OPERATIONAL FLEXIBILITY FOR INCREASING RENEWABLE ENERGY PENETRATION LEVEL BY MODIFIED ENHANCED PRIORITY LIST METHOD

SALEH Y. I. ABUJARAD

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Dedicated to

To my beloved parents, who without their enthusiasm and encouragement, I would never step in this way

and

To my kind, mindful understanding wife "Sawsan" and my children Sara, Yousef and Yamen, who supported me on each step of the way.

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ABSTRACT

The increasing concerns on climate change and the need for a more sustainable grid, recently has seen a fast expansion of renewable energy sources (RES). This leads to complexities in system balancing between the load and the integrated RES generation, as a result of increased levels of system variability and uncertainty. The concept of flexibility describes the capability of the power system to maintain a balance between generation and the load under uncertainty. Therefore, system operators need to develop flexibility measuring technique to manage the sudden intermittency of net-load. Current flexibility metrics are not exhaustive enough to capture the different aspects of the flexibility requirement assessment of the power systems. Furthermore, one of their demerits is that the start-up cost is not considered together with the other technical parameters. Hence, this thesis proposes a method that improves the assessment accuracy of individual thermal units and overall generation system. Additionally, a new flexibility metric for effective planning of system operations is proposed. The proposed metric considers techno-economic flexibility indicators possessed by generation units. A new ranking for Flexibility Ranked Enhanced Priority List (FREPL) method for increasing share of renewable energy is proposed as well. The assessment is conducted using technical and economic flexibility indicators characteristics of the generating units. An analytical hierarchy process is utilized to assign weights to these indicators in order to measure their relative significance. Next, a normalization process is executed and then followed by a linear aggregation to produce the proposed flexibility metric. Flexibility and cost ranking are coupled in order to improve the FREPL. The proposed technique has been tested using both IEEE RTS-96 test system and IEEE 10-units generating system. The developed method is integrated with the conventional unit commitment problem in order to assist the system operators for optimal use of the generation portfolios of their power system networks. The results demonstrate that the developed metric is robust and superior to the existing metrics, while the proposed Enhanced Priority List characterizes the system's planned resources that could be operated in a sufficiently flexible manner. The net-load profile has been enhanced and the penetration level of wind power has been upgraded from 28.9% up to 37.2% while the penetration level of solar power has been upgraded from 14.5% up to 15.1%.

ABSTRAK

Kebimbangan yang meningkat terhadap perubahan iklim dan keperluan grid yang lebih mampan, perkembangan pesat sumber tenaga boleh diperbaharui (RES) dapat dilihat kebelakangan ini. Ini membawa kepada kerumitan dalam imbangan sistem antara beban dan penjanaan RES bersepadu, hasil dari peningkatan tahap kepelbagaian sistem dan ketidakpastian. Konsep fleksibiliti memerihal keupayaan sistem kuasa untuk mengekalkan keseimbangan antara penjanaan dan beban di bawah ketidakpastian. Oleh yang demikian, pengendali-pengendali sistem perlu membangunkan teknik pengukuran fleksibiliti bagi mengurus keterputus-putusan mendadak beban bersih. Metrik fleksibiliti semasa tidak begitu menyeluruh dalam mengambilkira aspek berlainan penilaian keperluan fleksibiliti sistem kuasa. Tambahan lagi, salah satu daripada kekurangan tersebut adalah kos permulaan tidak dipertimbangkan bersama dengan parameter teknikal yang lain. Oleh itu, tesis ini mencadangkan satu kaedah yang memperbaiki ketepatan penilaian bagi setiap unit terma individu dan keseluruhan sistem penjanaan. Di samping itu, metrik fleksibiliti baharu untuk perancangan berkesan operasi sistem dicadangkan. Metrik yang dicadangkan mempertimbangkan penunjuk fleksibiliti tekno ekonomi yang dimiliki oleh setiap unit penjana. Satu pemeringkatan baharu untuk kaedah Senarai Keutamaan Kebolehlenturan Berpangkat Dipertingkat (FREPL) untuk meningkatkan perolehan tenaga boleh diperbaharui juga dicadangkan. Penilaian dibuat menggunakan ciri-ciri penunjuk fleksibiliti teknikal dan ekonomi untuk setiap unit penjana. Proses hierarki analitikal digunakan untuk menentukan pemberat kepada penunjuk ini bagi mengukur kepentingan relatif mereka. Seterusnya, proses normalisasi dilaksanakan dan diikuti dengan pengagregatan linear untuk menghasilkan metrik fleksibiliti yang dicadangkan. Fleksibiliti dan kos pemeringkatan digandingkan bagi menambahbaik FREPL. Teknik yang dicadangkan telah diuji menggunakan kedua-dua sistem ujian IEEE RTS-96 dan sistem penjanaan IEEE 10-unit. Kaedah yang dibangunkan disepadukan dengan masalah komitmen unit konvensional untuk membantu pengendali-pengendali sistem bagi penggunaan optimum portfolio penjanaan rangkaian sistem kuasa mereka. Keputusan menunjukkan bahawa metrik yang dibangunkan adalah teguh dan lebih baik dari metrik sedia ada, manakala Senarai Prioriti Dipertingkat yang dicadangkan mencirikan sumber terancang sistem yang boleh beroperasi dalam cara yang cukup fleksibel. Profil beban bersih turut dipertingkatkan dan tahap penetrasi kuasa angin telah ditingkatkan daripada 28.9% kepada 37.2%, manakala tahap penetrasi kuasa solar turut ditingkatkan daripada 14.5% kepada 15.1%.

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LIST OF ABBREVIATIONS

AHP	-	Analytic Hierarchy Process
AI	-	Artificial Intelligence
ALR	-	Adaptive Lagrangian Relaxation
ANN	-	Artificial Neural Network
AWFM	-	Adjusted Weight Flexibility Metric
BF	-	Bacterial Foraging
BPSO	-	Binary Particle Swarm Optimization
CR	-	Consistency Ratio
CSC	-	Cold Start-up Cost
DG	-	Distributed Generator
DP	-	Dynamic Programming
DPLR	-	Dynamic Programing based Lagrangian Relaxation
ED	-	Economic Dispatch
EDRP	-	Emergency Demand Response Program
ELD	-	Economic Load Dispatch
EP	-	Evolutionary Programming
EPL	-	Enhanced Priority List
ES	-	Energy Storage
GA	-	Genetic Algorithm

HR	-	Heat Rate
ICGA	-	Integer-Coded Genetic Algorithm
IEA	-	International Energy Agency
IEEE	-	Institute of Electrical and Electronics Engineers
LR	-	Lagrangian Relaxation
LRGA	-	Lagrangian Relaxation and Genetic Algorithms
MA	-	Memetic Algorithm
MBtu	-	Million British Thermal Unit
MCS	-	Monte Carlo Simulation
MDT	-	Minimum down Time
MILP	-	Mixed Integer Linear Programming
MILP	-	Mixed Integer Linear Programming
MRCGA	-	Matrix Real-coded Genetic Algorithm
MUT	-	Minimum up Time
MW	-	Mega Watt
NERC	-	North American Electric Reliability Corporation
NFI	-	Normalized Flexibility Index
O&M	-	Operation and Maintenance
PDF	-	Probability Distribution Function
PEV	-	Plug-in Electric Vehicle
PHES	-	Pumped Hydro-energy Storage
PL	-	Priority List
PSO	-	Particle Swarm Optimization
PV	-	Photovoltaic
RDR	-	Ramp-down Rate

RES	-	Renewable Energy Source
RTS	-	Reliability Test System
RUR	-	Ramp-up Rate
S	-	Scenario
SDT	-	Shut down Time
SFLA	-	Shuffled Frog Leaping Algorithm
SR	-	Spinning Reserve
SUC	-	Start-up Cost
SUT	-	Start-up Time
TLBO	-	Teaching–learning Based Optimization
TOC	-	Total Operation Cost
UC	-	Unit Commitment
UC-ED	-	Unit Commitment and Economic Dispatch
USD	-	United States Dollar
VG	-	Variable Generation
VRE	-	Variable Renewable Energy
WICPSO	-	Weighted Improved Crazy Particle Swarm Optimization

LIST OF SYMBOLS

U_n^t	-	The unit n at hour t
P_n^t	-	Output power of unit n at hour t
N	-	The total generating units
$F_n^t\left(P_n^t\right)$	-	The fuel cost of n^{th} with p^{th} output power at t^{th} hour
a_n, b_n, c_n	-	The fuel cost coefficient of n^{th} unit
S_n^t	-	Generator start-up cost
CSU_n	-	Cold start-up cost of generating unit n
HSU_n	-	Hot start-up cost of generating unit n
t	-	Operation hour
T	-	The time horizon which is 24 hours
T_n^{on}	-	Total up-time (hours) of n^{th} unit
T_n^{off}	-	Total down-time (hours) of n^{th} unit
OFF_n^t	-	Cumulative number of hours that the generator n has been off
ON_n^t	-	Total up-time (hours) of n^{th} unit
MUT_n	-	Minimum up-time of n^{th} unit
MDT_n		Minimum down-time of n^{th} unit
n^{th}	-	Unit number n

HSC_n	-	Hot start-up cost of unit n
CSC_n	-	Cold start-up cost of unit n
TOC	-	Total operation cost
U_n^t	-	Unit n at hour t
P_D^t	-	System load demand at hour t (MW)
P_R^t	-	System spinning reserve hour t (MW)
CO_2	-	Carbon Dioxide
h	-	Operation hour
H	-	Total number of hours
λ	-	Lagrange multiplier
$P_n^t(\min)$	-	Minimum real output power (MW) of unit n at hour t
P_n^t	-	Real output power (MW) of unit n at hour t
$P_n^t(\max)$	-	Maximum real output power (MW) of unit n at hour t
P_D^t	-	Total system load demand (MW) at t^{th} hour
UR_n	-	Ramping up (MW/h) of n^{th} unit
DR_n	-	Ramping down (MW/h) of n^{th} unit
P_R^t	-	System spinning reserve (MW) at t^{th} hour
HR_i	-	Heat rate of generating unit i
$F_i\left(P_i^{\max}\right)$	-	fuel cost function of i^{th} unit at maximum generation output
$\mathrm{Cos}\,t_i$	-	Full load average production cost for unit
PUS_n^t	-	Matrix for primary unit scheduling
$P_{solar}(t)$	-	Solar output power at t^{th} hour

P_{pv}	-	Generated power from PV
G	-	Solar radiation (KW/m^2)
A_{PV}	-	PV area (m^2)
η_{pv}	-	PV module efficiency
$P_{wind}(t)$	-	Wind output power at t[th] hour
P_{WTG}	-	Wind turbine output power
P_r	-	Wind turbines rated power
V_{ci}	-	Cut-in wind speed
V_r	-	Rated wind speed
V_{co}	-	Cut-out wind speed
P_{NL}	-	Net-load
UR_n	-	Ramping up of n[th] unit
DR_n	-	Ramping down of n[th] unit
RUR	-	Ramp-up rate
RDR	-	Ramp-down rate
HSC_n	-	Hot start-up cost of unit n
CSC_n	-	Cold start-up cost of unit n
I_{ji}	-	Normalized value of x_{ji}
x_{ji}	-	Value of the parameter j for the generating unit i
$\max_i(x_j)$	-	Maximum value of parameter j across all generating units i
$\min_i(x_j)$	-	Minimum value of parameter j across all generating units i
r_{xy}	-	Correlation between variables x and y

n	-	Number of values for each of indicator x and y
σ_x	-	Standard deviation indicator x
σ_y	-	Standard deviation of indicator y
CR	-	Consistency ratio
$\lambda_{\max}$	-	Principal eigenvalue
$\frac{1}{2} Ramp(i)$	-	Average of $ramp_{up}(i)$ and $ramp_{down}(i)$
w_{RC}	-	Intensity of importance of ramping in relation to capacity

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CHAPTER 1

INTRODUCTION

1.1 Background

With increasing concerns about climate change and the need for a more sustainable grid, power systems have seen a fast expansion of Renewable Energy Sources (RES) in recent years. Environmental and economic benefits that results from the integration of RES into the power system lead to increased levels of system variability and uncertainty because of their intermittent nature. With increasing penetration levels of RES in future power systems, there has been a growing need to study its impact on power system operations planning [1]. Complexities in balancing load with generation have introduced new challenges in regards to maintaining system reliability at the least production cost with the satisfaction of system constraints [2].

With RES in the generation mix portfolio, the concept of “net-load” arises because of the merit-order preference given to the RES units. The net-load represents the demand that must be supplied by the conventional thermal generation fleet if all of the RE is to be utilized. The output level of the remaining generators must change more quickly and be turned to a lower level with RES in the system [3]. As a result, more flexible resources are needed to meet the increasingly substantial ramping requirements in the system [4]. Power system flexibility refers to the ability of system to deploy its resources to respond to changes in net load.

The term flexibility describes the ability of a power system to cope with variability and uncertainty in both generation and demand, while maintaining a satisfactory level of reliability at a reasonable cost, over different time horizons [5]. Ensuring sufficient operation flexibility, in such a technology mix, requires major changes in system operation [5]. This flexibility will need to come either from plants that are inherently less flexible or from alternative sources of flexibility. Storage, flexible power plants, integrated demand side management and combined heat and power units can provide flexibility to the power system [6]. Maintaining balance in power system operations requires controllable sources to adapt their output power to match the time-varying net-load which is uncertain in real-time operations [7] resulting in a greater demand for operational flexibility from these units [8, 9].

Conventional practices of power system planning and operation are seen to be gradually inadequate in addressing flexibility challenge. One major issue with a great importance among the literature is to estimate and quantify the potential operational flexibility of different power system generating units and overall power system flexibility level. Power system operators are required to evaluate and plan for flexibility adequacy for their power systems to ensure an economical and feasible operation under higher penetration levels of RES. In a similar manner, generation companies are required to consider the concept of flexibility as part of their operations decisions [10]. In the flexibility studies, variability and constraints are typically captured using UC models [5, 11]. UC problem formulation represents the process of determining optimal schedule of generating units over a set of study period subject to device and system operating constraints [12].

This research aims to address major issues involved the flexibility adequacy planning problem at the operational time-frame. The UC problem formulation will be used to achieve the objectives of the research.

This thesis presents a study for the quantifying operational flexibility for increasing renewable energy penetration level by modified enhanced priority list method. The study involves the development of new flexibility quantification framework, development of new adjusted weight flexibility metric, development of new techno-economic flexibility metric and development of a new flexibility ranked enhanced priority list method.

1.2 Problem Statement

Traditionally, the system operators used to deal with some specific uncertainty and variability which normally used to arise from the load changes and generation outages. System operators used to have enough lead time and abundant capacity to solve these circumstances. Recently, the adoption of high penetration levels of RES within the power system generation portfolios has significantly intensified the degree of variability and uncertainty involved in the short-term operations and long-term planning. This is because, unlike conventional power sources, variable RESs, are described with variability which is the maximum available generation limit that changes with time, and this limit is not known with perfect accuracy (uncertainty). These characteristics reduce the available lead time, create requirements for large and sudden steeper ramping instances, and cause frequent start-ups and shutdowns for thermal generating units. These events pose substantial system balancing and frequency stability challenges to system operators. Maintaining balance in power system operations requires dispatchable resources to adapt their production level to match the time-varying net-load and uncontrollability of RESs which is uncertain in real-time operations.

These challenges warrant the re-thinking of conventional practices of system operation and planning in a way that improves and maintains the system reliability at the least production cost. In line with this, the ability of a power system to effectively perform system balancing has been a major issue within the current research. Flexibility requirement metrics and measures have been recently proposed to study the flexibility property from different aspects. Current flexibility requirement metrics are not exhaustive enough to capture the different aspects of the flexibility requirement assessment of the power systems. Inappropriate short-term flexibility planning tools will lead to insufficient flexibility in real time operation – inadequate power capacity combined with potentially inadequate maneuverability.

These can be in the form of: blackouts, load shedding, out-of-merit dispatch and potentially unnecessary RES curtailment. Generally, UC problem formulations try to solve this problem. However, they only focus on getting the right capacity but not the ramping ability. The potential flexibility of thermal generators assume larger importance since they are responsible to satisfy the net-load. Their flexibility is based on their current operational state and their technical constraints imposed by the technology on which they are based, types and numbers of power plants in the system. Power system operators and planners change their focus to having adequate flexibility resources. However, current UC models may not guarantee the schedule to be sufficiently flexible to accommodate higher penetration level of variable RESs.

Therefore, this research work aims to develop a computational assessment tool to quantify the flexibility level of a power system in the operational time frame. The metric is expected to characterize the system's planned resources that could be operated in a sufficiently flexible manner. It also aims to develop a flexibility ranked EPL method for the optimal solution of UC problem to increase the penetration level of RES in generation mix portfolio.

1.3 Objectives

The following are the objectives of the research:

i. To develop algorithm that provides an accurate quantification of technical flexibility within conventional generators and overall generation system for system operators.

ii. To develop a new flexibility metric that incorporates technical and economic flexibility parameters for effective planning of system operations.

iii. To develop flexibility ranked enhanced priority list method to solve UC problem under increasing share of renewable energy penetration.

iv. To develop an adjusted weight flexibility metric for actual flexibility quantification of thermal units and overall generation system.

1.4 Scope

This research focuses on the development of a whole system approach to quantify the value of flexibility from flexible generation resources, in systems with high RES penetration. This will establish the needs for and value of different flexibility provision mechanisms that evolve with increasing RES penetration in future power systems. The following are the focal aspects of the study:

i. Solar and wind power sources will only be considered for this study. Other types of renewable sources such as hydro, geothermal and others will not be considered for this study. Hydro will not be considered in the study as the study focus to study the impacts of solar and wind intermittency.

ii. The research will only consider the operational time frame tools particularly the UC problem. Unlike many of the recent research works, it will not consider the long-term planning models.

iii. For flexibility provision interventions, the research will not consider the demand side flexibility solutions. Only the thermal generation units will be considered as a mean to provide the flexibility requirement.

iv. This research will concentrate on developing deterministic type of metrics. This is because deterministic metrics are more intuitive than the probabilistic-based ones. They are also easier and more suitable for system operators and other stakeholder decision makers.

v. For optimization techniques, solution technique, the study will only consider an Enhanced Priority List (EPL) in order to achieve its objectives. Other types of evolutionary algorithms will not be considered for this study.

vi. Stochastic nature of solar and wind is considered to be covered under the SR which is 10% of the hourly load demand.

vii. For the UC model, a deterministic UC model will be considered in this study.

viii. Solar and wind are considered as a must run units for a better economical solution (No solar or wind curtailment is considered in this study even also not considered in the flexibility options).

ix. IEEE RTS-96 and IEEE 10-units generation system are utilized to test the proposed method and developed metrics.

1.5 Significance of the Research

The significance of this research can be broadly categorized as follows:

i. A flexibility framework for power systems will allow flexibility to be explicitly considered in the design of the system from a short-term perspective. It will also make it possible to quantitatively compare across different flexibility options open to system operators.

ii. From the technical perspectives of the power system operations, the development of efficient flexibility metrics has significance in achieving smooth system balancing actions. It also reduces the level of renewable energy curtailments which will otherwise lead to significant economic losses.

iii. Different studies have presented that some parameters of thermal generators are more important than others to handle unexpected changes in their output power and providing flexibility. Therefore, applying Analytical Hierarchy Process (AHP) in the formulation of the flexibility metric as a priority weighting (relative importance) scheme between the different technical flexibility parameters is significant to improve the accuracy of flexibility quantification.

iv. Introduction of flexibility ranked EPL method for the optimal solution of UC has a significant impact on increasing the penetration level of RES, therefore makes a valuable contribution to power systems operation.

v. The developed tools within this research are expected to help power system operators to deliver deeper insights for renewable energy stakeholders on the amount and type that might be suitable for a particular power system from the perspectives of the technical operational point of view.

1.6 Thesis Organization

This thesis comprises of five chapters. The first chapter provides the general overview of the study by discussing the research background, problem statement, research objectives, scope and significance of the research.

The second chapter is planned to deliver a comprehensive and critical literature review of the different research aspects considered in this thesis. It is divided into two major aspects. The first aspect focuses on the literature related to the UC problem, optimization techniques, and renewable generation within the UC problem solutions. The second aspect focuses on power system operational flexibility, flexibility metrics and their related issues.

The third chapter defines and establishes the methodology of the research. Similar to the arrangement of Chapter 2, UC problem calculations and enhancement of the PL method is firstly presented. Followed by the description of the flexibility parameters and the improvement of the flexibility metric framework and then the development of flexibility metrics is presented. Lastly, the development of a flexibility ranked based PL scheduling method is proposed.

The fourth chapter presents the results and discussion. This includes the optimal solution of UC problem and investigates for the maximum feasible penetration level. Followed by a flexibility quantification by different priority weighting mechanisms and the results for newly developed metrics. The last section of this chapter discusses the development of a flexibility ranked priority list method for optimal generation scheduling and its impact on increasing the penetration level of both solar and wind power.

Finally, conclusion, the contribution of the thesis and recommendation for future research are provided in Chapter five.

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