COORDINATED GENERATION AND TRANSMISSION MAINTENANCE SCHEDULING USING MIXED INTEGER LINEAR PROGRAMMING

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To My beloved husband, Muhamad Amzar and my cutest sons, Ahmad Aqeel Wafiy and Ahmad Aqeef Hafiy, for their enduring love, sacrifice, patience, encouragement and best wishes.

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ABSTRACT

Scheduling of electrical equipment for maintenance tasks is crucial in power system planning as it would affect system operating cost and security. Most existing Mixed Integer Linear Programming (MILP) approaches do not address the interactions between Generation Maintenance Scheduling (GMS), Transmission Maintenance Scheduling (TMS) and Security-Constrained Unit Commitment (SCUC). This research develops a MILP algorithm for the GMS, TMS and SCUC sub-problems to improve the accuracy of coordinated generation and transmission maintenance scheduling. Power flow equation which is based on sensitivity factors is modified to improve the accuracy of transmission maintenance scheduling. To reduce the complexity of the solution procedure as well as to enhance accuracy of the maintenance scheduling model, coupling constraints equations have been formulated to integrate the GMS, TMS and SCUC sub-problems. To further improve the maintenance scheduling ability, a new technique for total operating cost assessment is developed based on an hourly basis to achieve the lowest possible operating cost. Numerical case studies were evaluated on the 6-bus, IEEE 118-bus and utility systems. A comparative study is carried out between the coordinated and individual maintenance scheduling, MILP and Lagrangian Relaxation (LR) approaches, and the maintenance scheduling based on the hourly and day-to-day basis. Simulation results show that coordinated maintenance scheduling is superior to individual maintenance scheduling as it yields lower operating costs. Besides, the proposed MILP outperformed the LR with a cost reduction of up to 5% and lowered the gap tolerance by 0.13%. Moreover, cost saving of nearly 0.14% was achieved using the hourly basis in comparison to the day-to-day basis. From this research, it can be concluded that coordinated maintenance scheduling can provide optimal maintenance schedule which would benefit most of the system planners.

ABSTRAK

Penjadualan peralatan elektrik untuk tugas-tugas penyelenggaraan adalah penting dalam perancangan sistem kuasa kerana ia akan memberi kesan kepada kos operasi sistem dan keselamatan. Kebanyakan kaedah Pengaturcaraan Linear Integer Campuran (MILP) sedia ada tidak mengambil kira interaksi antara Penjadualan Penyelenggaraan Penjanaan (GMS), Penjadualan Penyelenggaraan Penghantaran (TMS), dan *Security-Constrained Unit Commitment* (SCUC). Kajian ini membangunkan algoritma MILP untuk masalah GMS, TMS dan SCUC untuk menambahbaik ketepatan jadual penyelenggaraan bagi penjana dan talian terkoordinat. Persamaan aliran kuasa talian yang berasaskan faktor kepekaan diubah suai untuk meningkatkan ketepatan penjadualan penyelenggaraan penghantaran. Untuk mengurangkan kerumitan tatacara penyelesaian dan juga untuk meningkatkan ketepatan model penjadualan penyelenggaraan, persamaan kekangan gandingan telah digubal untuk menyepadukan masalah GMS, TMS dan SCUC. Bagi meningkatkan lagi keupayaan penjadualan penyelenggaraan, satu teknik baru untuk penilaian jumlah kos operasi dibangunkan berdasarkan pendekatan setiap jam untuk mencapai kos operasi serendah mungkin. Kajian kes berangka dinilai pada sistem-sistem 6-bas, IEEE 118-bas dan utiliti. Satu kajian perbandingan dijalankan di antara penjadualan penyelenggaraan tergabung dan individu, pendekatan MILP dan kelonggaran *Lagrangian* (LR), dan penjadualan penyelenggaraan berdasarkan pendekatan setiap jam dan hari-ke-hari. Keputusan simulasi menunjukkan bahawa penjadualan penyelenggaraan terkoordinat adalah lebih baik berbanding penjadualan penyelenggaraan individu kerana ia menghasilkan kos operasi yang lebih rendah. Selain itu, MILP yang dicadangkan mengatasi LR dengan pengurangan kos sehingga 5% dan menurunkan jurang toleransi sebanyak 0.13%. Tambahan lagi, penjimatan kos hampir 0.14% dicapai menggunakan pendekatan setiap jam berbanding pendekatan hari-ke-hari. Dari kajian ini, dapat disimpulkan bahawa penjadualan penyelenggaraan terkoordinat boleh memberikan jadual penyelenggaraan optimum yang akan memberi manfaat kepada kebanyakan perancang sistem.

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LIST OF ABBREVIATIONS

ACO	–	Ant Colony Optimization
BD	–	Benders Decompositions
CP	–	Constraint Programming
DP	–	Dynamic Programming
EP	–	Evolutionary Programming
ED	–	Economic Dispatch
GA	–	Genetic Algorithm
GAMS	–	General Algebraic Modelling System
GENCOs	–	Generation Companies
GGDFs	–	Generalized Generation Distribution Factors
GSDFs	–	Generation Shift Distribution Factors
GMS	–	Generation Maintenance Scheduling
HCT	–	Hill Climbing Technique
ISOs	–	Independent System Operators
IP	–	Integer Programming
LP	–	Linear Programming
LR	–	Lagrangian Relaxation
MILP	–	Mixed Integer Linear Programming
NSGA	–	Non-dominated Sorting Genetic Algorithm
ODFs	–	Outage Distribution Factors
PSO	–	Particle Swarm Optimization
SA	–	Simulated Annealing
SCUC	–	Security-Constrained Unit Commitment
TS	–	Tabu Search

TMS	–	Transmission Maintenance Scheduling
TRANSCOs	–	Transmission Companies
UC	–	Unit Commitment

LIST OF SYMBOLS

$A_{l,j}$	–	GSDF for line l, due to the generation shift of unit j
$C_{g,jt}$	–	Production cost of unit j in period t
$C_{m,jt}$	–	Maintenance cost of unit j in period t
$C_{m,lt}$	–	Maintenance cost of transmission line l in period t
C_j^u, C_j^d	–	Startup/shutdown cost of unit j in period t
$d_{l,f}$	–	ODF for line l, due to the outage of line f
$D_{l,j}$	–	GGDF for line l with respect to generator j
D_t	–	Total demand in period t
DP_j, UP_j	–	Shut-down/start-up ramp limits of unit j
DT_j, UT_j	–	Number of hours unit j must be initially offline /online
$I_{j,t}$	–	Commitment status of unit j in period t
j	–	Indices of thermal units
l, f	–	Indices of transmission lines
$L_{l,t}$	–	Maintenance status of line l in period t
$M_{l,t}$	–	Transmission line status of line l in period t
MD_j	–	Maintenance duration of unit j
MSR_j	–	Spinning reserve that can be provided by unit j in 1 minute
NT	–	Total number of time intervals
NG	–	Total number of generators
NL	–	Total number of transmission lines
NS	–	Total number of piecewise segments
$P_{j,t}$	–	Output power of unit j in period t
$PF_{l,t}$	–	Power flow for line l in period t
PS_j, PE_j	–	Starting and ending times for maintenance window of a unit j

q_j^{off}, q_j^{on}	–	Off/on time counter of unit j at the initial status
QSC_j	–	Quick-start capacity of unit j
RD_j, RU_j	–	Ramping down/ramping up limits of unit j
R_{st}, R_{ot}	–	System spinning/non-spinning reserve in period t
$SR_{j,t}, OR_{j,t}$	–	Spinning/non-spinning reserve provided by unit j at hour t
t	–	Indices of time intervals
T_j^{off}, T_j^{on}	–	Minimum off/on time limits of unit j
$X_{j,t}$	–	Maintenance status of unit j in period t
x_{mi}, x_{ki}	–	Imaginary parts of the impedance matrix
$X_l^{'}$	–	Reactance of line l from bus m to k
$X_f^{'}$	–	Reactance of line from bus s to e under maintenance
X_{ms}	–	Element of the reactance matrix between bus m and s

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CHAPTER 1

INTRODUCTION

1.1 Background of the Study

Maintenance is one of the major activities for electric utilities. In general, maintenance can be divided into two categories; breakdown maintenance and preventive maintenance. Breakdown maintenance is performed when a sudden equipment failure occurs, which requires a maintenance crew to execute some repair work. This is categorized as unscheduled maintenance which is done only if a breakdown occurs. Meanwhile, preventive maintenance is a periodic inspection procedure done upon parts of the equipment to lessen the likelihood of them failing. It is performed on the existing on-line equipment that has to be shut down temporarily for maintenance tasks. The differences between these types of maintenance are summarized in Table 1.1

Table 1.1: Comparison between breakdown and preventive maintenance

Breakdown Maintenance	**Preventive Maintenance**
To repair an unscheduled breakdown of equipment	To perform scheduled maintenance of equipment
To identify and rectify the fault	To maintain the equipment in good operating condition
Done after a problem	Done before a problem
Not pre-planned	Done at planned intervals
Will maximize the preventive actions	Will minimize the need for corrective action

Normally, all electrical equipment will deteriorate physically with time which would eventually cause malfunction or electrical failure. The deterioration process can be accelerated by many factors such as a hostile environment, overload, or a severe duty cycle. Regarding this, equipment needs to be regularly examined before failure develops. For example, contamination of a transformer's insulating oil has caused failure of the transformer that lead to a total plant shutdown. The contamination went undetected because the oil had not been tested for several years. In another case, the failure of a large motor shut down an entire industrial plant for several days. The cause of failure was overheating resulting from dust-plugged cooling ducts. This overheating might have been prevented if the motor and its housing had been regularly checked. Ironically, more than two-thirds of electrical system failures can be prevented by routine preventive maintenance. It can be concluded that, by doing preventive maintenance, the equipment's life span can be extended, force outage rate reduced, efficiency kept at a reasonable level, and system reliability ensured [1]. Failure prediction or maintenance policies that will manage the risks of equipment failure in the most effective way are not being discussed in this research work. More details on this matter can be referred in [2–4].

A maintenance task usually refers to the activities that involve regular field assessment, overhaul, refurbishment, and replacement of equipment. Among the types of tasks that are typically involved in preventive maintenance are; cleaning technical equipment, replacement of the elements subjected to wear, checking the inner state of some elements of a system, checking the proper operation of the instrumentation and its calibration, and features' verification. These tasks must be performed periodically so that any problem can be fixed immediately before a failure occurs. The maintenance tasks can only be performed by authorized persons - known as the maintenance crew. Usually, the number of maintenance crew is limited, thus they cannot execute more than one task at a time.

The cost related to the preventive maintenance task is quite expensive, since it includes the cost of labor, materials, and the down-time associated with the repair [5]. However, the cost of breakdown maintenance would be three to nine times more than preventive maintenance. The cost of breakdown maintenance includes loss of production, higher costs for parts and shipping, as well as time lost responding to emergencies and diagnosing faults while equipment is not working [6]. Based on that, power companies should always sustain their preventive maintenance so that they don't have to pay even more to replace a major faulty equipment. With proper planning, overall costs can be held to a practical minimum, while production is maintained at a practical maximum.

Maintenance decisions have a direct impact on the power production of each unit. Maintenance outages of a generator or transmission line may cause changes in other units' generation output, which will consequently impact on the production cost. For instance, the maintenance of one unit may trigger the usage of other generating plants that are more expensive and/or inefficient for supplying demand. However, the total operation cost may be minimized if such maintenance is scheduled during the off-peak periods. In comparison to the aforementioned maintenance cost, this production cost is more significant being one million times bigger [7]. With proper maintenance scheduling, the total production cost of the system can be totally reduced [5, 8]. Based on that, optimizing the maintenance schedule is important as, nowadays, most utilities are trying to cut their operating cost as much as possible.

This chapter presents the overview of the chapter followed by problem statements, research objectives, significance of the research, research scope, and thesis outline.

1.2 Problem Statements

Coordinated generator and transmission maintenance are two important issues in power system planning. Thus, four problem statements have been formulated. They are:-

i. The current Mixed Integer Linear Programming (MILP)-based approach does not consider the Generation Maintenance Scheduling (GMS), Transmission Maintenance Scheduling (TMS), and Security-Constrained Unit Commitment (SCUC) problems. This lead to impractical results as generators are interconnected via transmission lines. Hence, they are dependent on each other. Their integration is important as it could have a big influence on the reliability of the system.

ii. The current line flow equation which is based on sensitivity factors (Generalized Generation Distribution Factors (GGDFs) and Outage Distribution Factors (ODFs)) cannot be applied to evaluate the impact of individual maintenance line since its formulation cannot be accessed to the current status of each line.

iii. In Lagrangian Relaxation (LR)-based approach, GMS, TMS, and SCUC sub-problems have been solved separately and the integration is being realized through a series of multipliers. This may cause computational burden to the system.

iv. The current LR-based approach solved coordinated maintenance scheduling based on a day-to-day basis. Consequently, the maintenance schedule did not satisfy the loading and unloading characteristics of a generator since the ramp rate constraints on consecutive days had to be relaxed.

1.3 Research Objectives

The aims of the research work are as follows:-

i. To develop an integrated MILP algorithm for solving the GMS, TMS, and SCUC sub-problems in power system planning.

ii. To modify the line flow equation that is based on sensitivity factors (GGDFs and ODFs) for line maintenance evaluation.

iii. To formulate coupling constraints equations to integrate the GMS, TMS, and SCUC sub-problems in the proposed MILP algorithm.

iv. To develop a new technique for total operating cost assessment based on an hourly resolution basis.

1.4 Significance of the Research

This research work has offered a paradigm shift in the MILP approach as it has been used for solving the coordinated maintenance scheduling problem. The maintenance schedule obtained from the coordinated strategy could reduce the overall operating cost and ensure system security. Generators are interconnected via transmission lines; hence they are dependent on each other. Scheduling them separately may cause violations of the limit on certain lines.

Besides, the findings of this research work will contribute to the benefit of electricity companies in scheduling for the maintenance of their equipment, especially generators and transmission lines. Poor preventive maintenance schedules could lead to a sudden power blackout, which would cause greater losses. Normally, the cost of preventive work is expensive. However, the cost of repair due to breakdown may amount to more than ten times the cost of preventive scheduling. Therefore, having a good preventive maintenance schedule is important in power system planning.

1.5 Research Scope

Figure 1.1 shows the overall scope of research work regarding the proposed coordinated generation and transmission maintenance scheduling.

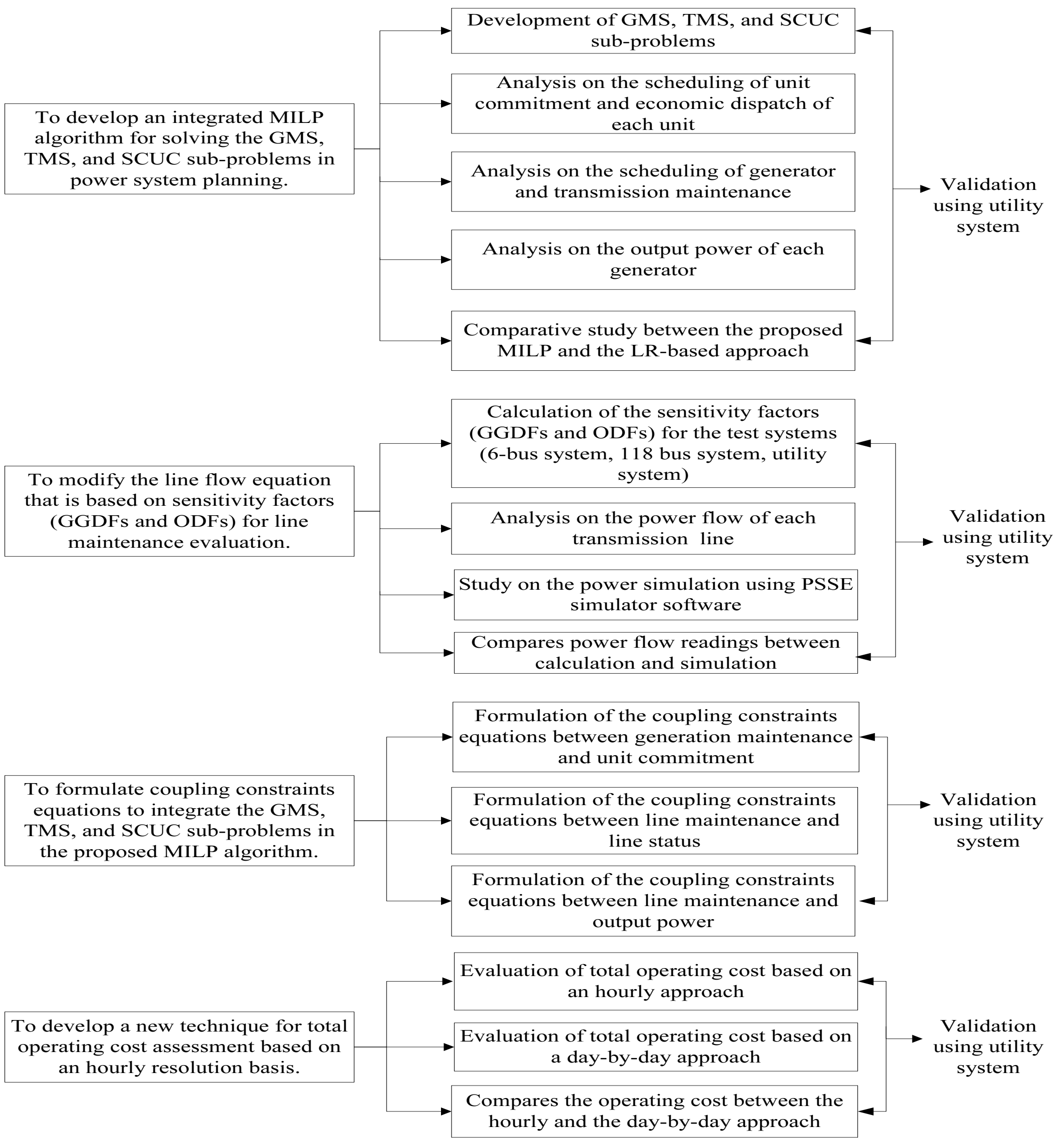

Figure 1.1: Scope of Research

1.6 Thesis Outline

This thesis is organized into five chapters, namely the introduction, literature review, research methodology, results and discussion, and conclusion and future recommendations.

Chapter 1 provides information on the background to the study, the problem statements, objectives, significance, and scope of research.

Chapter 2 discusses the maintenance problems, objective functions, and the constraints that they are subjected to. Besides, the existing optimization techniques that have been applied in the maintenance scheduling problem are also discussed in this chapter. The gaps in the research are presented at the end of this chapter.

Chapter 3 aims to focus on the methodology of the research work. A step-by-step explanation of the proposed approach is provided in this chapter. Here, four approaches which are complementary to the four objectives are discussed. A description of the CPLEX solver is briefly discussed in the final section of this chapter.

Chapter 4 discusses several assessments which are simulated with regard to the proposed approach. Several case studies are conducted which have been tested on a 6-bus system and the IEEE118-bus system. A comparison study is also performed between the proposed MILP and the LR-based approach. Then, the proposed MILP is validated by using real practical data.

Chapter 5 concludes the overall findings of the simulation results as well as highlighting the contributions of this research. Several suggestions are recommended for possible directions of future work.

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