EVALUATION OF NEW ROTOR ANGLE DEVIATION REGULATOR FOR SYNCHRONOUS GENERATOR USING NONLINEAR SWING EQUATION

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DEDICATION

To my dearest husband, Mohd Nor Ilman bin Mahad, for his unwavering support and tolerance.

To my beloved parents, Mohamad Murad bin Zabidi and Norhaidah binti Abdullah for their persistent moral support.

To my precious children, Dhia Inas Safiya binti Mohd Nor Ilman and Idris Fahim bin Mohd Nor Ilman for making my life meaningful.

ABSTRACT

In power system operation, a deviation of the rotor angle of a synchronous generator perturbs the oscillation, deteriorates system performance, and damages protection schemes. In the case of an interconnected power system, any disturbances that occur cause a discrepancy in the rotor angle. Previous studies on rotor angle stability enhancement only focus on the simplified model that adopts a linearized swing equation where the damping power has been neglected, making the accuracy of the model disputed. As such, the need to develop a control algorithm for a synchronous generator of power system is crucial. In order to obtain stabilization upon rotor angle deviation, a regulator based on the Lypapunov algorithm for a synchronous generator is proposed in this research. The dynamic model of a synchronous generator is developed through the swing equation. Nonlinear parameters are included in the modeling, and hence the synchronous generator is portrayed as a nonlinear swing equation. From the nonlinear swing equation, the crucial parameters that affect the stability and transient performance of the synchronous generator are the synchronizing coefficient, P_S and the inertia constant, H. The proposed algorithm, named rotor angle deviation regulator (RADR), is formulated via the combination of backstepping and the Lyapunov redesign technique to regulate the rotor angle deviation in order to maintain the optimum angle of the power angle curve, hence maintaining the stabilization of the synchronous generator. The performance and efficacy of the proposed algorithm are validated via simulation in MATLAB with Simulink toolbox. The simulation result shows that regardless of the faults that occur in the power system, the RADR regulates the rotor angle deviation to always be approaching 0°. The comparison of the transient response between the tested system with and without RADR shows that the system with RADR results in a slower response in terms of rise time and settling time but an improved transient performance in terms of peak undershoot and peak time, except for the tested system with 1.8 p.u. fault occurences, which recorded an improved transient performance in terms of rise time, settling time, peak undershoot, and peak time. In all cases, the implementation of RADR in the systems results in an optimum percentage improvement of the peak value in the range of 99.9989% to 99.9999%. The significant decrease in integral of absolute error (IAE), integral of squared error (ISE), and sum of squared error (SSE) for the systems with implentation of RADR verified the asymptotic stability and robustness of the RADR towards the rotor angle stability.

PENILAIAN PENGATUR BAHARU SISIHAN SUDUT ROTOR UNTUK PENJANA SEGERAK MENGGUNAKAN PERSAMAAN AYUNAN TAK LINEAR

ABSTRAK

Dalam operasi sistem kuasa, lencongan sudut rotor penjana segerak mengganggu ayunan, menurunkan prestasi sistem, dan merosakkan skim perlindungan. Dalam kes sistem kuasa tersaling hubung, sebarang gangguan yang berlaku menyebabkan kelainan dalam sudut rotor. Kajian terdahulu mengenai peningkatan kestabilan sudut rotor hanya tertumpu pada model dipermudah yang menggunakan persamaan ayunan linear di mana kuasa redaman telah terabai, menjadikan kejituan model dipertikaikan. Oleh itu, keperluan untuk membangunkan algoritma kawalan untuk penjana segerak sistem kuasa adalah penting. Untuk mendapatkan penstabilan pada lencongan sudut rotor, pengatur berdasarkan algortima Lyapunov untuk penjana segerak diusulkan dalam kajian ini. Model dinamik penjana segerak dibangunkan melalui persamaan ayunan. Parameter tak linear dimasukkan kedalam pemodelan, dan oleh itu penjana segerak digambarkan sebagai persamaan ayunan tak linear. Dari persamaan ayunan tak linear, parameter penting yang mempengaruhi kestabilan dan prestasi fana penjana segerak ialah pekali menyegerak, P_s, dan pemalar inersia, H. Algoritma yang diusulkan, yang dipanggil pengatur lencongan sudut rotor (RADR), telah diformulasikan melalui gabungan melangkah balik (backstepping) dan teknik rekabentuk semula Lyapunov untuk mengatur lencongan sudut rotor supaya mengekalkan sudut yang optimum dari lengkung sudut kuasa, dengan itu mempertahankan kestabilan penjana segerak. Prestasi dan keberkesanan algoritma yang dicadangkan disahkan melalui simulasi dalam MATLAB dengan Simulink toolbox. Hasil simulasi menunjukkan bahawa tanpa mengira gelinciran yang berlaku dalam sistem kuasa, RADR mengatur lencongan sudut rotor supaya sentiasa mendekati 0°. Perbandingan tindak balas fana antara sistem yang diuji dengan RADR dan tanpa RADR menunjukkan bahawa sistem dengan RADR menghasilkan tindak balas yang lebih lambat dari segi masa kenaikan dan masa penetapan tetapi prestasi fana yang lebih baik dari segi lajakan-turun puncak dan masa puncak, kecuali untuk sistem yang dikaji dengan kejadian gelinciran 1.8 p.u., yang mencatatkan prestasi fana yang lebih tinggi dari segi masa kenaikan, masa penetapan, lajakan-turun puncak, dan masa puncak. Dalam semua kes, pelaksanaan RADR dalam sistem menghasilkan peningkatan peratusan optimum nilai puncak dalam julat dari 99.9989% hingga 99.9999%. Penurunan yang ketara dalam nilai tara ralat-mutlak (IAE), nilai tara ralat-persegi (ISE), dan jumlah ralat-persegi (SSE) untuk sistem dengan pelaksanaan RADR mengesahkan kestabilan berasimptot dan ketahanan RADR kearah keseimbangan sudut rotor.

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LIST OF ABBREVIATIONS

AC	-	Alternator current
AVR	-	Automatic voltage regulator
CCT	-	Critical clearing time
CES	-	Capacitor energy storage
DC	-	Direct current
ECRA		Electricity and Co-generation Regulatory Authority
ESS	-	Energy storage system
FCT	-	Fault clearing time
FIS	-	Fuzzy inference system
IAE	-	Integral of Absolute Error
ISE	-	Integral of squared error
KCL	-	Kirchhoff current Law
LQG	-	Linear quadratic gaussian
LQR	-	Linear quadratic regulator
MGGP	-	Multi-gene genetic programming
MMF	-	Magneto motive force
MPC	-	Model predictive control
MRAC	-	Model reference adaptive control
MVO	-	Multi-verse optimization
PID	-	Propoertionsl-integral-derivative
PRL	-	Power reaching law
PSO	-	Particle swarm optimization
PSS	-	Power system stabilizer

RADR	-	Rotor angle deviation regulator
R-SFCL	-	Resistive-type superconducting fault current limiter
SFCL	-	Superconducting fault current limiter
SMC	-	Sliding mode control
SMES	-	Superconducting magnetic energy storage
SMIB	-	Single-machine infinite-bus
SSE	-	Sum of squared error
TCSC	-	Thyristor controlled series compensator
VSC	-	Voltage source control

LIST OF SYMBOLS

α	-	Saturation type-parameter (decay function)
C	-	Feedback gain
D	-	Damping
E	-	Voltage behind transient reactance
E'	-	Generator voltage
f_0	-	Frequency
H	-	Per unit inertia constant
J	-	Combined moment of inertia
M	-	Inertia constant
p	-	Number of poles
P_D	-	Damping power
P_e	-	Electrical power
$P_{e(pu)}$	-	Per unit electrical power
P_m	-	Mechanical power
P_{max}	-	Maximum power
$P_{m(pu)}$	-	Per unit mechanical power
P_s	-	Synchronizing coefficient
S_B	-	Base power
R	-	State space region
r	-	Small region of state space
T_e	-	Electromagnetic torque
T_m	-	Mechanical torque

T_a	-	Accelerating or decelerating torque
u	-	Controller input
u_{nom}	-	Nominal control law
u_r	-	Robust control law
V	-	Voltage at terminal load
V_g	-	Generator terminal voltage
W_k	-	Kinetic energy of rotating mass
ω_m	-	Rotor speed/mechanical angular velocity
ω_n	-	Natural frequency
ω_{sm}	-	Synchronous speed/electrical velocity
X_{12}	-	Transfer reactance
X_1 and X_2	-	Transfer reactance
x'_d	-	Generator reactance
δ	-	Load angle/power angle
δ_o	-	Initial power angle
δ_m	-	Initial rotor position before disturbances
δ_{mech}	-	Mechanical power angle
$\Delta\delta$	-	Rotor angle deviation
ΔP	-	Fault/Power input
Δu	-	Input uncertainty
ε	-	Saturation type-control parameter (epsilon)
θ_m	-	Rotor angular displacement

LIST OF APPENDICES

LIST OF PUBLICATIONS

The followings are the list of publications related to the work on this thesis:

Murad, N.S.F.M., Kamarudin, M.N., Hanafi, A.N., Jamri, M.S., and Rozali, S.M., 2024. Rotor Angle Stability of a Linearized Synchronous Generator. *AIP Conference Proceedings*, 2895(1). (SCOPUS indexed).

Murad, N.S.F.M., Kamarudin, M.N., Hanafi, A.N., Rozali, S.M., and Ibrahim, M.A., 2024. Exploration of Characteristic Equation Towards the Analysis of Dynamical Stability for Synchronous Generators through Swing Equation. *International Journal of Electrical Engineering and Applied Sciences (IJEEAS)*, 7(1).

Murad, N.S.F.M., Kamarudin, M.N., Ismail, M.F., and Rozali, S.M., 2024. Modelling of a Nonlinear Swing Equation for a Non-Salient Pole Rotor Synchronous Generator. *2024 IEEE 4th International Conference in Power Engineering Applications: Powering the Future: Innovations for Sustainable Development, ICPEA 2024*, (March), pp. 232–236. (SCOPUS indexed).

Murad, N.S.F.M., Kamarudin, M.N., Rozali, S.M., and Zakaria, M.I., 2024. Power System Stability and Control: A Comprehensive Review Focusing on the Rotor Angle Case. *Bulletin of Electrical Engineering and Informatics*, 13(6), pp. 3897–3909. (SCOPUS indexed).

Murad, N.S.F.M., Kamarudin, M.N., and Zakaria, M.I., 2024. Rotor Angle Deviation Regulator to Enhance the Rotor Angle Stability of Synchronous Generators. *International Journal of Electrical and Computer Engineering*, 14(5), pp. 4879–4887. (SCOPUS indexed).

CHAPTER 1

INTRODUCTION

1.1 Background

One of the most important roles of the power system is transmitting electrical energy from the generation system to consumers (Zamee et al., 2016). Despite transmission and distribution systems, the generation system is considered the most important component of the power system due to the fact that the stability of power system operation will be assured by the generator even with the occurrence of failures (Shu and Tang, 2017). In generation systems, synchronous generators are the most commonly utilized generators.

The stability of the power system has become more crucial due to the rapid growth of the human population and the increasing demand for sustainability. Ensuring power system stability is crucial to avoid transmission failures and blackouts, which in turn improves the overall stability and reliability of the power system. The power system stability is commonly categorized into rotor angle stability, frequency stability, and voltage stability (Safavizadeh et al., 2022). Referring to synchronous generator in power system, the rotor angle stability is considered one of the most important types of power system stability. It is focused on generators' ability to maintain the rotor angle in the presence of disturbances. It can be categorized into two categories: small signal stability and large signal stability. Small signal stability considers the small disturbance condition, which refers to the slowly and randomly occurring occurrence of disturbance (Luo et al., 2020). Large signal stability, also known as transient stability, refers to the ability of the system to regain its synchronism when subjected to a large disturbance (Luo et al., 2020; Safavizadeh et al., 2022).

Numerous studies have been conducted by previous researchers in order to analyze and enhance rotor angle stability. Various control systems have been implemented in the studies, but there is still room for improvement in rotor angle stability.

1.2 Problem Statement

In a power system, one of the most crucial problems is maintaining the system's stability. Power system behavior depends on the mechanical and electrical processes of a synchronous generator. Consequently, the behavior of the synchronous generator after disturbances affect the stability of the power system (Yurika et al., 2019). This is because the disturbances perturb the oscillation of the rotor angle of the synchronous generator, which leads to instability (Hasan et al., 2020; Jiang and Wang, 2020; Sankar et al., 2022).

Power angle, also called rotor angle, is the angle between the relative position of the rotor axis and the resultant magnetic field axis, and this angle is fixed under normal operating conditions. However, during the occurrence of disturbances, the rotor will either accelerate or decelerate with regard to the synchronously rotating air gap magnetomotive force (MMF), hence the relative motion begins (Sarkar et al., 2021). This relative motion is described via nonlinear differential equation known as swing equation (Pandya et al., 2020; Munkhchuluun et al., 2019).

The stability of the synchronous generator is preserved if the rotor locks back into synchronous speed. The rotor returns to its normal operating condition if the disturbances do not result in any net change in power; otherwise, the rotor operates at a new power angle corresponding to the synchronously rotating field (Rahim, 2022). The performance of the synchronous generator will be degraded if the rotor angle changes due to the occurrence of disturbances (Sarkar et al., 2021). Thus, it is crucial to develop a control algorithm to improve transient performance, guarantee robustness against rotor angle deviation due to disturbances, and assure fast rotor angle regulation. As such, the problem addressed in this research is to formulate a Lyapunov-based algorithm in order to guarantee the asymptotic stability of the rotor angle for the optimum power angle. Preserving the optimal power angle guarantees the synchronous generator's stable output power and, hence, the stability of the power system.

1.3 Research Motivation

In this research, there are four hypotheses to create breakthroughs in knowledge, as follows:

i) There exist parameters that have a significant effect on the stability and transient performance of synchronous generators.

ii) A nonlinear swing equation has some additional parameters that require complex mathematics to solve as compared to a linearized swing equation.

iii) Regulating the rotor angle of a synchronous generator to zero deviation will bestow power system stability.

iv) The sufficiency and necessity of Lyapunov stability criteria must be met to ensure the asymptotic stability of any unstable system.