ADAPTIVE OUTPUT FEEDBACK CONTROLLER FOR ENHANCING DYNAMIC STABILITY IN INDUSTRIAL SYNCHRONOUS POWER SYSTEM

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Abstract

This paper presents the output state feedback approach, a unique adaptive control mechanism for power system dynamic stability. A new adaptive stabilizing method for synchronous power systems based on Minimal Control Synthesis (MCS) is proposed. Industrial applications can benefit from synchronous power systems. It boosts production and power efficiency. The MCS adaptive control structure uses hyper-stability theory. Power System Stabilizers (PSSs) have been used in industry for years to improve power system dynamic stability and dampening. most power systems are very dynamic and non-linear. Traditional PSS uses linearized power system model and fixed parameter linear control theory. Fixed parameter controllers can't sustain power system dynamic stability. The MCS method's key virtue is that it requires only a minimal framework and little computational resources. The controller manages plant nonlinearities, mild disturbances, and parameter changes using proportional and integral type adaptation to meet hyper-stability criteria. Stabilizing signals are created at the machine system's excitation input for well-defined closed-loop performance. Synthesizing an output feedback control from observed feedback signals is desirable and technically achievable. The proposed control structure overcomes the difficulties of generating an online parameter estimator and choosing a reference model compared to MRAC or STAC. The investigated power system has an endless bus connected to a synchronous machine. Simulations verify the controller's ability to moderate machine oscillations caused by minor power system disturbances. The results and MATLAB/Simulink operational simulation results end this research. The mode damping ratio is 0.0142, which is within the predicted range of 0.1 to 0.5.

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Graphical abstract

INTRODUCTION

Electrical power is produced, transmitted, and distributed through intricate networks known as synchronous power systems. They are built to deliver dependable and effective power to users while maintaining a steady frequency and voltage [1]. Adaptive controllers in synchronous power systems can substantially enhance industrial applications by improving power use efficiency, reliability, and cost-effectiveness [2].

Most power systems are highly dynamic, nonlinear systems. Uses of the fixed parameter linear control theory and the linearized power system model are used in conventional PSS [3]. The fixed parameter controller is unable to maintain the dynamic stability of the power system when there is a slight disturbance in the operational point changes. The dynamic stability of a synchronous power system can be increased by adapting a control system that employs an adaptive controller with output feedback. The power system operates fundamentally as a set of connected oscillators when there are load fluctuations and parameter changes. The damper or amortized effects can attenuate higher frequency oscillations. However, damper windings have little effect on the lower frequency oscillations, and these modes are linked to dynamic instability. The transmission of electricity is commonly limited by oscillation of modest magnitude and low frequency in the range of 0.5Hz to 2.5Hz. Additionally, it is presumed that the voltage regulator adds negative damping when the load is increased. However, there is still hope for solving the problems with the dynamic electric power system [4].

Newer ideas and approaches to problem-solving are always available in response to difficult new problems. Supplementary Stabilizing Signals (SSSs), produced artificially using supplementary excitation controls, are generally provided to increase system damping [5]. A Power System Stabilizer (PSS) is a network that generates PSSs during low-frequency oscillations.

The implementation of adaptive controllers in synchronous power systems can significantly enhance the efficacy, reliability, and cost-effectiveness of power management in manufacturing industries. The uninterrupted power supply that these controllers ensure is essential for industries with continuous operations, such as manufacturing, data centers, and healthcare, as they enhance dynamic stability. They facilitate the adoption of sustainable energy solutions by businesses, thereby reducing operational costs and carbon footprints, by stabilizing the integration of renewable energy and managing demand variations [6]. The lifespan of equipment is also enhanced by adaptive controllers, which reduce wear and strain on machinery by mitigating oscillations and disturbances. Moreover, their capacity to manage nonlinearities and adjust to system changes directly affects productivity and profitability by reducing outage and maintenance requirements. In general, they offer a comprehensive framework that enables industries to optimize power consumption, improve operational resilience, and comply with contemporary energy strategies [7].

According to reports, the ideal controllers are particularly successful at damping machine oscillations. However, the fixed parameter controllers are unable to maintain the dynamic stability of the power system when the operating condition changes due to a disturbance. For these controllers to deliver the appropriate performances, their parameters must be adjusted. The extra damping torque modulation introduces the additional damping signal through the excitation system [8]. Thus, adaptive controls have been suggested to enhance the dynamic characteristics of the system over a wide range of operating points. Power system engineers have identified two basic methods for adaptive control: model reference adaptive control (MRAC) and self-tuning adaptive control (STAC).

In the STAC scheme, system parameters are identified online using parameter identification techniques like the recursive least squares method, and these parameter estimates are then included in the control strategy [9]. The MRAC scheme's control strategy includes a reference model that displays the desired system response. The controller settings are updated to have the system output converge to the model output using the difference between the output of the real system and that of the reference model [10].

Although STAC or MRAC-based adaptive PSSs have been reported to be effective, their underlying assumptions and associated nonlinearities raise many fundamental issues whose real-world resolutions may complicate the control structure. In practice, it can be challenging to apply the parameter estimator design in STAC and the right choice of reference model in MRAC [11].

According to reports, an existing control method can be retrofitted with the MCS algorithm based on Popov's hyper-stability theory, considerably enhancing closed-loop robustness [12]. The MCS algorithm has already been used to dampen machine oscillations in a multi-machine power system with a decentralized control strategy. In power systems, the adaptive controller is frequently employed as an additional controller in addition to a traditional fixed parameter controller. The additional adaptive controller is used to improve the dynamic stability as well as return the system to normal operating conditions following a disruption. Conventional controllers govern the standard voltage and frequency modifications [13]. Here, a novel design strategy for a higher-order power system based on the MCS algorithm for the supplementary adaptive PSS is put forth. The effectiveness of this strategy has been examined using a numerical example of a Single

Machine Infinite Bus (SMIB) power system with control equipment. The simulation findings demonstrate that the MCS-based adaptive controller performs well with a range of tiny disturbances and system parameter modifications [14].

An adaptive controller modifies the control parameters in response to system output using output feedback. This indicates that even in the presence of disturbance, the controller can respond to changes in the system and maintain stability. The power system has identified two basic methods of adaptive control [15]. Overall, an output-feedback adaptive controller is an effective tool for enhancing the dynamic stability of synchronous power systems. Even in the presence of varying circumstances and disturbances, it can assist ensure that the system stays dependable and stable.

An adaptive control system adapts the parameters of the controller to changes in the parameters or structure of the controlled system in such a way that the entire system maintains optimal behavior according to the given criteria, independent of any changes that might have occurred [16].

The goal of adaptive control is to develop a control algorithm that can automatically adjust its parameters to optimize the system's performance. Power System Stabilizers (PSSs) have been used for many years to increase system damping and enhance power systems' dynamic stability.

1.1 SELF-TURNING ADAPTIVE CONTROL (STAC)

Self-turning control system that can adjust to modifications in a process or environment without outside assistance is also known as adaptive control. It is a type of feedback control that responds to changes in the system it is controlling by modifying its parameters using mathematical methods [17].

The control system's self-turning feature is derived from its capacity to automatically modify its settings in reaction to modifications in the process it regulates. Adaptive algorithms, which are made to learn from the behavior of the system and modify the control inputs appropriately, are used to accomplish this. Self-turning adaptive control's ability to function well in extremely changeable settings or processes that are challenging to fully understand is one of its main advantages[18]. Even in extremely dynamic circumstances, the system can maintain accurate control by continuously monitoring it and modifying its parameters in reaction to changes [19]. Self-turning adaptive control is frequently employed in industrial operations like transportation systems, power generation, and chemical manufacturing. Additionally, autonomous systems and robotics can be used to modify their behavior in reaction to environmental changes. Self-turning adaptive control is a potent method for attaining accurate control in dynamic and complicated systems, and its applicability is expanding across numerous sectors and applications [20].

1.2 MODEL REFERENCE ADAPTIVE CONTROL (MRAC)

Reference Model is a kind of adaptive control system used to manage dynamic systems that may fluctuate or change over time is called Adaptive Control (MRAC). It operates by first comparing the system's actual behavior with a reference model of the expected behavior, and then minimizing the discrepancy between the two by modifying the control inputs [21]. In MRAC, the actual behavior of the system is measured using sensors or other measuring tools, whereas the reference model is usually a mathematical model that depicts the intended behavior. The adaptive control system modifies the control inputs in response to variations in the error signal, which is the difference between the two [22].

MRAC's adaptiveness stems from its real-time control input adjustments in response to error signal variations. This is accomplished by adaptive algorithms that modify the control settings based on feedback from the error signal. MRAC's primary benefit is its ability to manage systems with variable or unknown parameters, which makes it appropriate for a variety of applications [23]. It is frequently utilized in robotics and other autonomous systems, as well as control systems for industrial, automotive, and aerospace industries. All things considered, MRAC is a potent method for managing dynamic and complex systems, and its application is growing in popularity across a variety of sectors and uses [24].

2.0 METHODOLOGY

The behavior of linear systems, such as those seen in engineering and physics, can be studied mathematically using eigenvalues. The eigenvalues of a system can be used to assess a system's dynamic stability and determine whether it is stable or unstable [25]. The stability of a system is specifically assessed using the eigenvalues of its state matrix. The system is stable if all the eigenvalues have negative real portions, which indicates that it will stabilize following a modest disturbance. The system is unstable if any of the eigenvalues contain positive real components, which means that it will oscillate unboundedly in response to slight perturbations [26].

Eigenvalues are the special set of scalar values that are associated with the set of linear equations most probably in the matrix equations. The eigenvectors are also termed as Characteristic roots. It is a nonzero vector that can be changed at most by its scalar factor after the application of linear transformations. Let ? ?? a 2*2 matrix. A Scaler ? is called an eigenvalue of A if there is a nonzero vector ? such that A? = ?? such a vector ? is called an eigenvector of A corresponding to ? [27].

$$\mathit{Show}\ \text{that}\ \bar{x} = \begin{bmatrix} 2 \\ 1 \end{bmatrix}$$

$$\text{Eigenvector of } A = \begin{bmatrix} 3 & 2 \\ 3 & -2 \end{bmatrix}$$

$$\text{Corresponding to } \lambda = 4$$

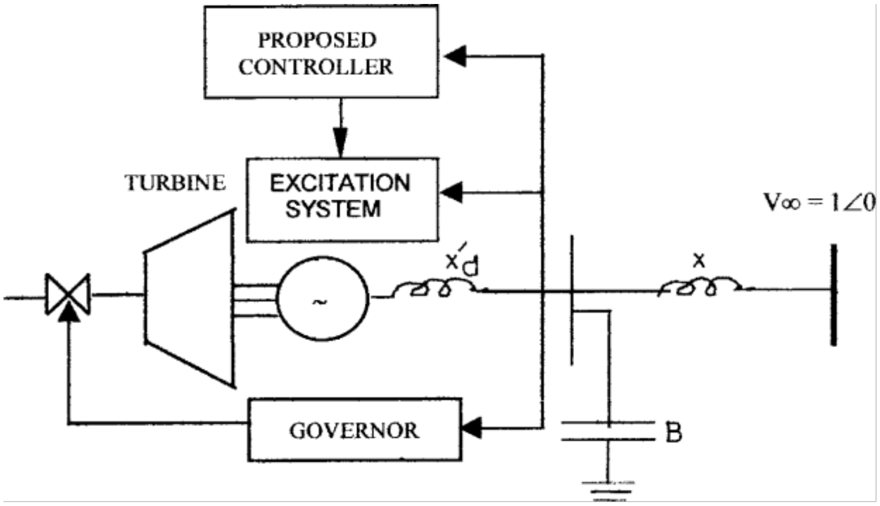
$$A\bar{x} = \lambda\bar{x}$$

$$\begin{bmatrix}3 & 2\\ 3 & -2\end{bmatrix}\begin{bmatrix}2\\ 1\end{bmatrix} = 4\begin{bmatrix}2\\ 1\end{bmatrix}$$

$$\left[\frac{3*2+2*1}{3*2(-4)*1}\right] = \begin{bmatrix}8\\ 4\end{bmatrix}$$

$$\begin{bmatrix}8\\ 4\end{bmatrix} = \begin{bmatrix}8\\ 4\end{bmatrix}$$

If ? is an eigenvalue of A, and ? is an eigenvector belonging to ?, any non-zero multiple of ? will be an eigenvector.



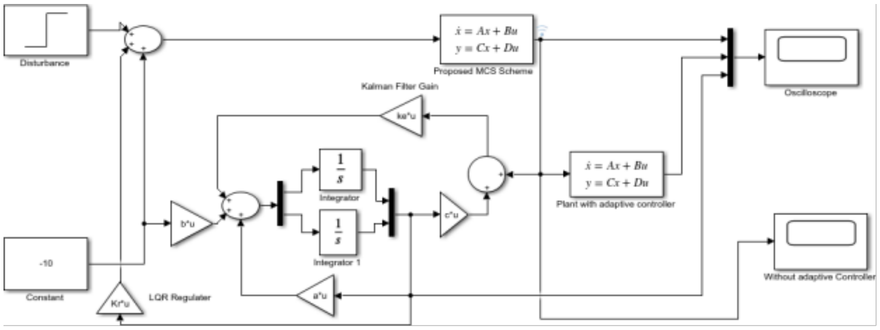


Figure 2.1: Proposed Adaptive Control Scheme

The suggested adaptive MCS control scheme uses a mathematical model of the system to create a control rule that meets specific performance requirements, like stability and tracking accuracy. The scheme uses an online identification approach to estimate real-time system model parameters. The control law is then updated, and the system's control inputs are modified using the predicted model parameters.

A feedback loop in the control system enables the system to modify its behavior in response to the discrepancy between the intended and actual outputs. The feedback loop adjusts the control input by comparing the system's actual output with the intended output and using the discrepancy, known as the error signal. The components of a feedback loop are sensors, a controller, an actuator and a plant. The sensor gives the controller information by measuring the system's real output [28]. The control input is determined by the controller using a control algorithm and transmitted to the actuator. The actuator could be any mechanism that alters the system's behavior, such as a motor or valve. Finally, the sensor measures the output produced by the plant once it receives the control input from the actuator.

The power system comprises a synchronous machine alternator unit linked to an infinite bus via a transmission line. The system incorporates controls for voltage regulation and speed governance.

3.0 RESULTS AND DISCUSSION

This research examines the performance of an uncontrolled system with low damping ratio, focusing on the Electromechanical Mode (EM) and Trace (B?1) eigenvalues. The damping ratio is improved by striping eigenvalues and solving the popular Lyapunov equation. The control mechanism is tested using computer Simulink, with the best response found to be 20.53 and 10.98 (Fig: 3.2 to 3.3). The proposed controller effectively dampens low frequency oscillations under normal operating conditions. The system's first input is a unit phase input from the controller, and it provides effective oscillation damping to sudden shocks. The controller can be adjusted by changing the rotor angle, mounting more flywheels, and connecting additional reactance at the generator terminal. The results demonstrate the effectiveness of the proposed adaptive controller in the presence of parameter changes can be shown in Fig. 3.3.

The eigenvalues of the uncontrolled system, where the $\mathrm{A_m}$matrix displays eigenvalues, are examined first in the inquiry.

Λ(A) = [-0.0114 ± j0.8019, - 0.1951, - 0.0572, - 0.0772 +- j0.1146, - 0.274, -13.70]

The first two eigenvalues stand for the electromechanical mode (EM), which is mostly related to rotor oscillations. Here is the formula for determining the damping ratio in this mode:

$$-0.0114 \pm j0.8019$$

$$= \frac{0.0114}{\sqrt{(-0.0114)^2 + (0.8019)^2}}$$

$$= 0.0142$$

This value falls significantly below the acceptable range of 0.1 to 0.5, highlighting the system's poor oscillatory behavior. In order to solve this problem, the eigenvalues are updated by applying the strip eigenvalue assignment where h1= - 0.05 and h2= - 0.45 resulting in updated eigenvalues:

Λ(A) = [0.0395 ± j0.7191, - 0.1569, - 0.0173, - 0.0372 +- j0.1947, - 0.274, - 13.70]

The eigenvalues are changed by the controller's power, with trace (? F1) is determined to be 0.1581. After recalculating the damping ratio for the upgraded electromechanical mode, the results demonstrate that the system is much more stable than before, falling squarely within the predicted range of 0.1 to 0.5.

A positive semi-definite P matrix is obtained by solving the Lyapunov equation with the identity matrix, then solving for , in order to verify stability. Consistent with earlier observations, the eigenvalues of this matrix validate stability enhancements. The steady-state gain, K(t), of the controller is found by the function K(t) contains the following values:

10^3 [0.0395 +- j0.7191, - 0.1569, - 0.0173, - 0.0372 +- j0.1947, - 0.274, - 13.70]

Computer simulations are employed to examine the controller's performance. The damping behavior is assessed across a range of parameters:

α varies from 0 to -20.5

β varies from 0 to -10.98

the best values are determined to be α=-20.53 and ?=-10.98. A minor disturbance is applied to the system using the parameter $[0, 0.02, 0, 0, 0, 0, 0]^t$ from Fig: 3.3. Quick reduction of low-frequency oscillations is shown by the graphical results. The controlled system exhibits much reduced oscillations when excited with a unit step input from Fig. 3.1 compared to the uncontrolled one.

Rotor angle modifications, extra flywheel installations, and reactance variations are some of the system factors that can be altered to conduct further robustness testing. The controller still shows effective damping, as seen in the simulation results from Fig. 3.2 even when ? varies by 30%.

This research highlights the suggested controller's impressive flexibility and durability. In contrast to more conventional approaches, this adaptive controller can dynamically stabilize the system in the face of perturbations and large-scale changes to its parameters. Its real-world effectiveness is proven by eigenvalue reassignment, Lyapunov stability verification, and practical simulation results.

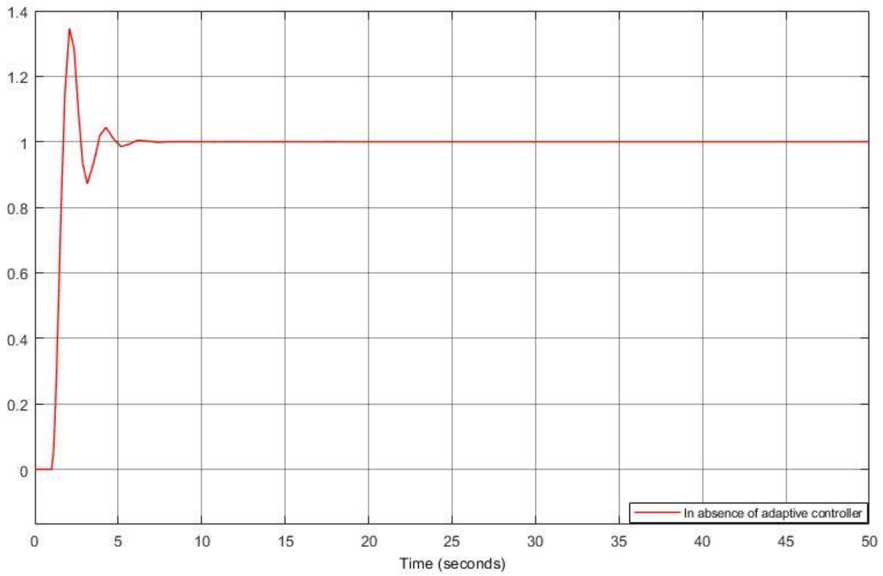


Figure 3.1: Initial system responses without adaptive controller. (a) In absence of adaptive controller.

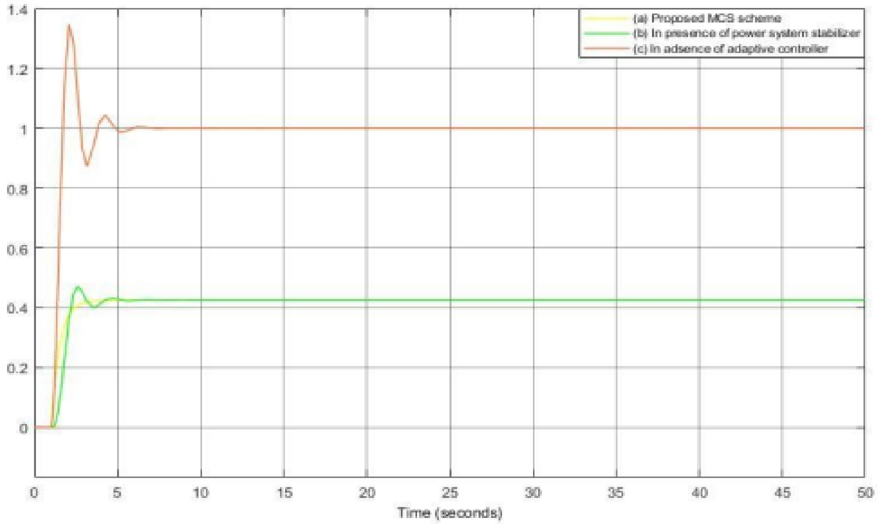


Figure 3.2: time response to system parameter variation with controller. (a) Proposed MCS scheme, (b) In presence of power system stabilizer, (c) In absence of adaptive controller.

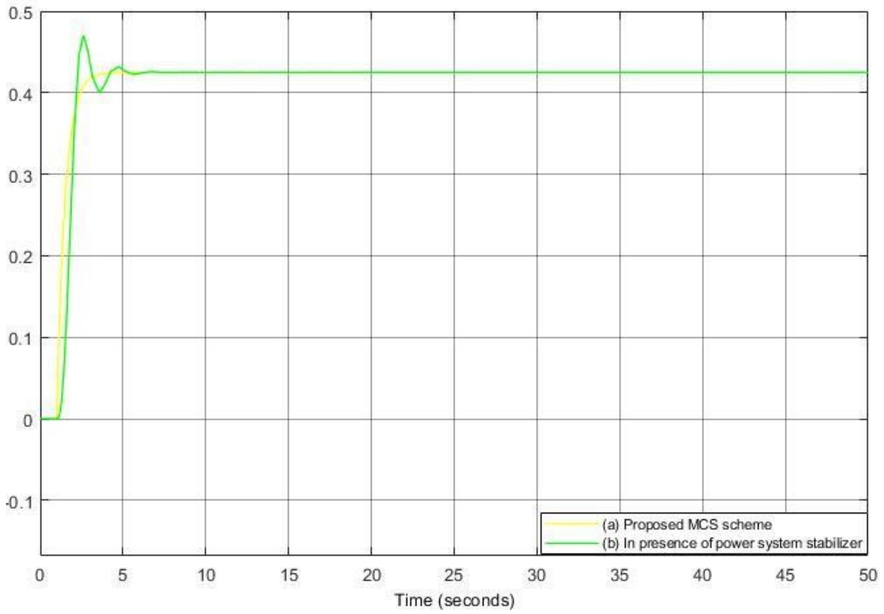


Figure 3.3: time response to system parameter variation with controller. (a) Proposed MCS scheme. (b) In presence of power system stabilizer.

4.0 CONCLUSION

Output feedback adaptive controllers can improve synchronous power system dynamic stability. The controller monitors system output variables to assess status and change control actions to maintain stability. State output feedback and hyper-stability theory are used to create an adaptive controller for higher-order power systems [29]. Adaptive controllers increase synchronous power system dynamic stability. An adaptive controller's main goal is to stabilize and prevent oscillations by continuously modifying system settings. The adaptive controller continuously evaluates system performance and adjusts control signals via a feedback loop. The controller's simplicity simplifies the design technique and reduces computation [30]. This study concludes with MATLAB and Simulink operational simulation results. The mode's damping ratio, 0.0142, matches its expected range of 0.1 to 0.5. The numerical expression indicates that the suggested control works effectively with changing disturbances, operating conditions, and system features. The adaptive scheme under development will soon include a decentralized framework for large-scale multi-machine power systems. The proposed method can be applied to large-scale, networked power systems using system passivity since hyper-stability is linked to passivity.

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