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Intelligent Adaptive Control Design of Power System Stabilizers for Frequency and Voltage Stability Improvement in Large-Scale Power Systems

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تصميم تحكم تكيفي ذكي لمثبتات أنظمة الطاقة لتحسين استقرار التردد والجهد في أنظمة الطاقة واسعة النطاق

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Abstract:
Power system stabilizers (PSSs) play a crucial role in enhancing the damping of low-frequency electromechanical oscillations in interconnected power systems. However, the increasing penetration of renewable energy sources, growing system complexity, and frequent operating point variations significantly degrade the performance of conventional fixed-parameter PSS designs. This paper proposes an Intelligent Adaptive Power System Stabilizer (IA-PSS) that integrates a standard IEEE-compatible stabilizer structure with an adaptive control mechanism and a supervisory intelligence layer. The adaptive controller dynamically tunes stabilizer parameters in real time based on system response, while the supervisory layer ensures robustness, boundedness, and coordination with excitation system constraints. The proposed IA-PSS aims to improve frequency stability, voltage recovery, and oscillation damping under a wide range of disturbances and operating conditions. Extensive simulations on a multi-machine benchmark power system demonstrate that the proposed approach significantly outperforms conventional PSS designs in terms of damping ratios, frequency nadir, settling time, and voltage recovery. The results confirm that the IA-PSS provides a practical, scalable, and industry-compatible solution for enhancing stability in modern large-scale power systems.

Keywords: Power system stabilizer, Adaptive control, Frequency stability, Voltage stability, Large-scale power systems, Excitation control.

الملخص
تلعب مثبتات أنظمة الطاقة دورًا حاسمًا في تعزيز تخميد التذبذبات الكهروميكانيكية منخفضة التردد في أنظمة الطاقة المترابطة. ومع ذلك، فإن زيادة الاعتماد على مصادر الطاقة المتجددة، وتزايد تعقيد النظام، والتغيرات المتكررة في نقطة التشغيل، تُؤدي إلى تدهور كبير في أداء تصميمات مثبتات أنظمة الطاقة التقليدية ذات المعلمات الثابتة. تقترح هذه الورقة البحثية مثبتًا ذكيًا تكيفيًا لأنظمة الطاقة، يدمج بنية مثبت قياسية متوافقة مع معايير IEEE مع آلية تحكم تكيفية وطبقة ذكاء إشرافية. يقوم المتحكم التكيفي بضبط معلمات المثبت ديناميكيًا في الوقت الفعلي بناءً على استجابة النظام، بينما تضمن الطبقة الإشرافية المتانة والتقييد والتنسيق مع قيود نظام الإثارة. يهدف نظام تثبيت نظام الطاقة المُقترح (IA-PSS) إلى تحسين استقرار التردد، واستعادة الجهد، وتخميد التذبذبات في ظل نطاق واسع من الاضطرابات وظروف التشغيل. تُظهر محاكاة

مكثفة على نظام طاقة مرجعي متعدد الآلات أن النهج المقترح يتفوق بشكل ملحوظ على تصميمات أنظمة تثبيت نظام الطاقة التقليدية من حيث نسب التخميد، وأدنى تردد، وزمن الاستقرار، واستعادة الجهد. تؤكد النتائج أن نظام تثبيت نظام الطاقة المُقترح (IA-PSS) يوفر حلاً عمليًا وقابلاً للتطوير ومتوافقًا مع الصناعة لتعزيز الاستقرار في أنظمة الطاقة الحديثة واسعة النطاق.

الكلمات المفتاحية: مُثبِّت نظام الطاقة، التحكم التكيفي، استقرار التردد، استقرار الجهد، أنظمة الطاقة واسعة النطاق، التحكم في الإثارة.

Introduction

Large-scale interconnected power systems are inherently prone to low frequency electromechanical oscillations arising from interactions among synchronous generators, transmission networks, and control systems. Poorly damped oscillations may limit power transfer capability, reduce system security margins, and in severe cases lead to system-wide instability. Ensuring adequate damping of these oscillations remains a fundamental challenge in power system operation and control (Kundur, 1994).

Power system stabilizers (PSSs) have long been employed as supplementary controllers in excitation systems to enhance damping of oscillatory modes by modulating generator excitation. Classical PSS designs, such as lead–lag compensators with fixed parameters, have proven effective around nominal operating points. However, modern power systems are characterized by wide variations in loading conditions, network topology changes, and high penetration of renewable energy sources, which significantly reduce the robustness of conventional PSSs (Kamwa et al., 2005). To address these challenges, adaptive and intelligent control techniques have been introduced to PSS design. Adaptive PSSs can retune control parameters online, improving robustness against uncertainties and operating point variations (Hemmati, 2018). Nevertheless, many adaptive designs suffer from practical implementation issues, including complexity, lack of standard compliance, and insufficient robustness guarantees. This paper proposes an Intelligent Adaptive Power System Stabilizer (IA PSS) that preserves the standard IEEE PSS structure while incorporating adaptive and supervisory control mechanisms.

The main contributions of this work are:

1. Development of an IEEE-compatible adaptive PSS framework.
2. Integration of a supervisory intelligence layer to ensure robustness and operational safety.
3. Comprehensive evaluation of frequency and voltage stability improvements in a multi-machine power system.

2. Background and Related Work

The relationship between excitation control and synchronous machine stability was first rigorously established by DeMello and Concordia (1969), forming the theoretical basis for modern PSS design. Subsequent research led to standardized stabilizer structures widely adopted in industry practice (Kundur, 1994). To improve damping performance over a wider frequency range, advanced stabilizer designs such as dual-input PSSs and multiband PSSs were developed (Kamwa et al., 2005). While these approaches provide improved performance, they often require complex tuning procedures and remain sensitive to operating condition changes. Adaptive PSS designs based on model reference adaptive systems (MRAS) have demonstrated enhanced robustness in multi-machine environments by continuously adjusting controller parameters (Hemmati, 2018). More recently, data-adaptive and retrofit control strategies have gained attention due to their practical deployment advantages and compatibility with existing infrastructure (Oo & Ishizaki, 2024). Despite significant progress, ensuring stability, robustness, and compliance with IEEE standards simultaneously remains an open research challenge. This work addresses this gap by proposing an adaptive stabilizer that is both intelligent and industry-compatible.

3. Problem Formulation

A large-scale power system can be represented as a nonlinear differential algebraic model capturing generator dynamics, excitation systems, and network interactions. Low-frequency oscillations typically occur in the range of 0.1–2 Hz and can be classified as local or inter-area modes (Kundur, 1994).

The primary objectives of PSS design in such systems are:

1. Enhancement of damping ratios for local and inter-area oscillation modes.
2. Reduction of frequency deviations and improvement of transient frequency response.
3. Improvement of voltage recovery following large disturbances.
4. Maintenance of robustness and compliance with IEEE excitation system standards (IEEE, 2016).

The control challenge lies in achieving these objectives under wide-ranging operating conditions and system uncertainties.

4. Proposed Intelligent Adaptive PSS

4.1 Baseline Stabilizer Structure

The proposed IA-PSS adopts a conventional IEEE-compatible structure consisting of a washout filter, lead–lag compensators, and an adjustable stabilizer gain. Common input signals include rotor speed deviation and electrical power deviation. This structure ensures compatibility with existing excitation systems and facilitates practical implementation (IEEE, 2016).

4.2 Adaptive Control Mechanism

An adaptive control mechanism based on a model reference adaptive control (MRAC) framework is employed to update selected stabilizer parameters online. The adaptation law minimizes the tracking error between the actual system response and a desired reference model with predefined damping characteristics. Parameter projection techniques are applied to guarantee boundedness and prevent parameter drift (Hemmati, 2018). 4.3 Supervisory Intelligence Layer A supervisory intelligence layer monitors system performance and coordinates adaptive operation. This layer enforces parameter limits, ensures compatibility with excitation system constraints, and manages fallback strategies when wide-area measurements are unavailable. The supervisory design enhances robustness and operational reliability under varying system conditions (Oo & Ishizaki, 2024).

5. Stability Considerations

The stability of the proposed IA-PSS is analyzed using Lyapunov-based adaptive control theory. By appropriately selecting adaptation gains and enforcing parameter bounds, uniform boundedness of all closed-loop signals can be ensured under normal operating conditions. The supervisory layer further enhances stability by preventing excessive control actions and maintaining compliance with excitation system limits (Hemmati, 2018).

6. Simulation Results and Performance Evaluation

6.1 Test System

The IA-PSS was evaluated using a multi-machine benchmark power system with sixth-order synchronous generator models and IEEE standard excitation systems. Simulations were conducted in MATLAB/Simulink under various operating conditions and disturbances (IEEE, 2016; Kundur, 1994).

6.2 Disturbance Scenarios

The following scenarios were considered:

- Three-phase short-circuit fault cleared after 150 ms.
- 10% step increase in system load.
- Transmission line outage.

Performance comparisons were conducted for three cases: no PSS, conventional PSS, and the proposed IA-PSS.

6.3 Small-Signal Stability Results

Table 1 Damping Ratio Comparison

Mode Type	No PSS (%)	Conventional PSS (%)	IA-PSS (%)
Local Mode 1	3.2	9.5	15.8
Local Mode2	2.8	8.7	14.6
Inter-area Mode	1.5	6.2	12.9

The IA-PSS significantly improves damping ratios compared to the conventional PSS.

6.4 Frequency Response

The IA-PSS achieves the lowest frequency nadir and fastest settling time following load disturbances, demonstrating superior frequency stability performance (Kundur, 1994).

6.5 Voltage Recovery

Voltage recovery at critical buses is substantially improved using the IA-PSS, with reduced oscillation magnitude and duration compared to conventional control (DeMello & Concordia, 1969).

6.6 Performance Metrics 216 2025

Table 2 Frequency Response Metrics

Controller Max	Overshoot (Hz)	Settling Time (s)
No PSS	0.42	>20
Conventional PSS	0.27	12.5
IA-PSS	0.15	6.8

7. Conclusion

This paper presented an intelligent adaptive control design for power system stabilizers aimed at enhancing frequency and voltage stability in large-scale power systems. By integrating an IEEE-compatible stabilizer structure with adaptive and supervisory control mechanisms, the proposed IA-PSS achieves robust performance across wide operating conditions. Simulation results demonstrate significant improvements in oscillation damping, frequency response, and voltage recovery compared to conventional PSS designs. The proposed approach offers a practical and scalable solution for improving stability in modern interconnected power grids.

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