UNIVERSITI PUTRA MALAYSIA

COI-BASED QUANTITATIVE FREQUENCY SECURITY ASSESSMENT OF POWER SYSTEM IN ESTIMATING MAXIMUM PENETRATION LEVEL OF WIND POWER

ATHRAA IESSA SHAABAN AL MENTEFIK

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By

ATHRAA IESSA SHAABAN AL MENTEFIK

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirement for the Degree of Master of Science

January 2017

DEDICATION

This thesis is dedicated to my mom for her endless love, to my family for their support, and my friends for their encouragement.

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfillment of the requirement for the degree of Master of Science

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Chairman : Noor Izzri Abdul Wahab, PhD
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Due to the increase in sustainable energy resource integration, the operation and control of power system have become very complicated. This has resulted in a significant challenge faced by system operators to maintain a stable power system operation. With the widespread integration of wind power to the system, the frequency security assessment (FSA) has become essential due to the impact of less inertia and variable nature brought by this power on system frequency.

Many studies have been conducted assessing the frequency security level of power system. However, these methods can only measure the severity of disturbance at one point in time. On top of that, most assessment methods depend on a unit frequency that may differ according to disturbance location or unit status. Therefore, there is a need to find a comprehensive method for assessing frequency security covering the time of frequency deviation based on equivalent system frequency. Thus, the present study was conducted to explore and address a new method to evaluate frequency security, identify system's weakest frequency bus and estimate the maximum wind penetration level using transient frequency deviation index (TFDI) based on the Centre of Inertia frequency (f_{COI}).

The first objective of this study is to use f_{COI} together with TFDI to quantitatively assess system's security level. Thus, a methodology evaluating the frequency security level is presented in this study. The second objective of this thesis seeks to identify the weakest frequency bus using the ability of TFDI to evaluate the security level of individual buses (consumers). The final purpose of this study is to introduce a method to estimate the maximum level of wind power that can be integrated into the grid by maintaining acceptable operation frequency.

The first contribution of this study is represented by the development of a new and particular method for FSA to enhance security assessment. By using f_{COI} features, the security level of system disturbances can be easily achieved without identifying all system bus frequencies. Additionally, this method is able to evaluate whole system security levels irrespective of affected generator or disturbance location. Previously, TFDI was not used to identify system's weakest bus. Therefore, the second contribution of this study is the introduction of an approach that can identify system's weakest bus frequency using the ability of TFDI to evaluate the security level of individual bus and use it as a wind power integrated bus to enhance the accuracy in estimating maximum wind power penetration level. Finally, the third contribution of the study is that it provides a simple method to estimate the maximum allowable amount of wind power that can be added to the grid without affecting system frequency security. This new method is simple as it does not require complicated calculations or historical data.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Master Sains

PENILAIAN KUANTITATIF KEKERAPAN KESELAMATAN SISTEM KUASA BERASASKAN COI DALAM MENGANGGAR TAHAP PENEMBUSAN MAKSIMUM KUASA ANGIN

ATHRAA IESSA SHAABAN AL MENTEFIK

Januari 2017

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Peningkatan dalam integrasi sumber tenaga lestari mengakibatkan operasi dan kawalan sistem kuasa menjadi sangat rumit. Ia seterusnya menjadi satu cabaran besar bagi pengendali sistem untuk mengekalkan operasi sistem kuasa yang stabil. Dengan meluasnya integrasi kuasa angin kepada sistem kuasa, penilaian keselamatan kekerapan (FSA) menjadi penting disebabkan oleh kurangnya kesan inersia dan sifat berubah-ubah yang dibawa oleh kuasa ini kepada kekerapan sistem.

Banyak kajian dijalankan bagi menilai tahap keselamatan frekuensi sistem kuasa. Walau bagaimanapun, kaedah-kaedah ini hanya mampu mengukur tahap gangguan pada satu ketika dalam satu masa. Selain itu, sebahagian besar kaedah penilaian bergantung kepada kekerapan unit yang mungkin berbeza mengikut lokasi gangguan atau status unit. Oleh itu, wujud kepentingan untuk mencari kaedah yang komprehensif bagi menilai keselamatan kekerapan meliputi masa sisihan frekuensi berdasarkan kekerapan sistem setara. Oleh itu, kajian ini dijalankan untuk meneroka dan memperkenalkan satu kaedah baru yang menilai keselamatan kekerapan, mengenal pasti bas kekerapan paling lemah dalam sistem dan menganggarkan tahap penembusan angin maksimum menggunakan fana indeks sisihan frekuensi (TFDI) berdasarkan pusat inertia kekerapan f_{COI}.

Objektif pertama kajian ini adalah untuk menggunakan fCOI bersama-sama dengan TFDI bagi menilai tahap keselamatan sistem secara kuantitatif. Oleh itu, kaedah menilai tahap keselamatan kekerapan itu dikemukakan dalam kajian ini. Objektif kedua kajian ini bertujuan mengenal pasti bas kekerapan yang paling lemah menggunakan keupayaan TFDI untuk menilai tahap keselamatan bas individu (pengguna). Tujuan akhir kajian ini adalah untuk memperkenalkan satu kaedah menganggar tahap maksimum kuasa angin yang boleh disepadukan ke dalam grid dengan mengekalkan kekerapan operasi yang sesuai.

Sumbangan pertama kajian ini diwakili oleh pembangunan kaedah baru dan tertentu untuk FSA meningkatkan penilaian keselamatan. Dengan menggunakan ciri-ciri fCOI, tahap keselamatan gangguan sistem boleh dicapai dengan mudah tanpa mengenal pasti semua frekuensi bas sistem. Selain itu, kaedah ini dapat menilai tahap keselamatan sistem keseluruhan tanpa mengambil kira penjana yang terjejas atau lokasi gangguan. Sebelum ini, TFDI tidak digunakan untuk mengenal pasti bas paling lemah dalam sesuatu sistem. Oleh itu, sumbangan kedua kajian ini adalah dengan memperkenalkan pendekatan yang boleh mengenal pasti kekerapan bas paling lemah sistem menggunakan keupayaan TFDI untuk menilai tahap keselamatan bas individu dan menggunakannya sebagai bas kuasa angin bersepadu bagi meningkatkan ketepatan dalam menganggar tahap penembusan kuasa angin maksimum. Akhir sekali, sumbangan ketiga kajian ini adalah ia menyediakan satu kaedah yang mudah untuk menganggar jumlah penambahan maksimum kuasa angin yang dibenarkan ke grid tanpa menjejaskan keselamatan kekerapan sistem. Kaedah baru ini adalah mudah kerana ia tidak memerlukan pengiraan yang rumit atau data sejarah.

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I certify that a Thesis Examination Committee has met on 19 January 2017 to conduct the final examination of Athraa Iessa Shaaban Al Mentefik on his thesis entitled "COI-Based Quantitative Frequency Security Assessment of Power System in Estimating Maximum Penetration Level of Wind Power" in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the Master of Science.

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This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Master of Science. The members of the Supervisory Committee were as follows:

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Declaration by graduate student

I hereby confirm that:

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This is to confirm that:

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LIST OF ABBREVIATIONS

ANN	Artificial Neural Network
β	Sensitivity Index
β_{sys}	Frequency Probabilistic Index
COI	Center of Inertia
DFIGs	Doubly Fed Induction Generators
DSA	Dynamic Security Assessment
DT	Decision ion Tree
DI	Digital Input
EEAC	Extended Equal Area Criterion
FDI	Total Frequency Deviation Index
f_{COI}	Center of inertia frequency
$f_{COI\ (dev.)}$	Center of Inertia Frequency Deviation
FSA	Frequency Security Assessment
FSI	Frequency security Index
f	Frequency response
f_{cr}	Critical Frequency
f_N	Normal Frequency
H	Inertia Constant
FSIGs	Fixed Speed Induction Generators
MDFI	Maximum Frequency Deviation Index
ROCOF	Rate of Change of Frequency
SSA	Static Security Assessment
t_b	Break time
t_{cr}	Critical time
TDS	Time Domain Simulation
WAMs	Wide Area Measurements
WECC	Western Electricity Coordinating Council
WGNC	Doubly fed induction generators model in DSA tools
WGNCE	Wind turbine electrical control model in DSA tools
WGNCT	Wind turbine pitch control model in DSA tools

CHAPTER 1

INTRODUCTION

This chapter demonstrates the background of research, objectives, and targets. It further highlights an overview of the thesis on the research findings and expectations. The chapter aims at enhancing the reader's knowledge towards understanding the research expected results, and why the research was conducted.

1.1 Background

Recently, most of the electrical power systems are working under a huge pressure due to the escalated demand in electricity for both industrial and service sectors. This situation had caused the power system to operate exceeding their stability limits. Consequently, this weakness has led to the widespread of outage around the world such as the blackout in Malaysia on 1996 (Horne, et al, 2004), European interconnected grid blackout in November 2006 (Chunyan,et al, 2007), Australia's major interruption on January 2007(Refinery, 1999), as well as India's power grid blackout on July 2012 (Desismartgrid., 2012).

Generally, these blackouts and cascading failures occur by a series of event where a system exceeds its acceptable security limits, thus making it to become unable to force multiple contingencies. However, these failures can be avoided if the system's emergency control takes appropriate actions including load shedding and islanding controlling (Ahmed, el al, 2003) (Adibi, Kafka, et al, 2006). To remove the weaknesses of a system, it is important to ensure whether or not the power system can withstand all credible contingencies and meet specified security criteria. This evaluation is known as the Dynamic security assessment (DSA), which is defined as the ability of a power system to withstand any credible contingency and propose proper actions to remove its weaknesses (Wehenkel, 1997). DSA includes rotor angle security, voltage security, and frequency security.

Frequency security refers to the ability of a power system to maintain steady frequency following a severe system upset, resulting in a significant imbalance between the generation and demand without interrupting consumer service (Morison, Lei, & Kundur, 2004). Frequency is an important operating parameter compulsory in maintaining the acceptable limit of a power system as it reflects the conditions of the power system. Furthermore, the frequency behaviour is able to demonstrate any mismatch found between generation and demand. Ideally, frequency should be kept at its nominal value. However, the use of nonlinear loads, sudden load–generation imbalance and integration of variable energy resources has resulted in an unstable frequency of operating system. Therefore, it is essential to evaluate the system frequency security and estimate the ability of the system to withstand any change in system condition that may be occurred due to disturbance.

The power system frequency protection schemes including over/under frequency (response-driven and event-driven) are always set to specific limits and duration of frequency deviation. These limits and duration are usually displayed in two element tables (f_{cr}, t_{cr}). Consequently, the stability of the power system will break if the frequency deviation exceeds these limits (Zhuang,et al, 2012). There are several indices that can evaluate the frequency security introduced due to the relationship between critical and minimum frequencies (Doherty et al., 2010) (Castro, et al, 2012)(Zhang & Liu, 2010). However, these indices cannot measure the severity of contingency along with its affecting duration. Nevertheless, they are able to reflect deviation trajectory details. Therefore, the transient frequency deviation index (TFDI) was proposed to quantitatively assess the frequency security of the power system (Zhang, & Liu, 2010). TFDI depends on the minimum area surrounded by frequency deviation trajectory and critical frequency.

Many studies have been implemented to present the behaviour of system frequency and suggest that initial system frequency vary according to different locations (Ørum, Laasonen, et al, 2015). These studies also state that the disturbance location has a major impact on the frequency behaviour by the fact that the closer generator response is more severe (Terzija, 2006). Therefore, it is crucial to find the centre of inertia f_{COI} to represent the whole frequencies of the system. F_{COI} is a mathematically derived variable that describes the average network frequency during electromechanical transients when local generator frequencies are not similar (Terzija, 2006). The f_{COI} will provide more information on frequency security level of a power system compared to the single generator frequency. In addition, the inertia constant of f_{COI} is larger since it includes the inertia constant of all generators in the power system than single generator inertia constant. Moreover, the oscillation of F_{COI} is also smaller (Nedic, 2003). To assess the security level of multi-machines power system regardless disturbance locations as well as to take advantage on quantitative assessment of system security using TFDI, a new method evaluating the frequency security of multi-machines power system was validated in this research.

Wind power, a renewable energy resource, has the potential to become one of the crucial energy resources in many countries, since it is pollution free and powered by the abundant availability of wind. However, wind power cannot be randomly integrated into the grid, due to its fluctuating nature and less inertia of wind turbine. Besides, wind fluctuation leads to the decrease in efficiency of the power system to maintain the balance between generation and demand (Ramirez & Ipn, 2015). The wind turbine is permanently equipped with converters, which decouple the turbine from the grid. Consequently, no inertial response will be provided by these turbines during frequency events (Tielens & van Hertem, 2012). Therefore, the estimation of allowable wind level that maintains system frequency becomes a serious issue. Thus, the proposed approach of using TFDI based on F_{COI} in evaluating system security was used to estimate the maximum allowable wind integration level through a very simple and effective method.

1.2 Problem Statement

Off normal frequency deviation may significantly affect the power system behaviour by damaging system equipment, overloading transmission lines and triggering the protection devices leading to a system collapse (Zhang, et al, 2010). Frequency should be kept at its nominal value. However, the utilisation of nonlinear loads, the sudden load–generation imbalance and the integration of variable energy resources have resulted in the unstable frequency of operating system. Therefore, it is essential to evaluate the system frequency security and estimate the ability of the system to withstand any change in system condition that might happen due to any disturbance, due to that, the assessment of the system's ability to maintain a nominal frequency has become a serious issue. Frequency deviation is a good indicator of system stability. Most frequency security assessment studies have utilised the frequency deviation indices such as maximum frequency deviation index (MFDI), total frequency deviation index (FDI), and frequency security index (FSI) (Dai et al., 2012) (Xu Taishan, 2002). Nonetheless, theses indices can only measure the rigorousness of disturbance at one time, which means that they are incapable of measuring the effect of frequency deviation during this period. Moreover, most assessment methods depend on unit frequency that may differ according to disturbance location or unit statuses. Therefore, there is a need to find a comprehensive method for frequency security assessment covering the time of deviation and based on equivalent system frequency (Zhang, Li, & Liu, 2015).

Monitoring the frequency deviation at several critical points of power system including bus or substation would help in deciding whether or not the loss of load or generator would affect the system security. It is also important to find the weak frequency points of network to select the wind turbine integration bus to accurately estimate the maximum allowable wind power level according to the impact of turbine on system frequency. Therefore, finding a method that is able to select critical points of the system (the bus with weakest frequency) is essential.

The FSA is very important for the power system with increasing the trend of wind power penetration, which significantly changes the power system frequency behaviour. There is a principle difference between a wind turbine and the conventional turbine of power plants in the world such as steam, gas or hydraulic turbines. By utilising conventional turbines, the rotation speed can be almost constant and locked to the system frequency. However, the speed of a wind turbine is not synchronous with the network and is controlled to maximise the production energy. Therefore, the production of wind power plant is not inherently coupled to the system frequency, and historically, the wind power stations are not vital to participate in the regulation of system frequency(Nicholas & Elahi, 2011). Large disturbances may cause serious frequency deviations that further lead to stability problems due to the impact of less inertia and variable nature of this power on system frequency. Since wind turbine is usually connected to distribution network, the subject of voltage and frequency behaviour is very essential for consumers at the receiving end of the electrical network. This is because a good quality of power from the network, (acceptable voltage and frequency) is what demanded by the consumers.

Though the two elements cannot be kept constant in practice all the time, they are however kept within allowable limits. The wind turbine is permanently equipped with converters that decouple the turbine from the grid. Consequently, no inertial response will be provided from these turbines during frequency events (Tielens & Hertem, 2012). Therefore, estimating the allowable wind level that maintains system frequency becomes is of important.

1.3 Thesis objectives

The specific objectives of this study are summarised as below:

- To identify a comprehensive method for frequency security assessment that covers the effective duration of frequency deviation using TFDI index based on equivalent system frequency f_{COI}.
- To use the ability of TFDI in assessing the security level of individual bus in identifying system weakest bus frequency.
- To evaluate a simple, efficient and accurate method in estimating the maximum penetration level of wind power using TFDI index that is based on $f_{COI.}$

1.4 Scope of work

This study was focuses on evaluating the multi-machine power system frequency security using TFDI based on F_{COI}. The New England 39-bus and WSCC 9-bus test systems were used to obtaine the study results. The study is also concentrating on the estimation of maximum wind penetration level by considering the frequency security. However, there is also limitation in this study as wind speed was not taken into account. This is due to the use of the most recent and most popular wind turbine (variable speed DFIG) that connects with the grid through rotor side convertor and has the ability to work at variance wind speed to provide large level of generation power (Vittal, 2008) (Miao, et al, 2009). Therefore, this study has only considered the inertia response and capacity of the units.

1.5 Thesis organisation

This thesis is organised as follows:

Chapter 1 focuses on giving a brief background, problem statement, research hypothesis, objectives, and contribution of the study. Meanwhile, Chapter 2 reviews the previous works related to the current study. This review begins with the fundamental concept of dynamic security of a power system. Frequency security definition, assessment methods and indices are also addressed in this chapter as well as the participants of F_{COI} in the power control system and protection. Moreover, the weakest bus frequency, impact of wind integration and the estimation of maximum wind power, which are among the important research outlines, are reviewed.

Furthermore, Chapter 3 describes the methodologies of numerical verification using the F_{COI} in system security evaluating, which also include the main steps in the methodology of selecting the weakest bus frequency and the estimation of maximum wind penetration level. Furthermore, the modeling and test system details are also included in this chapter.

Chapter 4 presents the case studies and detailed results. The results presented were obtained based on test cases. These include the F_{COI} numerical verification, weakest bus selection, and maximum wind power level results. Besides, a brief discussion and summary of significant results are also highlighted in this chapter.

Lastly, Chapter 5 demonstrates and concludes the major findings of this study as well as the discussion on the possible future works. The contribution of this study is also provided in this chapter.

1.6 Summary

In summary, this chapter considered the important outlines of this study. It began by introducing the importance of DSA and FSA. After that, the explanation on problem statement is presented. This was followed by demonstrating the objectives and scopes of research work in this chapter. The organisation of the study is also provided in this chapter.

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