OPTIMAL MAINTENANCE SCHEDULING FOR TRANSMISSION LINES

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ABSTRACT

OPTIMAL MAINTENANCE SCHEDULING FOR TRANSMISSION LINES

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The fundamental mission of a transmission system operator is to supply desired electricity to all parts of the network continuously within acceptable economic and quality standards. Transmission lines provide the essential infrastructure to carry the power from generation stations to customers. Maintenances of the transmission lines are of great importance for not only power system reliability but also operational costs and equipment life span. Furthermore, operating the system with all available equipment holds the system at most secure level.

This thesis presents a methodology to form optimal schedule for yearly preventive maintenances of transmission lines with minimum duration of maintenance condition. Network and operational constraints are included in the problem considering the power systems that have seasonally changing load and generation profiles. In order to model and solve the optimization problem, linear power flow and linearization techniques are utilized. Furthermore, a relaxation method is developed and applied to the large-sized problem in order to eliminate excessive time requirement of solution with actual method.

The proposed methodology and relaxation method was applied to Turkish Power Network model of 2017. The obtained schedules are evaluated, and tradeoffs between the actual and relaxation methods are presented.

Keywords: Transmission System Planning, Transmission System Maintenance, Mixed Integer Linear Programming, DC Load Flow

ÖZ

İLETİM HATLARI İÇİN EN UYGUN BAKIM PROGRAMININ OLUŞTURULMASI

Özmen, Engin Berk
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Tez Yöneticisi: Dr. Öğr. Üyesi Murat Göl

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Elektrik sistemi işletmecilerinin temel amacı sistemin tüm noktalarında talep edilen elektriksel gücü belirli ekonomik ve kalite standartları çerçevesinde sürekli olarak sağlamaktır. İletim hatları, üretim tesislerinde üretilen gücün son kullanıcılara taşınması için gereken altyapıyı sağlamaktadır. İletim hatlarının bakım işlemleri güvenilir ve sürekli elektrik sağlamanın yanında işletme maliyetleri ve ekipman hizmet süreleri için de önem arz etmektedir. Öte yandan, elektrik sistemini mevcut ekipmanların tümü çalışır halde işletmek sistem güvenilirliğini en üst seviyeye taşımaktadır.

Bu tezde, iletim hatları için sistemi bakım durumunda en az süreyle işletmeyi amaçlayan önleyici bakım programının oluşturulması için geliştirilen bir yöntem sunulmuştur. Enerji arz ve talep profili mevsimlere göre önemli derecede değişiklik gösteren elektrik sistemleri göz önünde bulundurularak, bağlantı ve işletme kısıtları probleme dahil edilmiştir. Optimizasyon modelinin oluşturulması ve problemin çözülmesi için doğrusal yük akışı denklemleri ve doğrusallaştırma tekniklerinden yararlanılmıştır. Ayrıca, önerilen yöntemin uygulanabilmesi için gereken uzun çözüm süresi problemini gidermek amacıyla bir teknik geliştirilmiş ve probleme uygulanmıştır.

Önerilen yöntem ve teknik, 2017 yılı Türkiye Elektrik Sistemi modeline uygulanmıştır. Elde edilen bakım programları değerlendirilmiş ve karşılaştırılmıştır.

Anahtar Kelimeler: İletim Sistemi Planlaması, İletim Sistemi Bakımları, Tamsayı Karışık Doğrusal Programlama, Yük Akış Analizi

To My Family

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INTRODUCTION

1.1 Motivation

An electric power system is a network that is composed of components for generation, transmission and distribution of electric power. It provides the essential infrastructure for energy transformation from fuels or renewable sources, and electricity transfer to end users.

Generation systems consist of power plants, which produce electrical energy and supply to the transmission system. Power plants transform mechanical, solar or chemical energy that are obtained from natural gas, coal, nuclear, wind, sun or geothermal sources to electrical energy. Generally, power plants are not located at load centers. Transmission systems facilitate the transfer of electrical energy from generation stations to distribution centers with high voltage lines, cables and transformers. Distribution systems convert the electrical power to a suitable form and make it available for the end users. Until the late 1980s, power systems worldwide were organized and operated in vertically integrated mechanisms. Nevertheless, the monopolistic structure of the power systems were reshaped, and the integrated utilities were decoupled as generation, transmission, distribution and retail companies by vertically unbundling processes during last three decades. The main objectives of the unbundling of power systems were to implement competition into power market, and promote the efficiency and economy of the industry. Although, generation and distribution systems were privatized with the expanding deregulation trend, transmission systems generally remained in non-profit structure and operated by government or an independent system operator due to strategic importance and high investment costs.

The basic mission of a system operator is to supply desired electricity to all parts of the network continuously within acceptable economic standards. In today's world, the power system reliability is important not to decrease the comfort of the modern society and to avoid interruption. Although the continuous supply of electricity on demand is impossible owing to the unexpected failures that are outside the control of system operators, the probability of the interruption can be reduced with investments in the scope of system expansion plans or effective asset management.

Operation of an electric power system requires various types of assets such as human, equipment or financial. Power delivery infrastructure of a power system is composed of physical components such as transformers, generators, transmission lines and circuit breakers. Therefore, the equipment have to be operated in economically and practically efficient way in order to reduce the failure risks and power outages. Asset management that involves planning and operation aspects can achieve efficient operation of the system components. Maintenance planning, risk analysis, life cycle assessment and financial assessment of components can be considered as the parts of asset management concept. For example, operating or maintaining an equipment instead of renewing despite failure risk is in the scope of asset management. The purpose of the application is to maximize the asset value; however, failure of the equipment may cause unfortunate results. Similarly, asset management includes maintenance strategies of components that involve type and schedule. Minor maintenance can be applied to equipment in order to extend lifetime or maintenances can be scheduled to increase reliability of the system or to maximize revenue.

Maintenances of system components are operators' responsibility and have to be carried out for a secure and reliable power system operation. Therefore, maintenance strategies are of great importance for the operation of a power system. Schedule of maintenances must not cause bottlenecks in the system or limit market operation. On the other hand, preventive and corrective maintenances are applied to the components to improve the system operation. In order to reduce the ratio of corrective maintenance, which are carried out for the unexpected failures, risk analysis should be performed for the components and application should be decided. The electrical equipment in the system are monitored regularly by the regional operators, and maintenance demands are determined. However, a central operator should coordinate the maintenances that are significant for the operation of the system in order not to cause a failure, since the system is interconnected. In this context, maintenances of the high voltage transmission lines that form the backbone of a power system have to be handled carefully. In this thesis, a methodology that proposes the optimal maintenance schedule for the high voltage transmission lines based on minimum maintenance duration and network constraints is developed and applied to the Turkish Power System of 2017.

1.2 Problem Definition

The aim of this study is to decide maintenance period and order of each transmission line, which is predetermined to be maintained within a one-year time interval, while maximizing the duration in which all of the transmission lines are in operation. At the same time, reliable energy should be supplied to customers by transmission system operator (TSO) and outage of any transmission lines should not influence the market environment.

In an interconnected system, generators and loads are located in different areas and power transactions are made over transmission lines. Furthermore, generation and load profiles in different regions may change according to seasonal conditions or fuel and electricity costs, because different types of generation units and loads can be clustered around different areas depending on regional and environmental conditions. For example, hydroelectric power plants are constructed near rivers or thermal power plants are constructed near coalmines or harbors in general. Their power generation may increase or decrease in different seasons. Similarly, industrial loads are concentrated in specific regions or residential loads in touristic regions grow in tourism seasons. Because of these changing behaviors of loads and generations in different regions, transmission lines also operate on different loading levels during a year. This situation causes various reliability conditions of electricity networks due to predefined maintenance programs.

TSO of an electricity grid is responsible for maintenance of the network equipment, while supplying reliable and high quality electricity to the customers. Besides, there are power markets in deregulated generation systems and generation companies participate in these markets by bidding or bilateral trading in competitive environment. Therefore, any maintenance outage of transmission lines must not limit the amount of power generation of any power plant, because a possible restriction is against the nature of the free market, and not leading to such conditions are specially stated as requirement in grid codes of deregulated power systems [1]. On the other hand, preventive maintenances of all equipment in transmission system have to be scheduled and completed in coordination in order to extend the lives of the system components and decrease the risk of failures during operation.

Consequently, annual periodic maintenances of transmission lines should be scheduled and outage time of each transmission line should be determined at the beginning of the year. Many alternative maintenance schedules for transmission lines may be created in a year. However, transmission bottlenecks may arise in power systems due to seasonal conditions, fuel costs, renewable energy penetration levels or people behaviors. Similarly, unexpected maintenance need or outage demands for another application may cause transmission bottlenecks in the system. Therefore, the operators that are responsible for maintenance planning have to consider and take precautions against the possible bottlenecks. From this aspect, the duration of operation in maintenance state, which is the consequence of maintenance of one or more transmission lines in the system, is aimed to be minimized. Hence, maximum duration of most secure condition of electricity network in a year can be obtained with this objective. In other words, robustness of the system can be increased by operating electric grid with all transmission lines during normal state. Besides, the topology of electrical network for next year can be formed and this provides a basis for the other planning and operational studies.

1.3 Contribution of the Thesis

In this study, an optimization model for maintenance scheduling of transmission lines considering network constraints is proposed. With this model, an optimal maintenance schedule with minimum duration within a year is formed for the periodic maintenances of transmission lines while providing a reliable power system. Furthermore, power market is also considered and guaranteed not to be restricted with network constraints, if possible.

In order to satisfy the network constraints, DC Power Flow equations are incorporated into the model. However, DC Power Flow equations turns into nonlinear equations with the integration of the branch states in the model. Linearization is applied to the nonlinear equations to simplify the model. For the linear power flow equations, realized generation and demand data are utilized as the bus power injections, and ratings that are changing according to the weather temperature are defined as the bounds of the constraints.

The proposed methodology is applied to the Turkish Power System with historical generation, demand and topology data. Since the national load dispatch center is responsible for the maintenance schedule of only 380 kV transmission lines, the other transmission lines at lower voltage levels were not considered in the case study. In this sense, the power system is converted to equivalent reduced model including only 380 kV buses and transmission lines. Based on the changing generation and demand characteristics of the regions, seasonal choices for maintenances are assumed and studied in the problem.

Due to the large size of the problem, a relaxation approach that suggests the division of the problem is developed and applied to the same model in the thesis. In order to divide the problem, Line Outage Distribution Factors (LODFs) for the transmission lines in the system are calculated and utilized. With LODFs, the transmission lines in the system were decoupled to two groups to schedule the maintenances of each group individually. The problem size and solution time are decreased by parallel processing, but suboptimal maintenance schedule is obtained with this method.

1.4 Thesis Outline

In Chapter 2, maintenance types, demands and scheduling strategies for power systems and information about maintenance scheduling in Turkish Power System are given. Furthermore, theoretical background and essential preliminary works for the study is explained in detail. Mixed Integer Linear Programming (MILP) solution method for the problem and generation and demand forecast studies, which are necessary for the DC Power Flow equations are clarified. Finally, literature review about maintenance scheduling of transmission lines is summarized in the chapter.

The proposed methodology and construction of the mathematical optimization model in theoretical view for the problem are given in Chapter 3. The variables, objective function and constraint functions are clearly explained, and linear equations for the model are presented.

Implementation of the mathematical optimization model on computer environment and results are presented in Chapter 4. Firstly, the matrix forms of the constraint equations suitable for the solver and the results are illustrated. After that, evaluation and discussion of the obtained results are given.

A relaxed method for the defined problem is proposed, and results are presented in Chapter 5. Furthermore, the results of the approach are discussed and compared with the results of the actual method.

In Chapter 6, the study is concluded with the summary of the work, and future works to improve the study are mentioned.

CHAPTER 2

GENERAL INFORMATION AND LITERATURE REVIEW

In this chapter, general overview of power system maintenance is presented and a literature survey is provided. Firstly, maintenance types and strategies are given. After that, policies of transmission line maintenances in Turkish Power System is mentioned. In the second section, a detailed literature review about transmission line maintenances is given.

2.1 Maintenance in Power Systems

2.1.1 Maintenance Strategies in Power Systems

Not only in power systems but also in most processes, that includes physical components, no equipment is produced without errors and cannot be expected to work forever. This reality also applies for the mechanisms containing human factors. Errors and failures in the systems may result in reduced service quality and increased financial losses. Although, removing these errors and faults completely is not possible, risks can be reduced with preventive or corrective maintenances. Moreover, maintenances are of great importance to extend the lifetime of equipment.

The aim of power system maintenances are listed as:

- to provide safe and secure environment for field workers,
- improving service quality and efficiency, while decreasing operational costs,
- providing continuity of service by preventing interruption caused by faults,

- decreasing investment costs for new equipment by extending life cycles of facilities, machines and electrical components in the system,
- increasing capacity factors of components.

Maintenances in power systems can be categorized as corrective and preventive maintenances according to application purposes as in Figure 1. Corrective maintenances correspond to unplanned applications; on the other hand, preventive applications that include periodic and predictive actions correspond to scheduled applications.

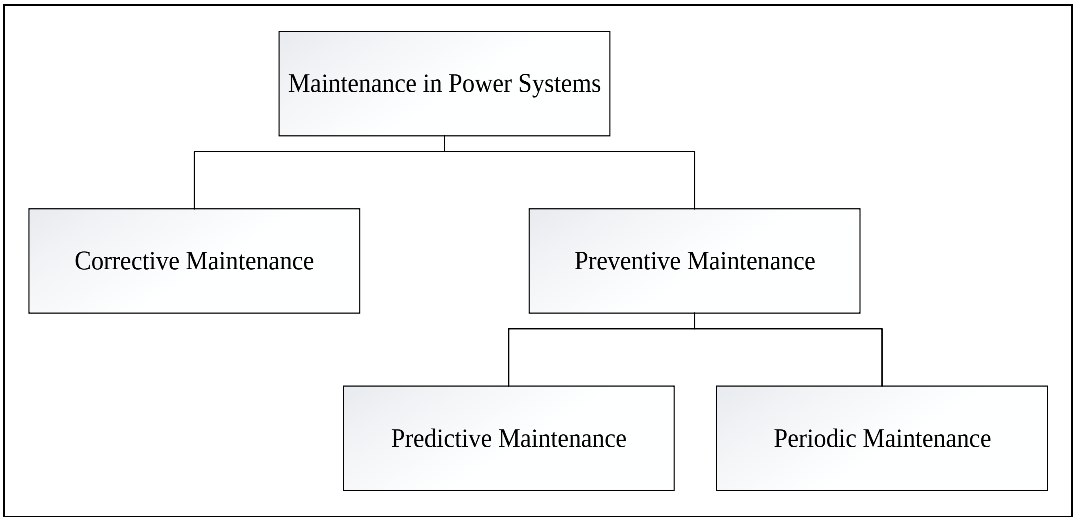

Figure 1. Transmission System Maintenance Types

Corrective maintenances are the actions performed after unstable operation or breakdown of an equipment. The purpose of corrective maintenance is to restore the system component to a satisfactory condition within the shortest time possible. However, this type of maintenance is not taken into account in maintenance scheduling studies. Detection and repair of malfunction of a circuit breaker in a power system can be an example for corrective maintenance.

Preventive maintenances are applied to avoid premature aging of equipment and causing outages in the systems. Unlike corrective maintenances, preventive maintenances are scheduled actions, which aim to increase reliability level of the system and decrease unexpected failures in the system. Moreover, preventive maintenances involve the spare part repairs to extend equipment life and avoid the investment cost for new equipment.

Power systems are composed of generation systems, transmission systems and distribution system, and maintenances in each part should be scheduled and performed in coordination carefully in order to provide continuous and secure electricity to end users in high quality. Maintenances in generation systems involve maintenances of generators, step-up transformers and auxiliary systems. In general, maintenance of generators are planned and the other equipment are overhauled during that period. Generator failures may cause supply adequacy, dispatch problems and higher operational costs. Transmission system maintenances involve maintenances of transmission lines, transformers, series and shunt compensators, circuit breakers, switches, separators and buses. In order to prevent contingencies and bottlenecks in the system, the maintenances should be scheduled and carried out in transmission system. Transformers, cables and protection equipment in distribution systems are maintained in the scope of maintenances in distribution systems.

Predictive maintenances are condition-based applications and performed when it is considered as necessary according to periodic or continuous monitoring, tests and analysis of equipment or system. On the contrary, periodic maintenances are time-based applications and involve replacement or repair of the components. Very frequent maintenances in a system cause quite high operational costs and may result in maintenance-induced faults. On the other hand, performing maintenances rarely leads to increase of failure risks and early equipment wear-out. In other words, system operators who develop maintenance strategies encounter with a trade-off between higher operational costs and failure risk in a power system. Thus, the maintenance policy depends on the objective of maintenances such as minimizing operational costs or maximizing reliability. Consequently, different maintenance strategies can be optimal for different power systems. However, preventive maintenances have to be scheduled carefully regardless of the objective of maintenance.

Preventive maintenance of a transmission line in power system is planned by regional operator, and tasks, period and essential crew for maintenance are determined in the scope of plan. Afterwards, maintenance requests of regional operators for branches are collected by central operator and scheduled at the beginning of the year. Service loss resulting from maintenances should not preclude the safe operation of the system.

Period of maintenance for a transmission line depends on demands, costs, system conditions and objectives. Maintenance scheduling is determination of the periods of each planned maintenance within a prospective duration. In other words, finding optimal outage periods of transmission lines for an objective while enough source and conditions are available is called as maintenance scheduling. The most common objectives of maintenances are minimization of costs and providing reliable electricity to the end users as mentioned before.

Transmission lines and auxiliary equipment are generally damaged by environmental factors such as storm, humidity, pollution, lightning, ground stability, tree and flying animals or vehicles. According to the application on field, two types of maintenance are applied to the transmission lines, which are hot line and cold line maintenances. No outage is needed for hot line maintenances. On the other hand, cold line maintenances can be applied after outage of the line. Compared to hot line maintenances, more workforce and time are required for cold line maintenances. In this study, cold line maintenances are considered and scheduled for outage. Common actions applied to the lines in the scope of maintenances are listed below:

- replacement of insulator string,
- tightening or replacement of loose nuts and bolts of the joints,
- washing of insulators,
- repair of defects and punctured insulators identified during routine patrols,
- rectification of displacement,

- tests or application for circuit breakers or measurement transformers,
- refurbishment of tower.

A transmission line is supposed to be in service for 50 years in average with an efficient maintenance strategy. Although, various numbers or periods are mentioned or suggested for transmission line maintenances in literature, the frequency of maintenances are usually determined based on operational experiences.

2.1.2 Transmission Line Maintenance in Turkish Power System

In Turkey, maintenance applications in distribution and transmission systems are coordinated by TEİAŞ that is the TSO of Turkish Power System. Grid code states that the maintenance and outage of a facility or equipment are scheduled by TEİAŞ in accordance with the demand and energy estimation [1]. In generation system, TEİAŞ schedules maintenances in collaboration with generation companies; on the other hand, TEİAŞ is the only responsible for the maintenances in transmission system.

In the present case, major part of the transmission line maintenances are carried out as corrective and predictive maintenances. Since an efficient asset management is not available, conditions and requirements of the equipment in the system cannot be detected. Hence, long-term maintenance schedule cannot be formed for transmission lines. Corrective maintenances are carried out after the faults to bring the lines operable state. In predictive maintenance process, regional operators detect the urgent maintenance requirements of components according to inspections and tests, and then demand outage and maintenance permission in short term from national load dispatch center. Considering demand and generation trends in the system, a maintenance program in near future is designated based on operational experiences. However, these strategies solve the problems temporarily, and may cause recur of the failures. Furthermore, enough time cannot be allocated for all components and operational costs increase because of these strategies. Eventually, long-term maintenance schedule is a need for efficient system operation.

2.2 Literature Review on Transmission System Maintenance Studies

It is known that electricity consumption in residential, commercial and industrial areas is rapidly growing worldwide with the expansion of global economy and population. Expanding the supply and network in power systems with new investments in order to meet the increasing demand is one of the challenges especially in developing countries. Besides that, sustainable operation of the power systems is of great importance for stable and continuous power supply, because modern society has been becoming more dependent on electricity every day. Therefore, effective and timely maintenance of transmission system equipment plays important role for reliable power system operation and extension of lifespan of the infrastructure. Finding the optimal period for maintenance of each equipment in a system requires maintenance scheduling studies. In this sense, many studies are conducted and methods are developed in literature for transmission system maintenances from various aspects.

Transmission line maintenance studies can be categorized into two groups. In the first group, maintenances of transmission lines are integrated as constraints to maintenance studies of generation units [4-9]. In these type of studies, master problem is scheduling of generation units' maintenances in a power grid, which satisfies the network constraints. On the other hand, studies based on maintenances of transmission lines are also available in literature [10-17]. Alternative objectives and solution approaches are applied to the problem in these studies.

Initially, maintenances of generating units are scheduled based on primitive approaches and network constraints are not included in the studies. Maintenances of generating units are scheduled considering crew and reliability constraints while aiming to minimize the operational costs [2]. Loss of generation due to the units in maintenances is limited for reliability constraint. Similarly, generating units are scheduled for maintenances with dynamic programming and objective is to maximize the net reserve over the year [3]. Transmission network is introduced to the generating unit maintenance problem, which also aims minimum operating cost [4]. Voltage and equipment operational limits are considered as system constraints, and demand and available powers are matched during maintenance periods. Maintenances of generating units and transmission lines are scheduled with Benders decomposition technique [5, 6]. In master problems, decision variables for maintenances are obtained, and then operational costs are minimized by sub-problems. Network constraints are included to observe the effect on extension of units' maintenances and operational costs. Fuel and emission constrains are included in [6]. Load balance equations, generation limits and transmission constraints are taken into consideration in a maintenance scheduling of generating units and transmission lines in a vertically unbundled system [7]. Maintenances demanded by Generation Companies (GENCOs) and Transmission Companies (TRANSCOs) are coordinated by Independent System Operator (ISO) for adequate reliability. Penalty factors are utilized for conflicting objectives of GENCOs and TRANSCOs that are maximum profit and minimum maintenance costs, respectively. Instead of probabilistic models, fuzzy evolutionary programming method is used for the uncertainties such as load forecast, fuel prices, maintenance costs and maintenance crews in order to schedule the maintenances of generation and transmission system [8]. Hourly maintenance schedule of generating units and transmission lines that aims minimum maintenance costs is obtained by applying security constrained unit commitment to the problem [9]. Both Lagrangian relaxation and Benders decomposition are utilized for the large-scale problem.

Network security and equipment reliability are two prominent perspectives to transmission system maintenance scheduling problem. Local transmission system operators or distribution system operators generally analyze equipment reliability for cost effectiveness. Optimal maintenance actions for equipment to minimize operational costs while satisfying system reliability are determined in these type of studies. Probabilistic maintenance models are developed and Markov model is utilized for the problems [10-12]. Similarly, a cost effective maintenance scenario is formed with failure risk model of equipment [13]. Advantages of linear programming over Markov model for long-term period studies is given. System security concern is integrated into traditional maintenance strategies [14]. System state is detected with planned outages and contingency analyses are performed for possible failure risks. For problematic cases, optimal power flow is utilized and generations are rescheduled to minimize load curtailment. An artificial intelligent tool is developed for automatic scheduling of outages for transmission maintenances [15]. The target of the tool is to minimize the period of doing maintenance activity with preventing any carry-over of work activity to next week. Given the maintenance schedules from long-term scheduling study and power transaction schedules, short-term line maintenance problem is analyzed to minimize TSO's loss of revenue [16]. Hourly line maintenance and system constraints are taken into consideration. Yearly maintenances of transmission lines pursuing maximum transmission capacity margin are scheduled with mixed integer linear programming [17]. Market environment is also considered as lower level problem in the study.

2.3 Theoretical Background and Preliminary Work

In order to model and solve a problem data and knowledge in the scope of study is mandatory. Essential data should be given as input and proper techniques should be applied to model and solve the problem. For transmission line maintenance scheduling problem, network data should be prepared and corresponding techniques should be applied for network constraints and optimization. Process of the maintenance scheduling of transmission lines in a power system is shown in Figure 2. Firstly, forecast studies are performed for essential demand and generation data. Furthermore, DC Power Flow technique should be applied for network constraints. In order to model and solve the optimization problem linear programming method is utilized.

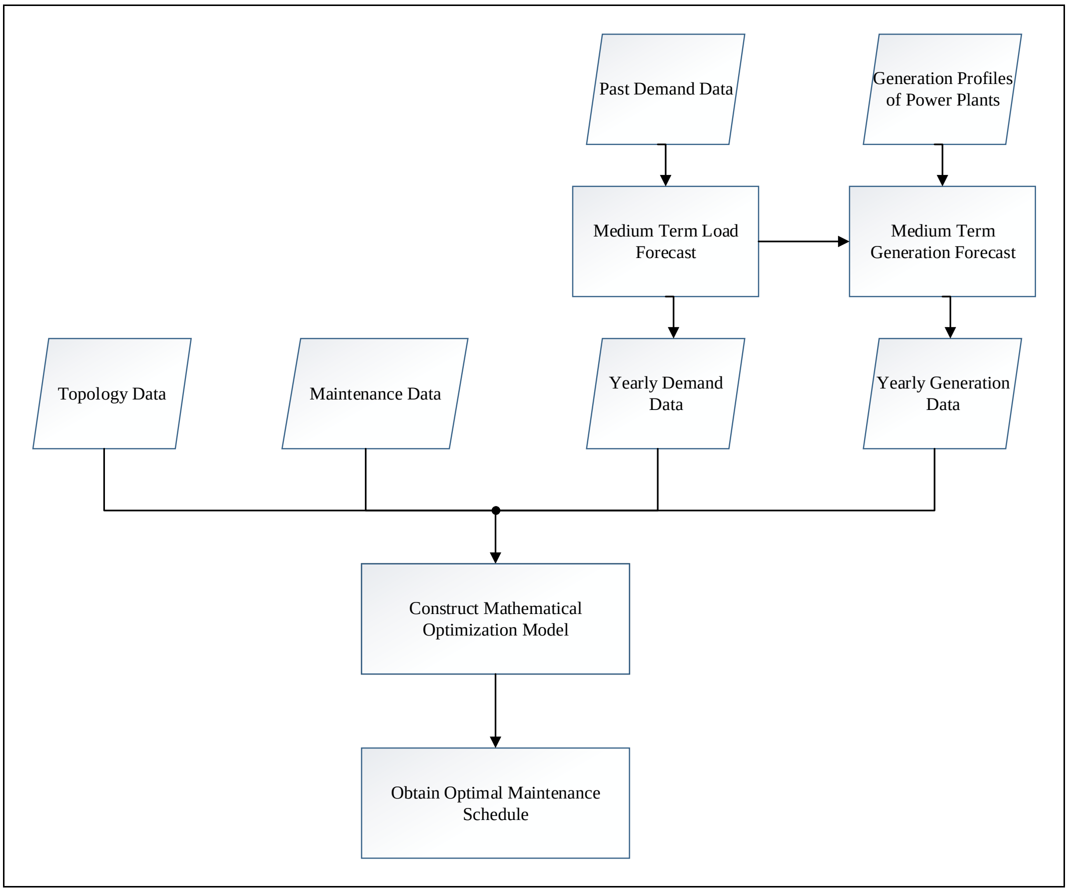

Figure 2. Concept of Transmission Line Maintenance Scheduling

For annual planning problems including network constraints, estimated data of next year has to be utilized. In other words, the weekly system topologies with dispatches that are formed to model load flow equations does not reflect the exact system due to the load demand and generation uncertainty. Furthermore, approximate solution is enough for long-term studies, especially for the applications that require repetitive and fast solutions due to its linearity. In this study, DC power flow technique is utilized for weekly study cases and reactive power flows in the grid are not taken into consideration.

2.3.1 Linear Programming

Optimization study can be described as making the best choice from a set of alternatives in the most general sense. Mathematically, calculating minimum or maximum value of a function by selecting the variables within an allowed range. An optimization problem can be formed by the following equations:

$$\begin{array}{ll} \textit{minimize or maximize} & f(x) \\ \textit{such that} & f_i(x) \leq b_i \end{array} \tag{2.1}$$

In (2.1), $x = (x_i, \dots, x_n)$ corresponds to the optimization or function variable set, f represents the objective function that will be minimized or maximized, f_i represents the constraint functions and b_i corresponds to the constraint bounds. A set x' is called optimal variable set, if the value of the objective function computed with the set is the smallest or largest according to the study and the constraint functions are satisfied.

Types of optimization problems may change according to types of objective function, constraint functions and optimization variables. For example, the functions can be linear or nonlinear, or the variables can be continuous or discrete. Consequently, the method to solve the problem depends on these types of the functions and variables. Nonlinear programming is the proper method for the problems with nonlinear functions, while linear programming is the proper method for the problems with linear functions. Generally, solution of linear problems are simpler than the nonlinear ones. Therefore, linearization process is an alternative way to choose the linear programming method for a problem with nonlinear functions. For this study, linear programming is selected as proper method to solve the problem, because the objective function and almost all of the constraints are linear functions. In addition, the nonlinear constraints can be linearized. The optimization variables include the states of the transmission lines that are binary information and the power flows on the transmission lines that are continuous type variables. As a result, Mixed Integer Linear Programming (MILP) method is selected as the solution method for the problem in this thesis.

2.3.2 DC Power Flow Analysis

Power flow study is a numerical analysis that is performed to calculate the bus voltages, bus angles and power flows on transmission lines in an interconnected system under a predetermined generation and demand condition. This study is of great importance not only for operation of existing power networks but also for planning the future investments of electrical systems.

Power flow studies are usually performed by using full model; that is, active and reactive power injections, voltage magnitudes and voltage angles of each bus in an interconnected system are taken into consideration. Various types of methods such as Newton-Raphson or Gauss-Seidel can accomplish power flow equations with iterative solutions. In order to solve full power flow equations, nonlinear equations that include also complex numbers must be handled. This situation enlarges the size of the problem and make it difficult to solve. In addition to this, the convergence of solution for the problem may not be completed. With DC Power Flow technique, the problem is simplified and convergence of solution is guaranteed. This method is usually used for the problems that require recursive and fast power flows solutions. Similarly, DC Power Flow algorithm is used frequently to deal with contingency analysis studies due to the reduced complexity and enough accuracy with respect to the results as mentioned in [18].

In DC Power Flow, nonlinear behavior of AC Power Flow is linearized by applying following assumptions:

- Resistances of transmission lines are neglected because $\mathrm{R} \ll \mathrm{X}$; that is, active power losses are neglected.
- Voltage angle differences between buses are too small, so $\sin(\delta) = \delta$.
- All bus voltage magnitudes are 1 p.u..

Based on the assumptions, the power injections at buses are known, but the bus angles come up as the unknowns. Through the algorithm, the bus angles are computed after one iteration and power flow on each line can be computed according to the angles.

The formulations for active and reactive power injections at each bus are given in the following equations:

$$\begin{aligned} P_i &= V_i \sum_{j=1}^{N} V_j \left(G_{ij} cos\theta_{ij} + B_{ij} sin\theta_{ij}\right) \\ Q_i &= V_i \sum_{j=1}^{N} V_j \left(G_{ij} sin\theta_{ij} + B_{ij} cos\theta_{ij}\right) \end{aligned} \tag{2.2}$$

where N is number of buses, G_{ij} corresponds conductances and B_{ij} corresponds susceptances of the lines that are connected to bus i. Through the above assumptions, (2.2) is converted to (2.3).

$$P_i = \sum_{j=1}^{N} B_{ij} \left(\theta_i - \theta_j\right) \tag{2.3}$$

After calculation of bus angles, active power flows can be obtained by using (2.4).

$$P_{ij} = B_{ij} * \left(\theta_i - \theta_j\right) \tag{2.4}$$

2.3.3 Preliminary Work

In this thesis optimization problem of maintenance scheduling is solved. Therefore, it is assumed that the load and generation forecasts are available. In this section, the essential preliminary work procedure for the study is clarified.

In order to solve power flow equations for a system and get bus angles by using DC Power Flow algorithm, active power injections for each bus should be known except the slack bus. The active power injections at buses correspond to the generation and demand data of real system. Since the optimization study in this thesis is proposed for the following year, it requires prospective system information. Therefore, demand and generation forecast studies are mandatory besides topology information to prepare the essential data before starting the main study. Although, these studies seem to be under different scopes, the demand forecast information shapes the generation forecast study. Firstly, the demand forecast study is performed according to the time horizon and the total generation is dispatched according to the generation profiles of power plants.

Electrical demand forecast studies are of great importance for planning and operation of interconnected electrical systems. Electricity demand information for future may be utilized for generation and trading of electricity, investment plan for the expansion of the system or maintenance planning studies by generation, distribution, trading and transmission actors of the system. These studies can be categorized as short-term, medium-term and long-term forecast studies according to the length of the periods. The duration ranges of short-term demand forecast studies is up to one-week period, while it is up to one-year for medium-term and more than one-year for long-term studies. The scope of short-term studies involves contingency analysis and electricity pricing. Medium-term forecast studies might be performed for annual maintenance schedules and bilateral energy contracts. On the other hand, long-term demand studies may be preliminary works for investment or capacity expansion plans.

During the maintenance condition of the network, all of the load flow equations should be solved successfully as mentioned before. Therefore, active power injection at each bus for one-week resolution should be known considering the required data for power flow studies.

Several algorithms can be used for medium-term demand forecast studies. Comparisons and application areas of different algorithms can be found in [19]. Generally, Artificial Neural Network (ANN) method that is based on artificial intelligence gives more reliable predictions for medium-term studies than the other techniques. From the rule of generation and demand balance in an interconnected system, the predicted total power should be dispatched to the power plants for each week. In an interconnected system, there may be different power plants with different fuel types such as coal, gas, nuclear or renewable energy. Therefore, generation of power plants may differ within a year according to weather conditions or fuel prices. For the dispatch study, a comprehensive forecast study that includes past generations of plants for statistical information should be performed.

In this study, load demand and generation data of weekly peak demand hours in 2017 is utilized. The data is obtained from the Dispatcher Information System of Turkish Power System.

CHAPTER 3

PROPOSED METHODOLOGY FOR OPTIMAL MAINTENANCE SCHEDULING

In this chapter, the problem underlying maintenance scheduling study and solution methodology for this problem are explained comprehensively. At first, source of the problem and constraints, which should be taken into account before proposing a solution, are described. After that, objective of the study, preliminary work, theoretical background for solution and mathematical model of the problem are given.

3.1 Methodology

This part is composed of two sub-parts, which contain proposed methodology for solution and optimization model of the problem, respectively. Firstly, the general algorithm behind the major study is summarized in the first part. After that, construction of mathematical model of the problem is clarified in detail in the second part.

Before proposing a solution and starting maintenance scheduling of transmission lines study, the problem should be analyzed in depth. The objective, constraints and required data should be determined in order to develop a roadmap for the study. Firstly, the list of transmission lines in an electrical network, which are planned to be maintained, and estimated maintenance durations of them are essential to describe the problem. According to the estimated maintenance durations of transmission lines, the resolution of the study should be determined in the next step.

The factors that determine the maintenance durations are the actions during maintenances and the length of transmission lines. Each equipment in the system is monitored periodically and the applications in the scope of maintenance for the equipment is decided by regional operators. After that, regional operators determine the estimated durations for the necessary periodic maintenances of the equipment.

Generally, durations for periodic maintenances of transmission lines are observed as changing within one day to two weeks, when the historical data of Turkish Power System is examined. Since inventory information of branches is not available for this study, required applications and related durations cannot be determined. Therefore, the durations for maintenances are assigned to the branches with respect to their lengths considering the effect of field works. Hence, maintenance durations for transmission lines are determined as one, two and three weeks in accordance with their lengths to simplify the problem.

Maintenances that are shorter than one week are assumed as one week, between one and two weeks are assumed as two weeks and more than two weeks are assumed as three weeks. Furthermore, the excess of time durations provides flexibility to the operators to accomplish the maintenance within the scheduled period. After that, the one-year time horizon for the maintenance schedule is divided into weeks according to the maintenance duration assumptions. Similarly, the resolution of maintenance scheduling study for transmission lines is determined as one week, but each week is also split into two parts as weekdays and weekend in [17].

Since the outages of transmission lines for the maintenance conditions continue for one or two weeks in this study, differences in the topology occurs between the weeks throughout the year. Different study cases are built for each week and each study case represents whole of the corresponding week, because there is no change in the topology in one week according to this assumption. The purpose of the assumption is reducing the problem size and simplifying the problem. Besides, the most important requirement of the problem is that the electricity network, which will be in maintenance state due to the line outages, has to be operated without a trouble. This requirement corresponds to successful load flow calculations without violating restrictions of electricity networks in theoretical manner. Namely, all of the load flow equations must be satisfied during the maintenance of one or more transmission lines at the same time.

Alternative maintenance programs for transmission lines can be formed within a year with these basic requirements, which are maintenance durations and power flow equations. Therefore, an objective is defined and optimization study is carried out through the objective in this study. By the way, weekly topology, generation, demand data of the network and maintenance data of the transmission lines should be prepared before starting the optimization study. Maintenance types and durations of transmission lines are decided by the TSO, so the maintenance and base topology data is also provided by the TSO. However, the generation and demand data that are used for the power flow equations can be obtained by doing a preliminary forecast work.

The purpose of this study is defined as determination of the outage period of each transmission line in the system within a year in the scope of the objective function. In accordance with this purpose, on/off states of the transmission lines and the power flows over them for each week come up as unknowns of the optimization problem. Furthermore, constraints of the optimization problem are composed of maintenance requirements and operational limitations. According to the objective function and constraints, linear programming is selected as the optimization method, and then optimization problem is modeled.

As a result, the modeled problem is implemented and solved on computer environment. In conclusion, the maintenance schedule of transmission lines is obtained as the output of the optimization study. The flowchart of the study is given in Figure 3.

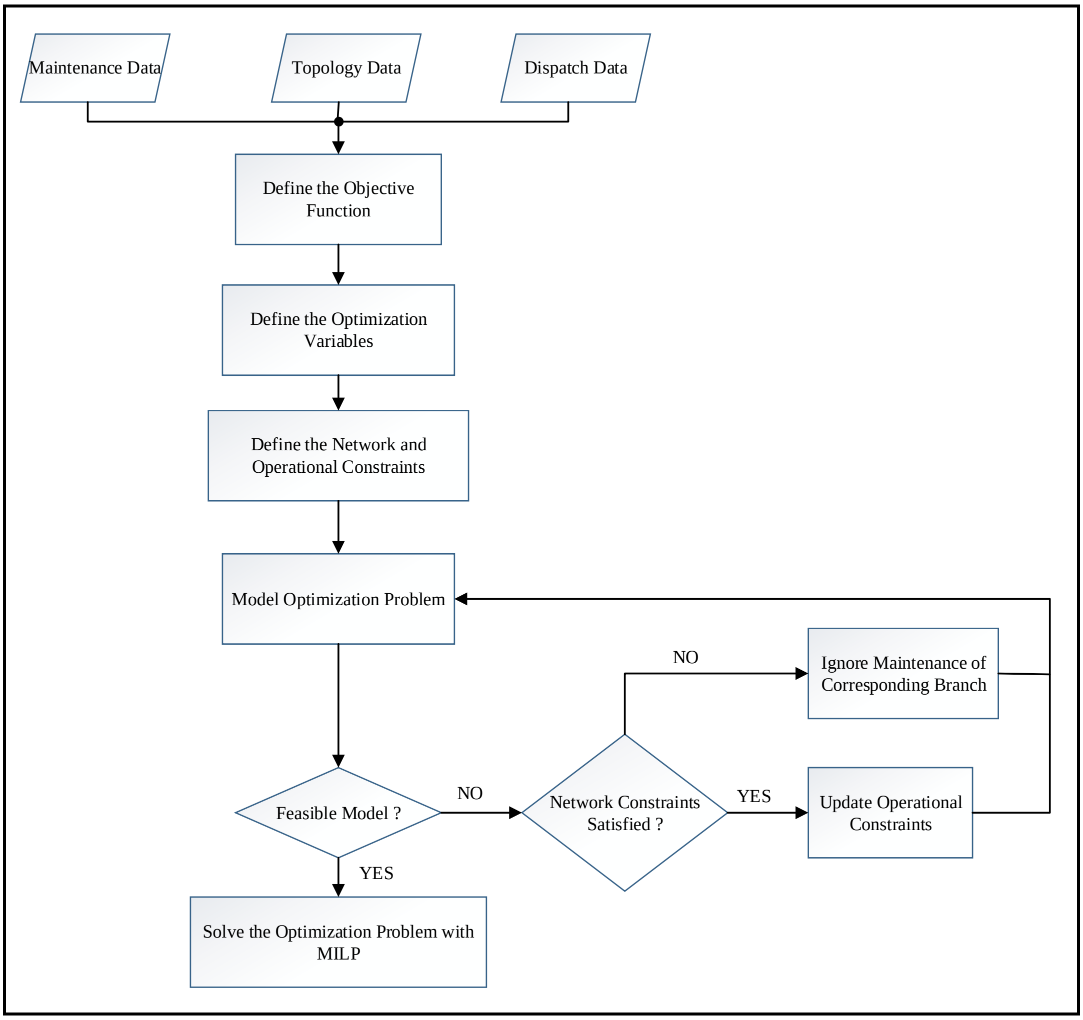

Figure 3. Transmission Line Maintenance Scheduling Process

3.2 Mathematical Optimization Model

The mathematical model of the optimization problem is composed of three bases, and these are objective function, constraint functions and optimization variables. Firstly, objective function and constraint functions are clearly defined. After that, the variables in order to model the functions are decided. Eventually, the mathematical model of the problem is formed. In the following parts, objective, constraints and variables of optimization problem are described first. Afterwards, modeling and mathematical expressions suitable for MATLAB environment are clarified.

In this study, the objective is defined as minimization of total time for maintenance state that the interconnected system in, while not interrupting reliability and market operation. In other words, maximization of the number of weeks in which all the transmission lines are in operation is targeted. The reasons to choose this objective function are listed below:

- to maximize duration of robust system operation,
- to minimize workload and cost of work,
- to create spare time for maintenance of other components.

Several constraints may be defined for this problem based on the operation. However, satisfying power flow equations for all weeks is prerequisite for reliable operation of a power system. This constraint also involves connectivity of the network; that is, no isolated areas are allowed within the scope of system operation. Operational constraints that are considered in this study are given below:

- Maintenance of predetermined lines: maintenance of transmission lines that are planned to be maintained should be completed within the time horizon.
- Continuity and duration of maintenances: required time duration should be reserved for each line and lines should be maintained in single step.
- Critical cases for double circuits: transmission lines of double circuits should not be maintained at the same time.

- Crew information: number of simultaneous maintenance cannot be greater than the number of crews.
- Seasonal choices for regions: maintenance conditions for specific regions can be prevented or preferred in different seasons.
- Operational limits: operational limits for branches should not be violated.

Optimization variables are defined according to the unknowns of the problem. The unknowns of the problem must be investigated in detail, because redundant variables enlarge the size of the problem and make it difficult to solve. The problem must not include a variable, which can be expressed with another one, so the functions should be expressed with minimum number of variables. In this study, the states of the branches, the bus angles, the branch flows and a variable to detect the system condition for each week are defined as the variables. For example, loading information should be calculated from branch flows instead of defining new variables if it is necessary.

Abbreviations that are used in the mathematical expressions are given below:

T : number of periods
N : number of buses in power network
L : number of branches in power network
L_m : number of branches to be maintained
d_i : maintenance duration of branch *i*
c_i : available number of crews for i^{th} region
x_i^t : state of i^{th} branch during t^{th} week (1: in service, 0: out of service)
x_{ij}^t : branch state between buses *i* and *j* during t^{th} week (1: in service, 0: out of service)
P_i^t : power flow on i^{th} branch during t^{th} week
P_{ij}^t : power flow on branch between buses *i* and *j* during t^{th} week
$P_{inj_i}^t$: injected power at bus *i* during t^{th} week
θ_i^t : angle value of i^{th} bus during t^{th} week
m^t : flag variable for system condition (1: no maintenance, 0: maintenance)

Construction of optimization model for problem is started with the optimization variables. Variable types and numbers are given in Table 1. Since the states of the transmission lines, which are not planned to be maintained, are 1 for all weeks within the year, dimensions of state and power flow variables are different. Similarly, a reference bus is selected for power flow equations, and angle of this bus is zero for all study cases. Therefore, number of variables for bus angles equal to $\mathrm{N} - 1$.

Table 1. Variable Structure of Optimization Problem

	Types	**Number of Variables**
Branch States	Integer	$T * L_m$
Bus Angles	Continuous	$T * (N - 1)$
Branch Flows	Continuous	$T * L$
Flag Variables	Integer	T

In order to model the objective function a binary variable that reveals the system condition during the corresponding week is defined. This flag variable takes 0 value if the system is in maintenance condition or 1 if there is no line in maintenance during the corresponding week. Therefore, maximizing the sum of flag variables or minimizing the sum of minus values of flag variables is the objective of this problem. Since, minimization term is frequently used for optimization processes, the statements in this study also formed according to minimization procedure. (3.1) represents the objective function of the problem. Determination of the value for flag variables is achieved by creating two additional constraint functions that are given in (3.2) and (3.3). These constraint functions force the flag variable to take its value according to the system condition. The value for state variable of a branch is 1 if the branch is in service and 0 otherwise as mentioned before. Therefore, these assignments for states result with equality of sum of branch states and number of lines to be maintained when no lines are in maintenance. (3.2) states that m variable for t^{th} week has to take 0 value if one or more lines are in maintenance, because left side of the inequality is nonzero for maintenance condition. However, the formulation does not guarantee taking value 1 for no maintenance condition. Thus, a second inequality is formed to satisfy the required condition. If, there is no maintenance in the power network, the right side of (3.3) is 0 and m should take value of 1 for t^{th} week.

$$minimize \qquad -\sum_{t=1}^{T} m^t \tag{3.1}$$

$$L_m - \sum_{i=1}^{L_m} x_i^t \leq L_m * (1 - m^t) \tag{3.2}$$

$$(1 - m^t) \leq L_m - \sum_{i=1}^{L_m} x_i^t \tag{3.3}$$

Power flow equations consist of bus and branch equations, hence *N* bus equations and *L* branch equations are formed for each week. In other words, power balance of system for time horizon is expressed with $\mathrm{T} * (\mathrm{N} + \mathrm{L})$ equalities and inequalities. Bus balance equations and branch flow equations are given in (3.4) and (3.5) correspondingly. As seen in the expressions, states of the branches are integrated into the power equations.

$$P_{inj_i}^t = \sum_{j=1}^{N} x_{ij}^t * B_{ij} * (\theta_i^t - \theta_j^t) \tag{3.4}$$

$$P_{ij}^t = x_{ij}^t * B_{ij} * (\theta_i^t - \theta_j^t) \tag{3.5}$$

where B_{ij} is the susceptance of line between buses i and j. (3.4) states that sum of injected active power amounts that are loads and generations at bus i is equal to the sum of power flow in bus i direction of online branches. Besides, each branch flow is expressed with (3.5). (3.4) is converted to (3.6) to simplify the implementation of model.

$$P_{inj_i}^t = \sum_{j=1}^{N} P_{ij}^t \tag{3.6}$$

When (3.5) is focused on, inclusion of two optimization variable can be seen. Multiplication of two or more unknowns makes a problem nonlinear and it cannot be solved with linear programming methods directly. Hence, possible linearization applications are applied as solutions for these situations. The nonlinear constraint (3.5) is replaced with following two linear constraints for linearization process.

$$-\left(1 - x_{ij}^t\right) * M_1 \leq P_{ij}^t - B_{ij} * \left(\theta_i^t - \theta_j^t\right) \leq (1 - x_{ij}^t) * M_1 \tag{3.7}$$

$$-x_{ij}^t * M_2 \leq P_{ij}^t \leq x_{ij}^t * M_2 \tag{3.8}$$

where M_1 and M_2 are large enough numbers. According to (3.7), branch flow $\mathrm{P}_{\mathrm{ij}}^{\mathrm{t}}$ has to be calculated as equal to the multiplication of susceptance of line and angle difference of buses when the branch is online and $\mathrm{x}_{\mathrm{ij}}^{\mathrm{t}}$ is equal to 1. On the other hand, (3.8) forces the branch flow to zero when the branch is in maintenance and $\mathrm{x}_{\mathrm{ij}}^{\mathrm{t}}$ is equal to 0. Through this assumption, M_1 should be selected large enough considering the worst case because angle difference between disconnected buses may not be small. M_2 can be selected as $\mathrm{P}_{\mathrm{max}}$ for the branch between buses i and j because result of this equation can take positive and negative branch capacity value according to the branch flow direction in the worst case. Furthermore, (3.8) also satisfies the operational limit constraints of branches.

Operational constraints that are mentioned before are also expressed and modeled with equalities and inequalities. (3.9) forces each branch to maintenance within the time horizon. This equation states that sum of the state values of branch i is equal to time horizon minus maintenance duration because state value is 0 for maintenance condition.

$$\sum_{t=1}^{T} x_i^t = T - d_i \tag{3.9}$$

If TSO wants to complete maintenance process of a branch in one-step, (3.10) can be used in order to achieve the constraint. However, special cases such as starting of maintenance during 1$^{\mathrm{st}}$ week or near last week should be taken into consideration. (3.11) and (3.12) are formed to integrate those cases to the model, respectively.

$$x_i^{t-1} - x_i^t + x_i^{t+d_i-1} \leq 1 \tag{3.10}$$

$$-x_i^t + x_i^{t+d_i-1} \leq 0 \tag{3.11}$$

$$x_i^{t+1} - x_i^{t+d_i-1} \leq 0 \tag{3.12}$$

where t is week number in range [2, ($time\ horizon - d_i + 1$)].

Maintenance of double circuit transmission lines can be assessed as special cases for a TSO. Although double circuits stand for connection between two buses, they are modeled with split branches in transmission system topologies. For example, branches i and j are assumed as double circuit connection between two buses in the system and the TSO do not want to lose connection between those two buses at any time. This requirement can be satisfied with (3.13). This constraint does not allow $\mathrm{x}_\mathrm{i}^\mathrm{t}$ and $\mathrm{x}_\mathrm{j}^\mathrm{t}$ to be 0 at same time. Although this constraint is formed for the maintenance of double circuits, it can be applied for two or more branches of transmission corridors of a system depends on the requirement of TSO.

$$x_i^t + x_j^t \geq 1 \tag{3.13}$$

Although central operator of TSO controls the system and decides operational conditions of system, there are regional directorates under the central operator for large power systems. These sub-operators are determine the applications and durations of maintenances, and inform central operator for maintenance scheduling of transmission lines. According to the schedule, sub-operators are responsible for maintenance processes of transmission lines. For the sub-operators of large power systems or single TSO for a small power system who are responsible for maintenances processes, number of crews may be a constraint to carry out the maintenances. That is, number of branches in maintenance condition cannot be larger than number of crews at a time. This constraint can be written as (3.14).

$$LR_i - c_i \leq \sum_{j=1}^{LR_i} xr_j^t \tag{3.14}$$

where $\mathrm{LR_i}$ is the number of branch which is in control area of region i and $\mathrm{xr_j^t}$ is the state of branch j. (3.14) means that sum of states of branches in region i can be as large as number of total branches in the region minus total crew number at least during a week. This constraint should be modeled for each region if the system is operated in above manner.

According to the seasonal conditions, generation and load profile may change in different regions, and reliable system operation may be a challenge for system operators. Hence, main or sub-operators want to hold the system in secure state and does not prefer maintenance state for those tough conditions. Similarly, weather conditions may not be convenient for fieldworks. This type of constraints can be expressed by (3.15) in accordance with the request. According to (3.15), sum of states of branches in region i should be equal to number of branches in that region for $\mathrm{t^{th}}$ week.

$$\sum_{j=1}^{LR_i} xr_j^t = LR_i \tag{3.15}$$

Since branch flows are defined as optimization variables, upper and lower bounds of variables can control loading conditions of branches. In addition, the constant M_2 in (3.8) is a limit for branch flows. M_2 and the bounds of variables should be consistent.

Mathematical expressions are formed and explained for objective and constraint functions. There are several tools in order to construct the optimization model and solve the problem in computer environment. For this study, MATLAB is used to form the optimization model due to simplicity of programming language, useful interface and opportunity to use alternative solvers inside the program. In fact, the problem is solved with IBM CPLEX toolbox of MATLAB.

Both MATLAB and IBM CPLEX requires an objective function, inequality constraints, equality constraints and upper/lower bounds of variables in suitable form in order to solve a linear optimization problem. Since, MATLAB is primarily based on matrices; required data for optimization problem should be prepared in matrix form. General structure of an optimization problem in MATLAB is given in (3.16). Mathematical expressions that are formed for the optimization data have to be converted into these forms.

$$\begin{aligned} &\textit{min} && f * x \\ &\textit{such that} && A_{ineq} * x \leq b_{ineq} \\ & && A_{eq} * x = b_{eq} \\ & && l_b \leq x \leq u_b \end{aligned} \tag{3.16}$$

where x and f corresponds to variable and scalar of objective function vector respectively. Moreover, $\mathrm{b_{ineq}}$, $\mathrm{b_{eq}}$, $\mathrm{l_b}$ and $\mathrm{u_b}$ are scalars. $\mathrm{A_{ineq}}$ and $\mathrm{A_{eq}}$ represents the constraint functions.

CHAPTER 4

CASE STUDY – TURKISH ELECTRIC GRID

In this chapter, application and results of the proposed methodology to the Turkish Electric Grid of 2017, are presented. In order to compare the application results with realization of system operation, historical data is selected for the case study application. Study cases for one-year time horizon is prepared in a suitable form to model the problem, and optimal maintenance schedule for transmission lines is obtained for system operation of 2017.

Turkish Electrical System consists of 66.285 km of transmission lines, 729 substations and 12 interconnection lines with neighbor power systems by the end of 2017. The installed generation capacity is 87.139 MW and peak demand of 2017 is 47.660 MW [20]. Transmission system operator of Turkish Power System is TEİAŞ, which consists of 10 sub-operators named as load dispatch directorates. One of them is the National Load Dispatch Center, that is the manager and decision-maker of the system, and the others are regional load dispatch directorates that are responsible for the operation of their own region. Maintenances of 380 kV transmission lines are scheduled by national load dispatch center according to the maintenance demands from regional directorates at beginning of each year. Maintenances of the other transmission lines at lower voltage levels are coordinated by regional load dispatch directorates.

The proposed methodology is applied to schedule the maintenance of 380 kV transmission lines of the system. Therefore, in this case study only 380 kV transmission network is considered. The electrical network with realized generation and load data is reduced to include only 380 kV level substations and transmission lines. Generations and loads at lower voltage levels aggregated and defined as power injections at 380 kV buses. Furthermore, transfer buses at substations that has main and transfer bus arrangement are eliminated to simplify the system. In addition, topology changes such as out of service or new transmission system equipment within 2017 are eliminated because operational changes cannot be foreseen and are not considered for planning studies. By the way, effects of new equipment in transmission system are not in the scope of this study. After reduction process, bus groups are formed that are connected to the remaining of the network through single 380 kV transmission line. Normally, the connection would be provided by 154 kV transmission level, when this single 380 kV transmission line is out of service during maintenance. However, connectivity of the power network would be violated during maintenance of the branch for this study, because other voltage levels are not included in the optimization model. Thus, virtual transmission lines that are parallel with the lines in that condition are added to the network in order to satisfy the connectivity constraint of problem. Seven transmission lines were in this situation after reduction process, so new transmission lines with high impedances are incorporated into the system. Minimum 10 times of the reactance of parallel line is defined as reactance value to each virtual line in order not to affect the scheduled power flows. The redundant transmission lines are not taken into consideration for maintenance in the study. Besides that, the model involves five interconnection transmission lines that are in service. Maintenances of the interconnection lines are also not considered in the scope of the study. As a result, 53 study cases for each week with 158 buses and 264 transmission lines are formed for the study.

Data imported to construct the optimization model includes the following information:

- Topology Data: bus, branch, demand and generation dispatch information.
- Region Data: branches under regional directorates, crew information and seasonal preferences.
- Maintenance Data: branches to be maintained and maintenance durations.

Generation and load data is acquired from Load Dispatcher Information System of Turkey's power grid. Snapshot of peak demand hour for each week is selected to represent the whole week in order to consider the worst-case conditions. Otherwise, constraints, which are based on branch capacities, may be violated with scheduled maintenances for higher system loading conditions than the planned one. At first, days are grouped according to their week numbers in the year; then, peak demand hour of the week is obtained from these groups. According to the numeration of Microsoft Excel, days are clustered into 53 weeks, so 53 study cases including realized generation and load data are obtained. However, amount of demand and generation in the system is decreased due to aggregation at lower levels during reduction process of topology. For example, 100 MW generation and 50 MW load at 34.5 kV bus at a substation is reflected as 50 MW generation to the 380 kV bus of that substation. Load profile of reduced Turkish Electrical Network within 2017 is given in Figure 4.

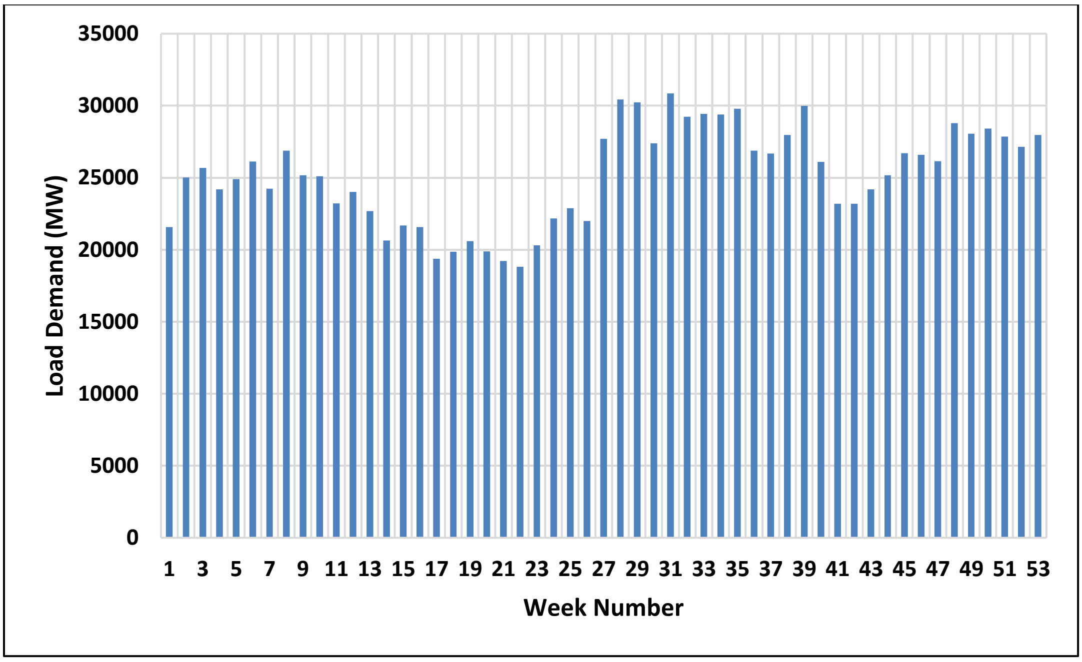

Figure 4. Weekly Peak Demand of Reduced Turkish Electrical System

There are nine regional load dispatch directorates in Turkish Electrical System and each of them is responsible for reliable operation of their own region in coordination with the other regions. These regions are split according to their geographic locations and they can be seen in Figure 5.

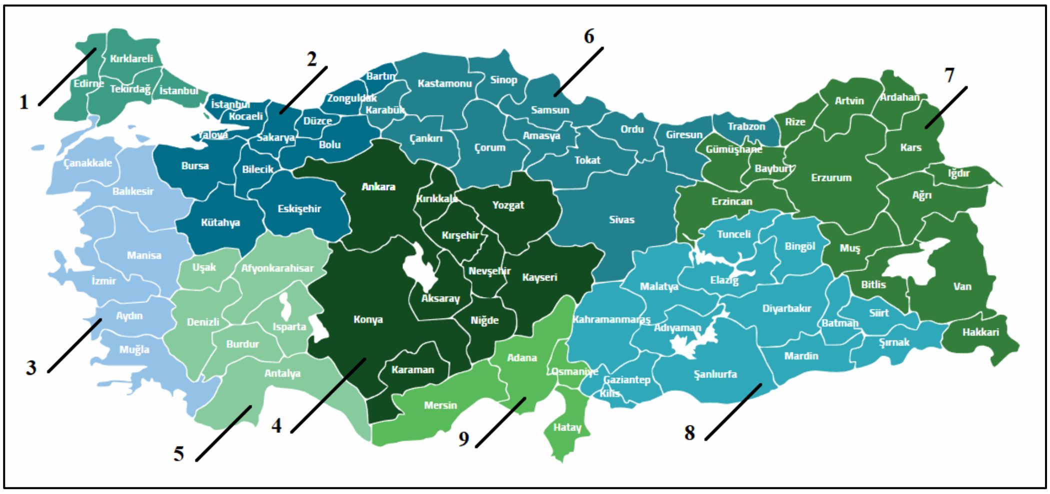

Figure 5. Map of Regional Load Dispatch Directorates [21]

In addition, number of branches under responsibility of each region are shown in Table 2.

Table 2. Branch Groups According to the Regions

Region	**Number of Branches**	**Region**	**Number of Branches**	**Region**	**Number of Branches**
1	27	4	40	7	19
2	42	5	21	8	41
3	33	6	24	9	17

Turkish Electrical System has changeable demand and generation characteristics with different climate conditions. Although, northwestern and western regions have become the most power demanding bases of the country due to increase of population and industrial plants near that regions, power demand dramatically increases near coastlines in west and south with growth in tourism in summer. Besides that, power generation is mainly supplied by hydropower during spring season, and hydro power plants are generally located in eastern parts of the country. As a result, Turkish Power System is generally split into demand and generation bases in western and eastern regions respectively, and operation of the transmission corridors between these regions is of great importance in spring seasons. Apart from these, climate conditions may restrain transportation facilities in eastern region of the country. For these reasons, regional operators may prefer shifting maintenances to periods when the system conditions are more flexible. Based on these situations, regional constraint scenarios are created and modeled to the problem due to inconvenience conditions for fieldwork and in order not to cause bottlenecks in the system. These constraints are listed below:

- Spring season is not preferred for regions 6 and 8: weeks 11 to 26.
- Spring and winter seasons are not preferred for region 7: weeks 1 to 26 and weeks 50 to 53.
- Peak demand weeks are not preferred for region 4: weeks 28 to 39 and weeks 48 to 53.
- Summer season is not preferred for regions 3,5 and 9: weeks 27 to 41.

With the increase of temperatures after winter season, power generation of hydropower plants increases. This situation caused by the increase of water volume behind dams and flow rate of rivers with snowmelt. Figure 6 indicates the power generation trend of eastern region 6, region 7 and region 8 through 2016. Run-of-river type hydropower plants generally located around eastern part of region 6 and region 7, so higher generation potential during spring season can be seen from the diagram. Similarly, power generation tends to increase during spring season in region 8. In addition, region 8 also contributes total generation during peak demand periods. Consequently, transmission of power from these regions is generally provided by the power transfer corridors over region 6 and 4. Transmission lines over region 6 is of great importance to transfer generated power by run-of-river type hydropower plants. On the other hand, transmission corridors over region 4 constitutes the backbone of Turkish Electric Grid not only for spring season conditions but also for peak demand conditions. Moreover, fieldwork and transportation might become impossible because of harsh weather conditions in region 7 in winter. As a result, above three scenarios are created to make the problem more realistic.

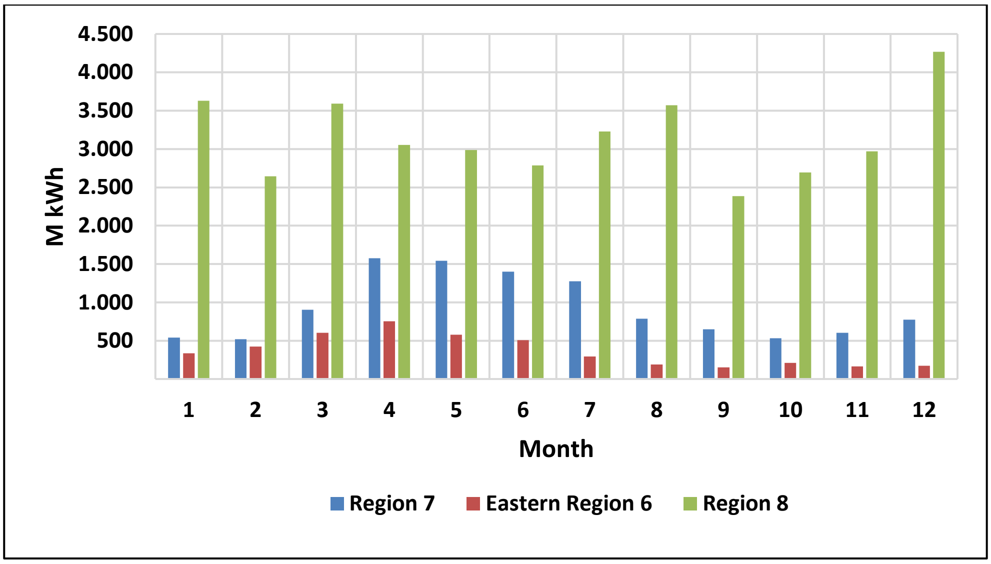

Figure 6. Power Generation Profile of Regions 6, 7 and 8 through 2016

Power demand variations of regions 3, 5 and 9 with respect to the months are shown in Figure 7. As mentioned before, electricity dissipation grows during summer season due to overpopulation. In order not to cause any interruption, regional operators do not prefer to lose transmission alternatives or decrease transmission capacities in the region during loaded system conditions. Therefore, this situation is also defined as a constraint to the problem and modeled.

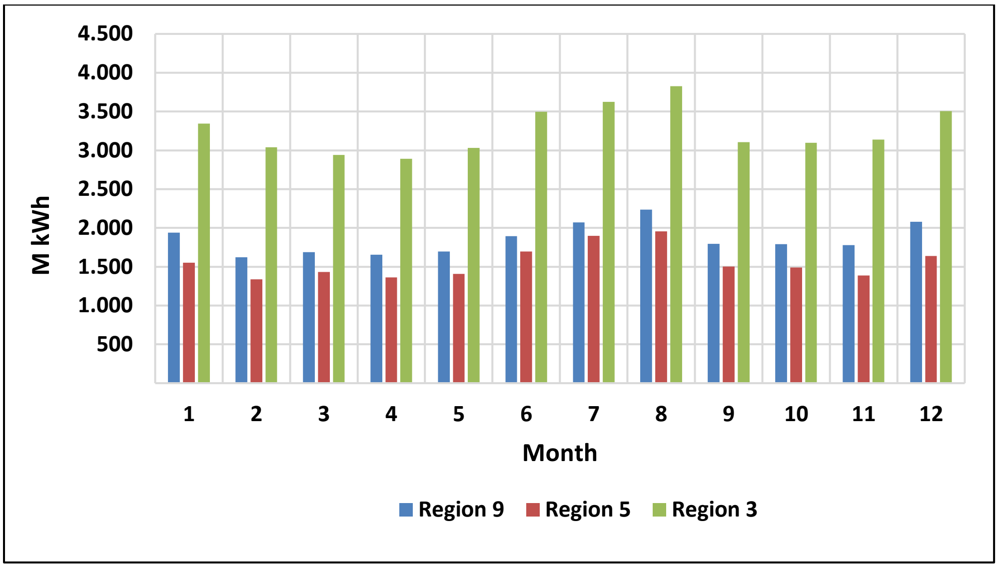

Figure 7. Power Demand Profile of Regions 3, 5 and 9 through 2016

Due to the virtual and interconnection transmission lines, 252 transmission lines remained for maintenance among the lines in the system. Length and maintenance duration information of the branches are given in Table 3. Maintenance durations of transmission lines are determined with respect to their lengths. In this context, maintenance durations of transmission lines whose length is smaller than 150 km, between 150 and 300 km and larger than 300 km are defined as 1 week, 2 weeks and 3 weeks respectively.

Table 3. Length and Maintenance Duration Information of Branches in the System

Length	Number	Maintenance Duration
< 150 km	206	1 Week
150 km - 300 km	45	2 Weeks
> 300 km	1	3 Weeks

4.1 Model Implementation

In this part creation of optimization variables, objective function and constraint functions suitable for MATLAB are clarified and illustrated.

Variable vector X holds the variables of optimization problem and the variables take optimal values when the solution converges to the optimal point. Structure of constructed X vector for this problem is given in (4.1). Furthermore, explanations are also given below.

$$X = \begin{bmatrix} \boldsymbol{x_i^t} \\ \boldsymbol{\theta_i^t} \\ \boldsymbol{P_l} \\ \boldsymbol{m^t} \end{bmatrix} \tag{4.1}$$

where,

- $\mathbf{x_i^t}$ is $(L_m * T)$ x 1 branch state vector. The order of variables in the vector is in the form of $x_1^1\ x_1^2\ \ldots\ x_1^{53}\ \ldots\ldots\ldots x_{252}^1\ x_{252}^2\ \ldots\ x_{252}^{53}$. State variables are created as integer variables, and lower and upper bounds are defined as 0 and 1 respectively.
- $\boldsymbol{\theta_i^t}$ is $(T * (N-1))$ x 1 bus angle vector. The order of variables in the vector is in the form of $\theta_1^1\ \theta_2^1\ \ldots\ \theta_{158}^1\ \ldots\ldots\ldots \theta_1^{53}\ \theta_2^{53}\ \ldots\ \theta_{158}^{53}$. Angle values are used in radian, so lower and upper bounds are defined as -3 and 3 respectively.
- $\mathbf{P_l}$ is $(L * T)$ x 1 branch flow vector. The order of variables in the vector is in the form of $P_1^1\ P_1^2\ \ldots\ P_1^{53}\ \ldots\ldots\ldots P_{264}^1\ P_{264}^2\ \ldots\ P_{264}^{53}$. Lower and upper bounds for branch flows are defined as $-P_{max}$ and P_{max} of branches.
- $\mathbf{m^t}$ is T x 1 flag variable vector. The order of variables in the vector is in the form of $m^1 m^2\ \ldots\ m^{53}$. Flag variables are created as integer variables, and lower and upper bounds are defined as 0 and 1 respectively.

L_m, L, N and T are equal to 252, 264, 158 and 53 respectively, so number of optimization variables is equal to 35722 for this case study.

The structure of the f vector and objective function ($f * X$) to be minimized is given in (4.2) and (4.3). Optimization function only includes the flag variable that is defined to determine the system condition. Therefore, corresponding multipliers of the other variables are 0 in f vector. The bold type values in f vector represents the value of whole sub-vector.

$$\boldsymbol{f} = \begin{bmatrix} \mathbf{0}_{(T*L_m)\text{ x }1} \\ \mathbf{0}_{(T*(N-1))\text{ x }1} \\ \mathbf{0}_{(T*L)\text{ x }1} \\ -\mathbf{1}_{T\text{ x }1} \end{bmatrix} \tag{4.2}$$

$$\begin{bmatrix} \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{-1} \end{bmatrix} \begin{bmatrix} \boldsymbol{x_{ij}^t} \\ \boldsymbol{\theta_i^t} \\ \boldsymbol{P_l} \\ \boldsymbol{m^t} \end{bmatrix} = \begin{bmatrix} -1 * \sum_{t=1}^{T} m_t \end{bmatrix} \tag{4.3}$$

(3.2) and (3.3) that force the flag variables to take the right value are converted to suitable forms as below for optimization model. Furthermore, implementations in matrix form are given in (4.6) and (4.7). These illustrations only represent the equations of 1st week, so 52 more equations are created for complete model of each constraint. For example, -1 and 0 values in (4.6) and (4.7) represent the multipliers of the branch state variables; that is, state of each branch for the first week multiplied by -1. At the same time, the indicator variable for the first week is multiplied by 252 that is the total number of branches to be maintained. As a result, $-x_1^1 - x_2^1 - x_3^1 - x_4^1 \ldots - x_{252}^1 + 252 \times m^1 \leq 0$ is obtained with (4.6).

$$L_m * m^t - \sum_{i=1}^{L_m} x_i^t \leq 0 \tag{4.4}$$

$$-m^t + \sum_{i=1}^{L_m} x_i^t \leq L_m - 1 \tag{4.5}$$

$$\begin{bmatrix} -1\ 0\ldots0\ -1\ 0\ldots0\ \ldots\ldots\ -1\ 0\ldots0 & \mathbf{0} & \mathbf{0} & 252\ 0\ \ldots\ 0 \end{bmatrix} \begin{bmatrix} \boldsymbol{x_{ij}^t} \\ \boldsymbol{\theta_i^t} \\ \boldsymbol{P_l} \\ \boldsymbol{m^t} \end{bmatrix} \leq \begin{bmatrix} 0 \end{bmatrix} \tag{4.6}$$

$$\begin{bmatrix} 1\ 0\ldots0\ 1\ 0\ldots0\ \ldots\ldots\ 1\ 0\ldots0 & \mathbf{0} & \mathbf{0} & -1\ 0\ldots0 \end{bmatrix} \begin{bmatrix} \boldsymbol{x_{ij}^t} \\ \boldsymbol{\theta_i^t} \\ \boldsymbol{P_l} \\ \boldsymbol{m^t} \end{bmatrix} \leq \begin{bmatrix} 251 \end{bmatrix} \tag{4.7}$$

Linearized power flow equations are split and converted to (4.8), (4.10), (4.12) and (4.14) that are given below. Moreover, the equations are illustrated in matrix forms in (4.9), (4.11), (4.13) and (4.15). Illustration is based on an example and line in the example is not from the case study model. The matrices are formed for a power flow over line between buses 1 and 2 of a fictitious system during 1^{st} week. M_1 is selected as 10^7 for this study because maximum scalar value computed 5428100 as multiplier for angle difference during maintenance conditions in the left side of equation. Moreover, branch capacity values are assigned to M_2 constants in equations (4.12) and (4.14). Ratings for transmission lines change according to weather temperature, hence ratings are multiplied by seasonal derating factors that are given in Appendix A. Similar equations are formed in matrix form for power flow of each branch for each week.

$$P_{ij}^t - B_{ij} * \theta_i^t + B_{ij} * \theta_j^t + x_{ij}^t * M_1 \leq M_1 \qquad (4.8)$$

$$\begin{bmatrix} M_1\ 0\ldots0 & -B_{12}\ B_{12}\ 0\ \ldots\ 0 & 1\ 0\ldots0 & \mathbf{0} \end{bmatrix} \begin{bmatrix} \boldsymbol{x_{ij}^t} \\ \boldsymbol{\theta_i^t} \\ \boldsymbol{P_l} \\ \boldsymbol{m^t} \end{bmatrix} \leq \begin{bmatrix} M_1 \end{bmatrix} \qquad (4.9)$$

$$-P_{ij}^{t} + B_{ij} * \theta_i^t - B_{ij} * \theta_j^t + x_{ij}^t * M_1 \leq M_1 \qquad (4.10)$$

$$\begin{bmatrix} M_1\ 0\ldots0 & B_{12}\ -B_{12}\ 0\ \ldots\ 0 & \text{-}1\ 0\ldots0 & \mathbf{0} \end{bmatrix} \begin{bmatrix} \boldsymbol{x_{ij}^t} \\ \boldsymbol{\theta_i^t} \\ \boldsymbol{P_l} \\ \boldsymbol{m^t} \end{bmatrix} \leq \begin{bmatrix} M_1 \end{bmatrix} \qquad (4.11)$$

$$P_{ij}^t - x_{ij}^t * M_2 \leq 0 \qquad (4.12)$$

$$\begin{bmatrix} -M_2\ 0\ldots0 & \mathbf{0} & 1\ 0\ldots0 & \mathbf{0} \end{bmatrix} \begin{bmatrix} \boldsymbol{x_{ij}^t} \\ \boldsymbol{\theta_i^t} \\ \boldsymbol{P_l} \\ \boldsymbol{m^t} \end{bmatrix} \leq \begin{bmatrix} 0 \end{bmatrix} \qquad (4.13)$$

$$-P_{ij}^t - x_{ij}^t * M_2 \leq 0 \tag{4.14}$$

$$\begin{bmatrix} -M_2\ 0\ldots0 & \mathbf{0} & -1\ 0\ldots0 & \mathbf{0} \end{bmatrix} \begin{bmatrix} \boldsymbol{x_{ij}^t} \\ \boldsymbol{\theta_i^t} \\ \boldsymbol{P_l} \\ \boldsymbol{m^t} \end{bmatrix} \leq \begin{bmatrix} 0 \end{bmatrix} \tag{4.15}$$

Simplified bus balance expression is converted to (4.16). Matrix formation of the expression is also given in (4.17). Matrix is formed for an example balance equation of bus 1 during first week that is connected to the system with branches 1 and 2. Similar expressions are also created in matrix form for the 157 buses and 53 weeks.

$$\sum_{j=1}^{N} P_{ij}^t = P_{inj_i}^t \tag{4.16}$$

$$\begin{bmatrix} \mathbf{0} & \mathbf{0} & 1\ 0\ldots0\ \ 1\ 0\ldots0\ 0\ldots\ldots\ 0 & \mathbf{0} \end{bmatrix} \begin{bmatrix} \boldsymbol{x_{ij}^t} \\ \boldsymbol{\theta_i^t} \\ \boldsymbol{P_l} \\ m^t \end{bmatrix} = \begin{bmatrix} P_{inj_1}^1 \end{bmatrix} \tag{4.17}$$

The constraint that guarantees realization of maintenances of branches is expressed and illustrated below. Expression for first branch is presented in matrix form, and 52 more equations are created for complete model of this constraint.

$$\sum_{t=1}^{53} x_1^t \ = 53 - d_i \tag{4.18}$$

$$\begin{bmatrix} 1\ 1 \ldots 1\ \ 0 \ldots\ldots 0 & \mathbf{0} & \mathbf{0} & \mathbf{0} \end{bmatrix} \begin{bmatrix} \boldsymbol{x_{ij}^t} \\ \boldsymbol{\theta_i^t} \\ \boldsymbol{P_l} \\ \boldsymbol{m^t} \end{bmatrix} \leq \begin{bmatrix} 53 - d_i \end{bmatrix} \tag{4.19}$$

Constraints expressed in (3.10), (3.11) and (3.12) for continuous maintenance operation are illustrated for an example branch whose maintenance duration is 3 weeks. In this example, time horizon is 10 weeks; that is, maintenance for a period of 3 weeks in 10 weeks horizon is modeled. For the branch, formed 10 equations that is given below guarantees the continuity of maintenance. Therefore, 53 equations are formed in matrix form for each branch whose maintenance duration is more than 1 week in this study.

$$\left[\begin{array}{c|c|c|c} \begin{array}{l} -1\ 0\ 1\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ \ 0 \ldots\ldots 0 \\ 1\ -1\ 0\ 1\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ \ 0 \ldots\ldots 0 \\ 0\ 1\ -1\ 0\ 1\ 0\ 0\ 0\ 0\ 0\ 0\ \ 0 \ldots\ldots 0 \\ 0\ 0\ 1\ -1\ 0\ 1\ 0\ 0\ 0\ 0\ 0\ \ 0 \ldots\ldots 0 \\ 0\ 0\ 0\ 1\ -1\ 0\ 1\ 0\ 0\ 0\ 0\ \ 0 \ldots\ldots 0 \\ 0\ 0\ 0\ 0\ 1\ -1\ 0\ 1\ 0\ 0\ 0\ \ 0 \ldots\ldots 0 \\ 0\ 0\ 0\ 0\ 0\ 1\ -1\ 0\ 1\ 0\ 0\ \ 0 \ldots\ldots 0 \\ 0\ 0\ 0\ 0\ 0\ 0\ 1\ -1\ 0\ 1\ \ 0 \ldots\ldots 0 \\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 1\ -1\ 0\ \ 0 \ldots\ldots 0 \\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 1\ -1\ \ 0 \ldots\ldots 0 \end{array} & \mathbf{0} & \mathbf{0} & \mathbf{0} \end{array}\right] \left[\begin{array}{c} \boldsymbol{x_{ij}^t} \\ \hline \boldsymbol{\theta_i^t} \\ \hline \boldsymbol{P_l} \\ \hline \boldsymbol{m^t} \end{array}\right] \leq \left[\begin{array}{c} 0 \\ 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 0 \\ 0 \end{array}\right] \tag{4.20}$$

Constraint that is defined for critical cases such as maintenance of double circuits at same time is formed in matrix form and given in (4.22). 29 critical cases are modeled to the problem in this study as below.

$$-x_i^t - x_j^t \leq -1 \tag{4.21}$$

$$\left[\begin{array}{c|c|c|c} -1\ 0\ldots0\ \ -1\ 0\ldots0\ 0\ldots\ldots\ 0 & \mathbf{0} & \mathbf{0} & \mathbf{0} \end{array}\right] \left[\begin{array}{c} \boldsymbol{x_{ij}^t} \\ \hline \boldsymbol{\theta_i^t} \\ \hline \boldsymbol{P_l} \\ \hline \boldsymbol{m^t} \end{array}\right] \leq \left[\begin{array}{c} -1 \end{array}\right] \tag{4.22}$$

Number of crews are defined as two for each region in this study and this limitation is modeled to the problem in matrix form as in (4.24). This illustration is based on a virtual region that involves branches 1, 2 and 3. Furthermore, number of crew is 1 for the region.

$$-\sum_{j=1}^{LR_i} xr_j^t \leq -LR_i + c_i \tag{4.23}$$

$$\begin{bmatrix} \text{-1 0…0 -1 0…0 -1 0…0 0…… 0} & \mathbf{0} & \mathbf{0} & \mathbf{0} \end{bmatrix} \begin{bmatrix} \boldsymbol{x_{ij}^t} \\ \boldsymbol{\theta_i^t} \\ \boldsymbol{P_l} \\ \boldsymbol{m^t} \end{bmatrix} \leq \begin{bmatrix} -2 \end{bmatrix} \tag{4.24}$$

Finally, seasonal preferences are implemented as in (4.26). This illustration is based on a virtual region that involves branches 1, 2 and 3. For the first week, no maintenance is allowed by the regional operator in this example.

$$\sum_{j=1}^{LR_i} xr_j^t = LR_i \tag{4.25}$$

$$\begin{bmatrix} \text{1 0…0 1 0…0 1 0…0 0…… 0} & \mathbf{0} & \mathbf{0} & \mathbf{0} \end{bmatrix} \begin{bmatrix} \boldsymbol{x_{ij}^t} \\ \boldsymbol{\theta_i^t} \\ \boldsymbol{P_l} \\ \boldsymbol{m^t} \end{bmatrix} = \begin{bmatrix} 3 \end{bmatrix} \tag{4.26}$$

Summary for the mathematical model of the problem is given in Table 4.

Table 4. Summary of the Mathematical Model of the Optimization Problem

Model Components	**Explanation**	**Symbol**	**Dimension**
Variables	States and PF Results	X	35722x1
Obj. Function	Min. Duration of Maintenance State	f	1x35722
Constraint	Critical Cases	$A1$	1537x35722
Constraint	Critical Cases	$b1$	1537x1
Constraint	Number of Crews	$A2$	477x35722
Constraint	Number of Crews	$b2$	477x1
Constraint	Continuity of Maintenance	$A3$	2438x35722
Constraint	Continuity of Maintenance	$b3$	2438x1
Constraint	Branch Flow Equation	$A4$	13992x35722
Constraint	Branch Flow Equation	$b4$	13992x1
Constraint	Branch Flow Equation	$A5$	13992x35722
Constraint	Branch Flow Equation	$b5$	13992x1
Constraint	Branch Flow Equation	$A6$	13992x35722
Constraint	Branch Flow Equation	$b6$	13992x1
Constraint	Branch Flow Equation	$A7$	13992x35722
Constraint	Branch Flow Equation	$b7$	13992x1
Constraint	Bus Balance Equation	$A8$	8374x35722
Constraint	Bus Balance Equation	$b8$	8374x1
Constraint	Bus Balance Equation	$A9$	8374x35722
Constraint	Bus Balance Equation	$b9$	8374x1
Constraint	Constraint for Flag Variable	$A10$	53x35722
Constraint	Constraint for Flag Variable	$b10$	53x1
Constraint	Constraint for Flag Variable	$A11$	53x35722
Constraint	Constraint for Flag Variable	$b11$	53x1
Constraint	Maintenance Duration	$Aeq1$	252x35722
Constraint	Maintenance Duration	$beq1$	252x1
Constraint	Angle of Slack Bus	$Aeq2$	53x35722
Constraint	Angle of Slack Bus	$beq2$	53x1
Constraint	Seasonal Preference	$Aeq3$	166x35722
Constraint	Seasonal Preference	$beq3$	166x1

4.2 Results

In this section results of the case study are given in detail. Furthermore, results of an alternative scenario that is studied to see the effect of crew number are presented. The optimization problem was solved with IBM CPLEX toolbox of MATLAB 2016 on a computer with four processors clocking at 3.4 GHz and 24 GB of RAM. The optimum solution was reached after approximately 45 hours.

Firstly, maintenance schedule of all transmission lines is presented, and then results of maintenances based on region and week information are presented. Finally, summary of maintenances in Turkish Electrical System is given.

Maintenance periods of branches are listed in Table 5.

Table 5. Maintenance Periods of Transmission Lines

Branch	**Region**	**Maint. Week**	**Branch**	**Region**	**Maint. Week**	**Branch**	**Region**	**Maint. Week**
1	1	23	21	1	24	40	2	15
2	1	43	22	1	8	41	2	40
3	1	8	23	1	40	42	2	5
4	1	4	24	1	3	43	2	23
5	1	47	25	1	1	44	2	35
6	1	45	26	1	45	45	2	46
7	1	6	27	1	44	46	2	25
8	1	42, 43	28	1	1	47	2	1, 2
11	1	6	29	1	40	48	2	48
13	1	5	30	1	27	49	2	47
14	1	25, 26	31	1	47	50	2	36
15	3	6	32	2	44, 45	51	2	10
16	3	26	33	2	7	52	2	23
17	3	8	34	2	1	53	2	8
18	3	45	35	2	26	54	4	18
19	1	44	38	2	43	55	4	2, 3
20	1	35	39	2	10	56	2	48

Branch	Region	Maint. Week	Branch	Region	Maint. Week	Branch	Region	Maint. Week
57	2	14, 15	97	3	15	138	4	47
58	2	36	98	3	25	139	4	42
59	2	35	99	3	7	140	4	25
60	2	26, 27	100	3	23	141	4	47
61	2	21	102	3	14	142	4	20
62	2	41	103	3	48	143	4	43
63	2	24	104	3	1	144	4	21
64	2	40	105	3	6	145	4	23
65	2	46	106	3	5	146	4	9, 10
66	2	25	107	3	21	147	4	26, 27
67	2	44	108	3	21	148	4	40, 41
68	3	47	109	5	48	149	4	42
69	2	2	110	3	42	150	5	48
70	3	24	111	4	3	151	5	4, 5
71	2	5	112	4	45, 46	152	5	9
72	2	41	113	4	20	153	5	21
73	3	24, 25, 26	114	4	10	154	5	14
74	5	3	115	4	4	155	5	25, 26
75	4	6	116	4	14, 15	156	5	6
76	2	7	117	4	5, 6	157	5	7
77	4	9	118	4	24	158	5	46
78	2	21	119	4	23	159	5	23
79	2	17	120	4	17, 18	161	5	47
80	2	24	121	4	14, 15	162	5	43, 44
81	4	7, 8	122	4	45, 46	163	5	46
82	6	45, 46	123	4	1	164	5	44
83	2	27	124	4	26, 27	165	5	4, 5
84	3	18	125	4	1, 2	166	5	2, 3
85	3	20	126	4	7, 8	167	5	26
86	3	46	127	6	4	168	5	14
87	3	42, 43	128	6	36	169	6	4
88	3	17	129	6	47, 48	170	6	46
89	3	17	130	4	17	171	6	9
90	3	45	131	4	4	172	6	41
91	3	2	132	4	5	173	6	2, 3
92	3	15	133	6	8, 9	174	6	2, 3
93	3	5	134	4	24, 25	175	6	42
94	3	4	135	4	40, 41	176	6	41
95	3	20	136	4	44	177	6	1
96	3	44	137	4	43, 44	178	6	35, 36

Branch	Region	Maint. Week	Branch	Region	Maint. Week	Branch	Region	Maint. Week
179	6	5	209	8	44	236	8	42
180	6	35	210	8	46	237	8	5
181	6	47	211	8	36	238	8	47
182	6	44	212	8	2	239	8	7
183	6	8	213	8	6	240	8	1
184	6	1	214	8	41	241	8	48
185	6	42	215	8	6	242	8	4
186	6	48	216	8	46	245	8	40
187	6	10	217	8	45	246	8	8
188	7	35, 36	218	8	7, 8	247	8	27
189	7	35	219	8	2	248	9	3
190	7	43	220	8	47	249	9	8
191	7	44, 45	221	8	35	250	9	3
192	7	46, 47	222	8	43	251	9	17
193	7	40	223	8	45	252	9	10
195	7	41, 42	224	8	9, 10	253	9	7
197	7	44, 45	225	8	3, 4	254	9	15
198	7	36	226	8	5	255	9	15
199	7	48	227	8	3	256	9	26
200	7	40	228	8	35	257	9	8
201	7	47, 48	229	8	48	258	9	21
203	7	27	230	8	1	259	9	46
204	7	42	231	8	44	260	9	4
205	7	27	232	8	10	261	9	45
206	7	43	233	8	43	262	9	7
207	8	41, 42	234	8	27	263	9	10
208	8	9	235	8	40	264	9	45

Numbers of scheduled lines for maintenances in Region 1 and Region 2 during each week are shown in Figure 8 and Figure 9, respectively.

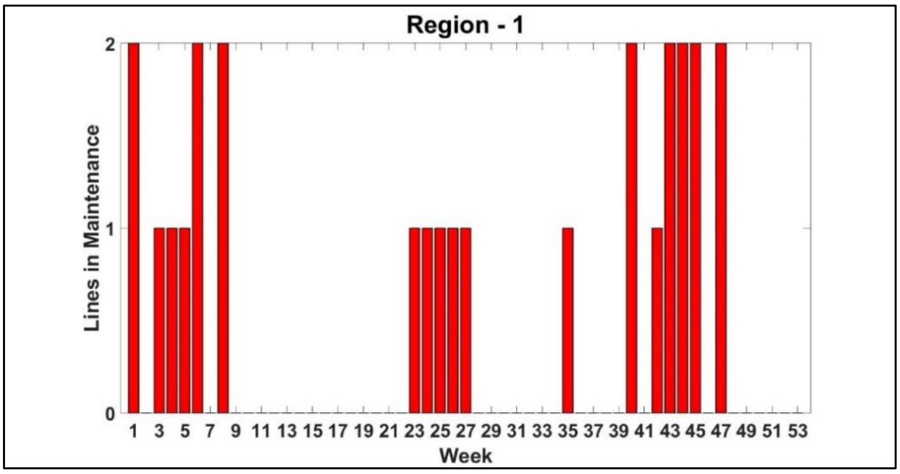

Figure 8. Distribution of Line Maintenances within Year - Region 1

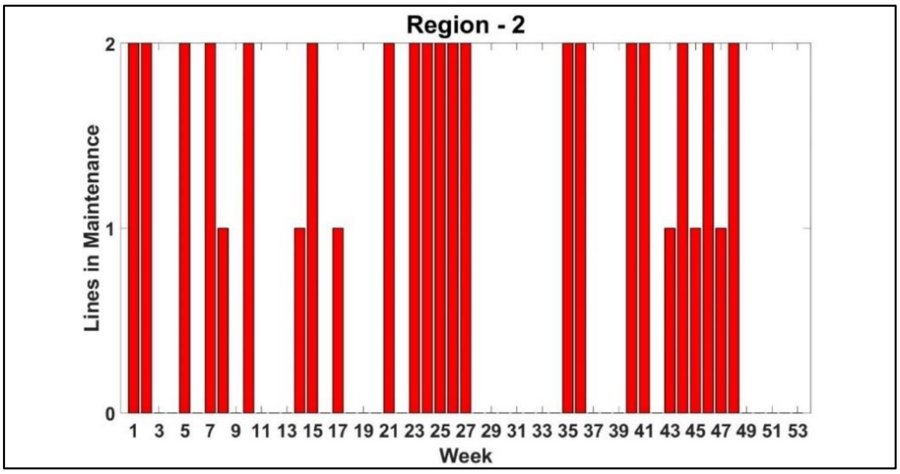

Figure 9. Distribution of Line Maintenances within Year - Region 2

Numbers of scheduled lines for maintenance in Region 3 and Region 4 during each week are shown in Figure 10 and Figure 11 respectively.

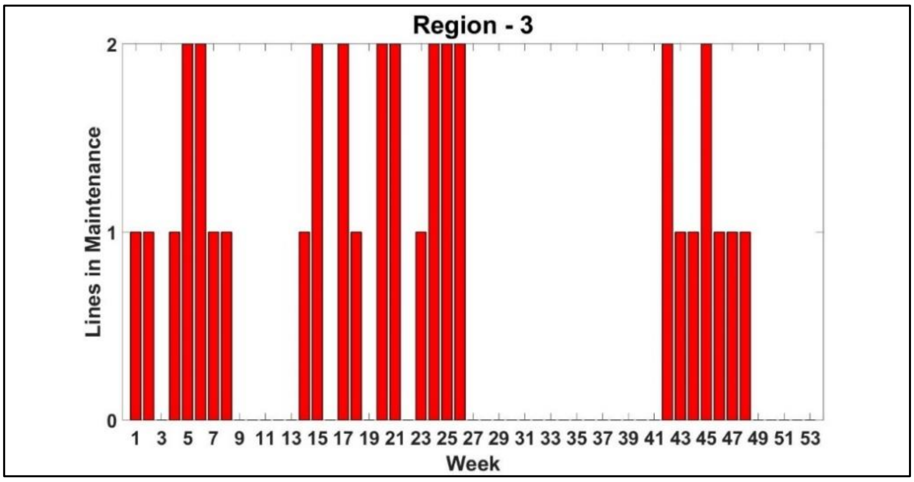

Figure 10. Distribution of Line Maintenances within Year - Region 3

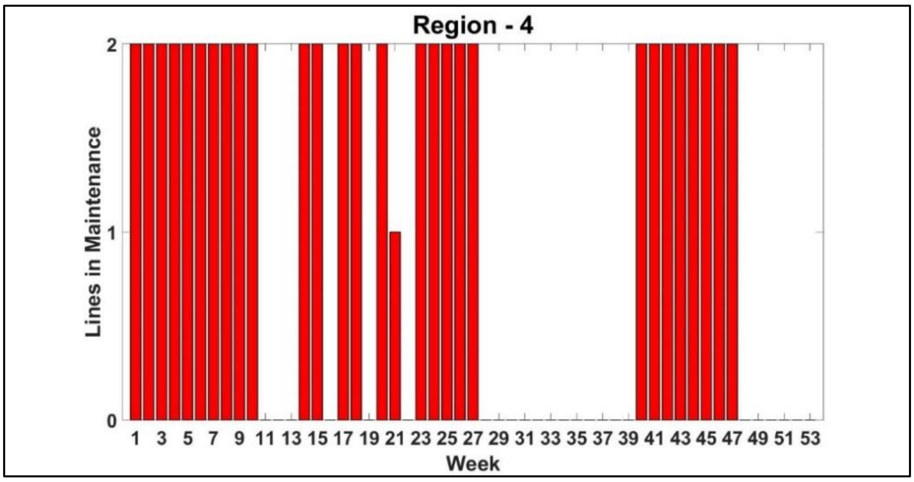

Figure 11. Distribution of Line Maintenances within Year - Region 4

Numbers of scheduled lines for maintenance in Region 5 and Region 6 during each week are shown in Figure 12 and Figure 13 respectively.

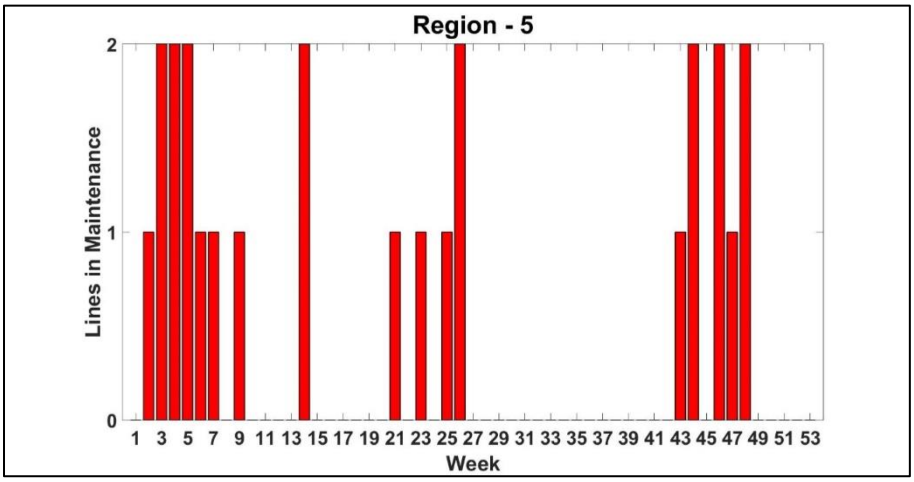

Figure 12. Distribution of Line Maintenances within Year - Region 5

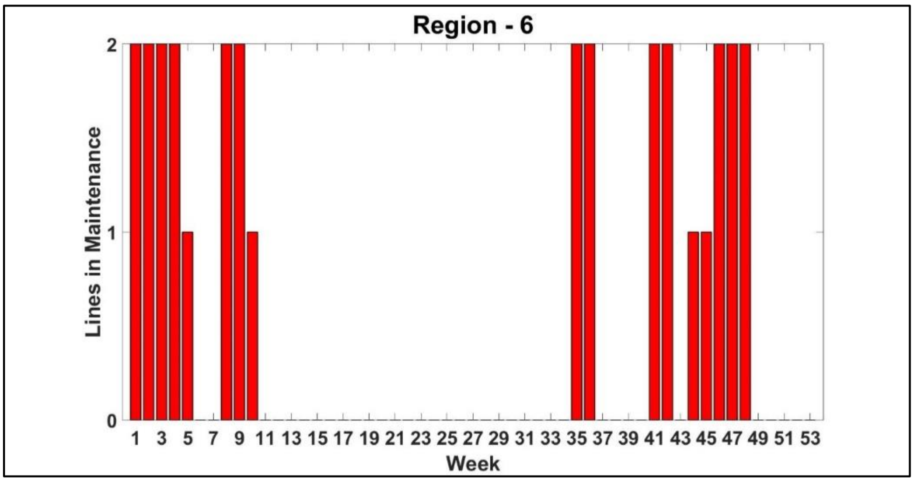

Figure 13. Distribution of Line Maintenances within Year - Region 6

Numbers of scheduled lines for maintenance in Region 7 and Region 8 during each week are shown in Figure 14 and Figure 15 respectively.

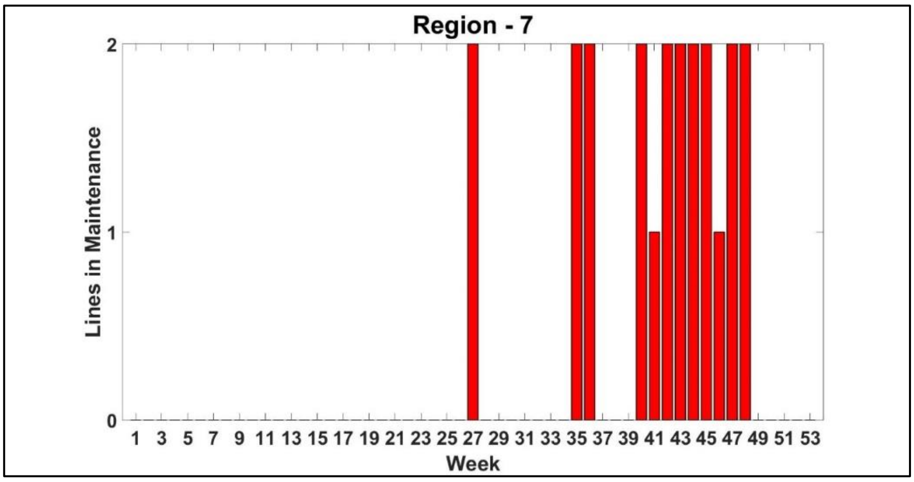

Figure 14. Distribution of Line Maintenances within Year - Region 7

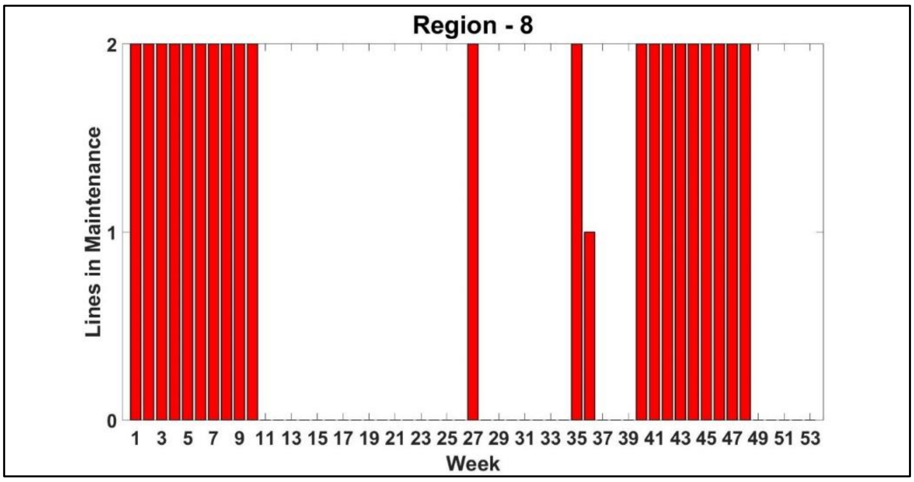

Figure 15. Distribution of Line Maintenances within Year - Region 8

Number of scheduled lines for maintenance in Region 9 during each week are shown in Figure 16. Furthermore, number of scheduled lines for maintenance in Turkish Power Network during each week are shown in Figure 17.

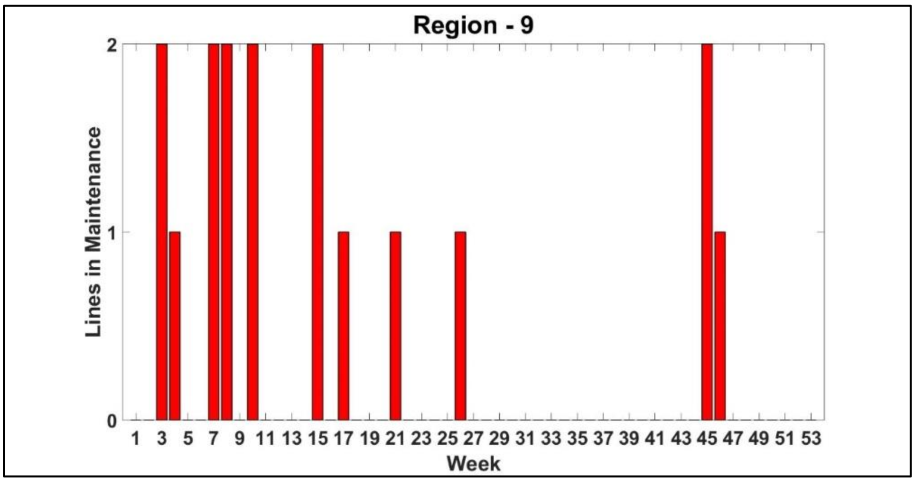

Figure 16. Distribution of Line Maintenances within Year - Region 9

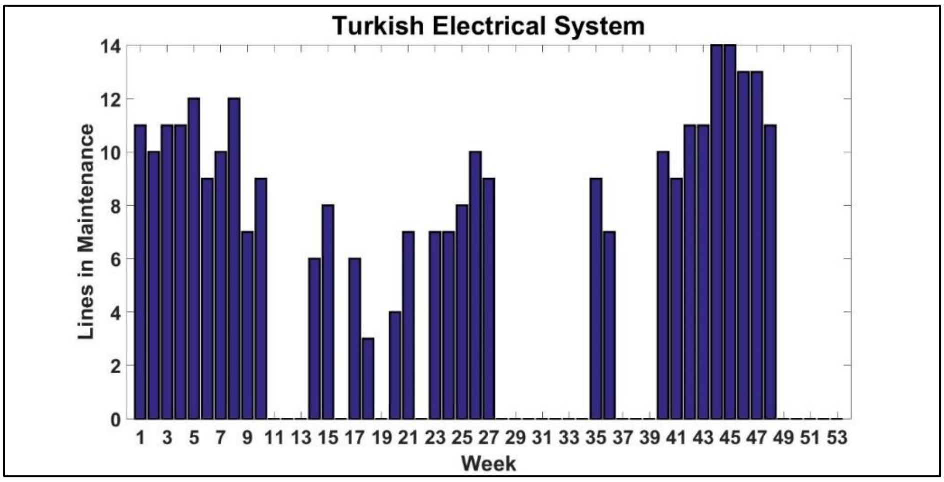

Figure 17. Distribution of Line Maintenances within Year – Turkish Power System

4.2.1 Effect of Crew Number

For the case study, crew number for each region is defined as two; that is, maximum two branches can be maintained simultaneously for each region according to the constraint. Crew number or number of simultaneous maintenance preferences depend on operators' choices in the system. In order to observe the effect of the crew number on the results, the constraint is relaxed and number of crews for each region is raised to five for an alternative scenario.

Firstly, maintenance schedule of all transmission lines is presented in Table 6, and weekly numbers of maintenances in Turkish Electrical System is given in Figure 18.

Table 6. Maintenance Periods of Transmission Lines (Alternative Scenario)

Branch	**Region**	**Maint. Week**	**Branch**	**Region**	**Maint. Week**	**Branch**	**Region**	**Maint. Week**
1	1	46	21	1	47	40	2	2
2	1	2	22	1	1	41	2	2
3	1	4	23	1	45	42	2	1
4	1	47	24	1	1	43	2	45
5	1	45	25	1	42	44	2	2
6	1	2	26	1	2	45	2	46
7	1	41	27	1	43	46	2	47
8	1	1, 2	28	1	41	47	2	46, 47
11	1	46	29	1	41	48	2	39
13	1	41	30	1	45	49	2	45
14	1	1, 2	31	1	46	50	2	46
15	3	1	32	2	1, 2	51	2	46
16	3	47	33	2	47	52	2	3
17	3	46	34	2	41	53	2	40
18	3	43	35	2	41	54	4	47
19	1	1	38	2	42	55	4	1, 2
20	1	45	39	2	3	56	2	47

Branch	Region	Maint. Week	Branch	Region	Maint. Week	Branch	Region	Maint. Week
57	2	3, 4	97	3	3	138	4	1
58	2	41	98	3	4	139	4	40
59	2	47	99	3	1	140	4	44
60	2	1, 2	100	3	43	141	4	44
61	2	46	102	3	44	142	4	4
62	2	3	103	3	43	143	4	4
63	2	44	104	3	4	144	4	45
64	2	41	105	3	47	145	4	40
65	2	45	106	3	42	146	4	1, 2
66	2	45	107	3	44	147	4	1, 2
67	2	42	108	3	42	148	4	40, 41
68	3	46	109	5	4	149	4	3
69	2	45	110	3	47	150	5	43
70	3	45	111	4	44	151	5	3, 4
71	2	3	112	4	40, 41	152	5	4
72	2	4	113	4	3	153	5	2
73	3	44, 45, 46	114	4	1	154	5	4
74	5	47	115	4	40	155	5	42, 43
75	4	47	116	4	42, 43	156	5	3
76	2	39	117	4	45, 46	157	5	44
77	4	4	118	4	43	158	5	44
78	2	40	119	4	2	159	5	3
79	2	41	120	4	45, 46	161	5	42
80	2	43	121	4	42, 43	162	5	45, 46
81	4	46, 47	122	4	2, 3	163	5	44
82	6	2, 3	123	4	4	164	5	1
83	2	40	124	4	43, 44	165	5	46, 47
84	3	3	125	4	41, 42	166	5	42, 43
85	3	42	126	4	41, 42	167	5	1
86	3	3	127	6	46	168	5	42
87	3	42, 43	128	6	39	169	6	46
88	3	45	129	6	2, 3	170	6	4
89	3	45	130	4	46	171	6	44
90	3	4	131	4	44	172	6	44
91	3	42	132	4	3	173	6	2, 3
92	3	3	133	6	2, 3	174	6	46, 47
93	3	4	134	4	45, 46	175	6	1
94	3	3	135	4	41, 42	176	6	45
95	3	4	136	4	43	177	6	41
96	3	46	137	4	3, 4	178	6	2, 3

Branch	Region	Maint. Week	Branch	Region	Maint. Week	Branch	Region	Maint. Week
179	6	45	209	8	45	236	8	40
180	6	43	210	8	47	237	8	3
181	6	1	211	8	39	238	8	41
182	6	44	212	8	42	239	8	44
183	6	4	213	8	44	240	8	42
184	6	45	214	8	4	241	8	44
185	6	45	215	8	44	242	8	42
186	6	45	216	8	43	245	8	39
187	6	44	217	8	2	246	8	44
188	7	46, 47	218	8	40, 41	247	8	45
189	7	46	219	8	2	248	9	43
190	7	46	220	8	46	249	9	46
191	7	41, 42	221	8	41	250	9	1
192	7	39, 40	222	8	46	251	9	4
193	7	46	223	8	3	252	9	3
195	7	41, 42	224	8	46, 47	253	9	46
197	7	40, 41	225	8	40, 41	254	9	42
198	7	47	226	8	2	255	9	46
199	7	41	227	8	46	256	9	1
200	7	40	228	8	39	257	9	43
201	7	39, 40	229	8	46	258	9	45
203	7	42	230	8	1	259	9	46
204	7	43	231	8	40	260	9	3
205	7	43	232	8	41	261	9	4
206	7	42	233	8	1	262	9	2
207	8	2, 3	234	8	40	263	9	1
208	8	47	235	8	3	264	9	2

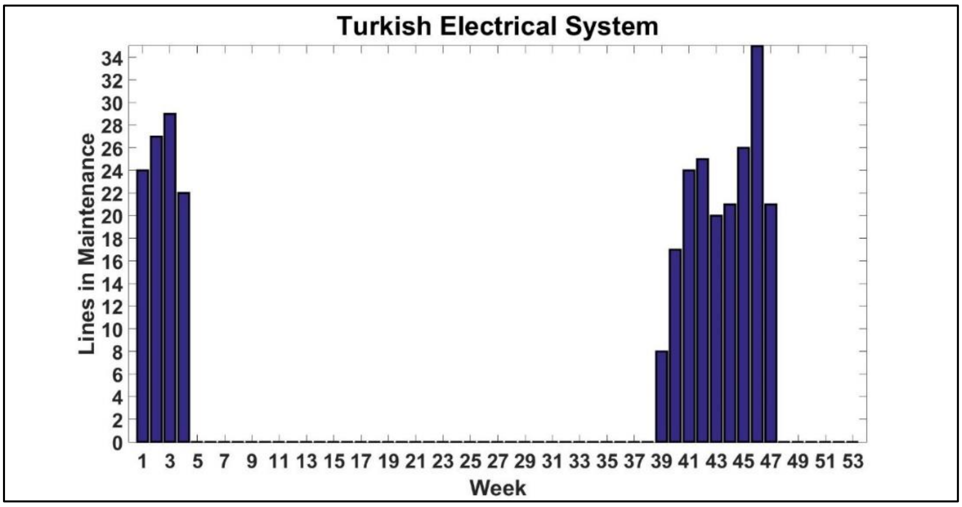

Figure 18. Distribution of Line Maintenances within Year – Turkish Power System (Alternative Scenario)

4.3 Evaluation of the Results

In the scope of case study, a yearly maintenance schedule for 380 kV transmission lines in Turkish Power System is formed. Maximizing number of transmission lines that are maintained at the same time is aimed while forming the schedule. Firstly, the results of the case study are evaluated in this section. After that, results of the alternative scenario are compared with the case study.

Clustering of maintenances around certain periods within year is an expected result because of the objective. Hence, the system will be operated with all transmission lines for 21 weeks within year according to the schedule of the case study. An alternative scenario is studied to observe the effect of operational constraints by relaxing the constraint regarding crew number, and the maintenances are completed in 13 weeks in those conditions.

4.3.1 Case Study

The optimization problem is solved to minimize the duration of maintenance condition of the system within the year. According to the obtained schedule, the maintenances of the transmission lines are completed in 32 weeks. In other words, the maintenances of transmission lines can be carried out in minimum 32 weeks. During the optimization process and for the objective, the solver has investigated the minimum number of weeks for maintenance condition, and then resulted with a certain solution when there was no possible schedule that completes maintenances less than 32 weeks. However, it is not guaranteed that the obtained result is the only optimum schedule; that is, there may be another schedule that also offers operation of 21 weeks without maintenances.

Considering weekly peak demand in Figure 4, maintenances are supposed to be scheduled in spring and autumn seasons due to lower demand. However, seasonal preferences or operational constraints may cause shift of maintenances to other periods. Since simultaneous maintenances of maximum number of lines is aimed during the search, unexpected but feasible maintenance periods can be assigned to the transmission lines. Although, spring season seems to be the most feasible term for the maintenances, winter and autumn weeks are also scheduled for maintenances. This situation is mainly caused by seasonal preferences. Maintenances of transmission lines under responsibility of regions 6, 7 and 8 are not allowed to be scheduled in spring, and the other transmission lines whose maintenances are possibly scheduled together with those lines are also shifted to the other weeks due to the objective. Therefore, the other feasible terms that are winter and autumn weeks for maintenances are also scheduled for maintenances. On the other hand, summer season and starting of winter season, when the peak demand of the system is realized, are mostly not scheduled for maintenances.

Figure 19 shows the change in loading average of branches in region 1 within year according to the historical demand and generations. From the figure loadings of the transmission lines greater in spring and summer seasons with respect to other seasons. Hence, maintenances of transmission lines in region - 1 are generally scheduled in winter and autumn weeks as can be seen from the Figure 8. Some of the transmission lines are scheduled in weeks when the demand is lower in summer season.

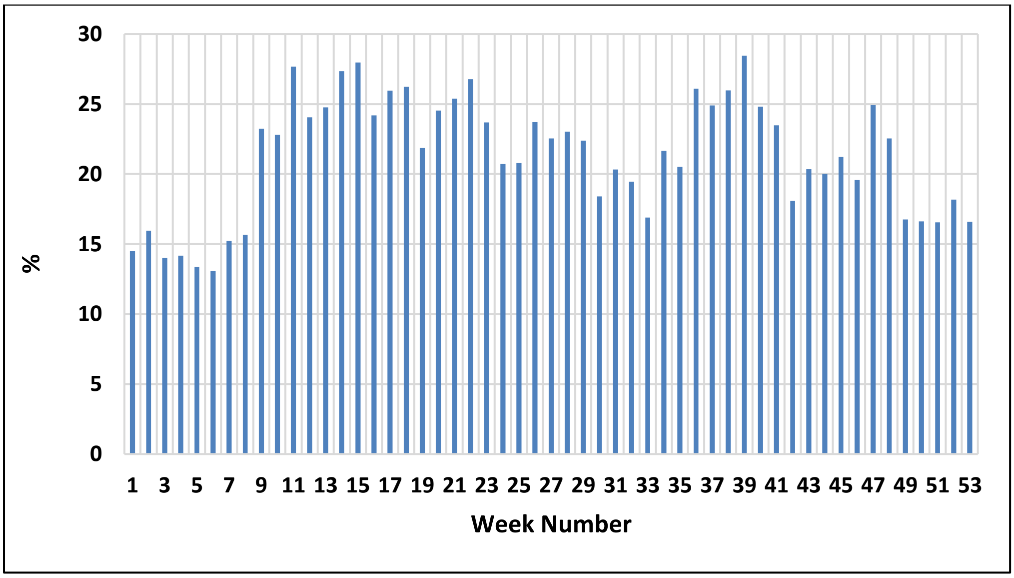

Figure 19. Weekly Average Loading of Transmission Lines in Region-1

There are 42 transmission lines under responsibility of region 2 and 40 transmission lines under responsibility of region 4. Since number of simultaneous maintenances of branches for each region is limited as two with crew number, maintenances in these regions were supposed to be spread over the year. Hence, most of weeks that are scheduled for maintenances include transmission lines from region 2 and 4. Similarly, operators of region 8 are responsible for 41 transmission lines and the maintenances are spread over weeks of the year except the avoided weeks for that region.

Loading average of transmission lines in region 3, 5 and 9 are presented in Figure 20, Figure 21 and Figure 22. Loading profiles of branches shows changing behavior within the year. For the regions, no maintenance is scheduled in summer weeks due to seasonal preferences. Moreover, it can be said that the loading averages have effect on the maintenance schedules of the regions. It is observed that the weeks with higher average branch loadings are also not scheduled for maintenances. For example, the period between week 8 and week 14 for region 3, the period between week 16 and week 21 for region 5 and the period between weeks 10 and weeks 17 for region 9 are not scheduled for maintenances. Nevertheless, the objective was to find the suitable weeks for the maximum simultaneous maintenances from different regions, so the argument is not valid for all weeks with high loading averages.

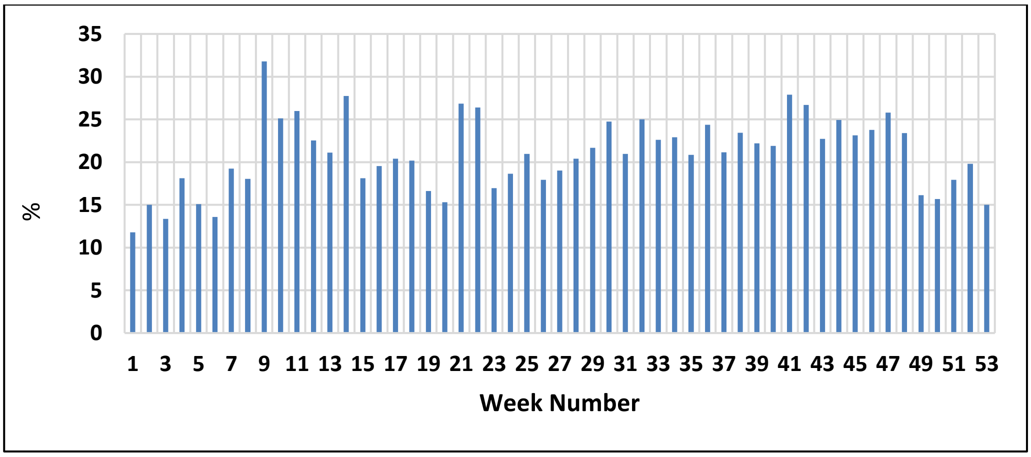

Figure 20. Weekly Average Loading of Transmission Lines in Region-3

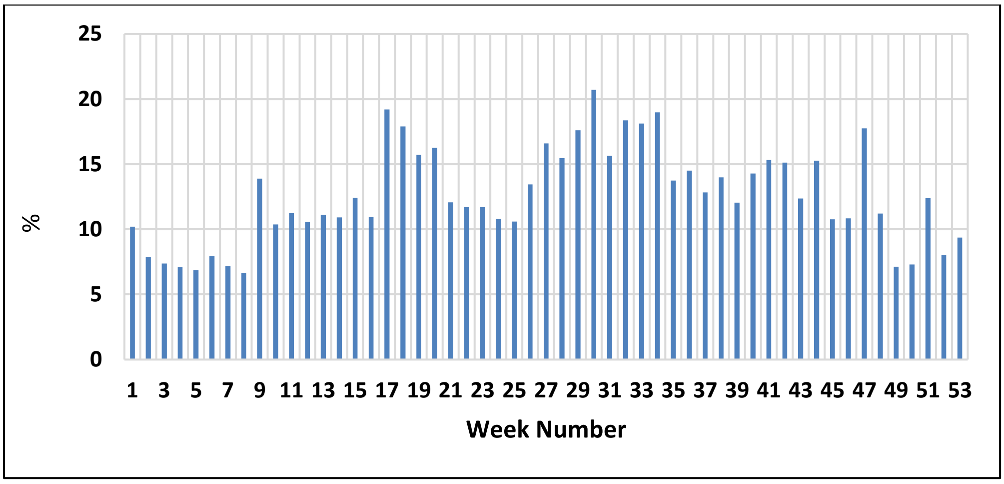

Figure 21. Weekly Average Loading of Transmission Lines in Region-5

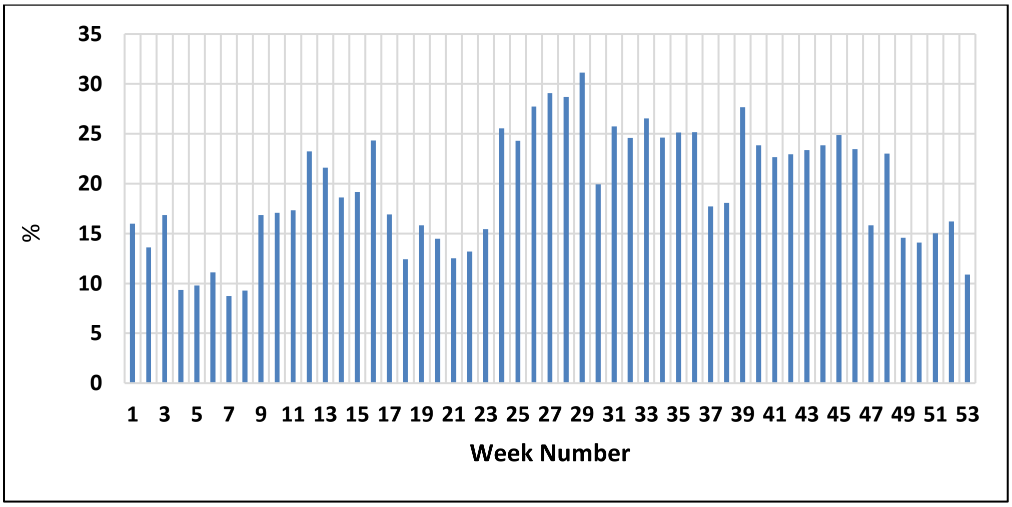

Figure 22. Weekly Average Loading of Transmission Lines in Region-9

The transmission lines under responsibility of region 6 and 7 are also scheduled considering the seasonal preferences. These two regions are more flexible with respect to number of lines to be maintained and seasonal preferences. Apart from the avoided weeks for the regions, maintenances of the transmission lines may have shifted according to the other regions' schedules.

4.3.2 Alternative Scenario

In this scenario, the constraint that restricts simultaneous maintenances with insufficient crew number is changed to see whether the method converges to the expected results or not. Crew number for each region is raised from 2 to 5; that is, at most 5 transmission lines can be maintained at the same time. With this change, the restriction with crew number was almost removed from the problem and the expected clustering of the maintenances became more distinctive. The maintenances of all transmission lines in the system can be carried out in 13 weeks according to the schedule. The maintenances are scheduled to the weeks that are involved in the common seasonal preferences of all the regions.

Crew information is an operational concern, so available or allocated number of crews for maintenances is decided by the operators of the system. Besides that, maximum number of simultaneous maintenances is also determined by the operator for the system security. The maximum simultaneous maintenance number is 14 according to schedule obtained from the case study. On the other hand, it is 35 for the alternative scenario where the constraint about crew is relaxed. The schedule was tested and DC power flow equations were solved successfully for all weeks. However, AC power flow solution did not converge for the system condition in which 35 transmission lines were in maintenance simultaneously because accuracy of linearity assumption was lost for that condition. Since the number of transmission lines in maintenance at the same time is limited with crew number in the study case, additional weeks are scheduled for maintenances and the program is spread. For example, the maintenance schedule of transmission lines in region 1 according to alternative scenario is given in Figure 23. In the first week, five transmission lines are scheduled for maintenance. In the case study, this number is limited with two, and the solver is forced to select optimum two transmission lines from region 1 for maintenance together with the lines from other regions to maximize the number of maintained lines during that week. Furthermore, maintenances of the remaining lines in the region 1 had to be scheduled for other weeks.

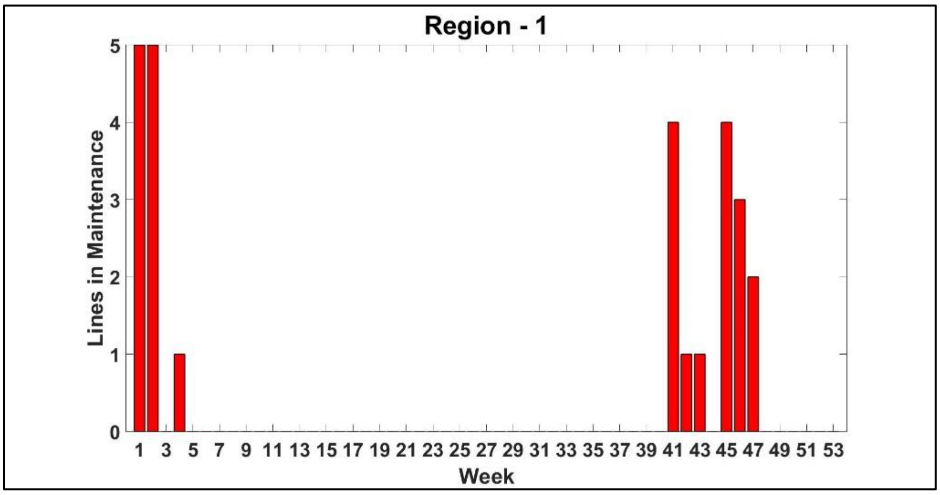

Figure 23. Distribution of Line Maintenances within Year – Region 1 (Alternative Scenario)

CHAPTER 5

RELAXATION APPROACH

Solution process of an optimization depends on the structure of the problem. Although solution method used by the solver determines the procedure, number of variables, number of constraints, types of variables and tolerances for solution affect the necessary time to achieve the optimal solution. IBM CPLEX decides about the solution method according to the problem type and model structure automatically; hence branch and bound algorithm is used for the case study. During solution of a linear optimization problem with branch and bound algorithm, variable types are of great importance. In the beginning, the algorithm ignores the integrality constraints of the variables and finds a solution as if all variables are continuous. After that, the calculated fractional values of integer type variables are improved for integrality constraints by forming branches and nodes; that is, a search tree is formed. Therefore, the number of integer type variables has impact on the duration of solution process. Since case study involves integer type of variables for branch states and maintenance state indicators; the solution of the problem has taken approximately 2 days. The small tolerances for bus balance and branch flow equations also caused the long time duration of solution.

The necessary time for solution of the case study restricts observing the effects of differences in the system. In other words, in order to see the change of maintenance schedule according to different scenarios, the scheduler has to wait approximately 2 days for each change in the model. For example, TSO may want to see the effect of different seasonal constraint scenarios or effect of number of crews on the maintenance schedule to see the need of recruitment. Although, these different study cases depend on requirements, shorter time for solution brings flexibility and practicality to the TSO. Moreover, the necessary time for solution grows exponentially, when the proposed methodology is applied to larger power systems. Number of variables and constraint equations increase with the number of buses and branches.

Considering these concerns, relaxation approach is developed in order to speed up the solution process. By this approach, the main problem is divided into sub-problems and solved with parallel processing method. Parallel processing method is used to execute different operations at the same time by using different processors on computer. Although, the needed time for solution process is decreased, sub-optimal results may be obtained instead of global optimum result by this approach.

Relaxation of the optimization problem is based on sensitivity factors in power systems. Sensitivity factors are used to obtain the approximate changes in the line flows after changes in generation or the possible outages of branches. The factors that provide quick results for all transmission lines in the system are derived from DC Power Flow method. Basically, there are two types of sensitivity factors in power system as below:

- Generation shift factors: represent the sensitivity of a branch flow with respect to a generation change at a bus. Generation shift factors can be used for capacity expansion studies.
- Line outage distribution factors: represent the sensitivity of a branch flow with respect to outage of another branch. Line Outage Distribution Factors can be used for contingency analysis, because power flows on lines after a contingency can be updated quickly.

Generation shift factor for line l according to change in generation at bus i is expressed in (5.1). The change in generation at bus i is compensated by an opposite change in generation at reference bus; hence total generation in the system remains fixed [22].

$$a_{l_i} = \frac{\Delta f_l}{\Delta P_i} \tag{5.1}$$

where ΔP_i is the change in generation at bus i and Δf_l is the active power change in flow on line l according to ΔP_i.

Similarly, line outage distribution factor (LODF) for line l after outage of line k is expressed in (5.2). LODF is used to observe the distribution of active power flow of a branch to the other branches after its outage.

$$d_{l,k} = \frac{\Delta f_l}{f_k^0} \tag{5.2}$$

where f_k^0 is power flow on line k before outage and Δf_l is the active power change on line l after the outage.

Since the long duration of the solution process is caused by the large size of the system, dividing the system into isolated sub-systems is aimed with relaxation approach. In other words, decoupled areas in the network are investigated in order to determine the lines whose outages have less effect on the others. The idea behind the application is that, maintenances of branches in the decoupled groups can be scheduled independently for each group if decoupled groups of lines are observed in the network. Line Outage Distribution Factors are used for this application to see which transmission lines are influenced remarkably by outage of a transmission line. For each transmission line in the system, LODFs are calculated with respect to the outage of other transmission lines. Factors below than 5 percent is assumed as zero and resulted LODF map is obtained as in Figure 24.

In the figure, the values in each column represents the LODFs that are calculated for the outage of the corresponding line. The blue dots mean that corresponding branch in a row is affected by the outage of the branch in the column. From the figure, two decoupled branch clusters can be seen, and numbers of the members in the groups are below 84 and above 139 respectively. In other words, outage of a branch from one group does not change the active power flow on the branches in the other group significantly. However, outages of a transmission lines that connects these two clusters can change active power flow on branches of both clusters.

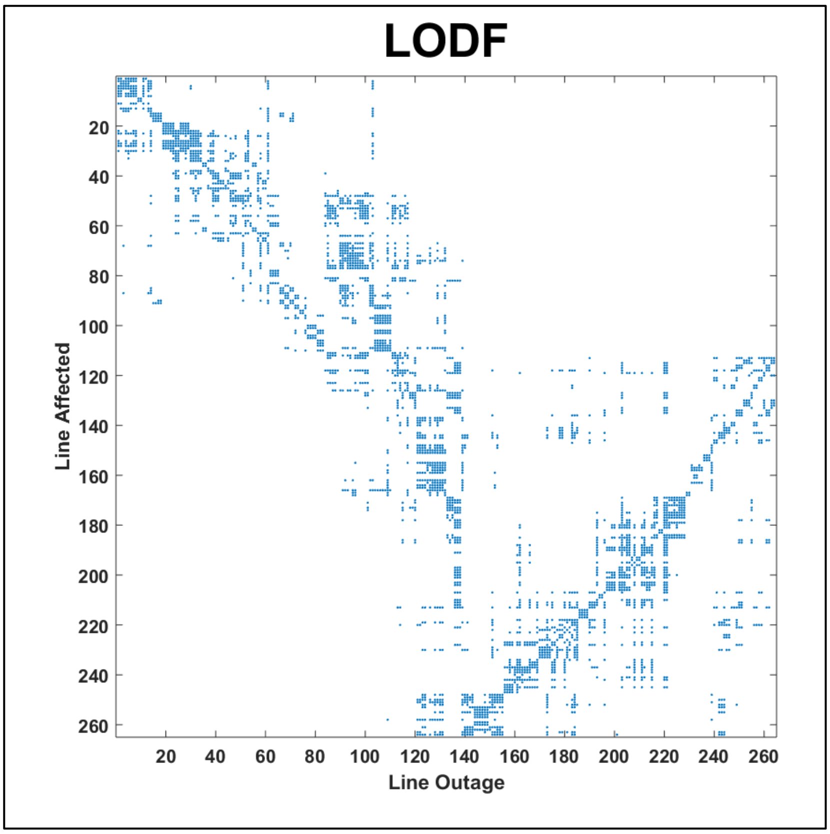

Figure 24. LODF Map of the Turkish Power Network

Decoupled branch groups and the connections between them are remarked in Figure 25. As seen from the figure, any of the affected branches by the outage of transmission lines from upper left rectangle (below 84) and lower right rectangle (above 139) are not common. Therefore, the relaxation approach is developed for maintenance schedules of these two decoupled groups. Maintenances of branches in decoupled groups can be formed independently and combined based on the same solution method of the case study with less number of branches. In other words, the system is divided into two subsystems each including the branches of one decoupled group and both including the branches that provide connection for the decoupled groups. After that, maintenances are scheduled for the subsystems with the same objective. Finally, the more suitable period for each branch of connection group is chosen from two alternatives for total schedule.

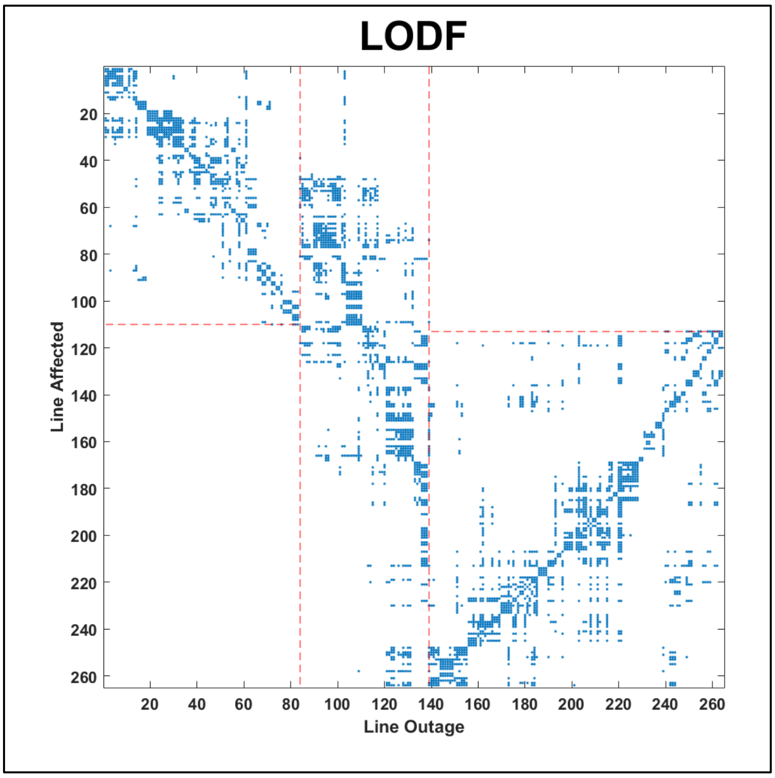

Figure 25. Decoupled Branch Clusters

The branch clusters are illustrated on the map of Turkey and shown in Figure 26. The red and blue transmission lines show the decoupled branch clusters with respect to LODFs. On the other hand, the black transmission lines represent the connection group.

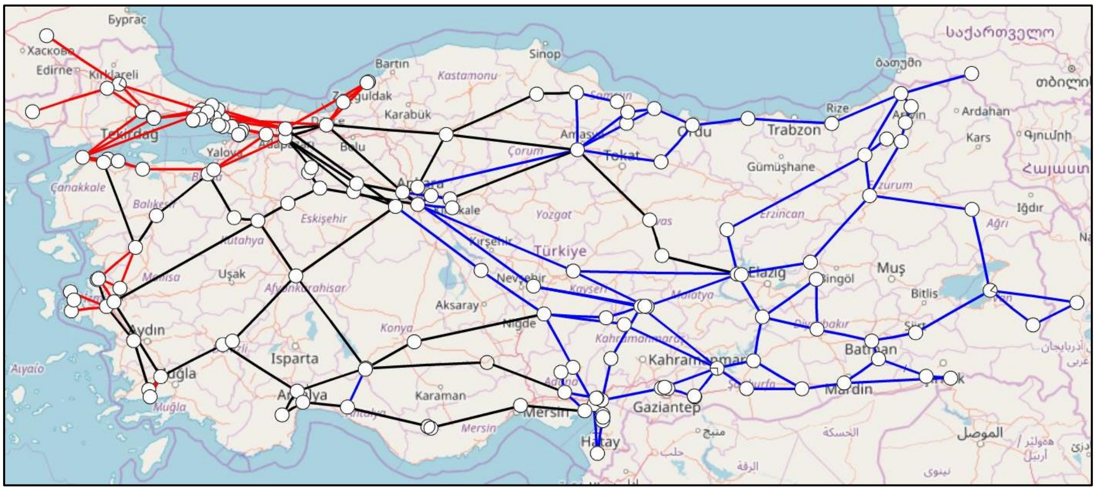

Figure 26. Decoupled Branch Clusters in Turkey Electrical Network

5.1 Results

According to LODF, the network is separated into three branch groups as first decoupled, second decoupled and the connection group as in Figure 26. The groups involve 77, 119 and 56 transmission lines respectively. As a result, the subsystems for independent maintenance scheduling has 133 and 175 transmission lines.

Two optimization models are constructed for the subsystems with same operational constraints. The differences between the models are the transmission lines to be maintained. After that, each problem is solved individually and two maintenance schedules are obtained to be combined. However, the branches of the connection group are included in both of the schedules and one of them has to be selected for each branch. In this study, the week, which less amount of transmission lines are in maintenance during, is selected for the lines of connection group. However, it can also be determined according to the operators' preferences. The solution for optimal maintenance schedules of the transmission lines has taken approximately 4.5 hours and 11 hours for subsystems 1 and 2 respectively. Since the problems are independent and can be solved by parallel processing; total schedule can also be obtained after 11 hours. Scheduled weeks for the maintenances of the branches in subsystem 1 are given in Table 7.

Table 7. Maintenance Periods of Transmission Lines in Subsystem 1

Branch	**Region**	**Maint. Week**	**Branch**	**Region**	**Maint. Week**	**Branch**	**Region**	**Maint. Week**
1	1	6	11	1	4	20	1	46
2	1	4	13	1	44	21	1	9
3	1	42	14	1	9, 10	22	1	47
4	1	5	15	3	46	23	1	42
5	1	3	16	3	1	24	1	44
6	1	5	17	3	1	25	1	46
7	1	10	18	3	44	26	1	3
8	1	7, 8	19	1	43	27	1	47

Branch	Region	Maint. Week	Branch	Region	Maint. Week	Branch	Region	Maint. Week
28	1	1	67	2	5	105	3	44
29	1	45	68	3	5	106	3	9
30	1	6	69	2	5	107	3	5
31	1	1	70	3	47	108	3	10
32	2	11, 12	71	2	21	109	5	43
33	2	23	72	2	7	110	3	4
34	2	44	73	3	21, 22, 23	111	4	46
35	2	6	74	5	9	112	4	9, 10
38	2	9	75	4	1	113	4	6
39	2	45	76	2	47	118	4	46
40	2	10	77	4	3	119	4	9
41	2	23	78	2	24	123	4	47
42	2	43	79	2	1	126	4	6, 7
43	2	47	80	2	19	127	6	1
44	2	4	81	4	10, 11	128	6	9
45	2	10	82	6	46, 47	133	6	5, 6
46	2	1	83	2	9	137	4	4, 5
47	2	11, 12	84	3	8	138	4	43
48	2	3	85	3	7	148	4	4, 5
49	2	4	86	3	6	149	4	3
50	2	46	87	3	20, 21	151	5	5, 6
51	2	22	88	3	42	155	5	3, 4
52	2	45	89	3	42	156	5	43
53	2	42	90	3	7	159	5	1
54	4	1	91	3	9	162	5	10, 11
55	4	43, 44	92	3	19	164	5	9
56	2	3	93	3	10	165	5	5, 6
57	2	19, 20	94	3	20	166	5	3, 4
58	2	7	95	3	4	171	6	9
59	2	24	96	3	43	173	6	3, 4
60	2	20, 21	97	3	46	174	6	3, 4
61	2	8	98	3	3	178	6	5, 6
62	2	43	99	3	19	186	6	1
63	2	6	100	3	3	187	6	43
64	2	22	102	3	45	258	9	46
65	2	42	103	3	47			
66	2	44	104	3	45			

The maintenance periods for the branches in subsystem 2 is given in Table 8.

Table 8. Maintenance Periods of Transmission Lines in Subsystem 2

Branch	**Region**	**Maint. Week**	**Branch**	**Region**	**Maint. Week**	**Branch**	**Region**	**Maint. Week**
52	2	43	119	4	5	154	5	24
53	2	3	120	4	12, 13	155	5	14, 15
54	4	1	121	4	9, 10	156	5	47
55	4	19, 20	122	4	25, 26	157	5	8
57	2	19, 20	123	4	42	158	5	44
59	2	3	124	4	44, 45	159	5	20
67	2	30	125	4	42, 43	161	5	24
69	2	40	126	4	14, 15	162	5	6, 7
70	3	24	127	6	8	163	5	44
71	2	30	128	6	35	164	5	2
72	2	42	129	6	3 4	165	5	42, 43
73	3	12, 13, 14	130	4	4	166	5	45, 46
74	5	2	131	4	43	167	5	7
75	4	40	132	4	10	168	5	42
76	2	10	133	6	44, 45	169	6	8
77	4	46	134	4	23, 24	170	6	40
81	4	1, 2	135	4	3, 4	171	6	41
82	6	47, 48	136	4	14	172	6	40
84	3	7	137	4	8, 9	173	6	1, 2
87	3	8, 9	138	4	15	174	6	9, 10
96	3	19	139	4	19	175	6	1
98	3	20	140	4	27	176	6	6
99	3	42	141	4	44	177	6	46
102	3	1	142	4	47	178	6	43, 44
103	3	4	143	4	12	179	6	35
109	5	12	144	4	47	180	6	4
110	3	42	145	4	13	181	6	43
111	4	27	146	4	40, 41	182	6	30
112	4	25, 26	147	4	7, 8	183	6	46
113	4	6	148	4	5, 6	184	6	41
114	4	20	149	4	7	185	6	42
115	4	41	150	5	48	186	6	27
116	4	2, 3	151	5	19, 20	187	6	6
117	4	45, 46	152	5	48	188	7	41, 42
118	4	23	153	5	15	189	7	40

Branch	Region	Maint. Week	Branch	Region	Maint. Week	Branch	Region	Maint. Week
190	7	27	217	8	40	241	8	9
191	7	45, 46	218	8	42, 43	242	8	35
192	7	46, 47	219	8	6	245	8	27
193	7	30	220	8	46	246	8	6
195	7	44, 45	221	8	35	247	8	47
197	7	41, 42	222	8	27	248	9	20
198	7	27	223	8	4	249	9	2
199	7	35	224	8	44, 45	250	9	15
200	7	30	225	8	1, 2	251	9	4
201	7	47, 48	226	8	45	252	9	23
203	7	40	227	8	3	253	9	42
204	7	43	228	8	3	254	9	12
205	7	35	229	8	4	255	9	14
206	7	48	230	8	41	256	9	26
207	8	42, 43	231	8	47	257	9	6
208	8	44	232	8	48	258	9	10
209	8	2	233	8	10	259	9	45
210	8	48	234	8	1	260	9	15
211	8	30	235	8	7	261	9	12
212	8	7	236	8	5	262	9	14
213	8	8	237	8	5	263	9	19
214	8	41	238	8	9	264	9	6
215	8	8	239	8	40			
216	8	46	240	8	10			

Combined transmission line maintenance schedule is presented in Table 9. The common lines for both subsystems are given in the cells with yellow background.

Table 9. Combined Maintenance Periods of Transmission Lines

Branch	**Region**	**Maint. Week**	**Branch**	**Region**	**Maint. Week**	**Branch**	**Region**	**Maint. Week**
1	1	6	41	2	23	76	2	10
2	1	4	42	2	43	77	4	46
3	1	42	43	2	47	78	2	24
4	1	5	44	2	4	79	2	1
5	1	3	45	2	10	80	2	19
6	1	5	46	2	1	81	4	10, 11
7	1	10	47	2	11, 12	82	6	47, 48
8	1	7, 8	48	2	3	83	2	9
11	1	4	49	2	4	84	3	8
13	1	44	50	2	46	85	3	7
14	1	9, 10	51	2	22	86	3	6
15	3	46	52	2	45	87	3	20, 21
16	3	1	53	2	42	88	3	42
17	3	1	54	4	1	89	3	42
18	3	44	55	4	19, 20	90	3	7
19	1	43	56	2	3	91	3	9
20	1	46	57	2	19, 20	92	3	19
21	1	9	58	2	7	93	3	10
22	1	47	59	2	24	94	3	20
23	1	42	60	2	20, 21	95	3	4
24	1	44	61	2	8	96	3	19
25	1	46	62	2	43	97	3	46
26	1	3	63	2	6	98	3	20
27	1	47	64	2	22	99	3	19
28	1	1	65	2	42	100	3	3
29	1	45	66	2	44	102	3	45
30	1	6	67	2	30	103	3	47
31	1	1	68	3	5	104	3	45
32	2	11, 12	69	2	40	105	3	44
33	2	23	70	3	24	106	3	9
34	2	44	71	2	21	107	3	5
35	2	6	72	2	7	108	3	10
38	2	9	73	3	21, 22, 23	109	5	12
39	2	45	74	5	2	110	3	42
40	2	10	75	4	40	111	4	27

Branch	Region	Maint. Week	Branch	Region	Maint. Week	Branch	Region	Maint. Week
112	4	25, 26	162	5	10, 11	214	8	41
113	4	6	163	5	44	215	8	8
114	4	20	164	5	2	216	8	46
115	4	41	165	5	42, 43	217	8	40
116	4	2, 3	166	5	45, 46	218	8	42, 43
117	4	45, 46	167	5	7	219	8	6
118	4	23	168	5	42	220	8	46
119	4	5	169	6	8	221	8	35
120	4	12, 13	170	6	40	222	8	27
121	4	9, 10	171	6	41	223	8	4
122	4	25, 26	172	6	40	224	8	44, 45
123	4	47	173	6	1, 2	225	8	1, 2
124	4	44, 45	174	6	9, 10	226	8	45
125	4	42, 43	175	6	1	227	8	3
126	4	14, 15	176	6	6	228	8	3
127	6	8	177	6	46	229	8	4
128	6	35	178	6	43, 44	230	8	41
129	6	3, 4	179	6	35	231	8	47
130	4	4	180	6	4	232	8	48
131	4	43	181	6	43	233	8	10
132	4	10	182	6	30	234	8	1
133	6	44, 45	183	6	46	235	8	7
134	4	23, 24	184	6	41	236	8	5
135	4	3, 4	185	6	42	237	8	5
136	4	14	186	6	27	238	8	9
137	4	8, 9	187	6	43	239	8	40
138	4	15	188	7	41, 42	240	8	10
139	4	19	189	7	40	241	8	9
140	4	27	190	7	27	242	8	35
141	4	44	191	7	45, 46	245	8	27
142	4	47	192	7	46, 47	246	8	6
143	4	12	193	7	30	247	8	47
144	4	47	195	7	44, 45	248	9	20
145	4	13	197	7	41, 42	249	9	2
146	4	40, 41	198	7	27	250	9	15
147	4	7, 8	199	7	35	251	9	4
148	4	4, 5	200	7	30	252	9	23
149	4	7	201	7	47, 48	253	9	42
150	5	48	203	7	40	254	9	12
151	5	19, 20	204	7	43	255	9	14
152	5	48	205	7	35	256	9	26
153	5	15	206	7	48	257	9	6
154	5	24	207	8	42, 43	258	9	10
155	5	14, 15	208	8	44	259	9	45
156	5	47	209	8	2	260	9	15
157	5	8	210	8	48	261	9	12
158	5	44	211	8	30	262	9	14
159	5	20	212	8	7	263	9	19
161	5	24	213	8	8	264	9	6

Numbers of scheduled lines for maintenance in Turkish Power Network during each week according to the relaxation approach are shown in Figure 27.

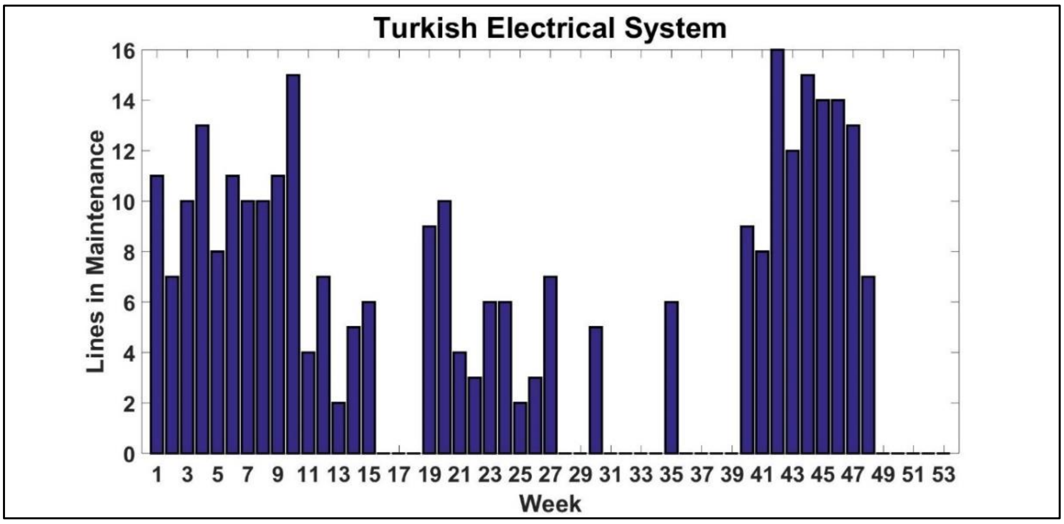

Figure 27. Distribution of Line Maintenances within Year – Relaxation Approach

5.2 Evaluation of the Results

Solution time needed for the case study problem is approximately 2 days on a regular computer. Although the solution time is acceptable for such a study that is performed once a year, reducing the time may be important for different purposes. For instance, an update or conditional study for the schedule can be required, or the method can be applied to a larger system. This duration can be reduced by solving the problem with supercomputer or simplifying the problem. For this purpose, an approach based on LODFs is developed and applied to the problem. Although suboptimal solution is obtained during the process, the solution time is reduced significantly.

The network is divided into two subsystems that involve 133 and 175 transmission lines respectively, and number of common lines for the subsystems is 56. For both subsystems, optimization problems are modeled and solved to minimize the total duration of maintenances within year as in the case study. The maintenances of the first subsystem is carried out in 23 weeks; on the other hand, the needed duration for the maintenances of the second subsystem is 32 weeks. 30 weeks for the first subsystem and 21 weeks for the second subsystem are not scheduled for maintenances and 18 of them are common for both subsystems. In the next step, the two schedules are united and a maintenance schedule is obtained for the complete system. Since the transmission lines of the connection group are scheduled twice in two independent schedules, one of the assigned period for each transmission line is eliminated. The elimination is carried out according to the number of lines in maintenance during corresponding weeks. The weeks with less number of maintained lines are considered as more secure and assigned for the maintenances of the common lines. As a result, 18 weeks are planned to be operated without maintenance based on the schedule obtained with relaxation approach, while it is 21 weeks for the actual methodology. That is, three more weeks are scheduled for transmission line maintenances with respect to actual method.

The solution time needed for the case study is approximately 45 hours; however, it is decreased to 11 hours with the approach based on the LODFs and parallel processing technique.

To sum up, a tradeoff between the objective of the study and solution time comes up after comparing the results of the actual methodology and relaxation approach. The difference in the objective corresponds to approximately 5 %, so it can be said that the approach gives solution close to the actual method. Since the obtained solution is realistic and the solution time is reduced to its quarter, the approach can be considered as acceptable for such problems. The system operator should compare the alternatives and select the suitable method according to the requirements.

CHAPTER 6

CONCLUSION

In this thesis, a methodology to determine the outage period of high voltage transmission lines for preventive maintenances within one-year time horizon was developed. Duration of the most secure condition of the network was intended to be maximized while the transmission lines were scheduled for maintenances. Furthermore, a relaxation method for the large-sized problem was proposed in the study. Both of the methods were applied to Turkish Electric Grid and detailed results were presented.

The process of maintenance scheduling for transmission lines is concluded as below:

- Firstly, objective of the maintenance scheduling study was selected as the minimization of the duration in which the system was in maintenance condition. The first reason for the selection of this objective was to operate the system with all transmission lines as much as possible. Moreover, the power systems whose generation and load profiles significantly change according to seasonal conditions were considered, and bottlenecks because of this behavior were avoided with the objective by shifting maintenances to flexible periods of the system.

- An optimization problem considering network and operational constraints were formed for the study. Network topology, annual generation and demand data, maintenance durations of transmission lines, crew information of regional system operators and seasonal maintenance preferences were given as input to the problem. Branch on/off states, bus angles and branch flows for every week, which are the unknowns of the problem, were defined as the optimization variables. Besides, the variable for each week that stands to indicate the existence of maintenance for that week was defined. Network constraints that correspond to successful load flow calculations, crew constraints and seasonal constraints were modeled to the problem.

- Introducing network constraints to the problem guaranteed continuity of service for the parts of the electric system. Not only interruptions were prevented for users but also transmission limitations were excluded and market environment was not disturbed with these constraints. DC Power Flow calculation for each week was utilized for the network constraints of the problem. All bus balance and branch flow equations were implemented for these constraints. Due to the state variable, the linear power equations turned into quadratic form. Linearization technique was applied to the nonlinear equations in order to simplify the problem.

- MILP (Mixed Integer Linear Programming) was selected as the method to solve the optimization problem. The technique guarantees to find the largest or smallest value in a feasible region if such a solution exist. Furthermore, expressing and implementing a problem in the scope of linear programming is simpler than other methods. Another advantage of linear programming is availability of many solver options. Unexpectedly good results can be obtained by autonomous and comprehensive solution procedure of solvers without further knowledge from user.

- The developed methodology was applied to the Turkish Power System of 2017 to schedule the maintenances of 380 kV transmission lines. The network, which was reduced for only 380 kV transmission system, consisted nine regional operational directorates, 158 buses and 264 transmission lines. Seasonal constraints for regions were defined and two maintenance teams for each region were assumed available. As a result, a maintenance schedule for all transmission lines was established and the maintenances could be accomplished in 32 weeks according to the schedule. Furthermore, maximum number of simultaneous maintenance in the system was 14 during 46^{th} week that is one of the low demand periods of the year.

An alternative scenario was studied in order to observe the effect of the crew constraints on the results. Providing that the objective function and other constraints remained the same, number of crews for each region was raised to five and the solution was repeated. In this scenario, the maintenances were completed in 13 weeks and maximum number of simultaneous maintenance in the system was 35. The maintenances were concentrated around periods that have relatively low demand in the year. In the presence of this many outages, the DC power flow model became irrelevant with the reality. Therefore, long-term schedules should be updated and supported with short-term studies that involve full power flow equations and contingency analyses. Eventually, these results indicated that the crew has affected the maintenance schedule in the case study and the model is accurate towards the objective function.

- Since the problem to be solved is an annual planning problem of a power system that is composed of many components, it can be described as a large-sized problem. Modeling and solution of such problems may require unexpected time and workload. In this thesis, the developed methodology was studied for high voltage transmission lines of a reduced power system with 158 buses and 264 lines. Although the transmission lines at lower voltage levels were excluded from the scope of the problem, the problem size was significantly large and the solution has taken approximately two days. It can be seemed as an acceptable duration for a solution of an annual planning problem, if the problem is solved for once. Nevertheless, the problem size and needed time for solution exponentially increases as the system enlarges. Furthermore, repetitive studies for different scenarios can be time consuming.

A relaxation method based on LODFs was developed and applied to the problem in order to overcome the problems mentioned above. The transmission lines were separated into three clusters by LODFs of the system. Two of the line groups were decoupled; that is, outage of a transmission line does not cause a significant change in flow of transmission lines in the other group. On the other hand, the other transmission lines whose outage possibly affect a transmission line from any group formed the third line cluster. As a result, the system was divided as two decoupled and one-connection networks. In the study, each decoupled network was joint with the connection network individually and the complete system was considered as two independent networks. After that, the methodology was applied and maintenance schedule of each network was formed. Since the maintenances of connection group were scheduled twice, one of them was eliminated according to the number of simultaneous maintenances during that week. The maintenance during the week that has more simultaneous maintenances was canceled for each line.

Comparing the results of the case study and relaxation approach, three more weeks were scheduled in the relaxation approach. On the other hand, the solution time was decreased to approximately quarter of actual method with the help of parallel processing. To sum up, close results with the case study were obtained in less duration with relaxation approach. For time limited works and researches, the approach can be applied to the problem. However, the assessment and modeling of the complete system in one problem should be used in order to obtain the optimum results if time is not a concern.

Reliability that represents the strength of a power system is a very important topic. Accordingly, transmission system maintenance is investigated by many researchers all over the world. Therefore, many other issues that are not taken into consideration in this study can be investigated in more detail in future studies. At first, the problem can be modeled on a daily basis, and exact daily maintenance periods of transmission lines can be determined. Furthermore, the methodology can be supported with short-term studies such as contingency analyses for the network with scheduled maintenances or AC power flow solutions of the study cases of each week. In order to advance the study, N-1 or N-2 contingency analyses can also be incorporated into the optimization problem. Besides that, other equipment types such as transformers, switches or generators in the network can also be considered and maintenances might be scheduled in coordination. Similarly, the study can be elaborated with maintenance types, strategies, costs and risk analysis.

REFERENCES

[1] EPDK, "Elektrik Piyasası Şebeke Yönetmeliği," [Online]. Available: http://www.epdk.org.tr/Detay/Icerik/3-0-159-3/yonetmelikler. [Accessed June 2014].

[2] W. Christiaanse and A. Palmer, “A technique for the automated scheduling of the maintenance of generating facilities,” IEEE Trans. Power App. Syst., vol. PAS-91, no. 1, pp. 137–144, 1972.

[3] J. Yellen, T. Al-Khamis, S. Vemuri, and L. Lemonidis, “A decomposition approach to unit maintenance scheduling,” IEEE Trans. Power Syst., vol. 7, no. 2, pp. 726–733, May 1992.

[4] E. Silva, M. Morozowski, L. Fonseca, G. Oliveira, A. Melo, and J. Mello, “Transmission constrained maintenance scheduling of generating units: A stochastic programming approach,” IEEE Trans. Power Syst., vol. 10, no. 2, pp. 695–701, May 1995.

[5] M. Marwali and S. Shahidehpour, “Integrated generation and transmission maintenance scheduling with network constraints,” IEEE Trans. Power Syst., vol. 13, no. 3, pp. 1063–1068, Aug. 1998.

[6] M. Marwali and S. Shahidehpour, “Long-term transmission and generation maintenance scheduling with network, fuel and emission constraints,” IEEE Trans. Power Syst., vol. 14, no. 3, pp. 1160–1165, Aug. 1999.

[7] T. Geetha and K. S. Swarup, “Coordinated maintenance scheduling of gencos and transcos in restructured power systems,” in Proc. Power India Conf., 2006.

[8] M. Y. El-Sharkh and A. A. El-Keib, “Maintenance scheduling of generation and transmission systems using fuzzy evolutionary programming,” IEEE Trans. Power Syst., vol. 18, no. 2, pp. 862–866, May 2003.

[9] Y. Fu, M. Shahidehpour, and Z. Li, “Security-constrained optimal coordination of generation and transmission maintenance outage scheduling,” IEEE Trans. Power Syst., vol. 22, no. 3, pp. 1302–1313, Aug. 2007.

[10] N. Moslemi, M. Kazemi, S. M. Abedi, H. Khatibzadeh-Azad, and M. Jafarian, “Maintenance Scheduling of Transmission Systems Considering Coordinated Outages,” IEEE Systems Journal, Feb. 2017.

[11] Endrenyi, J., Anders, G.J., Silva, L.: ‘Probabilistic evaluation of the effect of maintenance on reliability. An application’, IEEE Trans. Power Syst., 1998, 13, (2), pp. 576–583.

[12] S. K. Abeygunawardane and P. Jirutitijaroen, “New State Diagrams for Probabilistic Maintenance Models”, IEEE Trans. Power Syst., vol. PP, no. 99, pp. 1–1, Feb. 2011.

[13] A. Abiri-Jahromi, M. Fotuhi-Firuzabad, and E. Abbasi, “An efficient mixed-integer linear formulation for long-term overhead lines maintenance scheduling in power distribution systems,” IEEE Trans. Power Del., vol. 24, no. 4, pp. 2043–2053, Oct. 2009.

[14] Li Wenyuan, J. Korczynski, “A reliability-based approach to transmission maintenance planning and its application in BC hydro system,” IEEE Transaction on Power Delivery. Canada, vol. 19, pp. 303-308, January 2004.

[15] S. M. Askar and F. Y. Al-Somali, “Automatic Scheduling Method for Maintenance Outages Plan of Transmission System,” Engineering Management Research, vol. 2, no. 1, pp. 88–97, 2013.

[16] M. Marwali and S. Shahidehpour, “Short-term transmission line maintenance scheduling in a deregulated system,” IEEE Trans. Power Syst., vol. 15, no. 3, pp. 1117–1124, Aug. 2000.

[17] H. Pandzic, A. Conejo, I. Kuzle, and E. Caro, “Yearly Maintenance Scheduling of Transmission Lines Within a Market Environment”, IEEE Transactions on Power Systems, vol. 27, no. 1, Feb. 2012, pp. 407-415.

[18] A. Gopal, D. Niebur, and S. Venkatasubramanian, “DC power flow based contingency analysis using graphics processing units,” in Power Tech, 2007 IEEE Lausanne. IEEE, 2007, pp. 731–736.

[19] E. Doveh, P. Feigin, D. Greig, and L. Hyams, “Experience with FNN models for medium term power demand predictions,” IEEE Trans. Power Syst., vol. 17, no. 2, pp. 538–546, May 2002.

[20] Türkiye Elektrik İletim A.Ş., "Rakamlarla Türkiye’de Elektrik İletimi", [Online]. Available: https://www.teias.gov.tr/. [Accessed July 2018].

[21] Türkiye Elektrik İletim A.Ş., "Yük Tevzi İşletme Müdürlükleri Haritası", [Online]. Available: https://www.teias.gov.tr/. [Accessed July 2018].

[22] A. J. Wood, B. F. Wollenberg, “Power Generation, Operation, and Control”, Wiley, 1984.

APPENDIX A

DERATING FACTORS FOR THERMAL CAPACITY OF TRANSMISSON LINES

Table A - 1 Seasonal Derating Factors

Months	Derating Factors
January	1.2
February	1.2
March	1
April	1
May	1
June	0.85
July	0.85
August	0.85
September	1
October	1
November	1
December	1.2