Modeling the Efficiency of Power Distribution Networks

by

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This is to certify that I have examined this copy of a master's thesis by

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and have found that it is complete and satisfactory in all respects,
and that any and all revisions required by the final
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To My Family..

ABSTRACT

In 2009, power loss occupied approximately fifteen percent of the total generated electricity in Turkey. These losses can be classified into two subgroups, technical and non-technical losses. Technical losses occur mainly because of the electricity system components; (i)transformers, (ii)cables which are being used in transmission and distribution lines, and (iii)measurement systems. Among these components, cables that carry electricity remain as the major factor for the technical power losses. In cables, corona loss and resistive loss are the primary reasons behind the losses during transmission of power. Non-technical losses can be listed as electricity theft, non-payment by customers and errors in record keeping and accounting.

Technical losses can be minimized by selecting the right type of material and optimizing the network parameters, which include resistance, size and length of the cables. In this thesis, main motivation is to minimize power generation cost by reducing power loss during transmission while satisfying capacity and balance constraints. Whole analysis is implemented by the GAMS software. All data used for the analysis is taken from TEIAS, Turkish Electricity Transmission Company.

ÖZETÇE

2009 yılında Türkiye'nin ürettiği elektrik gücünün yüzde 15'i iletim ve dağıtımda yaşanılan kayıplar sebebiyle boşa harcanmıştır. Bu kayıplar teknik ve teknik olmayan kayıplar olarak iki gruba ayrılır. Trafolar, iletim ve dağıtımda kullanılan kablolar ve ölçüm sistemleri, teknik kayıpların elektrik ağında oluştuğu yerlerdir. Elektrik sisteminde kullanılan kablolar teknik kayıpların büyük oranını kapsamaktadır. Kablolarda korona olayı ve kabloların direnci iletimde ve dağıtımda oluşan teknik kayıpların nedenlerindendir. Teknik olmayan kayıplar ise kaçak elektrik kullanımı, ödenmemiş faturalar ve muhasebe ve kayıtlarda yapılan hatalar sebebiyle oluşmaktadır.

Teknik kayıplar, sistem parametrelerinin doğru seçilmesiyle ve sistemde doğru tip kablo çeşidinin kullanımıyla minimuma indirilebilmektedir. Bu çalışmada, amacımız teknik güç kayıplarını en aza indirip sistemin daha verimli çalışmasını sağlamaktır. Geliştirilen modeller, GAMS yazılımıyla analiz edilmiştir. Analizlerde kullanılan tüm veriler TEİAŞ (Türkiye Elektrik İletim Anonim Şirketi)'tan alınmıştır.

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INTRODUCTION

Energy is needed in order to meet the necessities of life since the occurrence of humanity. The worlds total energy demand is increasing with each day as a result of rapid developments of the countries. As a consequence of this, energy has become one of the most important strategic value of our era because of its importance in human life and development of countries.

It is extremely important to provide energy in an adequate amount, a reliable way, time and low cost because energy is an indispensable element of economic development and social welfare. Plans about demand, generation, transmission, distribution, fuel and tariff should be done for functioning of countrys energy sector in a properly and healthy way. In addition, it is important to prevent quality problems that can cause energy interruptions and consumer dissatisfaction.

In order to produce some amount of power, power plants consume some resources which are not free. Since there will be a lack of resource in the future, it is important to use present resources efficiently. Losses are the parts of electricity supply, which are not paid for by users [1]. High amount of losses in the network increase the amount of power generated and as a result more resources will be consumed. So this will increase the price of electricity in countries.

Losses can be classified as technical and non-technical losses. Technical losses exist mainly because of the electricity system components including transformers, cables which are being used in transmission and distribution lines and measurement systems. Examples of non-technical losses are electricity theft, non-payment by customers and errors in record keeping and accounting. They can be counted as external factors to the power system.

This thesis will mainly focus on transmission line losses, which are one of the technical losses in the system. Two important sources of losses in transmission lines are resistive loss and corona loss. Non-zero resistance of transmission/distribution wire causes resistive loss. Corona loss is an ionization of the air that occurs when the electric field around a conductor exceed a limit value.

According to several works in the literature, technical losses can be minimized by carefully designing the system parameters, including operating voltage, diameter and length of conductors, as well as selecting the right type of material. Moreover, it is shown that controlling each parameter in the power system is essential. In power systems design, the aim has so far been to operate economically at maximum efficiency and high reliability. In this aspect, our goal is to determine;

- The importance of selecting the right type of material in the network
- The effect of the parameters, including operating voltage and diameter and length of conductors
- How to decrease the amount of power loss
- The effect of optimal power allocation.

In this thesis, the analysis of the models and suggestions for power transmission systems are investigated. Minimizing power generation cost by reducing transmission power loss while satisfying several constraints, including capacity of the power plants, current capacity of the cables and power balance constraint. Two different models are developed in the thesis. The first model tries to allocate power with minimum power loss. Here, cable types between each node are known from a realistic data and optimal distribution of the power to demand points is studied. In the second model, cable types between each nodes are unknown and represented with a decision variable. While allocating the power as in the first model, optimum cable types are determined additionally in the second model. As the first model is solved by Non-Linear Programming, second one is solved by Mixed Integer Non-Linear Programming.

A set of data is taken from TEIAS, Turkish Electricity Transmission Company, in order to test all of the analyses and models in the thesis. Data belonging to two regions, European side of Istanbul and Thrace, are studied in this thesis.

In Chapter 2 literature review on electrical power transmission including key concepts, definitions and solution techniques is provided. Firstly, a general information on electrical power is given. Secondly, transmission line losses will be studied in the chapter and economic power dispatch models in the literature will be introduced.

Chapter 3 introduces the models that are studied in order to minimize the total power generation cost. Main motivation is to minimize the power losses by optimal power allocation and optimal cable types. There are two models in the chapter. Also data, which are taken from TEIAS, are shown in Chapter 3.

In Chapter 4, outputs of the models in Chapter 3 are discussed. Comparisons of the results with the real data from TEIAS are explained in the chapter.

The thesis is concluded with a short summary of the study and recommendations future research in Chapter 5.

Chapter 2

LITERATURE REVIEW

This chapter gives basic information on electrical power transmission including key concepts, definitions and solution techniques. First a brief introduction about electrical power will be given, next how power is generated and distributed will be studied. Moreover, types of losses, which are corona loss and resistive loss, will be examined in this chapter. Finally, models in the literature will be introduced.

2.1 Electrical Power

Electrical power is the amount of energy that produced by electric energy sources/consumed by devices using this energy in unit time. In SI unit system, voltage, current and power are stated by volt (V), ampere (A) and watt (W) units, respectively. During one second period, one joule energy consuming devices power is one watt.

The instantaneous expression of power (p(t)) can be obtained by the potential difference (v(t)) between the ends of a device that connected to electric circuit at an any t instant multiplied by the current flow (i(t)) on it. This expressions mathematical equation can be obtained as

$$p(t) = v(t) \times i(t) \tag{2.1}$$

For DC circuits this equation becomes

$$P = V \times I \tag{2.2}$$

Sources that provides supplying of energy in any means are called energy resources. Energy resources are divided into two in traditional. First one of these is primary energy resources. Primary energy resources are sources that found in nature in their own right and ready for use. Primary energy resources are divided into two about renewable and non-renewable properties, too. This classification can also be named by inexhaustible and exhaustible. Secondary energy resources are resources that obtained by using one of the primary energy resources. Electric, heat, steam and gas can be considered in these.

The classification of energy resources is possible according to the assets giving rise to formation. They are sun, worlds internal heat, tide, nuclear energy and hydrogen. Energy resources can be classified as clean and dirty resources according to cause of environmental pollution during use.

Industrial buildings established for electric production are called power plants. In the center of a lot of power plant, there is a generator that is rotational machine converts mechanical energy to electrical energy by rotating relative motion between a magnetic field and a conductor. Turbines provide needed mechanical force that will provide the rotation of generator for electric production. Turbine is a device for converting a fluids energy into work. It consists of one shaft and blades on it. All turbines are rotated by moving fluid as an energy conveyor. The fluid gives motion to turbine shaft by striking to turbines blades, the motion converts to work at the end of the shaft. Turbines structure changes according to fluid that used. Energy resources of turbines are generally steam, water and wind.

Power plants take name according to energy resource that used. Thermal reactors are plants that convert chemical energy in solid, liquid or gas fuels to heat energy, heat energy to motion energy, motion energy to electrical energy. Hydroelectric power plants are plants that produce electrical energy by using motion energy of water falling from a high point. In this type plants, turbine is worked by using motion energy of fallen waters mass. Wind power plants are mechanisms that converting motion energy of moving air to mechanical energy by wind turbines. There are power plant types like nuclear, wave energy, geothermal, photovoltaic except of these.

Projects about electrical energy are high-cost investments. So energy resource, fuel supply, electric production plant, needed transmission and distribution plants should be handled with integrity and all investment steps should be performed in co-ordination. Deterioration of supply and demand balance cause significant damage to country economy. If supply is not enough, therell be seen economical and social losses. However, if supply capacity is higher than demand, it means idle capacity and dead investment.

Electricity market can be investigated in three main sections: (1) Generation, (2) Transmission, (3) Distribution. Electricity is produced in a power plant by using different tech-

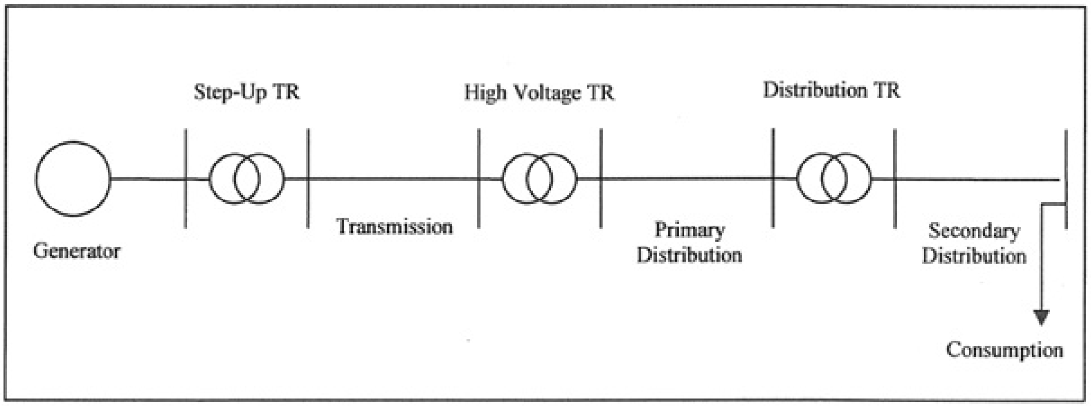

Figure 2.1: Electricity Systems Major Components

nologies (like hydroelectric, wind, nuclear) in generation phase. Transmission phase is conveying electricity from generation places to long distances. Electricity that produced in power plant steps up by transformers that can be conveyed on long distance electric lines for this reason. Electricity voltage steps down by other type transformers at the target points and becomes suitable for home, industry and office appliances. This is the distribution phase[2]. Electric distribution consists of transmission lines, transformers, secondary transformers and other equipment that will provide electricity conveying from high voltage lines to end users[3].

The transmission system is the system that provides conveying of electric energy from generation points linked to system that produced in a planned and controlled way in it to distribution lines by 154 kV and 380 kV transmission lines. Transmission system investments are expensive and construction of these systems take a long time. Their operation is of great importance in terms of the countrys economy, too. It is mandatory to make local development targets, load forecasts and generation plans in a reliable way.

At the power plant, the electricity first goes to a transformer that boosts the voltage for distribution through high voltage transmission lines. High voltage transmission lines transmit electricity over long distances to transmission substations. At transmission substations, voltage reduction happens because of distribution to other points in the system through high voltage transmission lines. Voltage steps down for commercial and residential appliances at distribution substations, which connect to the primary distribution network.

The distribution system has facilities for processing sequence of the electricity distribution from the transmission system to end users. The distribution system is commonly divided into three parts:

1. Distribution Substations

2. Primary Distributions

    (a) Primary feeders

    (b) Transformer substations

    (c) Secondary feeders

3. Secondary Distribution

    (a) Distribution transformers

    (b) Load feeders

Distribution substations supply distribution system. It can be designed an almost infinite number of distribution subsystems. These designs can be based on load density, voltage levels, land availability, reliability requirements, load growth, voltage drop, emergency conditions, cost and loss considerations. High side bus voltage is 380 kV or 154 kV generally.

Primary Distribution is the part of the electric system between the distribution substations and the distribution transformers, known also as the medium voltage system. Previously this system consists of two voltage levels; a voltage level of $6.3 - 15$ kV, and an overlay of 34.5 kV. But due to high investment costs and losses, only 34.5 kV feeders are used and the lower voltage levels are increased by stages. The 34.5 kV system design in different ways is possible.

Radial system, only one supply path to the distribution transformers is present. The major drawback is that any problem usually leaves a number of customers out of service until the problem is solved. The major advantages of this system are its simple and more economical structure to install than other types of systems.

Making a loop arrangement provides a great improvement as two way feed at each transformer. Any part of the primary can be isolated without interruption and primary faults are reduced in duration to the time required to locate a fault and do the switching action to restore service. The cable in each half of the loop must have capacity adequately to carry the whole load. The loop layout is very reliable and expensive.

Networks are designed to ensure service in a reliable way to areas with dense loads such as downtown and suburban business residential areas containing many high rise buildings.

Finally, in secondary distribution the distribution transformers purpose is to decrease the primary voltage to a level where it can be utilized by the customers. Three phase commercial distribution transformers are available from 25 kVA to 2500 kVA ranges.

2.1.1 Basic System Elements

Meters, cables and transformers are the basic system elements. The amount of power used in a particular area is recorded by power metering equipment. This equipment sent down data to a particular line and this data is used in a particular structure. Metering equipment ensures information about power using. The information is utilized for planning for future needs from power use trends and off course billing for revenue. Power meters use a current coil and a potential coil. These coils are used to turn. An induction disc is also used by power meters which then turns accumulating devices. The rotation of disc is proportional to the power passing through the line that metered by power meter. The same function can performed by microprocessor based electronic circuitry control. Accumulated power use data can also be transmitted to a central point or recorded in a digital memory for retrieval at the meter side by these circuits. Meters used for low voltage measurement can be hooked directly to the monitored line voltage and current. But for appliances like station monitoring and large commercial and industrial customers, power meters must be fed through instrument transformers.

Electrical power distribution lines are between the distribution substation and ultimate customer. Their properties should be economical, reliable, low in maintenance and long lasting. Generally, lines are constructed along sidewalks on streets.

There are only two metals that have cost effective and long enough in resistivity properties: copper and aluminium. Copper is mainly used material in insulated wires and cables because its much so heavier than aluminium. Pure aluminiums tensile strength is low for most applications. Aluminium alloys or steel reinforced aluminium alloys are used for this

Overhead	Underground
Cost is less.	Visual clutter is less.
Lifespan is long.	Chance is less for public contact.
Outage durations are shorter because fault finding and repair are faster.	Short and long-duration interruptions are fewer.
Overhead structures can more readily withstand overloads.	Voltage drops are less because of lower reactance.

Table 2.1: Overhead and Underground Lines Comparison

reason.

Conductors dc resistance is inversely proportional to the conductors area. It means doubling the area divides the resistance by two. Conductor s resistance is changed by temperature and frequency. A colder conductor ensures less resistance to the current flow.

Overhead or underground designs are performed for distribution system applications. Conductors, structures to support conductors and insulators are elements of overhead distribution and ducts, vaults and cables are elements of underground distribution.

Many of the distribution lines are overhead structures. These structures feed customers along alleys, streets, through woods and in backyards. Wood or steel poles, insulator supports and miscellaneous hardware for device and conductor attachment are elements of overhead structures.

Underground distribution is more reliable. It is much more hidden from view than overhead structures. Buried ducts, vaults and cables are elements of underground distribution systems. These systems are more expensive than an equivalent overhead system. Their lifespan is short, too. Due to their protected structures from storms, lightning and vehicle accidents, underground systems suffer fewer outages. Instead of aluminium for conductors, cables used in underground systems normally use stranded copper. Losses are decreased by the help of coppers lower resistivity.

These two systems have advantages. Cost is the most important advantage of overhead structures. An underground structure is typically costs anywhere from 1 to 2.5 times the equivalent overhead structure. The major drive from overhead system to underground system was primarily a response to environmental pressures. Table 2.1 shows the advantages of these two systems.

Transformers are important link in the electric power distribution system. They step down electricity voltage from high levels in utility transmission systems to voltage that can safely be used in business and home appliances. Transformers in distribution system often provide a local grounding reference.

Transformers two primary components are a core made of magnetically permeable material and a winding made of a low resistance material such as copper and aluminium. Liquid insulation material or air surrounds the transformer core and conductors. Insulation material or air cools and insulates the transformer electrically. Three sources of losses in a transformer are copper, hysteresis and eddy current. They reduce transformer efficiency because of using real power.

Current flowing through the winding resistance results copper losses. Increasing of the ac resistance of the transformer windings with frequency is the result of skin effect, so copper losses increase with frequency if the winding current remains constant. Copper losses can be minimized by proper sizing of the winding wire.

Energy needed to magnetize the core first in one direction and then the other as the applied AC voltage reverses in polarity causes hysteresis losses. The magnetic domains must be created in one direction, and then in the other direction. The domains must be reversed more frequently. As a result of this, frequency increase hysteresis losses. Hysteresis losses can be minimized by the proper choice of magnetic material. It has been developed magnetic material that has amorphous structure instead of small crystalline grain structure of most current magnetic materials. This means the magnetic domains are almost atomic in size and require very little reversing energy. The amorphous magnetic materials are not currently in use widely for many applications because their cost is relatively high. The losses occurring with conventional grain oriented magnetic steel are three times of those occurring with the amorphous magnetic steel. The volume of the core, the frequency and the maximum flux density effects hysteresis losses.

Near a magnetic field in metal, eddy current is induced. If the the metal object is surrounded by the field, the induced current will be a loop at the right angle to the flux. For eddy current to be induced in the core of a transformer, the core is ideally positioned with respect to the windings. The laminations break the core into many small thin pieces of metal, so voltage is reduced that is induced to drive eddy currents must flow because of the each laminations small cross-sectional area. Core volume, frequency, flux density, lamination thickness and resistivity of the core material effects eddy current losses.

Changes	No-Load Losses	Load Losses	Cost
Using less loss core materials	lower	same	higher
Increasing core cross sectional area , so flux density decreases	lower	higher	higher
Decreasing Volts/turn, so flux density decreases	lower	higher	higher
Decreasing conductor cross sectional area, so flux path length decreases	lower	higher	lower
Using less loss conductor materials	same	lower	higher
Increasing conductor cross sectional area, so current density decreases	higher	lower	higher
Decreasing core cross sectional area, so current path length decreases	higher	lower	lower
Increasing volts/turn, so decrease in current path length	higher	lower	higher

Table 2.2: Ways to Decrease Transformer Losses

Load losses are copper losses and no-load losses are hysteresis losses in addition to eddy current losses. They are continuous losses of a transformer and not dependent on the load. Load losses, no-load losses and purchase price are associated with each other. If load losses are reduced, it effects no-load losses by increasing and vice versa. Table 2.2 shows decreasing ways of transformer losses for different situations.

Many utilities evaluate the total lifetime cost of distribution transformers to assign initial values for the initial purchase price and the cost of losses over the lifespan of transformer (the total owning cost). Utilities typically evaluate equivalent present values for the no-load losses cost and another equivalent values for the load losses cost.

In [4] H. Doukas, C. Karakosta, A. Flamos and J. Psarras analyze the effects of electric power transmission on environment. Their purpose is to show a summary of electricity transmission burdens and their impacts. While implementing these effects, transmission operators and regulators try to satisfy both the demand for a high-performing grid and the publics concern about the environmental effects of electrical power transmission. According to the authors, some of these effects are transmission losses, electromagnetic fields, infrastructure, visual intrusion, noise, interruption of supply, land use, ecosystems and lowered property values.

2.1.2 Power Distribution Cable Systems

A single conductor or an assembly of conductors covered by solid electrical insulation is named as cable. Conductor and progress radially through the insulation and coverings are the initial points of cable specification. A typical list of specifications is below:

- Quantity of conductors in cable

- Size and material of conductor (American Wire Gage (AWG), circular mil)
- Type of insulation
- Rating of voltage
- System for required shielding
- Outer finishes (or covering)
- Installation

An alternative method of specifying cable is to provide the current carrying capacity of the circuit (amperes (A)), the voltage (phase to phase, phase to ground, grounded, or ungrounded), and the frequency, along with any other related system data.

Cable Construction: A typical cable includes conductors shielded by different types of material. One conductor or three conductors grouped as one is possessed by the cable. Copper and aluminum are used as conductor materials generally. Copper has historically been preferred for conductors of insulated cables primarily due to its desirable electrical and mechanical properties. The reason of aluminum using is based on its favorable conductivity-to-weight ratio (the highest of the electrical conductor materials), its ready availability, and primary metals stable low cost.

Voltage Cable Shielding: For operating voltages below 2 kV, non shielded constructions are used generally. For all nonmetallic, sheathed, single-conductor cables operating above 2 kV and all metallic sheathed cables and multi conductor cables above 5 kV insulation shielding is necessary. Shielding is the practice of limiting the electric field of the cable to the insulation surrounding the conductor by means of conducting or semiconducting layers, closely fitting or bonded to the inner and outer surfaces of the insulation. In other words, the outer shield limits the electric field to the space between conductor and shield. At or near the conductor potential is situated the inner or strand stress relief layer. The outer or insulation shield is designed to carry the charging currents and in many cases over currents.

For several purposes insulation shields are done:

- Limit the electric field within the cable
- Equalize voltage stress within the insulation, decreasing surface discharges to minimum level
- Preserve cable from induced potentials
- Confine electromagnetic or electrostatic interference (radio, TV, etc.)
- Decrease shock hazard (when properly grounded)

Ratings of Cable and Selection Criteria: Cables can be in different size designs. The size of a cable related to the current carrying capacity or voltage rating of the cable. Cables may include various conductor sizes, and the electrical characteristics of the cable are related to the conductor size that used.

The selection of power cables includes the consideration of various electrical and environmental conditions. These conditions contain the quantity and characteristics of the power being distributed and the degree of exposure to adverse mechanical and thermal stresses.

Cable Installations Types: There are different ways to install power distribution cables. Each method provides distribution of power with a unique degree of reliability, safety, economy, and quality for any specific set of conditions. These conditions contain the electrical characteristics of the power system, the distance and land of distribution, and expected mechanical and environmental conditions[5].

2.1.3 Cable Types

For each voltage level, different types of cables are used. Aluminium and copper cables are used in the system. Mostly, copper cables are used in underground cables. They are more expensive than the aluminium cables. In properties of the cables, AWG (American Wire Gauge) and MCM (Circular Mile) terms are used. MCM represents the conductor area of the cables.

Rose, Lily, Iris, Pansy and Poppy type cables are used in low level voltage ($1 - 1000$ V) lines. Properties of these cables are in Table 2.3.

	AWG	Conductor Surface Area (mm^2)	Resistance (Ohm/km)
Rose	4	21.14	1.3558
Lily	3	26.60	1.0776
Iris	2	33.53	0.8537
Pansy	1	42.49	0.6743
Poppy	1/0	53.48	0.5354

Table 2.3: Cable Types for Low Voltage Level Lines

	AWG	Conductor Surface Area (mm^2)	Resistance (Ohm/km)
Swallow	3	31.14	1.0700
Raven	1/0	63.44	0.5350
Pigeon	3/0	99.30	0.3360

Table 2.4: Cable Types for Medium Voltage Level Lines

	MCM	Conductor Surface Area (mm^2)	Resistance (Ohm/km)	Current Capacity (MVA)
Hawk	477	281	0.1190	132
Drake	795	468	0.0718	182
Cardinal	954	547	0.0597	204
2 Cardinal	2x954	2x547		408
Pheasant	1272	726	0,0449	247

Table 2.5: Cable Types for 154 kV Lines

For medium level voltage ($1 - 35$ kV) lines, Swallow, Raven and Pigeon type cables are used. Properties of these cables are in Table 2.4.

Cable types for 154 kV lines are given in Table 2.5. Electrical properties for cables are shown in the table. These cables are used in high voltage lines ($36 - 154$ kV).

In Table 2.6, cable types for 380 kV lines are given. Also electrical properties for cables are shown in the table. These cables are used in very high voltage lines (Above 154 kV).

Main raw material for underground cables is copper. 630 MCM and 1000 MCM cables are used for 154 kV lines. For 380 kV lines, 1600 MCM and 2000 MCM cables are used. In Table 2.7, properties of underground cables are shown.

2.1.4 Distribution System Planning

Distribution systems are an important part of electric system. Distribution system investments are expensive and construction of these systems take a long time. Their operation

	MCM	Conductor Surface Area (mm2)	Capacity (MVA)
2B, Rail	2x954	2x517	995
2B, Cardinal	2x954	2x547	1005
3B, Cardinal	3x954	3x547	1510
3B, Pheasant	3x1272	3x726	1825

Table 2.6: Cable Types for 380 kV Lines

	Conductor Surface Area (mm^2)	Capacity (MVA)
XLPE Copper	630	175
XLPE Copper	1000	250
XLPE Copper	1600	360
XLPE Copper	2000	987

Table 2.7: Cable Types for Underground Lines

is of great importance in terms of the countrys economy, too. It is mandatory to make local development targets, load forecasts and generation plans in a reliable way. Plans and investments about distribution should be revised periodically according to demands and grows in accordance with the changing requirements of the day. But these plans, installation and inspection procedures should be done by qualified personal and should be in practice adjusted to prevent from political and administrative impacts.

For a qualifier and more efficient distribution system;

- Standardization should be done in planning, project, plant and operation steps and compliance with the decisions of renewed principle should be done.

- Standards and principles should be revised in accordance with the technology and changing requirements of the day. Necessary parts should be updated.

- Effort should be made to use the maximum level of economic and technical life of the equipment and materials that used.

- High-quality materials and workmanship should be ensured in the establishment of investment projects.

2.2 Transmission Line Losses

As in [4] H.Doukas et al. states transmission and distribution losses are due to the transport and allocation of electricity and heat. Minimizing these losses is essential because they consume resources as they are produced. As the transmission losses increase, prices of the electricity, long distance transmission costs, CO2 emissions increase. Transmission losses occur more frequently where there are overhead lines. Underground cables and undersea cables are more resistant to transmission losses. Also the environmental effects of the losses can be defined as transmission external costs. In [4], theft is counted as a type of losses, but in the thesis, it will not be counted.

For the European Union 25, average transmission and distribution losses consist %7.5 of the total generated power [6]. In some of the developing countries this percentage can reach %30 - %40 [7]. The highest transmission and distribution losses in the world exist in India with %27 [8]. In India, most of the losses are because of technical losses and theft. In [4] H.Doukas et al. claims percentage of average transmission and distribution losses changes country to country, because amount of losses depend on the size of the country, length of the power lines, voltage used in the transmission and distribution lines, and quality of the network. Quality of the network depends on the complexity of the network, technology level which is used in the network, and the particular conditions for different regions of the network. Also using qualified cable decreases the amount of losses in countries.

In table 2.8, World average for total distribution and transmission losses is %8.9 [9]. From table 2.9, it is easy to figure out that Turkey's average of losses has been declining since 2000 [10].

As in [1] stated, losses are the parts of electricity supply, which are not paid for by users. Total losses are classified in two parts, technical and non-technical losses. Technical losses occur mainly because of the electricity system components, including transformers, cables which are being used in transmission and distribution lines, measurement systems and losses due to power plants. Technical losses can be grouped according to the place where loss happens. For example, power transformers, primary and secondary system of distribution and connections [11]. Electricity theft, non-payment by customers and errors in record keeping and accounting are the examples of non-technical losses which are present because of the external factors to the power system. In this thesis, non-technical losses will not be considered.

Loss rates for some provinces in Turkey, 2009, are given in Table 2.10. In those rates, technical losses and nontechnical losses are included. Rates in Table 2.10 show that in 2009

Table 2.8: Electricity Losses of OECD Countries in 2009

OECD Countries	
Australia	%11.6
Austria	%7.3
Belgium	%7.8
Canada	%13.4
Chile	%11.3
Denmark	%9.2
Estonia	%16.3
France	%12.8
Germany	%7.7
Greece	%8.8
Ireland	%8.1
Italy	%9.5
Japan	%6.5
Korea	%6.0
Mexico	%20.0
Portugal	%8.9
Spain	%5.9
Sweden	%9.4
Turkey	%16.7
United Kingdom	%9.7
USA	%8.6
OECD	%6.7
World	%8.9

Table 2.9: Annual Development of Electricity Losses in Turkey 2000-2009

Years	%
2000	%19.4
2001	%19.3
2002	%18.8
2003	%17.6
2004	%16.0
2005	%15.4
2006	%14.0
2007	%14.5
2008	%14.4
2009	%15.5

Province	%
Mardin	%79
Sanliurfa	%76
Sirnak	%70.7
Diyarbakir	%70.5
Batman	%66.9
Hakkari	%64.8
Van	%57.9
Agri	%55.7
Mus	%51.3
Bitlis	%41.9
Siirt	%40.6
Igdir	%38.2
Bingol	%26.3
Kars	%22.6
Artvin	%17.1

Table 2.10: Loss and Illegal Consumption Rates by Provinces[12]

most of the power was lost during transmission for some provinces.

Manohar, Vemuri and Rao investigates the power systems design where aim is to operate economically at maximum efficiency and high reliability [8]. According to the authors, technical losses can be minimized by designing the system parameters, including operating voltage and diameter and length of conductors, selecting the right type of material. These choices should be considered carefully. Moreover, controlling each parameter in the power system is essential.

High amount of both technical and non-technical losses may result in poor quality of services for customers and increase of costs [13]. In [13] Y. Al-Mahroqi et al. addresses the different techniques in order to decrease technical and non-technical losses. Theoretically technical losses vary between %3 and %6 and if the total power loss is high, it may be a proof of existing non-technical losses [14] [11]. In third world countries, average energy theft is between %10 and %40, while in developed countries it is approximately %3 [14]. Direct theft and manipulation of measurement systems also cause accounting errors in the production sides.

In power generation, efficiency of the most power plants are blow %50. Efficiency of electricity generation have been improving as technology has been improving. For example

Table 2.11: Efficiency in Electricity Generation

Power Plant	**Efficiency** %
Large Hydro	%95
Small Hydro	%90
Wind Turbine	%35
Coal Fired	%40
Large Gas Turbine	%38
Steam Turbine Coal Fired	%39
Steam Turbine Fuel-Oil	%38
Nuclear	%34
Solar	%14

in the 1950s, electricity generation efficiency was %25 and now it is around %34 worldwide. It is expected to increase in the following years slowly. Most of the energy loss is a waste as heat [15]. Efficiency of the generation plants is dependent with the mode of the generation. For instance, while hydroelectric production has more than %90 efficiency, thermal plants that fire coal have less than %25 efficiency. However, most of the power plants use firing coal as mode of generation. Particularly in China and India, %80 of the electricity generation is handled by thermal plants, because of the high availability of cheap coal. Worldwide, approximately %50 of the electricity generation is produced by steam plants. Large amount of losses occur in the thermal plant, while condensing steam. Additionally, in auxiliaries and generators consume %5 of the generated electricity [15]. Another factors for power generation efficiency are condition of the power plant, design of the power plant and ambient conditions. Condition of the power plant means how operation and maintenance of the power plant are managed. In table 2.11, approximate efficiencies for each mode of operation are shown [16].

After losses in power plants introduced, transformers are another source of power losses, in other words technical losses. In [13] Al Mahroqi et al. classified transformer losses in two groups, no load and load losses. Firstly, the energy to retain the continuously changing magnetic flux in the core and its invariant with load on transformer. This causes no load losses. In windings, conducting material is a source for resistive losses. This resistive loss varies with the loading and this can be classified as load losses in transformers [17]. While buying a transformer, it is essential to consider the initial costs and the future costs, which will arise from losses [11].

Distribution transformers have efficiency less than %0.5 and smaller transformers have higher than %97 efficiency. In [18] transformer losses are classified as dielectric loss, hysteresis loss, eddy current loss and resistive losses in conductors and due to eddy current losses in conductors. Dielectric losses occur because of the electrostatic stress reversals in the insulation. It is dependent with high voltage, frequency, thickness of the insulation and type of the insulation. Dielectric loss is very small, compared to other types of technical losses. Hysteresis loss takes the huge percentage of no load losses. In core of the transformer, molecular magnetic domains are the origins of hysteresis loss. When applied voltage changes the magnetic force produced by the primary of transformer, there occurs a realignment and a loss. Selecting the core material is essential to decrease the hysteresis loss. Magnetizing abilities and frequency are important factors for hysteresis loss. Hysteresis losses can be calculated by;

$$W_h = K_h \times f \times B_m^{1.6} \quad Watts/Kg \tag{2.3}$$

where, $K_h = \textit{the hysteresis constant}$

$f = \textit{frequency in Hertz}$

$B_m = \textit{maximum flux density in Tesla}$

Resistive losses in the windings are another type of losses in the transformers. Resistive loss depends on resistivity, conductor dimensions, and the temperature. The alternating flux creates an electromagnetic force in the bulk of the core, which is proportional to flux density and frequency. As a result eddy current losses in the core exist. This loss inversely dependent with the resistance of the material and directly dependent with the thickness of the core. Flux density, frequency, thickness of the core are the factors which affect eddy current loss in the core [18]. Eddy current loss W_e :

$$W_e = K_e \times f^2 \times B_m^2 \times t^2 \quad Watts/Kg \tag{2.4}$$

where, $K_e = \textit{the eddy current constant}$

$f = \textit{frequency in Hertz}$

$B_m = \textit{maximum flux density in Tesla}$

$t = \textit{Thickness of lamination strips}$

C. Harting studies the two major types of transmission line losses, corona losses and ohmic losses, in [19]. These losses are caused by the cables. In [20] M. Fekri Moghadam and H. Berahmandpour analyzes the ohmic loss of transmission lines as a function of the line current and the environmental condition of the operation. Since transmission lines are the connection between generation and consumption, it is important to formulate the losses in power networks [21], [22]. Fekri Moghadam and Berahmandpour states that the transmission losses are higher when the voltage of the network is less. They add that three main types of transmission line losses exist: ohmic loss, corona loss, and insulation leakage loss [23]. Physical conditions (e.g. radius and type of the conductor, type of the insulator) and environmental conditions such as temperature, air pressure are important factors in the transmission line losses.

Y.Al Mahroqi, I.A.Metwally, A.Al Hinai and A.Al Badi introduces the effect of temperature rise in power consumption [13]. For example, for 1 ^{o}C temperature rise may increase the power loading by %3.75 [24]. Also in [24], effect of lower temperature and rainy day on power consumption is studied.

2.2.1 Corona Loss

In [19], corona loss is represented as a major type of power loss in transmission lines. It is mostly caused by the ionization of air molecules near the transmission line conductors. These coronas do not spark across lines, but rather carry current (hence the loss) in the air along the wire. Corona discharge in transmission lines can lead to hissing/cackling noises, a glow, and the smell of ozone (generated from the breakdown and recombination of O_2 molecules)[25]. The color and distribution of this glow depends on the phase of the AC signal at any given moment in time. Positive coronas are smooth and blue in color, while negative coronas are red and spotty [26].

In [27], P. Sarma, D.H. Nguyen, and H. Hamadani-Zadeh analyzed the corona characteristics under dynamic over voltages. They discovered that under fair weather conditions, the corona losses of conductor bundles grow rapidly with the conductor surface voltage gradient and approach losses under heavy rain at higher gradients [27]. Jacques J. Clade and Claude H. Gary explain corona losses of high voltage lines in wet conditions [28]. O. Nigol and J. G. Cassan discuss the effects of corona loss from an existing project [29]. In [30], characteristics of the corona loss are determined where the conductors are contaminated in fair weather. They investigate the relation between surface gradient and corona loss.

Corona loss only occurs when the line to line voltage exceeds the corona threshold. Unlike resistive loss where amount of power lost was a fixed percentage of input, the percentage of power lost due to corona is a function of the signals voltage. Corona discharge power losses are also highly dependent on weather and temperature.

In [31], corona effects are appearance of a violet luminuous glow, hissing noise, production of ozone gas and power loss. The corona is more evident when the voltage of the line is greater than 100 kV. Corona depends on four factors, such as atmosphere, conductor size, spacing between conductors, and line voltage. State of the atmosphere is important for the corona phenomena. When the air is stormy, corona may appear at much less voltage level with respect to the level in fair weather. In cables, shape and conditions of the conductors play a great a role in corona formulation. Breakdown voltage value decreases because of the unevenness of the conductors surface. Solid conductor has higher breakdown voltage level than conductor with a irregular surface. If the spacing between conductors increases with respect to their diameters, corona effect may disappear, because of the reduction of electrostatic stresses. Mostly, corona is affected by voltage of the line. At low voltage levels, corona effect does not exist. As voltage level increases, electrostatic stresses increases and this leads corona effect to exist.

Corona has advantages and disadvantages. As an advantage of corona, system performance is improved and effects of transients produced by the surges decrease. Loss of power is the most important disadvantage of corona and this affects the efficiency of the transmission line. Corona loss causes ozone gas production. Additionally, a voltage drop may occur because of the corona phenomena. This voltage drop may bring some inference with communication circuits. Another disadvantage is that harmonics are introduced into the transmission line, and this increases the corona loss [31].

30-strands (two layers)	0.826 r
26-strands (two layers)	0.809 r
54-strands (three layers)	0.810 r

Table 2.12: X coefficients for GMR Calculation[34]

Corona loss has direct proportion with the frequency of the supply and air density correction factor. As frequency increases, corona loss increases. On hilly areas, there are more corona loss, than the loss on the plain areas. Corona loss increases during bad atmospheric conditions, because when the weather is bad, critical disruptive voltage decreases. Size of the conductor is in inverse proportion with corona loss. As size of the conductors increases, there will be less corona loss. Same proportion is valid for diameter of the conductor too. Larger diameter causes critical disruptive voltage to decrease and thus corona loss reduces. Using hollow, large diameter and bundled conductors decrease the corona effect [32].

Definition 1 *Critical disruptive voltage is the voltage at which complete disruption dielectric occurs. The gradient at the surface is equal to breakdown strength of air at this voltage.*

Critical disruptive voltage (V_c) is given by,

$$V_c = g_o \times m_o \times r \times \delta \times \log_e \frac{s}{r} \text{ kv / phase} \tag{2.5}$$

where, r is the radius of the conductor in cm and s is the distance between conductors in cm. In order to calculate the corona loss, geometric mean radius of the conductors is considered. Geometric mean radius (GMR) is calculated by

$$GMR = X \times r \tag{2.6}$$

In Equation 2.6, X is a constant coefficient for each type of conductor and r is the conductor radius [33]. For hollow stranded conductors and ACSR, X values are given in Table 2.12. GMR values for specific cable types are in Table 2.13.

For each voltage level, distance between conductors changes. Distance values between conductors are given in Table 2.14. For s parameter, geometric mean distance (GMD)

Cable Type	GMR (cm)
Hawk	0.804672
Drake	1.033272
Cardinal	1.1034
Pheasant	1.29845

Table 2.13: GMR Values for Specific Cable Types

Voltage Level	Distance Between Conductors (cm)
50 V - 3.500 V	35
3.500 V - 10.000 V	60
10.000 V - 50.000 V	90
50.000 V - 100.000 V	150
100.000 V - 250.000 V	300
250.000 V - 450.000 V	450

Table 2.14: Distances Between Conductors For Each Voltage Levels

formula is used. GMD formula is

$$GMD = \sqrt[n]{\prod_{i=1}^{n} d_i} \tag{2.7}$$

In Equation 2.7, n is the number of conductors in a cable and d_i is the distance between these conductors.

g_o is the dielectric strength of air and it is equal to 30 kv/cm peak (or 21.1 kv/cm r.m.s) when the temperate is 25^{o}C and the pressure is 76 cm of Hg. For other temperatures and pressures, dielectric strength of air is calculated by,

$$g_o = \frac{V}{r \times \log_e \frac{s}{r}} volts/cm \tag{2.8}$$

$$g = g_o \times \delta \tag{2.9}$$

where δ is the air density correction factor and is calculated by,

$$\delta = \frac{3.92 \times b}{273 + t} \tag{2.10}$$

Table 2.15: F values for Peterson's Formula

$\frac{V_{pk}}{V_c}$	0.6	0.8	1.0	1.2	1.4	1.6	1.8	2.0	2.2
F	0.012	0.018	0.05	0.08	0.3	1.0	3.0	6.0	8.0

where, b is the barometric pressure, cm of Hg is its unit, and t is the temperature (^{o}C). In equation 2.5, m_o represents the irregularity factor.

$$\begin{aligned} m_o &= 1.0 \text{ for polished wires,} \\ &= 0.98 \text{ to } 0.93 \text{ for roughened or weathered wires,} \\ &= 0.87 \text{ to } 0.83 \text{ for seven strand cables,} \\ &=\sim 0.90 \text{ for large cables with more than seven strands} \end{aligned}$$

From Peek's Formula [26], corona power loss is given by,

$$P = (241 \times 10^{-5}) \times (\frac{f+25}{\delta}) \times \sqrt{\frac{r}{s}} \times (V_{ph} - V_c)^2 \; kW/km/phase \tag{2.11}$$

where f is the frequency of the line in Hz, V_{ph} is the phase neutral voltage (r.m.s) and V_c is the critical disruptive voltage (r.m.s) per phase. Equation 2.11 is applicable for fair weather conditions, if the weather conditions are foul, then approximate loss should be calculated by taking V_c as 0.8 times voltage value for the fair weather. Also equation 2.11 is valid for following conditions; (i) if f is between $25Hz$ and $120Hz$, (ii) r$\geq 25cm$, and (iii) $\frac{V_{ph}}{V_c} > 1.8$ [31].

According to R.K.Rajput, U.A Bakshi and M.V. Bakshi claim if the corona loss is dominant, the Peak's formula is applicable. Otherwise, it is useful to use Peterson's formula [31], [32].Peterson's formula is;

$$P = \frac{21 \times 10^{-6} \times f \times V_{ph}^2}{(\log_{10} \frac{s}{r})^2} \times F \text{ kW/km/phase} \tag{2.12}$$

where, F is a factor which changes with $\frac{V_{ph}}{V_c}$. F is chosen from the table 2.15.

2.2.2 Resistive Loss

The conductors resistivity which in a transmission line is very low, but these conductors are not perfect. Transmitting electricity at high voltage decreases the fraction of energy lost to resistance, which varies depending on the specific conductors, the current flowing and the transmission lines length. For a given amount of power, a higher voltage decreases the current and thus the resistive losses in the conductor. For example, increasing the voltage by a factor of 10 reduces the current by a corresponding factor of 10 and therefore the I^2R losses by a factor of 100, provided the same sized conductors are used in both cases. Even if the size of conductor (cross sectional area) is decreased by 10 to match the lower current the I^2R losses are still decreased by 10. Resistance (R) formula is

$$R = \rho \times \frac{L}{S} \tag{2.13}$$

ρ is the electrical resistivity (Ω.m), L represents the material length (m). Moreover, S is the cross sectional area of the material (m^2). Unit of the resistance is Ω. General formula for the voltage is

$$V = I^2 \times R \tag{2.14}$$

From Equation 2.2, the formula for the current is

$$I = \frac{P}{\sqrt{3}\, U \cos(\varphi)} \tag{2.15}$$

After calculating the current, by combining Equation 2.14 and 2.13 formula for power loss is

$$PowerLoss = \frac{2 \times L \times I^2}{\alpha \times S} \tag{2.16}$$

where,

P: Power distributed (Watts)

U: Voltage of the line (Volts)

$\cos(\varphi)$: Power coefficient, assumed to be 0.8

L: Length of the line (Meters)

α: Electrical Conductivity (m/$\Omega \times mm^2$)

S: Surface Area (mm^2)

2.3 Previous Power Transmission Models in the Literature

In [35] R. Naresh, J. Dubey, and J. Sharma propose a two-phase optimization neural network based modeling framework in to solve the economic dispatch problem in large-scale problems. They define the aim of the economic load dispatch as to distribute generation levels to the different generating units in the system to satisfy the load demand in the most economical way while satisfying all systems and individual unit constraints. The significance of economic load dispatch is to obtain the maximum level of usable power while using minimum resources. Their main objective is to minimize the total cost of the generation while satisfying the whole load demand and satisfying other constraints such as power balance, unit generation limits, maximum ramp-rate limits, network losses and prohibited zone avoidance. In my study, prohibited zone avoidance and ramp rate limits are not studied. Naresh et al. however use only the generation part. They suggest that their optimization algorithm has useful attributes such as an integrated approach towards constraint dealing which is continuous in the output space and ability to promise the solution space in a large-scale problem. Model that is explained in [35]:

Sets

PG: set of generation unit

Parameters

P_D : Load Demand

P_L : Total Loss in the System

$MinP_i$: $i \in PG$ Minimum generation limit

$MaxP_i$: $i \in PG$ Maximum generation limit

Variable

P_i: Production amount

Objective

$$\min\ F = \sum_{i=1}^{n} f_i(P_i) \tag{2.17}$$

subject to

$$\sum_{i=1}^{n} P_i - P_D - P_L = 0 \tag{2.18}$$

$$MinP_i \leq P_i \leq MaxP_i \tag{2.19}$$

In the objective function P_i is the amount of power that is generated in power plant $i \in PG$ and,

$$f_i(P_i) = a_i P_i^2 + b_i P_i + c_i \tag{2.20}$$

a_i , b_i and c_i are constants for each power generation plant. In this model, power loss is calculated by using loss coefficient method (B-Matrix). B_{ij} are loss coefficients of the network.

$$P_L = \sum_{i=1}^{n} \sum_{j=1}^{n} P_i B_{ij} P_j \tag{2.21}$$

In the first constraint, there is a power balance constraint. Total generated power in the power generation plants should satisfy all the demand and the total power loss. In this constraint, P_L represents the loss which happens while generating power and distributed power will cover both demand and the loss which occurs while transmitting power. Second constraint is the generation capacity constraint. For stable operations, there should be an upper and lower limits for each power generation plants. In order to solve this economic dispatch model, in [35] Naresh et al. used a closed two-phase closed-loop neural network which is introduced by Shanblatt and Maa [36].

As the technology improves, digital computing skills improve and allow many solution techniques to be found. Artificial neural networks technique is one of those solution techniques. The economic dispatch problem in [37],[38],[39] is solved using the Hopfield neural network approach [40]. Researchers in [35], state that an analytic Hopfield method is used for faster computation in [38] but R. Naresh, J. Dubey and J. Sharma write that the Hopfield method does not implement the transmission losses. Also in [39], ramp-rate limits are not studied. Additional examples for remaining solution techniques are genetic algorithms [41] and simulated annealing based algorithms [42].

In [43] economic dispatch is defined as the generation schedule that minimizes the total generation and operation cost while satisfying all of the system operating constraints. A new technique including linear programming method is introduced. To solve the load flow problem, the Newton-Raphson method is used. A. Farag, S. Al-Baiyat and T.C Cheng applied their method to the 10-bus and 30-bus system. They claim that their results are similar to the other optimum dispatch methods.

The Pareto-based multi objective evolutionary algorithm is used to solve a nonlinear optimization problem in [44]. Abido includes a procedure to check the quality of the other techniques and a feasibility check procedure. Abido uses that algorithm with the 30-bus six-generator test system. The main aim of the economic dispatch problem is described as scheduling the committed generating unit outputs so as to satisfy the load demand at minimum operating cost without violating any unit and system equality and inequality constraints. The economic dispatch problem is a large-scale non linear optimization problem. Environmental dispatch is also examined. In environmental dispatch, emissions of the generating units are important factors while making decisions; however, in my work, emissions are not studied. In [44], three multi objective evolutionary algorithms were discussed and used to solve the economic and environmental dispatch problem. In [45] and [46] emission is taken as a constraint with a permissible limit and this allows the problem to be reduced. According to Abido, this technique has difficulties while observing the tradeoff between cost and emission. Also Abido states that in [43], there is no available information about the tradeoffs. Abido argues that converting the problem to a single objective problem by using linear combination of various objectives as a weighted sum as in [47], [48],[49] requires multiple runs. Moreover, Abido analyzed the technique of the multi objective stochastic search in [50] and declares it is time-consuming. Abido declared evolutionary algorithms eliminate all the difficulties of classical methods. In [51], [52], [53], [54], [55], multi objective evolutionary algorithms are used to solve economic and environmental dispatch problems. The quality and the diversity of the solutions of [51], [52], [53], [54], [55] have not been measured according to Abido.

In [56], B. H. Chowdbury and S. Rahman explain various reports about economic dispatch. They define economic dispatch as the process of assigning generation levels to the generating units so that the system operates most economically. They use the following mathematical models to find the optimal power flow: the transportation method, minimum cost flow technique, the reduced Hessian-based optimization technique, quadratic, linear, non-linear, integer and dynamic programming techniques, constraint relaxation and the network approach. To find the optimal power flow, Stefani et al. [57] writes a two level optimization method. Irving et al. [58] presents a dual revised simplex algorithm for economic dispatch. Somuah et al. [59] added another constraint, the maximum frequency deviation, to the economic dispatch problem. Shoults [60] establishes a different approach for calculating the loss coefficients. Burchett, et al.[61], [62], [63] analyzes the implementation of the Newton approach and quadratic programming to the optimal power flow.

D. P. Kothari and J. S. Dhillon [64] demonstrate the Newton-Raphson method and the efficient method to solve the economic dispatch. They specify the economic dispatch problem as that which minimizes the total operating cost while satisfying the total demand and the transmission losses within the generation capacities. They study only the generation part and model that version of the problem. Algorithms for each of the methods can be found in [64]. Also D.P Kothari and J. S. Dhillon show how to calculate the loss coefficients.

Chapter 3

MODEL

3.1 Introduction

In this chapter, model and the network, which are studied, will be explained. Network consists of power plants, demand points and the transmission cables. Model will focus on minimizing power generation while satisfying the demand with minimum power loss. In the first model, with the given cable type, problem is more likely an allocation problem. In other words, in the first model cable types between each demand point are known and how to distribute power to demand points will be examined. In the second case, cable types between each point are unknown and while allocating the power, also optimum cable types will be found.

Network in the model consists of three parts, power plants, demand points and transmission cables. As mentioned earlier, after power generated in power plant, its voltage is increased by transformers, which is known as generating step up transformer, to high voltage levels, in order to distribute the power. Also for long distances, high voltage levels are more efficient. Before transmitting power to demand points, voltage level is decreased again by transformers, which is known as substation step down transformer, to low voltage levels. Transformers are not included in the model, because they are assumed to work with %99 efficiency, so they do not cause so much technical loss. Also lines with low voltage levels will not be studied in the model, because as in explained in Chapter 2 corona loss does not appear in low voltage levels and low voltage level cables have less resistance. In Turkey, high voltage levels (154 kV) and extra high voltage levels (380 kV) are used to distribute power.Types of cables change with respect to the voltage of the line.

While choosing cables in the network, their resistance, weight, radius, current capacity, type of voltage level, and other electrical properties are important. In the model, only current capacity, radius, type of voltage level and resistance of the cables are considered, because model only focuses on calculation of losses.

3.2 Model for Power Allocation

In the first case, I denotes the all set of nodes. I_1 represents the power generation nodes and I_2 is for demand points. Also C denotes the set of cables.

Sets

I :	Set of Nodes
I_1 :	Set of Power Generation Nodes
I_2 :	Set of Demand Nodes
C :	Set of Cables

$$I = I_1 \cup I_2$$

First parameter is connection(i,j), it represents which nodes from set I are connected. It is 1, if there is a cable between node i to node j. Otherwise it is 0. Also if i is equal to j, then it is 0 too.

$$connection(i,j) = \begin{cases} 1, & \text{if node i-j is connected} \\ 0, & \text{otherwise} \end{cases} \qquad i, j \in I$$

$$connection(i,j) = \begin{cases} 0, & \text{if i=j} \end{cases}$$

Demands of each nodes are denoted by demand(i), $i \in I$. Demands of all power generation nodes are assumed to be zero. In other words, if $i \in I_1$, then demand(i) is 0.

demand(i) = Demand of node i , i $\in I$.

$$demand(i) = \begin{cases} 0, & \text{if i} \in I_1 \end{cases}$$

cable(i,j,k) represents the cable type, which is used between nodes i and j. It is equal to

1, if cable type k, k $\in C$ connects the nodes i and j, (i,j) $\in I$.

$$cable(i,j,k) = \begin{cases} 1, & \text{if (i,j) is connected with cable k, k} \in C \\ 0, & \text{otherwise} \end{cases} \quad i,j \in I$$

distance(i,j) is another parameter showing the distance between nodes i and j, (i,j) $\in I$. Its unit is in kilometers.

distance(i,j)= Distance between nodes i and j, (i,j) $\in I$.

In the model, power loss due to resistance of cables, excluding corona power loss, is calculated by the formulas in Chapter 2. The formula for the current is

$$I = \frac{P}{\sqrt{3}\ U \cos(\varphi)} \tag{3.1}$$

After calculating the current, formula for power loss is

$$PowerLoss = \frac{2 \times L \times I^2}{\alpha \times S} \tag{3.2}$$

where,

P: Power distributed (Watts)

U: Voltage of the line (Volts)

$\cos(\varphi)$: Power coefficient, assumed to be 0.8

L: Length of the line (Meters)

α: Electrical Conductivity (m/$\Omega \times mm^2$)

S: Cross Sectional Surface Area (mm^2)

All power plants has cost coefficients, which are c_1, c_2, c_3. They are related with the power generation characteristics of the power plants. Their unit is $ per hour. All cable types have specific parameters. Firstly, current capacity of cables are important factor, as current passing through the line, it should not pass the capacity. Its unit is in amperes.

Voltage level of the cable is another parameter, in the model there is two voltage levels, $154kVolts$ and $380kVolts$. This parameter is used while calculating the technical losses in the model. Also for calculating the technical losses, surface area and electrical conductivity of the cables are used. Unit of surface area is mm^2 and unit of electrical conductivity is $m/\Omega \times mm^2$. For the corona power loss, each cable type has a corona parameter, which is found by the formulas in Chapter 2. Unit of the parameter is kilo Watts per kilometers.

$MinP_i$, $MaxP_i$: Minimum and maximum generation limits for power plant i, i $\in I_1$

$c_1(i), c_2(i), c_3(i)$: Cost coefficients ($\$/h$ for power plant i, i $\in I_1$

corona(k): Corona power loss (kW/km) for cable k, k $\in C$

capacity(k): Current Capacity of cable k, k $\in C$

voltage(k): Voltage level of cable k, k $\in C$

conductivity(k): Electrical conductivity of cable k, k $\in C$

area(k): Surface area of cable k, k $\in C$

There are two positive variables in the first case. First one is the distributed amount of power between node i and j, $(i, j) \in I$. Power generated amount in power plant i, $i \in I_1$, is the other variable.

$Variables$

distpower(i,j): Distributed amount of power between nodes i and j, $(i, j) \in I$

powergen(i): Power generated in power plant i, $i \in I_1$

Objective

$$\min \quad \text{Total Cost} = \sum_{i \in I_1} c_1(i) powergen(i)^2 + c_2(i) powergen(i) + c_3(i) \tag{3.3}$$

subject to

$$powergen(i) \geq \sum_{j \in I} connection(i,j) distpower(i,j) \quad \forall i \in I_1 \tag{3.4}$$

$$MinP_i \leq powergen(i) \leq MaxP_i \quad \forall i \in I_1 \tag{3.5}$$

$$\begin{aligned} &\sum_{i \in I} connection(i,j) distpower(i,j) = \\ &\quad demand(j) + \sum_{i\prime \in I} connection(j,i') distpower(j,i') \\ &\quad + \sum_{i \in I} connection(i,j) \sum_{k \in C} cable(i,j,k) Power_{Loss}(i,j,k) \quad \forall j \in I \end{aligned} \tag{3.6}$$

$$distpower(i,j) \leq \sum_{k \in C} cable(i,j,k) capacity(k) \quad \forall (i,j) \in I \tag{3.7}$$

$$distpower(i,j) \geq 0 \quad \forall (i,j) \in I \tag{3.8}$$

$$powergen(i) \geq 0 \quad \forall i \in I_1 \tag{3.9}$$

$$connection(i,j) \in 0,1 \quad \forall (i,j) \in I \tag{3.10}$$

$$cable(i,j,k) \in 0,1 \quad \forall (i,j) \in I, \forall k \in C \tag{3.11}$$

First constraint can be called as balance constraint for power plants. Generated amount of power in power plants should be equal to the distributed power from power plants to the nodes, which are connected to each power plant. Second constraint is the limit constraint for power plants. Each power plant has minimum and maximum production capacity. There is a minimum production capacity, because it is expensive to shut down the facility and re-open again. In the third constraint, for each node inputs and outputs should be equal. Distributed power coming to a node should be equal to the demand of that node, distributed power from that node to other nodes and technical loss, which exists during distribution. Power loss is calculated by

$$Power_{Loss}(i,j,k) = \Big((\frac{distpower(i,j)}{\sqrt{3}voltage(k)0.8})^2 \frac{2distance(i,j)}{\alpha_k S_k} + corona(k)distance(i,j) \Big) \quad (3.12)$$

Each cable type has a current capacity and distributed power should not exceed that limit. Last constraint is for ensuring that limit. Other constraints are nonnegativity constraints.

This model can be solved by using Non-Linear Programming. Outputs of the model and comparison of the data from TEIAS with the output of the model will be discussed in Chapter 4.

3.3 Data

In order to implement the model on a real case, from TEIAS, Turkish Electricity Transmission Company, some relevant data is taken. Figures 3.1 and 3.2, shows the connection between nodes, demands of nodes, power generated in power plants and amount of power distributed between each node. This data belongs to summer 2012. Unit of the numbers in figures is megawatts.

In figures 3.1 and 3.2, Hamitabat and Ambarli are two important power plants. Moreover, there are small facilities, which uses solar energy or produce their own energy, but they produce small amounts with respect to Hamitabat and Ambarli. Demand points are shown as the green circles, and production facilities are shown as blue circles in the figures. In each line, the amount of power distributed is written over each line. Each number on top of green circles gives the demand of the respective district. For example, demand of Gelibolu is $12MWatts$. Also, each number on top of blue circles represents the amount of power generated in respective district. In the figures there are black and red lines between nodes. Red lines represents the $380kV$ lines and black ones shows the $154kV$ lines. For instance, line between Hamitabat and Babaeski is $380kV$ and line between Malkara and Uzunkopru is $154kV$. If the number on a line is positive, then it means that amount is out of the node. Moreover, if the number on a line is negative, then that amount of power came to the node. Difference between those numbers give the amount of technical loss between two nodes. For example, from Tekirdag $47.1MWatss$ is sent to Malkara, but transformers

	C1	C2	C3
Ambarli	0.0127	7.2592	7290.6
Hamitabat	0.0168	7.0663	6595.5

Table 3.1: Cost Coefficients of Power Plants ($/h)[66]

	Minimum Limit	Maximum Limit
Ambarli	245	1350
Hamitabat	190	1120

Table 3.2: Power Generation Limits for Power Plants (MW) [66]

in Malkara received $46.4MWatts$. This means $0.7MWatts$ is lost during distribution.

In the figures 3.3 and 3.4, cable types, distances between nodes and voltages of the lines are shown. On each link between nodes, there are two numbers. First one shows the type of cable, which is used in the link. All numbers are MCM. For example, between Etiler and Levent, there is 1000 MCM. In figures, there is also other types of cables, C and Ph. C means Cardinal and Ph means Pheasant. $630, 1000, 1600$ and 2000 MCM represents the underground cables. Other types, $477, 795, 954$ and 1272 MCM are for overhead lines. Other number, which is written on the links, indicates the length of the cables in kilometers. For instance, between Etiler and Levent there is 4 km long cable. Also, red cables show the 380 kV lines, and black ones show the 154 kV lines. For 380 kV lines, there is another number on the links (ex;$3C$), which shows the number of conductors in the cables. Moreover, power plants, solar energy facilities can be found from figures 3.3 and 3.4. Explanations of the symbols are in Figure 3.5.

In the model, two thermal power plants will be considered, Hamitabat and Ambarli. Data for European side of Istanbul and the rest of the European side of Turkey will be used. Cost coefficients of Hamitabat and Ambarli are in Table 3.1. In Table 3.2, power generation limits for each power plant are shown. In the model $MinP_i$ and $MaxP_i$ are the generating limit parameters. Unit of these limits is Megawatts.

Distance between each node is also important, because power loss will increase as distance increases. Distance between each interval is shown in Figures 3.4 and 3.3 and for the parameter distance(i,j), where (i,j)$\in$I,

For implementing the data in figures 3.3 and 3.4, a precise number is assigned to each

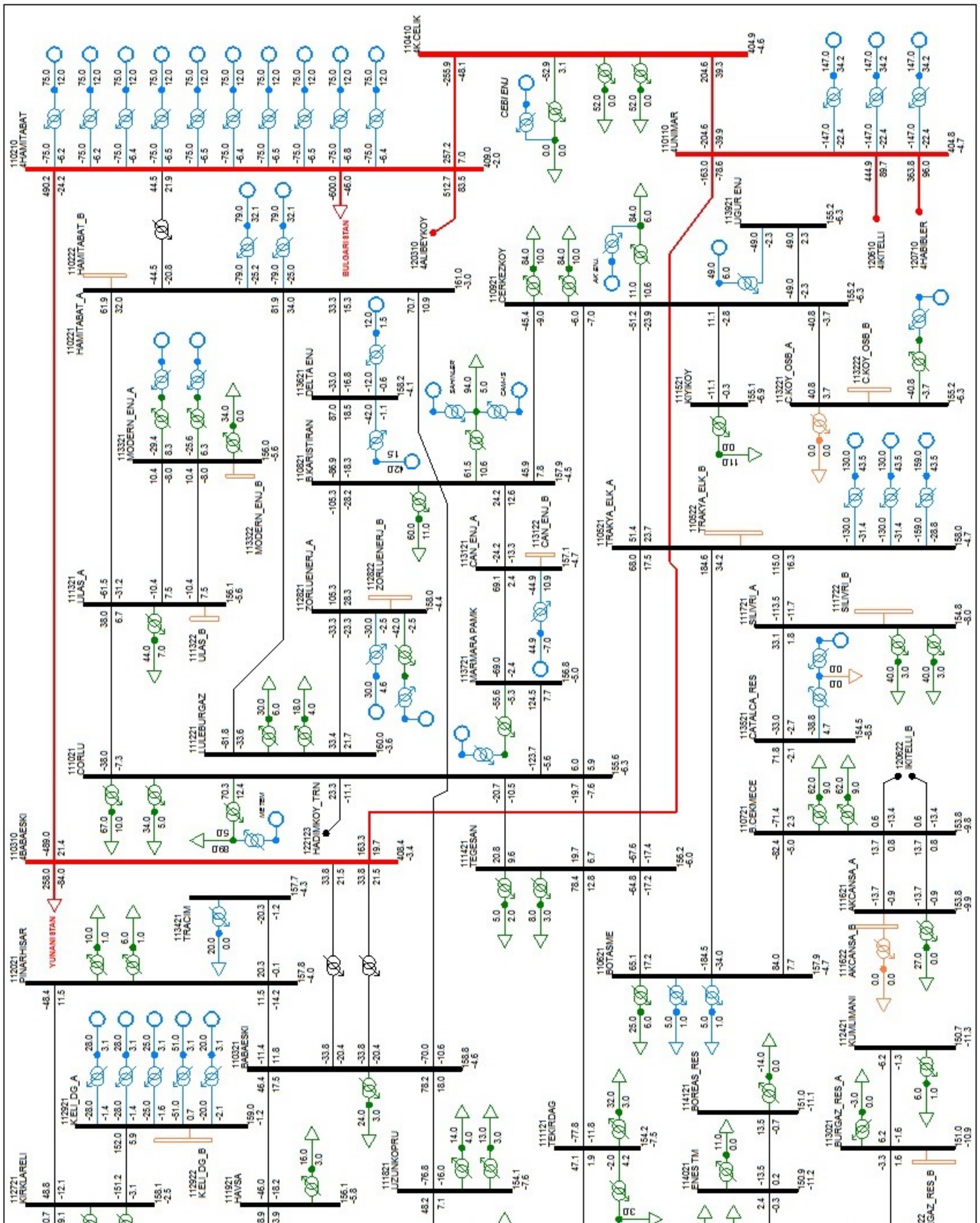

Figure 3.1: Connection data of Thrace

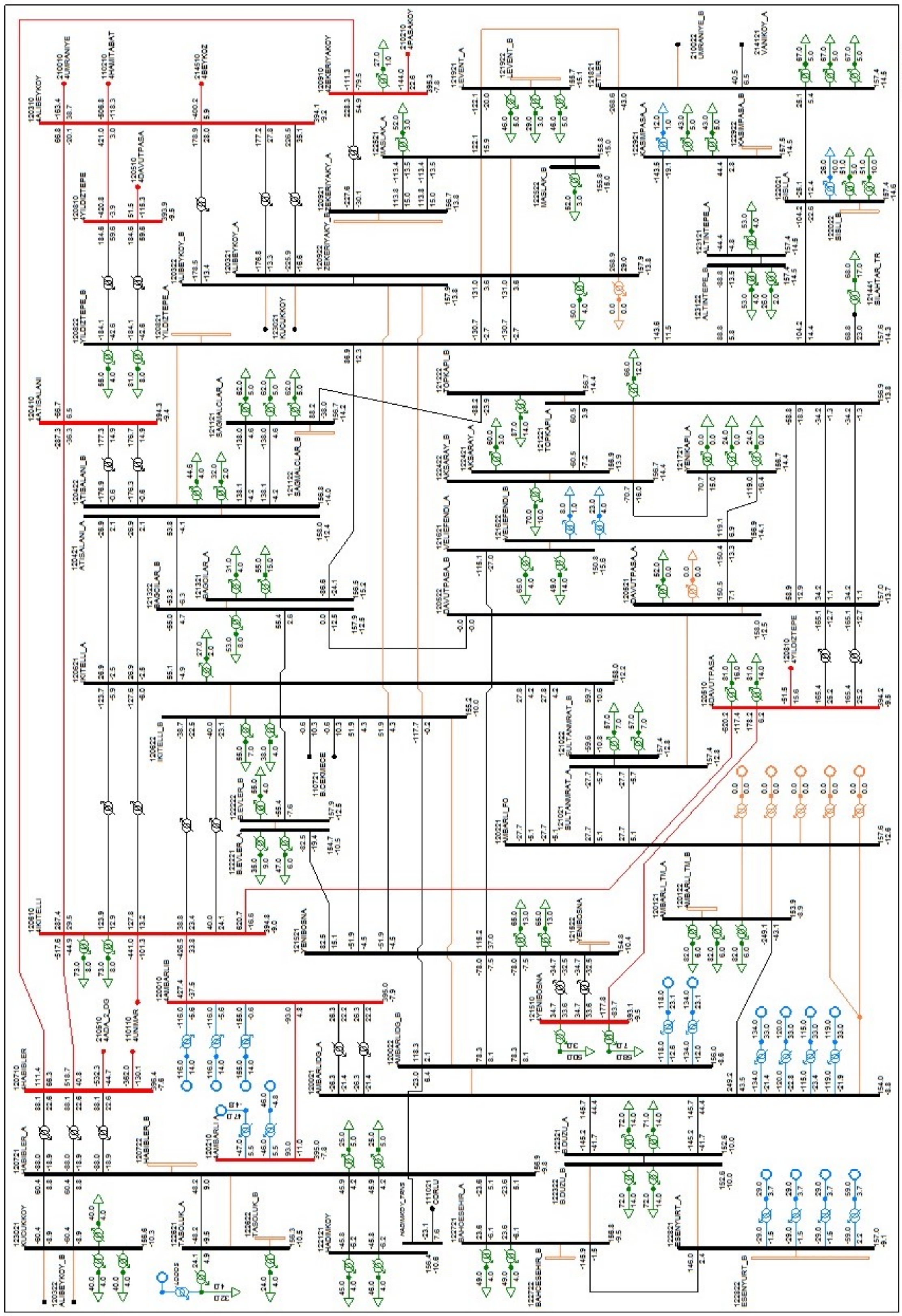

Figure 3.2: Connection data of European side of Istanbul

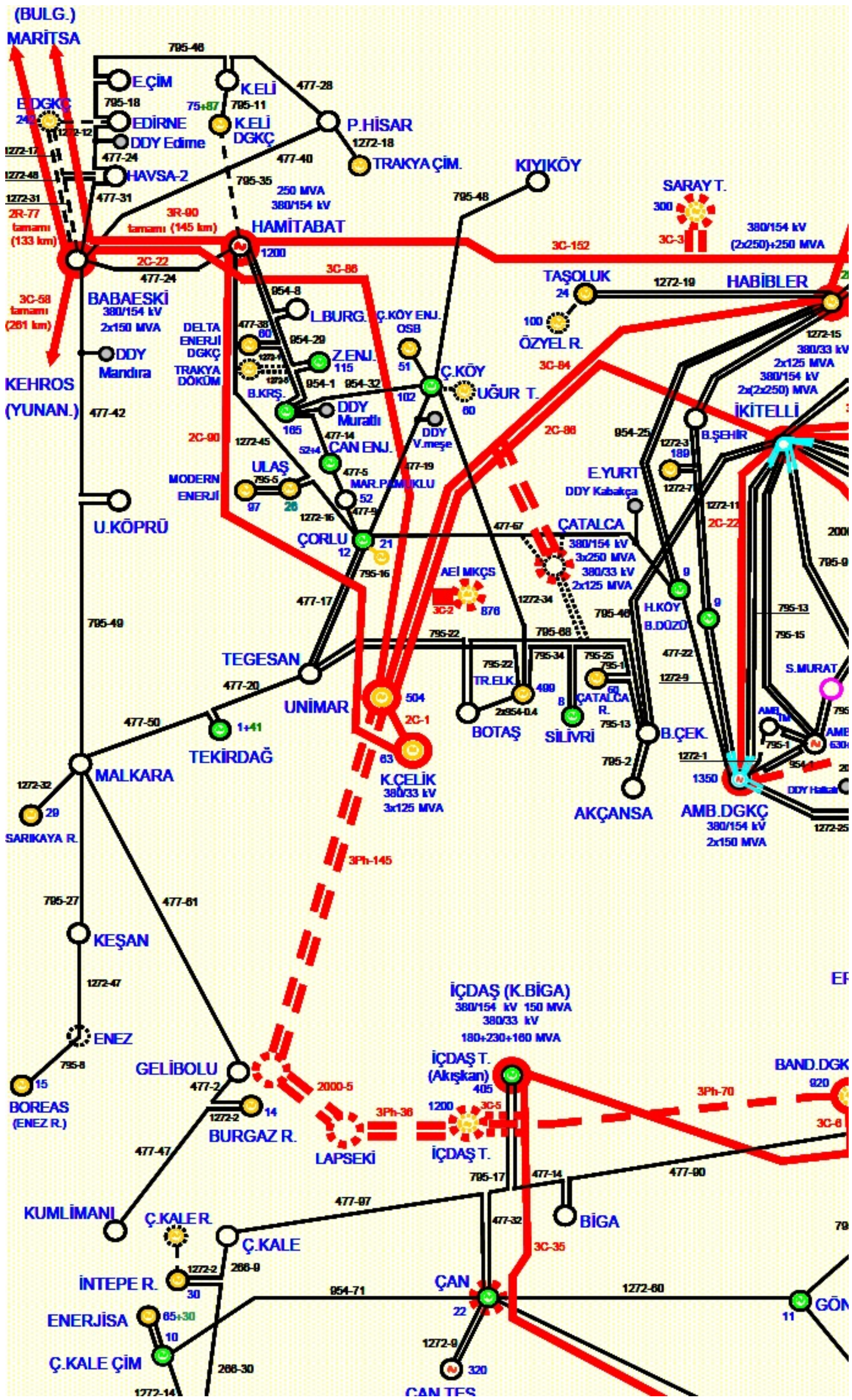

Figure 3.3: Cable properties for Thrace

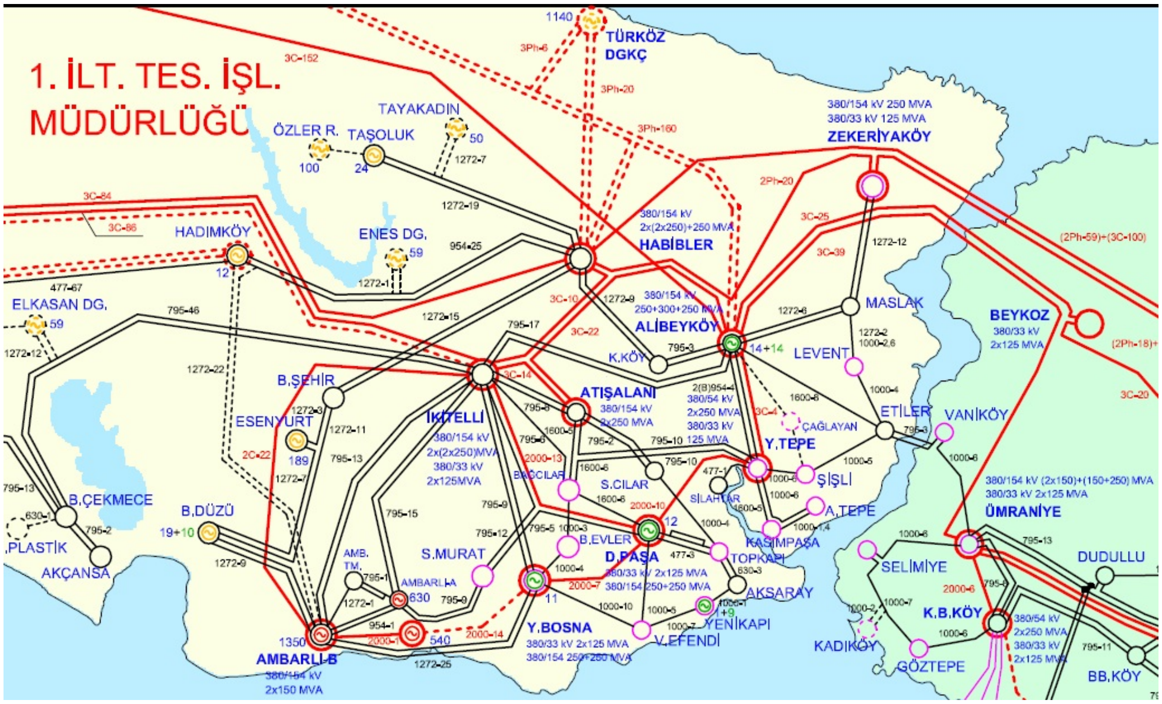

Figure 3.4: Cable properties for European side of Istanbul

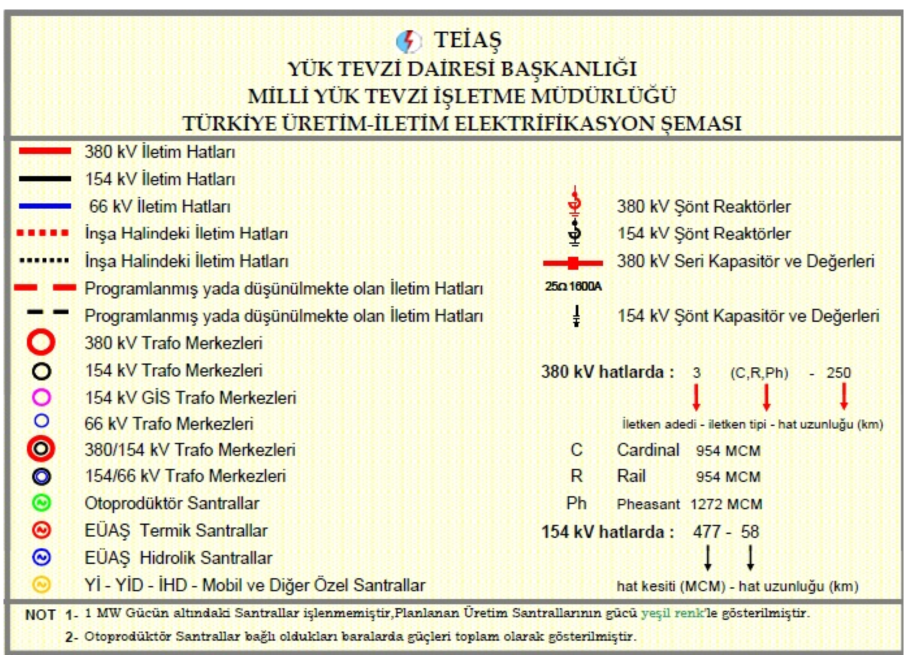

Figure 3.5: Detailed Description of the Maps in Turkish[65]

1. Ambarli	2. Esenyurt	3. Beylikduzu	4. Bahcesehir
5. Habibler	6. Zekeriyakoy	7. Ikitelli	8. Sultanmurat
9. Yenibosna	10. Veliefendi	11. Yenikapi	12. Aksaray
13. Topkapi	14. Davutpasa	15. Bahcelievler	16. Sagmalcilar
17. Bagcilar	18. Silahtar	19. Atisalani	20. Kucukkoy
21. Alibeykoy	22. Yildiztepe	23. Kasimpasa	24. Altintepe
25. Sisli	26. Maslak	27. Levent	28. Etiler
29. Hamitabat	30. UNIMAR	31. ADA2DG	32. Beykoz
33. Pasakoy	34. Umraniye	35. Babaeski	36. Bulgaristan
37. Kcelik	38. Ulas	39. Luleburgaz	40. Delta Enerji
41. Modern Enerji	42. Corlu	43. Pinarhisar	44. Kirklareli
45. Edirnecim	46. Edirne	47. Havsa	48. Keli DG
49. Tracim	50. Uzunkopru	51. Malkara	52. Sarikaya
53. Tekirdag	54. Kesan	55. Enes TM	56. Boreas
57. Botasme	58. Gelibolu	59. Burgaz Res	60. Kumlimani
61. Akcansa	62. Tegesan	63. Buyukcekmece	64. Catalca
65. Silivri	66. Trakya Elk	67. Kiyikoy	68. Cerkezkoy OSB
69. Cerkezkoy	70. BKaristiran	71. Zorlu Enerji	72. Hadimkoy
73. Yunanistan	74. Marmara Pamuk	75. Can Enerji	76. Ugur Enerji

Table 3.3: Numerical Assignment for each District

district in Table 3.3. There are 76 different districts, but two of them are Greece and Bulgaria, which are for importing and exporting electricity. Two nodes, Greece and Bulgaria, will be ignored in the remaining parts, because demands and other parameters are unknown for these two nodes. Also there are four nodes, including ADA2G, Beykoz, Pasakoy and Umraniye, from Anatolian side of Istanbul. They provide power to European side of Istanbul, so these nodes will be considered as power generating nodes.

From figures 3.3 and 3.4, demands for each node is determined. In Table 3.4, of each district is shown. Unit of the demands is in megawatts. In Table 3.4, there are some nodes with zero demand, they are power generating nodes. These nodes generate their own power or they are thermal power plant, like Hamitabat and Ambarli. Also demands of Greece and Bulgaria are counted as zero, because of the unknown parameters. This data is related with the demand(j) parameter.

A connectivity matrix is needed for the parameter connection(i,j), which equals to 1 if node i is connected to node j $\forall$ (i,j)$\in$ I. Connectivity matrix size is 76×76. In Tables 3.5 and 3.6, each connected districts, where parameter connectivity(i,j) equals to 1, are given.

1. Ambarli - 0	2. Esenyurt - 0	3. Beylikduzu - 144	4. Bahcesehir - 98
5. Habibler - 50	6. Zekeriyakoy - 27	7. Ikitelli - 266	8. Sultanmurat - 114
9. Yenibosna - 238	10. Veliefendi - 114	11. Yenikapi - 48	12. Aksaray - 130
13. Topkapi - 153	14. Davutpasa - 214	15. Bahcelievler - 173	16. Sagmalcilar - 186
17. Bagcilar - 139	18. Silahtar - 68	19. Atisalani - 77	20. Kucukkoy - 120
21. Alibeykoy - 50	22. Yildiztepe - 136	23. Kasimpasa - 86	24. Altintepe - 132
25. Sisli - 102	26. Maslak - 104	27. Levent - 121	28. Etiler - 201
29. Hamitabat - 0	30. UNIMAR - 0	31. ADA2DG - 0	32. Beykoz - 0
33. Pasakoy - 0	34. Umraniye - 0	35. Babaeski - 24	36. Bulgaristan - 0
37. Kcelik - 52	38. Ulas - 44	39. Luleburgaz - 48	40. Delta Enerji - 0
41. Modern Enerji - 34	42. Corlu - 101	43. Pinarhisar - 16	44. Kirklareli - 30
45. Edirnecim - 19	46. Edirne - 76	47. Havsa - 16	48. Keli DG - 0
49. Tracim - 0	50. Uzunkopru - 27	51. Malkara - 27	52. Sarikaya - 1
53. Tekirdag - 32	54. Kesan - 52	55. Enes TM - 11	56. Boreas - 14
57. Botasme - 25	58. Gelibolu - 12	59. Burgaz Res - 3	60. Kumlimani - 6
61. Akcansa - 27	62. Tegesan - 13	63. Buyukcekmece - 124	64. Catalca - 0
65. Silivri - 80	66. Trakya Elk - 0	67. Kiyikoy - 11	68. Cerkezkoy OSB - 0
69. Cerkezkoy - 179	70. BKaristiran - 121	71. Zorlu Enerji - 0	72. Hadimkoy - 91
73. Yunanistan -0	74. Marmara Pamuk - 0	75. Can Enerji - 0	76. Ugur Enerji - 0

Table 3.4: Demands of each District in MW

Each i∈I is connected to the related j∈I. For example, Beylikduzu (i= 3), is only connected with Bahcesehir (j= 4). There can be a flow from Beylikduzu to Bahcesehir. Also it is important that (i,j) means there can be a flow from i'th district to j'th district, but this does not mean there can be a flow from j'th to i'th district. For some nodes, especially for power plant nodes, connection is one directional. In other words, some nodes can pass power to another node, but they can not receive power from that node. Connections for Greece and Bulgaria are not counted as they have unknown parameters.

Distances between each connected nodes are given in Table 3.7. As distance increases, power loss will increase, so power distribution is important. In Table 3.7, for each (i,j) ∈ I, distance(i,j) value is given in the next column. Unit of the distance(i,j) parameter is kilometers. For example for (i,j)=$(1, 3)$, distance between i and j is 9 kilometers.

Voltage of the lines are also another important for calculating losses. In Turkey, 380 kV and 154 kV lines are being used to distribute power. So voltage(k), k∈C, parameter will be 380 or 154. Unit of the voltage(k) parameter is kilovolts. In Table 3.8 lines, which are 380 kV, are given. There are 29 380 kV lines in the area. For (i,j) values, (i,j)∈I, line between i'th district to j'th district, voltage(k) parameter is 380. For rest of the nodes, voltage(k) parameter is 154. An example for this is, voltage of the line between Habibler (i= 5) and

i	j	i	j
1	3,7,8,9,72	21	7,19,20,22,26,28
2	3,4	22	14,17,18,19,21,23,24,25
3	4	23	22,24
4	3,5	24	22,23
5	4,6,7,20,72	25	22,28
6	5,26	26	6,21,27
7	5,8,9,14,17,19,21,63	27	26,28
8	7,14	28	21,25,27
9	7,10,14,15	29	21,35,37,38,39,40
10	9,11	30	5,7,37
11	10,12	31	5
12	11,13	32	21
13	12,14,16	33	6
14	7,8,9	34	21
15	9,17	35	30,43,47,50
16	13,19	36	
17	7,14,15,19,22	37	30
18	22	38	41,42
19	7,16,17,21,22	39	71
20	5,21	40	70

Table 3.5: (i,j) Values, where Connection(i,j)=1

i	j	i	j
41	38	59	58,60
42	38,62,69,72,74	60	59
43	35,44,49	61	63
44	43,45	62	42,53,57,66
45	44,46	63	7,57,61,64
46	45,47	64	63,65
47	35,46	65	64,66
48	44	66	57,62,65,69
49	43	67	69
50	35,51	68	69
51	50,52,53,54,58	69	42,66,67,68,70
52	51	70	40,69,71,75
53	51,62	71	39,70
54	51,55	72	5,42
55	54,56	73	
56	55	74	42,75
57	62,63,66	75	70,74
58	51,59	76	69

Table 3.6: (i,j) Values, where Connection(i,j)=1

1.3	9	10.9	10	19.16	2	26.27	2	38.42	16	51.58	61	65.64	25
1.7	22	10.11	7	19.17	5	27.26	2	39.71	29	52.51	32	65.66	34
1.8	9	10.14	5	19.21	22	27.28	4	40.70	5	53.51	50	66.57	0,4
1.9	25	11.10	7	19.22	10	28.21	8	41.38	5	53.62	20	66.62	22
2.3	7	11.12	1	20.5	9	28.25	5	42.38	16	54.51	27	66.65	34
2.4	3	12.11	1	20.21	3	28.27	4	42.62	17	54.55	47	66.69	34
3.4	11	12.13	3	21.7	17	29.21	152	42.69	19	55.54	47	67.69	48
4.3	11	13.12	3	21.19	22	30.5	84	42.72	67	55.56	8	68.69	1
4.5	15	13.14	3	21.20	3	30.7	86	42.74	9	56.55	8	69.42	19
5.4	15	13.16	4	21.22	4	31.5	150	43.35	40	57.62	22	69.66	34
5.6	20	14.7	13	21.26	6	32.21	25	43.44	28	57.63	28	69.67	48
5.7	10	14.8	5	21.28	8	33.6	32	43.49	18	57.66	0,4	69.68	1
5.20	9	14.9	7	22.14	10	34.21	39	44.43	28	58.51	61	69.70	32
6.5	20	14.10	5	22.17	6	1.72	22	44.45	46	58.59	2	70.40	5
6.26	12	14.13	3	22.18	1	5.72	25	45.44	46	59.58	2	70.69	32
7.5	10	14.17	6	22.19	10	7.63	46	45.46	18	59.60	47	70.71	1
7.8	12	14.22	10	22.21	4	29.35	22	46.45	18	60.59	47	70.75	14
7.9	9	15.9	4	22.23	5	29.37	90	46.47	24	61.63	2	71.39	29
7.14	13	15.17	3	22.24	6	29.38	45	47.35	31	62.42	17	71.70	1
7.17	6	16.13	4	22.25	6	29.39	8	47.46	24	62.53	20	72.5	25
7.19	14	16.19	2	23.22	5	29.40	38	48.44	11	62.57	22	72.42	67
7.21	17	17.7	6	23.24	2	30.37	1	49.43	18	62.66	22	74.42	9
8.7	12	17.14	6	24.22	6	35.30	86	50.35	42	63.7	46	74.75	5
8.14	5	17.15	3	24.23	2	35.43	40	50.51	49	63.57	68	75.70	14
9.7	9	17.19	5	25.22	6	35.47	31	51.50	49	63.61	2	75.74	5
9.10	10	17.22	6	25.28	5	35.50	42	51.52	32	63.64	13	76.69	1
9.14	7	18.22	1	26.6	12	37.30	1	51.53	50	64.63	13		
9.15	4	19.7	14	26.21	6	38.41	6	51.54	27	64.65	25		

Table 3.7: (i,j) and Distance(i,j) Values in km

5.6	7.19	19.7	29.35	30.37	35.30
5.7	9.14	19.21	29.37	31.5	37.30
6.5	14.7	22.14	30.5	32.21	21.19
7.5	14.9	22.21	30.7	33.6	21.22
7.14	14.22	29.21	30.35	34.21	

Table 3.8: 380 kV (i,j) Lines

Zekeriyakoy(j= 6) is 380 kV.

Cables are the main reason for technical losses in the system. In order to have higher power efficiency in the system, it is important to use most suitable cable between nodes. Cable types for each links are given in Tables 3.9 and 3.10. In Chapter 2, properties of the cables are studied. In the system, $477, 630, 795, 954, 1000, 1272, 1600, 2000$ MCM cables are being used. Also Cardinal and Pheasant cables are being used in high voltage lines. $630, 1000, 1600$ and 2000 MCM cables are used for underground lines and they are copper wires. Rest of the cables are used for overhead lines and their raw material is aluminium. In order to use these data in the model, a number is assigned to each cable type. Electrical conductivity parameter, α, is 56 m/$\Omega \times mm^2$ for copper wires and 35 m/$\Omega\times$ mm^2 for aluminium wires.

For the corona parameter, corona(k) k$\in$C, Peek's formula Equation 2.11 and Peterson's formula Equation 2.12 are used. Criteria for using Peterson's formula is explained in Chapter 2. Critical disruptive voltage of each cables are calculated and F values for each value are found. For F$>$ 1.8, Peek's formula is used and for F$\leq$ 1.8, Peterson's formula is used.

In the Peek's formula, there is a parameter called air density factor. In this parameter, barometric pressure and temperature is important. Barometric pressure is assumed to be 76 cm. As the data from TEIAS is belong the summer data, average temperature value, which is taken from Turkish Meteorological Service, for 2012 summer is 23^{o}C.

Surface area is important for resistive loss. As the surface area increases, power loss decreases. S(k) is the parameter for the surface area in the model. Surface area values are shown in Table 3.11. In Chapter 2, cable types are studied in more detail.

In the model, units of the parameters are important. Unit of the most of the parameters is Megawatts, but in Peek's and Peterson's formula unit of the power loss is kW/km. So it is important to convert kW/km to MW/km. For calculating the parameter corona(k),

1.3	1272 MCM	10.9	1000 MCM	19.16	795 MCM	26.27	1000 MCM
1.7	795 MCM	10.11	1000 MCM	19.17	1600 MCM	27.26	1000 MCM
1.8	795 MCM	10.14	1000 MCM	19.21	3 C	27.28	1000 MCM
1.9	1272 MCM	11.10	1000 MCM	19.22	795 MCM	28.21	1600 MCM
2.3	1272 MCM	11.12	1000 MCM	20.5	1272 MCM	28.25	1000 MCM
2.4	1272 MCM	12.11	1000 MCM	20.21	795 MCM	28.27	1000 MCM
3.4	1272 MCM	12.13	630 MCM	21.7	795 MCM	29.21	3 C
4.3	1272 MCM	13.12	630 MCM	21.19	3 C	30.5	3 C
4.5	1272 MCM	13.14	477 MCM	21.20	795 MCM	30.7	2 C
5.4	1272 MCM	13.16	1000 MCM	21.22	3 C	31.5	3 C
5.6	2 PH	14.7	2000 MCM	21.26	1272 MCM	32.21	3 C
5.7	3 C	14.8	795 MCM	21.28	1600 MCM	33.6	2 PH
5.20	1272 MCM	14.9	2000 MCM	22.14	2000 MCM	34.21	3 C
6.5	2 PH	14.10	1000 MCM	22.17	1600 MCM	1.72	477 MCM
6.26	1272 MCM	14.13	477 MCM	22.18	477 MCM	5.72	954 MCM
7.5	3 C	14.17	1600 MCM	22.19	795 MCM	7.63	795 MCM
7.8	795 MCM	14.22	2000 MCM	22.21	3 C	29.35	2 C
7.9	795 MCM	15.9	1000 MCM	22.23	1600 MCM	29.37	2 C
7.14	2000 MCM	15.17	1000 MCM	22.24	1000 MCM	29.38	1272 MCM
7.17	795 MCM	16.13	1000 MCM	22.25	1000 MCM	29.39	954 MCM
7.19	3 C	16.19	795 MCM	23.22	1600 MCM	29.40	477 MCM
7.21	795 MCM	17.7	795 MCM	23.24	1000 MCM	30.37	2 C
8.7	795 MCM	17.14	1600 MCM	24.22	1000 MCM	35.30	3 C
8.14	795 MCM	17.15	1000 MCM	24.23	1000 MCM	35.43	477 MCM
9.7	795 MCM	17.19	1600 MCM	25.22	1000 MCM	35.47	477 MCM
9.10	1000 MCM	17.22	1600 MCM	25.28	1000 MCM	35.50	477 MCM
9.14	2000 MCM	18.22	477 MCM	26.6	1272 MCM	37.30	2 C
9.15	1000 MCM	19.7	3 C	26.21	1272 MCM	38.41	795 MCM

Table 3.9: Cable Types of (i,j) for $i < 38$

38.42	1272 MCM	51.58	477 MCM	65.64	795 MCM
39.71	954 MCM	52.51	1272 MCM	65.66	795 MCM
40.70	1272 MCM	53.51	477 MCM	66.57	954 MCM
41.38	795 MCM	53.62	477 MCM	66.62	795 MCM
42.38	1272 MCM	54.51	795 MCM	66.65	795 MCM
42.62	477 MCM	54.55	1272 MCM	66.69	1272 MCM
42.69	477 MCM	55.54	1272 MCM	67.69	795 MCM
42.72	477 MCM	55.56	795 MCM	68.69	477 MCM
42.74	477 MCM	56.55	795 MCM	69.42	477 MCM
43.35	477 MCM	57.62	795 MCM	69.66	1272 MCM
43.44	477 MCM	57.63	795 MCM	69.67	795 MCM
43.49	1272 MCM	57.66	954 MCM	69.68	477 MCM
44.43	477 MCM	58.51	477 MCM	69.70	954 MCM
44.45	795 MCM	58.59	477 MCM	70.40	1272 MCM
45.44	795 MCM	59.58	477 MCM	70.69	954 MCM
45.46	795 MCM	59.60	477 MCM	70.71	954 MCM
46.45	795 MCM	60.59	477 MCM	70.75	477 MCM
46.47	477 MCM	61.63	795 MCM	71.39	954 MCM
47.35	477 MCM	62.42	477 MCM	71.70	954 MCM
47.46	477 MCM	62.53	477 MCM	72.5	954 MCM
48.44	795 MCM	62.57	795 MCM	72.42	477 MCM
49.43	1272 MCM	62.66	795 MCM	74.42	477 MCM
50.35	477 MCM	63.7	795 MCM	74.75	477 MCM
50.51	795 MCM	63.57	795 MCM	75.70	477 MCM
51.50	795 MCM	63.61	795 MCM	75.74	477 MCM
51.52	1272 MCM	63.64	795 MCM	76.69	477 MCM
51.53	477 MCM	64.63	795 MCM		
51.54	795 MCM	64.65	795 MCM		

Table 3.10: Cable Types of (i,j) for i$\geq$ 38

Cable	Conductor Surface Area (mm^2)
477 MCM	281
630 MCM	630
795 MCM	468
954 MCM	547
1000 MCM	1000
1272 MCM	726
1600 MCM	1600
2000 MCM	2000

Table 3.11: Surface Areas of the Cables

k∈C, output of the Peek's or Peterson's formula should be multiplied by 0.001. Also this issue should be taken care of while calculating power loss in Equation 3.12. In Equation 3.12, parameter distpower(i,j) is in MW, so voltage(k) should be in Megavolts.

3.4 Model for Power Allocation with Variable Cable Types

In the first model cable types, which exist between nodes, are known from the TEIAS's data. In this section, how much improvement can be done by changing the cable types will be examined.

To start with explaining the sets of the model, as in the first model I denotes the all set of nodes. I_1 represents the power generation nodes and I_2 is for demand points. Also C denotes the set of cables. The difference in the second model is the separation of the cable set into two subsets. In the network, there are two different lines, 380 and 154 kV lines. So for each line, there are different sets of cables.

Sets

I :	Set of Nodes
I_1 :	Set of Power Generation Nodes
I_2 :	Set of Demand Nodes
C :	Set of Cables
C_1 :	Set of 380 kV Cables
C_2 :	Set of 154 kV Cables
	$I = I_1 \cup I_2$
	$C = C_1 \cup C_2$

In the second model, there are some same parameters from the first model in Section 3.2. Those parameters are connection, demand and distance of the nodes, cost coefficients of power plants and properties of cables. First parameter is connection(i,j), it represents which nodes from set I are connected. It is 1, if there is a cable between node i to node j.

Otherwise it is 0. Also if i is equal to j, then it is 0 too.

$$connection(i,j) = \begin{cases} 1, & \text{if node i-j is connected} \\ 0, & \text{otherwise} \end{cases} \qquad i,j \in I$$

$$connection(i,j) = \begin{cases} 0, & \text{if i=j} \end{cases}$$

Demands of each nodes are denoted by demand(i), $i \in I$, in Mega watts. Demands of all power generation nodes are assumed to be zero. In other words, if $i \in I_1$, then demand(i) is 0.

$$\text{demand(i)} = \text{Demand of node i , i} \in I$$

$$demand(i) = \begin{cases} 0, & \text{if i} \in I_1 \end{cases}$$

distance(i,j) is another parameter showing the distance between nodes i and j, (i,j) $\in I$. Its unit is kilometers.

$$distance(i,j) = \text{Distance between nodes i and j, (i,j)} \in I$$

Voltage(i,j) is a different parameter from the first model. Voltage(i,j) parameter represents the voltage level of the line between nodes i and j. It is a binary parameter and equals to 1 if line between (i,j) is 380 kV and 0 otherwise.

$$voltage(i,j) = \begin{cases} 1, & \text{if node i-j is 380 kV line} \\ 0, & \text{otherwise} \end{cases} \qquad i,j \in I$$

$$voltage(i,j) = \begin{cases} 0, & \text{if i=j} \end{cases}$$

C_1, C_2 and C_3 are the cost coefficients of power plants in the system. Also each power plant has minimum and maximum limits for production. $MinP_i$ and $MaxP_i$ are the parameters for these limits. Parameters for the cables are the same as in the first model. Corona(k), capacity(k), area(k) and conductivity(k) are the parameters for cables where k∈C.

$MinP_i$, $MaxP_i$: Minimum and maximum generation limits for power plant i, i $\in I_1$

$c_1(i), c_2(i), c_3(i)$: Cost coefficients ($\$/h$) for power plant i, i $\in I_1$

corona(k): Corona power loss (kW/km) for cable k, k ∈ C

capacity(k): Current Capacity of cable k, k ∈ C

conductivity(k): Electrical conductivity of cable k, k ∈ C

area(k): Surface area of cable k, k ∈ C

Corona(k) is the parameter for corona power loss. It is calculated from the Peek's formula, Equation 2.11 and Peterson's formula, Equation 2.12. Unit of the corona(k) is kW/km. Resistive loss will be calculated from the Equation 3.2, conductivity(k) and area(k) parameters will be used in this formula. Units of these parameters are (m/Ω× mm^2) and (mm^2) respectively. As current passing through the line, it should not pass the capacity. Capacity(k) represents the current capacity of the cable k, k∈C. Unit of this parameter is Ampere.

In the model there are two positive variables and one binary variable. First variable is for representing the distributed amount of power from node i to j with cable k, $(i, j) \in I, k \in C$. Secondly, power generated amount in power plant i, $i \in I_1$, is controlled by another variable. Finally, cable(i,j,k) is a binary variable and it expresses the cable type between node (i,j). It is equal to 1 if node (i,j)∈I is connected with cable k, k∈C.

Variables

distpower(i,j,k): Distributed amount of power from nodes i to j with cable k, $(i, j) \in I, k \in C$

powergen(i): Power generated in power plant i, $i \in I_1$

$$\text{cable(i,j,k)} = \begin{cases} 1, & \text{if node i-j is connected with cable-k, } (i,j) \in I, k \in C \\ 0, & \text{otherwise} \end{cases}$$

Objective

$$\min \quad \text{Total Cost} = \sum_{i \in I_1} c_1(i) powergen(i)^2 + c_2(i) powergen(i) + c_3(i) \tag{3.13}$$

subject to

$$powergen(i) \geq \sum_{j \in I} \sum_{k \in C} connection(i,j) distpower(i,j,k) \quad \forall i \in I_1 \tag{3.14}$$

$$MinP_i \leq powergen(i) \leq MaxP_i \quad \forall i \in I_1 \tag{3.15}$$

$$\begin{aligned} &\sum_{i \in I} \sum_{k \in C} connection(i,j) distpower(i,j,k) = \\ &\quad demand(j) + \sum_{i\prime \in I} \sum_{k \in C} connection(j,i') distpower(j,i',k) \\ &\quad + \sum_{i \in I} connection(i,j) \sum_{k \in C} distance(i,j) Power_{Loss}(i,j,k) \quad \forall j \in I \end{aligned} \tag{3.16}$$

$$distpower(i,j,k) \leq cable(i,j,k) capacity(k) \quad \forall (i,j) \in I, \forall k \in C \tag{3.17}$$

$$\sum_{k \in C} cable(i,j,k) = connection(i,j) \quad \forall (i,j) \in I \tag{3.18}$$

$$distpower(i,j,k) \geq 0 \quad \forall (i,j) \in I, \forall k \in C \tag{3.19}$$

$$powergen(i) \geq 0 \quad \forall i \in I_1 \tag{3.20}$$

$$connection(i,j) \in 0,1 \quad \forall (i,j) \in I \tag{3.21}$$

$$cable(i,j,k) \in 0,1 \quad \forall (i,j) \in I, \forall k \in C \tag{3.22}$$

Power loss constraint can be divided into subparts for different voltage levels. It can be

$$\begin{aligned} &\sum_{i \in I} connection(i,j) \sum_{k \in C} distance(i,j) Power_{Loss}(i,j,k) = \dots \\ &\quad \sum_{i \in I} connection(i,j) \Bigg(\sum_{k \in C_1} voltage(i,j) distance(i,j) Power_{Loss}(i,j,k) \dots \\ &\quad + \sum_{k \in C_2} \Big(1 - voltage(i,j)\Big) distance(i,j) Power_{Loss}(i,j,k) \Bigg) \forall j \in I \end{aligned} \tag{3.23}$$

When k$\in C_1$, $Power_{Loss}$ (i,j,k) can be calculated as

$$Power_{Loss}(i,j,k) = \Big((\frac{distpower(i,j,k)}{\sqrt{3} \times 0.380 \times 0.8})^2 \frac{2}{\alpha_k S_k} + corona(k)cable(i,j,k) \Big) \qquad (3.24)$$

When k $\in C_2$, $Power_{Loss}$ (i,j,k) can be calculated as

$$Power_{Loss}(i,j,k) = \Big((\frac{distpower(i,j,k)}{\sqrt{3} \times 0.154 \times 0.8})^2 \frac{2}{\alpha_k S_k} + corona(k)cable(i,j,k) \Big) \qquad (3.25)$$

In Equations 3.24 and 3.25, only difference is 0.380 and 0.154. For C_1 subset voltage of the line is 380kV. So in the Equation 3.2, voltage parameter (U) will be 380kV, but in the Equation 3.24 unit is Megawatts, so 380kV should be converted to Mega volts. 380 kV equals to 0.380 MV. Same calculations should be done to Equation 3.25 for 154 kV. So 154 kV equals to 0.154 MV.

In the model, first constraint is a balance constraint for power plants. Generated amount of power in power plants should be equal to the distributed power from power plants to the connected nodes. Second constraint is a limiting constraint for power plants. Each power plant has minimum and maximum production limits. There is a minimum production limit, because it is expensive to shut down and re-open the facility again. In the third constraint, for each node inputs should be equal to the outputs. Distributed power coming to a node should be equal to the demand of that node plus distributed power from that node to other nodes and technical loss, which exists during distribution. Power loss is calculated by Equation 3.24 or 3.25 according to the voltage level of the line.

Each cable type has a current capacity and distributed power should not exceed that limit. Next constraint is to limit the current passing through the line. Final constraint is for ensuring only one single type of cable should exist between one line. In other words, if i and j nodes are connected, only one type of cable should be chosen. Rest of the constraints are nonnegativity constraints.

Data from Section 3.3 will be applied to this model in order to test the outputs of the model. Also outputs of the model in Section 3.2 and outputs of the model in this section will be compared in Chapter 4.

As it is stated in Section 3.3, unit of the parameters are important. Unit of the most of the parameters is Megawatts and kilometers, so while solving the model, especially while calculating power losses, all parameters should be converted to Megawatts or kilometers.

This model can be solved by using Mixed Integer Non-Linear Programming. Outputs of the model and comparison of the data from TEIAS with the output of the model will be discussed in Chapter 4.

Chapter 4

RESULTS

In this chapter, outputs of the models in Chapter 3 will be discussed. Firstly, power allocation model will be examined and compared with the real data from TEIAS. Secondly, power allocation model with various cable types will be studied and again will be compared with the TEIAS's data.

4.1 Power Allocation Model

In Section 3.2, model is non-linear. So in order to solve this model Non-Linear Programming will be used. Model is implemented in GAMS solver. Parameters are taken from the TEIAS's data in Section 3.3.

In the model there is two variables. First one, distpower(i,j), controls the distributed amount of power between nodes and the second one, powergen(i), controls the generated amount of power for each power plants.

In the beginning, for simplicity nodes are divided into two parts, Thrace and European side of Istanbul. In Table 3.3, nodes $1 - 34$ belongs to first part, European side of Istanbul, and nodes between $35 - 76$ belongs to second part, Thrace. After analyzing two parts separately, two parts will be combined.

In the first part, for European side of Istanbul, the data from Figure 3.1 and Figure 3.2 are shown in Table 4.1. There are 34 nodes in Figure 3.2. In the table, total demand of these 34 nodes is 3433 MW and there is a %1 power loss in the system.

	MW
Total Demand	3433.6
Total Production	3468.6
Total Loss	35
Loss (%)	% 1

Table 4.1: Data for Istanbul, TEIAS

	MW
Total Demand	3433.6
Total Production	3451.887
Total Loss	18.2
Loss (%)	% 0.53

Table 4.2: Output of the model for Istanbul

	MW
Total Demand	1316
Total Production	1334
Total Loss	18
Loss (%)	% 1.35

Table 4.3: Data for Thrace, TEIAS

	MW
Total Demand	1316
Total Production	1325.034
Total Loss	9.034
Loss (%)	% 0.686

Table 4.4: Output of the model for Thrace

Outputs of the model in Section 3.2 are shown in Table 4.2. With different power allocation, power loss decreased. New power loss percentage is %0.53. This increase may seem small, but as the unit of the numbers is Megawatts, any decrease in power loss will save thousands of dollars and reduce CO_2 emission.

In the second part, for Thrace, the data from Figure 3.1 are shown in Table 4.3. There are 48 nodes in Figure 3.1. In the table, total demand of these 48 nodes is 1316 MW and there is a %1.35 power loss in the system.

For Thrace, outputs of the model in Section 3.2 are shown in Table 4.4. With different power allocation, power loss decreased. New power loss percentage is %0.682.

After implementing the regions separately, both 76 districts are implemented in one model, which is in Section 3.2. Bulgaria and Greece are in those 76 nodes, but their demands are counted as zero, because parameters of Bulgaria and Greece were unknown. Total demand of these 76 nodes is 4749.60. Output of the model for 76 nodes are shown in

	MW
Total Demand	4749.60
Total Production	4776.831
Total Loss	27.231
Loss (%)	% 0.573

Table 4.5: Output of the model for Eur. Istanbul and Thrace

	Only Europ. Istanbul	Only Thrace	All Nodes
# of variables	1,167	2,316	5,795
# of const.	1,201	2,358	5,869
# of iterations	1	1	1
CPU (sec.)	0.031	0.047	0.031

Table 4.6: Computational Results for Model in Section 3.2

Table 4.5. Power loss percentage is around %0.57.

As it is expected, biggest power loss exists between Hamitabat and Alibeykoy. Distance between these two districts is 152 km and this is the main reason for high power loss. Also another fact is that underground cables cause less power loss with respect to the overhead lines, but as it is discussed in Chapter 2, their cost is too high. The reasons for the difference between data and output might be non-technical losses and assumptions, which included in the model. For example, cables are assumed not to be roughened, but in real case cables might be roughened. So this will increase the power loss. Also effect of the temperature and pressure might be different in real case. Another important point is that power generation capacity of European side of Istanbul is not enough to meet the demand of European side of Istanbul, so huge amount of power is transmitted from Anatolian side of Istanbul and Hamitabat. So this increases the distance and the power loss.

In Table 4.6, computational results for the first model in Section 3.2 are given. As the number of nodes increased, number of iterations and number of variables increased.

4.2 Model for Power Allocation with Variable Cable Types

The model in Section 3.4 is non-linear. Also there is a binary variable. So in order to solve this model Mixed Integer Non-Linear Programming will be used. Model is implemented in GAMS solver. Parameters are taken from the TEIAS's data in Section 3.3.

	MW
Total Demand	3433.600
Total Production	3452.946
Total Loss	19.346
Loss (%)	% 0.56

Table 4.7: Output of the second model for Istanbul

There are two positive variables and one binary variable in the model. First variable represents the distributed amount of power from node i to j with cable k, $(i, j) \in I, k \in C$. Secondly, power generation amount in power plant i, $i \in I_1$, is controlled by another variable. Finally, cable(i,j,k) is a binary variable and it expresses the cable type between node (i,j). It is equal to 1 if node (i,j)∈I is connected with cable k, k∈C.

In the model, underground cables are not considered in Set C. This assumption is made, because if there were underground cables with less power loss, then model will choose those cables for every line between nodes. However, underground cables are hard to implement, because of their cost.

As in the Section 4.1, model will be studied in three parts. Firstly, only data for Istanbul will be studied. Secondly, data for only Thrace will be implemented in the model. Finally, all data will be combined together.

In the first part, for European side of Istanbul, there are 34 nodes. Outputs of the model are shown in Table 4.7. Efficiency of the network is approximately %99. Output of the first model in Section 4.1, without changing the cable types power loss percentage is %0.53 and from the TEIAS's data power loss percentage was around %1. So by changing cable types, power loss rate became %0.56. There might be several reasons why loss rate did not change much. Firstly, allocation in the first model might be close to the optimum solution. Another reason is that in Istanbul network, underground cables are being used, but in this section as an assumption underground cables are not considered in Set C. So, using cables with higher efficiency would decrease the power loss.

In order to see the difference of underground cables in Istanbul region, underground cables, which are used in real practice, are fixed. 630 MCM, 1000 MCM, 1600 MCM and 2000 MCM type cables are included into the model. After fixing those nodes with underground cables, outputs changed as Table 4.8. Loss percentage decreased to %0.518

	MW
Total Demand	3433.600
Total Production	3451.401
Total Loss	17.8
Loss (%)	% 0.518

Table 4.8: Output of the second model for Istanbul after fixing underground cables

	MW
Total Demand	1316.000
Total Production	1321.484
Total Loss	5.484
Loss (%)	% 0.415

Table 4.9: Output of the Second Model for Thrace

	MW
Total Demand	4749.600
Total Production	4772.320
Total Loss	22.72
Loss (%)	% 0.476

Table 4.10: Output of the Second Model for Eur. Istanbul and Thrace

from %0.56.

For Thrace, there are 48 nodes in the second part. Outputs of the model are shown in Table 4.9. Efficiency of the network is approximately %99. Output of the first model in Section 4.1, without changing the cable types power loss percentage is %0.682 and from the TEIAS's data power loss percentage was around %1.35. So by changing cable types, power loss rate decreased to %0.415.

After implementing the regions separately, both 76 districts are combined together and implemented in one model, which is in Section 3.4. Bulgaria and Greece are in those 76 nodes, but their demands are counted as zero, because parameters of Bulgaria and Greece were unknown. Output of the model for 76 nodes are shown in Table 4.10. Power loss percentage is around %0.476. In Section 4.1, power loss rate was around %0.57 and by changing cable types power loss rate decreased. As the unit of the numbers in tables is Mega watts, there is a huge amount of power savings in the network with this model.

	MW
Total Demand	4749.600
Total Production	4770.777
Total Loss	21.177
Loss (%)	% 0.44

Table 4.11: Output of the Second Model for Eur. Istanbul and Thrace after fixing underground cables

As it was studied before, Istanbul region has underground cables in real practice. Again, after fixing all nodes, which use underground cables, power loss rate became %0.44. Results are in Table 4.11.

From the results in Section 4.2, it appears that with selecting the right type of cable in each line decreases the power loss and increases the efficiency of the network. Of course, as it discussed in Section 4.1, assumptions will affect the efficiency and these power loss percentages will increase in practice. For example, cables are assumed not to be roughened in theory, but in real case cables might be roughened. So this will increase the power loss. Moreover, effect of the temperature and pressure might be different in practice. Another effect will be the non-technical losses. They will decrease the efficiency of the network too.

In the model, for 154 kV lines 1272 MCM, Pheasant, type of cable is mostly used. For 380 kV lines, 2xPheasant cable type is mostly used. Importance of surface area, capacity and the resistance can be seen from this result. Pheasant cables have the largest surface area and least resistance among other cable options. An additional point is that while choosing cable types in the network, there are more criteria. Those criteria, are mentioned in Chapter 2, are not included in this thesis. An additional study may be done including those criteria in the model as a future work.

In Table 4.12, computational results for the second model in Section 3.4 are given. As the number of nodes increased, number of iterations and number of variables increased. If computational results of first model are compared with the results of second model, CPU times and the number of iterations are the biggest difference. Especially for the 76 node case, CPU time is more than one minute. As a binary variable added to the model, number of variables increased and this made network more complicated. Also solving a Non-Linear Problem takes less time than solving a Mixed Integer Non-Linear Problem.

	Only Europ. Istanbul	Only Thrace	All
# of variables	8,234	27,659	69,411
# of 0-1 variables	6,936	13,824	34,656
# of const.	13,883	16,276	40,802
# of iterations	5	3	3
CPU (sec.)	12.525	12.916	73.564

Table 4.12: Computational Results for Model in Section 3.4

	Istanbul	Thrace	All Regions
Total Demand	3433.6	1316	4749.6
Total Production	3451.887	1325.034	4776.831
Total Loss	18.29	9.034	27.231
Loss (%)	% 0.53	% 0.686	% 0.573

Table 4.13: Outputs of the First Model with different objective function

	Istanbul	Thrace	All Regions
Total Demand	3433.6	1316	4749.6
Total Production	3452.939	1321.475	4772.317
Total Loss	19.339	5,475	22.717
Loss (%)	% 0.563	% 0.416	% 0.478

Table 4.14: Outputs of the Second Model with different objective function

In all of the models, objective function was to minimize power generation cost by reducing power loss during transmission. For an additional analysis, objective function is changed with only power loss. So new objective function is to minimize the power loss during transmission. New objective function is total power generated minus total demand. This difference will give the power loss. After implementing this change to all models, results are shown in Table 4.13. All results are same with the previous results. For the second model, after changing the objective function results are in 4.14. There is a slight decrease in results, reason for this decrease is the cost coefficients of power plants.

Chapter 5

CONCLUSION

In this thesis, detailed models and suggestions are developed for power transmission systems. Objective is to minimize power generation cost by reducing power loss during transmission while satisfying certain constraints. Technical power losses are considered in the thesis. For technical losses, we focused on corona loss and resistive loss in the network.

Two different models are presented. First model is likely an allocation problem. In the first model cable types between each demand point are known. How to distribute power to demand points is examined. In the second case, cable types between each points are unknown and while allocating the power, also optimum cable types are found.

Both models are implemented in GAMS solver. First model is solved by Non-Linear Programming and second one is solved by Mixed Integer Non-Linear Programming.

All of the analyses and models in the thesis have been performed with the data, which are taken from TEIAS. Two regions are studied in the thesis, European side of Istanbul and Thrace. Firstly, regions are studied separately, then combination of the models is examined. After implementing the data to models, results are shown in Chapter 4. According to the data, for European side of Istanbul in 2012 summer %1 of the generated power is lost during transmission/distribution. For Thrace, same rate is around %1.35. Results of the first model are promising, power loss rate is approximately %0.53 for Istanbul and %0.682 for Thrace. After combining regions, loss rate is %0.57. Without changing anything in the network, by using optimal routing power loss rate is decreased by approximately %50 both in Istanbul and Thrace. In the second model, after changing the cable types, power loss rate is approximately %0.56 for Istanbul and %0.415 for Thrace. After combining regions, loss rate is %0.476. Power loss percentages may seem small, but as the unit of the numbers is Megawatts, any decrease in power loss will save thousands of dollars and reduce CO_2 emission for the environment.

Results of the second model show that Pheasant cable type is used mostly in transmission lines for higher efficiency. Importance of surface area, capacity and the resistance can be seen from these results. Pheasant cables have the largest surface area and least resistance among other cable options.

In the second model by changing cable types, power loss rate became %0.56, but in the first model it was %0.53. There might be several reasons why loss rate did not change much. Firstly, allocation in the first model might be close to the optimum solution. Another reason is that in Istanbul network, underground cables are being used, but as an assumption underground cables are not considered in the second model. So, using cables with higher efficiency would decrease the power loss. In order to see the effect of underground cables, nodes, which uses underground cables in real practice, are fixed in the model. After fixing nodes with underground cables, power loss rate decreased to %0.518. Also after combining all regions, power loss rate became %0.44 by fixing underground cables, which are already being used in the network.

Underground cables have approximately zero resistance, so they cause less power loss with respect to overhead line cables. In the second model, we changed the cable types and found the optimal cable type. Changing cables will requires additional costs. Underground cables are much more expensive than the overhead line cables. There might be operational problems for underground cables. Electricity company should shut down the electricity for some time to change cables. Also there could be infrastructure issues in some cities, companies could not dig ground and implement underground cables. For the future work, costs of each cable type can be included into the objective function. By this way, it can be calculated whether it is worth to invest in cables or not.

Cables are assumed not to be roughened in theory, but in practice cables might be roughened and this will increase the power loss. Moreover, effect of the temperature and pressure might be different. Another effect will be the non-technical losses. They will decrease the efficiency of the network. For the future work, effect of these can be analyzed and renewable energy sources can be added to the network as a power production plant. Also real-time allocation of power can be a good research topic for future work.

VITA

Yiğit Can Ören completed the high school in Izmir Atatürk Anadolu Lisesi in 2005. He received his B. Sc. degree in Electric-Electronics Engineering from Bilkent University, Ankara, in 2010. Since 2010, he is in the M. Sc. program in Industrial Engineering of Koç University as a teaching/research assistant. For the completion of the program he has studied the thesis Modeling the Efficiency of Power Distribution Networks.

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