Faculty of Electrical Technology and Engineering

FORMULATION OF H_2 AND H_∞ POWER DEFICIT ESTIMATION METHOD FOR ISOLATED POWER SYSTEM

Mohd Saifuzam bin Jamri

Doctor of Philosophy

2024

FORMULATION OF H_2 AND H_∞ POWER DEFICIT ESTIMATION METHOD FOR ISOLATED POWER SYSTEM

MOHD SAIFUZAM BIN JAMRI

A thesis submitted
in fulfillment of the requirements for the degree of
Doctor of Philosophy

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

Faculty of Electrical Technology and Engineering

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

2024

DEDICATION

For my loving wife Siti Fatimah binti Masiran, Childs and my big family

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

ABSTRACT

An isolated power system network is described as an electrical network that is not connected to the larger power system grid. It was defined as a local electrical network comprising an isolation generator and transformer with branch circuits designed for certain applications. The local generator in an isolated power system network is basically used as the main source. The network is very sensitive to the sudden high equilibrium condition of electrical load demand that can lead to unbalanced power, delayed load performance, overloaded circuits, and severe frequency deviation problems. The undesired frequency response can harm the connected load, damage the protection devices, and cause the network to trip and experience a total blackout. According to the literature review, the rate of frequency deviations gives implicit information about the system's stability. There is an advantage to knowing the magnitude of the power deficit of the network by only observing the system's frequency behaviour. Hence, the main objective of this research is to observe and monitor the power deficit for isolated electrical network conditions through system frequency observation. In this research, the similarities between the structure of H_2 norm and H_∞ norm filtering problems are examined, and the state-space model equations are used in designing a power deficit estimator. The estimated power deficit is able to give preliminary information about the network stability condition before any further protection scheme takes place. However, the estimation becomes worse when the system has parameter uncertainty. Hence, modifications have been made to the estimator design, and the results show an improvement in steady-state estimation. The comparison between the proposed estimator and the conventional slope method has been conducted, and the results show that the proposed estimator provides better estimation under uncertainty. At the end of the research, the H_∞ norm method was chosen as the best estimator for a power deficit estimation in an isolated power system application, which has good estimation performance with only 0.1% estimation error in the uncertainty case and the lowest performance index equal to 0.00044982.

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

PERUMUSAN KAEDAH ANGGARAN DEFISIT KUASA H_2 DAN H_∞ BAGI SISTEM KUASA YANG TERASING

ABSTRAK

Rangkaian sistem kuasa terasing dihuraikan sebagai rangkaian elektrik yang tidak disambungkan ke grid sistem kuasa yang lebih besar. Ia ditakrifkan sebagai rangkaian elektrik tempatan yang terdiri daripada penjana pengasingan dan pengubah dengan litar cabangan yang direka untuk aplikasi tertentu. Penjana tempatan dalam rangkaian sistem kuasa terpencil pada asasnya digunakan sebagai sumber utama. Rangkaian ini sangat sensitif kepada keadaan ketidakseimbangan permintaan beban elektrik yang tinggi secara tiba-tiba yang boleh menyebabkan kuasa menjadi tidak seimbang, prestasi beban tertunda, litar terlampau beban, dan masalah sisihan frekuensi yang teruk. Tindak balas frekuensi yang tidak diingini boleh membahayakan beban yang disambungkan, merosakkan peranti perlindungan, dan rangkaian mungkin tersandung dan mengalami kegelapan sepenuhnya. Menurut kajian literatur, kadar sisihan frekuensi sebenarnya memberikan maklumat tersirat tentang kestabilan sistem. Terdapat kelebihan disebalik mengetahui magnitud jumlah defisit kuasa rangkaian dengan hanya memerhatikan gelagat frekuensi sistem. Oleh itu, objektif utama penyelidikan ini adalah untuk memerhati dan memantau keadaan jumlah kekurangan kuasa rangkaian elektrik terpencil melalui pemerhatian frekuensi sistem. Dalam penyelidikan ini, persamaan antara struktur penapisan norma H_2 dan H_∞ dikaji dan persamaan model keadaan ruang digunakan dalam mereka bentuk penganggar defisit kuasa. Anggaran jumlah kekurangan kuasa mampu memberikan maklumat awal tentang keadaan kestabilan rangkaian sebelum sebarang skim perlindungan selanjutnya mengambil bahagian. Walau bagaimanapun, anggaran menjadi lebih teruk apabila sistem mempunyai ketidakpastian parameter. Oleh itu, pengubahsuaian telah dibuat kepada reka bentuk penganggar dan keputusan menunjukkan penambahbaikan dalam anggaran keadaan mantap. Perbandingan antara penganggar yang dicadangkan dengan kaedah cerun konvensional telah dijalankan dan keputusan menunjukkan penganggar yang dicadangkan memberikan anggaran yang baik di bawah kes ketidakpastian. Pada akhir penyelidikan, kaedah norma H_∞ dipilih sebagai penganggar terbaik untuk anggaran defisit kuasa dalam aplikasi sistem kuasa terpencil yang mempunyai prestasi anggaran yang baik dengan hanya 0.1% ralat anggaran dalam kes ketidakpastian dan indeks prestasi terendah bersamaan dengan 0.00044982.

ACKNOWLEDGEMENTS

Alhamdulillah, this thesis has been successfully completed. First and foremost, I would like to take this opportunity to express my sincere gratitude acknowledgement to my supervisor Associate Professor Dr. Muhammad Nizam bin Kamarudin from the Faculty of Electrical Technology and Engineering, Universiti Teknikal Malaysia Melaka (UTeM) for his essential supervision, support and encouragement towards the completion of this thesis. I also would like to express my gratitude to my co-supervisor Associate Professor Ir. Ts. Dr. Mohd Luqman bin Mohd Jamil from the Faculty of Electrical Technology and Engineering, Universiti Teknikal Malaysia Melaka (UTeM) for his advice, suggestion and encouragement towards the improvement of the research work and thesis. Special thanks to my beloved wife, parents and children for their moral support in completing this study, and also thank you to everyone who had been involved directly or indirectly in the research work. Lastly, from the bottom of my heart, my humble apology for any mistakes along the journey in completing the study.

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

TABLE OF CONTENTS

UTeM
UNIVERSITI TEKNIKAL MALAYSIA MELAKA

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

LIST OF TABLES

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

LIST OF FIGURES

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

LIST OF ABBREVIATIONS

DG	- Distributed Generator
LFC	- Load Frequency Control
SDA	- Dynamic Security Assessment
PV	- Photovoltaic
DE	- Diesel Engine
BS	- Battery Storage
WT	- Wind Turbine
AC	- Alternating Current
DC	- Direct Current
RU	- Rectifier Unit
LCU	- Line Converter Unit
MMF	- Magnetomotive Force
RoCoF	- Rate of Change of Frequency
LoG	- Lost of Generation
SG	- Synchronous Generetor
DFIG	- Doubly-Fed Induction Generator
SNR	- Signal-to-Noise Ratio
LMI	- Linear Matrix Inequality
RMSE	- Root Mean Square Error
IAE	- Integral Absolute Error
ISE	- Integral Square Error
REs	- Renewable Energy sources
AVR	- Automatic Voltage Regulator
AGC	- Automatic Generation Control

اونيورسيتي تيكنيكل مليسيا ملاك
UNIVERSITI TEKNIKAL MALAYSIA MELAKA

LIST OF SYMBOLS

Δ	-	Deviation
P_e	-	Electrical power demand
P_m	-	Generator mechanical power
P_{gv}	-	Generator governor power
ω	-	Generator frequency response
R	-	Speed regulation setpoint
I_L	-	Line current
I_f	-	Field current
H	-	Generator per-unit inertia constant parameter
ω_s	-	Synchronous speed
$\frac{d}{d_t}$	-	The deviation with respect to time
H_N	-	Equivalent inertia constant
H_i	-	Inertia constant of each i-th generator
$P_{n,SG,i}$	-	Nominal power of each generator
y	-	Plant output state
$\hat{z}$	-	Estimated state
ω_d	-	Disturbance input
n	-	Noise input
$\tilde{z}$	-	Estimation error
G_{ed}	-	Transfer function from the input disturbance to the estimation error
γ	-	The upper bound of objective function
P_d	-	Power deficit

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

f_N	-	Nominal frequency
$f_z'\|_{t=t_0}$	-	The initial frequency droop at $t = 0$
θ_m	-	Angular displacement of the rotor
J	-	Moment of inertia
T_a	-	Acceleration torque
δ_m	-	Mechanical rotor angle position
ω_{sm}	-	Mechanical angular velocity
T_m	-	Mechanical torque
T_e	-	Electrical torque
W_k	-	Rotational kinetic energy
M	-	Inertia constant which depends to the rotor angular velocity
δ_e	-	Electrical power angle
ρ	-	Number of generator pole pair
S_B	-	Base power
$P_{m(pu)}$	-	Per unit mechanical power
$P_{e(pu)}$	-	Per unit electrical power
ω_{se}	-	Electrical angular velocity
τ_T	-	Generator turbine time constant
τ_{gv}	-	Generator governor time constant
∂	-	The ratio between percent change in load and percent change in frequency
$\dot{x}$	-	System differential equation
x	-	System state dynamic
x_N	-	The new system state dynamic after augmentation

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

u	-	System input state
$[\square]^T$	-	Transposition of state equation
F	-	Causal filter
P	-	Unknown plant
C_1	-	Power deficit output state matrix
C_2	-	Dynamical frequency output state matrix
$\hat{y}$	-	Estimated plant output state
L	-	Estimator gain
h	-	An additional augmented low pass filter transfer function
T_h	-	Time constant of additional low pass filter
$\tilde{P}$	-	Positive definite square matrix
$(\blacksquare)'$	-	Partition symmetric blocks in the symmetric matrices
P_G	-	Generator's active power output
Q_G	-	Generator's reactive power output
P_L	-	Active power at load
Q_L	-	Reactive power at load
$\ll$	-	The generator output is deficient
$>$	-	The generator output is excessive

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

LIST OF APPENDICES

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

LIST OF PUBLICATIONS

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

Jamri, M.S., Kamarudin, M.N. and Mohd Jamil, M.L., 2020. Average dynamical frequency behaviour for multi-area islanded micro-grid networks, *Telkomnika (Telecommunication Computing Electronics and Control)*, 18(6), pp. 3324–3330. (Indexed by SCOPUS)

Jamri, M.S., Kamarudin, M.N. and Jamil, M.L.M., 2021. An investigation of inertia constant in single generator on transient analysis for an isolated electrical network system, *Indonesian Journal of Electrical Engineering and Computer Science*, 23(3), pp. 1299–1305. (Indexed by SCOPUS)

Jamri, M.S., Kamarudin, M.N. and Jamil, M.L.M., 2021. Total power deficiency estimation of isolated power system network using full-state observer method, *Indonesian Journal of Electrical Engineering and Computer Science*, 23(3), pp. 1249–1257. (Indexed by SCOPUS)

Jamri, M.S., Kamarudin, M.N. and Mohd Jamil, M.L., 2023. Power deficit estimation for isolated power system network using H∞ norm method, *Bulletin of Electrical Engineering and Informatics*, 12(5), pp. 3142–3152. (Indexed by SCOPUS)

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

CHAPTER 1

INTRODUCTION

1.1. Introduction

An electric grid is a network of power providers and consumers that are connected by transmission and distribution lines and operated by one or more interconnections. Historically, the grid was introduced and built in the late 19th and early 20th centuries and operated in isolation. Conventionally, the power plants consisted of large and centrally located generators are basically delivered electricity in one direction to the communities as needed. In time with growing technology, the grid system became more interconnected and efficient providing safe, reliable and affordable electric service for more than a century. However, with a growing population, advancements in technology and many new electronic devices, people consume more electricity than they used. Electricity used today is more than 16 times greater than it was in 1950s and it is expected more than that in future. However, the energy sources can be generated more and closer to their point of use with the new sustainability initiatives in such in rise of renewable energy technologies. These developments are pushing the grid to do more than it was designed for and have forced it to evolve and modernize. Thus, the grid is getting smarter and advanced instrumentation and technologies such as relays, sensors and switches have become more affordable and are integrated into the existing grid network to enhance communication, adaptability and efficiency. The energy production provides many benefits to both the consumer and energy provider because the bidirectional system in the smart grid network gives a new business opportunity supporting the supply chain.

The rise of the smart grid has coincided with emerging technologies such as battery storage, renewable energy, smart meters and advanced metering infrastructure. These integrations made the grid has the capability to self-optimizing and effectively harness its own energy and feed back to the consumer. Hence, the arrival of these emerging technologies integration on the grid has supported the development of custom-designed grid called as microgrids which independent electric system. A microgrid network system has capable to operate as a single or autonomous in parallel to or independent (islanded) from the existing utility power grid. The development of microgrid network is as part of the effort to increase the electrification ratio in remote area. Malaysia has islanded microgrids in Banggi Island, Kema and Tanjung Batu Laut in Sabah and Tanjong Labian, Bario in Sarawak. All these areas covered by microgrids system are equipped with the photovoltaic, battery storage and diesel generator. These islanded microgrids are also defined as an isolated grid network or isolated power system network. It also defined as a local electrical network comprising an isolation generator and transformer with its branch circuits was designed for certain applications. The local generator in an isolated power system network basically used as a main source. The network is very sensitive towards the sudden high equilibrium condition of electrical load demand that can lead to unbalance power, delay load performance, overloaded the circuits and severe frequency deviation problem. The undesired frequency response can harm the connected load, damage the protection devices and the network may trip and experience to total black-out. The local generator in isolated power system network is called as diesel generator and has integrated with other system to control the generator responses towards the load demand (Ganguly et al., 2018, Muhtadi et al., 2019 and Salazar et al., 2015). Basically, the generator control system has consisted of turbine and governor

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

system. Turbine generator is a machine which converts mechanical energy into electrical energy by collecting outsourcing like fossil fuels, wind, solar and steam. Basically, this machine has coupled with generator shaft. There are four types of turbine generators used, such as wind turbines, steam turbines, hydro turbines and solar turbines (Beus and Pandzic, 2022, Cassimere et al., 2015, El-Hawary, 2002, Kure-Jensen and Hanisch, 1991, Polinder et al., 2013, Sterkhov et al., 2022 and G. Zhang et al., 2016). The name of each type is accordance to their source fuels like wind, heat, water and sun. The governor system on the other hand is the speed regulator for the diesel engine to maintain the generator output specifications. The generator output is vital for the isolated power system network as it provides the network frequency as well as the network voltage (Bryant et al., 2021, Mayouf et al., 2013, Peng et al., 2015 and Ramkumar and Durairaj, 2013). According to the literature review therein, the rate of frequency deviations provides the information about system stability condition and the magnitude of total power deficit. The power deficit is defined as a difference of power imbalance between generator power output and load demand output.

The main objective of this research is to estimate and monitor the total power deficiency of isolated power system network condition. To achieve the main objective, the power deficit estimator was designed through the theoretical of filtering of a linear dynamical system. The filtering of dynamical systems has historically been initiated through the application of the Kalman filter. The Kalman filter is an effective tool for estimating the states of a system and has been successfully applied in common industrial applications. However, Kalman filter has problematic in practical application due to mismatches between the underlying assumption and industrial state estimation problems. To resolve these issues, filters based on alternative performance criteria that are more predictable have been developed. The newly developed filter is the H_2 and H_∞ norm filter. Both filters follow the same structure as the Kalman filter. In this research, the utilization of H_2 and H_∞ norm filtering problem that augmented the state-space of network model equations gave an advantage in designing a power deficit estimator. Furthermore, their performance criteria for uncertain parameter conditions under convex polytopic uncertainty were also examined. It is shown that with a suitable change of variables, it can be solved using Linear Matrix Inequality (LMI) machinery. The results show that the estimator using H_∞ norm filter is the best, with robust performance under parameter uncertainty and multifarious load demand changes. Thus, this power deficit estimator method can be proposed to provide preliminary information about the network stability condition before any further protection schemes take place.

1.2. Research Motivation

The study of isolated power system network power deficit condition monitoring through the observation of local synchronous generator dynamical frequency response has received little investigation. Most of the work is subjected to a number of eventualities such as short circuit analysis for study in transient and dynamic regimes. A synchronous generator system is defined as a dispatchable distributed generator because of its ability to respond to load contingencies by automatically regulating the amount of energy provided by the governor system. The energy is then transferred to the prime mover as kinetic energy and transformed into electrical energy through the generator coils. The combination of all these components makes the system sensitive to any variations in electrical loads. The effect can be seen in the behaviour of generator rotor shaft which is translated into the dynamical behaviour of the frequency network. There is an advantage to knowing the network loading condition by observing this frequency dynamic. Furthermore, knowing the magnitude of total power deficiency between generation and load during the early stages of contingency can prevent severe damage to the network. However, in real applications, a direct measure