ROBUST APPROACH FOR CAPACITY BENEFIT MARGIN COMPUTATION WITH WIND ENERGY CONSIDERATION FOR LARGE MULTI-AREA POWER SYSTEMS

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DEDICATION

This thesis is dedicated to my beloved parents for their prayers, advice, moral and emotional support, I also dedicate this work to my wife (Abdulkadir Bukola Fauziyah) and my children for their endurance and prayers during the course of this study. If not for their supports, prayers and endurance this research would have never been completed.

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ABSTRACT

Capacity benefit margin (CBM) represents the tie-lines transfer capability margin for power interchange between interconnected areas. Accurate evaluation of CBM is essential for available transfer capability (ATC) determination. Most of the existing methods for CBM computation rely on complex optimization techniques. In these techniques, for every step increase in power transfer, to improve supply reliability of the deficient areas, the reliability must be recalculated and checked through optimization. Thus, for a large number of interconnected areas, these techniques might not scale well. Another shortcoming of these techniques is the simplifying assumption of only one deficient area with a fully connected network (i.e., all the areas have a direct connection or tie line with each other). In this thesis, a robust graph-theoretic approach is proposed to calculate CBM in a multi-area network with multiple deficient non-directly connected areas. Unlike the existing approaches, multiple deficient areas are considered and some of the areas are not fully connected. From literature, previous techniques only considered conventional generating units in the loss of load expectation (LOLE) computation. A strategy for the incorporation of wind power generating unit is proposed using Weibull probability distribution. This is important since the supply reliability of an area is measured using LOLE of the area and considering the random nature of wind generating systems which has a great effect on the supply reliability. In addition, LOLE which is commonly used as an index for the CBM computation is usually evaluated by using the area peak load demand and the available reserve capacity. The system peak demand usually occurs within a few weeks in a year; therefore, the period of off-peak demand is not efficiently accounted for in the LOLE evaluation. Hence, demand side management (DSM) resources; peak clipping and valley filling are employed to modify the chronological load model of the system which subsequently enhances the CBM quantification. Finally, the results of the CBM are incorporated in ATC computation to study the influence on the ATC evaluation. The proposed technique has been evaluated using IEEE RTS-96 test system because the system has all the required reliability data for LOLE computation. The technique can evaluate and allocate CBM among multi-area systems consisting of two deficient areas. The influence of renewable energy on LOLE has been efficiently evaluated and the DSM technique was efficiently employed to improve three-area test system generation reliability. The generation reliability of the interconnected areas has been improved by an average of 35%. This improvement is very significant in terms of the generation facilities and the financial implication that may be required to be put in place if the proposed DSM technique was not applied. The results and the performance evaluation showed that the proposed technique is simple and robust compared to the existing methods. The technique can also be used as a feasibility tool by utilities to verify the possibility of wheeling power to a deficient area using maximum flow algorithm.

ABSTRAK

Margin faedah muatan (CBM) mewakili margin keupayaan pemindahan talian-ikat untuk pertukaran kuasa di kawasan saling hubung. Penilaian tepat CBM adalah penting untuk keupayaan tersedia pindah (ATC). Kebanyakan kaedah sedia ada bagi pengiraan CBM bergantung kepada teknik pengoptimuman kompleks. Dalam teknik ini, setiap langkah peningkatan pemindahan kuasa bagi meningkatkan kebolehpercayaan di kawasan yang kurang bekalan, kebolehpercayaan ini harus dihitung semula dan diperiksa melalui pengoptimuman. Oleh itu, untuk kawasan saling hubung yang besar, teknik ini mungkin tidak sesuai. Satu lagi kelemahan teknik ini adalah andaian mudah dengan hanya satu kawasan yang kurang bekalan dengan rangkaian yang tersambung sepenuhnya (iaitu, semua kawasan mempunyai sambungan langsung atau talian-ikat di antara satu sama lain). Dalam tesis ini, pendekatan graf-teoritis yang lasak dicadangkan untuk pengiraan CBM dalam rangkaian pelbagai kawasan dengan gandaan kawasan kurang bekalan. Tidak seperti pendekatan yang sedia ada, gandaan kawasan kurang bekalan digunakan dan sebahagian kawasan tidak bersambung terus sepenuhnya. Daripada literatur, teknik terdahulu hanya mempertimbangkan unit penjanaan konvensional dalam pengiraan kehilangan jangkaan beban (LOLE). Strategi untuk penggabungan unit penjanaan kuasa angin dicadangkan menggunakan taburan kebarangkalian Weibull. Ini adalah penting kerana kebolehpercayaan bekalan sesuatu kawasan diukur menggunakan LOLE kawasan tersebut dan mengambilkira sifat rawak semulajadi dalam sistem penjanaan angin yang mempunyai kesan yang besar terhadap kebolehpercayaan bekalan. Di samping itu, LOLE yang lazim digunakan sebagai indeks untuk pengiraan CBM biasanya dinilai dengan menggunakan permintaan beban puncak kawasan dan kapasiti rizab tersedia. Permintaan puncak sistem biasanya berlaku dalam beberapa minggu dalam setahun. Oleh itu, tempoh permintaan luar puncak tidak dikira secara cekap dalam penilaian LOLE. Oleh itu, sumber pengurusan sisi permintaan (DSM), keratan puncak dan pengisian lembah digunakan untuk mengubah suai model beban kronologi sistem yang seterusnya meningkatkan pengkuantitian CBM. Akhirnya, keputusan CBM dimasukkan dalam pengiraan ATC untuk mengkaji pengaruh pada penilaian ATC. Teknik yang dicadangkan telah dinilai menggunakan sistem ujian IEEE RTS-96 kerana mempunyai semua data kebolehpercayaan yang diperlukan untuk perhitungan LOLE. Teknik ini dapat menilai dan memperuntukkan CBM di antara sistem pelbagai kawasan yang terdiri daripada dua kawasan kurang bekalan. Pengaruh tenaga boleh diperbaharui pada LOLE telah dinilai dengan cekap dan teknik DSM telah digunakan secara efisien untuk meningkatkan kebolehpercayaan bagi pengujian penjanaan tiga kawasan. Kebolehpercayaan penjanaan bagi kawasan saling hubung telah dipertingkatkan dengan purata 35%. Penambahbaikan ini amat bermakna daripada segi kemudahan penjanaan fasiliti dan implikasi kewangan yang mungkin perlu dilaksanakan jika teknik DSM yang dicadangkan tidak digunakpakai. Hasil dan penilaian prestasi menunjukkan bahawa teknik yang dicadangkan itu mudah dan lasak berbanding kaedah yang sedia ada. Teknik ini juga boleh digunakan sebagai alat perkakas ketersauran oleh utiliti bagi mengesahkan kemungkinan penghantaran kuasa ke kawasan kurang bekalan tertentu menggunakan algoritma aliran maksimum.

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LIST OF ABBREVIATIONS

AC PF	-	Alternating Current Power Flow
ATC	-	Available Transfer Capability
AI	-	Artificial Intelligence
CBM	-	Capacity Benefit Margin
COPT	-	Capacity Outage Probability Table
CPF	-	Continuation Power Flow
DATC	-	Dynamic Available Transfer Capability
DC PF	-	Direct Current Power Flow
DE	-	Differential Evolution
DSM	-	Demand Side Management
EP	-	Evolutionary Programming
ETC	-	Existing Transmission Commitments
FERC	-	Federal Energy Regulatory Commission
FOR	-	Forced Outage Rate
ISO	-	Independent System Operator
LAM	-	Linear Approximation Method
LDC	-	Load Duration Curve
LOLE	-	Loss of Load Expectation
LOLP	-	Loss of Load Probability
MAAC	-	Mid-Atlantic Area Council
MCLM	-	Modified Chronological Load Model
MCS	-	Monte Carlo Simulation
OASIS	-	Open Access Same-time Information System
OPF	-	Optimal Power Flow
PDF	-	Probability Density Function
PF	-	Power Flow
PTDF	-	Power Transfer Distribution Factor
PSO	-	Particle Swarm Optimization
RPF	-	Repeated Power Flow
TRM	-	Transmission Reliability Margin

TTC - Total Transfer Capability

WTG - Wind Turbine Generator

LIST OF SYMBOLS

P_{Gi}, Q_{Gi} - active and reactive power generations at bus i

P_{Li}, Q_{Li} - active and reactive loads at bus i

λ - scalar parameter denoting power transfer increment, $\lambda = 0$ for base case transfer $\lambda = \lambda_{max}$ for maximum power transfer

U_i, U_j, - magnitudes of the voltages at buses i and j

φ_i,φ_j - angles of the voltages at buses i and j

Y_{ij}, θ_{ij} - magnitude and angle of the bus admittance matrix of the ij^{th} element

U_i^{min}, U_i^{max} - voltage magnitude limits at bus i

S_{Li}^{max} - the limits of the i^{th} transformer or line loading

$|S_{Li}|$ - the transformer or line loading

N - the number of buses

N_L - the number of branches

P_{Gi}^0 - initial active power generations at bus i in the source area

P_{Li}, Q_{Li} - active and reactive loads at bus i in the sink area

k_{Gi} - constant denoting the rate of change in the generation at bus i as λ changes

k_{Li} - constant indicating the rate of load change at bus i as λ chang

$P_I(C_s)$ - capacity outage probability of the individual unit at state s

n - total number of states of generating units

A - Availability

U - Unavailability

$P_c(k)$ - cumulative probability of capacity outage

G_{out} - generation capacity outage

N_h - number of hours in one year

C_g(pu) - total installed generation capacity in per-unit

k - unit of the installed capacity

$G_{out}(k)$ - is the smallest capacity outage at which loss of load occurs for a given load L_i

$PL_{base,l}$ - base case load at bus l,
N_{lb} - number of load buses
$f_{i,j}$ - amount of flow from node i to node j
$\mathrm{u}_{\mathrm{i,j}}$ - maximum amount of flow from node i to node j
Gen - generation matrix of an area
G_{n} - generation capacity of a unit n
G_{wn} - generation capacity of wind power unit
n_{n} - number of units
$\mathrm{n}_{\mathrm{n}.......1}$ - number of states of wind turbine output power
$\mathrm{FOR}_{\mathrm{n}}$ - FOR of generating unit n
Cap_prob - individual unit probability
$\mathrm{Avail}_{\mathrm{n}}$ - availability of unit n
PD - CBM allocated to an area
$f(v)$ - Probability density function
$F(v)$ - Cumulative distribution function
k - Weibull shape parameter
c - Weibull scale parameter
v - hourly wind speed
v_m - mean wind speed
σ - standard deviation of the wind speed data
V_{ci} - cut-in wind speed of the wind turbine generator
V_{co} - cut-out wind speed of the wind turbine generator
V_r rated wind speed of the wind turbine generator
$P_r.$ - rated power of the wind turbine generator
P_s - specified peak for the DSM technique
$L_M(t)$ - specified peak for the DSM technique
$\bar{L}_M(t)$ - original chronological load model of the system
K - modified chronological load model of the system
ψ - energy refilled at each hour
τ - off-peak period
b - on-peak period
\- the fraction of the energy clipped during the peak period and refilled during the off-peak period

Gen_i^a - output of generator i in area a

CBM_a - CBM allocated to area a

N_g^a - total number of generators in area a

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CHAPTER 1

INTRODUCTION

1.1 Research Background

The independent system operator (ISO) is the body in charge of coordinating the activities of market participants, system security and stability monitoring, balancing between demand and supply, and maintaining system reliability [1-3]. It is also the responsibility of the ISO to assess the system conditions and the available transfer capability (ATC) for the next business events [3]. Any contract for power transfer demand should be within the range of ATC of the interconnected systems. Therefore, it is imperative to accurately calculate the ATC value to evaluate the energy production for efficient marketing operations. The flexibility, robustness and system security are dependent on the amount of ATC which the system can accommodate for power transfer. An accurate value of ATC can be used in forecasting the future upgrading of the transmission network [4]. The precise calculation of ATC should include the system constraints, system uncertainties and the transfer capability margins [5, 6].

Overestimation of ATC can lead to system instability which could result to cascading collapse [7-10] and underestimation of ATC value capable of causing underutilization of the power system resources which can subsequently lead to loss of capital as a result of ineffective marketing operations. For example, the major blackout in the North-eastern United States and Ontario in August 2003 was as a result of an overestimation of ATC [10, 11]. Therefore, the consequences of under/over-estimation of ATC have enormous adverse effects on the utility. The United State Federal Energy Regulatory Commission (FERC) established Open Access Same-Time Information System (OASIS) in which all interconnected companies are required to send their ATC value at a regular interval to serve as a reference value for electricity market activities [8]. This information about the size of ATC is vital to system utilities and the planner as it depicts the general performance of the power system regarding efficiency and economic activities. Independent system operators are required to regularly update their ATC on OASIS for efficient system operation.

Essentially, ATC is a measure of the extra transmission capability above the base case power transfer for power marketing. ATC value can be derived by considering various parameters relating to transfer capabilities such as total transfer capability (TTC), transmission reliability margin (TRM), and capacity benefit margin (CBM). TTC is the summation of all the network transfers (base case and commercial transfers) including the margins for system security and reliability, and existing transmission commitments (ETC). TRM is the network margin reserved for system uncertainties [12] whereas, CBM is the network margin reserved for the utilities to have access to external generation in case of emergency generation outages [13]. CBM is commonly evaluated by using the loss of load expectation. CBM is an important parameter in ATC computation, it represents the supply adequacy in an interconnected system. It is a measure of the required transmission capability that is reserved for generation reliability purpose.

Several mathematical techniques have been proposed to calculate ATC and TRM in the literature [14-21]. However, despite the extensive research works on ATC, the work done on CBM determination is limited. For efficient and sustainable power generation reliability, utilities usually have reserve capacity for unforeseen circumstances (such as a sudden increase in load demand due to weather variability, decrease in supply due to faults in the system or unplanned maintenance, etc.). This reserve capacity in most cases remains unused, which may lead to inefficient use of generation resources. In interconnected power systems, this reserve capacity can be reduced without generation reliability degradation. This is achieved by power interchange between interconnected systems through tie lines [22]. To minimize this reserve capacity, utilities reserve some margin in the transmission network between interconnected areas and this margin is termed the CBM. The CBM indicates the transfer capability margin reserved by the utilities in case of accidental generation outages or unexpected increase in load. Accurate evaluation of CBM is crucial for ATC determination. Over/under-estimation of CBM can lead to inaccuracy of ATC results, which can eventually lead to ineffective utilization of transmission system facilities and sudden generation deficiency [10, 23]. Thus, CBM is used to quantify the amount of transmission reserve capability required to meet generation reliability.

Generally, loss of load expectation (LOLE) is commonly used as the reliability metric for CBM evaluation. LOLE is the average number of days or hours in a given period (usually one year) in which there is a loss of load i.e. the daily peak load or hourly load is expected to exceed the available generating capacity [24]. The LOLE mandated by Mid-Atlantic Area Council (MAAC), USA, is currently set to one day in ten years as stated in the MAAC Reliability Principles and Standards [25]. The specified LOLE value is equivalent to 24 hours for ten years or 2.4 hours per year. The criterion is to keep the LOLE of each area less than a specified standard value usually taken as 2.4 hours/year [25]. If the LOLE index of an area in an interconnected system is higher than this value, the area needs to improve its generation reliability by importing power from external areas to meet the generation reliability requirement. However, if the area LOLE is less than the specified value, the area is rich in generation and it can export power to support other areas facing power deficiency. Therefore, to transfer power to the deficient areas, the transmission provider has to reserve a particular amount of CBM depending on the specified value of LOLE.

Most of the previous methods to determine CBM employed optimization techniques such as PSO [26], EP [27], DE [28], and heuristic approach [29] using the LOLE criterion. These techniques may be efficient when dealing with a small number of interconnected systems, however, most of these techniques are not suitable for a large number of interconnected systems due to the iterative complex optimization procedures required to update CBM for every improvement in LOLE.

For efficient determination of CBM for multi-area systems with multiple deficient areas, this thesis presents a new approach for CBM computation in the presence of renewable energy sources. This involves the development of a graph-theoretic approach for CBM computation, development of a strategy for the incorporation of wind power generating unit in the CBM calculation, and development of demand side management approach for the enhancement of CBM. Finally, the results of CBM are incorporated in ATC calculation using repetitive power flow.

1.2 Problem Statement

Researchers have proposed some techniques for the computation of CBM; however, most of these methods rely on complex optimization techniques. In these techniques, for every step increase in power transfer, to improve the reliability of a deficient area, the reliability must be recalculated and checked through optimization. Thus, for a large number of interconnected areas, these techniques cannot scale well.

Another shortcoming of these techniques is the simplifying assumption of only one deficient area with a fully connected network (i.e., all the areas have a direct connection or tie line with each other).

In the past, system operators are more concern about the generation reliability associated with the conventional generators, however, the continuous growth in the integration of renewable power generation in the existing system has posed more threat to the generation reliability due to the variability in the renewable energy output, therefore, evaluation of CBM in the presence of renewable energy needs to be efficiently presented.

Furthermore, the LOLE, which is commonly used as an index for CBM computation, is evaluated by using the area peak load demand and the reserve capacity. The system peak demand usually occurs within a few weeks in a year; therefore the period of off-peak demand is not efficiently accounted for in the LOLE evaluation.

In addition, most of the existing ATC computations do not consider the effect of CBM on the ATC values, therefore, the results of the CBM from the stated objectives are incorporated in ATC computations.

1.3 Research Objectives

The objectives of the research are:

i. To develop a graph-theoretic based approach for efficient computation of capacity benefit margin for large multi-area power systems.

ii. To investigate the influence of wind power generation in the evaluation of CBM.

iii. To develop a strategy for the improvement of capacity benefit margin calculation using the flexibility of demand side management.

iv. To implement CBM in ATC computation in order to investigate its influence on ATC.

1.4 Scope of Work

This research work focuses on the development of a simple non-complex holistic approach for the computation of capacity benefit margin in the presence of renewable energy (wind energy) as well as exploring the demand side management for the enhancement of capacity benefit margin while incorporating the CBM results in ATC. The following are the main focus of this research:

i. This study focus on capacity benefit margin calculation and the results are incorporated in ATC computation, therefore, TRM is not considered in this work.
ii. This study uses the generation, load and the reliability data of the IEEE 24 bus RTS (IEEE RTS-96), and the system was modified to be able to test the efficacy of the proposed method.
iii. Only IEEE RTS-96 is employed in this work because it contains the reliability data required for the CBM computation.

iv. Voltage limit and thermal constraints are considered in the ATC computation.

v. Only tie-line capacity and areas' power reserve is considered as constraints in wheeling power between areas using maximum flow technique of graph theory.

vi. The hydro units in the IEEE RTS-96 are considered as a reservoir for demand side management implementation, details about the reservoir design are not considered.

vii. For reasonable accuracy, six multi-state output for the wind energy unit is considered, in the LOLE calculation. The multistate power generation is obtained by combining the multistate wind speed probability with the power output of the G90-2.0 MW wind turbine.

1.5 Significance of the Study

The significance of this research is highlighted as follows:

i. Accurate determination of CBM for effective power transfer between areas play an important role in system reliability, efficient utilization of transmission system, and secure power system operation. Inaccurate calculation of CBM will result in inaccurate determination of ATC, which will subsequently cause transmission system congestion or underutilization of the transmission facilities. Transmission congestion can result in system security violation and underutilization of transmission facilities can cause loss of capital.

ii. For more than a decade, various methods have been proposed to determine CBM between interconnected areas, however, most of these methods rely on complex optimizations. In large multi-area power systems, the computation of the CBM for several connected areas is not feasible using these complex optimization techniques. This study proposed a simple graph-theoretic approach for large multi-area power systems.

iii. None of the existing techniques has considered more than one deficient area in CBM computation, in a situation where there are more than one deficient areas, the existing techniques would require enormous iterative optimization to scale through. In this research, multiple deficient areas are considered in CBM computation.

iv. Moreover, if the interconnected areas are in critical condition, the CBM supports from other areas might not be feasible as well. Demand side management has also been proposed in this work to improve the supply reliability of the interconnected areas during a critical condition. If the proposed DSM approach was not in place, the system would require enormous generation facilities to be able to curtail the impending supply shortage.

v. Due to the increasing penetration of the renewable energy generation, a method has been proposed using Weibull probability distribution to incorporate wind energy generation units in the CBM evaluation. This would enable the deregulated system participants (ISO, GENCO, TRANSCO and DISCO) to view the likely influence of renewable energy system on the interconnected systems' generation reliability.

The proposed approaches in this research are envisaged to assist power system operators and transmission system management to easily quantify CBM and as well as improve interconnected system reliability. The proposed demand side management approach can also mitigate transmission congestion.

1.6 Organization of Thesis

This thesis consists of five chapters. Chapter 1 presents the general overview of the research by giving a discussion on the background of the research, problem statement, objectives of the research, scope, and the significance of the research.

A comprehensive literature review on the various aspects of this work is presented in Chapter 2. It is divided into various parts, it starts with power system restructuring, literature review on ATC, TRM and CBM, and the review of the various existing techniques for CBM computation. Wind power generation reliability assessment is also discussed in this chapter and finally, the chapter is summarized.

Chapter 3 starts with the introduction of the methodology employed, followed by the overall research structure. Then, capacity benefit margin formulations, the concept of the proposed graph-theoretic approach, and the application of the proposed approach for CBM computation are presented. The development of Algorithm1 and Algorithm 2 for LOLE and CBM computation and allocation respectively are also presented in this chapter. Wind power estimation technique is also presented in this chapter, then, the CBM computation incorporating wind power generation is presented, this is followed by the formulation of demand side management approach for CBM enhancement and the Algorithm for ATC computation and the formulation for the incorporation of CBM in ATC computation are also presented in this chapter. Finally, the chapter is summarized.

Results and discussion are presented in Chapter 4. The chapter starts with the introduction of the test system employed for the implementation of the proposed approaches and the results that are obtained in this work. The complete test system (IEEE 24 bus RTS) used is presented. The results of the CBM computation and allocation for six-area test system are presented and discussed, after then the same results for the three-area test system is obtained and used for comparison with the existing techniques. Five-area test system is employed for wind power integration in CBM computation, the results with- and without wind power are compared to study the influence of wind power system on CBM. Three-area test system with- and without wind power integration is employed for comparison with the only existing work which incorporated wind power in CBM evaluation. The results of the demand side management approach are also presented and discussed in this chapter, and this is followed by ATC results with- and without CBM. Finally, the chapter is summarized.

Conclusively, Chapter 5 presents the overall conclusion of the research and recommendations for further studies on this research.

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