UNIVERSITI PUTRA MALAYSIA

RELIABILITY ASSESSMENT OF POWER SYSTEM GENERATION ADEQUACY WITH WIND POWER USING POPULATION-BASED INTELLIGENT SEARCH METHODS

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By

ATHRAA ALI KADHEM

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfillment of the Requirements for the Degree of Doctor of Philosophy

December 2017

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DEDICATION

To my Parents,

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfillment of the requirement for the degree of Doctor of Philosophy

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ATHRAA ALI KADHEM

December 2017

Chairman : Associate Professor Noor Izzri Bin Abdul Wahab, PhD
Faculty : Engineering

Reliability of the generation system is an important aspect of planning for the expansion of future system capacity which ensures that the total installed capacity would be sufficient to provide adequate electricity, therefore, it is necessary to investigate the reliability of the power system. The reliability assessment of the adequacy of the generating system is normally calculated by using either analytical or simulation methods. The Monte Carlo simulation (MCS) method enables an accurate evaluation of reliability indices. The drawback of MCS is that it is not suitable for a system with large number of components in a system or high-reliability performance that require large computational effort which would take a long time to converge efficiently. This study sought to examine the performance of three newly proposed techniques, for reliability assessment of the power systems, namely Disparity Evolution Genetic Algorithm (DEGA), Binary Particle Swarm Optimisation (BPSO), and Differential Evolution Optimization Algorithm (DEOA). The proposed intelligent algorithms would rely on the population intelligent search (PIS) techniques considered as viable replacement for the MCS method in assessing the reliability indices of non-chronological system. The advantage of using these algorithms is obvious as they would speed up the computation to obtain higher accuracy with less computation effort. In recent years, the development of wind power to meet the demand for electricity has received considerable attention. However, this energy source differs considerably from the conventional generation sources because it is intermittent in nature and may lead to high-risk levels in the electrical system reliability. As such, the three novel PIS techniques (i.e., DEGA, DEOA, and BPSO) were proposed for reliability assessment of power generation systems with the integration of wind energy. These methods proved accurate in estimating the reliability indices, with less computation effort. In this study, analysis was made on the wind speed data characteristics and wind power potential assessment at three a given sites in Malaysia

namely Mersing, Kudat, and Kuala Terengganu. Results have shown that Mersing and Kudat were suitable as wind sites. The findings of this research have provided evidence to support those of the previous studies were conducted separately for Mersing and Kudat indicating that these sites could potentially be utilised to construct a new wind power plant in Malaysia. Additionally, the present study has developed a prediction model of wind speed for these three sites in Malaysia. This model took into consideration the seasonal wind speed variation during the year, in the format of the combined method comprising the Weibull model with artificial neural network (ANN), so that the forecasting errors of wind values would be lower than those generated by using only the Weibull model. It was suggested that the wind power should be connected to the Roy Billinton Test System (RBTS), from two sites in Malaysia. The reliability indices obtained before and after the inclusion of the two farms to the system under consideration were compared. Based on this analysis, it was found that, with the inclusion of wind power from both sites, the reliability indices had slightly improved the reliability of RBTS.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

PENILAIAN KEBOLEHPERCAYAAN KECUKUPAN PENJANAAN SISTEM KUASA DENGAN KUASA ANGIN MENGGUNAKAN KAEDAH CARIAN PINTAR BERASASKAN POPULASI

Oleh

ATHRAA ALI KADHEM

Disember 2017

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Fakulti : Kejuruteraan

Aspek kebolehpercayaan sesuatu sistem penjanaan ialah perkara penting dalam perancangan pengembangan kapasiti sistem tersebut untuk masa hadapan kerana ia menentukan bahawa jumlah kapasiti yang dijana dapat menjamin bekalan elektrik yang mencukupi, oleh yang demikian, aspek kebolehpercayaan sistem janakuasa ini adalah penting untuk dikaji. Penilaian terhadap kebolehpercayaan bagi menentukan bahawa bekalan yang dijana oleh sistem adalah mencukupi biasanya dikira berdasarkan sama ada kaedah analisis atau kaedah simulasi. Kaedah simulasi Monte Carlo atau Monte Carlo simulation (MCS) membolehkan penilaian indeks kebolehpercayaan dilakukan secara tepat. Namun begitu, kaedah MCS ini mempunyai kelemahan kerana ia tidak sesuai untuk sistem yang memiliki komponen yang banyak atau berprestasi tinggi yang memerlukan tahap kebolehpercayaan tinggi lantaran usaha lebih gigih diperlukan untuk membuat pengiraan dan hal ini akan mengambil masa lebih lama bagi memastikan penumpuan yang lebih cekap. Kajian ini bertujuan meneliti prestasi tiga jenis teknik yang dicadangkan untuk mengkaji penilaian kebolehpercayaan sistem kuasa iaitu Disparity Evolution Genetic Algorithm (DEGA), Binary Particle Swarm Optimisation (BPSO), dan Differential Evolution Optimization Algorithm (DEOA). Ketiga-tiga algoritma pintar yang dicadangkan ini bergantung pada teknik-teknik carian pintar berasaskan populasi atau population intelligent search (PIS) yang dianggap menjimatkan bagi menggantikan kaedah MCS dalam menilai indeks kebolehpercayaan sistem yang tidak mengikut kronologi. Kelebihan algoritma jenis ini sangatlah jelas kerana ia dapat meningkatkan kelajuan pengiraan bagi memastikan ketepatan yang lebih jitu dengan usaha yang paling minimum. Dalam tahun-tahun kebelakangan ini, pembangunan sistem janakuasa menggunakan kuasa angin bagi memenuhi permintaan terhadap bekalan elektrik telah mendapat perhatian ramai. Sungguhpun demikian, sumber tenaga ini begitu berbeza daripada sumber-sumber tenaga lain yang diperoleh secara konvensional kerana sifatnya yang terputus-

putus secara semula jadi dan mungkin membawa kepada risiko tahap tinggi pada kebolehpercayaan sistem elektrik. Oleh itu, ketiga-tiga teknik PIS baharu ini (yakni, DEGA, DEOA, and BPSO) telah dicadangkan bagi menilai kebolehpercayaan sistem janaan kuasa berintegrasikan tenaga angin. Kaedah-kaedah ini terbukti mampu membuat anggaran nilai-nilai indeks kebolehpercayaan yang sangat tepat dengan usaha yang paling minimum. Dalam kajian ini, analisis telah dilakukan terhadap ciri-ciri data kelajuan angin dan penilaian keupayaan kuasa angin yang direkodkan di tiga lokasi terpilih di Malaysia iaitu Mersing, Kudat, dan Kuala Terengganu. Keputusan menunjukkan Mersing dan Kudat sesuai dijadikan lokasi untuk kajian kuasa angin. Dapatan kajian ini telah menghasilkan bukti yang menyokong dapatan kajian-kajian lepas yang dilakukan secara berasingan di Mersing dan Kudat. Hal ini menunjukkan bahawa lokasi-lokasi ini berpotensi untuk dimanfaatkan bagi membina loji kuasa angin yang baharu di Malaysia. Selain itu, kajian ini telah membina satu model ramalan bagi kelajuan angin bagi tiga lokasi terpilih ini di Malaysia. Model ini telah mengambil kira perubahan kelajuan angin bermusim bagi tahun berkenaan dalam format model hibrid yang menggabungkan model Weibull dengan rangkaian neural buatan supaya nilai-nilai ralat peramalan angin adalah lebih rendah daripada nilai-nilai yang diramal menggunakan model Weibull semata-mata. Maka kuasa angin telah dicadangkan agar disambungkan kepada Sistem Ujian Roy Billinton atau Roy Billinton Test System (RBTS) daripada dua lokasi berkenaan di Malaysia. Perbandingan telah dibuat terhadap nilai-nilai indeks kebolehpercayaan sebelum dan selepas kedua-dua ladang diambil kira dalam sistem yang dikaji. Berdasarkan pada analisis ini, dengan mengambil kira kuasa angin daripada kedua-dua lokasi berkenaan, nilai-nilai indeks kebolehpercayaan telah menunjukkan sedikit peningkatan pada kebolehpercayaan RBTS.

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

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LIST OF ABBREVIATIONS

ACS	Ant Colony System
AEP	Annual Energy Production
ANN	Artificial Neural Network
BACS	Binary Ant Colony System
BPSO	Binary Particle Swarm Optimization
CE	Cross-Entropy
DE	Differential Evolution
DEGA	Disparity Evolution Genetic Algorithm
DEO	Differential Evolution Optimization
DEOA	Differential Evolution Optimisation Algorithm
DPLVC	Daily Peak Load Variation curve
EA	Evolutionary Algorithm
EC	Evolutionary Computation
EM	Empirical Method
EPSO	Evolutionary Particle Swarm Optimization
F & D	Frequency and Duration
FOR	Forced Outage Rate
GA	Genetic Algorithm
GOF	Goodness Of Fit

HL	Hierarchical levels
HLI	Hierarchical level-I
HLII	Hierarchical level-II
HLIII	Hierarchical level-III
Ia	lagging strand
Ie	leading strand
ISSP	Intelligent State Space Pruning
LDC	Load Duration Curve
LHS	Latin Hypercube Sampling
LOEE	Loss Of Energy Expectation
LOLD	Loss Of Load Duration
LOLE	Loss Of Load Expectation
LOLF	Loss Of Load Frequency
LOLP	Loss Of Load Probability
LSM	Least Square Method
MCS	Monte Carlo Simulation
MM	Moment Method
MMD	Malaysia Meteorological Department
MMLM	Modified Maximim Likelihood Method
MSGA	Modified Simple Genetic Algorithm
MTBF	Mean Time Between Failure

MTTR	Mean Time To Repair
P_c	crossover probability
PDF	Probability Density Function
PIS	population-based intelligent search
P_m	Mutation Probability
POCT	Probability Outage Capacity Table
pop_size	Population size
PSO	Particle Swarm Optimization
RBTS	Roy Billinton Test System
RMSE	Root Mean Square Error
SMCS	Sequential Monte Carlo Simulation
VRT	Variance Reduction Techniques
WECS	Wind Energy Conversion System
WTG	Wind Turbine Generator
λ	Failure Rate
μ	Repair Rate

CHAPTER 1

INTRODUCTION

1.1 Overview

The main purpose of the electrical power system is the efficient and cost-effective generation of electrical power for its customers, with good consideration of its quality and supply continuity. The contemporary power quest requires the utility companies to meet up with the consumers' electrical energy demand (Billinton & Allan, 1996) which, otherwise, may lead to a huge loss of income to the generators as well as the consumers. However, it is neither economically nor technically feasible to build an absolutely reliable power system due to some uncontrollable factors, such as the random failures of components, time-dependent energy resources, and load fluctuation.

Quantitative reliability assessments should not only evaluate a system's actual physical components in terms of performance and random behavior, but also the overall requirements, procedures, and engineering issues inherent in the system's operation (Wafa et al., 2006). A power system is an extremely complex, advanced and integrated structure (Cepin, 2011); even the most advanced computer programs lack the capacity for the comprehensive and holistic interpretation of the system. Consequently, power systems are frequently divided into appropriate subsystems that can be separately analyzed.

The most convenient means for segmenting an electrical power system are its main functional zones; namely its generating capacity systems, composite systems, and distributed power systems. Thus, Hierarchical Levels (HL) has been developed (Billinton & Allan, 1984) to determine an identical means of grouping and identifying the aforementioned functional zones, as illustrated in Figure 1.1. From the figure, Hierarchical Level I (HLI) refers to the facilities responsible for generating adequate power to meet the system demand whereas Hierarchical Level II (HLII) refers the composite generation and transportation network that is capable of transporting the generated energy to the major consumption or sub-transmission points. Hierarchical Level III (HLIII) refers to the entire system as well as the distribution system that is capable of disbursing individual customers' energy demand. This research work focuses on the analysis of the system adequacy that is conducted at the HLI.

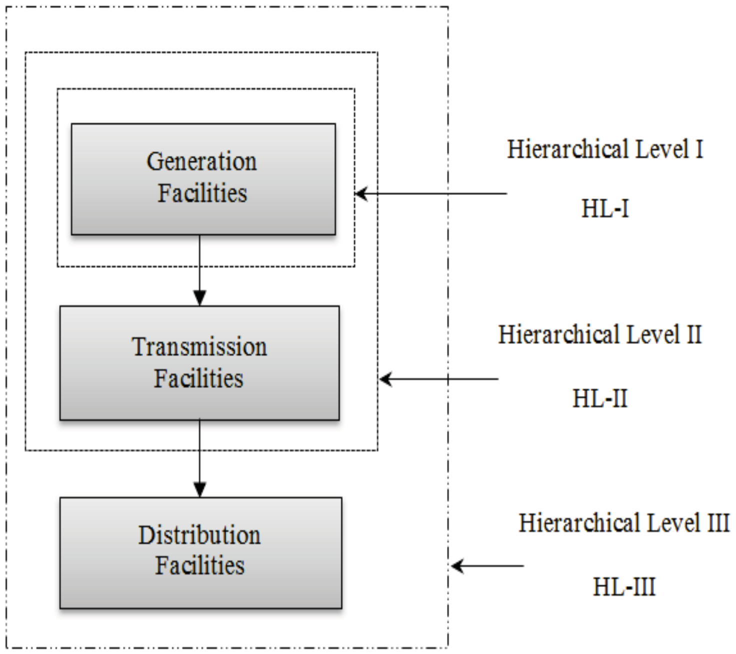

Figure 1.1 : Structures of hierarchical levels in a power system

The term reliability index, when applied to generation systems, refers to performance measures of the generating system capacity that can influence the continuity of electrical power supply to the customer. Two basic concepts are used in system capacity assessments which are adequacy and security. Generating capacity requirements can also be separated into two basic categories i.e., static capacity, which correlates with the long-term estimate of overall system demand; and operating capacity, which is a short-term correlation with the actual capacity required to meet a specified load. Adequacy assessment considers the entirety of the facilities within a system and their sufficiency to satisfy consumer load demands. Adequacy is therefore associated with a static level of demand which is exclusive of transient system disturbances (Billinton & Li, 1994). System security is defined as the ability of the electric system to withstand sudden disturbances such as electric short circuits or unanticipated loss of system elements. Security concept is therefore associated with operating capacity (Billinton & Allan, 1996).

Reliability analysis of the power system can be conducted by using various techniques as shown in Figure 1.2. Historically, power system reliability analyses have been carried out utilizing deterministic methods. These techniques use simple rule of thumb methods and are easy to apply. A major drawback of the deterministic approach is that it cannot respond adequately to the random behavior of the power system and customer demands. Meanwhile, probabilistic reliability evaluation methods can recognize random system characteristics, and are more suitable in modern power system applications. These assessment methods comprise of analytical and simulation techniques and both approaches are used in electric power utilities at the present time. Simulation techniques are used to imitate unpredictable performance in power systems, either in a random or sequential way (Pereira & Balu, 1992). Whereas, analytical assessment methods are easily and simply applied using mathematical analysis to derive precise analytical solutions to the value of reliability indices from the model (Billinton & Allan, 1988). Monte Carlo simulation is the preferred method for reliability assessment of large and complex systems due to the realism it introduces; therefore, it is adopted as the benchmark when comparing accuracies among different computational methods.

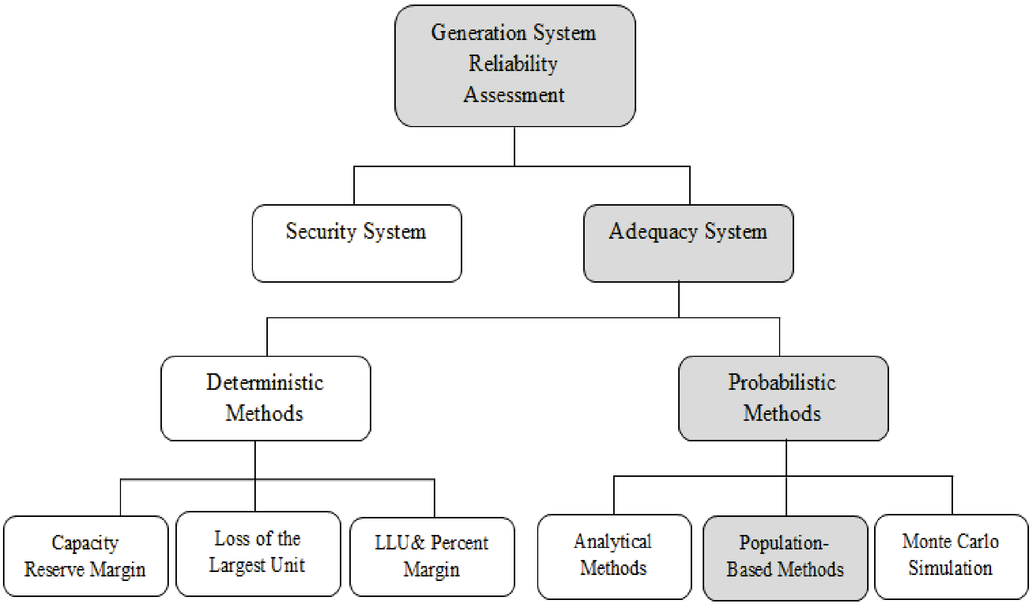

Figure 1.2 : Techniques used for power systems reliability analysis

In recent years, many efforts have been made in order to improve the computational efficiency of algorithms, especially those that are applied to problems of great complexity in power systems. Many optimization algorithms have been developed utilizing the nature of population-based intelligent search (PIS); these algorithms use all possible solutions by iteratively and stochastically changing rather than focusing on improving a single solution. Examples of these algorithms include the ant colony system (ACS), genetic algorithm (GA), particle swarm optimization (PSO), intelligent state space pruning (ISSP), and evolutionary computation (EC) (Benidris et al., 2015; Benidris & Mitra, 2014). These techniques have been utilized in different forms by researchers in the adequacy assessment of power system.

1.2 Power System Reliability Assessment with Wind Energy

Wind power has remarkable economic and environmental advantages when compared to other power generation sources (Sina et al., 2014). Presently, wind power is considered to be an essential alternative source for generating power. In addition, growing demand for electrical energy and the concerns associated with limited reserves of fossil fuels such as oil, natural gas, and coal are also responsible for the development and increase in wind energy utilization.

Wind power is the most promising renewable energy and is one of the fastest developing electric generating technologies in the whole world (Shi & Lo, 2013). Consequently, the pervasiveness of the wind power in power systems is increased. Figure 1.3 shows the global installed wind power capacity around the world from 2000 to 2015. A total of 432.419 MW of capacity had been installed world by the end of 2015 (GWEC, 2016).

The growing pervasiveness of wind energy in power system has a huge influence on the electrical system's reliability in relation to other conventional sources for power generation. Indeed, intermittent nature of wind generation gives rise to several issues; these issues may include the operation, planning of power systems with wind energy sources (Zheng & Zhong, 2010).

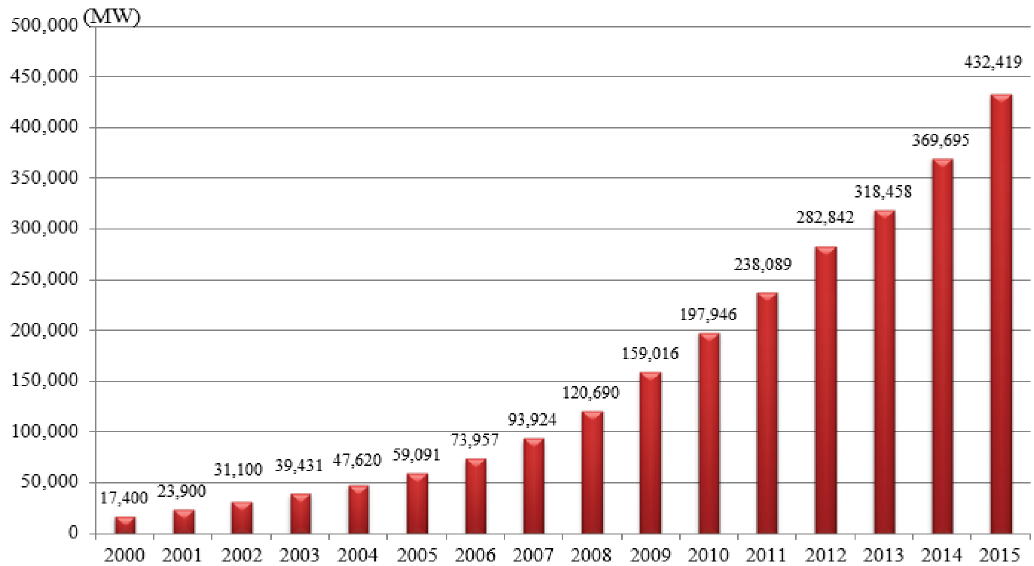

Figure 1.3 : Global Cumulative Installed Wind Capacities 2000-2015 (GWEC, 2016)

One of the great challenges of integrating wind energy into power systems can be seen from the reliability assessment perspective. Particularly, the method of involving wind generation capacity into the overall generation capacity assessment is a major challenge that often raises research questions.

Wind power has an interesting resource potential as well as technology and experience when considering energy mix options. Analysis of wind data characteristics and accurate wind power potential assessment at a given location is an imperative requirement before making a decision for the installation of WECS and evaluating plans for relating these projects with electrical power grid or for a remote area.

It is most likely that electricity demand in Malaysia is going to rise in the future. From the review of the several literatures, it is found that renewable resources seem to have a sufficient potential to develop a sustainable electricity system (Ahmad & Tahar, 2014). It is a fact that, in some of the rural areas and in the coastal regions in Malaysia, the electrical power can also be generated from wind energy. Even though the number of studies had been done by researchers on the potential of wind energy for adopting in Malaysia, and also there are a number of energy projects that are trying to adopt wind turbines in both small and large scales (Goh. et al., 2016; Islam et al., 2011). So far, these studies are not completed and still needed for a more investigation.

1.3 Problem Statement

Generation system reliability is an important aspect in the planning for future system capacity expansion to make sure that the total installed capacity is sufficient to provide adequate electricity when needed (Almutairi et al., 2015; Lin et al., 2014).

In general, an analytical approach is efficient to assess the reliability if not taking into consideration the complex operating conditions and the random failure probability for system components. Therefore, the analytical assessment methods have two main drawbacks when evaluating power generation systems; firstly, relating to the system's complexity and secondly, the number of potential system states, both of which increase exponentially with the number of system components (Billinton & Allan, 1988). The Monte Carlo simulation (MCS) method enables accurate evaluation of reliability indices. The main drawback of MCS is that it is requires large computational effort, so that not suitable for a system with high-reliability, which would take a long time to converge efficiently (Green II et al., 2011). It is important to note that MCS need a large number of simulation years in order to obtain an accurate result. Because a MCS is similar to a survey for calculating reliability indices, a result based on a sample differs from the result that would have been based on the overall simulation. Therefore, the margin of error associated to an estimator of a quantity of mean of reliability indices must computed in order to know if results are reliable (Henneaux et al., 2016). Also, MCS face some diffculties in dealing with rare events, e.g., to assess very small values of reliability indices.

Both the MCS and PIS methods have the state space models but are different in their mechanisms for sampling the reliability indices estimation in generation systems. So far, evaluation of sampling state for the power systems is still a very computational intensive issue and therefore needs much attention. A significant number of research papers in the power system reliability assessment in literature have introduced techniques using PIS methods, which were used to reduce the search space and the computational efforts.

Genetic algorithm (GA) is one of the powerful and primary methods that can be applied as a stochastic search tool that is based on the PIS techniques (Zhao & Singh, 2010). Although often applied with successes, the performance of these algorithms may suffer when applied on complex systems (Wang & Singh, 2007). Despite the efforts done in studying the reliability evaluation of power systems, new algorithms are needed as the complexity of the current power grid is being extended, by the integration of new capacity sources with conventional sources in generating systems. Furthermore, as the system complexity increases (in this context it means more WTGs are integrated), the computational efficiency advantage of the population-based stochastic search has become more evident.

The electric power systems continue to witness the high level of wind power integration as a global phenomenon (Benidris & Mitra, 2014) raising concerns associated with an effective power system planning and operation. The high level of wind power penetration into the electrical system mandates the assessment of their capacities and impacts on reliability by the system planning in line with their power utilization and environmental benefits. So, high penetration of intermittent wind energy resources into electric power systems require the need to investigate the system reliability when adding large amounts of highly variable capacity that differ considerably from conventional generation sources (Padma et al., 2014).

The production of wind energy often involves uncertainties as a result of the wind speed stochastic nature and the variation on the power curve. A technique for modelling wind speed plant in power system reliability evaluation requires the need to investigate and give an effective model for estimating wind power. The uncertainty of the wind power output therefore means the uncertainty of the power system reliability level (Sina et al., 2014; Soleymani et al., 2015).

For an effective development of wind power, the electric utility should ensure adequate survey of wind availability as the first measure. Regrettably, reliable wind speed data proper for wind resource estimation are difficult to obtain (Anurag & Saini, 2014; Kidmo et al., 2015). Therefore, particular wind speed models are developed from the available wind speed data records that have been previously collected. A crucial requirement to evaluate wind-connected power system's reliability is to precisely simulate its hourly wind speed. However, wind speed is time and site variant and the speed at a particular hour is related to that which precedes it.

1.4 Thesis Objectives

The specific objectives of this research are summarized as follows:

1. To propose new techniques based on PIS and compare with previously used techniques and MCS for calculating reliability indices for the generation systems adequacy reliability assessments in order to improve its computational time and accuracy.
2. To apply the proposed techniques and compare with the performances of previous methods in calculating the reliability indices to evaluate the power system reliability assessment with the integration of the wind energy.
3. To propose a combined Weibull and ANN method to estimate wind speed data in order to assess wind energy potential at any sites.
4. To suggest an effective statistical model for analysing wind speed data, in order to assess wind power potential for specific sites in Malaysia. Additionally, the capacity contribution of the wind power in the generating systems adequacy and the impact on generation systems reliability are to be analysed.

1.5 Scope of Research

The scope of this research includes the development of HL-I adequacy evaluation algorithms and methods for reliability assessment of generating systems containing wind energy. The three-year (2013-2015) wind speed data used in the research works were purchased from the Malaysia Meteorology Department consisting of wind data from three sites, i.e. (Mersing, Kudat, and Kuala Terengganu). The obtained data is used to assess wind power potential for specific sites in Malaysia. The system adequacy analysis associated with static capacity levels to make sure that the total installed capacity is sufficient to provide adequate electricity when needed. In order to show the effectiveness and validation of the proposed algorithms, the IEEE Reliability Test System (IEEE-RTS) are considered. All simulation works and coding are done using several softwares such as Matlab, R-Studio package, and WRPLOT View.

1.6 Thesis Outline

The rest of this thesis is organized as follows:

Chapter 2 presents background information pertaining to power system reliability and its relevant aspects. This chapter also reviews related concepts and the available techniques of generating system adequacy assessment and surveys the previously developed models with regard to wind energy in particular.

In Chapter 3, the required algorithms to evaluate the adequacy for conventional generation are presented using the common PIS algorithms. In this chapter, new techniques are proposed to calculate generation system adequacy indices. The techniques are the Disparity Evolution Genetic Algorithm (DEGA), Differential Evolution Optimization Algorithm (DEOA) and discrete Binary Particle Swarm Optimization (BPSO). The results obtained are compared between these new techniques and also with previously used techniques including the conventional MCS.

Chapter 4 presents the mathematical models necessary for performing the adequacy evaluation of the electric power generating systems containing wind energy by means of the sequential Monte Carlo simulation method and PIS techniques. The models of the wind speed and that of the WTG are presented and described.

In Chapter 5, an effective statistical model for analyzing wind speed data, in order to assess wind energy potential at specific locations in Malaysia. Four numerical methods are employed to estimate the values of the shape parameter k, and the scale parameter c. Furthermore, selection of wind turbine class and prediction of annual energy production (AEP) from the proposed turbine are done. In addition, the study developed a prediction hybrid model for the wind speed in order to simulate the operation of power system with penetration of wind energy to assess the reliability of the power systems.

Chapter 6 concludes the research works done and highlighting the contributions of this thesis and discusses possible future works.

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