Automatic Scheduling of Substation Maintenance Outages

BY

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بسم الله الرحمن الرحيم

الإهـــداء

إلى والدي العزيز

إلى والدتي العزيزة

إلى زوجتي الغالية شريكة الحياة

إلى أخواني وأخواتي شركاء العيش

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In the name of Allah, the most gracious, the most merciful

All praise is for Almighty Allah for having guided me at every stage of my life.

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Abstract

Name: **Ali Ahmad A. Al-AlShaikh**

Title: **Automatic Scheduling of Substation Maintenance Outages**

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The goal of substation maintenance scheduling is to ensure that all substation equipment will function properly when called upon to operate or during its normal operation. All of the diagnostic testing and maintenance work, necessary to achieve this goal, must be performed in as efficient manner as possible.

Two proposed methods for automatic scheduling of outage tasks for substations system maintenance using Tabu Search and Genetic Algorithms were studied. These methods investigated the implementation of the proposed techniques for solving the maintenance-scheduling problem, which consist of two combinatorial problems, work starting date and network configuration which is found without violating the power flow constraints. These advanced tools are a way to support maintenance schedulers and planners through automatic scheduling to reach the optimal system reliability. The methods performances were tested and checked through 5-Bus and IEEE 25 Bus Systems. The results showed that these methods are reliable and practical for the maintenance-scheduling problem of substations system.

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خلاصة الرسالة

أســـم الطالـــــب: علي أحمد عبد المحسن آل الشيخ

عنوان الرسالـــــة: جدولة صيانة محطات نقل الطاقة أتوماتيكيا

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تاريخ الشهــــادة: مـــايو ٢٠٠١ م

إنّ الهدف من صيانة شبكات و محطات نقل الطاقة هو التأكد من موثوقية و دقة عمل كلّ الأجهزة عندما تدعى للعمل أو خلال عملها الاعتيادي. ولنيل هذا الهدف فأن كلّ الاختبارات والصيانة التشخيصية الضرورية يجب أن تؤدّي بأسلوب كفء و فعال ما أمكن ذلك.

في هذة الرسالة، تمت دراسة طرق جديدة مقترحة للجدولة الآلية لصيانة شبكات و محطات نقل الطاقة باستخدام طريقة البحث الرياضي المعروفة بطريقة المنع و النظرية الجينية. وقد تم ايضاً دراسة مدى ملائمة هذه الطرق المقترحة لحل مشكلة جدولة الصيانة، و التي تتألف من مشكلتين اندماجيتين، الأولى تاريخ بدء عمل الصيانة و الثانية ترتيب الشبكة من دون الاخلال بقيود تدفق الطاقة.

تم تطبيق هذه الطرق من خلال استخدام شبكة مكونة من خمس محطات و شبكة الجمعية العالمية للمهندسين الكهربائيين والإلكترونيين المكونة من خمس و عشرين محطة وقد أظهرت النتائج أن هذه الطرق موثوقة و عملية لجدولة صيانة شبكات و محطات نقل الطاقة. أدوات الذكاء الصناعي المستخدمة في هذة الرسالة هي طرق لمساعدة المشرفين على جدولة الصيانة للوصول إلى افضل أداء للشبكة.

درجة الماجستير في العلوم

جامعة الملك فهد للبترول و المعادن

الظهران، المملكة العربية السعودية

مـــايو ٢٠٠١ م

NOMENCLATURE

MS	Maintenance Scheduling
TS	Tabu Search
GA	Genetic Algorithms
PM	Preventive Maintenance
TBPM	Time Based Preventive Maintenance
PdM	Predictive Maintenance
CBM	Condition Based Maintenance
RCM	Reliability Centered Maintenance
O&M	Operation and Maintenance
SF_6	Sulphur Hexafluoride
EPRI	Electrical Power Research Institute
FWC	Forbidden Work Combination
O/L	Overload

CHAPTER ONE

INTRODUCTION

1.1 General Introduction

Electricity plays a fundamental role as an energy source for industrial and residential applications. Modern industrialized societies depend on the availability of a reliable supply of electricity to sustain their functions and standards of living. Under this increase of power demand, power systems have been in fast expansion for the recent decades [1,2]. These expansions made the electric power systems and their operations the most complex systems of today's civilization, due to the highly nonlinear and computationally difficult environment involved. The planning and operation of these systems should therefore be as efficient and optimal as possible. This is a challenging task requiring a complete knowledge and understanding of the behavior, objectives and priorities involved in these systems.

The basic function of a power system is to supply customers with electric energy as economically as possible and with an acceptable degree of reliability and quality. They are required to meet high standard of reliability and availability at reasonable costs to customers. Power quality and reliability have become important tasks in power system operation and maintenance. System reliability depends on components' reliability. The condition of components directly affects system condition resulting in equipment/system failures leading to outages to customers. For this reason, the condition of power equipment is an area of great concern for all electric utilities. Failures of equipment may precipitate outages for large service areas and can cost millions of dollars in lost revenues, and damages. The ability to foresee a problem, or at least identify the existence of a questionable condition, which in turn would eventually lead to failure, is highly desirable [3,4,1].

So, to keep outages away, the operation and maintenance should be done in the most efficient and optimal way. Maintenance, which is the concern of this work, is essential to keep the equipment in good condition leading to more reliable operation of system with the optimal use of resources. Because of system complexity, the complete Generation-Transmission-Distribution systems must be evaluated on several levels to simplify the planning, operation and maintenance. In particular, substations' maintenance is one part of the overall maintenance program of the electric power system.

Substation equipment must receive a high standard of maintenance in terms of quality and not quantity. The current practices of substation maintenance are basically following the principle of time-based preventive maintenance which is doing routine checks and inspections at fixed intervals. However, the maintenance philosophy, now, is moving towards applying new advanced methods, such as, predicative maintenance and reliability centered maintenance.

1.2 Thesis Motivation

Maintenance scheduling optimization has been studied extensively in the open literature. Most of these studies and literature have been directly about or related to generation plants/units maintenance scheduling aiming to cut the fuel costs and obtaining good maintenance schedules. However, maintenance scheduling in transmission and distribution systems is occupying a small portion of the literature. This was the main motivation to study this subject.

1.3 Thesis Objective

The main objective of this thesis is to develop a model for automatic scheduling of outages tasks for substation maintenance using Artificial Intelligent tools (Tabu Search and Genetic Algorithms).

1.4 Thesis Outline

This thesis is organized in seven Chapters, it starts by a general introduction, Chapter One, about the maintenance subject and its importance. Chapter Two addresses the literature review, substation maintenance and their important-related subjects. Chapter Three presents a survey on substation maintenance programs. The problem formulation of automatic maintenance scheduling is given in Chapter Four. Then, in Chapter Five, Tabu Search and Genetic Algorithms implementations to the problem are explained. Chapter Six presents the simulation results of the proposed methods. Finally, Chapter Seven contains the thesis conclusions and recommendations. A list of all references and relevant appendices are included at the end of the thesis.

CHAPTER TWO

SUBSTATIONS SYSTEM MAINTENANCE

In this Chapter, the maintenance of substations system and some important related subjects are presented. This Chapter represents the literature review of the thesis' subject.

2.1 Introduction

With the increase dependency on electric power in our daily lives, it is becoming more and more necessary to improve the quality of electric power as well as the stability of power supply delivery. This has resulted in a greater need for maintenance in order to maintain a reliable supply of power.

Substation performance and reliability is critical for the whole system. Substations, operated and maintained in a cost effective manner, can provide the competitive advantages to the utilities who are seeking a reduction in the overall costs of their system. To achieve these advantages, substations must operate effectively while minimizing and reducing costly maintenance [5]. The only way to permanently reduce maintenance costs is to reduce the need for maintenance. Reducing the need for maintenance comes from diligent efforts to improve materials, designs, maintainability, and operations [5]. The improvement of substation reliability has its price as it implies higher investment costs.

To improve the reliability of electric power supply to customers it is important to reduce the time needed for restoration of the functional ability of supplying power after failure of its components or due to general maintenance work [6].

The deterioration of substation's electrical equipment is normal and it begins as soon as the equipment is installed. If deterioration is not checked it can cause electrical failures and malfunctions. With a well-organized and implemented Preventive Maintenance (PM) program, potential hazards that can cause failures of equipment or interruptions of electrical service can be discovered and corrected. However, it is inevitable that some failures will occur [2,7].

The goal of substation PM program is to ensure that all substation's equipment will function properly when called upon to operate or during its normal operation. All of the diagnostic testing and maintenance work necessary to achieve this goal must be performed in as efficient manner as possible [8].

Traditionally, maintenance philosophy for substations has been to perform work on a time-based requirement, i.e. planned (scheduled) maintenance (doing routine tests and inspections at fixed intervals), without any regard to the actual in-service duty or the condition or performance of the equipment [9,4]. However, maintenance is changing from a concept focused on how well a process or an individual machine works to a more complex concern with safety, quality, commercial availability, and cost efficiency. Also, computerized maintenance management systems are changing from programs constructed to control the worker to integrated maintenance information systems that support self-managing maintenance [5]. There has been a growing tendency towards predictive maintenance philosophies. That is, maintenance should only be performed when required and according to maintenance priorities [3,9,4].

Nowadays, additional competition and growing complexity in power systems as well as a need for high service reliability and low production costs, are provoking additional interests in automatic scheduling techniques for maintenance of generators, transmission and related equipment capable of providing optimal maintenance schedules [10].

Definitions

In the following, some widely used and accepted definitions in the field of maintenance are given below:

Preventive Maintenance (PM): is the performance of inspection and/or servicing tasks that have been *preplanned* (i.e., *scheduled*) for accomplishment at specific points in time to retain/keep the functional capabilities of operating equipment or systems [11].

There are three major types of PM:

- *Predictive (Condition-Based) Maintenance (PdM or CBM):* inspection/monitoring through human senses or sophisticated testing equipment and instrumentation is necessary, with thresholds established to indicate (predict) when potential problems start [12]. It is also described with titles such as monitoring and diagnostics, and performance monitoring. All of these names are intended to describe a process whereby some parameters are measured in a nonintrusive manner and trended over time. The said parameters being one with a direct relationship to equipment condition, or at least some specific aspects of equipment condition [11].

- *Condition Monitor Maintenance*: statistics and probability theory are the basis for condition monitor maintenance. Trend detection through data analysis often rewards the analyst with insight into the causes of failures and preventive actions that will help to avoid future failures [12].
- *Scheduled Time Based Preventive Maintenance (TBPM):* is the process of periodic overhauls or services of the equipment. These services and activities are performed at fixed intervals of calendar time (days, weeks, etc.), operating hours, or operating cycles [12,11].

Corrective Maintenance (CM): is the performance of *unplanned* (i.e., *unexpected/unscheduled*) maintenance tasks to restore the functional capabilities of failed or malfunctioning equipment or systems [11].

Reliability Centered Maintenance (RCM): is a methodology completely described in four unique features; preserving functions, identifying failure modes that can defeat the functions, prioritizing function need (via failure modes) and selecting only applicable and effective PM tasks [11]. Another definition for RCM is: it is a methodology which involve specifying and scheduling PM activities in accordance with the statically failure rate and/or life expectancy of the equipment being maintained and its criticality and productivity, and continually updating PM procedures and schedules to reflect actual maintenance experience [7].

Literature Review

Maintenance Scheduling (MS) optimization has been studied extensively in the open literature [13]. Most of these studies and literature had been directly about or related to generation plants/units maintenance scheduling. However, MS in transmission and distribution systems is occupying a small portion of the literature. The MS methods used in the literature differ both in terms of criteria and mathematical techniques employed [14].

In the following, some literature reviews are pointed out:

- Yamayee presented a description of MS problem, which discussed all important and widely-used terminology and features of the problem: a comprehensive critical survey of literature in this area [15].
- El-Sheikhi and Billinton were the first to investigate into the MS problem for an interconnected power system. Levelized reliability criterion was used to look into the effect of changing one utility peak demand on the maintenance schedule of the other utility and also the effect of increasing the tie-line capacity between the utilities [14].
- Silva presented a methodology for the MS that takes into account inter-area transfer limitations and stochastic reliability constraints. The optimization model is based on the Benders decomposition technique [16].
- Marwali focused on coordination between long-term and short term transmission MS. The long-term and short-term schedules were solved by using Benders Decomposition [17].
- Nahman suggested a method to optimize the spare items of substation components which have to be stored at the beginning of each year throughout a planning period. This sparing policy is conceived to provide the minimum total cost consisting of investment and load curtailment costs. The method uses the Hooke's and Jeeves' direct search optimization approach. The total cost includes

both the investment cost for spare components and load curtailment costs caused by the failure of substation components [6].

- W. Chan presented the development of an on-line distributed information monitoring system for keeping track of the condition of HV equipment in transmission substations, such as status of each SF_6 circuit breaker together with other operational parameters, transformer temperature, capacitor bank unbalanced currents and auxiliaries including pumps, batteries, compressors, etc [18].
- Bretthauer presented an integrated MS system taking into consideration device and system-specific data in order to coordinate the maintenance activities for constrained schedules. This supports the maintenance engineer to coordinate maintenance activities more effectively [19].
- Creemers described a novel application for MS activities on large distribution networks using constraint programming methods. It is claimed that constraint logic programming reduces the development time and makes the applications more flexible, while preserving the efficiency of specific implementations [20].
- Kaminaris presented an intelligent rule-based approach for substation maintenance planning for each of substation components based on a Fuzzy Risk Index (FRI). The proposed approach is based on the Fuzzy Sets Theory and the Expert System Methodology [4].
- Solvang described computer-based tools under development in Norway for medium and low voltage distribution network maintenance. These prove to be a promising tool in the maintenance program [21].

- Levi presented a powerful tool for fast, reliable and accurate evaluation of field tests of power equipment. It was developed for on-site analysis. In addition, a methodology for inventory control, statistical analysis, equipment MS, and a variety of other analytical and managerial aspects were discussed [3].
- Kaminaris described SUBES a rule based expert system approach for distribution substations troubleshooting and MS [2].
- Chan proposed Genetic Algorithms (GA) to outage planning of an electrical network. The paper shows that GA provide a simple, fast and effective way in scheduling the maintenance outages [22].
- Negnevitsky described an application of traditional GA to MS in power system. A representation, integrating any constraints, suitable for a variety of problems, is designed and appropriate chromosome evaluation is suggested [23].

2.2 Substation Maintenance Program

The management of maintenance program is an area of great concern for any company that depends on the smooth running of equipment to produce a product or carry out a mission at a profit or at low cost. Any failure in equipment or facilities will result in loss of productivity and a reduction in effective level of quality [24].

There are two important pieces of information that are required to define the ideal PM program in general. Specifically, we must identify (a) what PM tasks are to be done (planning) and (b) when each task should be done (scheduling) [11,25]. As a general rule, to carry out the successful operation of electrical equipment and apparatus, it is essential to set up an effective maintenance and testing program. Management should assign a high priority to maintenance program. Adequate resources - personnel, facilities, tools, test equipment, training, engineering and administrative support - should be devoted to the program.

2.3 Time Based Preventive Maintenance - TBPM

It is widely recognized that PM is an effective mechanism for increasing the utilization of equipment. The main feature of TBPM program is "*maintenance must be done in due time according to the prearranged/planned schedule even if the equipment is running without any questionable sign of failing or misoperation*" [26]. These activities are intended to prolong the useful life of the equipment and system and to assure that power system components provide the levels of reliability and service life designed into them. Appropriate time intervals between regularly performed maintenance tasks are important in achieving more reliable performance at a reasonable cost [27,28]. TBPM is best suited to failures that have a clear wear-out characteristic.

A variety of TBPM tasks are being implemented at different frequencies at utilities all over the world. A large fraction of these utilities is in the process of reducing PM costs and improving equipment performance by more closely matching PM tasks with the functional importance of equipment. For this to succeed, utilities require information on the most appropriate tasks and task intervals for important equipment types. Maintenance activities, as an example, in high voltage electrical energy systems are scheduled at fixed intervals without regard to the actual equipment condition. In order to reduce the risk of a malfunction, these intervals are usually rather short. Hence, maintenance expenditure can be reduced if the condition of the equipment is taken into account. As a consequence, many research activities concerning maintenance of power system deal with diagnostic techniques and methods in order to recognize the actual condition of the equipment. The main objective of these approaches is to maintain the equipment only when required by its condition and in this way to avoid unnecessary maintenance activities. However, since nowadays the majority of various components of power system are maintained periodically, and, even in the future, some components will not be monitored for economic or technical reasons, MS will always have to consider predetermined maintenance intervals and will have to react to spontaneous malfunctions. Moreover, even if it is possible to determine the condition of a certain device, it can only be maintained if the maintenance activity does affect neither system security nor reliability [19].

2.4 Reliability Centered Maintenance - RCM

Maintenance practices commonly in use today rely mainly on time or some other counters, such as, number of operations and/or visual inspections. The "repair all defects" philosophy to maintenance in common use may be overly conservative and unrelated to the actual condition of equipment, resulting in maintenance being performed when none is required or deferred when it is critical. New maintenance practices are needed that allows taking steps to ensure reliability while controlling, and even lowering, costs. Today, cutting Operations and Maintenance (O&M) costs and preserving service reliability are the top priorities for utilities. RCM offers a logical alternative to traditional electric utility maintenance practices. It provides a structured approach to evaluating maintenance needs for systems, and a basis for maintenance decisions since it calls for a maintenance program that is selective, depending on the sensitivity or the location of equipment within the network [12,27].

RCM is estimated to reduce O&M costs while preserving or even increasing substation reliability. It has been successfully demonstrated at several host utilities which shows lower maintenance costs in the range of 8-40% [27]. Companies that have used RCM report savings of 5% to 30% on their O&M budgets. Approximately 40 power distribution companies in the U.S. are currently using RCM [27]. PECO Energy applied EPRI's RCM as part of an overhaul of its PM program. The utility estimates it saves approximately $1 million annually by eliminating unnecessary maintenance tasks. Oklahoma Gas and Electric used EPRI's RCM to identify ineffective maintenance procedures. Application allowed the utility to eliminate about 25% of its maintenance tasks without compromising reliability [27]. RCM helps these companies to save because it is a method of establishing maintenance intervals based on actual system and component performance, rather than relying solely on manufacturer specifications, time-based schedules, or past company practices. It employs functional analysis to target maintenance resources on preventing failures with the most significant consequences.

Implementing RCM does not necessarily require a large investment of utility resources. What's needed is a serious desire to re-examine the utility's maintenance program from a new perspective, and to make available the records and personnel associated with maintenance activities. It can be applied to a single piece of equipment, a group of equipment, or a system [27]. Implementing RCM approach will help to establish priorities for the whole program.

2.5 Predictive (Condition-Based) Maintenance

Over the years, the maintenance strategy has changed from the old TBPM to a new type of maintenance called predictive maintenance: Predictive or (Condition-Based) Maintenance (PdM or CBM) avoids the high costs of intensified time driven tasks independent of equipment's condition. The PdM uses parameters which are indicative of machine health to trigger the maintenance activity. Regular tasks become scheduled inspections and measurements rather than repair or replacements, and actions are only scheduled when they are really needed [29]. In comparison with TBPM, the benefits and results are cost savings and lifetime extension [10]. For these reasons, utilities are placing an increased emphasis on PdM and failure prevention programs that supply early detection, monitoring, and diagnosis of system equipment problems. Utilities are seeking ways to extend the life and improve the availability of existing power system while maintaining safe operation. On-line diagnostic monitoring enables utilities to predict and detect the failures of substations' components in their incipient stages. With advance warning of a problem, maintenance personnel can have tools and parts ready to make repairs during regularly scheduled outages. In addition, on-line monitoring indicates when maintenance is not necessary, preventing a failure or averting an unanticipated outage [27].

The key to PdM lies in the grasp of existing technical state of equipment and evaluate the trend of changes of this state. In other words, the strategy to use PdM is to review existing maintenance efforts, then complement those efforts by applying a series of newly developed monitoring test methods to substation equipment. The channel for obtaining such information of equipment state is mainly from the result of routine tests and monitoring equipment. As far as this conception is concerned, improvement of equipment maintenance naturally starts from the improvement of the testing and monitoring work [26]. In order to execute PdM, the state parameters of each equipment should be grasped as complete as possible. But, at present, the more important thing is to concentrate the attention to the parameters which have special significance in evaluating the state of major equipment. The so-called major equipment includes those that are worth of great value, would cause great influence after failure and need a long period for repair. Monitoring of state is the foundation of practicing PdM, the deepening of PdM relies again on further development of testing and monitoring technology [26].

PdM has had a significant impact on PM philosophy. In areas where PdM has been implemented, it eliminated the need for most of TBPM activities. This saves a lot of money and time, as it allows to plan the required maintenance only as it is needed and it allows the company to run more effectively and to use the work force in other areas of importance [5]. EPRI studies' results of applying PdM program for periodic monitoring of critical substation equipment show a reduction in substation O&M costs up to 20-30% by implementing or enhancing PdM program [27]. Also, using PdM will provide many benefits as failure prevention, rapid recovery of service in case of faults and labor savings. For instance, about 80% of failures and troubles are estimated to be prevented by the system before actual failures [30].

2.6 Computerized Maintenance Management System - CMMS

In today's computerized world, it has become necessary to automate the collection, storage, and processing of vital data in order to achieve the required levels of operating efficiency. In the operation of large systems such automation is required in conducting and managing of maintenance program [11]. Traditionally, maintenance practices are typically time-directed and often adhere to manufacturers' overly conservative recommendations. Such practices are no longer adequate to meet the needs of today's utilities, which must adopt maintenance procedures capable of preventing failure of critical equipment while at the same time avoiding unnecessary maintenance and overhauls. To ensure they can optimize limited maintenance budgets, these companies need a centralized means for accessing and utilizing all of the information required to initiate, schedule, track, record, and analyze PM tasks. The needed software should also incorporate experience with numerous types of equipment, reliability concerns, and diagnostic technologies.

CMMS are an integral part of modern engineering maintenance management. In order for the whole maintenance program to function effectively, at least five principal subsystems should be designed correctly and effectively. These five subsystems are: [27,31]

1. Equipment control - for all the equipment in the substations that must be maintained and serviced including tools and maintenance equipment. Also, maintenance work orders planning, prioritization, and scheduling.
2. Work control - for the personnel that perform maintenance work. Resources availability checking, planning, usage, and allocation.
3. Maintenance spare parts and inventory control (Inventory Management) - for stock and stores used in maintaining, reporting, and overhauling equipment. Resources availability checking, planning, usage, and allocation.
4. Cost accumulation and reporting - for management control and planning.

5. Performance reporting/forecasting - for management to make strategic decisions to improve performance of all equipment and increase its availability.

These five computer subsystems control the three principal variables (equipment and facilities, labor, and materials); accumulate and summarize costs; measure performance in comparison to some standard; and report to management the effectiveness of the entire integrated management system [31].

Most CMMS programs include basic modules for work orders, planning and scheduling, PM, equipment history, and maintenance materials management and purchasing. These basic modules can provide the foundation for an effective maintenance management system [5]. The CMMS will meet utility maintenance and reliability needs through cost-effective integration of various tasks which provides utilities with a centralized means to build and manage a substation maintenance program. This integrated package reduces O&M costs while ensuring system reliability [27].

2.7 Substation Equipment's Diagnostics

By monitoring substation equipment using diagnostic tools, utilities can make more informed decisions regarding equipment maintenance and thus minimizing unnecessary downtime for maintenance. Accurate and reliable monitoring and diagnostic instrumentation techniques for substation equipment can help utilities in this regard. Hence, it will reduce equipment maintenance costs, increase system reliability, and extend equipment life [32]. Carrying out detailed diagnostic techniques require outage of equipment. This can be avoided through on-line condition monitoring. The on-line condition monitoring system is a valuable O&M tool, that identifies equipment malfunctions, prevents catastrophic failures and as an aid in planning for future maintenance. For example, at IREQ (USA) they produced savings estimated at over $1-million by detecting four functional breaker anomalies, and furnished crucial data to explain one catastrophic breaker failure that was not prevented [33]. Now, an ongoing debate centers around whether it is better to do continuous, on-line monitoring, or to rely on periodic spot checks based on known life cycles. Usually, the more costly continuous monitoring systems are reserved for major equipment (like, breakers and transformers) that are feeding critical lines or large loads.

During the last few years, a variety of new maintenance technologies have become available, including low-cost sensors and advanced diagnostics tools. These technologies can provide important benefits. Incorporating them into an integrated program, can create a maintenance revolution by lowering costs while improving system reliability [27]. The data can then be further processed in a central computer, identifying any abnormalities which require immediate action and, by reference to previously archived data related to the same item.

Some examples of monitoring equipment for substations are:

- Monitors for gas-in-oil detector or fault recorders that give operators advance indication of wearing circuit breaker parts, coking in transformer load tap-changer, or insulation breakdown in transformer windings [33].

- A new detection technology available to utilities is an SF_6 gas leak detector based on the infrared (IR) image produced by IR laser [33].
- Temperature profile of a winding, including hotspots, can be shown by backscattered light in an optical fiber [33].
- A transformer condition monitoring and diagnostic system developed by EPRI to extend transformer life and reduce forced outages by providing early detection of abnormal operating conditions [27].
- Corona inspection, using a detector such as the ultrasonic corona detector that locates sources of excess corona. Corona is produced by overstressed and ionized air around improperly shaped connectors and contaminated insulators, lightning arresters, and bushings. If left uncorrected, excess corona may result in flashover [34].
- Fiber-optic monitoring technique has become very advanced, sophisticated and reliable and the equipment has now been fully proven in service. It is stable over a long service period, robust, maintenance-free, easily installed and replaced, and easily accessible. [35].

These monitoring tools installations in any system should be considered only if there is an economic and technical justification, and if it benefits the user.

2.8 Planning and Scheduling of Substation Maintenance

Planning and scheduling are vital ingredients of a successful maintenance program. The vast majority of maintenance work that is performed should be planned and scheduled.

Only emergency repairs are made without advance planning or scheduling. All maintenance work should be planned so that the quality and cost-effectiveness of the work is assured. Even, emergency work must be planned as it is taking place, operation by operation [31].

A maintenance plan must take into account the related phenomena of generation, transmission and distribution systems. System reliability is affected by maintenance plan and any sub-optimality in the plan would mean reducing the supply-demand gap. Optimal maintenance plan can lead to substantial savings in reduction of unserved energy. Numbers of maintenance planning and scheduling methodologies have been developed and proposed by various researchers over the time [14,36].

Good planning starts at the design stage, certain requirements must be taken into account, specific checks must be implemented from the stage of manufacturing of each component right up to erection on site and even during operation of equipment [37]. All these measures ensure that these equipment have great reliability.

In the maintenance program, MS is a significant part of the overall program. The task of MS involves specifying dates at which manpower is to be allocated to maintain an element or group of elements in any part of the power system. To perform maintenance, a definite schedule of work to be performed must be established. Maintenance schedules must be based upon minimum downtime for the various operating equipment. The schedule of inspection, routine maintenance, and other work may vary for different equipment and will depend upon many factors [7].

MS is required to reduce the risk of capacity outage and to improve the availability of equipment. Scheduling of maintenance work can be handled in two degrees of refinement: [31]

- Long-rang or master work scheduling
- Short-range work scheduling

Long-Range Scheduling

Long-range scheduling is based upon the existing maintenance workload including all routine, general and PM and the anticipated work brought about through emergency repairs. Long-range scheduling is frequently carried out on a craft basis so that a balance of manpower will be maintained. It should be understood that long-range schedules would need to be revised regularly to accommodate changes in plans. More or fewer emergency repairs than anticipated can results in significant changes in the long-range schedules. The accuracy of the long-range schedule is based on the thoroughness of the planning [34]. A number of uncertainties are involved in dealing with this long-term scheduling problem. These include load uncertainty, price uncertainty, generation reliability, uncertainty in resources and crew availability [15].

Short-Rang Scheduling

Short-rang schedules are constructed from the long-rang schedule. It is usually done in daily, weekly or monthly basis. When planning the sequence of the work order scheduled for short range, consideration must be given not only to the nature of the repair of the equipment, but also to the availability of special components and stock to perform the repair. A priority is assigned that places the work order in its most favorable sequence [34].

2.9 Excessive (Unneeded) Maintenance Work

The maintenance work of substation equipment runs through a long period of time from their initial commission to ending retirement. Among the operation activities of power system equipment, maintenance is a very complicated and heavy task.

Most substations maintenance work nowadays is based on fixed schedules (based on time intervals) rather than on known need. The main feature of this program is "*maintenance must be done in due time according to prearranged schedule*" [38]. Actually it often cause "*excessive maintenance work*" with certain degree of blindness. The original intention of this maintenance policy is probably to put in excessive labors and materials for improving the reliability and operation of equipment. However, many years of operation experience showed that failures of equipment did not decrease with excessive maintenance [38]. This is due to the fact that some of the failures had inherently nothing to do with maintenance, such as, damage of dynamic stability of transformer windings. Also, some failures, such as malswitching operation, damage caused by improper maintenance and some accidents of injure of human body and death were just the "negative effects" of excessive maintenance [38]. Scheduled maintenance is essential and cannot be eliminated entirely, but priority should be given to equipment known to be deteriorated, defective or in need for maintenance. It makes no sense to perform costly, scheduled outage maintenance work when other equipment is failing because of undetected defects [34].

One example, a study confirms that PM in a generation plant approximates half of the work accomplished in most organizations. In this study, it was exactly 47%. In this plant, an overly simplistic conclusion would be that about $18 million of labor and material was wasted. When expressed in hours worked, PM appears to be 63% of this wasted money [5]. Another example, a study from China did a through review of the past maintenance practices, they decided to give up the existing periodical maintenance strategy. Under guidance of such strategy, continuous improvement of maintenance work of substation equipment has been carried out. This was a result of applying CBM, in the following some of the improvements are pointed out: [38]

- Canceling two testing items of acid value and flashing point of insulating oil: they had counted up the test results of 21188 pieces of oil samples taken from equipment in operation in the past 16 years (1978-1994), none of them were found with acid value or ignition point not standard. This means that in this area continuation of the above tests is no more necessary, so they are canceled.
- Circuit breaker: the actual condition of 2074 pieces have been counted up, times of overhauled circuit breakers in the past eleven years (1983-1993). Only 26 of them were found with obvious internal defects, amounting only to 1.22% of the total number of piece-times overhauled. This fully shows that there is serious over-maintenance in the practice of circuit breaker maintenance. Hence the adjustments were made on the maintenance policy of circuit breakers.
- Prolongation of testing period: as a whole, the technical state of equipment as compared with that in the past has obviously been greatly improved, which is mainly revealed in: the number of defects, especially that of major defects found in preventive tests are reduced year by year; the rate of equipment fault during operation becomes also less. Under such a condition, prolongation of tests period is feasible and necessary. Under the guidance of this idea, and according to the

important degree of position of the equipment in the system, the corresponding tests period was decided accordingly.

CHAPTER THREE

SURVEY ON SUBSTATION PREVENTIVE MAINTENANCE PROGRAMS

3.1 Objective of Survey

The main objective of the survey is to understand the existing maintenance practices, programs and the scheduling procedures at electricity utilities. This is achieved through data collection from the Kingdom's electricity utilities. The data is collected through surveys and questionnaires. The survey lasted for around three (3) months for twelve (12) 69/13.8kV substations. The data was taken from the substation maintenance database of one electrical utility at Saudi Arabia.

3.2 Survey Sample

The survey consists of ten (10) parts for each substation. Each part concentrates on one or two equipment's tests and inspections. The substation name, location and date of taking the data were first recorded. Then, the following were recorded, the duration of each test (in hours), the frequency of each test (in months), number of data samples taken, how many time the samples taken were OK or not?.

The tests and inspections in the survey were chosen based on the PM program of the utility. The tests and inspections of each part is given below:

Part 1: Transformer Tests

The following tests and inspections were considered:

1. Oil quality test
2. Overall power factor test
3. Megger test
4. Excitation currents test
5. Power factor test to bushings
6. Dissolved gas in oil analysis test (DGA test)
7. Calibration of oil temperature indicators of the transformer
8. Calibration of oil temperature indicators switch settings
9. Calibration of winding temperature indicators of the transformer
10. Calibration of winding temperature indicators switch settings
11. Dielectric breakdown test of the insulating oil (at field)
12. Main tank Buchholz relay test
13. Transformer pressure relief valve test
14. Insulation resistance test
15. General Inspection and Checks which include: cleaning the bushings, checking or replacing silica gel, checking any oil leakage, checking fans and pumps motors, checking the control circuits, and others where applicable.

Part 2: On Load Tap Changer (OLTC) Tests

The following tests and inspections were considered:

1. Transformer Turns ratio test (TTR test)
2. Excitation test
3. Resistor test
4. Continuity test
5. Oil quality test
6. Dielectric test of insulating oil
7. General Inspection and Checks which include: checking drive mechanism, interlock, tap changer Buchholz relay check, tap changer pressure relief valve check, tap changer limit switch, mechanical stops positions, breaking contactors, overrun blocking, auto test of tap changer, tap position indicator, electric continuity and hardware, and others where applicable.

Part 3: Circuit Breaker Tests - 13.8kV

The following tests and inspections were considered:

1. Timing test
2. Contact resistance Ductor test
3. Doble power factor test
4. Oil quality test
5. Megger test
6. Dielectric test of insulating oil
7. Checking the pressure/moisture/Oxygen for SF_6

8. Hi-pot test
9. General Inspection and Checks which include: checking leakages, inspecting the mechanism, operation and tripping, inspecting the motor, pump, compressor, operation of contacts, operation of auxiliary contacts, checking the pressure, electrical functional test for ground switches, mechanical check for ground switches, other tests and checks where applicable.

Part 4: Circuit Breaker Tests - 69kV

The following tests and inspections were considered:

1. Timing test
2. Contact resistance Ductor test
3. Doble power factor test
4. Oil quality test
5. Purity test
6. Moisture content test (Dewpoint test)
7. Megger test
8. Dielectric test of insulating oil
9. Checking the pressure/moisture/Oxygen for SF_6
10. General Inspection and Checks which include: checking leakage, inspecting the mechanism, operation, inspecting the motor, pump, compressor, checking the pressure, other tests and checks where applicable.

Part 5: Station Service Transformer Tests

The following tests and inspections were considered:

1. Tap changer test (ratio test)
2. Oil quality test
3. Megger test
4. Dielectric test of insulating oil (termination box)
5. General Inspection and Checks which include: inspecting the HV and LV termination boxes, cleaning the bushings and body, inspecting the grounding, checking other accessories where applicable (pressure, level and temperature gauges).

Part 6: Storage Batteries and Battery Chargers Tests

The following tests and inspections were considered:

Storage Batteries Tests

1. Cell voltage test
2. Specific gravity test
3. Battery temperature measurement test
4. Float voltage and current tests
5. Discharge test (capacity test)
6. General Inspection and Checks which include: complete check of the battery room, checking leakages, checking cells terminals, checking terminals torque, and others where applicable.

Battery Chargers Tests

1. Float voltage test
2. Equalize Voltage
3. Float current

Part 7: Disconnect Switch Tests – 69kV

The following tests and inspections were considered:

1. Ductor test (contacts joints)
2. Megger test
3. Hi-pot test
4. General Inspection and Checks which include: checking the insulators, checking open blade angle and open travel stop, checking the adjustment, alignment of blades with contacts, checking manual gear box operation, checking the over toggling in the open and closed positions, cleaning contacts and insulators, checking the hardware, and others where applicable.

Part 8: Ground Switch Tests – 69kV

The following tests and inspections were considered:

1. Ductor test (contacts joints)
2. Megger test
3. General Inspection and Checks which include: checking the insulators, checking open blade angle and open travel stop, checking the adjustment, alignment of blades with contacts, checking manual gear box operation, checking the over toggling in

the open and closed positions, cleaning contacts and insulators, checking the hardware, and others where applicable.

<u>Part 9: Switchgear Busbars Tests</u>

The following tests and inspections were considered:

Switchgear Busbars Tests - 69kV

1. Overall contact resistance Ductor test (at joints)
2. Megger test for each phase
3. General Inspections and Checks which include: complete inspection of busbars, cleaning busbars, and others where applicable.

Switchgear Busbars Tests - 13.8kV

1. Overall contact resistance Ductor test (at joints)
2. Megger test for each phase
3. General Inspection and Checks which include: complete inspection of busbars, cleaning busbars, and others where applicable.

<u>Part 10: Automatic Transfer Switch Tests - 13.8kV</u>

The following tests and inspections were considered:

1. Checking ATS panel
2. Checking operation of changeover switch
3. Checking operation of contactors
4. Checking operation of timer under voltage relay
5. Checking functional test

6. Checking interlock system
7. Checking phasing protection
8. Visual inspection
9. General Inspection and Checks

The survey sample is given in Appendix I.

3.3 Results and Concluding Remarks

As stated above, the survey was not intended to be a comprehensive search in this field, since such one needs a lot of effort, time and support from the electric utilities. The survey is intended to understand the current practices and procedures and give some recommendations for improving the maintenance work in these systems if any. In the following, the survey results and analysis are pointed out:

Part 1: Survey Results of Transformer Tests

The transformer is the most important and expensive equipment in the substation. Transformer tests should be done to maintain it in service and in good condition and in the same time these tests must be justified according to the actual need. The survey results for transformer tests are given in Table 3.1. The key findings of the results are:

- Out of fifteen (15) different tests, eight (8) tests were hundred percent satisfactory. These eight tests represent approximately half of the tests which indicate a clear sign of over maintenance.

- Dielectric breakdown of insulation oil test (23 samples), insulation resistance test (28 samples) and power factor test (21 samples) are all hundred percent satisfactory. These tests must be reconsidered according to actual need and not according to manufacturer recommendations.
- The elimination of only one test – for example the insulating resistance test – this will save (84 working hours × 4 persons = 336 working hours).
- Megger tests (12 samples) were hundred percent satisfactory. This means that the frequency of this test must be reconsidered and studied or even eliminated.
- There are no signs of under maintenance, even for general inspections and checks which were 28.33% not satisfactory. This result is misleading. Most of the encountered problems are considered as non-major ones, like, cleaning bushings, minor oil leaks and changing silica gel.

Part 2: Survey Results of On Load Tap Changer (OLTC) Tests

The results of OLTC tests, given in Table 3.2, show that out of seven (7) different tests, six (6) tests were hundred percent satisfactory of all the samples taken.

- Reconsidering the frequency of these tests may result in a lot of savings. For example, if the frequency of the tests is made as 72×2 = 144 months, this will save 230 working hours × 4 persons = 920 working hours.

Part 3: Survey Results of Circuit Breaker Tests - 13.8kV

In the same manner, the survey results for 13.8kV circuit breaker tests, given in Table 3.3, show a strong need for reconsideration.

- Six out of nine tests were hundred percent satisfactory.
- Megger tests (604 samples, 1208 working hours) do not indicate any problems. Reconsidering the frequency of these tests will save a lot.
- Most of the encountered problems were in the general inspections and checks (14.91%) which means that they must be emphasized and considered.

Part 4: Survey Results of Circuit Breaker Tests - 69kV

The survey results, given in Table 3.4, show the following:

- Six out of ten tests were hundred percent satisfactory.
- Megger test (135 samples, 405 working hours) do not indicate any problems.
- Most of the encountered problems were in the general inspections and checks (11.55%) and pressure checking (7.14%).

Part 5: Survey Results of Station Service Transformer Tests

The survey results, given in Table 3.5, show the following:

- Oil quality test shows 21.36% of the tests were not satisfactory. The ratio test shows 11.11% of results were not satisfactory. These results are considered high (under maintenance).
- Megger test results show, as always the case, hundred percent satisfaction. Hence, the test must be reconsidered.

Part 6: Survey Results of Storage Batteries and Battery Chargers Tests

The results are given in Tables 3.6a and 3.6b:

- The most encountered problems were low electrolyte level and some damaged cells (11.92% of general inspection and checks).
- Also, for the battery chargers tests, equalizing the voltage was 14.28% not satisfactory. This is a part of the general inspection and checks.
- The general inspection and checks must be given higher priority. For the rest of other tests, over maintenance is clear. Hence, complete reconsideration of these tests is needed.

Part 7: Survey Results of Disconnect Switch Tests – 69kV

The survey results, given in Table 3.7, show:

- Almost no problems (minimum 97.36% satisfaction) which is a sign of over maintenance.
- These tests must be reconsidered according to actual needs.

Part 8: Survey Results of Ground Switch Tests – 69kV

The survey results, given in Table 3.8, show:

- Complete, hundred percent, full satisfaction which is a clear sign of over maintenance.
- The survey strongly recommend reconsidering or eliminating some of these tests which shall save a lot.

Part 9: Survey Results of Switchgear Busbars Tests – 69kV and 13.8kV

The survey results given in Tables 3.9a and 3.9b show:

- Almost no problems (minimum 99.52% satisfaction). This indicate a great saving area.
- The survey strongly recommend reconsidering or eliminating some of these tests.

Part 10: Survey Results of Automatic Transfer Switch Tests - 13.8kV

Unfortunately, the number of data samples in this part as shown in Table 3.10 were not enough to draw any conclusion regarding the tests applied. For this reason this part is canceled.

Table 3.1: Survey Results of Transformer Tests

	Transformer Tests - 25-40MVA - 69/13.8kV	Duration of test (h)	Frequency of test (months)	Number of data samples	How many time it was? OK #	OK %	OK h	Not OK #	Not OK %	Not OK h
1.	Oil quality test	Lab	12 to 42	189	180	95.24	540	9	4.76	27
2.	Overall power factor test	4	72	4	4	100	16	0	0	0
3.	Megger test	2	72	12	12	100	24	0	0	0
4.	Excitation currents test	2	72	1	1	100	2	0	0	0
5.	Power factor test to bushings	2	72	21	21	100	42	0	0	0
6.	Dissolved gas in oil analysis test (DGA test)	Lab	12 to 24	70	62	88.57	186	8	11.43	24
7.	Calibration of oil temperature indicators of the transformer	3	24	35	34	97.14	102	1	2.86	3
8.	Calibration of oil temperature indicators switch settings	3	24	29	29	100	87	0	0	0
9.	Calibration of winding temperature indicators of the transformer	3	24	35	32	91.43	96	3	8.57	9
10.	Calibration of winding temperature indicators switch settings	3	24	28	28	100	84	0	0	0
11.	Dielectric breakdown test of the insulating oil (at field)	1	72	23	23	100	23	0	0	0
12.	Main tank Buchholz relay test	2	72	1	0	0	0	1	100	2
13.	Transformer pressure relief valve test	1 to 8	72	-	-	-	-	-	-	-
14.	Insulation resistance - polarization index test	3	72	28	28	100	84	0	0	0
15.	General Inspections/Checks	-	-	120	86	71.67		34	28.33	
	Most problems are:	• Oil leaks • Changing of silica gel • Cleaning of bushings								

Table 3.2: Survey Results of On Load Tap Changer Tests

	OLTC Tests - 69kV	Duration of test (h)	Frequency of test (months)	Number of data samples	How many time it was?					
					OK			Not OK		
					#	%	h	#	%	h
1.	Transformer Turns ratio test (TTR test)	4	72	48	48	100	192	0	0	0
2.	Excitation test	2	72	24	24	100	48	0	0	0
3.	Resistor test	2	72	26	26	100	52	0	0	0
4.	Continuity test	2	72	26	26	100	52	0	0	0
5.	Quality oil test	2	72	30	30	100	60	0	0	0
6.	Dielectric test of insulating oil	2	72	28	28	100	56	0	0	0
7.	General Inspections/Checks	-	-	34	32	94.11	-	2	5.88	-

Table 3.3: Survey Results of Circuit Breaker Tests - 13.8kV

	Circuit Breakers Tests - 13.8kV	Duration of test (h)	Frequency of test (months)	Number of data samples	How many time it was?					
					OK			Not OK		
					#	%	h	#	%	h
1.	Timing test	1	48 to 72	523	523	100	523	0	0	0
2.	Contact resistance Ductor test	1	48 to 72	602	602	100	602	0	0	0
3.	Doble power factor test	3	48 to 72	-	-	-	-	-	-	-
4.	Oil quality test	Lab	48 to 72	4	4	100	8	0	0	0
5.	Megger test	2	48 to 72	604	604	100	1208	0	0	0
6.	Dielectric test of insulating oil	2	48 to 72	-	-	-	-	-	-	-
7.	Checking the pressure/moisture/ Oxygen for SF_6	2	48 to 72	50	50	100	100	0	0	0
8.	Hi-pot test	-	-	48	48	100	-	0	0	-
9.	General inspections/Checks	-	-	684	582	85.1	-	102	14.9	-
	Most problems are:	• Minor oil leaks • Compressor oil • Mechanism • Contacts • Lubrications								

Table 3.4: Survey Results of Circuit Breaker Tests - 69kV

	Circuit Breakers Tests - 69kV	Duration of test (h)	Frequency of test (months)	Number of data samples	How many time it was?					
					OK			Not OK		
					#	%	h	#	%	h
1.	Timing test	1	48 to 72	186	186	100	186	0	0	0
2.	Contact resistance Ductor test	1	48 to 72	208	208	100	208	0	0	0
3.	Doble power factor test	2	48 to 72	-	-	-	-	-	-	-
4.	Oil quality test	Lab	48 to 72	14	14	100	28	0	0	0
5.	Purity test	2	48 to 72	73	73	100	146	0	0	0
6.	Moisture content test (Dewpoint test)	2	48 to 72	4	4	100	8	0	0	0
7.	Megger test	3	48 to 72	135	135	100	405	0	0	0
8.	Dielectric test of insulating oil	2	48 to 72	104	103	99.1	206	1	0.96	2
9.	Checking the pressure/moisture/ Oxygen for SF_6	2	48 to 72	56	52	92.8	104	4	7.14	8
10.	General inspections/Checks	-	-	251	222	88.4	-	29	11.55	-
	Most problems are:	• Oil leaks • Mechanism • Contacts • Lubrications								

Table 3.5: Survey Results of Station Service Transformer Tests

	- 200-500kVA - 13.8kV/380V	Duration of test (h)	Frequency of test (months)	Number of data samples	How many time it was?					
					OK			Not OK		
					#	%	h	#	%	h
1.	Tap changer test (ratio test)	2	24	27	24	88.88	48	3	11.11	6
2.	Quality oil test	Lab	24	117	92	78.63	184	25	21.36	50
3.	Megger test	2	24	33	33	100	66	0	0	0
4.	Dielectric test of insulating oil (termination box)	1	24	2	2	100	2	0	0	0
5.	General inspections/Checks	-	-	45	41	91.11	-	4	8.88	-

Table 3.6a: Survey Results of Storage Batteries Tests

	Storage Batteries Tests - 110-125V DC	Duration of test (h)	Frequency of test (months)	Number of data samples	How many time it was?					
					OK			Not OK		
					#	%	h	#	%	h
1.	Cell voltage test	1	-	657	649	98.78	649	8	1.21	8
2.	Specific gravity test	1	-	320	318	99.37	318	2	0.62	2
3.	Battery temperature measurement test	1	-	165	165	100	165	0	0	0
4.	Float voltage and current tests	0.5	-	414	411	99.27	205.5	3	0.72	1.5
5.	Discharge test (capacity test)	4	-	80	79	98.75	316	1	1.25	4
6.	General inspections/Checks	-	-	654	576	88.07	-	78	11.92	-
	Most problems are:	• Low electrolyte level • Some cells are damaged								

Table 3.6b: Survey Results of Battery Chargers Tests

	Battery Chargers Tests - 110-125V DC	Duration of test (h)	Frequency of test (months)	Number of data samples	How many time it was?					
					OK			Not OK		
					#	%	h	#	%	h
1.	Float voltage test	1	-	256	255	99.60	255	1	0.39	1
2.	Equalize Voltage	1	-	42	36	85.71	36	6	14.28	6
3.	Float current	-	-	210	210	100	-	0	0	-

Table 3.7: Survey Results of Disconnect Switch Tests – 69kV

	Disconnect Switch Tests – 69kV	Duration of test (h)	Frequency of test (months)	Number of data samples	How many time it was?					
					OK			Not OK		
					#	%	h	#	%	h
1.	Ductor test (contacts joints)	1	72	36	36	100	36	0	0	0
2.	Megger test	1	72	36	26	100	36	0	0	0
3.	Hi-pot test	-	-	6	6	100	-	0	0	-
4.	General inspections/Checks	1	72	38	37	97.36	37	1	2.63	1

Table 3.8: Survey Results of Ground Switch Tests - 69kV

	Ground Switch Tests - 69kV	Duration of test (h)	Frequency of test (months)	Number of data samples	How many time it was?					
					OK			Not OK		
					#	%	h	#	%	h
1.	Ductor test (contacts joints)	1	72	49	49	100	49	0	0	0
2.	Megger test	1	72	26	26	100	26	0	0	0
3.	General inspections/Checks	1	72	47	47	100	47	0	0	0

Table 3.9a: Survey Results of Switchgear Busbars Tests - 13.8kV

	Switchgear Busbars Tests - 13.8kV	Duration of test (h)	Frequency of test (months)	Number of data samples	How many time it was?					
					OK			Not OK		
					#	%	h	#	%	h
1.	Overall contact resistance Ductor test (at joints)	2	72	30	30	100	60	0	0	0
2.	Megger test for each phase	2	72	30	30	100	60	0	0	0
3.	General inspections/Checks	-	-	33	33	100	-	0	0	-

Table 3.9b: Survey Results of Switchgear Busbars Tests - 69kV

	Switchgear Busbars Tests - 69kV	Duration of test (h)	Frequency of test (months)	Number of data samples	How many time it was?					
					OK			Not OK		
					#	%	h	#	%	h
1.	Overall contact resistance Ductor test (at joints)	2	72	236	236	100	472	0	0	0
2.	Megger test for each phase	2	72	8	8	100	16	0	0	0
3.	General inspections/Checks	-	-	212	211	99.52	-	1	0.47	-

Table 3.10: Survey Results of Automatic Transfer Switch Tests - 13.8kV

	Automatic Transfer Switch Tests - 13.8kV	Duration of test (h)	Frequency of test (months)	Number of data samples	How many time it was?					
					OK			Not OK		
					#	%	h	#	%	h
1.	Checking ATS panel	-	-	1	1	100	-	0	0	-
2.	Checking operation of changeover switch	-	-	1	1	100	-	0	0	-
3.	Checking operation of contactors	-	-	1	1	100	-	0	0	-
4.	Checking operation of timer under voltage relay	-	-	1	1	100	-	0	0	-
5.	Checking functional test	-	-	1	1	100	-	0	0	-
6.	Checking interlock system	-	-	1	1	100	-	0	0	-
7.	Checking phasing protection	-	-	1	1	100	-	0	0	-
8.	Visual inspection	-	-	1	1	100	-	0	0	-
9.	General inspections and Checks	-	-	1	1	100	-	0	0	-

In the following, some of the key findings out of the survey are pointed out. Also, some observations, noticed during the period of collecting the data, will be mentioned.

- The maintenance program is following a TBPM concept. This type leads, usually, to over maintenance as seen by the results of the survey. Appropriate tests frequency (time intervals) between regularly performed maintenance tasks are important in achieving more reliable performance at a reasonable cost. TBPM is best suited to failures that have a clear wear-out characteristic. Hence, it is recommended to introduce the new concepts of PdM, RCM or a combination of these concepts into the maintenance program.
- Maintenance sheets are not giving specific information about the results of the tests or inspection. It should not be based on technician opinion or judgment. There should be a clear range of accepted results and whether it passes the tests or not.
- Failing should be easy to access or to deal with in the future. The manual filling usually cause wrong filling and misarranging. Filling should be computerized for future analysis and record keeping. The reporting system, as a whole, is poor and doesn't provide the data required to diagnose problems.
- There is no indication of installation of new equipment. There should be a form to be filled to indicate that some equipment has been changed.
- The type and name of the applied tests are not clear and sometimes it is not mentioned.
- The technician should clearly indicate what has he done, the parts used and the time taken for the job.

- Most of equipment maintenance tests seem to have over maintenance due to the fact that they depend on time rather than a condition.
- Spare parts unavailability and delay were noticed, especially for old equipment.
- It is very important to coordinate work between all crews to get the optimal outage plan. Good coordination was implemented and noticed.
- Adjusting the test items: adjusting or even canceling some of test items is necessary and reasonable. Determination of whether or not certain items are necessary and reasonable depends mainly upon the practice and results from the statistics.
- A much wider survey is needed. It should consider all aspects (direct or indirect), like, spare parts cost, labor cost and loss of power to customers due to outages. Such a survey will give insight view of the maintenance programs. Based on these results, the maintenance frequency may change (increase or decrease) to reach the optimal maintenance plan.

CHAPTER FOUR

PROBLEM FORMULATION: MAINTENANCE OUTAGE TASKS SCHEDULING

This Chapter presents the problem formulation of the maintenance outage tasks scheduling.

4.1 Introduction

The growing complexity in power systems, as well as, the need for high service reliability and low production and O&M costs, are putting additional interests in automatic scheduling techniques for maintenance of generation, transmission, distribution and related equipment, capable of providing the optimal maintenance schedules [10].

Power systems consist of facilities such as transmission lines, transformers, buses and power stations. These systems must be inspected regularly for maintenance work by the utility operators. Maintenance outages work scheduling, in a central load-dispatching center, is a task to coordinate outage work starting dates while power system reliability is maintained. This scheduling is based on the starting dates requests from maintenance centers for all jobs being done [39].

MS problem consists of two main combinatorial optimization sub-problems, work starting date of outages and network configuration. These can be solved by conventional mathematical programming tools but for reasonable small-scale problems. Also, the more we formulate the problem in details, the more difficult to obtain solutions since the number of solutions increases exponentially with the dimension of the problem. However, Artificial Intelligent (AI) tools such as *Tabu Search (TS) and Genetic Algorithms (GA)* can provide optimal solutions within reasonable period of time [39,40,41].

Substation MS determines the schedules for PM of the substation equipment over a predetermined period of time (operational planning period). This should be done so that O&M costs are minimized while system, reliability requirements and the maintenance constraints are satisfied.

4.2 Problem Statement

First, scheduling planners, in each local maintenance center (operation centers or divisions), must prepare the maintenance schedules (outage work requests or work orders) for the whole system. Usually they prepare a list of maintenance and repair activities to be carried out during the coming week or month taking care of the optimal reconfiguration of the system to guarantee the continuity of the energy supply to customers [20]. The scheduling planners develop all those details included on the work orders that will result in the job being done with high quality at a minimum cost and at a time compatible with the urgency of the request.

Secondly, local maintenance centers in charge of system maintenance send outage work requests to the central load-dispatching center. Requests are defined with several data:

task identification number, name of outage facilities and location, task duration and the proposed starting date. Upon receipt of the request, the central load-dispatching center starts to study the outages requests by starting load flow calculations and contingency analyses. The dispatchers schedule or reschedule the tasks considering conditions of forecasted demand-supply balance and network constraints. If the maintenance schedule is not possible for any reason, it has to be modified by local maintenance centers by shifting the beginning of some maintenance activities dates or by exchanging some tasks [19,39].

Although we are dealing with two distinct sub-problems, they are not independent at all. To find the solution to one of them, one has to take into account the solution space of the other. Hence, it is appropriate to tackle both simultaneously as one single global optimization problem.

4.3 Problem Constraints

There are two key constraints which the tasks should satisfy: one is the power flow constraints, the other is constraints on work combinations.

Power flow on branches (transmission lines, buses, etc.) are limited in case of a contingency. These limits depend on the power system stability and the rated capacity of the facilities.

Constraints on work combination are the avoidance of outage facility interference, and the requirements that some tasks are not allowed to be done at the same time. For example, if a substation is supplied by two transmission circuits, these circuits must not be maintained at the same time to ensure continuity of supply to the customers. There is a global rule that says no outage pattern is permitted which will split the system into two or more subsystems or shuts down a complete substation [42]. These forbidden work combinations are specified according to the network operations policy for highly reliable supply of power [39,42].

Beside the technical constraints on power flow and work combinations, it may also be necessary to satisfy administrative constraints such as a limitation of available maintenance crews, resource availability and allocation (resource constraints), interchange contracts and specific requirements from maintenance centers [39].

4.4 Objective Function

The main objective of the MS is to reduce costs by finding suitable combinations of maintenance activities. In this problem, the outages are scheduled primarily so as to maximize work progress of tasks in the scheduling period and to minimize deviations of work dates from that is requested by the local maintenance centers. Both of these objectives minimize carry-over work to the next scheduling period [39].

The objective function is defined from this criterion with some scheduling heuristics for work priority and work leveling considerations. The work priority heuristic requires that a task with higher priority is made faster. The work leveling heuristic requires that flatter accumulated tasks are preferred due to the limitation of available maintenance crews [39].

4.5 Mathematical Formulation of the Problem

We define the objective function (4.1) which to be minimized, as follows: [39]

$$E = w_1 * E_1 + w_2 * E_2 + w_3 * E_3 + w_4 * E_{4+} \; w_5 * E_5 + w_6 * E_6 + w_7 * E_7 \qquad (4.1)$$

Subject to the following constraints:

1- Power Flow Constraint:

$PFlow_{Min(i)} \leq pflow_i \leq PFlow_{Max(i)}$

This is a non-linear constraint solved by an iterative technique "Gauss-Seidel iterative technique".

2- Forbidden Work Combinations:

$$\sum_{t=1}^{T} \sum_{i \in FC}^{n} \sum_{j \in FC}^{n} u_i y_{it} u_j y_{jt} = 0$$

Where:

- Number of carry-over tasks (E_1):

$$E_1 = n - \sum_{i=1}^{n} u_i$$

- Work date deviation from requested date (E_2):

$$E_2 = \sum_{i=1}^{n} u_i \left| x_i - x_{0i} \right|$$

- Work priority (E_3):

$$E_3 = \sum_{i=1}^{n} u_i p_i$$

- Variance of number of daily tasks (E_4):

$$E_4 = \sum_{t=1}^{T} \sum_{i=1}^{n} u_i y_{it}^{\;2}$$

E5 = number of overloaded facilities.

$$E_6 = \sum_{i=1}^{m} \left| \frac{pflow_i}{PFlow_i} \right|$$

E_7 = *number of switched facilities.*

Where:

$PFlow_{Min(i)}$, $PFlow_{Max(i)}$	Lower and upper limits of power flow on branch *i*,
$pflow_i$	Power flow of branch *i*,
w_j	Weight of each component,
n	Number of tasks in scheduling period *T*,
$u_i = 1$	If scheduled when constraints are satisfied, otherwise = 0,
x_i, x_{0i}	Scheduled and requested starting date of task *i*,
p_i	Priority number of task *i*, smaller is higher.
	Priority is determined by type of work, voltage level, etc.
$y_{it} = 1$	If facility for task *i* is outed at *t*, otherwise = 0,
FC	Combination of forbidden task *i* and *j*,

$PFlow_i$	Operational power flow limit of branch *i*,
m	Number of overloaded facilities,
T	Scheduling period.

The MS problem will be solved by TS and GA methods.

4.6 AC/DC Load Flow

In general, the choice of a load flow method is a choice between speed and accuracy. For a given degree of accuracy, the speed depends on the size, complexity, configuration of the power system and on the numerical approach chosen.

4.6.1 AC LOAD FLOW

Load flow is an essential tool both for operation and planning analysis. Some of the important applications of load flow studies for system operations are economic dispatch of the generating stations to reduce operating costs, and contingency analysis to maintain reliable services. Some of the important applications of load flow studies for system planning are interchange of power capacity, maintenance outages planning and scheduling and generation adequacy studies [43].

Load flow analysis allows identification of real and reactive power flows, voltage profiles, power factor and any overload at any bus/line in the network. Also, it allows to investigate the performance of the network under varied of maintenance outage conditions which helps in planning and scheduling of system maintenance.

4.6.1.1 Load Flow Formulation

In the development of any load flow computer calculations, two primary steps are required: [43]

1. Mathematical formulation of load flow problem. This step results in a system of algebraic nonlinear equations. Such equations can be established using the bus or loop power matrices. The mathematical formulation, given by equation 4.2, at a bus, say *i*, is

$$P_i - jQ_i = V_i^* \sum_{n=1}^{N} Y_{in} V_n \tag{4.2}$$

Where

P_i Real power of bus *i*,

Q_i Reactive power of bus *i*,

V_i^* Voltage magnitude of bus *i* (* means conjugate),

Y_{in} Element *(i , n)* of bus admittance matrix (Y_{Bus}),

V_n Voltage magnitude of bus *n*,

N Total number of buses in the network.

2. Application of a numerical method for the solution of the nonlinear equations: This step requires the use of iterative computational techniques because of the nonlinearity involvement in the equations.

4.6.1.2 Gauss-Seidel Iterative Method

The load flow problem is described by equations 4.3 and 4.4. In this method the new calculated voltage V_i^{k+1} immediately replaces V_i^k and is used in the solution of the subsequent equations [43].

$$V_i^{k+1} = \frac{1}{Y_{ii}}\left[\frac{P_i - jQ_i}{\left(V_i^k\right)^*} - \sum_{n=1}^{i-1} Y_{in}V_n^{k+1} - \sum_{n=i+1}^{N} Y_{in}V_n^k\right] \tag{4.3}$$

$$Q_i = -\operatorname{Im}\left[\left(V_i^k\right)^*\sum_{n=1}^{i-1} Y_{in}V_n^{k+1} - \left(V_i^k\right)^*\sum_{n=i}^{N} Y_{in}V_n^k\right] \tag{4.4}$$

Where

V_i^{k+1}	New calculated voltage of bus *i*,
V_i^k	Previous calculated voltage of bus *i*,
Y_{ii}	Diagonal element *(i ,i)* of bus admittance matrix (Y_{Bus}),
Y_{in}	Element *(i , n)* of bus admittance matrix (Y_{Bus}),
k	Iteration count.

In some cases, the rate of convergence of iterative techniques can be increased by applying an acceleration factor, equation 4.5, to the approximate solution obtained from each iteration. A typical range for this factor is 1.4 to 1.6 [43].

$$(V_i^{k+1})_{accelerated} = V_i^k + \alpha \Delta V_i^{k+1} \tag{4.5}$$

Where

α Acceleration factor *(1.4 – 1.6)*.

The line flows (power flows) are calculated using the final bus voltage after the convergence took place. The line flow from bus *i* to bus *n* is given by equation 4.6: [43]

$$Pflow_{in} - jQflow_{in} = V_i^{*}(V_i - V_n)Y_{in} + V_i^{*}V_i\left(\frac{Y_{in}'}{2}\right) \qquad (4.6)$$

Where

$Pflow_{in}$	Real power flow from bus *i* to bus *n*,
$Qflow_{in}$	Reactive power flow from bus *i* to bus *n*,
$Y_{in}'/2$	Line charging of line *i-n*.

4.6.2 DC LOAD FLOW

In certain power system studies, a very large number of load flow runs may be needed. Therefore, a very fast (and not necessary accurate, due to liner approximation involved) method can be used for such studies. The method of calculating the real flows by solving first for the bus angles is known as the DC load flow method, in contrast with the exact nonlinear solution, which is known as the AC load flow method.

In this particular problem, DC load flow was not used due to the inaccurate results obtained. The results obtained were compared with hand calculations (for a small system of 5 buses) and the results were completely different. For this reason, AC load flow method was used in this work and the results obtained were accurate.

CHAPTER FIVE

SOLUTION METHODS:

TABU SEARCH AND GENETIC ALGORITHMS

In this Chapter, the general *Tabu Search and Genetic Algorithms* techniques are presented followed by their implementation details for solving the MS optimization problem.

5.1 General Background - Tabu Search

Tabu search (TS) is an iterative procedure for solving discrete combinatorial optimization problems. It was first suggested by Glover and since then has become increasingly used. It is a meta-heuristic approach designed to find a near-optimal solution for combinatorial optimization problems [44]. Like other traditional search methods, *TS* needs strong domain knowledge in order to utilize the procedure [45].

TS has proven itself to be very useful in providing good solutions for many problems in a reasonable amount of time. Examples of some applications include machine scheduling, employee scheduling, character recognition, telecommunications path assignment, quadratic assignment problems, graph coloring and partitioning problems, traveling salesman problems, etc. [44,45,46].

The most difficult part in applying TS is finding the right *tabu list size*. No single rule gives good sizes for all classes of problems. If the *tabu list size* is too small, the search process may start cycling and if it is too large, the search my be too restrictive. Therefore, an appropriate *tabu list size* has to be determined by noting the occurrence of cycling when the size is too small and the quality of the solution when the size is too large. It is a matter of arriving at the right compromise pending upon the problem being investigated. Several applications of TS that have employed tabu conditions have found the *magic number 7 (± 2)* to be a remarkably good choice for *tabu list size* [44,45,46].

For more comprehensive description of *TS* method, refer to the following references [44,45,47].

5.2 Tabu Search Implementation for Maintenance Scheduling of Outages Tasks

TS method is one of the combinatorial optimization methods and based on an efficient search with local optimum avoidance. With '*tabu list*' of *moves* or states forbidden for a certain number of steps, the search is controlled to avoid cycling, covering a wide solution space and reaching diversified solutions. A basic *move* to a new solution is chosen in the neighborhood space, except for *tabu moves*, even if the new solution is worse than the present solution, refer to Figure 5.1. Therefore the search speed is as fast as for a local search.

The basic steps in *TS* method are as follows [39]:

Step 1: Set initial solution (assumed to be the best solution). *Tabu list* is empty since no moves has been generated.

Step 2: Enumerate candidates (moves) which consist of the present solution's neighborhood, except for *tabu moves*. These *moves* must be in the neighborhood space solution.

Step 3: Move to the best candidate. Add the new *move* attribute to *tabu list* and discard the old *moves* attributes from the *tabu list* if the *tabu list* exceeds the specified length (*tabu list size*).

Step 4: Repeat Steps 2 and 3 until the *termination condition (stopping criteria)* is satisfied.

5.2.1 Search for Optimal Starting Dates

Neighborhood solutions are defined as schedules with the starting date of one task is moved, excluding *tabu* dates.

- Starting date x_i moves from [*1 to (T - working duration of task i + 1)*].
- Order of date changing task is priority from 1 to n (number of tasks).
- If the best neighborhood candidate starts task *i* at x_{1i}, starting date of task *i* changes to x_{1i} in the new solution.
- Then the move attribute *(i,* x_{1i}*)* is added to the tabu list so as to prohibit backtracking to the same state of x_i in certain steps.

In this work, different tabu list sizes were used and tested and seven (7) were used since it gave better performance than others numbers.

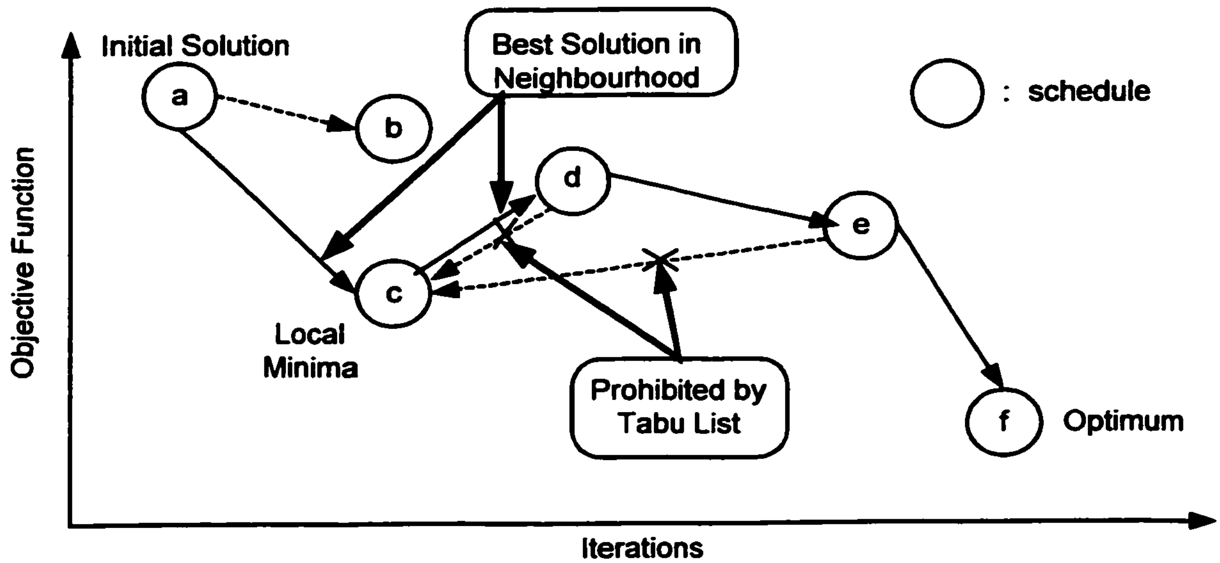

Figure 5.1: Optimization Process Using TS Method

To enhance the performance of computation, the searching process is divided into two steps [39]:

1. The first search step is executed considering constraints on forbidden task combinations. One task *i* is fixed on the schedule and another task *j* is eliminated to remove violation of task combination. Here power flow constraints are not considered and power flows are not calculated, so this solution is obtained fast, but it is a rough one. Figure 5.2 illustrates sample task move for the schedule. If focused on task is *A*, forbidden tasks *B* and *C* move as far as needed to eliminate the constraint violations. Then move attributes *(B,2)* and *(C,8)* are added to the tabu list. In the next step, the focused on task will be *B*, and then *C*, and so on. Again the focused on task returns to *A*.
2. The second search step considers both constraints on power flow and forbidden task combinations, while the initial solution is the best solution from the previous search step. If the network configuration is conditioned to no overload state, and addition of task *i* affects the network and causes overload branches, this constraint violation might be eliminated simply by changing the starting date of task *i*. Therefore neighborhood solutions are generated by moving starting date of task *i*. This is demonstrated in Figure 5.3. If it is found that task *i* on the network is incompatible with both constraints, starting date of task *i* is reset to initial date x_{oi}.

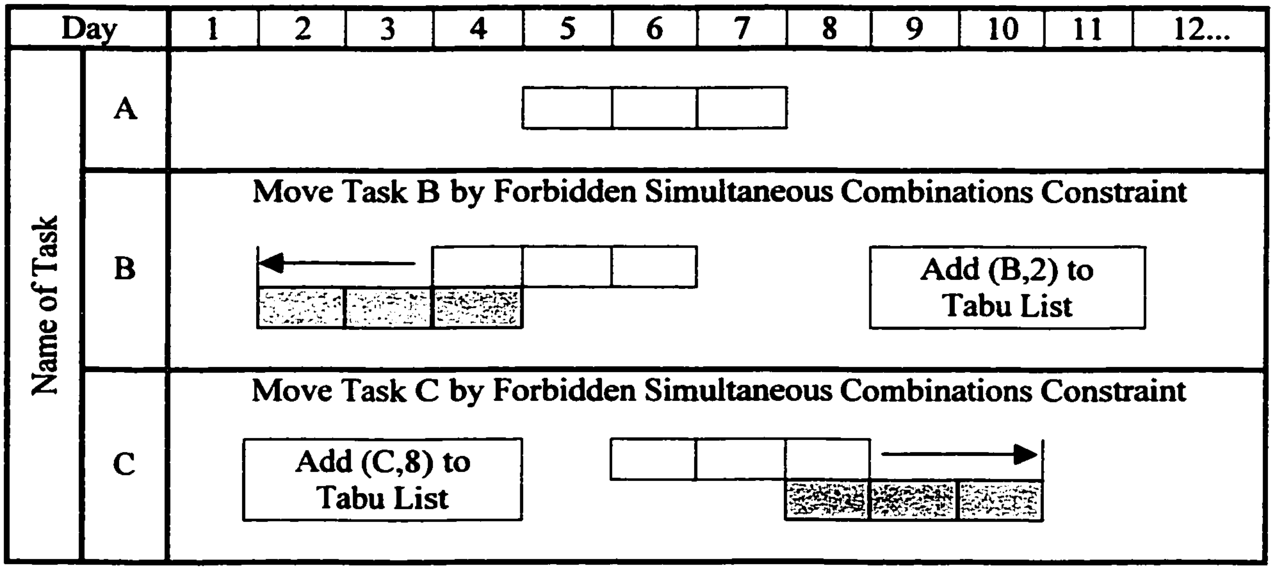

Figure 5.2: Action Against Violation of Prohibited Tasks Combinations Constraint

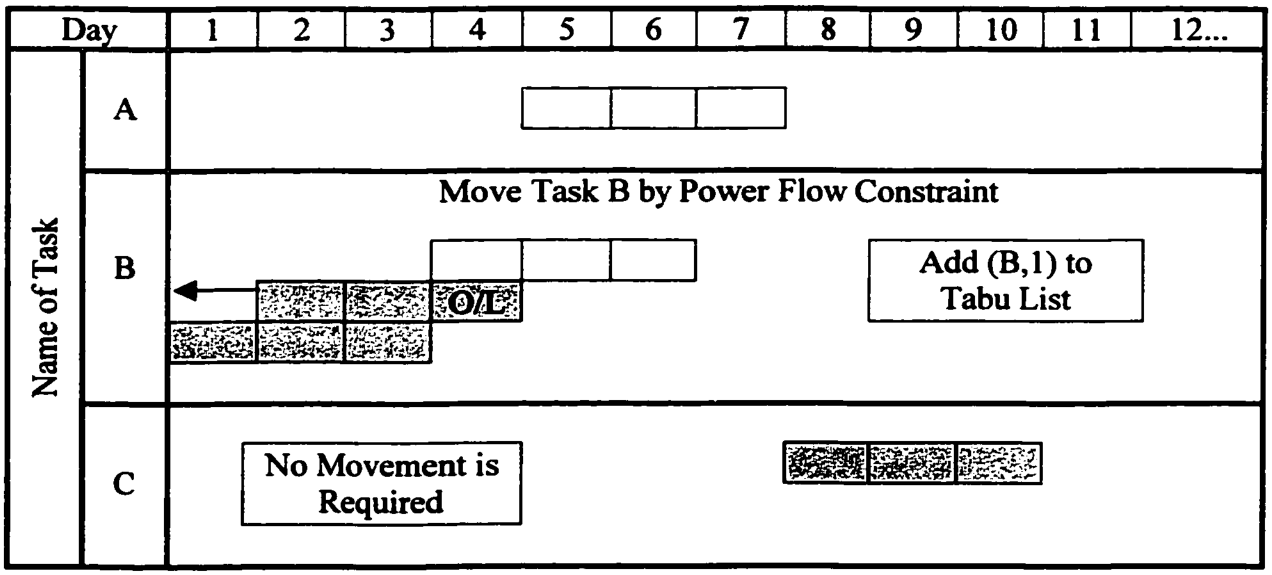

Figure 5.3: Action Against Violation of Power Flow Constraint

5.2.2 Elimination of Power Flow Overload

If the work starting dates are fixed and the incorporation of another task into the network causes an overload, then network reconfiguration, regulation of dispatched power or a change of unit commitment may eliminate this overload [39]. Two possible network reconfiguration methods are visible. One is based on heuristic rules for the network pattern. Rules of this kind are acquired from expert operators in the load dispatch centers which are usually based on the mission of the company or on agreements with customers [39]. The other is based on *TS*. In circuit configuration, neighbor solutions are defined so as to cause the overload branch's power flow to change in the configuration search space in terms of open-and-close circuit breakers, i.e. the close step makes a loop including the overload branch and an open step to cut the loop of circuit configuration. This restriction of neighbor solutions makes the performance of the computation enhanced. The best configuration is selected from the neighbor solutions for each search step even if the objective function to be minimized for overload condition mitigation becomes worse than before [39]. The switched branches are recorded in the *tabu list* to prohibit backtracking and cycling. The objective function for network reconfiguration is as follows:

$$F = w_5*E_5 + w_6*E_6 + w_7*E_7 \qquad (5.1)$$

If there is no overloaded branch, iteration stops and network configuration is determined. If in every iteration an overload exists, the outage task is carried over or the starting date of the task should be moved [39].

Figures 5.4 and 5.5 show examples of reconfiguration [39]. If branch b_a, b_b or b_c is closed in Figure 5.4, the loop with overloaded branch b_e can be made. The neighborhood for closing branch b_a is *(b_a,b_d), (b_a,b_f), (b_a,b_e), (b_a,b_g) and (b_a,b_h) – (as closed, open pairs).* There are other neighborhoods for closing branches b_b or b_c. Then the best configuration of the objective function, equation 5.1, is selected as shown in Figure 5.5. In Figure 5.5 branch b_a is closed and branch b_d is opened. Therefore only a combination of the branch name *(b_a,b_d)* is added to the ***tabu list***. Switching states are only open or closed. It is prohibited by the ***tabu list*** to change branch b_a or b_d state. If this change is not prohibited, further iteration may change b_a and b_d, then the same state combination in which b_a is open and b_d closed, may happen [39]. In some cases, a pair of closed and open branches can't remove the overloading in the system. Therefore, closing one branch only or a pair of closed and closed branches are applied which will form a loop to remove the overloading branche(s).

Regulation of dispatched power or change of unit commitment may also eliminate this overload. If overload on a branch occurs, unit commitment should be changed as new units start up in the flow-in network and units in operation shutdown in the flow-out network. Starting-up and shutdown units are determined by the priority order of the starting-up units, according to generation efficiency. If there are more than two branches which have an overload, the above procedure is applied by the priority of the branch, according to equipment importance [39].

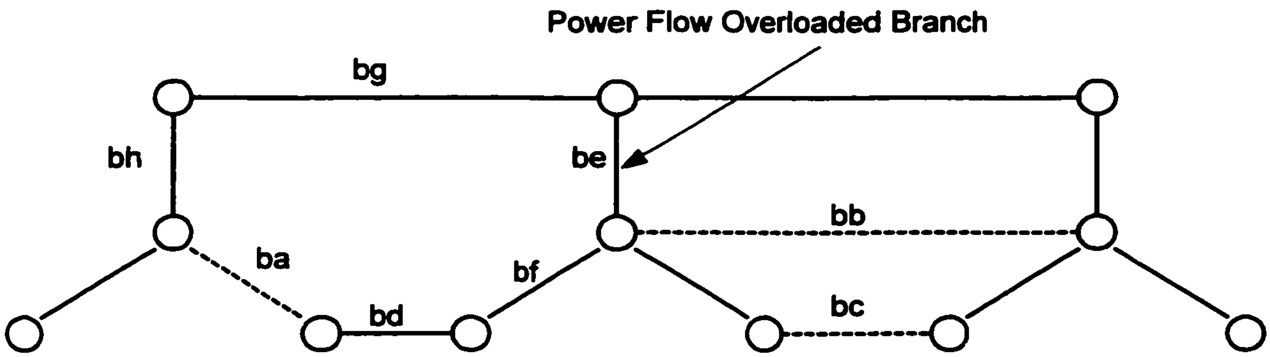

Figure 5.4: Power Flow Constraints Violation in Branch b_e

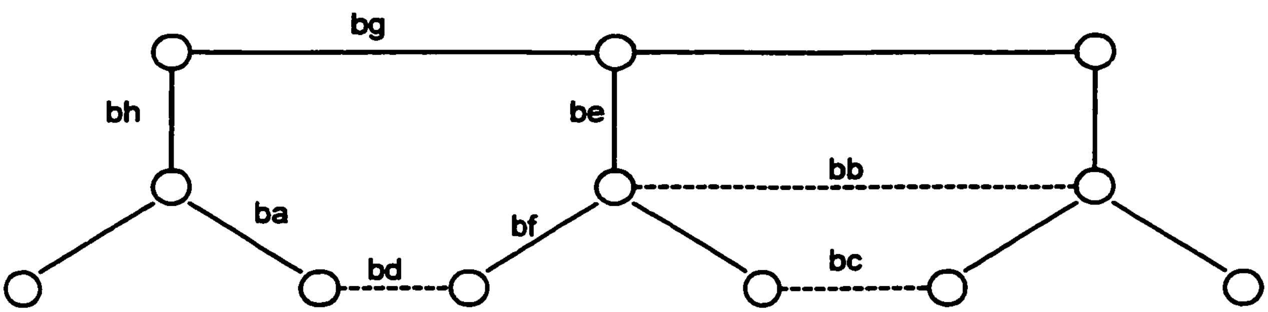

Figure 5.5: Selected Configuration from Neighborhood Solutions

5.2.3 Flowchart and Algorithm Description

Figure 5.6 shows the flowchart of maintenance outages work scheduling, input data for scheduling condition include tasks, requested date, duration and outage facility, dispatched power, etc. is introduced. First, the basic network including power flow values is constructed, and no overload condition is maintained. The automatic scheduling block schedules tasks so as to satisfy all the constraints. This problem consists of date scheduling and network configuration, both of which are combinatorial optimization problems [39].

Algorithm Description

The *TS flowchart* implementation as illustrated in Figure 5.6, is described in the following:

Step	**Description**
1.	Begin: Starting running the *TS* program.
2.	Load System and Scheduling Conditions Input Data: Reading in system data of the network to initialize the base configuration of the system (including buses, lines and generation data) and scheduling problem data (maintenance schedule data – the requested schedule by maintenance centers).
3.	Generate Base Configuration From System Input Data: This step includes building up the admittance matrix of the system which is considered to be the base configuration (original configuration) of the network before incorporating any changes (outages) requested by the maintenance centers.

4. Check The Base Configuration Considering The Overload Constraint: This step is very important to check the base configuration (original configuration of the network) for any overloaded facility/branch using AC load flow.

5. Is There Any Overload?: If there is any overloaded branch obtained by AC load flow go to step 6 otherwise go to step 7.

6. Reconfigure the Base Configuration: In this step the base configuration must be reconfigured to obtain a base configuration without any overloaded branches.

Automatic Scheduling of Maintenance Outages Tasks Using TS

7. Set And Save Initial Requested Schedule (Solution): Saving the initial maintenance outages schedule requested by maintenance centers. This step includes formatting the input data to be used by later steps.

8. Check The Initial Requested Solution For Both Constraints: This includes checking the initial schedule for any overloaded branches (by running AC load flow) or forbidden work combinations. The program gives the following (if any): any overloaded branches and at which day and any forbidden work combination at which day and between which facilities (branches). This step is useful to evaluate the initial requested maintenance schedule and whether it satisfies the constraints or not. Since it may be useful to get the status of the maintenance schedule for emergency cases.

9a. Does The Initial Solution Satisfy Both Constraints?: This step has four possibilities; (a) the initial schedule satisfies FWC constraint only, then go to *TS no. 2* (step 13). (b) the initial schedule satisfies overload constraint only, then go to *TS no. 1* (step 10). (c) the initial schedule satisfies non of constraints, then go to *TS no. 1* (step 10). (d) the initial schedule satisfies both constraints, go to *TS no. 2* (step 13).

9b. Save Initial Solution: Saving the initial maintenance schedule (solution) and its constraints to be used by step 14.

10. *Tabu 1*, Preliminary Scheduling Considering Simultaneous Forbidden Work Constraints: In this TS program, only FWC constraints is considered. Task i is fixed on the schedule and another task j is eliminated to remove the violation of FWC. If FWC is found on the schedule, the program checks which tasks are causing the FWC and which one is with less priority. Then, it moves the original starting date x_{oj} of task j to another date x_{1j} by tabu moves to dissolve the FWC problem and it puts (j, x_{oj}) in the *tabu list*. When a *move* is executed, the objective function and constraints of the new moved dates are calculated. The program stores the best solution. Repeat to resolve all FWC problems. Finally the obtained new solution schedule is ready for the next step. If the FWC can't be resolved reset task j to x_{oj}.

11. Check The Solution For Both Constraints?: This step includes checking the obtained new schedule for all constraints, similar to step 8.

12. Does The Solution Satisfy Both Constraints?: If the new schedule obtained from *TS no. 1* satisfy both constraints then *TS no. 2* (step 13) can be ignored to save time. It is optional, but in this program it is not ignored, in that case proceed to step 14 otherwise go to *TS no. 2*, step 13.

13. *Tabu 2*, Precise Scheduling Considering All Constraints: *TS no. 2* can be considered as the main program. Now, the obtained schedule from *TS no. 1* is to

be checked for overload branches and FWC (both constraints at the same time). The possible measures are moving the staring dates x_i of task i and reconfiguring the system by switching lines. (a) if the initial schedule (original) has no overloads and overload exists in the obtained schedule then moving the starting date x_j of task j "the already moved" to resolve the overload problem if possible (b) if there was an overload, reconfigure the network to resolve the problem (c) if it is found that task j on the network is incompatible with both constraints, starting date x_j is fixed to initial schedule.

14. Best Solution?: This step compares the solution obtained and the initial solution to determine the best solution based on the objective functions and their constraints.
15. Save Best Solution: Saving the best solution for the next step.
16. Check Terminating Condition?: In this step the terminating condition is checked, if it is satisfied then go to step 17 otherwise go to *TS no. 2* step 13.
17. Output Best Solution, Print Maintenance Schedule, Input and Output Data: This step will print the initial schedule, the best solution, the objective functions values, constrains, and all the FWC or overload problems (if any) of both schedules.
18. End/Stop: The end of the program.

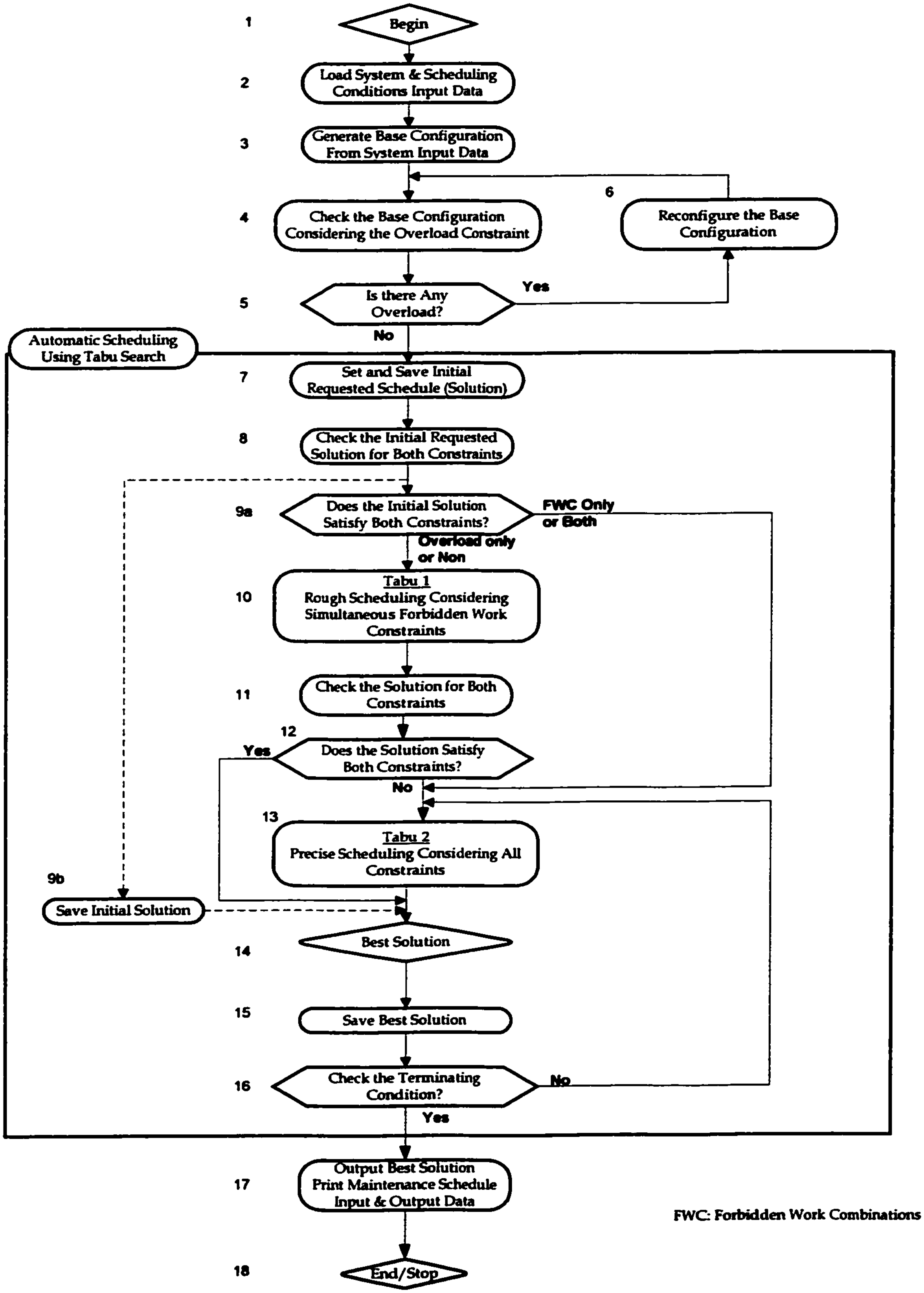

Figure 5.6: Flowchart of Maintenance Scheduling of Outages Using TS

5.3 General Background - Genetic Algorithms

Genetic Algorithms (GA) were invented by Holland in 1975 to mimic some of the processes of natural evolution and selection. In nature, each species needs to adapt to a complicated and changing environment in order to maximize the likelihood of its survival. The knowledge that each species gains is encoded in its chromosomes that undergo transformations when reproduction occurs. Over a period of time, these changes to the chromosomes give rise to species that are more likely to survive, and so have a greater chance of passing on their improved characteristics to future generations. Of course, not all changes will be beneficial but those which are not tend to die out [48].

The range of power system problems to which GA has been applied is broad. GA is often viewed as function optimizers and if each chromosome is considered to represent a point in search space, it is seen that GA differs from traditional techniques in several ways. The benefit is that integer solutions can be obtained by this method leading to immediate applications in operational problems, such as, unit commitment, MS, network reinforcement, etc. [22].

5.3.1 Genetic Algorithms Representation

Each chromosome represents a legal solution to the problem. It is composed of a string of genes, depending on the application, integers or real numbers are used. In fact, almost any representation can be used that enables a solution to be encoded as a finite length string [48]. Once a suitable representation has been decided upon for the chromosomes, it is necessary to create an initial population to serve as the starting point for the GA.

Maintenance outages tasks will be generated by maintenance centers forming the weekly schedules. The weekly maintenance schedules define the important information needed, such as, task identification number, name of outage facilities and location, tasks duration and proposed starting dates. With the application of GA, a proposed schedule can be developed, in which each chromosome is a proposed schedule (solution) in which each gene represents the starting date x_i of a given task i.

In this work, the chromosome is considered as a solution, see Figure 5.7. Its size is equal to the number of tasks n. Each gene represents the start date of a given task i. For example, the first gene value represents the starting date of the first task x_1 and so on.

5.3.2 Genetic Algorithms Operations/Operators

There are some basic elements in implementing GA, such as generation, fitness evaluation, selection, crossover, mutation, etc. These elements are critical in the performance of the GA. In the following, they are briefly described:

Generation

In developing GA, the first step is to create initial individuals (initial population). These individuals are used as the parents to whom the various genetic operators are applied to generate new individuals. The GA typically starts from a randomly generated population of candidate solutions. A population size between 30 to 100 is usually recommended [22].

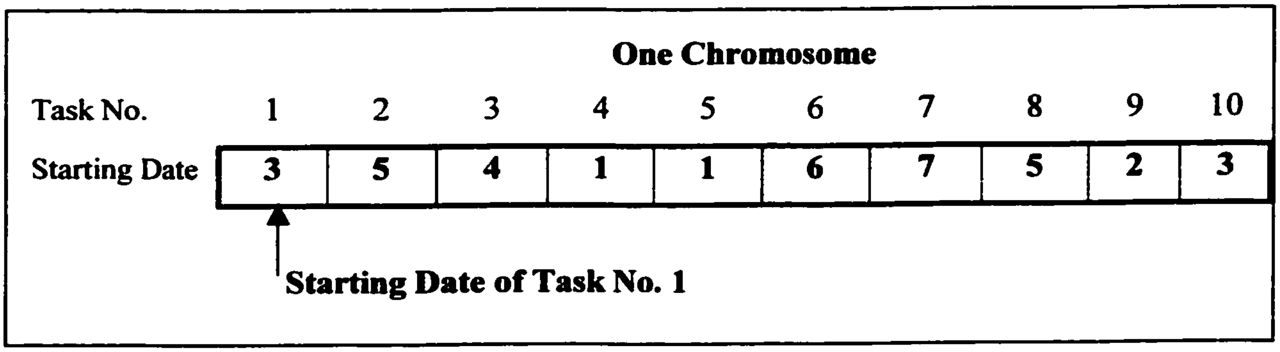

Figure 5.7: Typical Chromosome Representation

In this work, the generation number is 100. The randomly generated population of candidate solutions is not all applicable solutions to the problem because they must satisfy some important conditions. These solutions must be between 1 to 7 (one week), they must be positive (non-negative), they must be integer values. If the generated candidates satisfy these conditions, they are applicable solutions and vice versa. The non-applicable candidates (solutions) are not considered and they must be discarded.

Fitness Evaluation

Fitness evaluation involves defining an objective or fitness function against which each chromosome is tested for suitability for the environment under consideration. As the algorithm proceeds, the fitness of the chromosomes would be calculated [22].

In this work, the objective function is given by equation 4.1. All applicable candidates will be evaluated by the problem objective function.

Selection and Reproduction

Selection decides which individuals survive to make up the next generation. The selection procedure, usually, picks out two parent chromosomes, based on their fitness values, which are then used by the reproduction, crossover and mutation operators to produce offspring for the new population. The lower the fitness value the higher the probability of that chromosome being selected for reproduction [22,49].

In this work, two chromosomes are selected randomly from the population. One is defined for reproduction and the other is defined for replacement. The chromosome would reproduce itself to replace the other one only if its fitness is lower than that of the other one. Otherwise, another two chromosomes are selected till the reproduction process completed.

Crossover

Same as reproduction, two chromosomes are selected randomly. It involves choosing a section of genes in a chromosome. Crossover is performed when this section of one chromosome is swapped with the same section of the other one. In other words, it exchanges the genes within them. There are many variations of this operator, such as one-point, n-points and uniform crossover [49].

Once a pair of chromosomes has been selected, crossover can take place to produce offspring. A crossover probability of 1.0 indicates that all the selected chromosomes are used in reproduction i.e. there are no survivors. However, empirical studies have shown that better results are achieved by a crossover probability rate of between 0.65 and 0.85 [22].

In this work, single point crossover is used. Initially, a random point within the string was selected as the cut point. After some experimentation, it was found that the strategy of ensuring that a cut point within the third to the fifth gene gives better results. Dual-point crossover was attempted but there was little change in the efficiency compared to single-point crossover. So, single-point crossover was used. Different crossover rates were tested and 0.65 was used.

Mutation

Mutation, as in natural systems, is a very low probability operator and just flips or swapa specific bits. It is a randomized yet structured operator that allows information exchange between points. In most problem, the mutation rate ranges from 0.35 to 0.15 [22].

In this work, mutation is a gene-swapping operator that performs a position-based exchange. That is, one chromosome is selected from the population. Then, it selects two sets (each set consist of three genes) on the chosen chromosome and swaps the genes occupying these positions. Different mutation rates were tested and 0.30 was used. This rate is considered somehow high, however, since genes swapping (no flipping) is used, it is logical.

Termination Condition

The termination condition of GA can be arbitrarily set according to the number of evaluations, the number of generations, population convergence, or optimal value [49]. In this work, the termination condition was used based on solution convergence for consecutive iterations.

These parameters and operators completes one cycle of simple GA. The fitness of each chromosome in the new population is evaluated and the whole procedure is repeated until either an optimal or suitable sub-optimal has been found or the maximum number of generations has been exceeded.

Finding good parameter settings that work for a particular problem is not a trivial task. The critical factors are to determine robust parameter settings for all parameters. For example, if the population is too small, the GA will converge too quickly to a local optimal point and may not find the best solution. On the other hand, too many members in the population result in a long process time.

5.4 Genetic Algorithms Implementation for Maintenance Scheduling of Outages Tasks

Traditional methods of search and optimization are too slow in finding a solution in a very complex search space, even implemented in supercomputers. GA is a robust search method requiring little information to search effectively in a large or poorly understood search space [50].

The basic steps in the GA method for the MS of outages are as follows:

Sept 1: Generate random population (individuals).

Step 2: Evaluate fitness of current population.

Step 3: Select chromosomes, based on fitness, for reproduction.

Step 4: Perform GA operators, such as, crossover and mutation to give new improved population.

Step 5: Repeat steps 2 to 4 until the termination condition (stopping criteria) is satisfied.

5.4.1 Problem Representation

As stated above, a chromosome is a proposed schedule in which each gene represents the start date of a task (x_i). Meaning that each chromosome (string of genes) represents a possible solution, with each sub-string (gene) representing the starting date of a task. The algorithm starts from an initial population generated randomly.

5.4.2 Elimination of Power Flow Overload

If the schedule obtained has overloads, random switching of standby lines is performed to resolve the overload problem. The best configuration is selected from the neighbor solutions for each search step even if the objective function to be minimized, for overload mitigation, becomes worse than before. If there is no overloaded branch, iteration stops and network configuration is determined. The objective function for network reconfiguration is the same as for TS method, for details refer to section 5.2.2.

5.4.3 Flowchart and Algorithm Description

Figure 5.8 shows the flowchart of maintenance outages work scheduling using GA, input data for scheduling condition include tasks, requested date, duration and outage facility, dispatched power, etc. is introduced. First, the basic network including power flow values is constructed, and no overload condition is maintained. The automatic scheduling block schedules tasks so as to satisfy all the constraints.

Algorithm Description

The *GA* flowchart implementation as illustrated in Figure 5.8, is described below:

Step **Description**

1. Begin: Starting running the *GA* program.
2. Load System and Scheduling Conditions Input Data: Reading in system data of the network to initialize the base configuration of the system (including buses, lines and generation data) and scheduling problem data (maintenance schedule data – the requested schedule by maintenance centers).

3. Generate Base Configuration From System Input Data: This step includes building up the admittance matrix of the system which is considered to be the base configuration (original configuration) of the network before incorporating any changes (outages) requested by the maintenance centers.

4. Check The Base Configuration Considering The Overload Constraint: This step is very important to check the base configuration (original configuration of the network) for any overloaded facility/branch using AC load flow.

5. Is There Any Overload?: If there is any overloaded branch obtained by AC load flow, go to step 6, otherwise go to step 7.

6. Reconfigure the Base Configuration: In this step the base configuration must be reconfigured to obtain a base configuration without any overloaded branches.

Automatic Scheduling of Maintenance Outages Tasks Using GA

7. Set And Save Initial Requested Schedule (Solution): Saving the initial maintenance outages schedule requested by maintenance centers. This step includes formatting the input data to be used by later steps.

8. Initialization of GA Parameters (Population Size, Chromosome Length, etc.): This step loads the program with the needed information. It includes population size, chromosome length, iteration number, crossover rate and mutation rate.

9. Generate Initial Random Population: This is the first step in GA, it creates initial individuals (population) which represents possible solutions to the problem. These individuals are to be used by the GA operators to generate new individuals until satisfaction of the problem.

10. Check The Problem Constraints: This includes two steps, the first step is to check the applicability of the chromosomes (individuals) to the problem. For example, if the starting date of a task x_i (duration of thee days) is at day seven, then this chromosome (solution) is not applicable to the problem since day eight and nine are out of the scheduling period. The second is to check the population schedules for any overloaded branches or any forbidden work combinations.

11. Fitness Evaluation of each Individual in Population: The program will evaluate the objective function (fitness function) of each chromosome which represents a solution to the maintenance outages problem. Also, switching of standby lines is performed in this step (if required) to get the complete fitness function of the solutions.

12. Save the Best Individual: The best solution obtained is saved.

13. Check the Terminating Condition Satisfaction?: In this step the terminating condition is checked, it may be set according to the number of evaluations, number of generations, population convergence, or optimal value. If it is satisfied then go to step 18 otherwise go to step 14.

14. Perform GA Operators to Generate New Population by Selection and Reproduction, Crossover and Mutation: Two chromosomes are selected randomly from the population. One is defined for reproduction and the other is defined for replacement. The chromosome would reproduce itself to replace the other one only if its fitness is lower than that of the other one. For crossover, two chromosomes are selected randomly. It involves choosing a section of genes in a chromosome. Single point Crossover is performed when this section of one

chromosome is swapped with the same section of the other one. Mutation is a gene-swapping operator that performs a position-based exchange. That is, one chromosome is selected from the population. Then, it selects two sites on the chosen chromosome and swaps the genes.

15. Replace the Old Population by the New One: The generated new chromosomes from step 14 are used to replace the old population, to repeat the process.

16. Check The Problem Constraints: This includes checking the initial schedule for any overloaded branches by running AC load flow or any forbidden work combinations. This step is used to evaluate the initial requested maintenance schedule and whether it satisfies the constraints or not.

17. Fitness Evaluation of Initial Solution: The program will evaluate the objective function (fitness function) of initial chromosome which represents a solution to the maintenance outages problem.

18. Best Solution?: This step compares the obtained and the initial schedules to determine the best solution.

19. Output Best Solution, Print Maintenance Schedule, Input and Output Data: This step will print the initial schedule, the best solution, the objective function values, constrains, and all the FWC or overload problems (if any) of both schedules.

20. End/Stop: The end of the program.

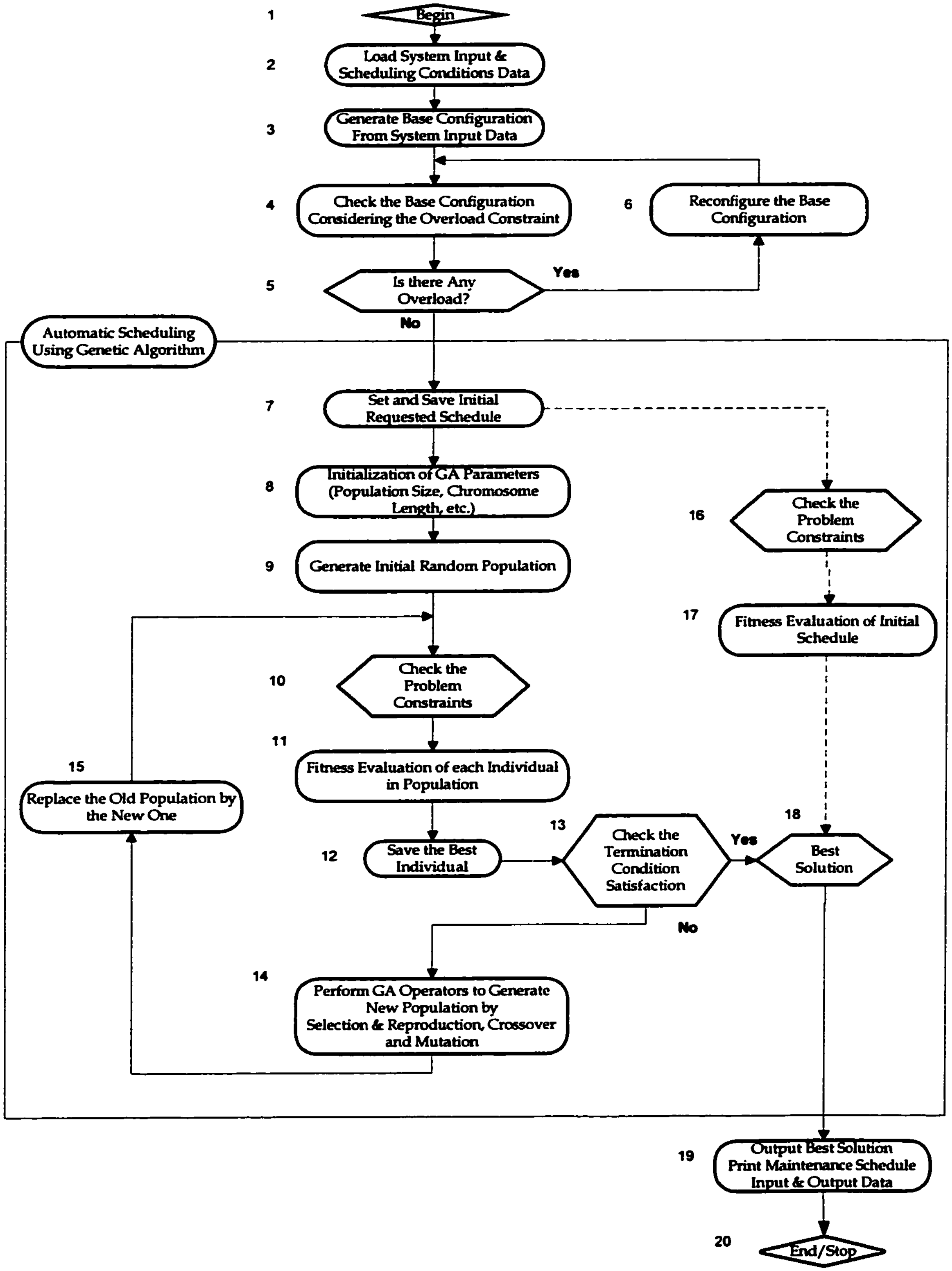

Figure 5.8: Flowchart of Maintenance Scheduling of Outages Using GA

CHAPTER SIX

SIMULATION RESULTS

The algorithms described in Chapter Five will be used to solve the MS problem described in Chapter Four. In this Chapter, the simulation results obtained using the proposed TS and GA methods are presented. The TS and GA were written in the programming language of Matlab® and run on an Intel-Pentium II (333 MHz and 256 RAM) PC.

6.1 5-Bus System

This section will demonstrate the solution obtained for the 5-bus system using the proposed TS algorithm. Although the system is small, it was used to validate the AC load flow and the proposed TS algorithm before applying them to the 25-bus system.

6.1.1 System Description

The 5-bus system, as shown in Figure 6.1, has generation on bus 1 and 2 which supplies the other buses. The line data of this system, the per unit values of the transmission line impedances and line charging admittances are given in Table II.1 in Appendix II. The bus data and the bus voltages in per unit are given in Table II.2 in Appendix II, which are, based on 100MVA and 230kV bases [43].

6.1.2 Automatic Scheduling and Results

In the following, six MS cases will be presented and discussed. These maintenance outage schedules were chosen based on possible outages of the system with the help of human expert maintenance schedulers because such data doesn't exist in the literature.

For the 5-bus system, the maintenance schedules were obtained subject to the following conditions:

- Each schedule has a maximum of six different maintenance tasks (considered as high number of tasks for such a small system).
- No standby lines are available in this system.
- Initial configuration of the system doesn't have any overloaded branch/facility.
- Priority of maintenance outage tasks is given by maintenance schedulers in the initial requested schedule obtained from maintenance centers.
- Branch outage priority depends on the type of work involved. Higher priority in the schedule would preferably be scheduled in the given initial schedule. Priority starts from 1 (highest) to 6 (lowest).
- The duration of each outage depends on the work involved. The duration of each outage is given by the initial requested maintenance schedule.

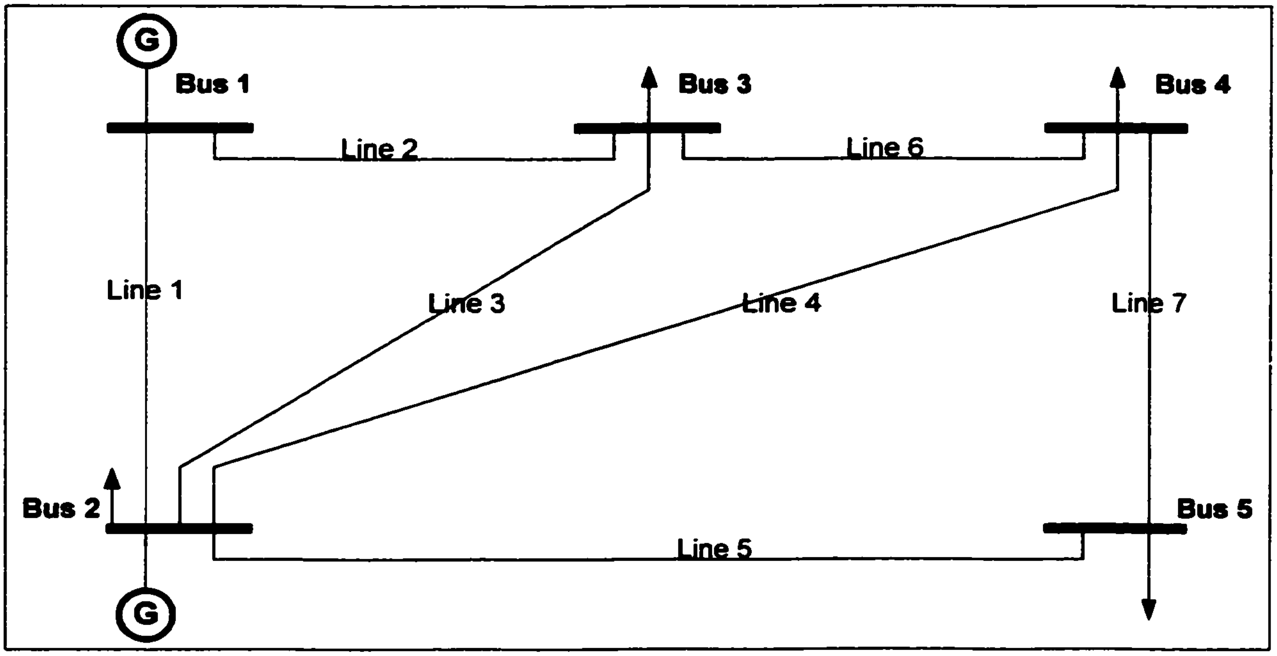

Figure 6.1: The 5-Bus System

- The required manpower depends on the type of work involved in the outage. In this work, manpower is assumed to be available and enough to execute the work (no shortage of manpower).
- Starting date is the starting date of executing the maintenance outage work. This is very important, since, it is used to define the period of the outage.
- Scheduling period (T) is assumed to be one week - seven (7) days.
- Resources (spare parts) are assumed to be available without any delay.
- The maintenance duration given to any equipment is enough to complete the maintenance work.

TS no. 1 was only applied to the 5-bus system, since there are no standby lines in the system. This means that there is no switching of circuit breakers in the system. The system is too small and only FWC constraints are considered in this system.

In each MS case, to follow, there are two schedules. The first one represents the initial maintenance outage schedule requested by local maintenance center. Also, it shows the following when running the TS program:

- The proposed (requested) starting date of each task.
- The priority of each task.
- Any existing FWC problem and between which tasks and in which day(s).
- Any existing overload and in which day(s).

The second schedule is the final output of the program after running TS no. 1. It shows the following:

- The starting date of each task (final).
- Any existing FWC problem and between which tasks and in which day(s).
- Any existing overload and in which day(s).
- The objective function of the maintenance outage schedule.

The proposed TS approach was tested on different cases to verify its effectiveness. In moving a task on the schedule, weighting factors in the objective function were specified as $w_1 > w_2 > w_3 > w_4$. This means a preference order of E_1, E_2, E_3 *and* E_4.

Throughout the application of TS on the 5-bus system, the TS parameters were as given in Table 6.1. These parameters are applicable to all MS cases of the 5-bus system.

Notes: *1.* *The representation of word "line" in the schedules, Tables and text doesn't necessarily means outage of a line. It may mean an outage of bus(es), circuit breaker(s) or transformer(s).*

2. *All program runs of the following cases (1-6) took less than one minuet to get the final solution.*

Table 6.1: Parameters of TS Program for the 5-Bus System

TS Parameters	Starting Dates Movement
TS List Size	7
Total Iteration	500

Maintenance Scheduling Case No. 1:

The maintenance schedule for case no. 1, given in Table 6.2, which is considered as the initial requested schedule by local maintenance centers or maintenance departments. It has five maintenance tasks. Maintenance task no. 1 proposes to maintain line between bus 2 and 3 (line 3) on day 1 (starting date of task no. 1 = day 1 and duration of task no. 1 = 1 day). Maintenance task no. 2 proposes to maintain line 5 on days 2 and 3 (starting date of task no. 2 = day 2 and duration of task no. 2 = 2 days). Maintenance task no. 3 will take line 7 on days 3 and 4. Maintenance task no. 4 will take line 1 on days 5 and 6 and task no. 5 will take line 4 on day 7.

According to the program flowchart of TS given in Chapter Five, the program will generate the base configuration of the system, based on the system input data. This is to make sure that the base configuration doesn't have any overload branch or facility. Also, it will save the given schedule as "the initial requested schedule" and will check for both constraints (FWC and Overload). As stated above, here only FWC constraint is considered. Table 6.2 gives that the maintenance schedule at day 3 has a FWC between tasks 2 and 3 (between lines 5 and 7), since, taking out line 5 and 7 at the same time will separate bus 5 out of the system. Also, it gives that at days 5 and 6, an overload exists in the system. Running TS no. 1 will solve this problem by moving the starting date of task 2 from day 2 to day 1 and no change to task 3 because the priority of task 3 is higher than task 2. The encountered moves to reach the final solution are given in Table 6.3. Table 6.3 gives a close view of the program procedure until reaching the final solution. It is important to note that move no. 2 has a better objective value but it has a FWC. Move no. 1 doesn't have FWC, that become the best solution. FWC may be obvious in small systems but in real systems it will not be that easy to notice them. Table 6.4 is the solution of MS case no. 1.

Maintenance Scheduling Case No. 2:

The maintenance schedule for case no. 2 is given in Table 6.5. This schedule satisfies the FWC constraint. Running the program gives that this schedule doesn't have any problem. It means that the initial requested schedule is the final schedule and no moves of staring dates is required. The final solution is given in Table 6.6.

Maintenance Scheduling Case No. 3:

Maintenance schedule of case no. 3, given in Table 6.7, has six maintenance tasks to be done during the week (7 days). The schedule proposes to maintain line 2 on days 5 and 6, Line 7 on days 3, 4 and 5 (3 days), Line 5 on days 2 and 3, Line 6 on days 1 and 2, Line 1 on day 7 and Line 4 on days 6 and 7. The schedule has a FWC between tasks 2 and 3 on day 3 (between lines 5 and 7). Since task no. 2 has higher priority than task no. 3, task no. 3 should be moved to resolve the FWC problem. The encountered moves to reach the final solution are given in Table 6.8. Table 6.9 shows the final schedule after running the TS program. This solved the problem of the initial requested schedule.

Table 6.2: Initial Requested Maintenance Schedule for the 5-Bus System - Case no. 1

<table>
<tr><th rowspan="2">Tasks</th><th rowspan="2">Priority</th><th colspan="7">Days</th></tr>
<tr><th>1</th><th>2</th><th>3</th><th>4</th><th>5</th><th>6</th><th>7</th></tr>
<tr><td>1</td><td>1</td><td>Line 3</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>2</td><td>3</td><td></td><td colspan="2">Line 5</td><td></td><td></td><td></td><td></td></tr>
<tr><td>3</td><td>2</td><td></td><td></td><td colspan="2">Line 7</td><td></td><td></td><td></td></tr>
<tr><td>4</td><td>4</td><td></td><td></td><td></td><td></td><td colspan="2">Line 1</td><td></td></tr>
<tr><td>5</td><td>5</td><td></td><td></td><td></td><td></td><td></td><td></td><td>Line 4</td></tr>
<tr><td colspan="2">FWC</td><td></td><td></td><td>(5,7)</td><td></td><td></td><td></td><td></td></tr>
<tr><td colspan="2">Overload</td><td></td><td></td><td></td><td></td><td colspan="2">Yes</td><td></td></tr>
</table>

Table 6.3: Encountered Moves of Task no. 2 for Case no. 1

Move #	New Starting Date	Any FWC	Objective Function	
1	1	No	0.278	Best
2	3	Yes	0.178	
3	4	Yes	0.378	
4	5	No	0.478	
5	6	No	0.578	

Table 6.4: Final Schedule of Case no. 1 Obtained by TS Program

<table>
<tr><th rowspan="2">Tasks</th><th rowspan="2">Priority</th><th colspan="7">Days</th></tr>
<tr><th>1</th><th>2</th><th>3</th><th>4</th><th>5</th><th>6</th><th>7</th></tr>
<tr><td>1</td><td>1</td><td>Line 3</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>2</td><td>3</td><td colspan="2">Line 5</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>3</td><td>2</td><td></td><td></td><td colspan="2">Line 7</td><td></td><td></td><td></td></tr>
<tr><td>4</td><td>4</td><td></td><td></td><td></td><td></td><td colspan="2">Line 1</td><td></td></tr>
<tr><td>5</td><td>5</td><td></td><td></td><td></td><td></td><td></td><td></td><td>Line 4</td></tr>
<tr><td colspan="2">FWC</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td colspan="2">Overload</td><td></td><td></td><td></td><td></td><td colspan="2">Yes</td><td></td></tr>
<tr><td colspan="9">Objective Function of TS no. 1 = 0.278</td></tr>
</table>

Table 6.5: Initial Requested Maintenance Schedule for the 5-Bus System - Case no. 2

Tasks	Priority	Days						
		1	2	3	4	5	6	7
1	1	Line 3						
2	3	Line 5						
3	2			Line 7				
4	5					Line 1		
5	4							Line 4
FWC								
Overload						Yes		

Table 6.6: Final Schedule of Case no. 2 Obtained by TS Program

Tasks	Priority	Days						
		1	2	3	4	5	6	7
1	1	Line 3						
2	3	Line 5						
3	2			Line 7				
4	5					Line 1		
5	4							Line 4
FWC								
Overload						Yes		
Objective Function of TS no. 1 = 0.185								

Table 6.7: Initial Requested Maintenance Schedule for the 5-Bus System - Case no. 3

<table>
<tr><th rowspan="2">Tasks</th><th rowspan="2">Priority</th><th colspan="7">Days</th></tr>
<tr><th>1</th><th>2</th><th>3</th><th>4</th><th>5</th><th>6</th><th>7</th></tr>
<tr><td>1</td><td>2</td><td></td><td></td><td></td><td></td><td colspan="2">Line 2</td><td></td></tr>
<tr><td>2</td><td>1</td><td></td><td></td><td colspan="3">Line 7</td><td></td><td></td></tr>
<tr><td>3</td><td>6</td><td></td><td colspan="2">Line 5</td><td></td><td></td><td></td><td></td></tr>
<tr><td>4</td><td>3</td><td colspan="2">Line 6</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>5</td><td>5</td><td></td><td></td><td></td><td></td><td></td><td></td><td>Line 1</td></tr>
<tr><td>6</td><td>4</td><td></td><td></td><td></td><td></td><td></td><td colspan="2">Line 4</td></tr>
<tr><td colspan="2">FWC</td><td></td><td></td><td>(5,7)</td><td></td><td></td><td></td><td></td></tr>
<tr><td colspan="2">Overload</td><td colspan="2">Yes</td><td></td><td></td><td colspan="3">Yes</td></tr>
</table>

Table 6.8: Encountered Moves of Task no. 3 for Case no. 3

Move #	New Starting Date	Any FWC	Objective Function	
1	1	No	0.298	Best
2	3	Yes	0.198	
3	4	Yes	0.398	
4	5	Yes	0.498	
5	6	No	0.598	

Table 6.9: Final Schedule of Case no. 3 Obtained by TS Program

<table>
<tr><th rowspan="2">Tasks</th><th rowspan="2">Priority</th><th colspan="7">Days</th></tr>
<tr><th>1</th><th>2</th><th>3</th><th>4</th><th>5</th><th>6</th><th>7</th></tr>
<tr><td>1</td><td>2</td><td></td><td></td><td></td><td></td><td colspan="2">Line 2</td><td></td></tr>
<tr><td>2</td><td>1</td><td></td><td></td><td colspan="3">Line 7</td><td></td><td></td></tr>
<tr><td>3</td><td>6</td><td colspan="2">Line 5</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>4</td><td>3</td><td colspan="2">Line 6</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>5</td><td>5</td><td></td><td></td><td></td><td></td><td></td><td></td><td>Line 1</td></tr>
<tr><td>6</td><td>4</td><td></td><td></td><td></td><td></td><td></td><td colspan="2">Line 4</td></tr>
<tr><td colspan="2">FWC</td><td colspan="7"></td></tr>
<tr><td colspan="2">Overload</td><td colspan="2">Yes</td><td></td><td></td><td colspan="3">Yes</td></tr>
<tr><td colspan="9">Objective Function of TS no. 1 = 0.298</td></tr>
</table>

Maintenance Scheduling Case No. 4:

The initial requested maintenance schedule of case no. 4 is given in Table 6.10. The schedule has a FWC between tasks 2 and 5 on days 1 and 2. Table 6.11 shows the obtained schedule after running the TS program, which solved the problem of the initial requested schedule.

Maintenance Scheduling Case No. 5:

The initial requested maintenance schedule of case no. 5 is given in Table 6.12. It has a FWC problem at schedule of day 7 between tasks 1 and 5. The proposed schedule by TS program is given in Table 6.13.

Maintenance Scheduling Case No. 6:

The initial maintenance schedule of case no. 6 is given in Table 6.14. It has six tasks to be scheduled on one week. Maintenance schedules at days 1 and 2 have FWC between tasks 2 and 5 and at day 7 between task 1 and 6. Running TS program solved the FWC problems as shown in Table 6.15.

Table 6.10: Initial Requested Maintenance Schedule for the 5-Bus System - Case no. 4

<table>
<tr><th rowspan="2">Tasks</th><th rowspan="2">Priority</th><th colspan="7">Days</th></tr>
<tr><th>1</th><th>2</th><th>3</th><th>4</th><th>5</th><th>6</th><th>7</th></tr>
<tr><td>1</td><td>2</td><td></td><td></td><td></td><td></td><td></td><td></td><td>Line 2</td></tr>
<tr><td>2</td><td>1</td><td colspan="5">Line 5</td><td></td><td></td></tr>
<tr><td>3</td><td>3</td><td></td><td></td><td></td><td colspan="2">Line 3</td><td></td><td></td></tr>
<tr><td>4</td><td>4</td><td colspan="3">Line 6</td><td></td><td></td><td></td><td></td></tr>
<tr><td>5</td><td>5</td><td colspan="2">Line 7</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td colspan="2">FWC</td><td colspan="2">(5,7)</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td colspan="2">Overload</td><td></td><td></td><td>Yes</td><td></td><td></td><td></td><td>Yes</td></tr>
</table>

Table 6.11: Final Schedule of Case no. 4 Obtained by TS Program

<table>
<tr><th rowspan="2">Tasks</th><th rowspan="2">Priority</th><th colspan="7">Days</th></tr>
<tr><th>1</th><th>2</th><th>3</th><th>4</th><th>5</th><th>6</th><th>7</th></tr>
<tr><td>1</td><td>2</td><td></td><td></td><td></td><td></td><td></td><td></td><td>Line 2</td></tr>
<tr><td>2</td><td>1</td><td colspan="5">Line 5</td><td></td><td></td></tr>
<tr><td>3</td><td>3</td><td></td><td></td><td></td><td colspan="2">Line 3</td><td></td><td></td></tr>
<tr><td>4</td><td>4</td><td colspan="3">Line 6</td><td></td><td></td><td></td><td></td></tr>
<tr><td>5</td><td>5</td><td></td><td></td><td></td><td></td><td></td><td colspan="2">Line 7</td></tr>
<tr><td colspan="2">FWC</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td colspan="2">Overload</td><td colspan="3">Yes</td><td></td><td></td><td></td><td>Yes</td></tr>
<tr><td colspan="9">Objective Function of TS no. 1 = 0.678</td></tr>
</table>

Table 6.12: Initial Requested Maintenance Schedule for the 5-Bus System - Case no. 5

Tasks	Priority	Days						
		1	2	3	4	5	6	7
1	2							Line 2
2	3			Line 5				
3	1				Line 3			
4	4		Line 6					
5	5						Line 1	
FWC								(1,2)
Overload			Yes					Yes

Table 6.13: Final Schedule of Case no. 5 Obtained by TS Program

Tasks	Priority	Days						
		1	2	3	4	5	6	7
1	2							Line 2
2	3			Line 5				
3	1				Line 3			
4	4		Line 6					
5	5					Line 1		
FWC								
Overload			Yes				Yes	
Objective Function of TS no. 1 = 0.278								

Table 6.14: Initial Requested Maintenance Schedule for the 5-Bus System - Case no. 6

<table>
<tr><th rowspan="2">Tasks</th><th rowspan="2">Priority</th><th colspan="7">Days</th></tr>
<tr><th>1</th><th>2</th><th>3</th><th>4</th><th>5</th><th>6</th><th>7</th></tr>
<tr><td>1</td><td>1</td><td></td><td></td><td></td><td></td><td></td><td></td><td>Line 2</td></tr>
<tr><td>2</td><td>5</td><td colspan="5">Line 5</td><td></td><td></td></tr>
<tr><td>3</td><td>3</td><td></td><td></td><td></td><td colspan="2">Line 3</td><td></td><td></td></tr>
<tr><td>4</td><td>4</td><td colspan="3">Line 6</td><td></td><td></td><td></td><td></td></tr>
<tr><td>5</td><td>6</td><td colspan="2">Line 7</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>6</td><td>2</td><td></td><td></td><td></td><td></td><td></td><td colspan="2">Line 1</td></tr>
<tr><td colspan="2">FWC</td><td colspan="2">(5,7)</td><td></td><td></td><td></td><td></td><td>(1,2)</td></tr>
<tr><td colspan="2">Overload</td><td></td><td></td><td>Yes</td><td></td><td></td><td colspan="2">Yes</td></tr>
</table>

Table 6.15: Final Schedule of Case no. 6 Obtained by TS Program

<table>
<tr><th rowspan="2">Tasks</th><th rowspan="2">Priority</th><th colspan="7">Days</th></tr>
<tr><th>1</th><th>2</th><th>3</th><th>4</th><th>5</th><th>6</th><th>7</th></tr>
<tr><td>1</td><td>1</td><td></td><td></td><td></td><td></td><td></td><td></td><td>Line 2</td></tr>
<tr><td>2</td><td>5</td><td colspan="5">Line 5</td><td></td><td></td></tr>
<tr><td>3</td><td>3</td><td></td><td></td><td></td><td colspan="2">Line 3</td><td></td><td></td></tr>
<tr><td>4</td><td>4</td><td colspan="3">Line 6</td><td></td><td></td><td></td><td></td></tr>
<tr><td>5</td><td>6</td><td></td><td></td><td></td><td></td><td></td><td colspan="2">Line 7</td></tr>
<tr><td>6</td><td>2</td><td></td><td></td><td></td><td></td><td colspan="2">Line 1</td><td></td></tr>
<tr><td colspan="2">FWC</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td colspan="2">Overload</td><td colspan="3">Yes</td><td></td><td>Yes</td><td></td><td>Yes</td></tr>
<tr><td colspan="9">Objective Function of TS no. 1 = 0.345</td></tr>
</table>

6.2 IEEE 25-Bus System

This section will demonstrate the solution obtained for the IEEE 25-bus system using the proposed TS and GA methods described in Chapter Five.

6.2.1 System Description

The IEEE 25-Bus system is shown in Figure 6.2. The line data is given in Table II.3, the generation capacity data is given in Table II.4, the generation and load data is given in Table II.5 and the standby lines data is given in Table II.6. The system data is given in Appendix II.

6.2.2 Automatic Scheduling and Results – Tabu Search

In the following, six MS cases will be presented and described. These maintenance schedules were chosen based on possible outages of the IEEE 25-Bus system with the help of human expert maintenance schedulers because such data doesn't exist in the literature.

For the IEEE 25-bus system, the maintenance schedules were obtained subject to the following conditions:

- Each schedule has a maximum of ten different maintenance tasks.

- Dotted lines, as showing in the Figure 6.2, represent standby lines in the system.
- Initial configuration of the system doesn't have any overloaded branch/facility.
- Priority of maintenance outage tasks is given by maintenance schedulers in the initial requested schedule obtained from maintenance centers.
- Branch outage priority depends on the type of work involved. Higher priority in the schedule would preferably be scheduled in the given initial schedule. Priority starts from 1 (highest) to 10 (lowest).
- The duration of each outage depends on the work involved. The duration of each outage is given by the initial requested maintenance schedule.
- The required manpower depends on the type of work involved in the outage. In this work, manpower is assumed to be available and enough to execute the work (no shortage of manpower).
- Starting date is the starting date of executing the maintenance outage work. This is very important, since, it is used to define the period of the outage.
- Scheduling period (T) is assumed to be one week - seven (7) days.
- Resources (spare parts) are assumed to be available without any delay.
- The maintenance duration given to any equipment is enough to complete the maintenance work.

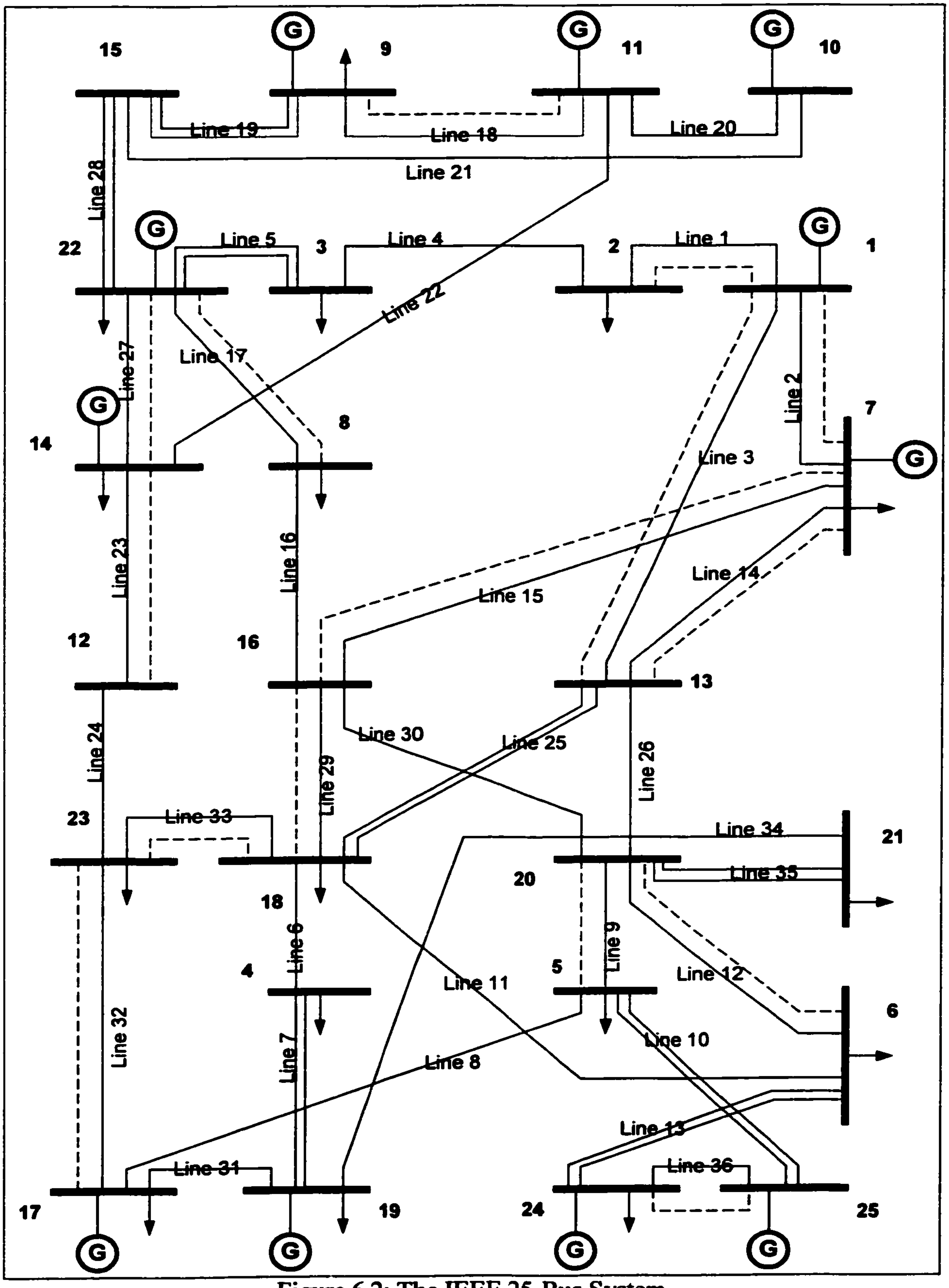

Figure 6.2: The IEEE 25-Bus System

In each MS case to follow, there are three schedules. The first one represents the initial maintenance outage schedule requested by local maintenance centers. Also, it shows the following when running the TS program:

- The proposed (requested) starting date of each task.
- The priority of each task.
- Any existing FWC problem and between which tasks and in which day(s).
- Any existing overload and in which day(s).

The second schedule is the output of the program after running TS no. 1. It shows the following:

- The starting date of each task.
- Any existing FWC problem and between which tasks and in which day(s).
- Any existing overload and in which day(s).
- The objective function of the maintenance outage schedule of TS no. 1 program.

The third schedule is the final output after running the complete program which represents the final solution of the given MS case. It also shows the following:

- The starting date of each task (final).
- Any existing FWC problems and between which tasks and in which day(s).
- The switched standby lines numbers and stages.
- Any existing overload and in which day(s).
- The final objective function for the maintenance outage schedule.

According to the program flowchart, and its description given in Chapter Five, the program will generate the base configuration of the system to make sure that the base configuration doesn't have any overload. Also, it will save the given schedule as "the initial requested schedule" and will check for both constraints (FWC and Overload). The automatic scheduling steps will then start until the final schedule is obtained.

One important stage in the program is the switching stages which is used whenever an overload problem exists. In this work, three (3) switching stages are used, which are described in the following:

1. First switching stage - switching of standby lines which are parallel to the lines that were switched off. This stage will try to remove the overloading in the system by the minimum number of switching operations. If the overloading is removed from the system, the switching stages will stop, otherwise, the second stage will start.
2. Second switching stage - switching of one standby line only: in this stage the TS program will search for the optimal solution to remove overloading by switching one neighbor standby line only. This restriction of neighbor solutions enhanced the performance of the computation process. The best configuration is selected from the neighbor solutions for each search step even if the objective function for the overload condition, becomes worse than before. These switched branches are recorded in the *tabu list* to prohibit backtracking and cycling. If the overloading is removed from the system, the switching stages will stop. If not, the third stage will start.

3. Third switching stage – switching of two standby lines: as in second switching stage, the third stage will proceed in the same manner to overcome the overloading.

The proposed TS approach, as described in Chapter Five, was tested on different cases to verify its effectiveness.

Notes: *1.* *The representation of word "line" in the schedules, Tables and text doesn't necessarily means outage of a line. It may mean an outage of bus(es), circuit breaker(s) or transformer(s).*

2. *All program runs of following cases (1-6) took from 1.0 to 1.5 minuets to get the Final Solution.*

In moving a task on the schedule, weighting factors in the objective function play a major role in getting the optimal solution. It is very important for the TS method to select the proper weighting factors in order to avoid cycling. Based on the sensitivity study of the effects of different values of weighting factors on the final output, weighting factors were seen to be best specified as $w_1 > w_2 > w_3 > w_4$. This means a preference order of E_1, E_2, E_3 and E_4. By this order, the best output values for different cases were obtained.

For switching of standby lines, the weighting factors in the objective function were specified as $w_5 > w_6 > w_7$. This means a preference order of E_5, E_6 and E_7 making lower overload branches preferred. If the number of overload branches is the same for some candidates, the solution with the largest power flow margin to its limit is chosen.

Throughout the application of TS on the IEEE 25-bus system, the TS parameters are as given in Table 6.16. These parameters are applicable for all MS cases of the IEEE 25-bus system given below.

Table 6.16: Parameters of TS Program for the IEEE 25-Bus System

TS Parameters	Starting Dates Movement	Switching of Standby Lines
TS List Size	7	7
Total Iteration	500	100

Maintenance Scheduling Case No. 1:

The proposed maintenance schedule for case no. 1, given in Table 6.17, is considered as the initial requested schedule by local maintenance centers. It has ten (10) maintenance outage tasks. The schedule proposes to maintain line 6 on days 1 and 2, line 14 on days 1, 2 and 3, line 7 on days 2, 3, 4 and 5, line 9 on days 5, 6 and 7 and so on.

According to the program flowchart of TS given in Chapter Five, the program will generate the base configuration of the system. Also, it will save the given schedule as "the initial requested schedule" and will check for both constraints (FWC and Overload). Table 6.17 shows that the schedule at day 2 has a FWC between tasks 1 and 3 (between lines 6 and 7), since, taking out line 6 and 7 at the same time will separate bus 4 out of the system completely. Also, it shows that the schedule has overloaded lines for all days. Running the TS program will satisfy the two constraints in two steps. The first step is done by movements of starting dates. Task no. 3 has higher priority than task no. 1 which will enforce the program to move task no. 1 to resolve the FWC problem. The encountered moves, until reaching the solution, is given in Table 6.18. Table 6.19 gives the output of TS no. 1.

The second step is the switching stage which will remove the overloading in the schedule. The switched standby lines and their order are given in Table 6.20 which is the final solution.

Table 6.17: Initial Requested Maintenance Schedule for the IEEE 25-Bus System - Case no. 1

<table>
<tr><th rowspan="2">Tasks</th><th rowspan="2">Priority</th><th colspan="7">Days</th></tr>
<tr><th>1</th><th>2</th><th>3</th><th>4</th><th>5</th><th>6</th><th>7</th></tr>
<tr><td>1</td><td>3</td><td colspan="2">Line 6</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>2</td><td>2</td><td colspan="3">Line 14</td><td></td><td></td><td></td><td></td></tr>
<tr><td>3</td><td>1</td><td></td><td colspan="4">Line 7</td><td></td><td></td></tr>
<tr><td>4</td><td>4</td><td></td><td></td><td></td><td></td><td colspan="3">Line 9</td></tr>
<tr><td>5</td><td>5</td><td></td><td></td><td></td><td></td><td></td><td colspan="2">Line 27</td></tr>
<tr><td>6</td><td>6</td><td></td><td></td><td colspan="3">Line 34</td><td></td><td></td></tr>
<tr><td>7</td><td>7</td><td></td><td></td><td></td><td></td><td></td><td colspan="2">Line 18</td></tr>
<tr><td>8</td><td>8</td><td></td><td></td><td></td><td></td><td colspan="3">Line 36</td></tr>
<tr><td>9</td><td>9</td><td colspan="4">Line 16</td><td></td><td></td><td></td></tr>
<tr><td>10</td><td>10</td><td></td><td></td><td colspan="2">Line 31</td><td></td><td></td><td></td></tr>
<tr><td colspan="2">FWC</td><td></td><td>(6,7)</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td colspan="2">Overload</td><td colspan="7">Yes</td></tr>
</table>

Table 6.18: Encountered Moves of Task no. 1 for Case no. 1

Move #	New Starting Date	Any FWC	Objective Function	
1	2	Yes	2.669	
2	3	Yes	2.749	
3	4	Yes	2.809	
4	5	Yes	1.956	
5	6	No	1.113	Best

Table 6.19: Schedule of Case no. 1 Obtained by TS no. 1 Program

<table>
<tr><th rowspan="2">Tasks</th><th rowspan="2">Priority</th><th colspan="7">Days</th></tr>
<tr><th>1</th><th>2</th><th>3</th><th>4</th><th>5</th><th>6</th><th>7</th></tr>
<tr><td>1</td><td>3</td><td></td><td></td><td></td><td></td><td></td><td colspan="2">Line 6</td></tr>
<tr><td>2</td><td>2</td><td colspan="3">Line 14</td><td></td><td></td><td></td><td></td></tr>
<tr><td>3</td><td>1</td><td></td><td colspan="4">Line 7</td><td></td><td></td></tr>
<tr><td>4</td><td>4</td><td></td><td></td><td></td><td></td><td colspan="3">Line 9</td></tr>
<tr><td>5</td><td>5</td><td></td><td></td><td></td><td></td><td></td><td colspan="2">Line 27</td></tr>
<tr><td>6</td><td>6</td><td></td><td></td><td colspan="3">Line 34</td><td></td><td></td></tr>
<tr><td>7</td><td>7</td><td></td><td></td><td></td><td></td><td></td><td colspan="2">Line 18</td></tr>
<tr><td>8</td><td>8</td><td></td><td></td><td></td><td></td><td colspan="3">Line 36</td></tr>
<tr><td>9</td><td>9</td><td colspan="4">Line 16</td><td></td><td></td><td></td></tr>
<tr><td>10</td><td>10</td><td></td><td></td><td colspan="2">Line 31</td><td></td><td></td><td></td></tr>
<tr><td colspan="2">FWC</td><td colspan="7"></td></tr>
<tr><td colspan="2">Overload</td><td></td><td colspan="6">Yes</td></tr>
<tr><td colspan="9">Objective Function of TS no. 1 = 1.113</td></tr>
</table>

Table 6.20: Final Schedule of Case no. 1 Obtained by TS Program

<table>
<tr><th rowspan="2" colspan="2">Tasks</th><th rowspan="2">Priority</th><th colspan="7">Days</th></tr>
<tr><th>1</th><th>2</th><th>3</th><th>4</th><th>5</th><th>6</th><th>7</th></tr>
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<tr><td colspan="2">2</td><td>2</td><td colspan="3">Line 14</td><td></td><td></td><td></td><td></td></tr>
<tr><td colspan="2">3</td><td>1</td><td></td><td colspan="4">Line 7</td><td></td><td></td></tr>
<tr><td colspan="2">4</td><td>4</td><td></td><td></td><td></td><td></td><td colspan="3">Line 9</td></tr>
<tr><td colspan="2">5</td><td>5</td><td></td><td></td><td></td><td></td><td></td><td colspan="2">Line 27</td></tr>
<tr><td colspan="2">6</td><td>6</td><td></td><td></td><td colspan="3">Line 34</td><td></td><td></td></tr>
<tr><td colspan="2">7</td><td>7</td><td></td><td></td><td></td><td></td><td></td><td colspan="2">Line 18</td></tr>
<tr><td colspan="2">8</td><td>8</td><td></td><td></td><td></td><td></td><td colspan="3">Line 36</td></tr>
<tr><td colspan="2">9</td><td>9</td><td colspan="4">Line 16</td><td></td><td></td><td></td></tr>
<tr><td colspan="2">10</td><td>10</td><td></td><td></td><td colspan="2">Line 31</td><td></td><td></td><td></td></tr>
<tr><td colspan="3">FWC</td><td colspan="7"></td></tr>
<tr><td rowspan="3">Switched Standby Lines</td><td rowspan="3">Stages</td><td>1</td><td>-</td><td>6</td><td>6</td><td>-</td><td>15,4</td><td>9,11,4</td><td>9,11,4</td></tr>
<tr><td>2</td><td>-</td><td>4</td><td>4</td><td>4</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>3</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td colspan="3">Overload</td><td colspan="7"></td></tr>
<tr><td colspan="10">Final Objective Function of TS Program= 1.686</td></tr>
</table>

Maintenance Scheduling Case No. 2:

The maintenance schedule of case no. 2 is given in Table 6.21. There is a FWC between Task no. 1 and 2 at day 2. Task no. 1 has a higher priority than task no. 3 which means that task no. 3 will be moved to remove the FWC problem. In the same manner as explained for case no. 1, case no. 2 will proceed until the final solutions is obtained by the TS program. Table 6.22 is the output of TS no. 1 and Table 6.23 is the final solution.

Maintenance Scheduling Case No. 3:

The maintenance schedule for case no. 3 is given in Table 6.24. The proposed schedule has a FWC between tasks no. 7 and 8 at day 2 (between lines 10 and 36) and overloading in all days. Since task no. 7 has a higher priority than task no. 8, task no. 8 will be moved by TS program to resolve this problem. The encountered moves are given in Table 6.25. Table 6.25 gives a closed view of the program procedure of movements until reaching the solution. Table 6.26 represents the solution after resolving the FWC problem which was obtained by TS no. 1. Table 6.27 represents the final solution of case no. 3 showing all switching standby lines and their order.

Table 6.21: Initial Requested Maintenance Schedule for the IEEE 25-Bus System - Case no. 2

Tasks	Priority	Days						
		1	2	3	4	5	6	7
1	6	Line 6	Line 6					
2	8	Line 14	Line 14	Line 14				
3	7		Line 7	Line 7	Line 7	Line 7		
4	9					Line 9	Line 9	Line 9
5	10						Line 27	Line 27
6	4			Line 34	Line 34	Line 34		
7	5						Line 18	Line 18
8	2					Line 36	Line 36	Line 36
9	3	Line 16	Line 16	Line 16	Line 16			
10	1			Line 31	Line 31			
FWC			(6,7)					
Overload		Yes	Yes	Yes	Yes	Yes	Yes	Yes

Table 6.22: Schedule of Case no. 2 Obtained by TS no. 1 Program

Tasks	Priority	Days						
		1	2	3	4	5	6	7
1	6	Line 6	Line 6					
2	8	Line 14	Line 14	Line 14				
3	7			Line 7	Line 7	Line 7	Line 7	
4	9					Line 9	Line 9	Line 9
5	10						Line 27	Line 27
6	4			Line 34	Line 34	Line 34		
7	5						Line 18	Line 18
8	2					Line 36	Line 36	Line 36
9	3	Line 16	Line 16	Line 16	Line 16			
10	1			Line 31	Line 31			
FWC								
Overload		Yes	Yes	Yes	Yes	Yes	Yes	Yes
Objective Function of TS no. 1 = 0.7130								

Table 6.23: Final Schedule of Case no. 2 Obtained by TS Program

<table>
<tr><th rowspan="2">Tasks</th><th rowspan="2" colspan="2">Priority</th><th colspan="7">Days</th></tr>
<tr><th>1</th><th>2</th><th>3</th><th>4</th><th>5</th><th>6</th><th>7</th></tr>
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<tr><td>2</td><td colspan="2">8</td><td colspan="3">Line 14</td><td></td><td></td><td></td><td></td></tr>
<tr><td>3</td><td colspan="2">7</td><td></td><td></td><td colspan="4">Line 7</td><td></td></tr>
<tr><td>4</td><td colspan="2">9</td><td></td><td></td><td></td><td></td><td colspan="3">Line 9</td></tr>
<tr><td>5</td><td colspan="2">10</td><td></td><td></td><td></td><td></td><td></td><td colspan="2">Line 27</td></tr>
<tr><td>6</td><td colspan="2">4</td><td></td><td></td><td colspan="3">Line 34</td><td></td><td></td></tr>
<tr><td>7</td><td colspan="2">5</td><td></td><td></td><td></td><td></td><td></td><td colspan="2">Line 18</td></tr>
<tr><td>8</td><td colspan="2">2</td><td></td><td></td><td></td><td></td><td colspan="3">Line 36</td></tr>
<tr><td>9</td><td colspan="2">3</td><td colspan="4">Line 16</td><td></td><td></td><td></td></tr>
<tr><td>10</td><td colspan="2">1</td><td></td><td></td><td colspan="2">Line 31</td><td></td><td></td><td></td></tr>
<tr><td colspan="3">FWC</td><td colspan="7"></td></tr>
<tr><td rowspan="3">Switched Standby Lines</td><td rowspan="3">Stages</td><td>1</td><td>6</td><td>6</td><td>6</td><td>-</td><td>15,4</td><td>9,11,4</td><td>9,11,4</td></tr>
<tr><td>2</td><td>8</td><td>8</td><td>8</td><td>8</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>3</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td colspan="3">Overload</td><td colspan="7"></td></tr>
<tr><td colspan="10">Final Objective Function of TS Program = 1.119</td></tr>
</table>

Table 6.24: Initial Requested Maintenance Schedule for the IEEE 25-Bus System - Case no. 3

<table>
<tr><th rowspan="2">Tasks</th><th rowspan="2">Priority</th><th colspan="7">Days</th></tr>
<tr><th>1</th><th>2</th><th>3</th><th>4</th><th>5</th><th>6</th><th>7</th></tr>
<tr><td>1</td><td>1</td><td></td><td></td><td colspan="3">Line 14</td><td></td><td></td></tr>
<tr><td>2</td><td>9</td><td>Line 18</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
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<tr><td>8</td><td>8</td><td colspan="2">Line 36</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>9</td><td>2</td><td></td><td></td><td colspan="2">Line 33</td><td></td><td></td><td></td></tr>
<tr><td>10</td><td>10</td><td></td><td></td><td></td><td></td><td colspan="3">Line 31</td></tr>
<tr><td colspan="2">FWC</td><td></td><td>(10,36)</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td colspan="2">Overload</td><td colspan="7">Yes</td></tr>
</table>

Table 6.25: Encountered Moves of Task no. 8 for Case no. 3

Move #	New Starting Date	Any FWC	Objective Function	
1	2	Yes	1.956	
2	3	Yes	2.809	
3	4	Yes	2.729	
4	5	Yes	2.649	
5	6	No	1.113	Best

Table 6.26: Schedule of Case no. 3 Obtained by TS no. 1 Program

<table>
<tr><th rowspan="2">Tasks</th><th rowspan="2">Priority</th><th colspan="7">Days</th></tr>
<tr><th>1</th><th>2</th><th>3</th><th>4</th><th>5</th><th>6</th><th>7</th></tr>
<tr><td>1</td><td>1</td><td></td><td></td><td colspan="3">Line 14</td><td></td><td></td></tr>
<tr><td>2</td><td>9</td><td>Line 18</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>3</td><td>3</td><td colspan="3">Line 16</td><td></td><td></td><td></td><td></td></tr>
<tr><td>4</td><td>4</td><td></td><td></td><td colspan="5">Line 35</td></tr>
<tr><td>5</td><td>5</td><td></td><td></td><td></td><td colspan="2">Line 19</td><td></td><td></td></tr>
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<tr><td>7</td><td>7</td><td></td><td colspan="4">Line 10</td><td></td><td></td></tr>
<tr><td>8</td><td>8</td><td></td><td></td><td></td><td></td><td></td><td colspan="2">Line 36</td></tr>
<tr><td>9</td><td>2</td><td></td><td></td><td colspan="2">Line 33</td><td></td><td></td><td></td></tr>
<tr><td>10</td><td>10</td><td></td><td></td><td></td><td></td><td colspan="3">Line 31</td></tr>
<tr><td colspan="2">FWC</td><td colspan="7"></td></tr>
<tr><td colspan="2">Overload</td><td>Yes</td><td></td><td colspan="5">Yes</td></tr>
<tr><td colspan="9">Objective Function of TS no. 1 = 1.113</td></tr>
</table>

Table 6.27: Final Schedule of Case no. 3 Obtained by TS Program

Tasks	Priority	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7
1	1			Line 14	Line 14	Line 14		
2	9	Line 18						
3	3	Line 16	Line 16	Line 16				
4	4			Line 35	Line 35	Line 35	Line 35	Line 35
5	5				Line 19	Line 19		
6	6						Line 20	Line 20
7	7		Line 10	Line 10	Line 10	Line 10		
8	8						Line 36	Line 36
9	2			Line 33	Line 33			
10	10					Line 31	Line 31	Line 31
FWC								
Switched Standby Lines	Stages 1	9	-	6,14	14	6	15	15
	Stages 2	12	-	12		12		
	Stages 3	-	-	-	-	-	10,6	10,6
Overload								
Final Objective Function of TS Program = 1.817								

Maintenance Scheduling Case No. 4:

The initial requested maintenance schedule of case no. 4 is given in Table 6.28. the schedule has no FWC problems but it has overloading in days 1 to 6. Since the proposed schedule has no FWC, no moves of starting dates are required. Therefore, TS no. 1 output, given in Table 6.29 is the same as the initial request schedule given in Table 6.28 since no moves were encountered. The final solution of case no. 4 in given in Table 6.30 which shows all the switched standby lines and their orders to overcome the overloading problems.

Maintenance Scheduling Case No. 5:

The proposed schedule, given in Table 6.31, has FWC problems in days 2 and 3 (between tasks no. 8 and 9) and in days 6 and 7 (between tasks no. 6 and 10). It has also an overloading on days 1 to 5. Based on the priorities of tasks, task no. 9 and 10 will be shifted to remove the FWC problems as shown in Table 6.32. Moving these tasks introduces a new overload in the system in days 6 and 7. The program will try to fix this situation by re-moving the starting date of the already moved tasks. However, task no. 9 can't be moved to other starting date. The starting date, as given in Table 6.32, is maintained and no movements were encountered and switching will be applied. Table 6.33 shows that switching stages that were able to remove this overloading from the system. Table 6.33 is the final solutions of case no. 5.

Maintenance Scheduling Case No. 6:

In the same manner as the previous case, the program will proceed until reaching the final optimal solution. Table 6.34 is the proposed initial schedule. Table 6.35 is the output of TS no. 1 and Table 6.36 is the final solutions of case no. 6.

Table 6.28: Initial Requested Maintenance Schedule for the IEEE 25-Bus System - Case no. 4

<table>
<tr><th rowspan="2">Tasks</th><th rowspan="2">Priority</th><th colspan="7">Days</th></tr>
<tr><th>1</th><th>2</th><th>3</th><th>4</th><th>5</th><th>6</th><th>7</th></tr>
<tr><td>1</td><td>1</td><td colspan="7">Line 1</td></tr>
<tr><td>2</td><td>2</td><td></td><td colspan="3">Line 5</td><td></td><td></td><td></td></tr>
<tr><td>3</td><td>3</td><td colspan="3">Line 23</td><td></td><td></td><td></td><td></td></tr>
<tr><td>4</td><td>4</td><td></td><td></td><td></td><td colspan="4">Line 10</td></tr>
<tr><td>5</td><td>5</td><td></td><td colspan="3">Line 16</td><td></td><td></td><td></td></tr>
<tr><td>6</td><td>6</td><td></td><td></td><td></td><td colspan="3">Line 18</td><td></td></tr>
<tr><td>7</td><td>7</td><td></td><td colspan="4">Line 32</td><td></td><td></td></tr>
<tr><td>8</td><td>8</td><td colspan="2">Line 2</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>9</td><td>9</td><td></td><td></td><td colspan="2">Line 25</td><td></td><td></td><td></td></tr>
<tr><td>10</td><td>10</td><td></td><td></td><td></td><td></td><td colspan="3">Line 34</td></tr>
<tr><td colspan="2">FWC</td><td colspan="7"></td></tr>
<tr><td colspan="2">Overload</td><td colspan="6">Yes</td><td></td></tr>
</table>

Table 6.29: Schedule of Case no. 4 Obtained by TS no. 1 Program

<table>
<tr><th rowspan="2">Tasks</th><th rowspan="2">Priority</th><th colspan="7">Days</th></tr>
<tr><th>1</th><th>2</th><th>3</th><th>4</th><th>5</th><th>6</th><th>7</th></tr>
<tr><td>1</td><td>1</td><td colspan="7">Line 1</td></tr>
<tr><td>2</td><td>2</td><td></td><td colspan="3">Line 5</td><td></td><td></td><td></td></tr>
<tr><td>3</td><td>3</td><td colspan="3">Line 23</td><td></td><td></td><td></td><td></td></tr>
<tr><td>4</td><td>4</td><td></td><td></td><td></td><td colspan="4">Line 10</td></tr>
<tr><td>5</td><td>5</td><td></td><td colspan="3">Line 16</td><td></td><td></td><td></td></tr>
<tr><td>6</td><td>6</td><td></td><td></td><td></td><td colspan="3">Line 18</td><td></td></tr>
<tr><td>7</td><td>7</td><td></td><td colspan="4">Line 32</td><td></td><td></td></tr>
<tr><td>8</td><td>8</td><td colspan="2">Line 2</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>9</td><td>9</td><td></td><td></td><td colspan="2">Line 25</td><td></td><td></td><td></td></tr>
<tr><td>10</td><td>10</td><td></td><td></td><td></td><td></td><td colspan="3">Line 34</td></tr>
<tr><td colspan="2">FWC</td><td colspan="7"></td></tr>
<tr><td colspan="2">Overload</td><td colspan="6">Yes</td><td></td></tr>
<tr><td colspan="9">Objective Function of TS no. 1 = 0.620</td></tr>
</table>

Table 6.30: Final Schedule of Case no. 4 Obtained by TS Program

Tasks	Priority	Days 1	2	3	4	5	6	7
1	1	Line 1	Line 1	Line 1	Line 1	Line 1	Line 1	Line 1
2	2		Line 5	Line 5	Line 5			
3	3	Line 23	Line 23	Line 23				
4	4				Line 10	Line 10	Line 10	Line 10
5	5		Line 16	Line 16	Line 16			
6	6				Line 18	Line 18	Line 18	
7	7		Line 32	Line 32	Line 32	Line 32		
8	8	Line 2	Line 2					
9	9			Line 25	Line 25			
10	10					Line 34	Line 34	Line 34
FWC								
Switched Standby Lines, Stages	1	1,10,2	1,10,13,2	1,10,13	1,9,13	1,9,13	1,9	-
	2	-	-	-	-	-	-	-
	3	-	8,2	8,2	8,2	-	-	-
Overload								
Final Objective Function of TS Program = 0.905								

Table 6.31: Initial Requested Maintenance Schedule for the IEEE 25-Bus System - Case no. 5

Tasks	Priority	Days 1	2	3	4	5	6	7
1	1		Line 12	Line 12	Line 12			
2	4				Line 11	Line 11	Line 11	Line 11
3	3	Line 13	Line 13					
4	5		Line 28	Line 28	Line 28			
5	6	Line 32	Line 32	Line 32				
6	2						Line 20	Line 20
7	7				Line 15	Line 15		
8	8		Line 4	Line 4	Line 4			
9	9	Line 1	Line 1	Line 1				
10	10					Line 21	Line 21	Line 21
FWC			(1,4)	(1,4)			(20,21)	(20,21)
Overload		Yes	Yes	Yes	Yes	Yes		

Table 6.32: Schedule of Case no. 5 Obtained by TS no. 1 Program

Tasks	Priority	Days 1	2	3	4	5	6	7
1	1		Line 12	Line 12	Line 12			
2	4				Line 11	Line 11	Line 11	Line 11
3	3	Line 13	Line 13					
4	5		Line 28	Line 28	Line 28			
5	6	Line 32	Line 32	Line 32				
6	2						Line 20	Line 20
7	7				Line 15	Line 15		
8	8		Line 4	Line 4	Line 4			
9	9					Line 1	Line 1	Line 1
10	10			Line 21	Line 21	Line 21		
FWC								
Overload			Yes	Yes	Yes	Yes	Yes	Yes
Objective Function of TS no. 1 = 1.006								

Table 6.33: Final Schedule of Case no. 5 Obtained by TS Program

Tasks	Priority	Days 1	2	3	4	5	6	7
1	1		Line 12	Line 12	Line 12			
2	4				Line 11	Line 11	Line 11	Line 11
3	3	Line 13	Line 13					
4	5		Line 28	Line 28	Line 28			
5	6	Line 32	Line 32	Line 32				
6	2						Line 20	Line 20
7	7				Line 15	Line 15		
8	8		Line 4	Line 4	Line 4			
9	9					Line 1	Line 1	Line 1
10	10			Line 21	Line 21	Line 21		
FWC								
Switched Standby Lines	Stages 1	-	5,13	5,13	5,7	1,7	1	1
	2	-	4	-	-	-	-	-
	3	-	-	2,4	2,4	2,9	9,13	9,13
Overload								
Final Objective Function of TS Program = 1.337								

Table 6.34: Initial Requested Maintenance Schedule for the IEEE 25-Bus System - Case no. 6

<table>
<tr><th rowspan="2">Tasks</th><th rowspan="2">Priority</th><th colspan="7">Days</th></tr>
<tr><th>1</th><th>2</th><th>3</th><th>4</th><th>5</th><th>6</th><th>7</th></tr>
<tr><td>1</td><td>1</td><td colspan="2">Line 18</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>2</td><td>2</td><td></td><td colspan="2">Line 19</td><td></td><td></td><td></td><td></td></tr>
<tr><td>3</td><td>3</td><td></td><td></td><td></td><td></td><td></td><td colspan="2">Line 26</td></tr>
<tr><td>4</td><td>4</td><td></td><td></td><td></td><td></td><td colspan="2">Line 33</td><td></td></tr>
<tr><td>5</td><td>6</td><td></td><td></td><td></td><td colspan="2">Line 34</td><td></td><td></td></tr>
<tr><td>6</td><td>5</td><td></td><td></td><td colspan="3">Line 35</td><td></td><td></td></tr>
<tr><td>7</td><td>7</td><td colspan="2">Line 10</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>8</td><td>8</td><td colspan="3">Line 3</td><td></td><td></td><td></td><td></td></tr>
<tr><td>9</td><td>9</td><td></td><td></td><td></td><td></td><td></td><td colspan="2">Line 6</td></tr>
<tr><td>10</td><td>10</td><td></td><td></td><td></td><td colspan="3">Line 7</td><td></td></tr>
<tr><td colspan="2">FWC</td><td></td><td>(18,19)</td><td></td><td colspan="2">(34,35)</td><td>(6,7)</td><td></td></tr>
<tr><td colspan="2">Overload</td><td></td><td>Yes</td><td></td><td></td><td></td><td colspan="2">Yes</td></tr>
</table>

Table 6.35: Schedule of Case no. 6 Obtained by TS no. 1 Program

<table>
<tr><th rowspan="2">Tasks</th><th rowspan="2">Priority</th><th colspan="7">Days</th></tr>
<tr><th>1</th><th>2</th><th>3</th><th>4</th><th>5</th><th>6</th><th>7</th></tr>
<tr><td>1</td><td>1</td><td colspan="2">Line 18</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>2</td><td>2</td><td></td><td></td><td colspan="2">Line 19</td><td></td><td></td><td></td></tr>
<tr><td>3</td><td>3</td><td></td><td></td><td></td><td></td><td></td><td colspan="2">Line 26</td></tr>
<tr><td>4</td><td>4</td><td></td><td></td><td></td><td></td><td colspan="2">Line 33</td><td></td></tr>
<tr><td>5</td><td>6</td><td></td><td></td><td></td><td></td><td></td><td colspan="2">Line 34</td></tr>
<tr><td>6</td><td>5</td><td></td><td></td><td colspan="3">Line 35</td><td></td><td></td></tr>
<tr><td>7</td><td>7</td><td colspan="2">Line 10</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>8</td><td>8</td><td colspan="3">Line 3</td><td></td><td></td><td></td><td></td></tr>
<tr><td>9</td><td>9</td><td></td><td></td><td></td><td></td><td></td><td colspan="2">Line 6</td></tr>
<tr><td>10</td><td>10</td><td></td><td></td><td colspan="3">Line 7</td><td></td><td></td></tr>
<tr><td colspan="2">FWC</td><td colspan="7"></td></tr>
<tr><td colspan="2">Overload</td><td></td><td></td><td></td><td></td><td></td><td colspan="2">Yes</td></tr>
<tr><td colspan="9">Objective Function of TS no. 1 = 0.699</td></tr>
</table>

Table 6.36: Final Schedule of Case no. 6 Obtained by TS Program

<table>
<tr><th rowspan="2">Tasks</th><th rowspan="2">Priority</th><th colspan="7">Days</th></tr>
<tr><th>1</th><th>2</th><th>3</th><th>4</th><th>5</th><th>6</th><th>7</th></tr>
<tr><td>1</td><td>1</td><td colspan="2">Line 18</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>2</td><td>2</td><td></td><td></td><td colspan="2">Line 19</td><td></td><td></td><td></td></tr>
<tr><td>3</td><td>3</td><td></td><td></td><td></td><td></td><td></td><td colspan="2">Line 26</td></tr>
<tr><td>4</td><td>4</td><td></td><td></td><td></td><td></td><td colspan="2">Line 33</td><td></td></tr>
<tr><td>5</td><td>6</td><td></td><td></td><td></td><td></td><td></td><td colspan="2">Line 34</td></tr>
<tr><td>6</td><td>5</td><td></td><td></td><td colspan="3">Line 35</td><td></td><td></td></tr>
<tr><td>7</td><td>7</td><td colspan="2">Line 10</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>8</td><td>8</td><td colspan="3">Line 3</td><td></td><td></td><td></td><td></td></tr>
<tr><td>9</td><td>9</td><td></td><td></td><td></td><td></td><td></td><td colspan="2">Line 6</td></tr>
<tr><td>10</td><td>10</td><td></td><td></td><td colspan="3">Line 7</td><td></td><td></td></tr>
<tr><td colspan="2">FWC</td><td colspan="7"></td></tr>
<tr><td rowspan="3">Switched Standby Lines</td><td>Stages 1</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td><td>14</td><td>-</td></tr>
<tr><td>2</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>3</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td><td>1,3</td><td>1,3</td></tr>
<tr><td colspan="2">Overload</td><td colspan="7"></td></tr>
<tr><td colspan="9">Final Objective Function of TS Program = 0.959</td></tr>
</table>

6.2.3 Automatic Scheduling and Results – Genetic Algorithms

In the following, six MS cases will be presented and described. These maintenance schedules were chosen based on possible outages of the IEEE 25-Bus system with the help of human expert maintenance schedulers because such data doesn't exist in the literature.

For the IEEE 25-bus system, the maintenance schedules were obtained subject to the same conditions given in section 6.2.2 of this Chapter.

In each MS case to follow, there are two schedules. The first one represents the initial maintenance outage schedule requested by local maintenance centers. The table, also, shows the following:

- The proposed starting (requested) date of each task.
- Any existing FWC problem and between which tasks and in which day(s).
- Any existing overload and in which day(s).

The second table is the output after running the GA program which represents the final solution of the given MS case. It shows the following:

- The starting date of each task (final).
- Any existing FWC problem and between which tasks and in which day(s).
- The switched standby lines numbers and stages.
- Any existing overload and in which day(s).
- The final objective function for the maintenance outage schedule.

According to the program flowchart and its description given in Chapter Five, the program will generate the base configuration of the system to make sure that the base configuration doesn't have any overload branch or facility. Also, it will save the given schedule as "the initial requested schedule". Then, the automatic scheduling steps will start until the final schedule is obtained as described in Chapter Five.

One important stage in the program is the switching stage which is used whenever an overload exists. In this work, three switching stages are used, which are described in the following:

1. First switching stage - switching standby lines which are parallel to the lines that were switched off. This stage will try to remove the overloading in the system by the minimum number of switching operations. If the overloading is removed from the system, the switching stages will stop, otherwise, the second stage will start.
2. Second switching stage - switching of one standby line only: in this stage the GA program will search for the optimal solution to remove overloading by switching one standby line randomly. If the overloading is removed from the system, the switching stages will stop. If not, the third stage will start.
3. Third switching stage – switching of two standby lines: as in second switching stage, the third stage will proceed in the same manner to overcome the overloading.

Notes: *1.* *The representation of word "line" in the schedules, Tables and text doesn't necessarily means outage of a line. It may mean an outage of bus(es), circuit breaker(s) or transformer(s).*

2. *All program runs of following cases (1-6) took from 2.0 to 3.0 minuets to get the Final Solution.*

3. *The initial requested schedules of all cases (1-6) are the same as the ones given in section 6.2.2 "Automatic Scheduling and Results – Tabu Search".*

In moving a task on the schedule, weighting factors in the objective function were specified as $w_1 > w_2 > w_3 > w_4$. This means a preference order of E_1, E_2, E_3 and E_4.

For switching of standby lines, the weighting factors in the objective function were specified as $w_5 > w_6 > w_7$. This means a preference order of E_5, E_6 and E_7 making lower overload branches preferred. If the number of overload branches is the same for some cases, the solution with the largest power flow margin to its limit is chosen.

Throughout the application of GA on the IEEE 25-bus system, the GA parameters are as given in Table 6.37.

Table 6.37: Parameters of GA Program for the IEEE 25-Bus System

GA Parameter	Value
Chromosome Size	10
Population Size	100
Crossover Rate	0.65
Mutation Rate	0.30
Total Iteration	500

Maintenance Scheduling Case No. 1:

The proposed maintenance schedule for case no. 1 is already given in Table 6.17. It is considered as the initial requested schedule by local maintenance centers. It has ten (10) maintenance tasks.

According to the program flowchart of GA given in Chapter Five, the program will generate the base configuration of the system, based on the system input data, to make sure that the base configuration doesn't have any overload branch or facility. Table 6.17 shows that at day 2 there is a FWC between tasks 1 and 3 (between lines 6 and 7), since, taking out line 6 and 7 at the same time will separate bus 4 out of the system completely. Also, it gives that all schedule days have overload. The GA program will first generate the initial population which represents possible solutions (schedules) to the problem. Then the individuals will be evaluated according to the fitness function and so on to reach to the final solution which is given in Table 6.38. Table 6.38 shows also the switched standby lines and their order.

Maintenance Scheduling Case No. 2:

Similarly, maintenance schedule of case no. 2, given in Table 6.21, will proceed until getting the final solution which is given in Table 6.39.

Table 6.38: Final Schedule of Case no. 1 Obtained by GA Program

Tasks	Priority		Days 1	2	3	4	5	6	7
1	3								Line 6
2	2							Line 14	
3	1					Line 7			
4	4						Line 9		
5	5						Line 27		
6	6			Line 34					
7	7					Line 18			
8	8				Line 36				
9	9						Line 16		
10	10							Line 31	
FWC									
Switched Standby Lines	Stages	1	-	15	-	-	-	-	6
		2	-	-	12	1	1	-	-
		3	-	-	-	-	-	1,2	-
Overload									
Final Objective Function = 7.9910									

Table 6.39: Final Schedule of Case no. 2 Obtained by GA Program

Tasks	Priority		Days 1	2	3	4	5	6	7
1	1								Line 6
2	2						Line 14		
3	3				Line 7				
4	4				Line 9				
5	5							Line 27	
6	6					Line 34			
7	7						Line 18		
8	8							Line 36	
9	9			Line 16					
10	10								Line 31
FWC									
Switched Standby Lines	Stages	1	-	4	4	4	15,9,11	15	15
		2	-	-	-	1	-	-	-
		3	-	-	-	-	-	1,2	1,2
Overload									
Final Objective Function = 2.993									

Maintenance Scheduling Case No. 3:

Similarly, schedule of case no. 3 given in Table 6.24 will proceed until getting the final solution which is given in Table 6.40.

Maintenance Scheduling Case No. 4:

Similarly, schedule of case no. 4 given in Table 6.28 will proceed until getting the final solution which is given in Table 6.41.

Maintenance Scheduling Case No. 5:

Similarly, schedule of case no. 5 given in Table 6.31 will proceed until getting the final solution which is given in Table 6.42.

Maintenance Scheduling Case No. 6:

Similarly, schedule of case no. 6 given in Table 6.34 will proceed until getting the final solution which is given in Table 6.43.

Table 6.40: Final Schedule of Case no. 3 Obtained by GA Program

Tasks	Priority	Days 1	2	3	4	5	6	7
1	1				Line 14			
2	2	Line 18						
3	3		Line 16					
4	4					Line 35		
5	5				Line 19			
6	6		Line 20					
7	7		Line 10					
8	8						Line 36	
9	9				Line 33			
10	10		Line 31					
FWC								
Switched Standby Lines Stages	1	9	-	6	6,14	6,14	15	15
	2	1,12	1,15	1,2,15	15	2	-	-
	3	-	-	-	-	-	-	-
Overload								
Final Objective Function = 3.936								

Table 6.41: Final Schedule of Case no. 4 Obtained by GA Program

Tasks	Priority	Days 1	2	3	4	5	6	7
1	1				Line 1			
2	2			Line 5				
3	3		Line 23					
4	4					Line 10		
5	5			Line 16				
6	6						Line 18	
7	7			Line 32				
8	8			Line 2				
9	9		Line 25					
10	10						Line 34	
FWC								
Switched Standby Lines Stages	1	-	1	1	13	1,9,13	1,9	1,9
	2	-	8	8	8	-	-	-
	3	-	-	-	-	-	-	-
Overload								
Final Objective Function = 1.020								

Table 6.42: Final Schedule of Case no. 5 Obtained by GA Program

Tasks	Priority	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7
1	1		Line 12	Line 12	Line 12			
2	2				Line 11	Line 11	Line 11	Line 11
3	3	Line 13	Line 13					
4	4		Line 28	Line 28	Line 28			
5	5	Line 32	Line 32	Line 32				
6	6	Line 20	Line 20					
7	7	Line 15	Line 15					
8	8				Line 4	Line 4	Line 4	
9	9	Line 1	Line 1	Line 1				
10	10					Line 21	Line 21	Line 21
FWC								
Switched Standby Lines Stages	1	7,13	7,13	13	-	-	-	-
	2	-	11	-	-	-	-	-
	3			2,10	10,12	1,2	1,2	1,2
Overload								
Final Objective Function = 2.263								

Table 6.43: Final Schedule of Case no. 6 Obtained by GA Program

Tasks	Priority	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7
1	1			Line 18	Line 18			
2	2	Line 19	Line 19					
3	3	Line 26	Line 26					
4	4			Line 33	Line 33			
5	6				Line 34	Line 34		
6	5	Line 35	Line 35	Line 35				
7	7				Line 10	Line 10		
8	8	Line 3	Line 3	Line 3				
9	9						Line 6	Line 6
10	10			Line 7	Line 7	Line 7		
FWC								
Switched Standby Lines Stages	1	-	-	-	-	-	14	-
	2	1,15	1,15	2,15	2,14	14,15	-	-
	3	-	-	-	-	-	-	-
Overload								
Final Objective Function = 2.383								

6.2.4 Comparison Between the Results Obtained by Tabu Search and Genetic Algorithms

The results obtained both from the application of TS or GA as given in pervious sections of this Chapter show that these tools are practical for the MS problem. The results obtained by TS were obtained faster and better as explained in Table 6.44 and 6.45. This is due to the fact that the GA start from initial random solution making their convergence slower. GA depends largely on the initialization which is controlling the performance of the program and the final solution. Also, GA will need more time to evaluate the fitness function for every individual in the population for every iteration.

Table 6.44 is a general comparison between the two methods and Table 6.45 is a comparison between the results obtained by the two methods in this Chapter. Table 6.45 shows the date deviations between the requested and the obtained schedules.

Generally, scheduling problem is solved by many artificial intelligent techniques but the results show that TS performed well against other algorithms [52].

6.3 Comparison with Published Results

The TS method used in this work was used in similar study conducted by [39]. The constraints considered were the forbidden work combinations and power flow constraints. The test systems used by this work, however, is different than the one used by [39]. They used a portion of real system (Kansai Electric Company, Japan). The obvious difference was in the way of reconfiguration and switching in the network, since, the one used by [39] did not consider the number of switched lines. The results in both was promising showing that this new developed method for automatic scheduling of maintenance outage tasks using TS is a practical MS optimization tool. Since March 1998, the developed system by [39] has been made practical at KEPCO central load dispatching center.

In the same manner, GA was used to improve the system performance of outage scheduling of maintenance tasks in distribution system [22]. The objective function was in terms of cost functions (manpower cost and system cost). The constraints considered were supply continuity and system security, load pattern and outage window. The proposed GA approach was tested on a model network and on outage plan arranged manually by the planning engineer. The obtained results gave a better arrangement than the original one in a fast and efficient way. The difference between this proposed method and the one proposed in this work is that [22] did not consider the switching to resolve the overloaded braches. Also, it did not gave an attention to the starting date requested by the initial maintenance schedule.

Table 6.44: General Comparison Between TS and GA

	TS	GA
Search Space	Needs a strong domain knowledge of the problem for better performance	No need for strong domain knowledge of the problem – good for poorly understood problems
Performance Dependence	Depends on TS parameters (better performance)	Depends largely on initialization and on GA parameters
Time	Less time consuming (faster than GA)	Needs time for fitness evaluation of the population

Table 6.45: Requested Date Deviation for TS and GA Methods

		TS	GA
Requested Date Deviation	**MS Case no. 1**	1	9
	MS Case no. 2	1	6
	MS Case no. 3	1	5
	MS Case no. 4	0	3
	MS Case no. 5	2	3
	MS Case no. 6	3	7
For IEEE 25-Bus System			

6.4 Application Areas

The proposed scheduling tools can be used to support planners and schedulers, through automatic scheduling of substations system maintenance outage tasks, to reach the optimal reliability of the system while performing the required maintenance work.

The proposed techniques can be applied to scheduling of substation maintenance tasks to maximize work progress of tasks in the scheduling period and to minimize deviations of the work dates from that requested. Also, minimizing carry-over work to the next scheduling period by giving attention to scheduling by work priority and work leveling.

CHAPTER SEVEN

CONCLUSIONS AND FUTURE WORK

This Chapter concludes the thesis and highlights some proposed future work related to the concern subject.

7.1 Conclusions and Remarks

An optimization model has been studied and applied for the purpose of scheduling of maintenance outages in transmission and distribution systems. A feature of this model is the ease in which constraints can be formulated. This problem can be solved using dynamic programming, however, the problem will be very large. Accordingly, only practical work starting date problem (one constraint) is too large to be solved by dynamic programming. Therefore, it is preferable to use heuristic techniques to solve the MS optimization problem.

The developed method for automatic scheduling of maintenance outage tasks for transmission and substation systems using TS and GA is systematically applied to reconfiguration of networks and work starting date scheduling. The developed scheduling methods were applied to 5-Bus and 25-Bus test systems for maintenance outage schedules. From the results given in Chapter Six, it is confirmed that the developed methods are useful and practical as scheduling tools.

TS and GA are powerful heuristic optimization techniques. They are easy to implement, may escape local minima and also cope with large-scale problems involving complex constraints. In this thesis, the search strategy has been implemented for scheduling maintenance outages for substations system. The objective, mainly, to maximize works progress of tasks in the scheduling period which minimize the carry-over work to the next scheduling period and minimize deviations of the work date from that requested by the local maintenance centers. A survey, about the current practices of maintenance, was conducted using actual data from an electrical company.

Relative to the dimension of the MS problem, results have been obtained in low execution times. The efficiency of using these techniques have been already proved in the literature [22,39].

7.2 Recommendations for Future Work and Research

The MS model used in this work was tested on test systems which is encouraging to apply and develop the model on realistic systems, however, this require a lot of data from an electric company such as their network parameters, MS data and their constraints.

The objective function can be used to include one or more new terms, like, limitation of maintenance crews and materials and specific requirements from maintenance centers. By such an addition, the proposed method will be more practical to be applied in real systems.

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APPENDIX I

SURVEY ON SUBSTATION PREVENTIVE MAINTENANCE TESTS

(SURVEY SAMPLE)

Survey on Substation Preventive Maintenance Tests

Substation Name:	Location:	Date:

	Transformer rating: Voltage rating:	Duration of test (hours)	Frequency of test (months)	Number of Data samples taken	How many time it was?	
					OK	Not OK
	Transformer Tests					
1	Oil quality test					
2	Overall power factor test					
3	Megger test					
4	Excitation currents test					
5	Power factor test to bushings					
6	Dissolved gas in oil analysis test (DGA test)					
7	Calibration of oil temperature indicators of the transformer					
8	Calibration of oil temperature indicators switch settings					
9	Calibration of winding temperature indicators of the transformer					
10	Calibration of winding temperature indicators switch settings					
11	Dielectric breakdown test of the insulating oil (at field)					
12	Main tank Buchholz relay test					
13	Transformer pressure relief valve test					
14	Insulation resistance - polarization index test					
15	General Inspections/Checks*					

* These includes:
cleaning the bushings,
checking/replacing silica gel,
checking any oil leakage,
checking fans/pumps motors,
checking the control circuits,
and others where applicable.

Thermovision			

Most problems are:

		Duration of test (hours)	Frequency of test (months)	Number of Data samples taken	How many time it was?	
					OK	Not OK
	OLTC Tests					
1	Transformer Turns ratio test (TTR test)					
2	Excitation test					
3	Resistor test					
4	Continuity test					
5	Quality oil test					
6	Dielectric test of insulating oil					
7	General Inspections/Checks*					

* These includes: checking
drive mechanism,
interlock,
tap changer Buchholz relay check,
tap changer pressure relief valve check,
tap changer limit switch,
mechanical stops positions,
breaking contactors,
overrun blocking,
auto test of tap changer,
tap position indicator,
electric continuity & hardware,
and others where applicable.

Most problems are:

	CB Type:	Duration of test (hours)	Frequency of test (months)	Number of Data samples taken	How many time it was? OK	Not OK
	Circuit Breaker Test [illegible]					
1	Timing test					
2	Contact resistance Ductor test					
3	Doble power factor test					
4	Oil quality test					
5	Megger test					
6	Dielectric test of insulating oil					
7	Checking the pressure/moisture/Oxygen for SF6					
8	General Inspections/Checks*					

* These includes:
checking leakages,
inspecting the mechanism/operation/tripping,
inspecting the motor/pump/compressor,
operation of contacts,
operation of auxiliary contacts,
checking the pressure,
electrical functional test for Ground switches,
mechanical check for Ground switches,
other tests/checks where applicable (high/low pressure switches, safety valves, levels, charging times, interlocks, switches, etc.)

Most problems are:

	CB Type:	Duration of test (hours)	Frequency of test (months)	Number of Data samples taken	How many time it was? OK	Not OK
	Circuit Breaker Tests 69/115/230 kV [illegible]					
1	Timing test					
2	Contact resistance Ductor test					
3	Doble power factor test					
4	Oil quality test					
5	Purity test					
6	Moisture content test (Dewpoint test)					
7	Megger test					
8	Dielectric test of insulating oil					
9	Checking the pressure/moisture/Oxygen for SF6					
10	General Inspections/Checks*					

* These includes:
checking leakage,
inspecting the mechanism/operation,
inspecting the motor/pump/compressor,
checking the pressure,
other tests/checks where applicable (high/low pressure switches, safety valves, levels, charging times, interlocks, switches, etc.)

Most problems are:

Rating:
Voltage:

		Duration of test (hours)	Frequency of test (months)	Number of Data samples taken	How many time it was?	
					OK	Not OK
	Station Service Transformer Tests					
1	Tap changer test (ratio test)					
2	Quality oil test					
3	Megger test					
4	Dielectric test of insulating oil (termination box)					
5	General Inspections/Checks*					

* These includes:
inspecting the HV & LV termination boxes,
cleaning the bushings/body,
inspecting the grounding,
checking other accessories where
applicable (pressure, level and temperature gauges).

Most problems are:

	Rating voltage:	Duration of test (hours)	Frequency of test (months)	Number of Data samples taken	How many time it was? OK	Not OK
	Storage Batteries Tests					
1	Cell voltage test (number of cells =)					
2	Specific gravity test					
3	Battery temperature measurement test					
4	Float voltage and current tests					
5	Discharge test (capacity test)					
6	General Inspections/Checks*					
	Chargers Tests					
1	Float voltage test					
2	Equalize Voltage					
3	Float current					

* These includes:
complete check of the battery room,
checking leakages,
checking cells terminals,
checking terminals torque,
and others where applicable.

electrolyte level of cells check		

Most problems are:

	Rating:	Duration of test (hours)	Frequency of test (months)	Number of Data samples taken	How many time it was? OK	Not OK
	Disconnect Switches Tests					
1	Ductor test (contacts joints)					
2	Megger test					
3	General Inspections/Checks*					

* These includes:
checking the insulators,
checking open blade angle & open travel stop,
checking the adjustment/alignment of blades with contacts,
checking manual gear box operation,
checking the overtoggling in the open/closed position,
cleaning contacts and insulators,
checking the hardware,
and others where applicable.

Most problems are:

	Rating:	Duration of test (hours)	Frequency of test (months)	Number of Data samples taken	How many time it was?	
					OK	Not OK
[illegible]	Ground Switches Tests					
1	Ductor test (contacts joints)					
2	Megger test					
3	General Inspections/Checks*					

* These includes:
checking the insulators,
checking open blade angle & open travel stop,
checking the adjustment/alignment of blades with contacts,
checking manual gear box operation,
checking the overtoggling in the open/closed position,
cleaning contacts and insulators,
checking the hardware,
and others where applicable.

Most problems are:

	Rating:	Duration of test (hours)	Frequency of test (months)	Number of Data samples taken	How many time it was? OK	Not OK
	Switchgear Busbars (34.5kV and below) Tests					
1	Overall contact resistance Ductor test (at joints)					
2	Megger test for each phase					
3	General Inspections/Checks*					
	Rating:					
	Switchgear Busbars (above 34.5kV) Tests					
1	Overall contact resistance Ductor test (at joints)					
2	Megger test for each phase					
3	General Inspections/Checks**					

* These includes:
complete inspection of busbars,
cleaning busbars,
ground switches inspection,
and others where applicable.

** These includes:
complete inspection of busbars,
cleaning busbars,
and others where applicable.

Most problems are:

		Duration of test (hours)	Frequency of test (months)	Number of Data samples taken	How many time it was?	
					OK	Not OK
Automatic Transfer Switch 13.8kV [illegible]						
1	Checking ATS panel					
2	Checking operation of change over switch					
3	Checking operation of contactors					
4	Checking operation of timer under voltage relay					
5	Checking functional test					
6	Checking interlock system					
7	Single phasing protection					
8	Visual inspection					
9	General Inspections/Checks					

Most problems are:

APPENDIX II

5-BUS AND IEEE 25-BUS SYSTEMS DATA

Table II.1: Line Data of the 5-Bus System

Line No.	Between Buses	Impedance (per unit) Ohm	Total Line Charging (per unit) Mho	Line Capacity (per unit)
1	1 – 2	0.02+j0.06	j0.030	1
2	1 – 3	0.08+j0.24	j0.025	1
3	2 – 3	0.06+j0.18	j0.020	1
4	2 – 4	0.06+j0.18	j0.020	1
5	2 – 5	0.04+j0.12	j0.015	1
6	3 – 4	0.01+j0.03	j0.010	1
7	4 – 5	0.08+j0.24	j0.025	1

Table II.2: Bus Data of the 5-Bus System

Bus No.	Bus Voltage (per unit)	Generation		Load	
		Real Power (per unit)	Reactive Power (per unit)	Real Power (per unit)	Reactive Power (per unit)
1	1.06+j0.0	-	-	0	0
2	1.0+j0.0	0.40	0.30	0.20	0.10
3	1.0+j0.0	0	0	0.45	0.15
4	1.0+j0.0	0	0	0.40	0.50
5	1.0+j0.0	0	0	0.60	0.10

Table II.3: Line Data of the IEEE 25-Bus System

Line No.	Between Buses			Impedance (per unit) Ohm	Total Line Charging (per unit) Mho	Line Capacity (per unit)
1	1	-	2	0.0014+j0.0108	j0.0455	8.00
2	1	-	7	0.0111+j0.0865	j0.0909	0.65
3	1	-	13	0.0124+j0.0966	j0.1015	1.00
4	2	-	3	0.0025+j0.0198	j0.0833	5.00
5a	3	-	22	0.0030+j0.0231	j0.0243	2.00
5b	3	-	22	0.0030+j0.0231	j0.0243	2.50
6	4	-	18	0.0268+j0.1037	j0.0141	10.00
7a	4	-	19	0.0328+j0.1267	j0.0172	2.50
7b	4	-	19	0.0328+j0.1267	j0.0172	2.50
8	5	-	17	0.0218+j0.0845	j0.0115	8.00
9	5	-	20	0.0228+j0.0883	j0.0120	9.40
10a	5	-	25	0.0080+j0.0902	j0.0030	2.20
10b	5	-	25	0.0080+j0.0902	j0.0030	2.50
11	6	-	18	0.0427+j0.1651	j0.0224	4.40
12	6	-	20	0.0427+j0.1651	j0.0223	2.80
13a	6	-	24	0.0159+j0.0614	j0.0083	10.80
13b	6	-	24	0.0159+j0.0614	j0.0083	2.50
14	7	-	13	0.0061+j0.0476	j0.0499	2.50
15	7	-	16	0.0061+j0.0476	j0.0499	0.90
16	8	-	16	0.0054+j0.0418	j0.0879	4.90
17	8	-	22	0.0050+j0.0389	j0.0409	0.65
18	9	-	11	0.0016+j0.0129	j0.0545	2.60
19a	9	-	15	0.0018+j0.0144	j0.0152	2.50
19b	9	-	15	0.0018+j0.0144	j0.0152	2.50
20	10	-	11	0.0087+j0.0678	j0.0712	8.00
21	10	-	15	0.0135+j0.1053	j0.1106	2.50
22	11	-	14	0.0031+j0.0245	j0.1030	7.00
23	12	-	14	0.0067+j0.0519	j0.0546	1.00
24	12	-	23	0.0023+j0.0839	-	0.70
25a	13	-	18	0.0023+j0.0839	-	1.00
25b	13	-	18	0.0023+j0.0839	-	2.50
26	13	-	20	0.0023+j0.0839	-	2.50
27	14	-	22	0.0022+j0.0173	j0.0182	2.00
28a	15	-	22	0.0033+j0.0259	j0.0273	3.60
28b	15	-	22	0.0033+j0.0259	j0.0273	2.50
29	16	-	18	0.0023+j0.0839	-	2.50
30	16	-	20	0.0023+j0.0839	-	5.64
31	17	-	19	0.0026+j0.0139	j0.2306	4.00
32	17	-	23	0.0546+j0.2112	j0.0286	3.50
33	18	-	23	0.0308+j0.1190	j0.0161	1.50
34	19	-	21	0.0497+j0.1920	j0.0260	1.10
35a	20	-	21	0.0139+j0.0605	j1.2295	1.80
35b	20	-	21	0.0139+j0.0605	j1.2295	2.50
36	24	-	25	0.0160+j0.1805	j0.0060	2.20

Table II.4: Generation Capacity Data of the IEEE 25-Bus System

Bus No.	Minimum MW Capacity (pu)	Maximum MW Capacity (pu)	Minimum MVAR Capacity (pu)	Maximum MVAR Capacity (pu)
1	1.32	6.60	-1.25	3.10
2	-	-	-	-
3	-	-	-	-
4	-	-	-	-
5	-	-	-	-
6	-	-	-	-
7	1.19	5.94	0.00	2.40
8	-	-	-0.50	2.00
9	0.80	4.00	-0.50	2.00
10	0.60	3.00	-0.60	2.96
11	0.80	4.00	-0.50	2.10
12	-	-	-	-
13	-	-	-	-
14	0.43	2.15	-0.50	1.10
15	-	-	-	-
16	-	-	-	-
17	0.38	1.92	-0.50	0.72
18	-	-	-	-
19	0.38	1.92	-0.50	0.72
20	-	-	-	-
21	-	-	-	-
22	0.31	1.55	-0.50	0.80
23	-	-	-	-
24	0.60	3.00	0.00	1.80
25	1.32	6.60	-1.25	3.10

Table II.5: Generation and Load Data of the IEEE 25-Bus System

Bus No.	Generation Power (pu)	Real Power Demand (pu)	Reactive Power Demand (pu)	Voltage Magnitude (pu)
1	-	-	-	1.01 (slack)
2	-	1.28	0.26	1.00
3	-	1.81	0.37	1.00
4	-	0.74	0.15	1.00
5	-	0.71	0.14	1.00
6	-	0.71	0.35	1.00
7	5.94	2.65	0.54	1.01
8	-	1.94	0.39	1.01
9	4.00	3.33	0.68	1.01
10	3.00	-	-	1.01
11	4.00	-	-	1.00
12	-	-	-	1.00
13	-	-	-	1.00
14	0.43	3.17	0.64	1.01
15	-	-	-	1.00
16	-	-	-	1.00
17	0.40	1.08	0.22	1.01
18	-	1.75	0.36	1.00
19	0.40	0.97	0.20	1.01
20	-	1.95	0.40	1.00
21	-	1.36	0.28	1.00
22	1.55	1.00	0.20	1.01
23	-	1.80	0.37	1.00
24	0.60	1.25	0.25	1.01
25	3.30	-	-	1.01

Table II.6: Line Data of the IEEE 25-Bus System (Standby Lines)

Line No.	Between Buses			Impedance (per unit) Ohm	Total Line Charging (per unit) Mho	Line Capacity (per unit)
1	1	-	2	0.0023+j0.0839	-	2.50
2	1	-	7	0.0023+j0.0839	-	2.50
3	1		13	0.0023+j0.0839	-	2.50
4	5	-	20	0.0023+j0.0839	-	2.50
5	6	-	20	0.0023+j0.0839	-	2.50
6	7	-	13	0.0023+j0.0839	-	2.50
7	7	-	16	0.0023+j0.0839	-	2.50
8	8	-	22	0.0023+j0.0839	-	2.50
9	9	-	11	0.0023+j0.0839	-	2.50
10	12	-	14	0.0023+j0.0839	-	2.50
11	14	-	22	0.0023+j0.0839	-	2.50
12	16	-	18	0.0023+j0.0839	-	2.50
13	17	-	23	0.0023+j0.0839	-	2.50
14	18	-	23	0.0023+j0.0839	-	2.50
15	24	-	25	0.0023+j0.0839	-	2.50

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