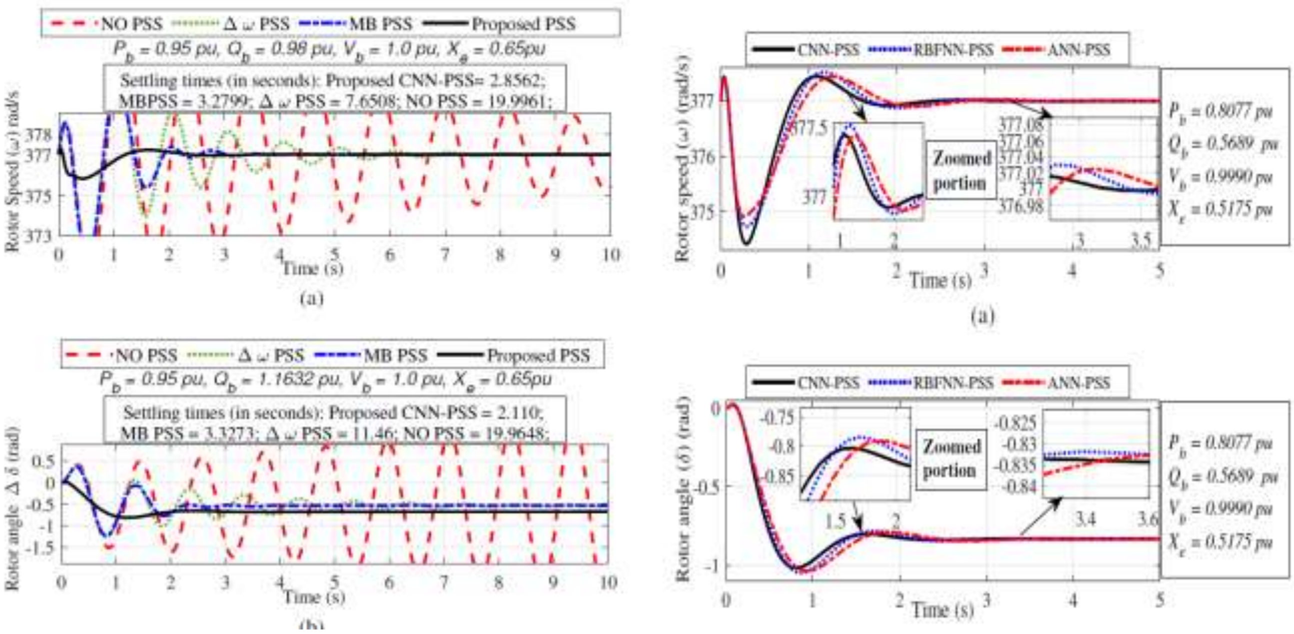
Comparison with Other Machine Learning Algorithms:

Stabilizers based on ANN and RBFNN form a benchmark for the proposed CNN-PSS. While Table 2 compiles important statistics, Fig. 7 shows the rotor speed and angle comparisons.

Table II: Comparison of ML-Based PSS Designs

	ANN-PSS	RBFNN-PSS	CNN-PSS
K_{stab}	35.4825	33.7934	33.1450
T_1	0.1478	0.2175	0.2280
T_2	0.2543	0.1218	0.1535
Elapsed Time (s)	41.85	5.23	33.74
ω Settling Time (s)	2.62	2.41	2.09
δ Settling Time (s)	2.88	2.68	1.76

Faster damping and effective capture of system dynamics are obtained by the CNN-based PPS. It regularly beats both ANN and RBFNN models, although needing more computational time than RBFNN. Faster stabilization of rotor speed and angle deviations compared to CPSS, MBPSS, ANN, and RBFNN approaches is achieved by the CNN-based PSS showing better damping performance across SMIB and MMPS configurations. Its robustness and adaptability confirm its possibility to improve the stability of contemporary power systems.



VIII. Conclusion

This work proposed a CNN-based Power System Stabilizer (PSS) intended to improve damping of local and inter-area low-frequency oscillations in both SMIB and multi-machine systems. The CNN efficiently optimized stabilizer parameters using a lead-lag compensator structure, so obtaining faster rotor speed recovery and enhanced rotor angle stability than in conventional PSS models. Under many running conditions, comparative studies showed the better performance of the suggested method over conventional PSS and ANN-based designs. The results show the possibilities of CNN-based stabilizers for implementation in contemporary, renewable-integrated power systems. Future research could concentrate on extending this framework to bigger power systems and including hybrid optimization methods for even more improvement.

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