UNIVERSITI TEKNIKAL MALAYSIA MELAKA

Faculty of Electrical Engineering

LOAD FREQUENCY CONTROL USING AUGMENTATION PI-LQR CONTROLLER FOR A TWO-AREA HYDROPOWER SYSTEM

Nabilah binti Mohd Shaharudin

Master of Science in Electrical Engineering

2019

LOAD FREQUENCY CONTROL USING AUGMENTATION PI-LQR CONTROLLER FOR A TWO-AREA HYDROPOWER SYSTEM

NABILAH BINTI MOHD SHAHARUDIN

A thesis submitted
in fulfillment of the requirements for the degree of Master of Science
in Electrical Engineering

Faculty of Electrical Engineering

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

2019

DECLARATION

I declare that this thesis entitled "Load Frequency Control using Augmentation PI-LQR Controller for a Two-Area Hydropower System" is the result of my own research except as cited in the references. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

Signature	:	……………………………...…………….
Name	:	Nabilah Binti Mohd Shaharudin
Date	:	……………………………...…………….

APPROVAL

I hereby declare that I have read this thesis and in my opinion this thesis is sufficient in terms of scope and quality for the award of Master of Science in Electrical Engineering.

Signature	:	………………..…………………..
Supervisor Name	:	Dr. Muhammad Nizam Bin Kamarudin
Date	:	………………..…………………..

DEDICATION

For my Parents Mohd Shaharudin Bin Mohd Hassan and Haniah Binti Mohd Yassin.

ABSTRACT

Hydropower is a vital renewable energy source which harnesses the power of moving water to produce electricity. Maintaining synchronism between different parts of hydropower is getting difficult over time. Frequency deviation can cause stalling in loads. If synchronism between generator and the power systems is lost at any time, voltage and current fluctuations may have happened that give catastrophic effect to the end users and power systems. A large frequency deviation can harm the equipment, delay load performance, cause the transmission line to be overloaded, damage protection schemes and ultimately lead to frequency instability. In case of interconnected power system, any small sudden load change in any of the areas causes the fluctuation of the frequencies of each and every areas and also there is fluctuation in the tie line. Many conventional load frequency control (LFC) with conventional Proportional-Integral (PI) have successfully stabilized the system. However, the speed of the recovery time is highly depending on the integral and proportional gain of PI controller. Increasing the gain may cause instability as the closed loop system tends to move system poles to unstable region. Therefore, this research proposes the augmentation of Linear Quadratic Regulator (LQR) with conventional PI in order to obtain a fast settling time without the need to judiciously adjust the PI parameters. The main goals of LFC are, to maintain the real frequency system to its acceptable limit i.e. $\pm$ 2.5 Hz while maintaining the power exchange among the control areas at specific value. To formulate the control scheme, the dynamic of the hydropower system is modeled in the time domain. The hydropower unit consists of the hydro governor, transient droop compensation, hydro turbine and load. Afterward, the LFC is designed via conventional PI controller wih Ziegler Nichols tuning. The LQR is then augmented to the conventional PI. In this stage, the dynamic of PI controller is embedded into the 11×11 state variable model of the hydropower system. The LQR parameters are obtained based on the algebraic Riccati equation where the stability is guaranteed by Lyapunov stability criteria. The effectiveness and the efficacy of the proposed PI-LQR and the conventional PI in LFC is validated via simulation in MATLAB with SIMULINK® toolbox. The comparative results showed that the closed loop two-area hydropower system with PI-LQR able to achieve asymptotic stability despite the injection of multifarious load perturbations. Compared to LFC with conventional PI controller, the settling time of LFC with PI-LQR has reduced at almost 85% for both area 1 and area 2. Whereas, 93.56% reduction in settling time for the tie line power changes is recorded. Moreover, LFC with PI-LQR managed to reduce the settling time for the system frequency at almost 95.26% when the perturbation occurs. In conclusion, the result shows that the LFC with PI-LQR controller guarantee faster transient with lower integral of absolute error as compared with the conventional PI controller

ABSTRAK

Kuasa hidro adalah sumber tenaga boleh diperbaharui yang penting yang memanfaatkan kuasa air bergerak untuk menghasilkan elektrik. Mengekalkan penyegerakan antara bahagian-bahagian kuasa hidro yang lain semakin sukar dari masa ke masa. Herotan frekuensi boleh menyebabkan beban yang terhenti. Jika penyegerakan antara penjana dan sistem kuasa hilang pada bila-bila masa, turun naik voltan dan arus mungkin telah berlaku yang memberikan kesan buruk kepada penguna akhir dan sistem kuasa. Herotan frekuensi yang besar boleh merosakkan peralatan, menunda prestasi beban, menyebabkan talian penghantaran menjadi berlebihan, merosakkan skim perlindungan dan akhirnya membawa ketidakstabilan frekuensi. Dalam kes sistem kuasa yang saling berkaitan, sebarang perubahan beban mendadak kecil di mana-mana kawasan menyebabkan turun naik frekuensi setiap kawasan dan juga terdapat turun naik dalam garisan talian. Banyak kawalan frekuensi beban konvensional (LFC) dengan kamiran-berkadar (PI) konvensional telah berjaya menstabilkan sistem. Bagaimanapun, kelajuan masa pemulihan sangat bergantung kepada pekali berkadar-kamiran pengawal PI. Peningkatan pekali boleh menyebabkan ketidakstabilan kerana sistem gelung tertutup cenderung untuk menggerakkan kutub sistem ke kawasan yang tidak stabil. Oleh itu, kajian ini mencadangkan penambahan Pengawal Selia Kuadratik Lurus (LQR) dengan PI konvensional untuk mendapatkan masa penyelesaian yang cepat tanpa perlu menyesuaikan parameter PI dengan tepat. Matlamat utama LFC adalah, untuk mengekalkan sistem frekuensi sebenar ke hadnya yang boleh diterima i.e. ± 2.5 Hz sambil mengekalkan pertukaran kuasa di antara kawasan kawalan pada nilai tertentu. Untuk merangka skema kawalan, dinamik sistem kuasa hidro dimodelkan dalam domain masa. Unit tenaga hidro terdiri daripada gabenor hidro, pampasan droop sementara, turbin hidro dan beban. Selepas itu, LFC direkabentuk melalui pengawal PI konvensional dengan penalaan Ziegler Nichols. LQR kemudiannya ditambah kepada PI konvensional. Pada peringkat ini, dinamik pengawal PI tertanam ke dalam model pembolehubah keadaan 11×11 *sistem hidro. Parameter LQR diperoleh berdasarkan persamaan Riccati algebra di mana kestabilan dijamin oleh kriteria kestabilan Lyapunov. Keupayaan dan keberkesanan cadangan PI-LQR dan PI konvensional di LFC disahkan melalui simulasi di MATLAB dengan kotak peralatan SIMULINK®. Keputusan perbandingan menunjukkan bahawa gelung tertutup sistem hidro dua kawasan dengan PI-LQR dapat mencapai kestabilan asimptot walaupun dengan kemasukan pelbagai gangguan beban. Berbanding dengan LFC dengan pengawal PI konvensional, masa penetapan LFC dengan PI-LQR telah berkurangan hampir 85% untuk kedua-dua kawasan 1 dan kawasan 2. Sedangkan pengurangan masa 93.56% dalam masa penetapan untuk perubahan kuasa tali talian dicatat. Tambahan, LFC dengan PI-LQR berjaya mengurangkan masa penetapan untuk frekuensi sistem hampir 95.26% apabila gangguan berlaku. Kesimpulannya, hasil menunjukkan bahawa LFC dengan pengawal PI-LQR menjamin sambutan fana yang lebih pantas dengan kamiran ralat yg lebih rendah berbanding denagn pengawal PI konvensional.*

ACKNOWLEDGEMENTS

During the three years research life in Universiti Teknikal Malaysia Melaka (UTeM), I receive a great deal of selflessly help from a lot of people that I would like to say thanks to. First and foremost, I would like to take this opportunity to express my sincere acknowledgement to my supervisor Dr. Muhammad Nizam bin Kamarudin from Faculty of Electrical Engineering, Universiti Teknikal Malaysia Melaka (UTeM) for his essential supervision, support and encouragement towards the completion of this thesis. His enthusiasm and inspiration lightened the road of completing this work.

I would also like to express my greatest gratitude to Dr. Mohd Hendra Bin Hairi and En. Mohd Hafiz Bin Jali also from the Faculty of Electrical Engineering, UTeM, who is the co-supervisor of this project for their advice and suggestion in establishment of this thesis.

Particularly, to Fundamental Research Grant Scheme (RAGS) Grant No. RAGS/1/2015/TK0/FKE/03/B00097, Centre for Robotics and Industrial Automation (CeRIA), and Minister of Higher Education (MOHE) for the financial and technical support that had been given throughout this project.

Last but not least, special thanks to everyone that were involved directly or indirectly in the development of this project and the writing of the thesis.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF APPENDICES

LIST OF ABBREVIATIONS

ACE	-	Area Control Error
ACO	-	Ant Colony Optimization
AGC	-	Automatic Generation Control
ANFIS	-	Adaptive Neuro Fuzzy Inference System
ANN	-	Artificial Neural Network
ARE	-	Algebraic Riccati Equation
AVR	-	Automatic Voltage Regulator
BA	-	Bee Algorithm
BFO	-	Bacteria Foraging Optimization
DFIG	-	Doubly Fed Induction Generator
FLC	-	Fuzzy Logic Control
GA	-	Genetic Algorithm
GRC	-	Generation Rate Constraints
IAE	-	Integral of Absolute Error
IP	-	Inverted Pendulum
ISE	-	Integral of Squared Error
ITAE	-	Integral of Time Absolute Error
LFC	-	Load Frequency Control
LMI	-	Linear Matrix Inequalities

LQR	-	Linear Quadratic Regulator
MPPT	-	Maximum Power Point Tracking
MPRS	-	Maximum Peak Resonance Specification
PI	-	Proportional Integral
PID	-	Proportional Integral Derivative
PSO	-	Particle Swarm Optimization
PV	-	Photovoltaic
RSME	-	Root Mean Square Error
SLP	-	Step Load Perturbation
SMES	-	Superconducting Magnetic Energy Storage
VIU	-	Vertically Integrated Utility
ZN	-	Ziegler Nichols

LIST OF SYMBOLS

ΔPt_{w1}	-	Change in turbine power output of area 1
ΔPt_{w2}	-	Change in turbine power output of area 2
δ	-	Change in rotor angle
$\int ACE_1$	-	Control signal output of area 1
$\int ACE_2$	-	Control signal output of area 2
R	-	Control weight matrix
$\Delta\delta$	-	Fault angle
f	-	Frequency
B	-	Frequency bias parameter
Δf_1	-	Frequency deviation of area 1
Δf_2	-	Frequency deviation of area 2
T_g	-	Governor time constant
H_∞	-	H-infinity
ΔP_{d1}	-	Load disturbance of area 1
ΔP_{d2}	-	Load disturbance of area 2
ΔP_m	-	Mechanical output deviation
u	-	Minimum energy
ΔPg_2	-	Output measure for the transient droop compensation of area 1
ΔPg_4	-	Output measure for the transient droop compensation of area 2

J	-	Performance index
R_P	-	Permanent droop
K_L	-	Power system gain
T_L	-	Power system time constant
X_{tie}	-	Reactance in tie line
ΔP_V	-	Real power command signal
T_R	-	Resetting time
Q	-	State weight matrix
ΔPg_1	-	Steam valve displacement of area 1
ΔPg_3	-	Steam valve displacement of area 2
Δf	-	System frequency deviation
$\Delta P_{tie(1,2)}$	-	Tie line power deviation between area 1 and area 2
R_T	-	Temporary droop
T_W	-	Water starting time

LIST OF PUBLICATIONS

1. Shaharudin, N., Kamarudin, M. N., Hairi, M. H., Rizman, Z. I., 2018. "Achieving Power System Stability for Two Area Hydro Power System via LQR Techniques," International *Journal of Engineering and Technology (IJET),* 7(3.14), pp. 396-402. (Indexed by SCOPUS)
2. Murad, N. S. F. M., Kamarudin, M. N., Rozali, S. M., Shaharudin, N. M., Khamis, A., Husain, A. R., 2017. "Variable Speed Control of Two-Mass Wind Turbine with Unknown Stiffness," *Journal of Telecommunication, Electronic and Computer Engineering (JTEC),* 9(4), pp. 117-121. (Indexed by SCOPUS)
3. Murad, N. S. F. M., Kamarudin, M. N., Rozali, S. M., Shaharudin, N. M., 2017. "Review on Wind Turbine Technology and Control," *Journal of Advanced Manufacturing Technology (JAMT),* 11(2), pp. 87-100. (Indexed by SCOPUS)
4. Kamarudin, M. N., Shaharudin, N. M., Jali, M. H., Rozali, S. M., Aras, M. S. M., 2017. "Achieving Thermal Power System Stability Using Load Frequency Controller," In *Modelling, Design and Simulation of Systems. AsiaSim 2017. Communication in Computer and Information Science (CCIS),* 751, pp. 455-467. Singapore: Springer. (Indexed by SCOPUS)

CHAPTER 1

INTRODUCTION

1.1 Background studies

Load frequency control (LFC) or Automatic generation control (AGC) (Khan et al., 2018) is the mechanism augmented to the power system in order to retain system frequency at the scheduled level and control the net tie line interchange power in a multi area interconnected power system (Hore, 2014; Jain et al., 2014). LFC objectives are met by measuring control error signal called area control error (ACE), which represents the real power imbalance between generation and load, and is a linear combination of net power interchanges and frequency deviations (Shah et al., 2012).

An interconnected power system consists of control areas which are connected to each other by tie line. In an interconnected power system, there are two variables that are disturbed during transient power load which are the area frequency and tie line power interchange. The key is to maintain the steady state or the tie line power interchange (P_{tie}) at null position (Jain et al., 2014; Kumar and Naidu, 2014). Any sudden small load perturbation in any of the interconnected area will cause the deviation of frequency of all areas and also the tie line powers.

The load frequency control issued to maintain the frequency of electrical network and keep it at rated value (in Malaysia = 50 Hz & United State = 60 Hz) during any disturbance happened from generation side of the load side. In addition to that, there is other disturbance that come from other area connected to the same network. For instance, if we have two areas connected together and because of internal fault in area one the turbine will be tripped and the generation from area one will be lost.

The reason for constant frequency is because the speed of the alternating current motors depends on the frequency of the power supply. There are situations where speed consistency is expected to be of high order. If the normal frequency is 50 Hertz and the system frequency falls below 47.5 hertz or goes up above 52.5 hertz then the blades of the turbine are likely to get damaged so as to prevent the stalling of the generators (Sarker and Hasan, 2016).

Load frequency control (LFC) is the automatic generation controller that applied to the power system in order to ensure the power system stability when there is frequency deviation due to load changes or load perturbation. The power systems, frequency are dependent on active power and voltage dependence on reactive power limit. The control power system is separated into two independent problems. The control of frequency by active power is called as load frequency controller (LFC) (Lokanatha and Vasu, 2014).

One of the objectives of LFC is to return the frequency deviation (Δf) back to zero. In a power system consisting of interconnected areas, each area agrees to export or import a scheduled amount of power through transmission line interconnection, or tie lines, to its neighboring areas. Thus, a second LFC objective is to have each area absorb its own load changes during normal operation. This objective is achieved by maintaining the net tie line power flow out of each area at its scheduled value. The main purpose of operating the load frequency control is to keep uniform the frequency changes during the load changes. During the power system operation rotor angle, frequency and active power are the main parameters to change.

Occasionally, load on the system is increased suddenly then the turbine speed drops before the governor can adjust the input of the water or steam to the new load. As the change in the value of speed diminishes, the error signal becomes smaller and the position of the governor get closer to the point required maintaining the constant speed. One way to restore the speed or frequency to its nominal value is to add an integrator on the way. As the load of the system changes continuously, the generation is adjusted automatically to restore the frequency to the nominal value. This scheme is known as automatic generation control (AGC).

Automatic generation control (AGC) plays an important role in steady state operation or healthy operation of power system. When there is mismatch between the load demand and the generation, then changes in frequency occurs (Esmail et al., 2017). When generation is greater than load then frequency increases and when generation is less than load then frequency decreases.

In an interconnected system consisting of several pools, the role of the AGC is to divide the load among the system, stations and generators so as to achieve maximum economy and reasonably uniform frequency. In case of a hydropower, the power system frequency regulation can be affected due to water flow fluctuation. This lead to imbalance between power generation and power demand, and result, frequency will deviate from its nominal value (Rajaguru et al., 2015). Significant frequency deviations may cause under or over frequency relay operations and finale disconnect some parts of system load and generation. The principle block of the power system studied in this research is shown in Figure 1.1.

Two parts of this system can be considered. A considerable attention should be pay to the LFC section. Changes in real power mainly affect the system frequency, while reactive power is less sensitive to changes in frequency and is mainly dependent on changes in voltage magnitude. The LFC thus controls the real power and the frequency of the system. It also has a major role in the interconnection of different power plants (Altas and Neyens, 2006).

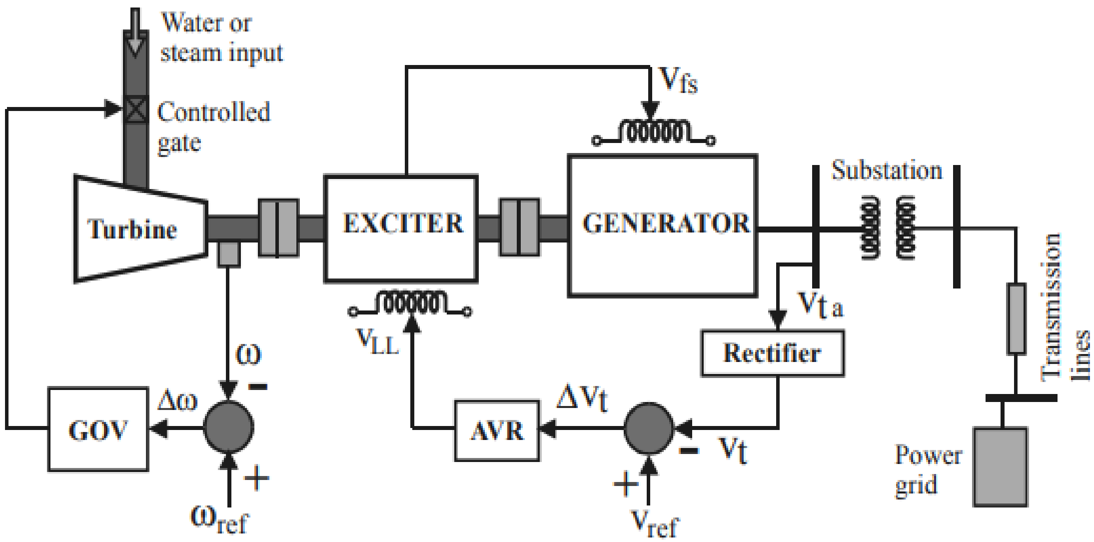

Figure 1.1: Principle block diagram of the power system (Altas and Neyens, 2006)

The most applied controller for LFC is a conventional Proportional plus Integral (PI). Conventionally, PI controller is used to construct an automatic generation controller to guarantee the stability of the system when being perturbed by load change. However, based on literature and references therein (Talaq and Al-Basri, 1999; Çam and Kocaarslan, 2005; Altas and Neyens, 2006), classical Integral based controller has several shortcomings. One of the shortcomings is the sluggish settling time, which is the paramount criteria to the transient performance of power system stability.

Therefore, a Linear Quadratic Regulator (LQR) with full state feedback is proposed in order to control the frequency deviation. In this thesis, a two-area hydropower system with PI controller is represented in state space form. The controllability and observability of the system is tested. Presuming that the state of the state space model is not available for feedback, a frequency deviation observer for both areas is formulated. Hence, the state-feedback (pole placement) via LQR is designed to preserve the stability of the power system due to load frequency deviation. It is expected that the proposed controller guarantee the stability of the frequency deviation due to load perturbation. The transient performance is expected to be improve as compared to PI controller-based LFC system.

1.2 Problem statement

In power system, one most crucial problem is maintaining the system stability. In case of hydropower, the power system frequency regulation can be effected due to water flow fluctuation that leads to imbalance between power generation and power demand. As a result, frequency will deviate from its nominal value. In other word, any mismatch between generation and demand causes the system frequency to deviate from its nominal value and eventually, high frequency deviation will lead to system collapse.

For load frequency control, the design of Proportional-Integral (PI) decentralized controller is widely used in power industry. This gives adequate system response considering the stability requirements and the performance of its regulating units. Conventional PI controllers of fixed structure and constant parameters are usually tuned for one operating condition. Since the characteristics of the power system elements are non-linear, these controllers may not be capable of providing the desired performance for other operating conditions. Therefore, the response of this controller is not satisfactory enough and large oscillations may occur in the system.

Moreover, the dynamic performance of the system is highly dependent on the selection of the PI controller gain. A high gain may deteriorate the system performance having large oscillations and in most cases it causes instability. Subsequently, a number of decentralized load frequency controllers were developed to eliminate the above drawback. However, most of them are complex state-feedback or high-order dynamic controllers,