OPTIMAL ALLOCATION OF SECTIONALIZING SWITCHES IN RURAL DISTRIBUTION SYSTEMS

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ABSTRACT

OPTIMAL ALLOCATION OF SECTIONALIZING SWITCHES IN RURAL DISTRIBUTION SYSTEMS

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The distribution system which forms the final connection between customers and power source plays a vital role in an electrical network. Different studies show that substantial proportion of the customer interruptions occurs due to the failures on distribution network.

The ongoing privatization process of the electrical distribution services in Turkey raises the importance of reliable and continuous electricity supply significantly. The new regulations come up with this privatization process and the electrical distribution companies are strictly required to comply with these regulations to ensure the reliability of the distribution network. The legal framework and severe punishments applied to the electrical distribution companies exceeding the continuity of supply indices force them to invest on their network in order to increase the reliability of their system.

As the reliability of electricity supplied increases, investment cost also increases. However, low system reliability causes higher outage frequency and duration which will increase the damage of these outages to customers and also increases the cost of the distribution company as a result of the penalty payments. This tradeoff between *Outage Cost* and *Utility Cost* requires consideration of an optimization when determining the optimal reliability level.

In rural areas where electrical distribution network consists of long radial overhead lines in arborescent structure, continuity of supply is a major problem due to the high failure rates. The implementation of protection devices having reclosing capability and automated sectionalizing switches enhances the continuity of supply on rural networks substantially. The balance between the cost associated with installation of switches and the reduction on *Outage Cost* is an important optimization issue for distribution network operators.

In this thesis study an algorithm is developed in order to determine the optimum number and locations of the sectionalizing switches on a rural electrical distribution network in Turkey which gives an optimum investment level with an optimum *Outage Cost*.

ÖZ

KIRSAL DAĞITIM ŞEBEKESİNDE OPTİMAL AYIRAÇ YERLEŞİMİ

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Tüketici ile elektrik kaynağı arasındaki son bağlantıyı teşkil eden elektrik dağıtım sistemi elektrik şebekesindeki en önemli görevlerden birini yerine getirmektedir. Çeşitli çalışmaların ortaya koyduğu üzere tüketicilerin maruz kaldığı elektrik kesintiler önemli oranda dağıtım şebekesi kaynaklı arızlardan kaynaklanmaktadır.

Elektrik dağıtım hizmetinde devam eden özelleştirme süreci ile birlikte elektrik enerjisi tedarik sürekliliği Türkiye'de ciddi bir önem kazanmıştır. Özelleştirme süreci ile birlikte gelen ve elektrik dağıtım şirketlerinin tabi oldukları yeni düzenlemelerle birlikte dağıtım şebekesinin güvenirliliği ciddi gereklilik arz etmektedir. Yeni düzenlemelerle birlikte, tedarik sürekliliği limitlerinin aşılması durumunda ortaya çıkacak ağır cezalar dağıtım şirketlerini şebekelerinin güvenilirliğini iyileştirmek için yatırım yapmaya zorlamaktadır.

Şebekenin güvenirliliğinin arttırılması, yatırım ve bakım maliyetleri gibi işletme maliyetlerinin de artmasını beraberinde getirmektedir. Düşük sistem güvenirliliği sık arızalara ve uzun kesinti sürelerine sebep olacağı için, elektrik tüketicilerinin maruz kalacağı zararları ve dağıtım şirketinin ödemek zorunda olacağı ceza ödemelerini arttıracaktır. İstenilen sistem güvenirliliğini sağlarken, yatırım maliyetleri ile kesinti maliyetleri arasındaki dengeyi sağlamak bir optimizasyon ihtiyacını doğurmaktadır.

Özellikle elektrik dağıtım şebekesinin uzun ve dal budak formunda havai hatlardan oluştuğu kırsal şebekede, yüksek arıza oranları nedeni ile tedarik sürekliliği ana problemlerden biridir. Tekrar kapama özelliği olan devre koruma ekipmanlarının ve otomatik ayırma anahtarlarının dağıtım şebekesinde uygulanması ile birlikte kırsal şebekelerde tedarik sürekliliği önemli ölçüde iyileştirilebilir. Elektrik dağıtım şirketleri için yeni ekipmanların getireceği maliyet artışı ile kesinti maliyetindeki düşüşün arasındaki dengeyi kurmak önemli bir optimizasyon konusudur.

Bu tez çalışmasında Türkiye kırsal şebekesinde uygun seviyede yapılacak bir yatırımla kesinti maliyetini düşürecek, otomatik ayırıcı anahtarlar için ideal sayıyı belirleyen ve uygun yerleşimleri üreten bir algoritma ortaya koyulmaktadır.

To My Family

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CHAPTER 1

INTRODUCTION

1.1. Introduction

Continuity of supply refers to uninterrupted electricity service and characterized by the number and duration of supply interruptions [1]. It is widely accepted that it is neither technically nor economically feasible for a power system to ensure that electricity is continuously available on demand. Instead, the basic function of a power system is to supply power that satisfies the system load and energy requirement economically and also at acceptable levels of continuity and quality [2]. Reliability refers to the ability of a power system to provide an adequate and secure supply of electrical energy at any point in time [3]. Supply interruptions regardless of their cause, mean a reduction in reliability.

Continuity of supply matters to all types of customers and for numerous reasons. For large industrial users interruptions of even a relatively short duration can lead to substantial financial losses, whilst for domestic users interruptions can leave people without heating, lighting and cooking facilities [2]. The four main features of continuity of supply can be summarized as follows;

- Type of interruption,
- Duration of the interruption,
- The voltage levels of faults and other causes of interruptions,
- The type of continuity indicators.

1.2. Regulations on the Continuity of Supply

As a result of the liberalization of the electric power market, service quality and in particular continuity for service have been playing an ever increasing role. End users take continuity of service for granted and even the shortest interruption is unacceptable.

In an increasingly competitive market, however, profit margins of utilities get lower and investments on distribution networks might decrease. Such a phenomenon would be in contrast with the continuity of supply, to the detriment of the quality that customers expect. In order to oppose this process, Regulatory Authorities introduce a regulatory system which aims at encouraging *Distribution System Operators* (DSOs) to maintain and improve the quality of service.

Quality parameters are increasingly becoming competitive factors, which affect the profits of electricity distribution utilities through “price-cap” schemes and the payment of penalties or bonuses. Standards of the electricity supply continuity are often used as tools of its regulation. By this standard the regulatory office or another competent authority establishes the interval within which the chosen reliability index should occur. When this index reaches a value that lies outside the established interval and thus indicates a worsened level of the electricity supply continuity, financial sanctions may be imposed upon the distribution company. However, it is possible in certain cases that the distribution company may receive a bonification when the respective index attains a value that lies outside the set interval but represents a better level of the electricity supply continuity than the established one [4]. In Turkey, case continuity of electrical supply regulation does not define any bonification for the better level performance for continuity of supply but only defines the penalty payments in case of exceeding the desired continuity of supply quality level.

In general, each standard of the electricity supply continuity has the following three attributes:

- Evaluated reliability indices (basic or aggregated),
- Limits of each evaluated index (numerical values),
- Economical relation (incentive/penalization, direct/indirect).

When some of these basic attributes are absent, it is not possible to speak about a standard correctly. A standard without the economical relation and/or without the established quality limit would loose the meaning and it would become only another (misleading) name for the given reliability index. Anyone of the basic and aggregated reliability indices may become the index that is evaluated. As the usual objective of the regulation is to ensure that each consumer may receive the minimum level of the electricity supply continuity at least by utilization of aggregated (system-wide) reliability indices such as *System Average Interruption Duration Index* (SAIDI) and *System Average Interruption Frequency Index* (SAIFI). In this study the continuity of supply quality will be evaluated by utilization of the aggregated (system-wide) reliability indices SAIDI and SAIFI.

1.3. Turkish Regulations on Continuity of Supply

1.3.1. Control of the Quality of Continuity of Supply

All the requested information for each interruption must be recorded and documented by DSO. Each year utilities shall submit main continuity of supply indicators to *Energy Market Regulatory Authority* (EMRA).

EMRA then makes audits to check the consistency of the recorded interruption data according to the requirements of the regulation. After pre-evaluation of the records which are submitted by the utilities, audits also can be carried out on site due to the customer complaints [5]. Authority calculates the penalty payments in case the continuity of supply indicators which are calculated in the basis of the records submitted by the DSO exceeds the defined boundaries.

1.3.2. Recording of the Interruption Data

DSO should record the transient, short time and long time interruptions and the records should contain at least the information given below [5];

- Voltage level and location,
- Occurrence date and time,
- Cause of the interruption,
- Total number of MV and LV customers affected,
- Number of affected customers in each interrupted customer group,
- Interruption duration for each MV and LV group of customers which experience the same interruption duration,
- Total duration of the interruption till last affected group of customer is energized.

The information listed above should be recorded both for MV level and LV level long interruptions. In case of transient and short time interruptions the information listed above are recorded only for MV level. Long time interruptions are sub-divided in two basic groups,

- Notified interruptions (announcement needed 48 hours in advance),
- Non-notified interruptions.

1.3.3. Types, Origin and Causes of the Interruptions

In the regulations, interruptions are classified according to the duration time as given below [5];

- Transient interruption denotes to the interruption of duration < 1 second.
- Short interruption denotes to the interruption of duration ≤ 3 minutes and > 1 second.
- Long interruption denotes to the interruption of duration > 3 minutes.

Interruption data are also classified according to the voltage level at which they originated as given below [5];

- Transmission grid,
- MV distribution grid,
- LV distribution grid.

The cause for each interruption should also be recorded. DSO is not impeached for the outages due to the causes given below [5];

- User or third party responsibility,
- Emergencies or disasters (fire, theft, etc.) attested to by local or national authorities,
- External causes such as interruptions due to the external interconnections with other countries,

Interruptions due to the causes listed above are not taken into consideration for the calculation of continuity of supply quality indices.

1.3.4. Calculation of Number of Affected Customers

Distribution Company must record the number of MV and LV users affected from long time (both for notified and non-notified), short time and transient interruptions. If the calculation of the actual number of affected customers is not possible, some estimation which is given by regulation can be utilized [5].

For MV level, the estimation of MV affected users for short and long time interruptions is obtained by multiplying the number of MV distribution centers affected with the average number of MV users per distribution center.

For LV level,

- In case of an occurrence of interruption at transmission or MV distribution network the estimation of LV affected users is obtained by multiplying the number of MV/LV distribution transformers affected with the average number of users per transformer.

- In case of an occurrence of interruption at LV distribution network the estimation of LV affected users is obtained by multiplying the number of LV distribution feeders affected with the average number of users per LV feeder.

1.3.5. Quality of Supply Indicators

Quantifying the continuity of electricity supply requires continuity indicators, typically referred to as “continuity indices” or also “reliability indices”. The basis for the calculation of continuity indicators is the collection of information on individual interruptions.
From information on all individual interruptions that took place during the reporting period in the system that is being monitored, a number of system indices are calculated.

The majority of indices in use provide a measure for the average number of interruptions that took place or for the average time during which electricity supply was not available. The disadvantage of system indices is that they only provide information for the average customer, not for any individual customer. An individual customer is, in principle, only interested in the interruptions that impact its point of connection. Suitable indicators for individual customers are the number of interruptions experienced by the individual customers during a given year and the number of minutes that electricity supply was not available for the individual customer [6].

However, it is not practical to publish indices for each individual customer. This is one of the reasons why, typically, only system averages are published (another important reason is related to the way in which the data is collected). Some indices are available that give more information than just the average number or duration of interruptions of all customers. An intermediate step, used by some regulators and system operators, is to calculate the continuity indicators for each individual feeder (such as EKSUREG and EKSIKG in Turkey case). In that way, a better impression is obtained of the difference in performance between different parts of the system. Some regulators are also using indicators on a geographical level for areas with equivalent characteristics, e.g., rural and urban networks [6]. In Turkish regulation on continuity of supply the threshold limit values for OKSÜREG (SAIDI) and OKSIKG (SAIFI) indices are given for urban and rural regions separately.

According to Turkish regulations on continuity of supply, the following reliability indices have to be reported annually [5];

- System Average Interruption Duration Index (SAIDI-OKSÜREG)
- System Average Interruption Frequency Index (SAIFI-OKSIKG)
- Equivalent Interruption Duration Index (EKSÜREG)
- Equivalent Interruption Frequency Index (EKSIKG)

The threshold values for the reliability indices listed above are given in APPENDIX A (see Table 45, Table 46 and Table 47).

1.3.5.1 System Average Interruption Duration Index (SAIDI, OKSUREG)

SAIDI gives the average amount of time per year that the supply to a customer is interrupted. It is defined as OKSÜREG in the Turkey regulation and expressed in minutes per customers per year. SAIDI is calculated as given by equation (1).

$$SAIDI = \frac{\sum_{i=1}^{n}\sum_{j=1}^{m}(U_{i,j}\, t_{i,j})}{U_{tot}} \tag{1}$$

where;

$U_{i,j}$ denotes to the number of customers affected by the i_{th} interruption (where i =1, ….,n) and belonging to the j^{th} group which experienced the same interruption length (where j=1, …,m)

$t_{i,j}$ denotes to the duration of the interruption for the $U_{i,j}$'th group of customers.

U_{tot} denotes to the total number of customers supplied by the company in the area at all municipality levels.

1.3.5.2 System Average Interruption Frequency Index (SAIFI, OKSIKG)

SAIFI gives the average number of times per year that the supply to a customer is interrupted. It is defined as OKSIKG in the Turkey regulation and expressed in interruptions per customer per year. SAIFI is calculated as given by equation (2).

$$SAIFI = \frac{\sum_{i=1}^{n} U_i}{U_{tot}} \tag{2}$$

where;

U_i denotes to the number of affected customers per i_{th} interruption

U_{tot} denotes to the total number of customers supplied by the company in the area at all municipality levels.

n denotes to the total number of interruptions per year

1.3.5.3 Equivalent Interruption Duration Index (EKSÜREG)

EKSÜREG is reported annually for each MV distribution feeder and calculated as given by equation (3).

$$EKSÜREG = \sum_{i=1}^{n} t_i \tag{3}$$

where;

t_i denotes to the duration of the i_{th} interruption for the feeder concerned

1.3.5.4 Equivalent Interruption Frequency Index (EKSIKG)

EKSIKG is reported annually for each MV distribution feeder and equals to the total annual frequency of interruptions for the MV distribution feeder concerned. Although EKSIKG and EKSUREG are intended to be used for the feeder based continuity of supply quality calculations, a clear feeder definition should be utilized in order to reach the desired

1.3.6. Penalty Payment

When the continuity of supply quality index which is calculated per feeder is exceeded in a calendar year, Electricity Distribution Company must pay a compensation penalty to all affected customers. Compensation payments to the customers which are supplied from the interrupted feeder are made in proportional to their connected capacity.

a) Compensation payment per feeder for exceeding the annual threshold of *EKSÜREG* is calculated as given by equation (4),

$$CP_f = (EKSÜREG_f - MDEKSÜREG_f) \times CUENS \times AD_f \tag{4}$$

where;

CP_f = Compensation payment value for the feeder

$EKSÜREG_f$ = Equivalent Interruption Duration Index value calculated for the aforementioned year

$MDEKSÜREG_f$ = Threshold value for the Equivalent Interruption Duration Index

CUENS = Cost of unit energy not supplied to the customer (TL/kW),

AD_f = Average annual demand on the affected feeder in terms of kW

b) Compensation payment per feeder for exceeding the annual threshold of *EKSIKG* is calculated as given by equation (5),

$$CP_f = (EKSIKG_f - MDEKSIKG_f) \times \frac{EKSÜREG_f}{EKSIKG_f} \times CUENS \times AD_f \tag{5}$$

where;

CP_f = Compensation amount which is paid to the affected customer

$EKSIKG_f$ = Equivalent Interruption Frequency Index value calculated for the aforementioned year

$MDEKSIKG_f$ = Threshold value for the Equivalent Interruption Frequency Index

$CUENS$ = Cost of unit energy not supplied to the customer,

AD_f = Average annual demand on the affected feeder in terms of kW

1.4. Continuity of Supply Studies in European Countries, CEER

In 1999 the Council of European Energy Regulator (CEER) has been constituted as an association among all EU regulators, in order to both share information and knowledge and to build a common position for trans-national issues. Within CEER several working groups (WGs) have been created to discuss specific regulatory common problems. The objectives of the CEER WG on quality of electricity supply are [7];

- Comparing strategies and experience in implementing quality of service regulation, including commercial quality, continuity of supply and voltage quality;
- Identifying and describing quality of service indicators and selecting possible comparators;
- Performing benchmarking studies on quality of service.

Four benchmarking reports have been published in years 2001, 2003, 2005 and 2008. A large number of countries are actively participating in the WG activities such as regulators from Austria, Belgium, Bulgaria, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy (that chairs the WG), Netherlands, Norway, Portugal, Romania, Spain, Sweden and United Kingdom.

Although quality regulation's main objectives are the same in all the countries, with customer protection and overall quality improvement being the fundamental ones, strategies adopted by regulators significantly differ from one country to another. Comparative publishing of quality figures is a common activity for quality regulators. In some countries companies and their associations are responsible for this activity. Comparative publishing can be very effective if data requirements are clearly defined and companies' quality records are audited.

In most countries both guaranteed standards and overall standards are adopted. Guaranteed standards are generally subject to penalty payments in case of mismatch, whilst overall standards are generally used to promote overall quality improvement through comparative publishing of actual levels. Only a subset of these countries introduced financial incentives that link continuity of supply to tariffs or utility revenues. Notwithstanding the similarities in the objectives, implemented mechanisms for continuity regulation are quite different among EU regulators.

In order to briefly compare the main EU experiences of continuity regulation, it's useful to state the following items for comparison;

- Scope: Some regulations encompass only unplanned long (i.e., duration > 3 min.) interruptions, whilst others include also other types of interruptions (i.e., planned).

- Regulated indicators: Some regulations refer only to duration indexes, whilst others use both duration and frequency of interruptions indexes.

- Exclusions: In some regulations distribution companies can exclude some events from regulated indicators, assuming these events are out of the utility’s control.

- Recording requirements: Rules are required to define common practice for recording, interruptions. In some countries recording requirements are set by the regulatory authority, in others otherwise they are a product of a self-regulation process.

- Baseline for targets: In some but not all countries regulators set objectives for minimum compulsory improvement.

- Incentives/penalties: The economic effect of continuity regulation can be symmetric (i.e. incentives and penalties are equal in absolute value for the same variation from the baseline) or not.

1.5. Purpose and Scope of the Thesis

In this thesis, the continuity of supply performance (reliability) of the Turkish rural electrical power distribution system is analyzed in detail. With the utilization of reclosers and automated sectionalizing switches it is shown that the continuity of supply performance of the rural electrical distribution system can be gradually improved.

As the continuity of supply quality of the distribution system enhances with the sectionalizing switch installations, investment cost also increases. However, low system reliability causes higher outage frequency and duration which will increase the damage of these outages to customers and also increases cost of the distribution company as a result of the penalty payments.

This tradeoff between *Outage Cost (OTC), Penalty Cost (PNC)* and *Utility Cost (UTC)* requires an optimization when determining the number of sectionalizing switches and their locations. In this study, an optimization algorithm is implemented which successfully determines the optimal number and locations for the sectionalizing switches in rural distribution systems.

In Chapter 2, rural distribution network layout in Turkey is briefly explained and the failure data for different regions are presented. Then the reliability model of the rural distribution network which is used in the optimization calculations is introduced.

In Chapter 3, firstly operational principles of re-closers and sectionalizing switches and common implementation examples are given. Then the enhancement on the continuity of supply of the rural distribution system by the implementation of reclosers and sectionalizing switches is studied with the reliability analysis.

In Chapter 4, the formulations derived for *Outage Cost*, *Utility Cost* and *Penalty Cost* are presented. In Chapter 5 the algorithm which is implemented in order to determine the optimal locations for sectionalizing switches is explained. Finally in Chapter 6 the main conclusions reached throughout the study are stated and the work for future investigation is summarized.

CHAPTER 2

RELIABILITY MODEL OF THE RURAL ELECTRICAL DISTRIBUTION NETWORK

2.1. Introduction

In this chapter, firstly rural distribution network layout in Turkey is explained. Then failure statistics of a DSO which provides electricity distribution service in the Central Anatolian and Western Black Sea regions is presented and basic concerns with respect to reliability of the failure data and the approach for the interpretation of the failure data will be discussed. Finally the reliability model of distribution network utilized in the optimization calculations is presented and calculation of the relevant failure parameters such as annual failure rates and durations are explained.

2.2. Rural Distribution Network Layout in Turkey

Rural MV electrical distribution network of Turkey mainly consists of long radial overhead lines outgoing from small distribution cabinets which are called as KÖK (Kesici Ölçü Kabini – Small MV Distribution Cabinet). These distribution cabinets which are the MV switching centers of rural regions, are simply formed from single MV busbars and circuit breakers located at the beginning of each main outgoing feeder.

With the help of KÖKs, the long radial feeders are segmented and the enhancement of continuity of supply is aimed by prevention of tripping of the circuit breaker located in the main MV substation which lies at the upstream of the KÖK. Typically 2 to 4 outgoing overhead feeders exit from each KÖK and supply a particular region with the branches tapped off the main line. These main overhead distribution feeders exiting from KÖKs have a radial topology following an arborescent structure with branches from them. Each branch from the main feeder which is called as cluster in this thesis study supplies a particular rural region. A cluster is a group of overhead power lines and distribution transformers that supply a rural settlement such as a village or town. The sub-branches in a cluster share a common connection point to the main line.

After the examination of the electrical distribution network in the rural regions of Turkey it is noticed that, conventionally, connection points of branches to the main feeders are protected with a fuse [22]. However the fuses on the connection points of the branches are mostly not operative due to the several reasons. Therefore in the scope of this thesis study connection points of branches to the main line are treated as the candidate locations for the installation of sectionalizing switches.

2.3. Evaluation of Failure Statistics

The most reliable way to record failure data of an electrical distribution network is to utilize telemetry systems. In most of the developed countries telemetry systems such as Distribution Network SCADA are utilized for data acquisition and control of the MV distribution system [6]. However a telemetry system to collect and record interruption data for customer requires a huge investment. Therefore in most of the electrical distribution systems interruption data relies on the records of field maintenance crews. Data presented in this chapter relies on the records of the maintenance crews working on the field. Table 1 shows the outage durations and frequencies of electrical distribution grid components. Data presented in the table given below relies on the records of the electrical distribution network operator maintenance field crew.

Table 1 Failure data of the distribution system elements of six cities

Regions	Years	MV/LV TR		Overhead Line		
				Sustained		Transient
		Total Duration of Failures (hours)	# of Failures	Total Duration of Failures (hours)	# of Failures	# of Failures
Kastamonu	**2010**	942	68	1.538	416	1.645
	2009	1.430	106	1.778	447	2.292
	2008	706	51	2040	662	2.164
	Average	**1.026**	**75**	**3.402**	**715**	**1.538**
Kırıkkale	**2010**	13	7	217	148	552
	2009	12	3	190	192	570
	2008	10	4	245	188	1.326
	Average	**12**	**5**	**217**	**176**	**816**
Bartın	**2010**	101	21	720	279	597
	2009	172	30	734	172	408
	2008	169	38	263	119	532
	Average	**147**	**30**	**572**	**190**	**512**
Çankırı	**2008**	58	21	410	203	1.655
	2009	79	20	663	274	1.111
	2010	137	31	576	214	1.050
	Average	**91**	**24**	**576**	**230**	**1.272**
Zonguldak	**2010**	67	12	54	14	340
	2009	107	9	326	181	378
	2008	109	36	448	393	837
	Average	**94**	**19**	**276**	**196**	**519**
Karabük	**2010**	178	15	381	126	404
	2009	163	26	376	141	380
	2008	101	11	371	113	324
	Average	**147**	**17**	**376**	**127**	**369**

In the rural areas of Turkey electrical energy is distributed with branched and long over headlines. Distributing electrical energy with overhead lines in rural areas is a common implementation for distribution utilities because it is easy to install and cheap. As it is shown in Table 1 faults on the electrical distribution network are mostly caused by the overhead power lines. The faults on the distribution transformers are very rare compared to lines because distribution transformers are much more reliable elements and less subjected to the ambient conditions like humidity, dust, lightning strokes, animal contacts, etc. Moreover distribution transformers have a fuse protection on their MV voltage side. Theoretically, when there is a fault occurs on MV side of a distribution transformer fuse protection reacts before the circuit breaker at the beginning of the line and cleans the fault. However considering the real life scheme of the Turkey rural area protection, it is assumed that for the half of the distribution transformer MV side faults transformer fuse protection does not react before the circuit breaker at the beginning of the feeder.

When examining the failure data it was noticed that there is an important portion of fault records which were concerned for circuit breakers (CBs). However it is known that circuit breakers are too reliable elements which do not break down and cause outages frequently [8]. Therefore the failure records of the maintenance field crew for CBs need a detailed consideration.

Considering the common attitude of maintenance field crew when classifying the faults, it was realized that most of the failures which are recorded as CB fault (wrong trip action) are actually due to the transient nature failures occurring on the distribution network. When a transient fault occurs on a MV overhead power line (due to tree-fall, animal contact, etc.), it causes the protection device at the beginning of the feeder to trip. Therefore after the maintenance crew on the field re-closes the circuit breaker at the beginning of the feeder and notices that the fault does not remain anymore (CB does not trip again), it is recorded as a CB fault (wrong CB tripping). Therefore it can be claimed that a high portion of the failures which are recorded as a CB fault are originated from the transient nature faults occurring on the electrical distribution network.

Different studies show that %50-%90 percent of the faults on the overhead power lines are of the transient nature [9], [10], [11]. With the usage of re-closers at the beginning of the MV overhead power lines, transient faults can be cleared without becoming a sustained fault. Therefore in the scope of thesis study, a recloser is located at the beginning of each main feeder since its significant positive effect on the outage frequencies and durations by clearing the transient nature faults. The effect of the recloser on the failure durations and frequencies in rural electrical distribution network will be presented in Chapter 3.6 with calculations of the reliability indices which are namely SAIDI and SAIFI. The details of the operational principles and implementation of re-closers with sectionalizing switches on the branches of the main power lines will be given in Chapter 3.4 and Chapter 3.5.

2.4. Reliability Model of Rural Distribution Network

This thesis study focuses on the electrical distribution network starting with the MV busbar in a rural switching center (KÖK) and includes the main rural feeders and branch lines from the main line. The representation of typical rural network studied in the scope of this thesis study is illustrated in Figure 1.

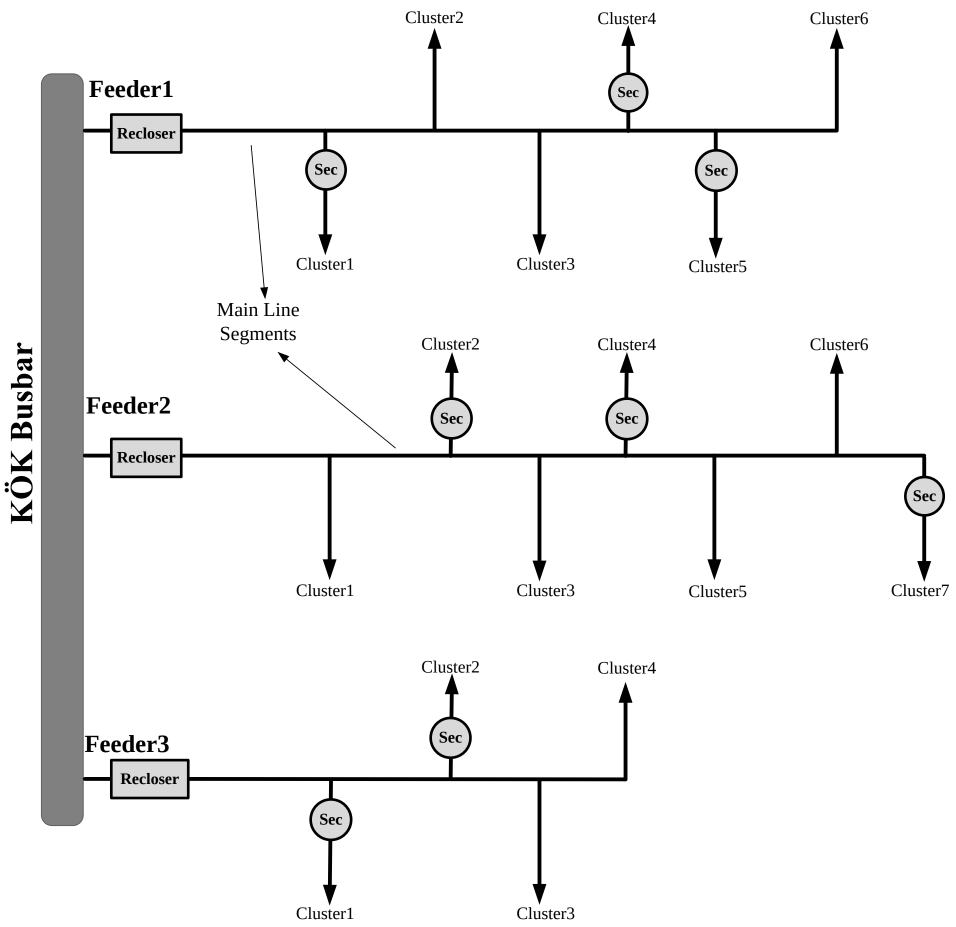

Figure 1 Typical rural network structure

Two types of switching devices considered are reclosers and sectionalizing switches. The conventional circuit breaker at the beginning of each main feeder is replaced with a recloser. Reclosers at the beginning of main feeders prevent transient faults to cause sustained outages by tripping and reclosing on the momentary fault. Branches coming out the mainline providing electric energy to their particular load points are called as cluster. Each connection point of a branch to main line is a candidate location for a sectionalizing switch installation. Sectionalizing switches are not conventional protection devices that open fault current but isolates the faulted branch in case of a sustained fault and allows healthy parts of feeder to be energized.

In this study the locations and quantities of sectionalizing switches are design variables which need to be selected to optimize costs arisen due to the outage durations, investment and penalty payments for a defined objective function. As it can be seen from Figure 1 for each radial outgoing feeder from the KÖK busbar an equivalent feeder model is created. The cluster which consists of MV/LV distribution transformers and arborescent overhead lines is modeled as its equivalent circuit element which is a branch line segment with a total length of the arborescent overhead lines in that cluster.

For each cluster the parameters given below are calculated

r_{tr} : annual TR outage duration of cluster

$r_{\ln}$: anuual line outage duration of cluster

λ_{tr} : annual TR failure rate of cluster

$\lambda_{\ln}$: annual line failure rate of cluster

L : average kW load connected to the cluster (load point)

N : total number of connected customer at cluster

For each main line segment the parameters given below are calculated;

$r_{m\ln}$: anuual line outage duration

$\lambda_{m\ln}$: annual line failure rate

2.5. Calculation of Average Annual Failure Rate and Outage Duration of Line and TR Elements

As seen from Figure 1 the study model consists of clusters and mainline segments. The annual failure frequency of a cluster due to the failures of distribution transformers in that cluster is calculated as given below;

$$\lambda_{tr} = (\#\ of\ MV/LV\,TRs\ in\ the\ cluster) \times \left(\frac{Total\ Number\ of\ MV/LV\ TR\ Failures}{Total\ Number\ of\ MV/LV\,TRs} \right) \quad (6)$$

The failure duration due to the outage of a distribution transformer in the cluster is calculated as given below;

$$r_{tr} = \frac{Total\ Duration\ of\ MV/LV\,TR\,Outages}{Total\ Number\,of\ MV/LV\,TRs} \quad (7)$$

The annual failure frequency of a cluster due to the failures of overhead power line segments in that cluster is calculated as given below;

$$\lambda_{\ln} = (Total\ Overhead\ Line\,Length\ in\ the\ Cluster) \times \left(\frac{Total\,Number\ of\ Line\ Failures}{Total\,Length\ of\ Overhead\,Line} \right) \quad (8)$$

The failure duration due to the overhead power line segments in the cluster is calculated as give below;

$$r_{\ln} = (Total\ Overhead\ Line\ Length\ in\ the\ Cluster) \times \left(\frac{Total\ Duration\ of\ Overhead\ Line\ Outages}{Total\ Length\ of\ Overhead\ Line} \right) \quad (9)$$

The annual failure frequency of a main line segment is calculated as given below;

$$\lambda_{m\ln} = (Length\ of\ the\ mainline\ segment) \times \left(\frac{Total\ Number\ of\ Overhead\ Line\ Failures}{Total\ Length\ of\ Overhead\ Line} \right) \tag{10}$$

The failure duration due to the overhead power line segments in the cluster is calculated as given below;

$$r_{m\ln} = (Length\ of\ the\ mainline\ segment) \times \left(\frac{Total\ Duration\ of\ Overhead\ Line\ Outages}{Total\ Length\ of\ Overhead\ Line} \right) \tag{11}$$

The calculated average MV/LV transformer outage parameters for different regions are as given below in Table 2.

Table 2 Calculated average outage parameters for MV/LV transformer

Regions	**MV/LV Transformer Average Outage Parameters**	
	Average Outage Duration (hours)	**Annual Average Outage Frequency (failures/year)**
Kastamonu	12,716	0,014
Kırıkkale	2,419	0,002
Karabük	7,738	0,008
Bartın	5,194	0,014
Çankırı	3,924	0,009
Zonguldak	4,974	0,004
Average	**6,161**	**0,009**

The calculated average overhead line outage parameters for different regions are as given below in Table 3.

Table 3 Calculated average outage parameters for overhead line

Regions	**Overhead Line Average Outage Parameters**	
	Average Outage Duration (hours/year*km)	**Annual Average Outage Frequency (failures/year*km)**
Kastamonu	0,402	0,123
Kırıkkale	0,089	0,075
Karabük	0,277	0,103
Bartın	0,515	0,163
Çankırı	0,230	0,093
Zonguldak	0,087	0,062
Average	**0,267**	**0,103**

2.6. Average Total kW Load and Connected Customer Calculations of Clusters

The average loading of a distribution transformer is assumed as 20% for the base case. Loading measurements of MV/LV distribution transformers in different rural regions of Turkey reveals that even around the peak times the loadings of the MV/LV rural distribution transformers are in the range of 10-25% in average [12]-[17].

The power factors of the modeled MV/LV distribution transformers are taken as 0,8. The total installed kVA capacity of a cluster is the sum of installed capacities of MV/LV distribution transformers.

Average kW load in a cluster is calculated by multiplying total installed kVA power with power factor and average loading factors. The average kW loading of a cluster calculated as given below;

$$L(kW) = Lf \times pf \times \sum_{i=1}^{n} Installed\ Capacity\ of\ TR_i \tag{12}$$

where;

n : Total number of MV/LV distribution transformers in the cluster

pf (power factor): 0,8 lagging

Lf (loading factor): 0,2 for the base case

Another parameter which is required for the calculation of system reliability indices, SAIDI and SAIFI, is the number of connected customers connected in each cluster. In the scope of this study the average installed capacity per rural residential and agricultural customer is assumed as 1 kVA and 10 kVA respectively [12]-[17]. By using a similar approach for calculation of the average peak loading of a transformer, the number of connected customers in a cluster is calculated by dividing the total installed power in a cluster to average installed capacity per rural customer as in the formulation given below;

$$N_{cluster(i)} = \frac{\sum_{i=1}^{n} Installed\ \ Capacity\ \ of\ TR_i}{\text{Average Installed Capacity per Rural Customer}} \tag{13}$$

where;

n :Total number of MV/LV distribution transformers in the cluster

CHAPTER 3

DEFINITION OF THE EQUIPMENT AND DESIGN DETAILS

3.1. Introduction

In the rural electrical distribution system of Turkey in order to enhance the continuity of supply small distribution switching centers which are called as KÖK are implemented at strategic points of long overhead power lines. With the usage of KÖKs, long radial feeders are segmented and faulted segments can be isolated from the rest of the distribution network. Generally KÖKs consist of one input feeder with an isolating switch and two to four output feeders protected by circuit breakers. If a fault occurs on one of the outgoing feeders the circuit breaker in the KÖK trips and prevents the tripping of upstream circuit breaker located in the main distribution center. Although this configuration aims to enhance the continuity of supply by preventing the tripping of the circuit breaker located at the main distribution center, it is a poor configuration due to the high frequency levels of long overhead lines.

Continuity of supply in the rural regions can be enhanced gradually with the usage of reclosers (circuit breaking device with reclosing capability) at the KÖKs and sectionalizing switches at the branch points. As it has been mentioned in Chapter 2.3 due to their significant positive effect on outage frequency and duration by preventing the conversion of transient faults into sustained faults, installation of reclosers at the beginning of each main outgoing feeder is advised in this study.

The minimization of the outage durations due to the sustained faults is aimed in this thesis with the installation of optimum number of sectionalizing switch at optimum branch point locations.

The faults on the rural overhead power lines are mostly caused by a transient nature effect such as animal contact, lightning stroke, wind, tree fall, etc. Rural network forms in arborescent structure and branches from a main line are protected conventionally by the circuit breakers located in the KÖK. There all of the customers supplied from the main line remain non-energized due to tripping of the CB in KÖK because of a fault on one of the branches. In order to prevent the conversion of the transient faults into the sustained faults and to isolate the faulted branch from the rest of the network;

- Circuit Protection with Reclosing Capability (Recloser),
- Automatic Sectionalizing Switches (Sectionalizing switch)

are aimed to be utilized in this thesis.

Actually in 2004 TEDAŞ (Turkish National Distribution Operator Company) went to a tender for the procurement of reclosers and automated sectionalizing switches and carried out a pilot study which covers 110 installation points in total. In the scope of that pilot study 55 reclosers and 55 sectionalizing switches are installed in 17 different regions however the implementation of these equipments was not extended afterwards [18], [19].

3.2. Sectionalizing Switches

Sectionalizing switches are automatic switches that are controlled by a built-in logic system. The logic system uses operations of a source side reclosing device to determine if a permanent fault is occurring in the sectionalizing switch protection zone and, if so, to automatically open the sectionalizing switch during one of the source side recloser temporary open periods. After the sectionalizing switch opens, the source-side recloser closes, restoring service to unaffected sections of the system. If the fault is temporary and is cleared before the sectionalizing switch count reaches the predetermined number, the sectionalizing switch remains closed and resets to its original state after a predetermined time period. In case of an sustained fault all the operation sequence which ends with the isolation of the faulted branch from rest of the network is completed in less than 3 minutes. Therefore the effect of the sustained outage on a branch to the healthy parts of the network is prevented. According to Turkey's regulations on continuity of supply, during the calculation of the distribution network reliability indices (used also for penalty payments) outages last more than 3 minutes are taken into the consideration [5].

The typical operation sequence of an electronic sectionalizing switch (3 count) with a recloser is illustrated below in Figure 2.

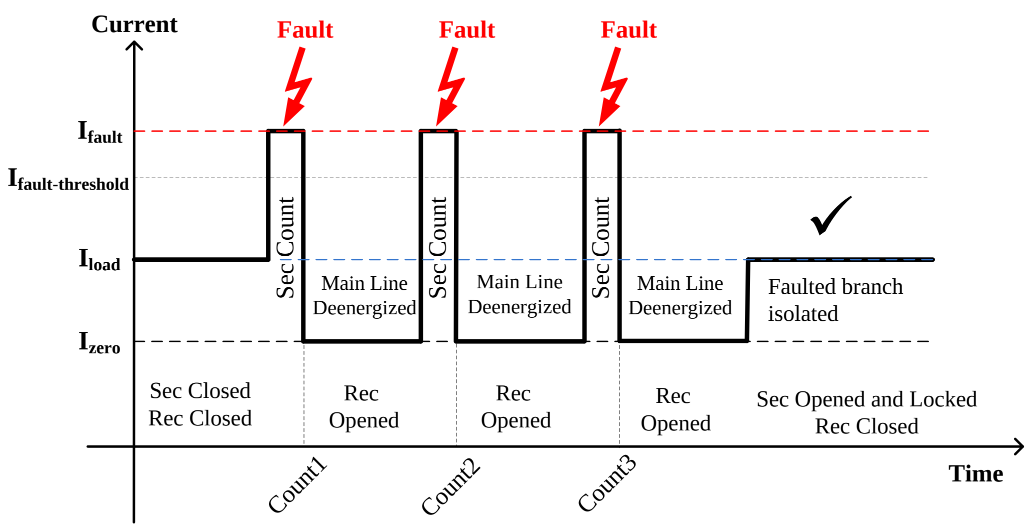

Figure 2 Sectionalizing switch operation sequence

An automatic line sectionalizing switch is an automatic switch that does not interrupt fault currents, does not have time-current characteristics, and is dependent on the operating of a source-side device for proper function. Because it does not interrupt fault currents and is not capable of operating independently, it should not be thought of as a protective device in the classical sense, but should be thought of as an automated switch. These characteristics give sectionalizing switches some distinct advantages over protective devices as given below;

- there is no need to be concerned about interrupting rating,
- there is no need to time-current coordinate with load-side fuses or source-side reclosers,

By developing a proper methodology in order to determine optimum locations for sectionalizing switches, continuity of supply can be enhanced substantially with an optimum investment cost. The following parameters listed below are beneficial to select the correct place to locate a sectionalizing switch;

- Number of connected MV/LV distribution transformers to each branch,
- Total installed power of connected MV/LV distribution transformers to each branch,
- Length of the main line and branch lines,
- Annual failure frequency of branches,
- Weather condition of the region,
- Geographical conditions of the region (forest environment, seaside, etc.),
- Isoceraunic level,
- Age of the asset,
- General condition of the asset material (poor, medium, good etc)

In Turkey since reliable information for most of the parameters listed above such as isoceraunic level, age of asset, weather is not available, in this thesis study a methodology based on the failure statics, length of the lines and number of distribution transformers was developed in order to determine optimum locations of the sectionalizing switches.

Basically sectionalizing switches can be implemented on two locations;

- At connection points of the branches to the main line as seen in Figure 3 (common implementation) [20],
- At the middle of the main line (Figure 4 and Figure 5) [20].

Figure 3 Sectionalizing switch placed at a branch connection

Figure 4 Sectionalizing switch placed on a main line in series

Figure 5 Sectionalizing switch placed on a main line in series-2

There are two general types of current sensing sectionalizing switches;

- Hydraulic sectionalizing switches that look like small single phase reclosers,
- And electronic sectionalizing switches that look like a solid barrel or blade cutout with a “donut” current transformer around the middle of the barrel.

In past decades the dominant sectionalizing switch type was the “hydraulic” sectionalizing switch. Its application was limited to light loading behind a single recloser with an [1-3] operating sequence. However the development of electronic sectionalizing switches in recent years has resulted in sectionalizing switches that can operate properly when carrying large loads; behind reclosers with a 2-2 operating sequence; and when placed to the source side of recloser [23].

Sectionalizing switches may be single-phase or three-phase switching and the logic system may key on current or voltage. In the scope of this thesis study three-phase current controlled electronic sectionalizing switches are concerned [24]. The logic system of current sensing sectionalizing switch must make three decisions, and if the outcome of these decisions match the logic scheme, then it will automatically open the sectionalizing switch while the circuit is de-energized by a source-side reclosing device [23].

The sectionalizing switch must determine that a fault exists in the circuit beyond it (the load-side circuit). It does this by recognizing a current flowing through the sectionalizing switch that exceeds a predetermined current “threshold”. This current is called as the actuating current or the arm-to-count current.

The sectionalizing switch must determine that the fault is not temporary in nature. It does this by “counting” the number of times that a source side reclosing device operates, determined by the number of times in a set time period that an actuating current has occurred followed by a low current indication. A low current indication is a current below the “minimum threshold” (indicating a de-energized circuit). It is typical for sectionalizing switches to assume that a fault is permanent if there are 2 or 3 counts in a set time frame (about two minutes for an electronic sectionalizing switch) [21], [25], [26].

3.3. Reclosers

Reclosers have been around for a long time and have always been considered one of the "workhorses" of distribution system overcurrent protection. A distribution recloser is designed to interrupt both load and fault current. Moreover, as its name refers to it is designed to “reclose” on the fault repeatedly in a predefined sequence in an attempt to clear the fault [27]. The common operation sequence of a recloser is illustrated below in Figure 6.

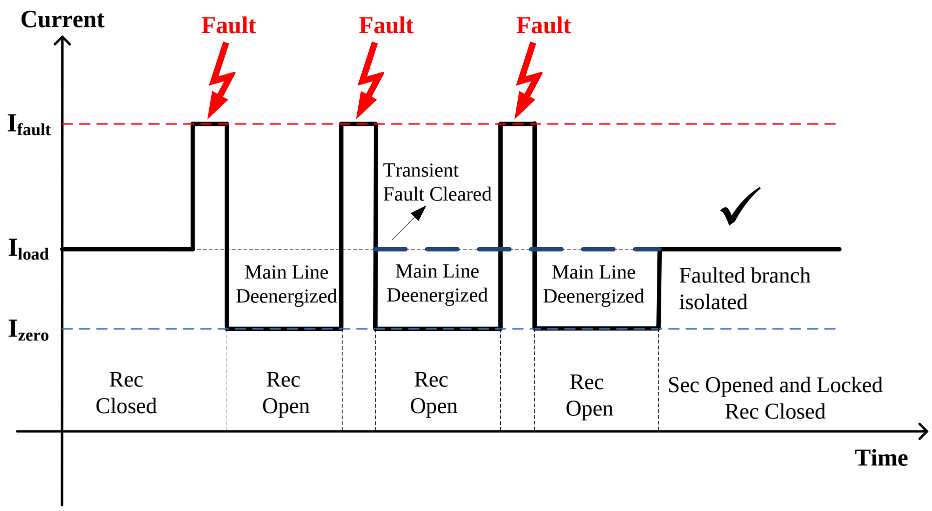

Figure 6 Recloser operation sequence

Reclosers are predominantly located on the distribution network overhead power lines, though as the continuous and interrupting current ratings increase, they are more likely now to be seen in substations (KÖKs), where traditionally a circuit breaker is located.

The installation of a pole type recloser means an additional asymmetrical load around 260-300 kg [28] (in winter it might reach to 400-500kg with snow load) should be carried by the pole. In case of installation of the recloser on the poles, the asymmetric load carrying capacity of the pole should be analyzed carefully and terminal steel power poles should be used. Considering the weight of a recloser, locating them in the KÖKs seems more practical. Therefore for the implementation of Turkey rural regions, kiosks (KÖKs) in which conventional circuit breakers are located, are the most applicable candidate locations for the recloser placement. In Figure 7, recloser installation at the beginning of a main line and, in Figure 8, at connection point of a branch line is shown respectively [20] .

Figure 7 Pole type recloser installation at the beginning of a main line

Figure 8 Pole type recloser installation at branch connection point

Reclosers have two basic functions on the system, reliability improvement and overcurrent protection. While one of the philosophies for the use of reclosers is to increase reliability by preventing the conversion of transient faults into sustained faults, in the past their use for many utilities was determined primarily because the feeder breaker did not have protective reach to the end of the feeder. This was due to the fact that high load currents forced the minimum trip setting to a higher value than the fault level at the end of the feeder. Nowadays, reclosers on rural radial feeders are more frequently applied for reliability reasons, mainly due to reclosing capability [29].

The control system for the reclosers allows a selected number of attempts to restore service after adjustable time delays. Time delays between two successive closing attempts can be set to different values. Typically the set value for time delay between two successive closing attempts is around few seconds to 30 seconds.

A recloser may have 2 or 3 "fast" reclose operations with a few seconds delay, then a longer delay and one reclose; if the last attempt is not successful, the recloser will lock out and require human intervention to reset. If the fault is a permanent fault (downed wires, tree branches lying on the wires, etc.) the recloser will exhaust its pre-programmed attempts to re-energize the line and remain tripped off until manually commanded to try again.

Reclosers are made in single-phase and three-phase versions, and use either oil, vacuum, or SF6 interrupters. Controls for the reclosers range from the original electromechanical systems to digital electronics with metering and SCADA functions. The ratings of reclosers run from 2.4–38 kV for load currents from 10–1200 A and fault currents from 1–16 kA [28]-[31] .

3.4. Coordination Details of Reclosers and Sectionalizing Switches

Reclosers have tripping relays and reclosing operations. These mechanisms are either hydraulic, electro mechanical or electronic. The recloser scheme uses multiple recloses separated by adjustable times of a few seconds to 15 or 30 seconds. These longer delay times can result in hydraulic sectionalizing switches losing count of the fault current shots. The longer count retention time of an electronic sectionalizing switch enables use of the sectionalizing switch where a hydraulic sectionalizing switch would lose count and result in a breaker or recloser lock out. Hydraulic sectionalizing switches were originally designed to coordinate with hydraulic reclosers which typically have a 2 second delay between trip and reclose. Electronic sectionalizing switches can have count retention times of two minutes and are more suited to application directly behind a feeder breaker.

The typical coordination scheme with a recloser which can be seen in Figure 9 utilizes a 4 shot sequence with the first one or two operations being a fast trip to clear a fault and the last two or three shots being a delayed trip to force the fuse to blow if the fault is indeed downstream of a fuse. The recloser sequences are typically labeled [2-2] or [1-3] with the first number being the quantity of fast trips and the second number being the quantity of slow or time delayed trips.

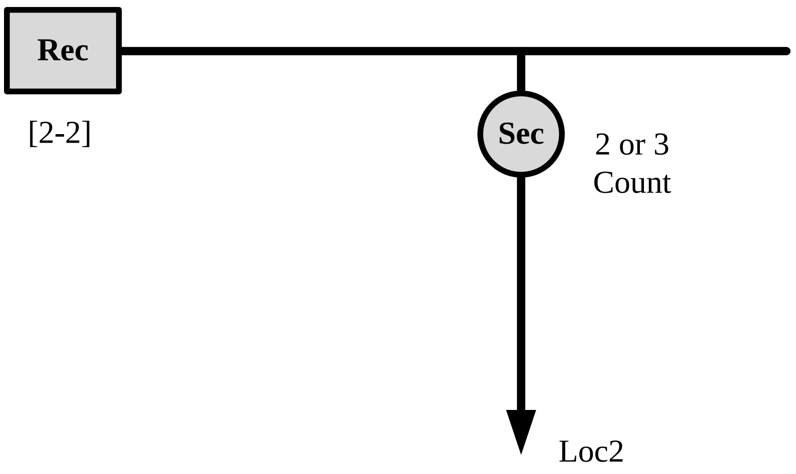

Figure 9: [2-2] recloser installation with 2/3 count sectionalizing switch

Consider the circuit in Figure 9 with a [2-2] recloser and a 3 shot sectionalizing switch. A fault occurs at Loc2. The sequence of operations would look as shown in Figure 10.

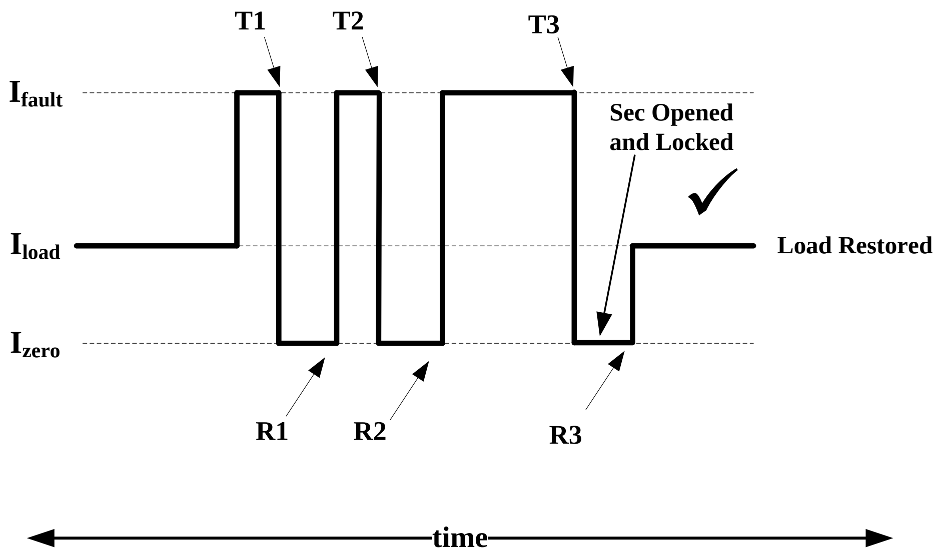

Figure 10 Sequence of a [2-2] recloser and a 3 shot sectionalizing switch

When the fault at Loc2 occurs the recloser trips on a fast trip curve (T1). After a short delay the recloser closes (R1). The fault remains and the recloser trips again on a fast trip curve (T2). After another short delay the recloser closes (R2). The recloser is then on a slow curve to allow any downstream fuse to blow. If no fuse clears the fault the recloser trips again (T3). While the recloser is open the sectionalizing switch drops open and isolates the branch line.

Now consider the same scheme with a 2 shot sectionalizing switch in place of the 3 shot sectionalizing switch as shown in Figure 9. The recloser operates similarly as before but the sectionalizing switch drops open after the second trip (T2). This removes the concern of conductor burn down, since all trips when the small wire branch line is exposed to fault current are on a fast or instantaneous time basis.

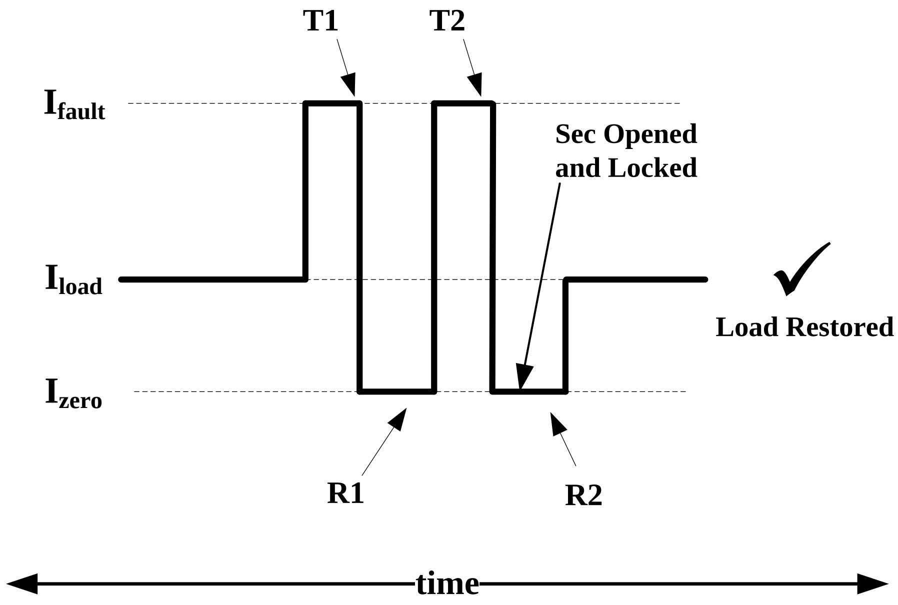

Figure 11 Sequence of a [2-2] recloser and a 2 shot sectionalizing switch

If the fault was temporary the fault would clear after the first trip (T1), assuming the delay time before recluse (R1) is long enough to allow the temporary fault to extinguish and clear. This scheme would work and coordinate properly independent of fault current levels. The electronic sectionalizing switches longer count retention time allows longer reclose times (R1) while maintaining count so that the scheme can work in high fault current areas where fuse save coordination is not achievable due to fuse and breaker speeds. Thus the scheme of using a breaker set to a [2-2] sequence and a 2 shot sectionalizing switch is known as an Electronic Fuse Scheme [11].

3.5. Implementation Examples for Electronic Sectionalizing Switches with Reclosers

Below are examples of typical recloser and sectionalizing switch implementations. All examples include a sectionalizing switch with a source-side reclosing device and a load-side fuse or recloser.

Implementation 1: Sequence of 3 count electronic sectionalizing switch for a fault beyond a load-side fuse when the sectionalizing switch is behind a [2-2] recloser

- Step 1 (Fault 1) – Current flows through the recloser, sectionalizing switch, and fuse. The sectionalizing switch arms. The recloser opens on the fast curve, protecting the fuse. The sectionalizing switch counts "one".

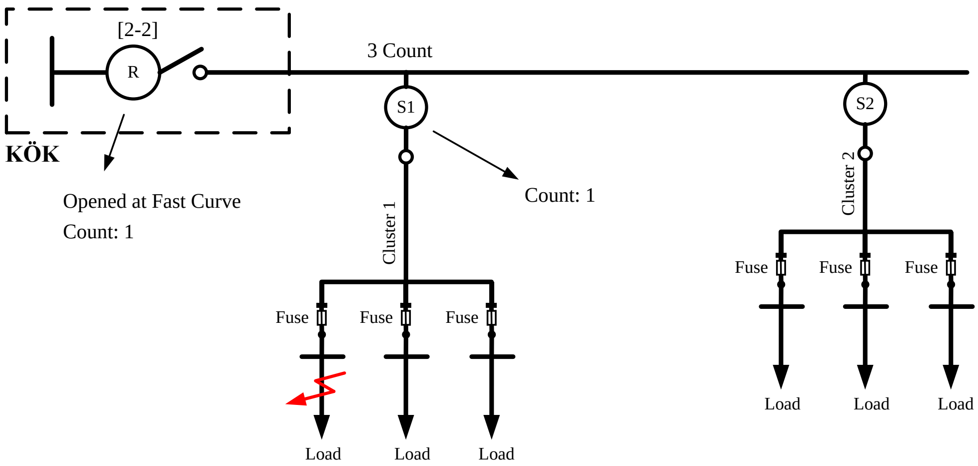

Figure 12 Implementation 1 - Step 1

- Step 2 (Fault 2) – The recloser closes and the sectionalizing switch arms. The recloser opens on the fast curve, protecting the fuse. The sectionalizing switch counts "two".

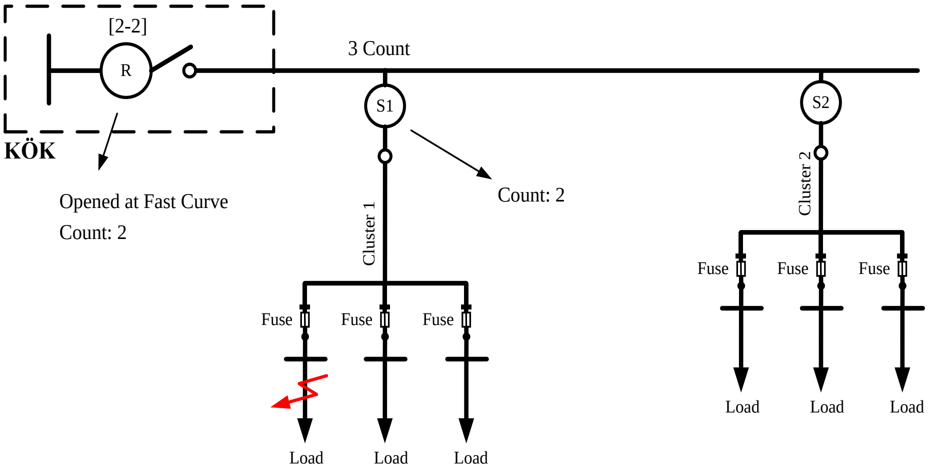

Figure 13 Implementation 1 - Step 2

- Step 3 (Fault 3) – The recloser closes and the sectionalizing switch arms. The recloser opens on the slow curve, the fuse blows. The sectionalizing switch does not count and remains closed because load current exists. There is now only one device open, the fuse closest to the fault.

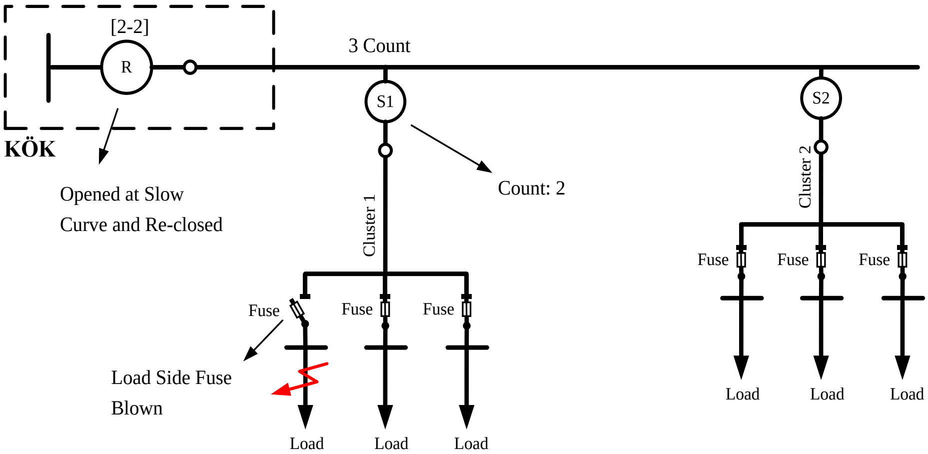

Figure 14 Implementation 1 - Step 3

Implementation 2: Sequence of 2 count electronic sectionalizing switch for a fault beyond a load-side [2-2] recloser when the sectionalizing switch is behind a [1-3] circuit breaker or recloser,

- Step 1 (Fault 1) – Current flows through the source-side breaker, sectionalizing switch, and load-side recloser. The sectionalizing switch arms. The recloser opens on the fast curve, clearing the fault. When the recloser opens, the over current disappears but the load current in the sectionalizing switch zone exists. Therefore the sectionalizing switch does not count.

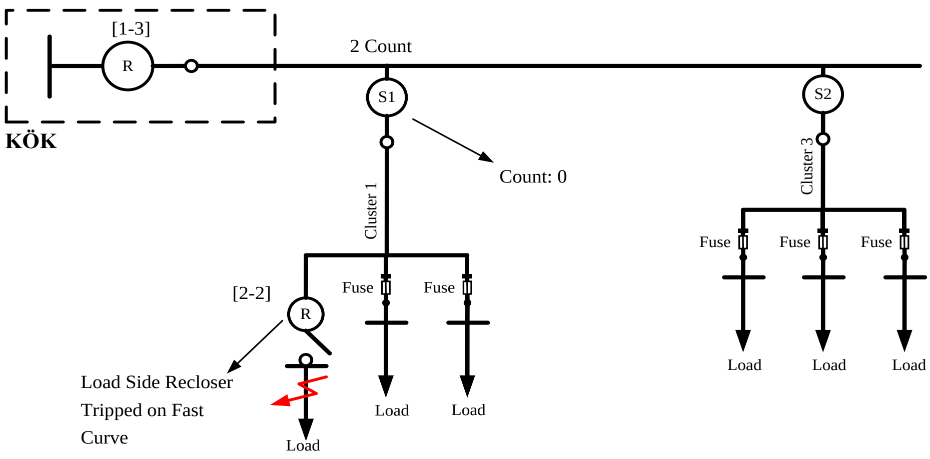

Figure 15 Implementation 2 - Step 1

- Step 2 (Fault 2) – The load-side recloser closes and the sectionalizing switch arms. The recloser opens on the fast curve, clearing the fault. The sectionalizing switch continues to see load current and does not count.

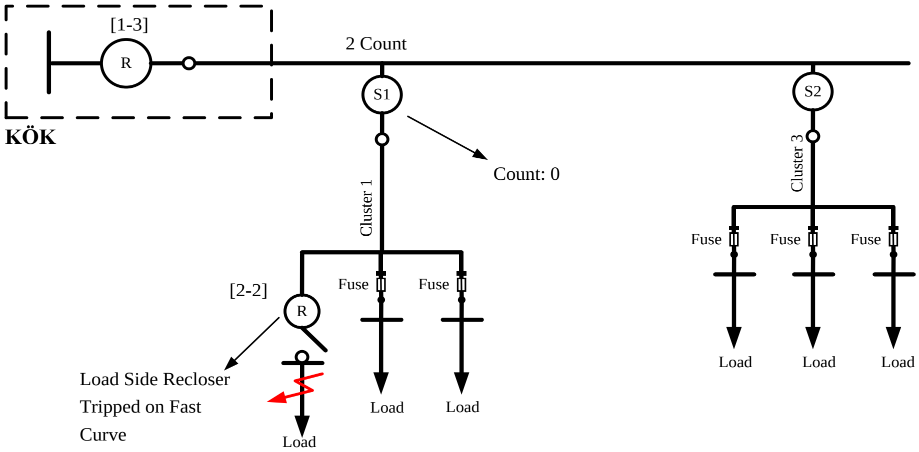

Figure 16 Implementation 2 - Step 2

- Step 3 (Fault 3) – The load-side recloser closes and the sectionalizing switch arms. The recloser is now on the slow curve, causing the source-side breaker to clear the fault on its fast curve (this would not occur with properly applied sequence coordination). The sectionalizing switch sees current drop below threshold and counts "one".

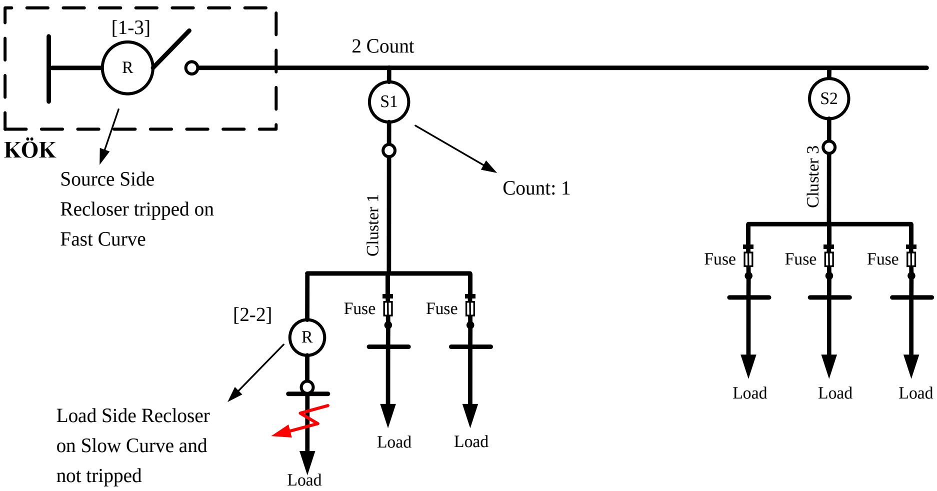

Figure 17 Implementation 2 - Step 3

- Step 4 (Fault 4) – The source-side device closes and the sectionalizing switch arms. The recloser opens on the slow curve, clearing the fault. The sectionalizing switch continues to see load current and does not count.

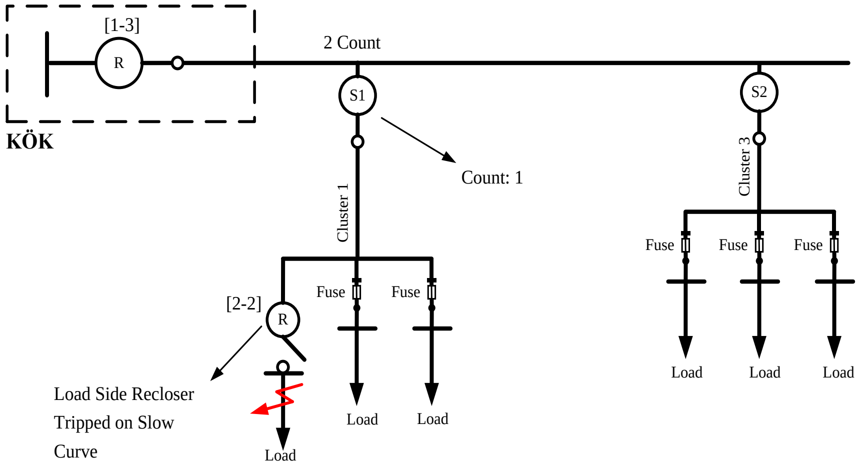

Figure 18 Implementation 2 - Step 4

- Step 5 (Fault 5) – The load-side recloser closes and the sectionalizing switch arms. The recloser opens on the slow curve, locks out. The sectionalizing switch continues to see load current and does not count. The sectionalizing switch will reset to “zero” count after about 2 minutes.

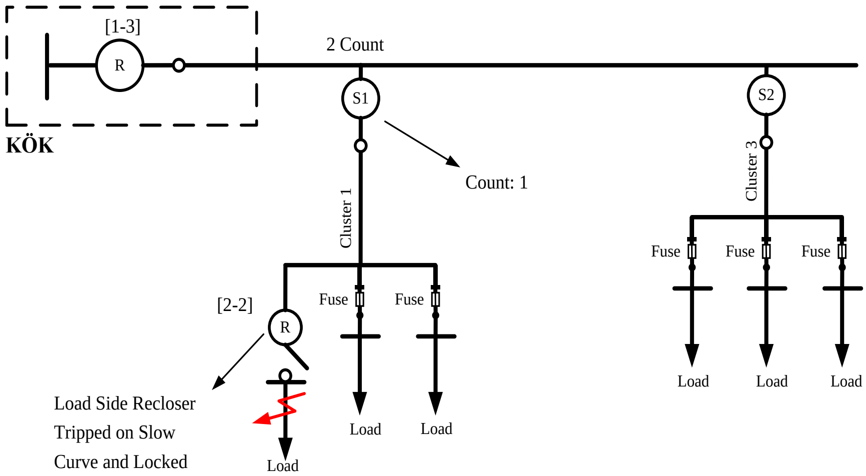

Figure 19 Implementation 3 - Fault 5

Implementation 3: Sequence of 2 count electronic sectionalizing switch sequence for a fault between the sectionalizing switch and a load-side [2-2] recloser when the sectionalizing switch is behind a [1-3] recloser,

- Step 1 (Fault 1) – Current flows through the source-side breaker and sectionalizing switch. The sectionalizing switch arms. The source side breaker opens on the fast curve, clearing the fault. When the breaker opens, the sectionalizing switch sees current drop below threshold and counts “one”.

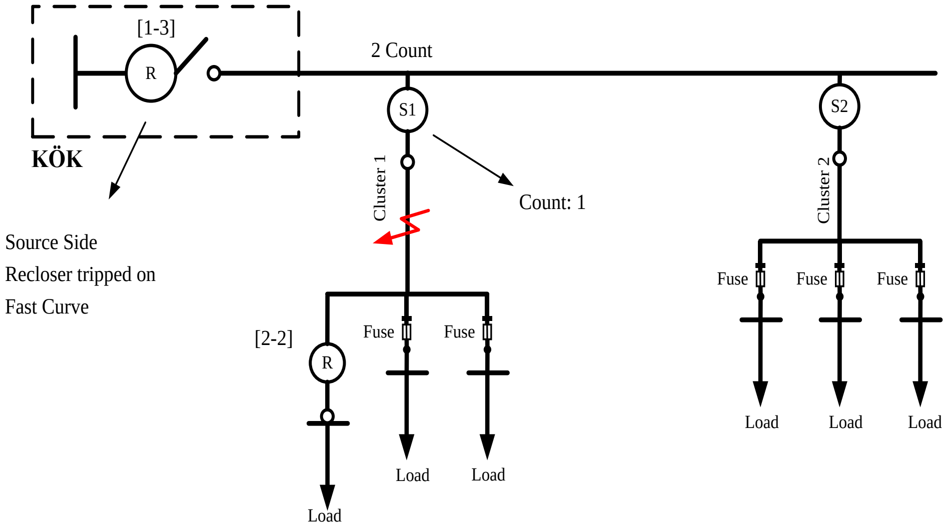

Figure 20 Implementation 3 - Step 1

- Step 2 (Fault 2) – The source-side breaker closes and the sectionalizing switch arms. The source-side breaker opens on the slow curve, clearing the fault. The sectionalizing switch sees current drop below threshold, opens and locked.

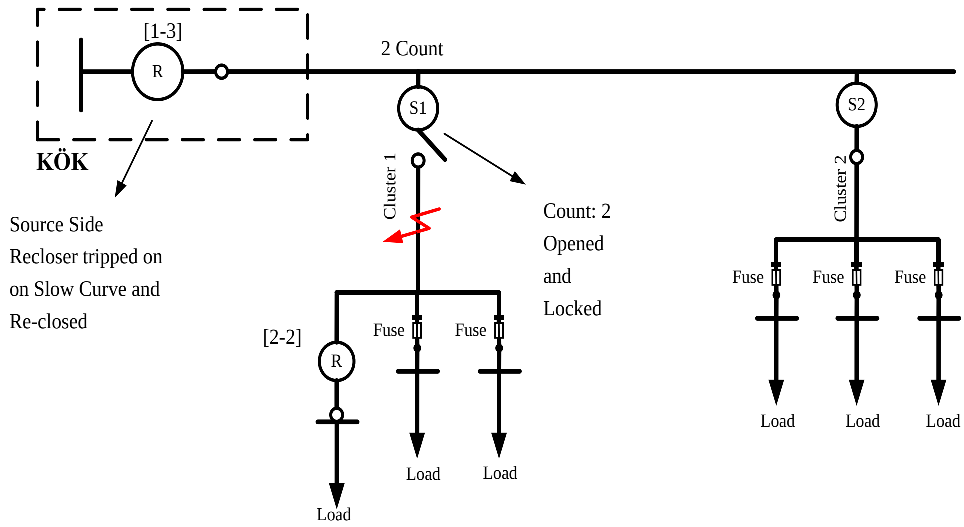

Figure 21 Implementation 3 - Step 2

3.6. Enhancement of Continuity of Supply in Electrical Distribution Network with the Usage of Reclosers and Sectionalizing Switches

In this section enhancement of the distribution system reliability indices SAIDI and SAIFI with the usage of reclosers and sectionalizing switches is presented. According to Turkish regulations on continuity of supply during the calculation of SAIDI (OKSÜREG) and SAIFI (OKSIKG) indices only the outages last more than 3 minutes which are called as *sustained (long) outages* are taken into the consideration [5]. Especially in rural regions an important portion of the distribution network faults occurs because of the transient nature reasons. As it has been mentioned several times, in the scope of thesis study a recloser is located at the beginning of each mainline outgoing from the KÖK busbar due to the its significant positive effect on the continuity of supply. Reclosers eliminate the negative effect of transient nature faults on the reliability indices by preventing the conversion of transient faults into sustained outages.

Failure rates and the recovery durations used in the model are generated from the statistics of an electrical distribution company which is the electrical distribution network operator of the Central Anatolian and Western Black Sea regions. During the calculations it is assumed that 70% of the failures on the overhead power lines are of the transient nature. The study model used in the simulations represents a typical MV (medium voltage) rural distribution feeder with 8 branches.

System reliability indices are calculated with the tool developed in the scope of thesis study. The reliability indices which are calculated with the tool developed is verified by comparing the calculated results with the results of probabilistic reliability analysis module of the Power Factory DigSilent Version 14.0.520.0 [32].

3.6.1. Reliability Indices Formulations

Three indices SAIDI, SAIFI and CAIDI are the main indices used in the majority of countries. These indices are defined among others in IEEE Std.1366, where weighting based on number of customers is used. With both SAIFI and SAIDI, a reduction in value indicates an improvement in the continuity of supply. With CAIDI this is not the case. A reduction in both SAIDI and SAIFI could still result in an increase in CAIDI. Whereas CAIDI remains as a useful index although it is not suitable for comparisons or for trend analysis [6].

3.6.1.1 SAIDI Formulation

SAIDI is the average duration of all interruptions per utility customer during the period of analysis and calculated by dividing the sum of all customer interruption durations with the total number of customer served by the network. It is usually measured over the course of a year. The expression for the calculation of SAIDI in IEEE Guide for Electric Power Reliability Indices [33] is as given by equation (14)**;**

$$SAIDI = \frac{\sum_{i=1}^{n} \left(t_i \, N_i \right)}{N_T} \tag{14}$$

where;

N_i = number of customers affected by the i_{th} interruption

t_i = duration of the i_{th} interruption

N_T = total number of customers served

The SAIDI formulation derived for the radial feeders studied in the scope of this thesis is as given by equation (15);

$$SAIDI = \frac{\sum_{i=1}^{n} \left[\begin{array}{l} \left(\left(r_{tr\,i} \, \lambda_{tr\,i} + r_{\ln i} \, \lambda_{\ln i} \right) \, x_i \sum_{j=1}^{n} N_j \right) \\ + \left(\left(r_{tr\,i} \, \lambda_{tr\,i} + r_{\ln i} \, \lambda_{\ln i} \right) \, N_i \, (1 - x_i) \right) \\ + \left(r_{m \ln i} \, \lambda_{m \ln i} \, \sum_{j=1}^{n} N_j \right) \end{array} \right]}{\sum_{j=1}^{n} N_j} \tag{15}$$

where;

n : Total number of clusters (load points) in the feeder

$r_{tr\,i}$: Outage duration due to the transformer outage in cluster i

$r_{\ln i}$: Outage duration due to the line outage in cluster i

$r_{m\ln i}$: Outage duration due to the outage of main line segment i

$\lambda_{tr\,i}$: Annual outage frequency of transformers in cluster i

$\lambda_{\ln i}$: Annual outage frequency of line in cluster i

$\lambda_{m\ln i}$: Annual outage frequency of main line segment i

N_i : Number of connected customer in cluster i

x_i : Sectionalizing switch installation index of cluster i

- $x_i = 0$ means a sectionalizing switch is installed at i_{th} cluster,
- $x_i = 1$ means a sectionalizing switch is not installed at i_{th} cluster,

x_j : Sectionalizing switch installation index of cluster j

- $x_j = 0$ means a sectionalizing switch is installed at j_{th} cluster
- $x_j = 1$ means a sectionalizing switch is not installed at j_{th} cluster

The dividend of (15) is the annual sum of all customer interruption durations. Outages in the network studied can be occurred due to the faults in either clusters or main line segments. Therefore the annual sum of all customer interruption durations in (15) has two basic contributors which are outage durations due to the clusters and outage durations due to the main line segments. The divider of (15) is the total number of customers connected to the network.

3.6.1.2 SAIFI Formulation

SAIFI is the average number of interruptions per utility customer during the period of analysis and calculated by dividing the total number of customer interruptions with the total number of customer served by the network. It is usually measured over the course of a year. The expression for the calculation of SAIFI in IEEE Guide for Electric Power Reliability Indices [33] is as given by equation (16)**;**

$$SAIFI = \frac{\sum_{i=1}^{n} N_i}{N_T} \tag{16}$$

where;

N_i = number of customers affected by the i_{th} interruption

N_T = total number of customers served

The SAIFI formulation derived for the radial feeders studied in the scope of this thesis in as given by equation (17);

$$SAIFI = \frac{\sum_{i=1}^{n} \begin{bmatrix} \left((\lambda_{tr\,i} + \lambda_{\ln i})\; x_i \sum_{j=1}^{n} N_j \right) \\ + \left((\lambda_{tr\,i} + \lambda_{\ln i})\; N_i\, (1 - x_i) \right) \\ + \left(\lambda_{m\ln i} \; \sum_{j=1}^{n} N_j \right) \end{bmatrix}}{\sum_{j=1}^{n} N_j} \tag{17}$$

where;

n : Total number of clusters (load points) in the feeder

$\lambda_{tr\,i}$: Annual outage frequency of transformers in cluster *i*

$\lambda_{\ln i}$: Annual outage frequency of line in cluster *i*

$\lambda_{m\ln i}$: Annual outage frequency of main line segment *i*

N_i : Number of connected customer in cluster *i*

x_i : Sectionalizing switch installation index of cluster *i*

- $x_i = 0$ means a sectionalizing switch is installed at i_{th} cluster,
- $x_i = 1$ means a sectionalizing switch is not installed at i_{th} cluster,

x_j : Sectionalizing switch installation index of cluster *j*

- $x_j = 0$ means a sectionalizing switch is installed at j_{th} cluster
- $x_j = 1$ means a sectionalizing switch is not installed at j_{th} cluster

The dividend of (17) is the total number of the annual customer interruptions. Outages in the network studied can be occurred due to the faults in either clusters or main line segments. Therefore the total number of the annual customer interruptions in (17) has two basic contributors which are outages due to the clusters and outages due to the main line segments. The divider of (17) is the total number of customers connected to the network.

3.6.1.3 CAIDI Formulation

CAIDI gives the average duration of a customer interruption and calculated by dividing sum of all customer interruption durations with the total number of customer interruptions. The expression for the calculation of CAIDI in IEEE Guide for Electric Power Reliability Indices [33] is as given by equation (18)**;**

$$CAIDI = \frac{\sum_{i=1}^{n} (t_i \; N_i)}{\sum_{i=1}^{n} (N_i)} \tag{18}$$

where;

N_i = number of customers affected by the i_{th} interruption

t_i = duration of the i_{th} interruption

λ_i = frequency of the i_{th} interruption

N_T = total number of customers served

The CAIDI formulation derived for the radial feeders studied in the scope of this thesis in is as given by equation (19);

$$CAIDI = \frac{\sum_{i=1}^{n}\begin{bmatrix}\left((r_{tr\,i}\,\lambda_{tr\,i} + r_{\ln i}\,\lambda_{\ln i})\ x_i \sum_{j=1}^{n} N_j\right) \\ + \left((r_{tr\,i}\,\lambda_{tr\,i} + r_{\ln i}\,\lambda_{\ln i})\ N_i\,(1 - x_i)\right) \\ + \left(r_{m\ln i}\,\lambda_{m\ln i}\ \sum_{j=1}^{n} N_j\right)\end{bmatrix}}{\sum_{i=1}^{n}\begin{bmatrix}\left((\lambda_{tr\,i} + \lambda_{\ln i})\ x_i \sum_{j=1}^{n} N_j\right) \\ + \left((\lambda_{tr\,i} + \lambda_{\ln i})\ N_i\,(1 - x_i)\right) \\ + \left(\lambda_{m\ln i}\ \sum_{j=1}^{n} N_j\right)\end{bmatrix}} \qquad (19)$$

where;

n : Total number of clusters (load points) in the feeder

$r_{tr\,i}$: Outage duration due to the transformer outage in cluster *i*

$r_{\ln i}$: Outage duration due to the line outage in cluster *i*

$r_{m\ln i}$: Outage duration due to the outage of main line segment *i*

$\lambda_{tr\,i}$: Annual outage frequency of transformers in cluster *i*

$\lambda_{\ln i}$: Annual outage frequency of line in cluster *i*

$\lambda_{m\ln i}$: Annual outage frequency of main line segment *i*

N_j : Number of connected customer in cluster *j*

x_i : Sectionalizing switch installation index of cluster *i*

- $x_i = 0$ means a sectionalizing switch is installed at i_{th} cluster,
- $x_i = 1$ means a sectionalizing switch is not installed at i_{th} cluster,

x_j : Sectionalizing switch installation index of cluster *j*

- $x_j = 0$ means a sectionalizing switch is installed at j_{th} cluster
- $x_j = 1$ means a sectionalizing switch is not installed at j_{th} cluster

3.6.2. Reliability Analysis

3.6.2.1 Default Configuration

The first simulation represents a conventional overhead rural feeder configuration implemented in rural regions of Turkey. In this configuration the only protection element, which is a circuit breaker, is located in the KÖK at the beginning of the distribution feeder. In default configuration there is neither a protection element nor a switching element located at the connection points of the branches to the main line. In this configuration since the head circuit breaker has not the reclosing property, transient nature faults on the overhead power lines cause sustained outages.

Calculated failure rates, recovery durations and other relevant parameters for each main line segment and the cluster are given in Table 4. Average annual failure rates and average outage durations due to the failed elements are derived by use of the failure statistics of an electrical distribution company which is the electrical distribution network operator of the Central Anatolian and Western Black Sea regions. Calculation of these failure parameters and the detailed explanation of the study model has been given in Chapter 2.

Table 4 Failure rates and recovery durations

Name	Length (km)	# of TR	# of Cust	λline (fail/year)	λtr (fail/year)	rline (hours)	rtr (hours)
Cluster1	12,0	8	400	5,8954	0,1395	7,899	6,16
Cluster2	17,0	12	600	8,3519	0,2092	11,190	6,16
Cluster3	2,5	2	60	1,2282	0,0349	1,646	6,16
Cluster4	5,6	4	200	2,7512	0,0697	3,686	6,16
Cluster5	13,0	8	450	6,3867	0,1395	8,557	6,16
Cluster6	7,6	5	270	3,7338	0,0872	5,002	6,16
Cluster7	8,7	8	400	4,2742	0,1395	5,727	6,16
Cluster8	4,0	4	190	1,9651	0,0697	2,633	6,16
Main Line Segment1	1,5	-	-	0,7369	-	0,987	-
Main Line Segment2	2,3	-	-	1,1300	-	1,514	-
Main Line Segment3	5,0	-	-	2,4564	-	3,291	-
Main Line Segment4	4,3	-	-	2,1125	-	2,830	-
Main Line Segment5	5,6	-	-	2,7512	-	3,686	-
Main Line Segment6	1,5	-	-	0,7369	-	0,987	-
Main Line Segment7	3,8	-	-	1,8669	-	2,501	-
Main Line Segment8	4,5	-	-	2,2108	-	2,962	-

As it can be seen in Figure 22 and Figure 23 in the feeder study model the non-energized regions are indicated with red color while energized regions are black colored.

In case of a fault either on a main line segment or on a branch, the circuit breaker at the beginning of the feeder is tripped and the whole area remains non-energized (see Figure 22). Since the protection element at the beginning of the feeder is a conventional circuit breaker without reclosing facility, even a transient nature fault causes whole region to remain non-energized.

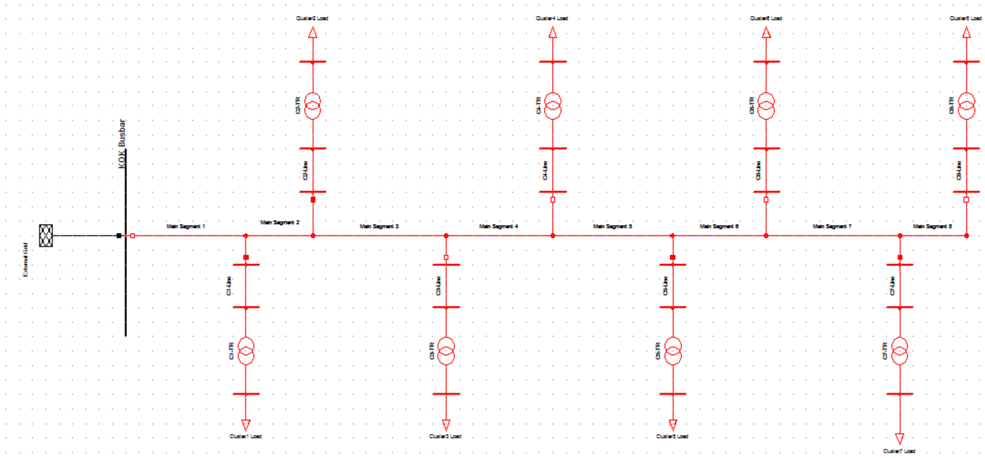

Figure 22 Main line fault or cluster fault case for default configuration

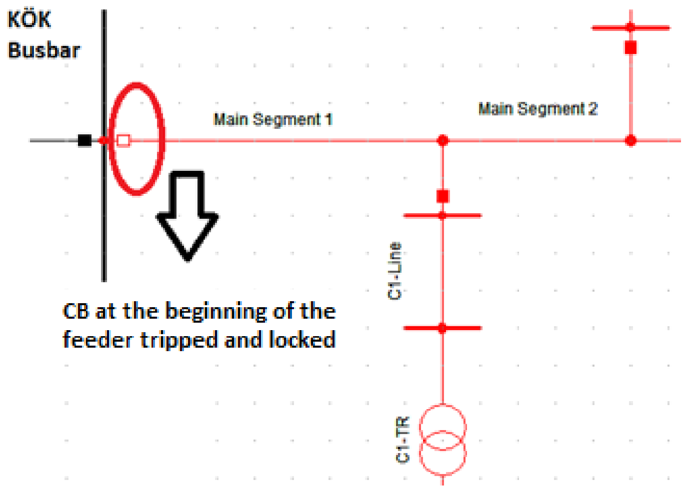

Figure 23 Detailed view of tripped CB at the beginning of the feeder

In case of default configuration the system reliability indices namely SAIDI and SAIFI are calculated as given below in Table 5. As seen from the table successful calculation of the indices is achieved with the tool developed in the scope of thesis study according to results gathered from DigSilent Power Factory analysis tool.

Table 5 Default case reliability analysis results

Conf.	Explanation	DigSilent		Calculated		Difference (%)	
		SAIDI (hours/ year)	SAIFI (failures/ years)	SAIDI (hours/ year)	SAIFI (failures/ years)	SAIDI	SAIFI
Default Configura tion	CB at the beginning of the main line and no sectionalizing switch on the branches	299,232	49,477	299,227	49,477	0,002%	0,000%

3.6.2.2 Configuration with Recloser

In the following simulations the CB at the beginning of the feeder is replaced with a recloser. Since the protection device at the beginning of the feeder now can reclose on a transient fault, conversion of the transient nature faults into sustained outages is prevented. During the calculations it is assumed that 70% of the failures on the overhead power lines are caused by transient nature reasons. When the fault on an overhead power line is caused by a transient nature reason such as tree fall or animal contact, the recloser trips and recloses to the fault several times (3 or 4 times depending on the implementation). The reclosing sequence has to be completed in maximum three minutes because the outages last more than three minutes are considered as sustained and taken into the consideration during the calculations of SAIDI and SAIFI according to the Turkish regulations on continuity of supply [5]. In case of replacing the conventional circuit breaker with recloser, system reliability indices, namely SAIDI and SAIFI, are calculated as given below in Table 6.

Table 6 Reliability improvement with recloser installation

Conf.	Explanation	DigSilent		Calculated		Difference (%)	
		SAIDI (hours/ year)	**SAIFI (failure s/year)**	**SAIDI (hours/ year)**	**SAIFI (failures/ years)**	**SAIDI**	**SAIFI**
Default Case	CB at the beginning of the main line and no sectionalizing switch on the branches	299,232	49,477	299,227	49,477	0,002%	0,000%
Case1	Recloser at the beginning of the main line and no sectionalizing switch on the branches	49,543	25,183	49,540	25,183	0,007%	0,000%

As it can be seen from Table 6 with the replacement of conventional CB at the beginning of the feeder with a recloser, substantial improvement is achieved on the continuity of supply. According to results of the analysis for the typical rural feeder studied in that case the improvement on SAIDI is about 83% and on SAIFI it is 49% compared to default configuration. As a conclusion since its significant effect on continuity of supply, a recloser is placed at the beginning of each rural feeder analyzed in the scope of this thesis study.

3.6.2.3 Configurations with Recloser and Sectionalizing Switches

With the implementation of reclosers at the beginning of the main feeder and sectionalizing switches at the connection points of branches to the main line further improvement on the continuity of supply can be achieved by the isolation of faulted branches in case of sustained faults. In case of a sustained fault on a branch/cluster, with the help of sectionalizing switch the faulted branch can be isolated from rest of the network. Then healthy parts of the network can be energized in a time less than 3 minutes which is the minimum time for an outage to be classified as sustained outage defined by the continuity of supply regulations.

In following figures (Figure 24, Figure 26 and Figure 27) the operation steps of the switching elements (recloser and sectionalizing switches) after the occurrence of a sustained fault on one of the branches are presented by the help of the simulations executed with DigSilent Power Factory analysis tool. The isolation of faulted branch and the power restoration to the healthy parts are presented step by step.

In the first step as seen in Figure 24 when a fault occurs on the third cluster, the recloser at the beginning of the line sees the fault and trips. As it is shown in the figure since the CB at the beginning of the feeder is tripped whole feeder is de-energized and colored in red.

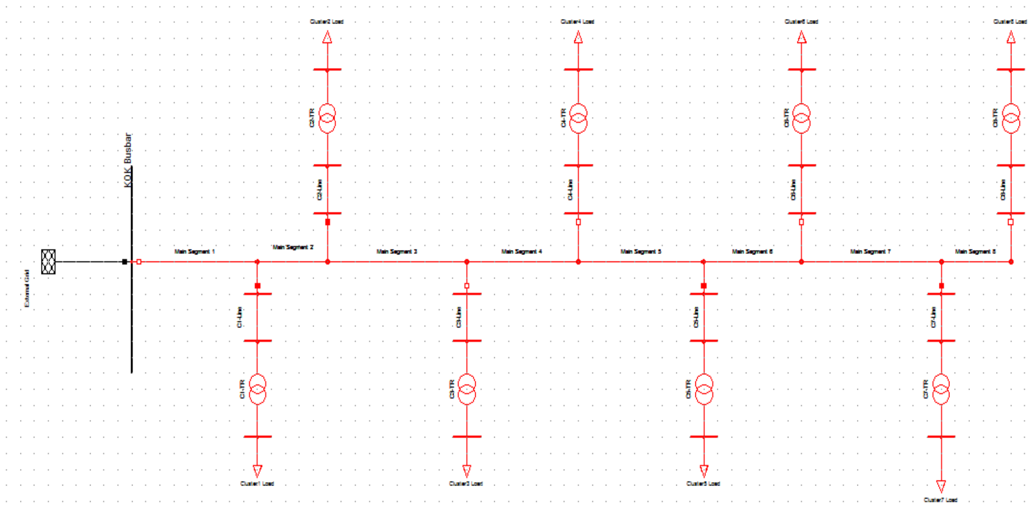

Figure 24 Faulted branch isolation and power restoration - Step 1

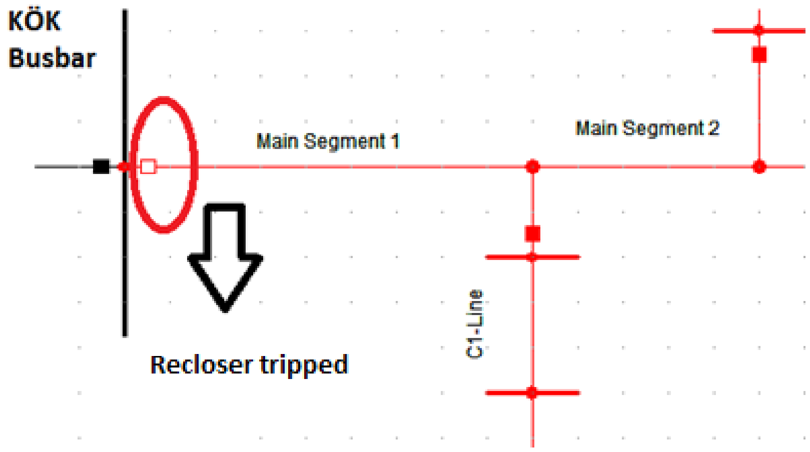

Figure 25 Recloser trip detailed view

In the second step which is illustrated in Figure 26 and Figure 27 after the sequence of reclosing completed and the counter of the sectionalizing switch of the faulted branch reaches to its set value (2 or 3 depending to the implementation), sectionalizing switch opens and locks. Thus the sustained fault on branch three is isolated from the rest of the network by open-locking of the sectionalizing switch.

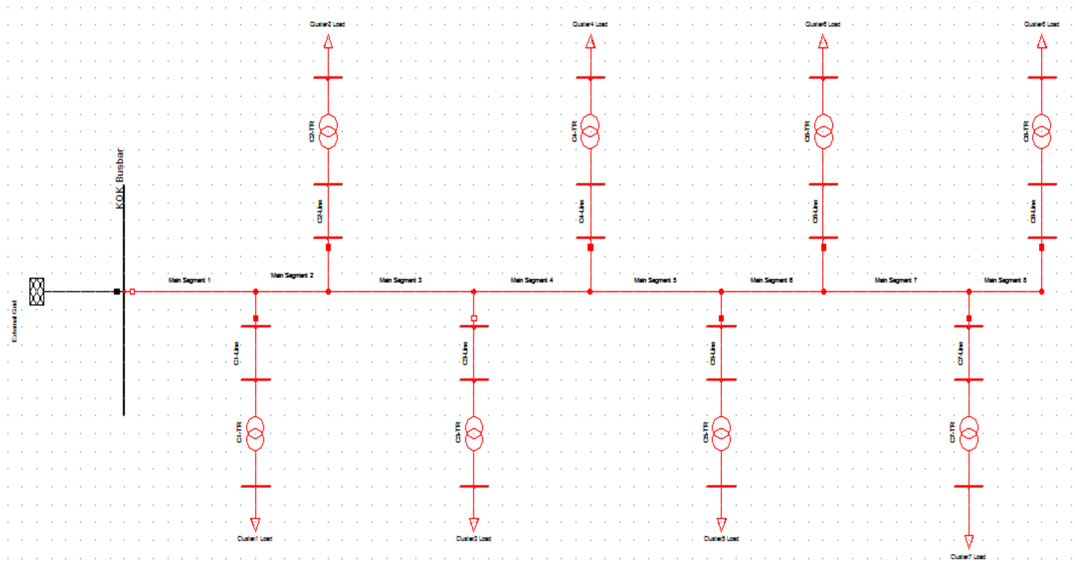

Figure 26 Faulted branch isolation and power restoration - Step 2

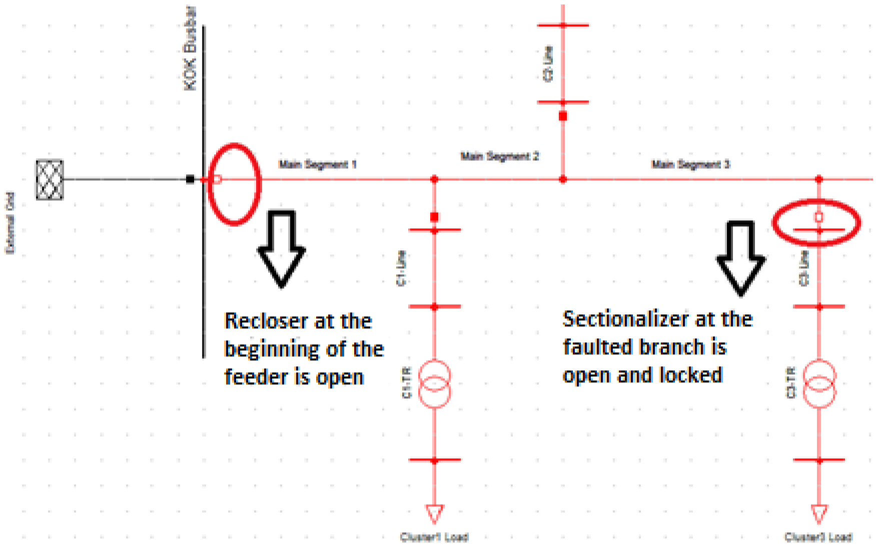

Figure 27 Faulted branch isolation and power restoration - Step 2 detailed view

At the last step, after the isolation of the faulted branch, rest of the network should be reenergized. This is done with the reclosing of the recloser which is shown in Figure 28 and Figure 29. As seen in the Figure 29 only non-energized region is cluster three (faulted branch) and indicated with red color.

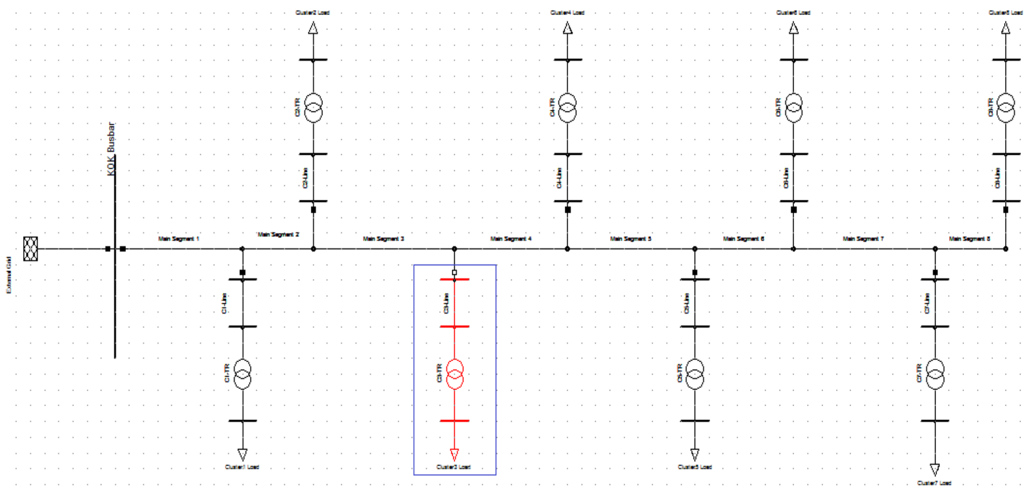

Figure 28 Faulted branch isolation and power restoration - Step 3

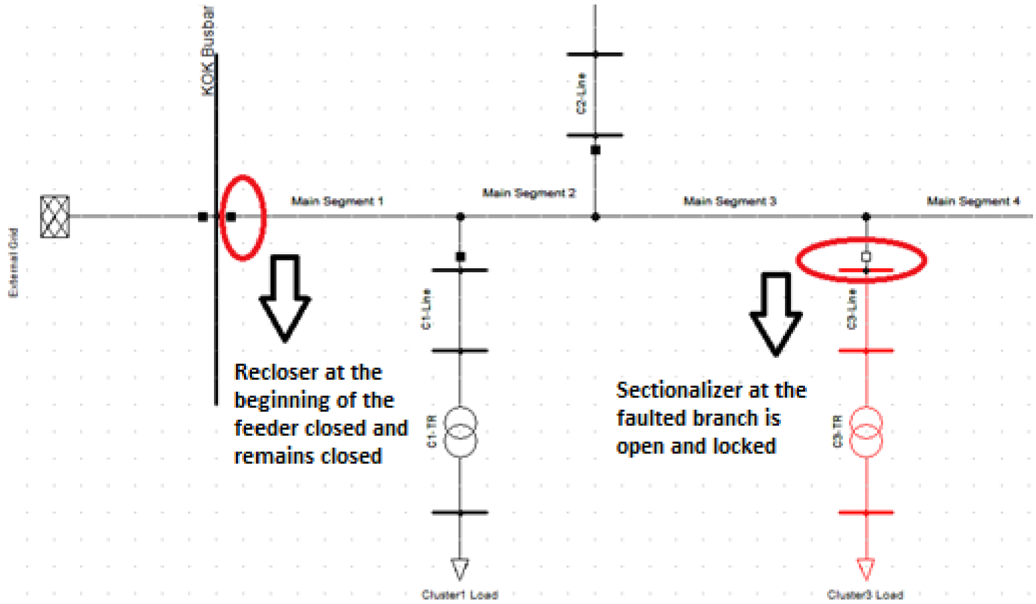

Figure 29 Faulted branch isolation and power restoration - Step 3 detailed view

Table 7 Reliability improvement with sectionalizing switch installation

Conf.	**Explanation**	**SAIDI (hours/cust*year)**	**SAIFI (failures/cust*year)**	**CAIDI (hours/failure)**
Case1	Recloser at the beginning of the main line and no sectionalizing switch on the branches	49,540	25,183	1,967
Case2	Recloser at the beginning of the main line and sectionalizing switches on 3rd, 4th, 6th and 8th branches	43,130	20,493	2,105
Case3	Recloser at the beginning of the main line and sectionalizing switches on 1st, 2nd, 5th and 7th branches	19,887	14,544	1,367
Case4	Recloser at the beginning of the main line and sectionalizing switches on all the branches	13,477	9,854	1,368

Table 7 reveals the positive effect of the reclosers and sectionalizing switches on continuity of supply of the rural networks. The improvements on SAIDI and SAIFI can be realized by the graphs given in Figure 30 and Figure 31.

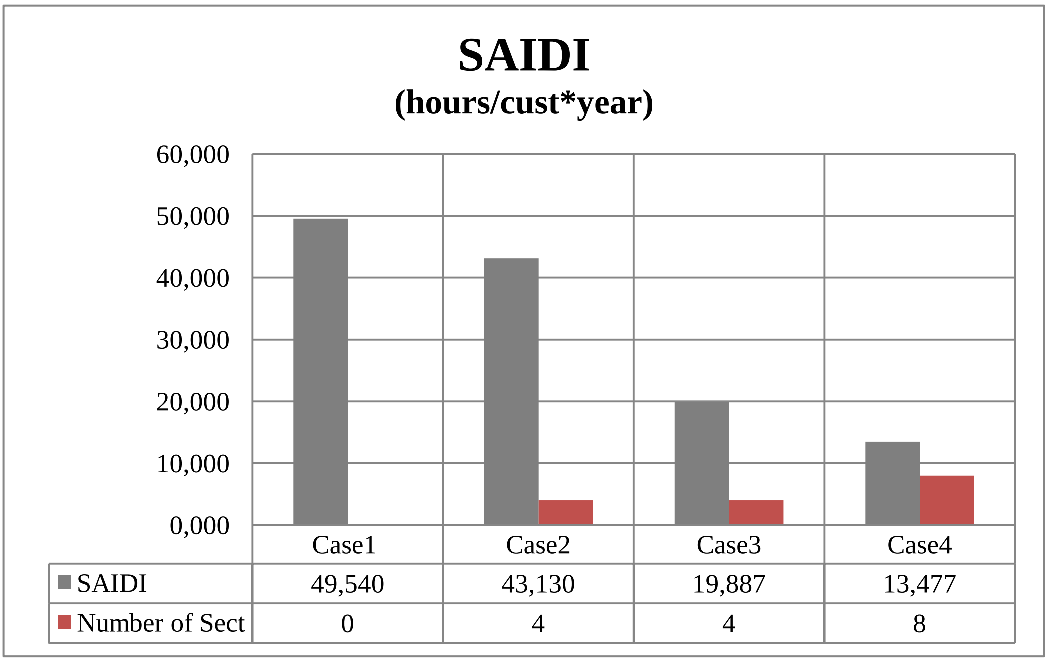

Figure 30 SAIDI improvement with sectionalizing switch installation

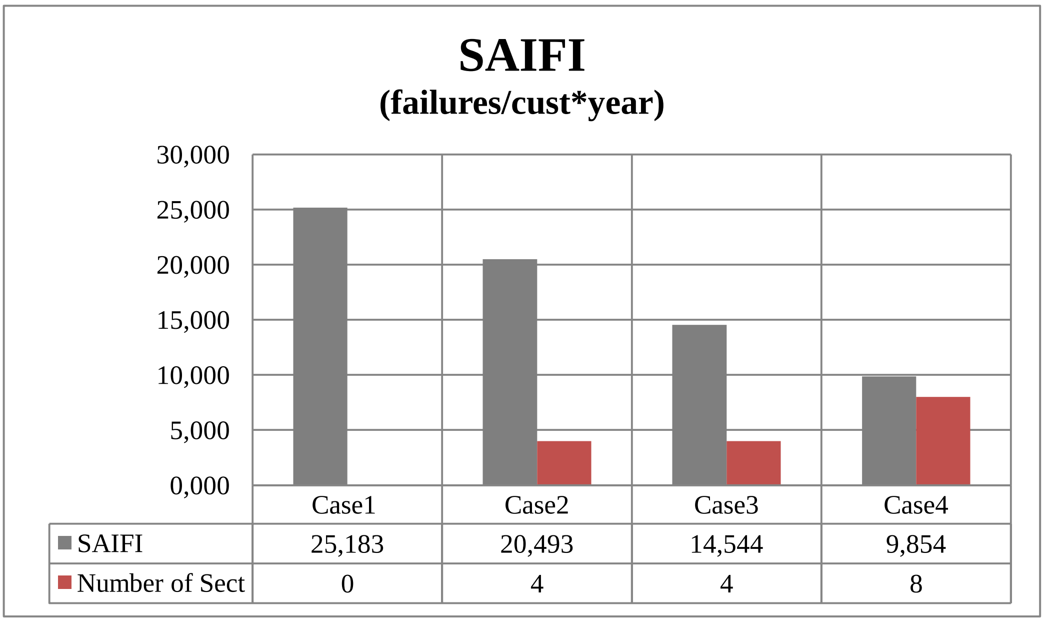

Figure 31 SAIFI improvement with sectionalizing switch installation

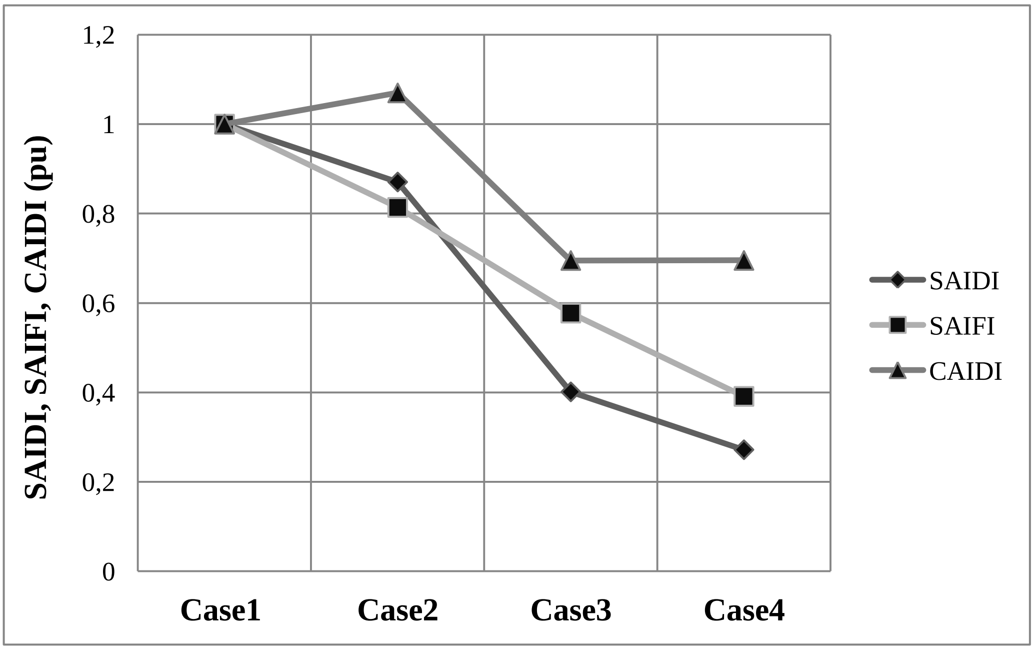

Figure 32 Sectionalizing switch installation effect on SAIDI, SAIFI and CAIDI (pu)

When case 1 and case 3 are compared the substantial enhancement on SAIDI and SAIFI should be noticed. In case 3, the branches 1, 2, 5 and 7 which consist of relatively longer lines and have higher number of distribution transformers (and connected customers) are equipped with a sectionalizing switch at their connection points to the main line. Thus they can be isolated in case of a sustained fault and healthy parts of the feeder are not affected. As seen from the results this brings with substantial improvement on average interruption duration and frequency indices of the system.

In case 2, this time the branches 3, 4, 6 and 8 which consist of relatively shorter lines and have less number of distribution transformers (and connected customers) are equipped with a sectionalizing switch at their connection points to the main line. Although in case 2 equal number of switches are used with case 3, the improvement on average interruption duration and frequency indices of the system, namely SAIDI and SAIFI is not significant.

Moreover as it is seen in case2 (see Figure 32) that a reduction in both SAIDI and SAIFI could still result in an increase in CAIDI which shows that CAIDI is not suitable for trend analysis.

When case 3 and case 4 compared it is realized that there is not a significant difference on the reliability indices. Although all branch points are equipped with sectionalizing switch switches in case 4 which means that 100% of additional switches are installed compared to case 3, the enhancement on the reliability indices is minor.

As a conclusion these results reveal that an optimization is needed to enhance continuity of supply with an optimum number of switches (optimum investment) installed on most applicable locations. This optimization need is the basic motivation of this thesis study.

CHAPTER 4

FORMULATION OF COST FUNCTION

4.1. Introduction

In this chapter, the formulations derived for *Outage Cost (OTC)*, *Utility Cost (UTC)* and *Penalty Cost (PNC)* are presented. First the formulation of the *Outage Cost* due to the outages in the distribution network is explained. Then the *Utility Cost* arisen with the recloser and sectionalizing switch installations is given. Finally the formulation of the *Penalty Cost* that the distribution network operator company is charged in case of exceeding the maximum threshold values defined by the continuity of supply regulations for the total outage duration and outage frequency is presented.

The basic motivation of this thesis study is the optimization of sectionalizing switch allocation for minimum *Total Cost* which is the sum of OTC, UTC and PNC given by equation (20).

$$TC = OTC + UTC + PNC \tag{20}$$

4.2. Outage Cost

As its name refers to *Outage Cost (OTC)* in a distribution network is the incurred cost due to the durations during which the electricity cannot be supplied to the connected customers of the network. The *OTC* for the radial rural feeder topology studied in the scope of this thesis study is formulated as given by equation (21);

$$OTC = \sum_{i=1}^{n} \left[\begin{array}{c} L_{av,i} \left[\begin{array}{l} \left(\sum_{j=1}^{n} \Big(C_i(r_{tr\,j})\, \lambda_{tr\,j} + C_i(r_{\ln j})\, \lambda_{\ln j} \Big)\, x_j \right) \\ + \Big(C_i(r_{tr\,i})\, \lambda_{tr\,i} + C_i(r_{\ln i})\, \lambda_{\ln i} \Big)(1 - x_i) \end{array} \right] \\ + \left(\lambda_{m\ln i} \left(\sum_{j=1}^{n} L_{av,j}\, C_j(r_{m\ln i}) \right) \right) \end{array} \right] \tag{21}$$

where;

n : Total number of clusters (load points) in the feeder

$L_{av,i}$: Average kW load connected to the cluster *i*

$r_{tr\,i}$: Outage duration due to the transformer outage in cluster *i*

$r_{\ln i}$: Outage duration due to the line outage in cluster *i*

$r_{m\ln i}$: Outage duration due to the outage of main line segment *i*

$\lambda_{tr\,i}$: Annual outage frequency of transformers in cluster *i*

$\lambda_{\ln i}$: Annual outage frequency of line in cluster *i*

$\lambda_{m\ln i}$: Annual outage frequency of main line segment *i*

x_i : Sectionalizing switch installation index of cluster *i*

- $x_i = 0$ means a sectionalizing switch is installed at i_{th} cluster,
- $x_i = 1$ means a sectionalizing switch is not installed at i_{th} cluster,

x_j : Sectionalizing switch installation index of cluster *j*

- $x_j = 0$ means a sectionalizing switch is installed at j_{th} cluster
- $x_j = 1$ means a sectionalizing switch is not installed at j_{th} cluster

$C_i(r_{trj})$: *Outage Cost* (TL/kW) of cluster *i* for an outage duration *r* due to the transformer outage of cluster *j*

$C_i(r_{tr\,i})$: *Outage Cost* (TL/kW) of cluster *i* for an outage duration *r* due to the transformer outage of cluster *i*

$C_i(r_{\ln j})$: *Outage Cost* (TL/kW) of cluster *i* for an outage duration *r* due to the line outage of cluster *j*

$C_i(r_{\ln i})$: *Outage Cost* (TL/kW) of cluster *i* for an outage duration *r* due to the line outage of cluster *i*

$C_j(r_{m\ln i})$: *Outage Cost* (TL/kW) of cluster *j* for an outage duration *r* due to failure of main line segment *I*

Interruption cost data compiled from customer surveys can be used to develop a *Sector Customer Damage Function (SCDF)*. The *SCDF* is a function of customer class and outage duration, which can be used to estimate monetary loss incurred by customers due to power outages. The $C_{i\,j}$ in (24) represents the interruption costs of different types of customers, which is utilized for the agricultural and residential customers in this thesis study.

4.2.1. Sector Customer Damage Function

One of the basic technical functions of a modem power system is to satisfy its load and energy requirements at acceptable levels of continuity and quality. The ability of a power system to provide an adequate and secure supply of electrical power at any point in time is usually referred to as the system reliability [1]. Recent developments in the energy market liberalisation have shown additional interest for a more detailed justification of new system facilities and their associated reliability levels. Furthermore, it has become necessary to determine the worth of power supply to the customers with its associated financial value. The ability to assess the power supply reliability has been well established [34] while the ability to assess the worth of reliability needs further study and development of appropriate tools [35].

Actual or perceived costs of customer interruptions can be utilised to determine the worth of electric service reliability. A variety of approaches have been used to investigate these costs [36]. One method which has been used to establish acceptable reliability worth estimates is to survey electrical consumers in order to determine the monetary losses associated with supply interruptions. The data compiled from these surveys leads to the formulation of sector cost functions, which are referred to as the *Sector Customer Damage Functions (SCDF).* The *SCDF* presents the sector interruption costs as a function of the interruption durations. Customer outage statistics clearly show that the distribution functional zone makes the greatest single contribution to customer supply adequacy [37], [38].

As it has been mentioned interruption cost can be identified by different approaches. According to the guidelines of *CEER* (Council of European Energy Regulators) Guidelines [39] recommended methods for interruption cost calculation are given in Table 8.

Table 8 CEER recommendation on use of cost-estimation method

Cost Estimation Methods	**Customer Types**					
	Households	**Commercial Services**	**Public Services**	**Indust**	**Large Cust**	**Infrastructre**
Direct Worth	A	A	A	A		
Contingent Valuation	A		A			
Conjoint Analysis	B					
Preparatory Action Method	(A)					
Preventative Cost Method						
Cost-estimation Method		(A)	(A)	(A)		
Direct Worth in Case Study					A	A
A Alternative A	B Alternative B	() Possible to use				

In Turkey a study for the estimation of interruption cost due to the electric outages has not been carried out yet. Therefore in this thesis study the *SCDF* for two sectors of customers for discrete outage durations given in Figure 33 is used [40]. Using interpolation and extrapolation techniques, the interruption cost per kW for different durations are obtained.

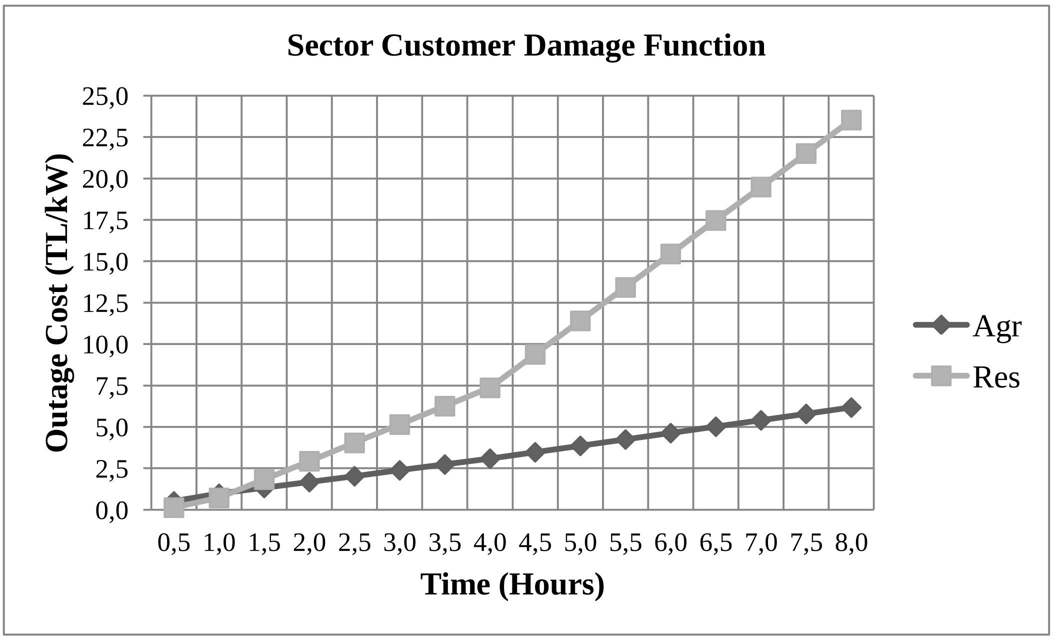

Figure 33 Sector customer damage function

4.3. Utility Cost

In order to reduce the durations and frequencies of outages subjected by the customers, the installation of reclosers at the beginning of main feeders and sectionalizing switches at the optimum locations are recommended in this thesis study. The *Utility Cost (UTC)* consists of *Annual Investment Capital Cost (AICC)* and *Annual Operational Cost (AOPC)* due to the equipment installation and maintenance. It is assumed that the *AOPC* is %5 of *AICC*.

The resultant *UTC* with the installation of required number of reclosers and sectionalizing switches is calculated as given below;

$$\text{UTC} = \text{AICC} + \text{AOPC} \tag{22}$$

where;

$$\text{AICC} = \frac{\text{Net Present Value} \times \text{Loan}}{1 - (1/(1 + \text{Loan}))^{\text{Life Span}}} \tag{23}$$

$$\begin{aligned}\text{Net Present Value} = {} & (\#\text{ of Recloser Installed} \times \text{Recloser Unit Price}) \\ & + (\#\text{ of Sectionalizer Installed} \times \text{Sectionalizer Unit Price})\end{aligned} \tag{24}$$

and;

$$\text{AOPC} = 0{,}05 \times \text{AICC} \tag{25}$$

Currently in the electrical distribution network of Turkey reclosers and sectionalizing switches are not widely used. Therefore a market in Turkey for these equipments has not been shaped yet. For the base case analysis, *Utility Cost* parameters used are as given below;

- Sectionalizing switch Unit Price: 30kTL
- Recloser Unit Price: 40kTL
- Loan: %8
- Sectionalizing switch Life Span: 25 Years
- Recloser Life Span: 25 Years

4.4. Penalty Cost

According to Turkish regulations on continuity of supply, the DSO is charged with a penalty payment in case of exceeding the threshold values set for annual total outage duration or frequency on a feeder. The penalty payment is proportional to amount that exceeds the threshold value set by the regulation [5]. There are different threshold values defined in the continuity of supply regulation for the feeders in urban and rural regions. Penalty payments are calculated both for exceeding the annual outage duration and annual outage frequency on a feeder and electrical distribution system operator company pays the bigger amount of these two penalty payments.

During the calculation of penalty payments, as the threshold values for outage duration and frequency are defined for "feeders" in the continuity of supply regulation of Turkey, in the scope of this thesis study only the outages that cause CB at the beginning of the feeder (recloser) to trip are taken into the consideration.

Duration Penalty Cost (DPC) due to exceeding the annual outage duration limit on a feeder is formulated as given by equation (26);

$$DPC = \left[\sum_{i=1}^{n} \left[\begin{matrix} \left(\left(r_{tr\,i}\, \lambda_{tr\,i} + r_{\ln i}\, \lambda_{\ln i} \right) x_i \right) \\ + \left(r_{m\ln i}\, \lambda_{m\ln i} \right) \end{matrix} \right] - MD_{dur} \right] \times CUENS \times \sum_{i=1}^{n} L_{av,i} \tag{26}$$

where;

n : Total number of clusters (load points) in the feeder

$L_{av,i}$: Average kW load connected to the cluster *i*

$r_{tr\,i}$: Outage duration due to the transformer outage in cluster *i*

$r_{\ln i}$: Outage duration due to the line outage in cluster *i*

$r_{m\ln i}$: Outage duration due to the outage of main line segment *i*

$\lambda_{tr\,i}$: Annual outage frequency of transformers in cluster *i*

$\lambda_{\ln i}$: Annual outage frequency of line in cluster *i*

$\lambda_{m\ln i}$: Annual outage frequency of main line segment *i*

x_i : Sectionalizing switch installation index of cluster *i*

- x_i = 0 means a sectionalizing switch is installed at i_{th} cluster,
- x_i = 1 means a sectionalizing switch is not installed at i_{th} cluster,

CUENS (TL/kW) = Price of unit energy not supplied

MD_{dur} *(hours)* = Threshold value for the annual total outage duration on a feeder

Penalty Cost (FPC) due to exceeding the annual outage frequency limit on a feeder is formulated as given by equation (27);

$$FPC = \left[\begin{array}{l} \left(\sum_{i=1}^{n} \left[\left(\left(\lambda_{tr\,i} + \lambda_{\ln i} \right) x_i \right) + \left(\lambda_{m\ln i} \right) \right] - MD_{freq} \right) \\ + \left(\dfrac{\sum_{i=1}^{n} \left[\left(\left(r_{tr\,i}\, \lambda_{tr\,i} + r_{\ln i}\, \lambda_{\ln i} \right) x_i \right) + \left(r_{m\ln i}\, \lambda_{m\ln i} \right) \right]}{\sum_{i=1}^{n} \left[\left(\left(\lambda_{tr\,i} + \lambda_{\ln i} \right) x_i \right) + \left(\lambda_{m\ln i} \right) \right]} \right) \end{array} \right] \times CUENS \times \sum_{i=1}^{n} L_{av,i} \qquad (27)$$

where;

n : Total number of clusters (load points) in the feeder

$L_{av,i}$: Average kW load connected to the cluster *i*

$\lambda_{tr\,i}$: Annual outage frequency of transformers in cluster *i*

$\lambda_{\ln i}$: Annual outage frequency of line in cluster *i*

$\lambda_{m\ln i}$: Annual outage frequency of main line segment *i*

x_i : Sectionalizing switch installation index of cluster *i*

- x_i = 0 means a sectionalizing switch is installed at i_{th} cluster,
- x_i = 1 means a sectionalizing switch is not installed at i_{th} cluster,

CUENS (TL/kW) = Price of Unit Energy Not Supplied

MD_{freq} = Threshold value for the annual total outage frequency on a feeder

CHAPTER 5

OPTIMAL SECTIONALIZING SWITCH ALLOCATION ALGORTIHM

In this chapter, the algorithms which are implemented in order to find the optimal *Total Cost* are presented. Determination of switch placement configurations which give the optimal *Total Cost* with an enhanced continuity of supply performance is explained with flow charts. Then the results of the optimization algorithm for different scenarios are presented and discussed.

5.1. Introduction

One of the most important duties of an electric distribution system is to provide high quality reliable electricity to customers while serving the demand sufficiently.

As the reliability of electricity supplied increases, investment cost also increases. However, low system reliability causes higher outage frequency and duration which will increase the damage of these outages to customers and also increases cost of the distribution company as a result of the penalty payments. This tradeoff between *Outage Cost* and *Utility Cost* requires consideration of an optimization when determining the optimal reliability level. The general characteristic related with reliability cost is represented in Figure 38 given below.

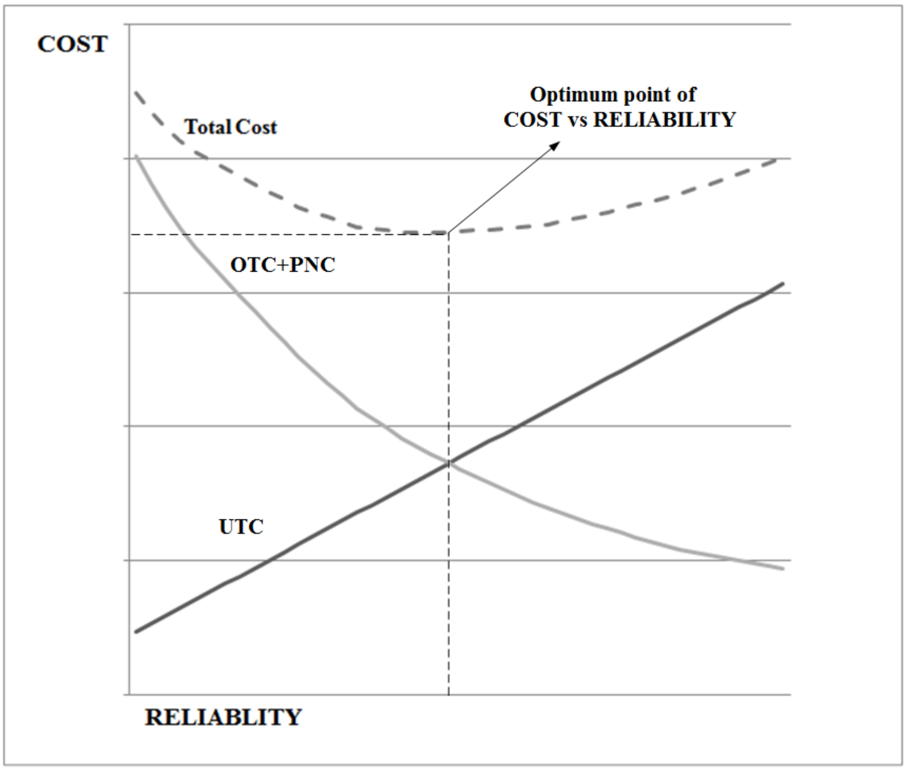

Figure 34 Cost vs reliability structure

As demonstrated in the figure above, *Outage Cost* decreases as the investment cost and reliability level increases. This cost structure results with a U-shaped *Total Cost* curve which can be stated as the equation given by (20).

In rural areas where electrical distribution network consists of long radial overhead lines in arborescent structure, continuity of supply is a major problem due to the high failure rates. The implementation of protection devices having reclosing capability and automated sectionalizing switches enhances the continuity of supply on rural networks substantially. The balance between the cost associated with installation of switches and the reduction on *Outage Cost* is an important optimization issue for distribution network operators.

5.2. Optimization Algorithm

As it has been explained in Chapter 2.4 the rural reliability distribution network for optimization consists of main line segments and several branches tapped off the main. At the beginning of each studied rural feeder a recloser is installed and connection points of branches to the main line are the possible candidate locations for sectionalizing switch installations. The more sectionalizing switches are used in the network, lower is the total outage duration and higher is the system reliability. However, the additional sectionalizing switches might cause a higher *Total Cost* despite a lower outage and penalty cost. The optimal reliability planning of distribution systems considered herein is undertaken to determine the optimum locations and the number of sectionalizing switches in the laterals so that the *Total Cost*, i.e., the summation of *Utility Cost*, *Outage Cost* and *Penalty Cost* can be minimized.

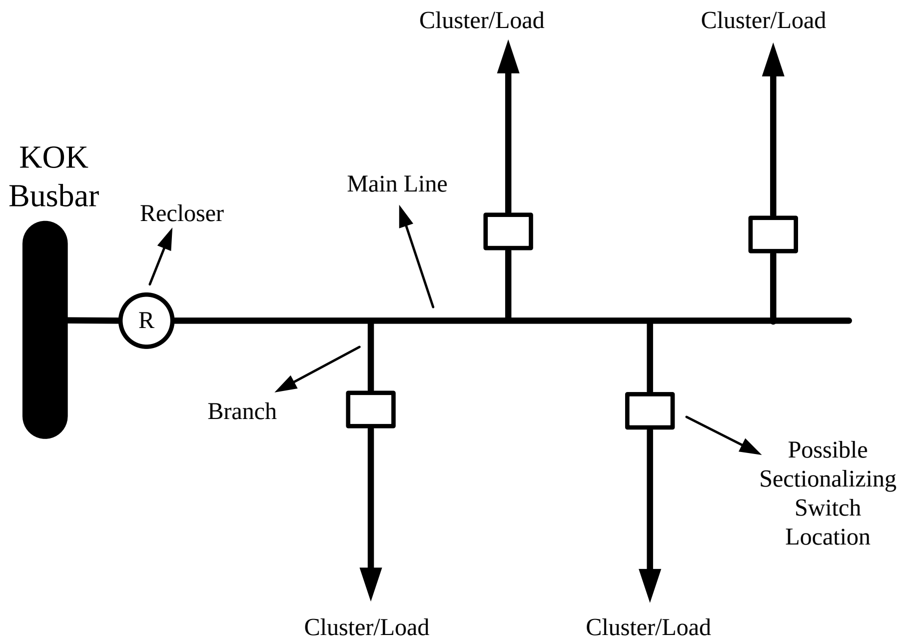

Figure 35 Reliability model for optimization

In the optimum allocation problem, a recloser is installed at the beginning of each rural feeder and the solution space consists of possible locations for sectionalizing switches installations. They are encoded as bitmaps before optimization is performed. The network is divided into several main line segments and branches (see Figure 35). Each connection point of braches to the main line segment is represented by 1 bit whose meaning is as given below.

$x_i = 0$: A sectionalizing switch installed at the i_{th} branch connection to the main line

$x_i = 1$: No sectionalizing switch installed at the i_{th} branch connection to the main line

5.2.1. Exhaustive Solution Method

In exhaustive solution method the outage, penalty and utility costs are calculated for all the possible sectionalizing switch allocation configurations of the network during optimization and then the results are sorted. Moreover, for each allocation configuration the reliability indices (SAIDI, SAIFI and CAIDI) are calculated too. The algorithm makes the cost calculations by following the steps given below;

Step 1: Gather network data.

Step 2: Evaluate the reliability parameters $r_{m\ln i}$ and $\lambda_{m\ln i}$ of load point *j* contributed by main line segment outage element *i*.

Step 3: Calculate customer interruption cost $L_{av,j}\, C_j(r_{m\ln i})$ of load point *j* due to outage of main line element *i* according to SCDF.

Step 4: Repeat Step 2 and Step 3 for all load points in order to calculate $\lambda_{m\ln i}\left(\sum_{j=1}^{n} L_{av,j}\, C_j\,(r_{m\ln i})\right)$ which is main line segment outage element i effect on load points.

Step 5: Repeat Step 2 to Step 4 for all main line outage segment elements in order to calculate;

$$OTC_{mainline} = \sum_{i=1}^{n}\left[\lambda_{m\ln i}\left(\sum_{j=1}^{n} L_{av,j}\, C_j\,(r_{m\ln i})\right)\right] \tag{28}$$

which is main line segment outage elements effect for all load points.

Step 6: Create the sectionalizing switch allocation configuration vector,

Step 7: Evaluate the reliability parameters $r_{tr\,j}$, $\lambda_{tr\,j}$ and $\lambda_{\ln j}$, $r_{\ln j}$ of load point i contributed by TR outage element j and line outage element j. The outage duration $r_{tr\,j}$ and $r_{\ln j}$ of load point i depends on its relative location to the outage elements j and the sectionalizing switch allocation at the cluster where outage elements j are belonged.

Step 8: Calculate customer interruption cost $C_i(r_{tr\,j})\,\lambda_{tr\,j} + C_i(r_{\ln j})\,\lambda_{\ln j}$ of load point i due to outages of elements j.

Step 9: Repeat Step 7 and Step 8 to calculate $L_{av,i}\left(\sum_{j=1}^{n}\Big(C_i(r_{tr\,j})\,\lambda_{tr\,j} + C_i(r_{\ln j})\,\lambda_{\ln j}\Big)\,x_j\right)$ of load point i for all outage elements.

Step 10: Evaluate the reliability indices $r_{tr\,i}$, $\lambda_{\ln i}$, $r_{\ln i}$, $\lambda_{tr\,i}$ of load point i contributed by TR outage element i and line outage element i.

Step 11: Calculate customer interruption cost $C_i(r_{tr\,i})\,\lambda_{tr\,i} + C_i(r_{\ln i})\,\lambda_{\ln i}$ of load point i due to outages of elements i.

Step 12: Repeat Step 7 to Step 11 for all load points to calculate

$$OTC_{cluster} = \sum_{i=1}^{n}\left[L_{av,i}\left[\begin{array}{l}\left(\sum_{j=1}^{n}\Big(C_i(r_{tr\,j})\,\lambda_{tr\,j} + C_i(r_{\ln j})\,\lambda_{\ln j}\Big)x_j\right)\\ +\Big(C_i(r_{tr\,i})\,\lambda_{tr\,i} + C_i(r_{\ln i})\,\lambda_{\ln i}\Big)(1-x_i)\end{array}\right]\right] \tag{29}$$

which is the cluster elements outage effect for all load points.

Step 13: Calculate

$$OTC = OTC_{mainline} + OTC_{cluster} \tag{30}$$

which is the total *Outage Cost* due to the cluster and mainline segment elements failures.

Step 14: Evaluate the reliability parameters $(r_{tr\,i}\,\lambda_{tr\,i} + r_{\ln i}\,\lambda_{\ln i})$ of load point *i* contributed by TR cluster element *i* and line cluster element *i*.

Step 15: Evaluate the reliability parameters $(r_{m\ln i}\,\lambda_{m\ln i})$ of load point *i* contributed by main line outage element *i*.

Step 16: Repeat Step 14 and Step 15 for all load points to calculate;

$$DPC = \left[\sum_{i=1}^{n} \begin{bmatrix} \left(\left(r_{tr\,i}\,\lambda_{tr\,i} + r_{\ln i}\,\lambda_{\ln i} \right) x_i \right) \\ + \left(r_{m\ln i}\,\lambda_{m\ln i} \right) \end{bmatrix} - MD_{dur} \right] \times CUENS \times \sum_{i=1}^{n} L_{av,i} \tag{31}$$

which is the *Duration Penalty Cost* due to the cluster and main line segment elements failure outages.

Step 17: Evaluate the reliability parameters $(\lambda_{tr\,i} + \lambda_{\ln i})$ of load point *i* contributed by TR outage element *i* and line outage element *i*.

Step 18: Evaluate the reliability parameter $\lambda_{m\ln i}$ contributed by main line outage element *i*.

Step 19: Repeat Step 17 and Step 18 for all load points to calculate;

$$FPC = \left[\begin{array}{l} \left(\sum_{i=1}^{n} \left[\left(\left(\lambda_{tr\,i} + \lambda_{\ln i} \right) x_i \right) + \left(\lambda_{m \ln i} \right) \right] - MD_{freq} \right) \\ \times \left(\dfrac{\sum_{i=1}^{n} \left[\left(\left(r_{tr\,i}\, \lambda_{tr\,i} + r_{\ln i}\, \lambda_{\ln i} \right) x_i \right) + \left(r_{m \ln i}\, \lambda_{m \ln i} \right) \right]}{\sum_{i=1}^{n} \left[\left(\left(\lambda_{tr\,i} + \lambda_{\ln i} \right) x_i \right) + \left(\lambda_{m \ln i} \right) \right]} \right) \end{array} \right] \times CUENS \times \sum_{i=1}^{n} L_{av,i} \tag{32}$$

which is the *Frequency Penalty Cost* due to the cluster and main line segment elements failure outages.

Step 20: Calculate *Penalty Cost* (PNC);

If $FPC > DPC \Rightarrow PNC = FPC$

If $DPC > FPC \Rightarrow PNC = DPC$

Step 21: Calculate *Utility Cost* (UTC) by using the total number of switches allocated in the configuration.

Step 22: Calculate *Total Cost*;

$$\mathrm{Total\,Cost} = \mathrm{OTC} + \mathrm{UTC} + \mathrm{PNC} \tag{33}$$

Step 23: Repeat step 5 to 22 for all the possible sectionalizing switch installation configuration vectors.

Step 24: If all the combinations of sectionalizing switch allocation configurations are solved, sort the results from highest *Total Cost* to lowest *Total Cost*.

The flow chart of the algorithm implemented for exhaustive solution of the *Total Cost* minimization with optimum allocation of sectionalizing switches problem is given in Figure 36. In Figure 37 the flow chart for the calculation of the reliability indices with exhaustive algorithm is illustrated.

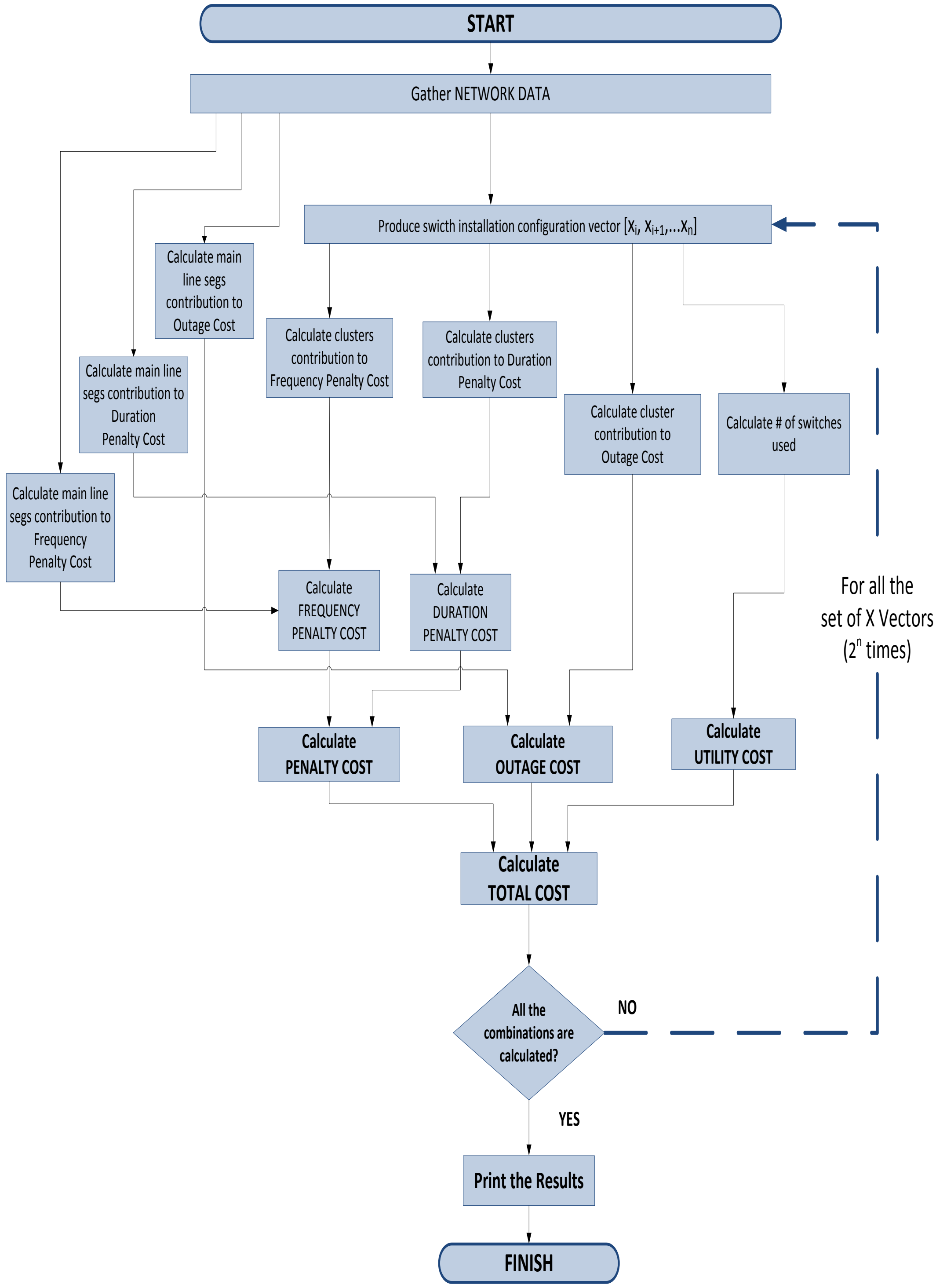

Figure 36 Exhaustive solution algorithm for total cost minimization

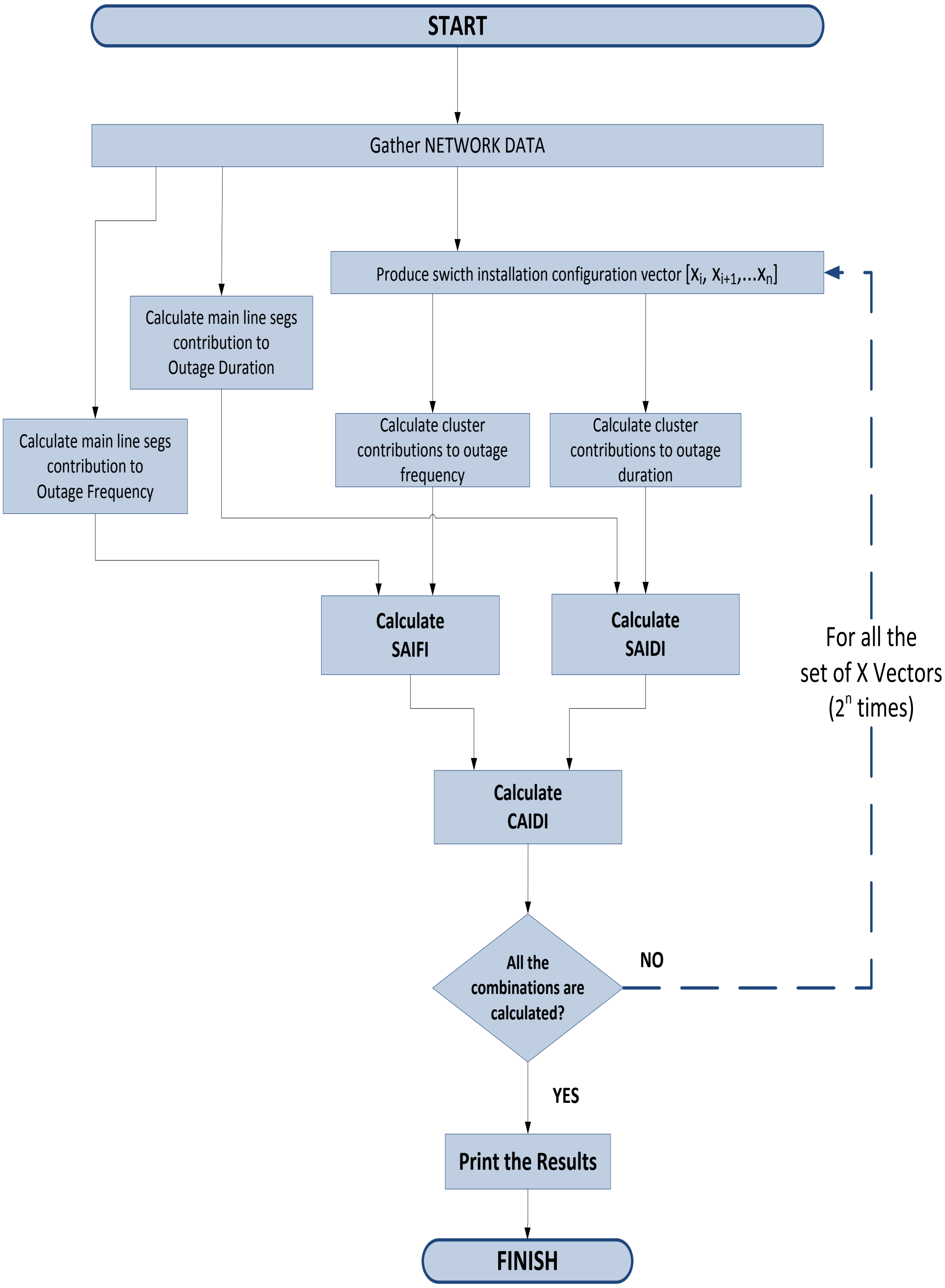

Figure 37 Reliability index calculation with exhaustive solution algorithm

5.2.2. Optimized Solution Method

In exhaustive method all the combinations of switch allocation configurations are solved in order to find the optimal sectionalizing switch allocation configuration which gives the minimum *Total Cost*. However when the number of possible locations for the sectionalizing switches increases, it becomes impossible to solve all the combinations of the allocation configurations because of the volume of the solution space. In exhaustive solution method when the number of possible locations for sectionalizing switch locations is n, the solution space consists of 2^n possible allocation configuration vectors.

Although the number of clusters/branch connection points (possible sectionalizing switch installation locations) on a characteristic rural distribution feeder in Turkey does not exceed 10, when the optimum allocation problem for a KÖK which consists of more than one feeder is considered, exhaustive method might not handle the volume of the solution space. For example for a KÖK which consists of 6 feeders and 45 clusters, number of possible sectionalizing switch installation configurations is 2^{45} which means that clever algorithm which reduces the volume of the solution space to find the optimum allocation configuration is needed.

In different optimal switch allocation problem studies several optimization methods such as genetic algorithm [41], [42], [43], immune algorithm [44], simulated annealing [45], Bellman's optimality principle [46] are implemented to handle the big solution space where the number of possible installation locations is higher. In the scope of this thesis study an algorithm is developed by use of Microsoft Visual Basic 6.5 in order to find the optimal sectionalizing switch allocation configuration for the electrical distribution network with many possible locations for sectionalizing switch installation.

In optimized solution method the algorithm first calculates the contribution of each cluster to the *Outage Cost* and sorts the clusters according to their contribution from most effective one to the least effective. Then the switch allocation configuration vectors are produced by using that sorted set. For n possible locations only n allocation vectors are produced and total number of calculations is reduced from 2^n to $2n$ (including the calculations for sorting the cluster with respect to their effect to cost function). In optimized algorithm, the optimal sectionalizing switch allocation configuration which gives the minimum *Total Cost* is determined by the following steps;

Step 1: Gather network data.

Step 2: Evaluate the reliability parameters $r_{m\ln i}$ and $\lambda_{m\ln i}$ of load point j contributed by main line segment outage element i.

Step 3: Calculate customer interruption cost $L_{av,j}\, C_j(r_{m\ln i})$ of load point j due to outage of main line element i according to *SCDF*.

Step 4: Repeat Step 2 and Step 3 for all load points in order to calculate $\lambda_{m\ln i}\left(\sum_{j=1}^{n} L_{av,j}\, C_j(r_{m\ln i})\right)$ which is main line segment outage element i affect on load points.

Step 5: Repeat Step 2 to Step 4 for all main line outage segment elements in order to calculate;

$$OTC_{mainline} = \sum_{i=1}^{n}\left[\lambda_{m\ln i}\left(\sum_{j=1}^{n} L_{av,j}\, C_j(r_{m\ln i})\right)\right] \tag{34}$$

which is the main line segment outage elements effect for all load points.

Step 6: Calculate each clusters' effect on *Outage Cost*.

Step 7: Sort the clusters with respect to their effect on the *Outage Cost*.

Step 8: Create the sectionalizing switch allocation configuration vector by using the sorted set.

Step 9: Evaluate the reliability parameters $r_{tr\,j}$, $\lambda_{tr\,j}$ and $\lambda_{\ln j}$, $r_{\ln j}$ of load point *i* contributed by TR outage element *j* and line outage element j. The outage duration $r_{tr\,j}$ and $r_{\ln j}$ of load point *i* depends on its relative location to the outage elements *j* and the sectionalizing switch allocation at the cluster where outage elements *j* are belonged.

Step 10: Calculate customer interruption cost $C_i(r_{tr\,j})\,\lambda_{tr\,j} + C_i(r_{\ln j})\,\lambda_{\ln j}$ of load point *i* due to outages of elements *j*.

Step 11: Repeat Step 9 and Step 10 to calculate $L_{av,i}\left(\sum_{j=1}^{n}\left(C_i(r_{tr\,j})\lambda_{tr\,j} + C_i(r_{\ln j})\lambda_{\ln j}\right)x_j\right)$ of load point *i* for all outage elements.

Step 12: Evaluate the reliability indices $r_{tr\,i}$, $\lambda_{\ln i}$, $r_{\ln i}$ and $\lambda_{tr\,i}$ of load point *i* contributed by TR outage element *i* and line outage element *i*.

Step 13: Calculate customer interruption cost $C_i(r_{tr\,i})\lambda_{tr\,i} + C_i(r_{\ln i})\lambda_{\ln i}$ of load point *i* due to outages of elements *i*.

Step 14: Repeat Step 9 to Step 13 for all load points to calculate

$$OTC_{cluster} = \sum_{i=1}^{n} \left[L_{av,i} \left[\begin{array}{l} \left(\sum_{j=1}^{n} \left(C_i (r_{tr\,j}) \lambda_{tr\,j} + C_i (r_{\ln j}) \lambda_{\ln j} \right) x_j \right) \\ + \left(C_i (r_{tr\,i}) \lambda_{tr\,i} + C_i (r_{\ln i}) \lambda_{\ln i} \right) (1 - x_i) \end{array} \right] \right] \tag{35}$$

which is the cluster elements outage effect for all load points.

Step 15: Calculate

$$OTC = OTC_{mainline} + OTC_{cluster} \tag{36}$$

which is the total *Outage Cost* due to the cluster and mainline segment elements failures.

Step 16: Evaluate the reliability parameters $(r_{tr\,i}\, \lambda_{tr\,i} + r_{\ln i}\, \lambda_{\ln i})$ of load point *i* contributed by TR cluster element *i* and line cluster element *i*.

Step 17: Evaluate the reliability parameters $(r_{m\ln i}\, \lambda_{m\ln i})$ of load point *i* contributed by main line outage element *i.*

Step 18: Repeat Step 16 and Step 17 for all load points to calculate;

$$DPC = \left[\sum_{i=1}^{n} \left[\begin{array}{l} \left(\left(r_{tr\,i}\, \lambda_{tr\,i} + r_{\ln i}\, \lambda_{\ln i} \right) x_i \right) \\ + \left(r_{m\ln i}\, \lambda_{m\ln i} \right) \end{array} \right] - MD_{dur} \right] \times CUENS \times \sum_{i=1}^{n} L_{av,i} \tag{37}$$

which is the *Duration Penalty Cost* due to the cluster and main line segment elements failure outages.

Step 19: Evaluate the reliability parameters $(\lambda_{tr\,i} + \lambda_{\ln i})$ of load point i contributed by TR outage element i and line outage element i.

Step 20: Evaluate the reliability parameter $\lambda_{m\ln i}$ contributed by main line outage element i.

Step 21: Repeat Step 19 and Step 20 for all load points to calculate;

$$FPC = \left[\begin{array}{l} \left(\sum_{i=1}^{n} \left[\left(\left(\lambda_{tr\,i} + \lambda_{\ln i} \right) x_i \right) + \left(\lambda_{m\ln i} \right) \right] - MD_{freq} \right) \\ \times \left(\dfrac{\sum_{i=1}^{n} \left[\left(\left(r_{tr\,i}\,\lambda_{tr\,i} + r_{\ln i}\,\lambda_{\ln i} \right) x_i \right) + \left(r_{m\ln i}\,\lambda_{m\ln i} \right) \right]}{\sum_{i=1}^{n} \left[\left(\left(\lambda_{tr\,i} + \lambda_{\ln i} \right) x_i \right) + \left(\lambda_{m\ln i} \right) \right]} \right) \end{array} \right] \times CUENS \times \sum_{i=1}^{n} L_{av,i} \tag{38}$$

which is the *Frequency Penalty Cost* due to the cluster and main line segment elements failure outages.

Step 22: Calculate *Penalty Cost* (PNC);

$$FPC > DPC \Rightarrow PC = FPC$$
$$DPC > FPC \Rightarrow PC = DPC$$

Step 23: Calculate *Utility Cost* (UTC) by using the total number of switches allocated in the configuration.

Step 24: Calculate *Total Cost*;

$$\mathrm{Total\,Cost} = \mathrm{OTC} + \mathrm{UTC} + \mathrm{PNC} \tag{39}$$

Step 25: Repeat step 7 to 24 for all the sorted sectionalizing switch installation configuration vectors.

The flow chart of the optimized algorithm implemented is given in Figure 38.

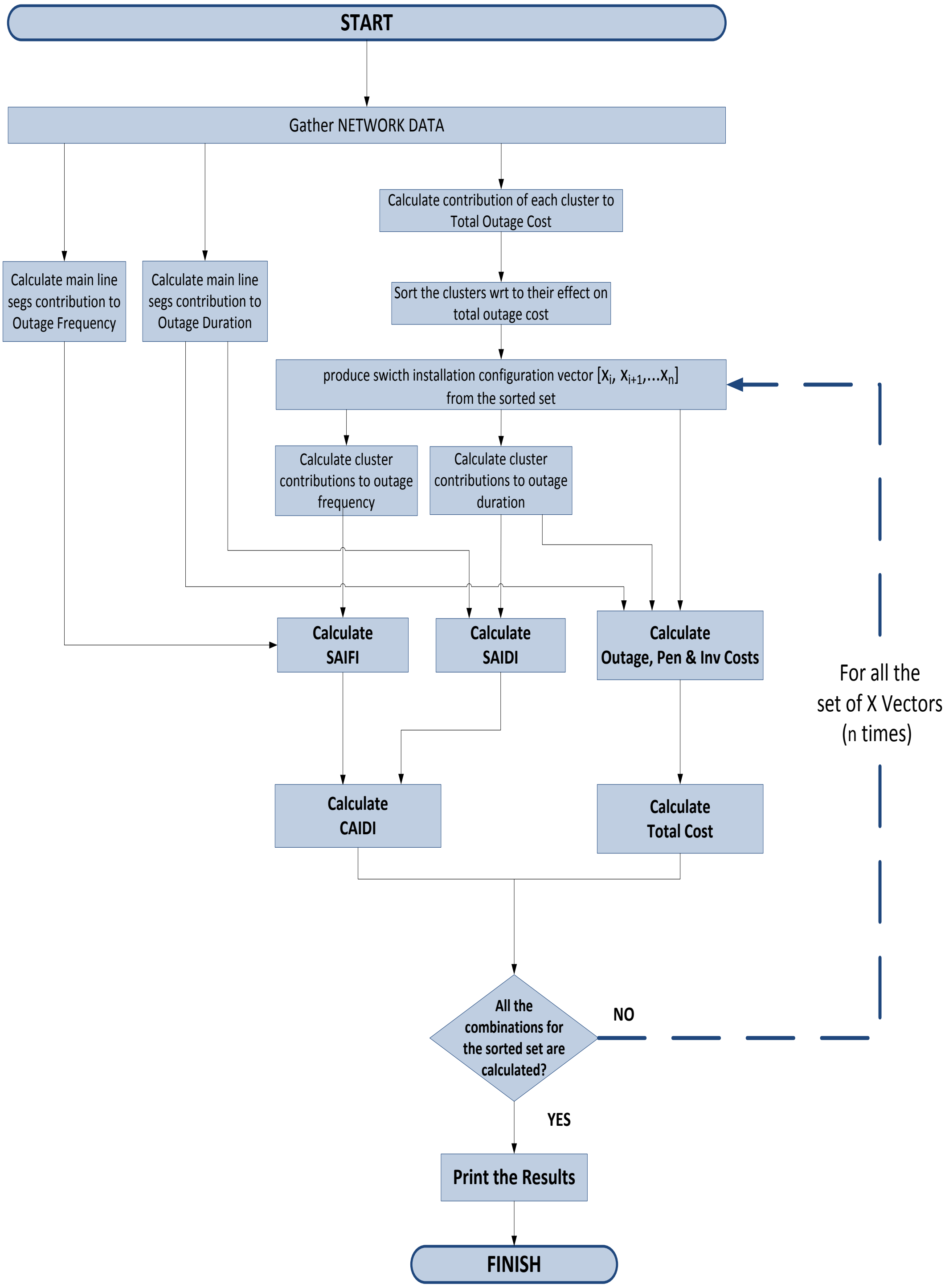

Figure 38 Optimized solution algorithm for total cost optimization

5.3. Verification of Optimized Algorithm Reliability

In this chapter by comparing the results generated by optimized algorithm with the results of exhaustive solution algorithm, the reliability of the optimized algorithm is verified. During the analysis a characteristic single rural feeder with ten clusters is studied.

The annual failure and outage duration parameters of the network elements used during the analysis are as is given in Table 9.

Table 9 Failure duration and frequency parameters

λline outage frequency (fail/year*km)	**λtr outage frequency (fail/year)**	**rline outage duration (hours/km)**	**rtr outage duration (hours)**
0,1231	0,0144	0,4019	8

For the calculation of the *Outage Cost* the *SCDF* given in Figure 33 is used.

Parameters used for the *Utility Cost* calculation is as given below;

- Sectionalizing switch Unit Price: 30kTL
- Recloser Unit Price: 40kTL
- Loan: %8
- Sectionalizing switch Life Span: 25 Years
- Recloser Life Span: 25 Years

And parameters used for the *Penalty Cost* calculation is as given below;

- Outage Duration Penalty Threshold: 96 hours
- Outage Frequency Penalty Threshold: 72

The feeder input data is as given in Table 10.

Table 10 Feeder input data

Name	**Length (km)**	**# of TR**	**Load Type**	**Load (kW)**	**Number of Connected Customers**
Cluster1	10,0	10	Res	64,00	400
Cluster2	1,0	1	Res	6,40	40
Cluster3	1,0	1	Res	6,40	40
Cluster4	17,0	15	Res	96,00	600
Cluster5	18,0	18	Res	115,20	720
Cluster6	3,0	2	Res	12,80	80
Cluster7	1,0	1	Res	6,40	40
Cluster8	0,5	15	Res	96,00	600
Cluster9	13,0	2	Res	12,80	80
Cluster10	12,0	14	Res	89,60	560
Mainline Seg1	2,0	-	-	-	-
Mainline Seg2	2,0	-	-	-	-
Mainline Seg3	2,0	-	-	-	-
Mainline Seg4	2,0	-	-	-	-
Mainline Seg5	2,0	-	-	-	-
Mainline Seg6	2,0	-	-	-	-
Mainline Seg7	2,0	-	-	-	-
Mainline Seg8	2,0	-	-	-	-
Mainline Seg9	2,0	-	-	-	-
Mainline Seg10	2,0	-	-	-	-

As it has been explained in Chapter 0, exhaustive algorithm calculates the cost terms for all the switch allocation configuration combinations. The results presented in Table 11 are the switch allocation combinations generated by the exhaustive solution algorithm which give the minimum *Total Cost* for 0 to 10 sectionalizing switch installations.

Table 11 Exhaustive algorithm results

Exhaustive Method Algorithm Results								
# of Sect Used	**Sectionalizing Switch Installation Locations**	**UTC (TL)**	**OTC (TL)**	**PNC (TL)**	**TC (TL)**	**SAIDI (hours)**	**SAIFI**	**CAIDI (hours)**
0	-	3.934	89.909	0	93.844	62,44	13,02	4,79
1	C5	6.885	68.917	0	75.802	48,46	11,11	4,36
2	C5, C4	9.836	48.393	0	58.229	35,48	9,23	3,84
3	C5, C4, C9	12.787	37.466	0	50.253	27,11	7,65	3,54
4	C5, C4, C9, C10	15.738	27.237	0	42.975	19,92	6,27	3,18
5	C5, C4, C9, C10, C1	18.688	20.635	0	39.324	14,59	5,06	2,88
6	C5, C4, C9, C10, C1,C8	21.639	18.550	0	40.189	13,18	4,84	2,72
7	C5, C4, C9, C10, C1,C8, C6	24.590	17.882	0	42.473	12,52	4,45	2,81
8	C5, C4, C9, C10, C1,C8, C6, C7	27.541	17.669	0	45.210	12,36	4,32	2,86
9	C5, C4, C9, C10, C1,C8, C6, C7, C3	30.492	17.455	0	47.948	12,20	4,19	2,912
10	C5, C4, C9, C10, C1,C8, C6, C7, C3, C2	33.443	17.242	0	50.685	12,03	4,04	2,98

And in Table 12 the results of the optimized algorithm is presented. When the results in Table 12 (optimized algorithm results) are compared with the results generated by the exhaustive algorithm, it is seen that optimized algorithm determines the optimal sectionalizing switch allocation configurations succesfully. Therefore the reliability of the optimized algoritm is asserted.

Table 12 Optimized algorithm results

Exhaustive Method Algorithm Results								
# of Sect Used	**Sectionalizing Switch Installation Locations**	**UTC (TL)**	**OTC (TL)**	**PNC (TL)**	**TC (TL)**	**SAIDI (hours)**	**SAIFI**	**CAIDI (hours)**
0	-	3.934	89.909	0	93.844	62,44	13,02	4,79
1	C5	6.885	68.917	0	75.802	48,46	11,11	4,36
2	C5, C4	9.836	48.393	0	58.229	35,48	9,23	3,84
3	C5, C4, C9	12.787	37.466	0	50.253	27,11	7,65	3,54
4	C5, C4, C9, C10	15.738	27.237	0	42.975	19,92	6,27	3,18
5	C5, C4, C9, C10, C1	18.688	20.635	0	39.324	14,59	5,06	2,88
6	C5, C4, C9, C10, C1,C8	21.639	18.550	0	40.189	13,18	4,84	2,72
7	C5, C4, C9, C10, C1,C8, C6	24.590	17.882	0	42.473	12,52	4,45	2,81
8	C5, C4, C9, C10, C1,C8, C6, C7	27.541	17.669	0	45.210	12,36	4,32	2,86
9	C5, C4, C9, C10, C1,C8, C6, C7, C3	30.492	17.455	0	47.948	12,20	4,19	2,912
10	C5, C4, C9, C10, C1,C8, C6, C7, C3, C2	33.443	17.242	0	50.685	12,03	4,04	2,98

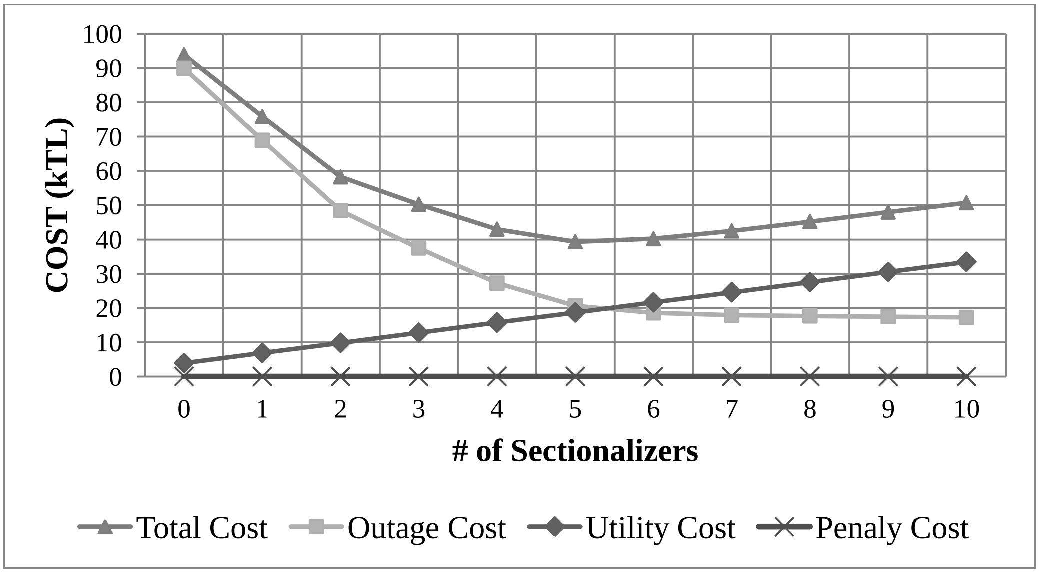

Figure 39 Results generated by exhaustive and optimized algorithms

In this example a ten clusters feeder is analyzed and optimization results are graphically represented in Figure 39. Looking through the results, it is seen that the minimum *Total Cost* (39.327TL) is achieved with the five sectionalizing switch installations among ten possible installation locations. In the optimum allocation configuration sectionalizing switches are installed at the C5, C4, C9, C10 and C1 clusters respectively. The ordering of the clusters are also according to their effect on the *Total Cost*. The *Utility Cost* is 18.688TL and the *Outage Cost* is 20.635TL for the minimum *Total Cost* sectionalizing switch allocation configuration Calculated SAIDI, SAIFI and CAIDI values for that configuration are 14,595, 5,065 and 2,881 respectively.

As expected minimum *Outage Cost* is achieved when all the clusters are equipped with a sectionalizing switch at their branch connection points which also gives the highest *Utility Cost*. The SAIDI, SAIFI and CAIDI are 12,038, 4,045 and 2,976 respectively.

5.4. Numerical Analysis

In this chapter optimized algorithm results are presented for a KÖK which consists of 6 feeders and 45 clusters in total. Different scenarios are analyzed and the results are evaluated. The input data of the network is as given in APPENDIX B (see Table 48)

5.4.1. Base Case

The annual failure and outage duration parameters of the KÖK analyzed in base case used during the analysis are as is given in Table 13. The input data and parameters given for the base case represent a characteristic KÖK implemented in the rural regions of Turkey.

Table 13 Failure duration and frequency parameters

λline outage frequency (fail/year*km)	**λtr outage frequency (fail/year)**	**rline outage duration (hours/km)**	**rtr outage duration (hours)**
0,1231	0,0144	0,4019	8

During the calculation of the *Outage Cost* the *SCDF* (Sector Customer Damage Function) which is given in Figure 40 is used.

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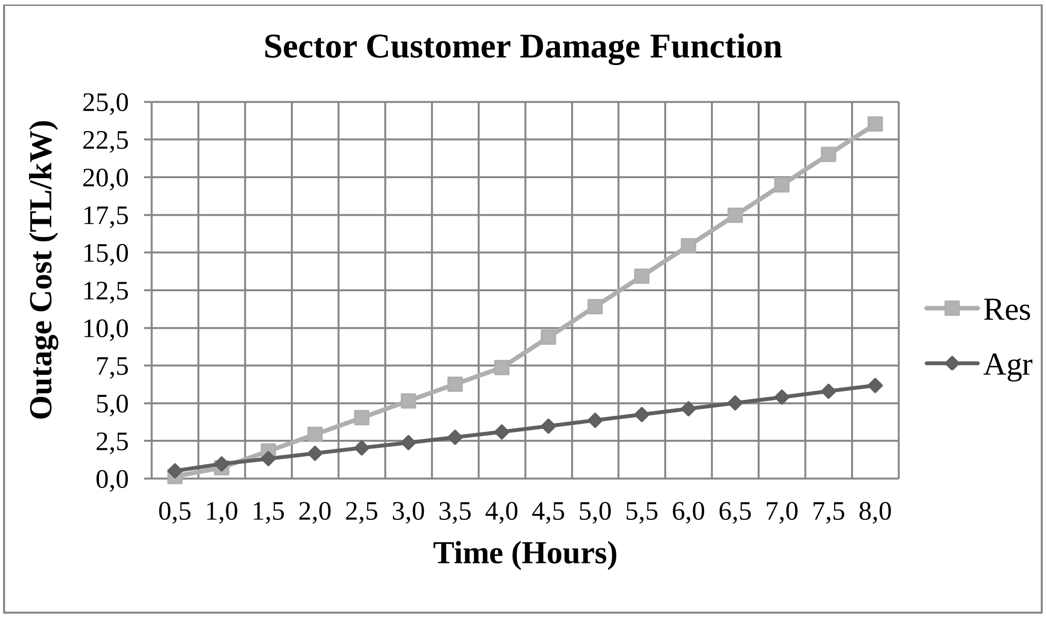

Figure 40 Sector customer damage function

Parameters used for the *Utility Cost* calculation is as given below;

- Sectionalizing switch Unit Price: 30kTL
- Recloser Unit Price: 40kTL
- Loan: %8
- Sectionalizing switch Life Span: 25 Years
- Recloser Life Span: 25 Years

And parameters used for the *Penalty Cost* calculation is as given below;

- Duration Penalty Threshold:96 hours
- Frequency Penalty Threshold: 72

The result of the optimization algorithm for the base case analysis is as given in Figure 41.

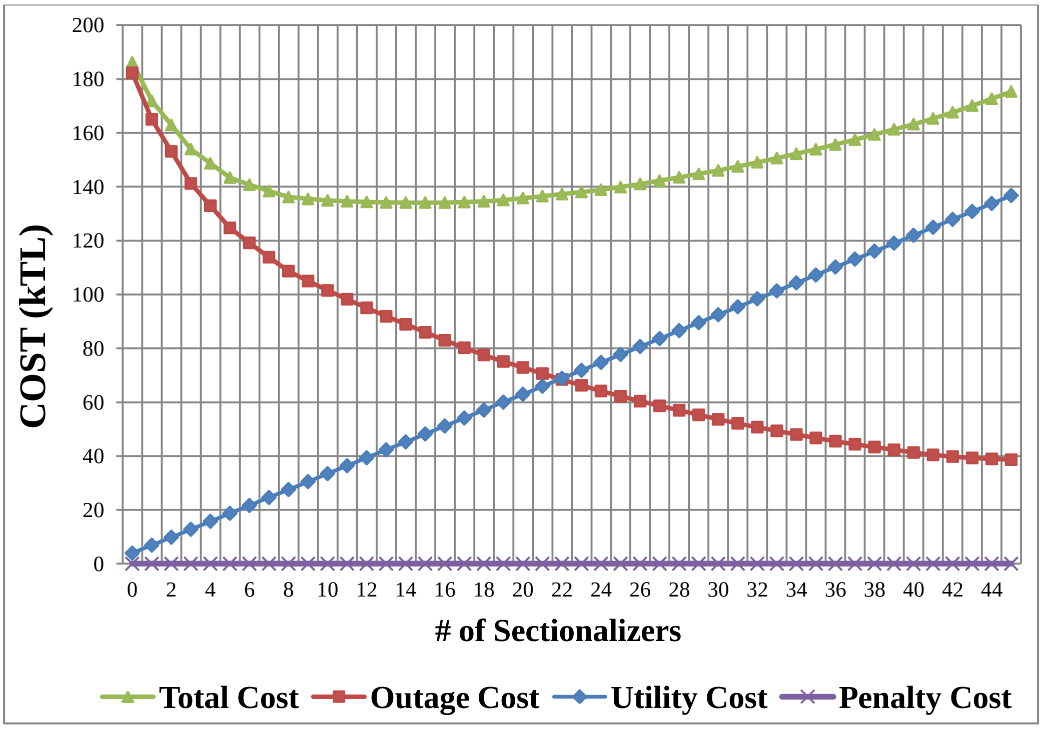

Figure 41 Base case results

As it is seen from Figure 41, *Outage Cost* decreases as the *Utility Cost* and reliability level increases. The *Total Cost* structure results with a U-shaped curve as it is expected. In the Base Case the minimum *Total Cost* is achieved with 16 sectionalizer installations among 45 possible locations. The locations of the sectionalizing switch installations in optimum allocation configuration are as given in Table 14.

Table 14 Base case sectionalizing switch allocations

Feeders	Clusters									
	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10
	x1	x2	x3	x4	x5	x6	x7	x8	x9	x10
F1	1	1	1	1	0	1	1	0	1	0
F2	1	0	0	0	0	0	0	0	0	1
F3	1	1	0	0	1	1	1	0	-	-
F4	1	1	1	1	1	1	1	-	-	-
F5	0	1	1	1	1	-	-	-	-	-
F6	1	1	1	0	1	-	-	-	-	-

The results for the cost and reliability indices with the optimal sectionalizing switches allocations are as given below in Table 15.

Table 15 Base case optimum allocation results

# of Sect Installed	Outage Cost (TL)	Utility Cost (TL)	Penalty Cost (TL)	Total Cost (TL)	SAIDI (hours/ year)	SAIFI (1/ year)	CAIDI (hours)
0	182.283	3.935	0	186.217	34,78	10,50	3,31
16	82.954	51.148	0	134.102	16,99	6,82	2,49

As it is seen from the results revealed in Table 15, for the base case none of the feeders exceeds the duration and frequency thresholds and the calculated *Penalty Cost* is zero. When it is considered that the base case represents the default situation, it can be said that the threshold limits (MD_{freq} and MD_{dur}) defined by the regulation for annual outage duration and the annual outage frequency of a rural feeder is high. Since the *Penalty Cost* contribution on the *Total Cost* does not exist, the main cost contributor which forces the sectionalizing switch installation investments in order to reduce the outage durations and frequencies that are subjected by the customers is the *Outage Cost*.

Table 15 also illustrates the reliability indices values when there is no sectionalizing switch is installed on the system and with the optimal allocation of sectionalizing switches the average interruption duration in the network (SAIDI) is decreased from 34,78 hours to 16,99 hours and the average interruption duration in the network (SAIFI) is decreased from 10,50 to 6,82.

5.4.2. Average Load Variation Cases

In that chapter optimization is carried out for different loading schemes. The results of different loading scenarios are presented and the effect of the average loading on optimization results is analyzed.

During the analysis different loading scenarios are created while all other parameters are kept same with the base case parameters. The loading cases analyzed are given in Table 16.

Table 16 Loading variation scenarios

Cases	**Average Loading of TRs**
Base Case	20%
Case 1	10%
Case 2	30%
Case 3	40%
Case 4	60%
Case 5	80%

Average Load Variation - Case1

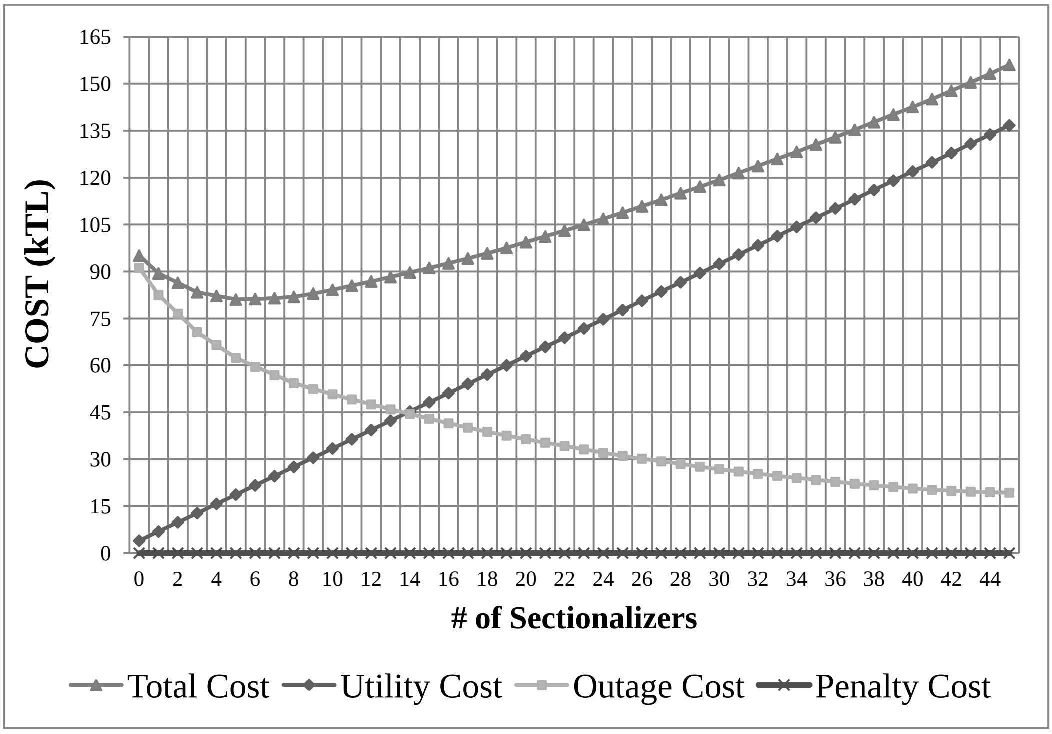

Figure 42 Case1: %10 average loading

In Case1 the average loading of MV/LV transformers is set to 10%. Since the average loading is decreased to 10%, the *Outage Cost* component effect on the *Total Cost* is relatively small compared to Base Case. In Case1 the highest value of the *Outage Cost* is 91.141TL while it was 182.282TL in Base Case. As it is expected that in Case1 the *Utility Cost* is the dominant component in *Total Cost* which prevents the sectionalizing switch installations. Therefore the optimization algorithm tends to allocate less sectionalizing switches compared to Base Case. As it is seen in Figure 42 at the minimum point of *Total Cost* which gives the optimal switch allocation configuration, only 5 sectionalizing switches are installed. At the optimal switch allocation configuration of Case1 the calculated values are as given in Table 17.

Table 17 Average loading variation case1 results

# of Sect Installed	Outage Cost (TL)	Utility Cost (TL)	Penalty Cost (TL)	Total Cost (TL)	SAIDI (hours/ year)	SAIFI (1/ year)	CAIDI (hours)
0	91.141	3.935	0	95.076	34,78	10,50	3,31
5	62.356	18.689	0	81.045	25,17	8,84	2,85

Table 17 also illustrates the reliability indices values when there is no sectionalizing switch is installed on the system and with the optimal allocation of sectionalizing switches the average interruption duration in the network (SAIDI) is decreased from 34,78 hours to 25,17 hours and the average interruption duration in the network (SAIFI) is decreased from 10,50 to 8,84.

Average Load Variation – Case2

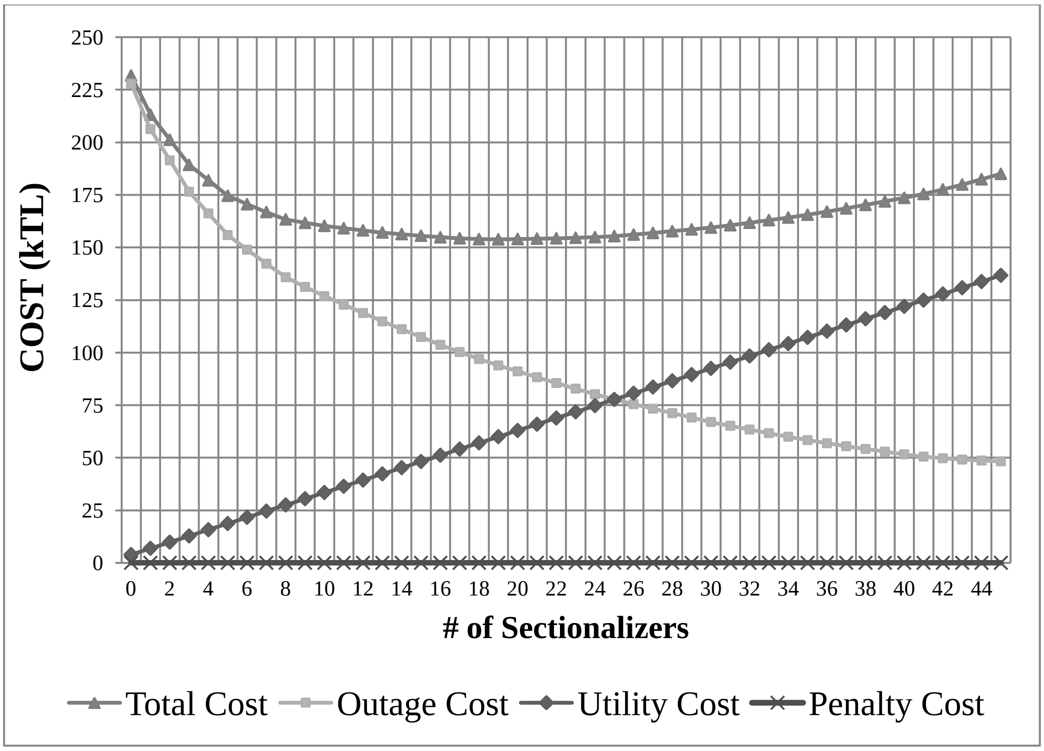

Figure 43 Case2: %30 average loading

In Case2 the average loading of MV/LV transformers is set to 30%. Since the average loading is increased slightly, the *Outage Cost* component effect on the *Total Cost* is slightly high compared to Base Case. In Case2 the highest value of the *Outage Cost* is 227.853TL while it was 182.282TL in Base Case. As it is expected that in Case2 the *Outage Cost* is the dominant component in *Total Cost* which forces the sectionalizing switch installations. Therefore the optimization algorithm tends to allocate more sectionalizing switches compared to Base Case. As it is seen in Figure 43 at the minimum point of *Total Cost* which gives the optimal switch allocation configuration, 19 sectionalizing switches are installed. At the optimal switch allocation configuration of Case2 the calculated values are as given in Table 18.

Table 18 Average loading variation case2 results

# of Sect Installed	Outage Cost (TL)	Utility Cost (TL)	Penalty Cost (TL)	Total Cost (TL)	SAIDI (hours/ year)	SAIFI (1/ year)	CAIDI (hours)
0	227.853	3.935	0	231.788	34,78	10,50	3,31
19	93.864	60.001	0	153.865	15,42	6,36	2,43

Table 18 also illustrates the reliability indices values when there is no sectionalizing switch is installed on the system and with the optimal allocation of sectionalizing switches the average interruption duration in the network (SAIDI) is decreased from 34,78 hours to 15,42 hours and the average interruption duration in the network (SAIFI) is decreased from 10,50 to 6,36.

Average Load Variation – Case3

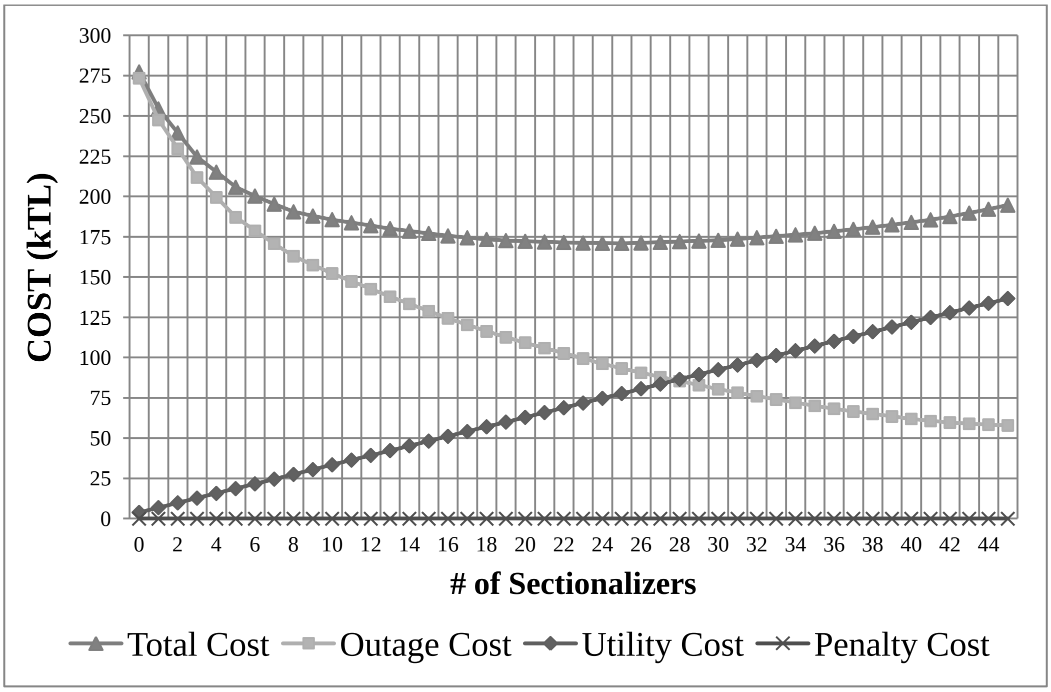

Figure 44 Case3: %40 average loading

In Case3 the average loading of MV/LV transformers is set to 40%. Since the average loading is increased, the *Outage Cost* component effect on the *Total Cost* is higher compared to Base Case. In Case3 the highest value of the *Outage Cost* is 273.424TL while it was 182.282TL in Base Case. As it is expected that in Case3 the *Outage Cost* is the dominant component in *Total Cost* which forces the sectionalizing switch installations. Therefore the optimization algorithm tends to allocate more sectionalizing switches compared to Base Case. As it is seen in Figure 44 at the minimum point of *Total Cost* which gives the optimal switch allocation configuration, 25 sectionalizing switches are installed. At the optimal switch allocation configuration of Case3 the calculated costs and reliability indices are as given in Table 19.

Table 19 Average loading variation case3 results

# of Sect Installed	Outage Cost (TL)	Utility Cost (TL)	Penalty Cost (TL)	Total Cost (TL)	SAIDI (hours/ year)	SAIFI (1/ year)	CAIDI (hours)
0	273.424	3.935	0	277.359	34,78	10,50	3,31
25	93.237	77.707	0	170.943	12,73	5,51	2,31

Table 19 also illustrates the reliability indices values when there is no sectionalizing switch is installed on the system and with the optimal allocation of sectionalizing switches the average interruption duration in the network (SAIDI) is decreased from 34,78 hours to 12,79 hours and the average interruption duration in the network (SAIFI) is decreased from 10,50 to 5,51.

<u>Average Load Variation – Case4</u>

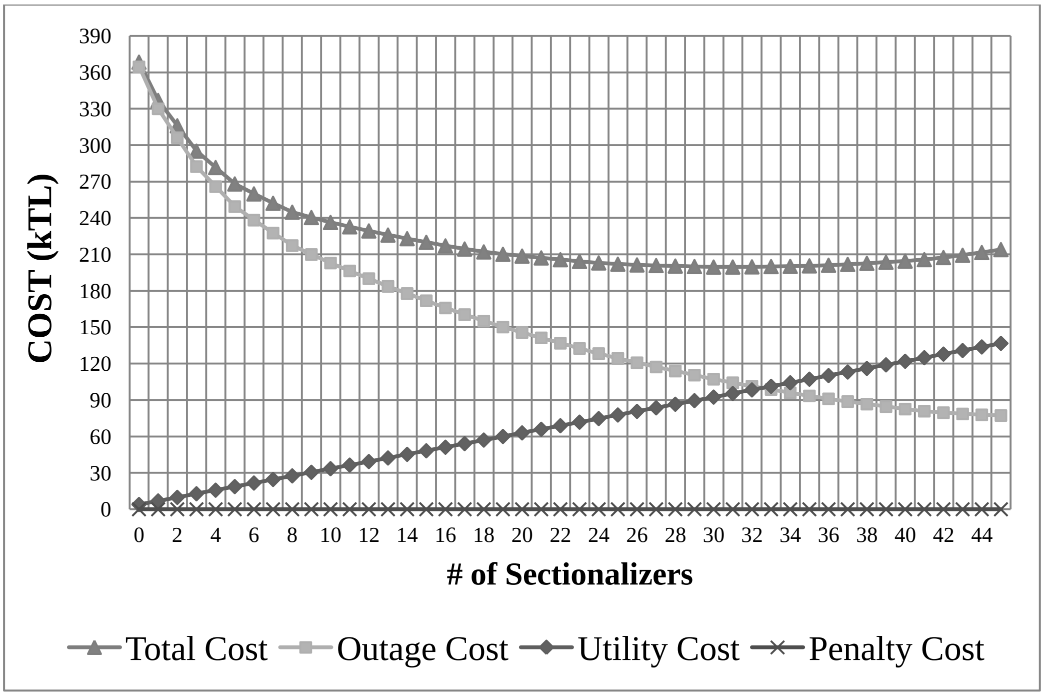

Figure 45 Case4: %60 average loading

In Case4 the average loading of MV/LV transformers is set to 60%. Since the average loading is increased substantially, the *Outage Cost* component effect on the *Total Cost* is much higher compared to Base Case. In Case4 the highest value of the *Outage Cost* is 364.565TL while it was 182.282TL in Base Case. As it is expected that in Case4 the *Outage Cost* is the dominant component in *Total Cost* which forces the sectionalizing switch installations. Therefore the optimization algorithm tends to allocate much more sectionalizing switches compared to Base Case. As it is seen in Figure 45 at the minimum point of *Total Cost* which gives the optimal switch allocation configuration, 30 sectionalizing switches are installed. At the optimal switch allocation configuration of Case4 the calculated costs and reliability indices are as given in Table 20.

Table 20 Average loading variation case4 results

# of Sect Installed	**Outage Cost (TL)**	**Utility Cost (TL)**	**Penalty Cost (TL)**	**Total Cost (TL)**	**SAIDI (hours/ year)**	**SAIFI (1/ year)**	**CAIDI (hours)**
0	364.566	3.935	0	368.500	34,78	10,50	3,31
30	107.184	92.461	0	199.644	10,98	4,99	2,20

Table 20 also illustrates the reliability indices values when there is no sectionalizing switch is installed on the system and with the optimal allocation of sectionalizing switches the average interruption duration in the network (SAIDI) is decreased from 34,78 hours to 10,98 hours and the average interruption duration in the network (SAIFI) is decreased from 10,50 to 4,99.

Average Load Variation – Case5

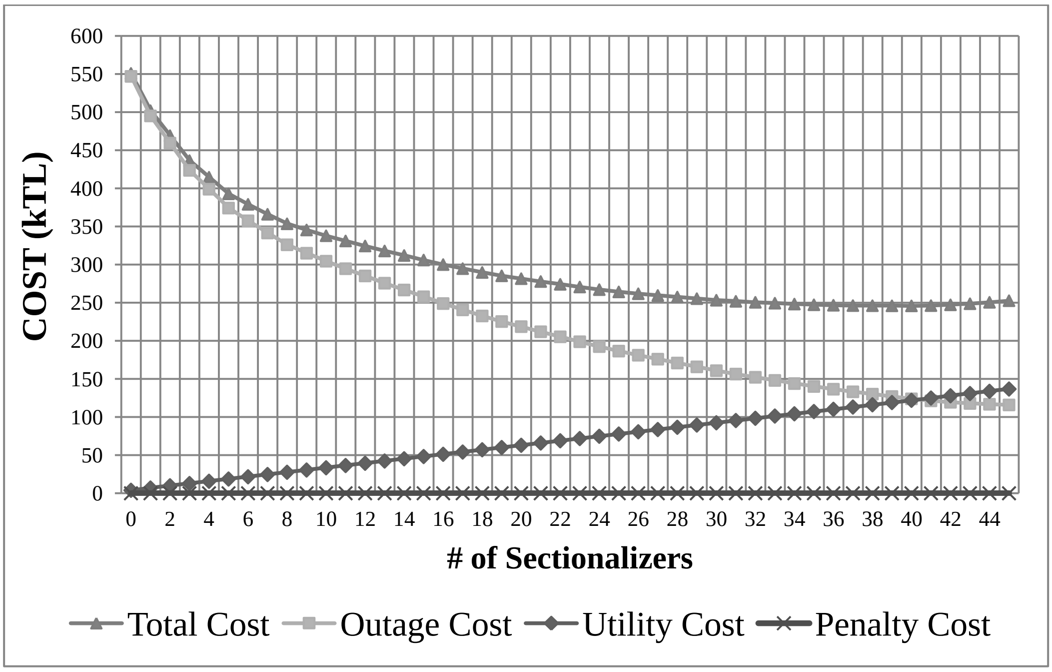

Figure 46 Case5: %80 average loading

In Case5 the average loading of MV/LV transformers is set to 80%. Since the average loading is increased substantially, the *Outage Cost* component effect on the *Total Cost* is much higher compared to Base Case. In Case5 the highest value of the *Outage Cost* is 546.848TL while it was 182.282TL in Base Case. As it is expected that in Case5 the *Outage Cost* is the dominant component in *Total Cost* which forces the sectionalizing switch installations. Therefore the optimization algorithm tends to allocate much more sectionalizing switches compared to Base Case. As it is seen in Figure 46 at the minimum point of *Total Cost* which gives the optimal switch allocation configuration, 41 sectionalizing switches are installed. Therefore nearly at each possible location a sectionalizing switch is installed by the optimization algorithm except the least effective four locations. At the optimal switch allocation configuration of Case5 the calculated costs and reliability indices are as given in Table 21.

Table 21 Average loading variation case5 results

# of Sect Installed	Outage Cost (TL)	Utility Cost (TL)	Penalty Cost (TL)	Total Cost (TL)	SAIDI (hours/ year)	SAIFI (1/ year)	CAIDI (hours)
0	546.848	3.935	0	550.783	34,78	10,50	3,31
41	123.869	121.970	0	246.179	8,53	4,09	2,09

Table 21 also illustrates the reliability indices values when there is no sectionalizing switch is installed on the system and with the optimal allocation of sectionalizing switches the average interruption duration in the network (SAIDI) is decreased from 34,78 hours to 8,53 hours and the average interruption duration in the network (SAIFI) is decreased from 10,50 to 4,09.

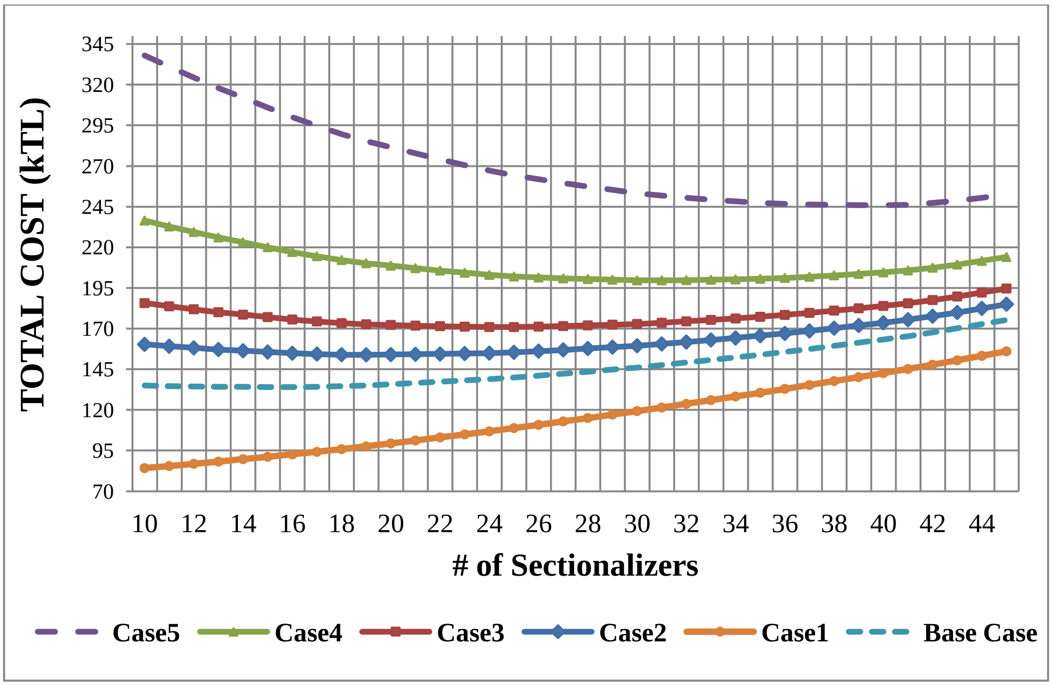

Figure 47 Total cost behavior with average loading variation

In Figure 47 the *Total Cost* behavior with average load variation is presented. As the average loading is increased naturally the *Total Cost* level of the network increases because of the Outage Cost component effect.

As it can be seen from the Figure 47 the optimization algorithm tends to allocate more sectionalizing switches with the increasing average load. Outage Cost is a function of both the average load and outage duration. When the load increases, optimization algorithm tends to reduce the Outage Cost by decreasing the total outage duration and allocate more sectionalizing switches.

The decreasing behavior of *Outage Cost* with sectionalizing switch installations can be seen in Figure 48. Figure 48 also shows that the increasing average load also increases the *Outage Cost* level. For example *Outage Cost* of Case1 which simulates the lowest loading case moves along the bottom level while *Outage Cost* of Case5 which simulates the highest loading case moves along at the top level in Figure 48.

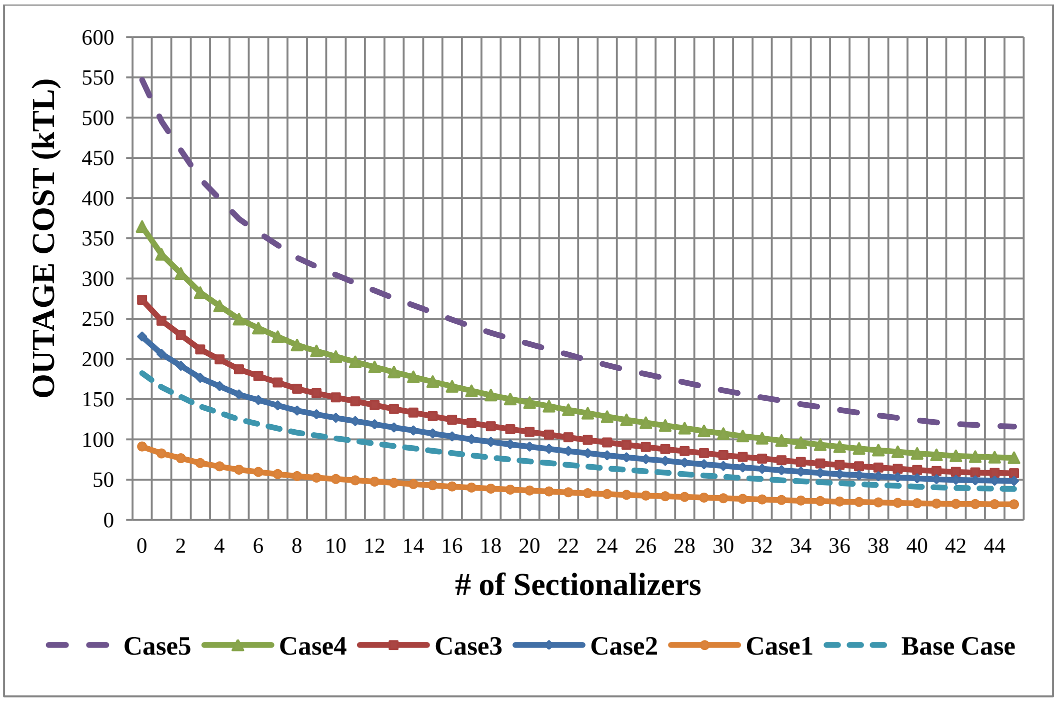

Figure 48 Outage cost behavior with average loading variation

As a summary the calculated results of the costs and reliability indices for analyzed 6 cases are given in Table 22. The results presented inTable 22 are the optimal sectionalizing switch allocation configurations which give the minimum *Total Cost*.

Table 22 Average load variation cases optimal sectionalizing switch allocation results

Cases	Average Loading	# of Sect Installed	OTC (TL)	UTC (TL)	PNC (TL)	TC (TL)	SAIDI (hours/ year)	SAIFI (1/ year)	CAIDI (hours)
Base Case	20%	16	82.954	51.149	0	134.103	16,988	6,818	2,492
Case1	10%	5	62.356	18.689	0	81.045	25,170	8,838	2,848
Case2	30%	19	93.864	60.001	0	153.865	15,423	6,358	2,426
Case3	40%	25	93.237	77.707	0	170.943	12,735	5,514	2,310
Case4	60%	30	107.184	92.461	0	199.644	10,985	4,993	2,200
Case5	80%	41	121.258	124.921	0	246.179	8,370	4,028	2,078

5.4.3. Failure Duration Variation Cases

In that chapter optimization is carried out for different failure duration schemes. The results of different failure duration scenarios are presented and the effect of the overhead line per km outage duration on optimization results is analyzed.

During the analysis per km outage duration of overhead line is changed while all other parameters are kept same with the base case parameters. The cases analyzed are given in Table 23.

Table 23 Failure duration variation scenarios

Cases	**Line per km failure duration (pu)**
Base Case	1,00
Case 1	0,50
Case2	1,50
Case 3	2,00
Case 4	2,50
Case 5	3,00

<u>Failure Duration Variation – Case1</u>

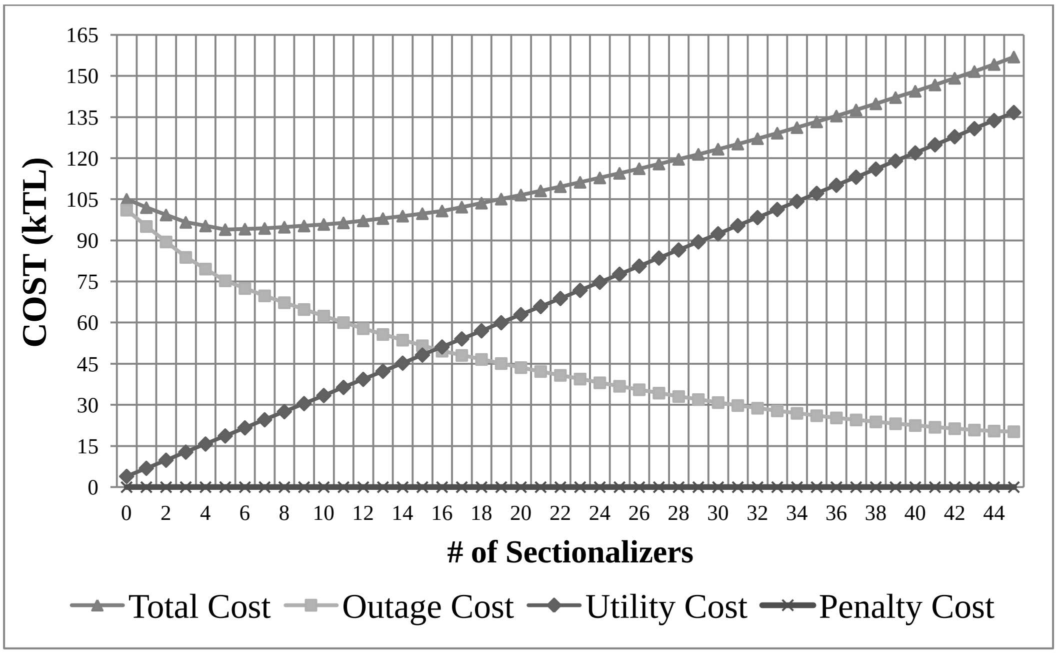

Figure 49 Case1: Line per km failure duration 0,5pu

The Base Case overhead line per km failure duration is taken as the base value and in Case1 the per km overhead line failure duration is set to 0,5pu. Since the per km failure duration is decreased, the *Outage Cost* component effect on the *Total Cost* is relatively small compared to Base Case. In Case1 the highest value of the *Outage Cost* is 101.079TL while it was 182.282TL in Base Case.

As it is expected that in Case1 the *Utility Cost* is the dominant component in *Total Cost* which prevents the sectionalizing switch installations. Therefore the optimization algorithm tends to allocate less sectionalizing switches compared to Base Case. As it is seen in Figure 49 at the minimum point of *Total Cost* which gives the optimal switch allocation configuration, only 7 sectionalizing switches are installed among 45 possible locations. At the optimal switch allocation configuration of Case1 the calculated values are as given in Table 24.

Table 24 Failure duration variation case1 results

# of Sect Installed	**Outage Cost (TL)**	**Utility Cost (TL)**	**Penalty Cost (TL)**	**Total Cost (TL)**	**SAIDI (hours/ year)**	**SAIFI (1/ year)**	**CAIDI (hours)**
0	101.079	3.935	0	105.014	21,07	10,50	2,01
7	69.809	24.591	0	94.400	14,58	8,32	1,75

Table 24 also illustrates the reliability indices values when there is no sectionalizing switch is installed on the system and with the optimal allocation of sectionalizing switches the average interruption duration in the network (SAIDI) is decreased from 21,07 hours to 14,58 hours and the average interruption duration in the network (SAIFI) is decreased from 10,50 to 8,32.

Failure Duration Variation – Case2

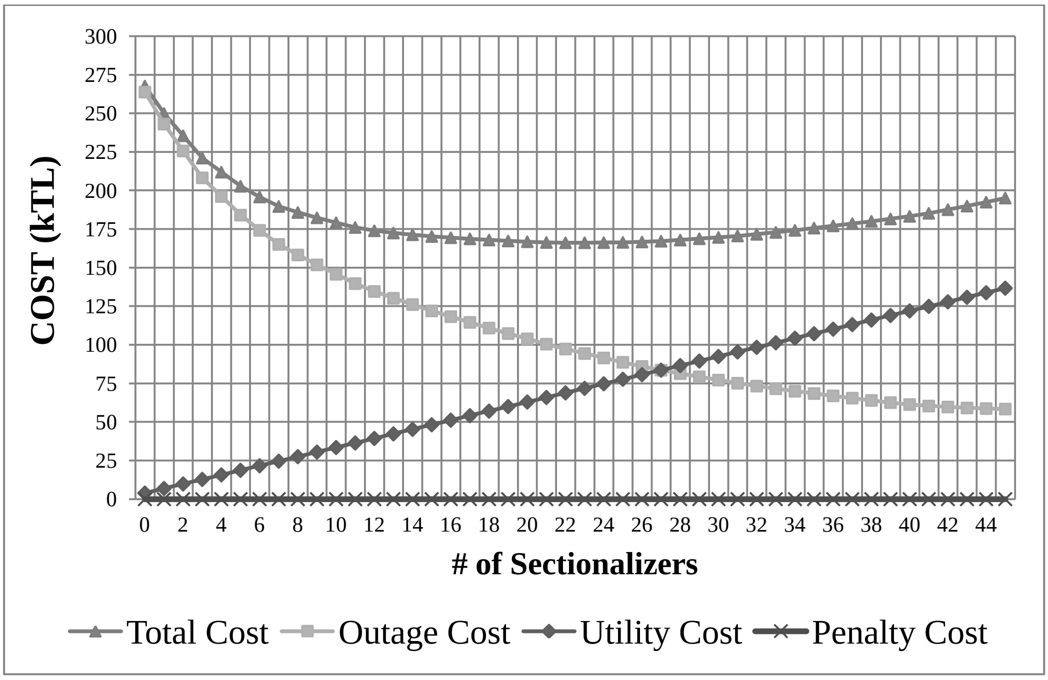

Figure 50 Case2: Line per km failure duration 1,5pu

In Case2 the per km overhead line failure duration is set to 1,5pu. Since the per km failure duration is increased, the *Outage Cost* component effect on the *Total Cost* is higher compared to Base Case. In Case2 the highest value of the *Outage Cost* is 263.774TL while it was 182.282TL in Base Case. As it is expected that in Case2 the *Outage Cost* is the dominant component in *Total Cost* which forces the sectionalizing switch installations. Therefore the optimization algorithm tends to allocate more sectionalizing switches compared to Base Case. As it is seen in Figure 50 at the minimum point of *Total Cost* which gives the optimal switch allocation configuration, 23 sectionalizing switches are installed among 45 possible locations. At the optimal switch allocation configuration of Case2 the calculated values are as given in Table 25.

Table 25 Failure duration variation case2 results

# of Sect Installed	Outage Cost (TL)	Utility Cost (TL)	Penalty Cost (TL)	Total Cost (TL)	SAIDI (hours/ year)	SAIFI (1/ year)	CAIDI (hours)
0	263.774	3.935	0	267.709	48,49	10,50	4,62
23	94.361	71.805	0	166.166	18,54	5,79	3,20

Table 25 also illustrates the reliability indices values when there is no sectionalizing switch is installed on the system and with the optimal allocation of sectionalizing switches the average interruption duration in the network (SAIDI) is decreased from 48,49 hours to 18,54 hours and the average interruption duration in the network (SAIFI) is decreased from 10,50 to 5,79.

Failure Duration Variation – Case3

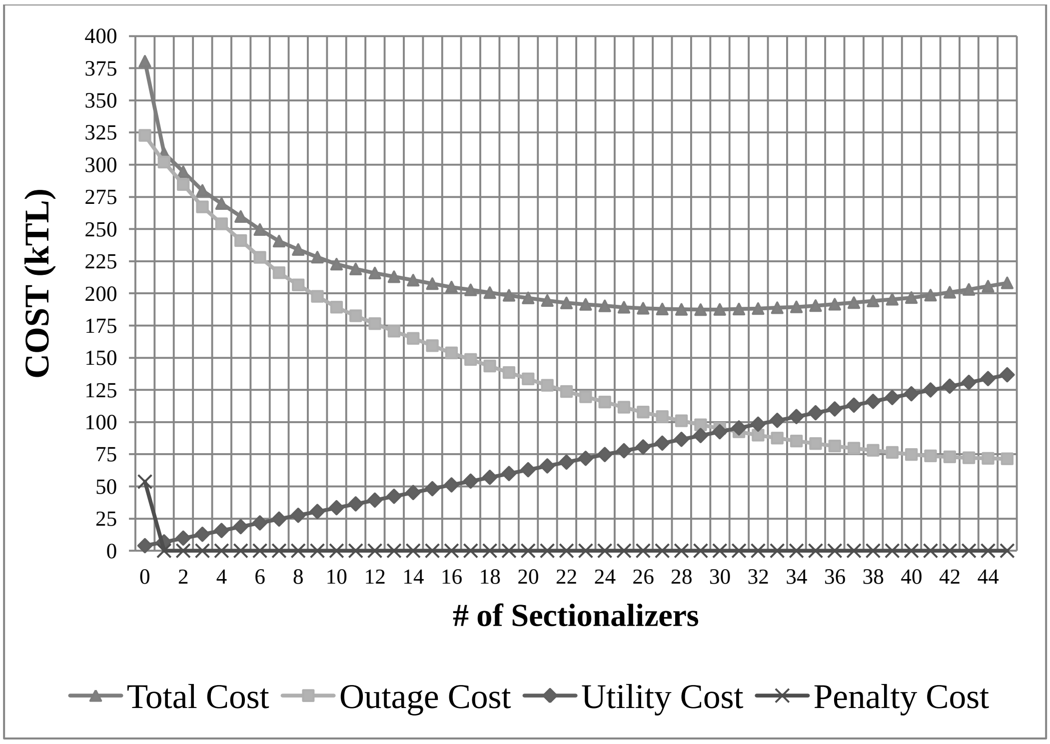

Figure 51 Case3: Line per km failure duration 2pu

In Case3 the per km overhead line failure duration is set to 2pu. Since the per km failure duration is increased, the *Outage Cost* component effect on the *Total Cost* is higher compared to Base Case. In Case3 the highest value of the *Outage Cost* is 322.725TL while it was 182.282TL in Base Case. As it is expected that in Case3 the *Outage Cost* is the dominant component in *Total Cost* which forces the sectionalizing switch installations. Therefore the optimization algorithm tends to allocate more sectionalizing switches compared to Base Case. As it is seen in Figure 51 at the minimum point of *Total Cost* which gives the optimal switch allocation configuration, 29 sectionalizing switches are installed among 45 possible locations. At the optimal switch allocation configuration of Case2 the calculated values are as given in Table 26.

Table 26 Failure duration variation case3 results

# of Sect Installed	Outage Cost (TL)	Utility Cost (TL)	Penalty Cost (TL)	Total Cost (TL)	SAIDI (hours/ year)	SAIFI (1/ year)	CAIDI (hours)
0	322.726	3.935	53.673	380.333	62,21	10,50	5,92
29	97.862	89.510	0	187.372	19,71	5,10	3,86

Table 26 also illustrates the reliability indices values when there is no sectionalizing switch is installed on the system and with the optimal allocation of sectionalizing switches the average interruption duration in the network (SAIDI) is decreased from 62,21 hours to 19,71 hours and the average interruption duration in the network (SAIFI) is decreased from 10,50 to 5,10.

Failure Duration Variation – Case4

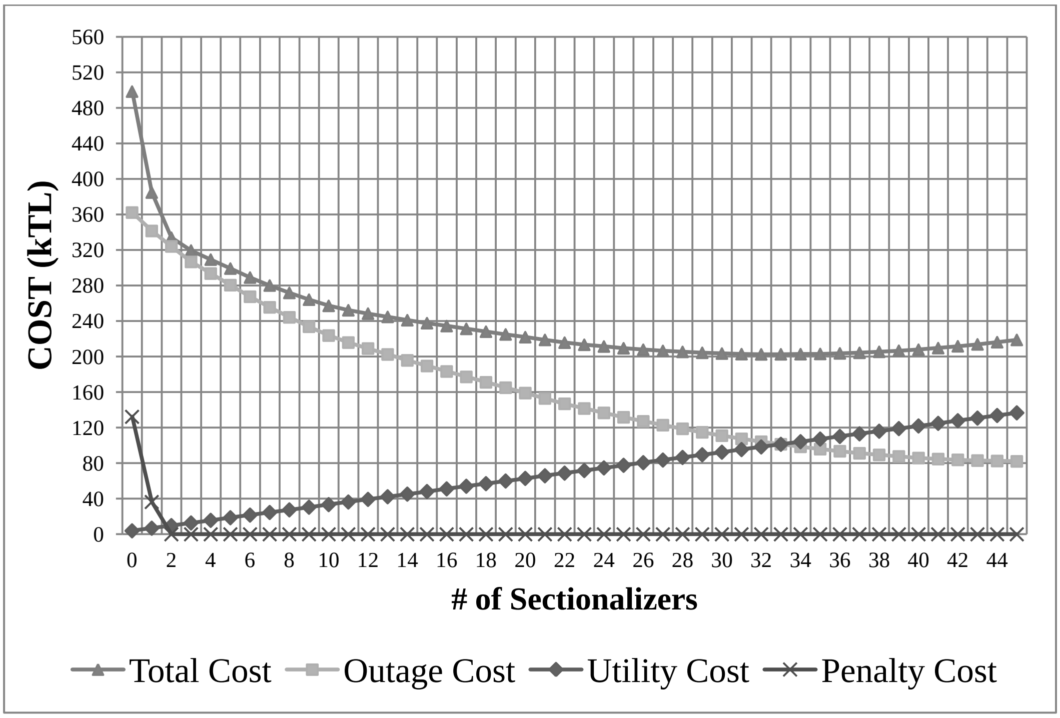

Figure 52 Case4: Line per km failure duration 2,5pu

In Case4 the per km overhead line failure duration is set to 2,5pu. Since the per km failure duration is increased, the *Outage Cost* component effect on the *Total Cost* is higher compared to Base Case. In Case4 the highest value of the *Outage Cost* is 362.167TL while it was 182.282TL in Base Case. As it is expected that in Case4 the *Outage Cost* is the dominant component in *Total Cost* which forces the sectionalizing switch installations. Therefore the optimization algorithm tends to allocate much more sectionalizing switches compared to Base Case. As it is seen in Figure 52 at the minimum point of *Total Cost* which gives the optimal switch allocation configuration, 32 sectionalizing switches are installed among 45 possible locations. At the optimal switch allocation configuration of Case4 the calculated values are as given in Table 27.

Table 27 Failure duration variation case4 results

# of Sect Installed	Outage Cost (TL)	Utility Cost (TL)	Penalty Cost (TL)	Total Cost (TL)	SAIDI (hours/ year)	SAIFI (1/ year)	CAIDI (hours)
0	362.168	3.935	132.267	498.370	75,92	10,50	7,23
32	104.195	98.363	0	202.558	22,13	4,80	4,60

Table 27 also illustrates the reliability indices values when there is no sectionalizing switch is installed on the system and with the optimal allocation of sectionalizing switches the average interruption duration in the network (SAIDI) is decreased from 75,92 hours to 22,13 hours and the average interruption duration in the network (SAIFI) is decreased from 10,50 to 4,80.

Failure Duration Variation – Case5

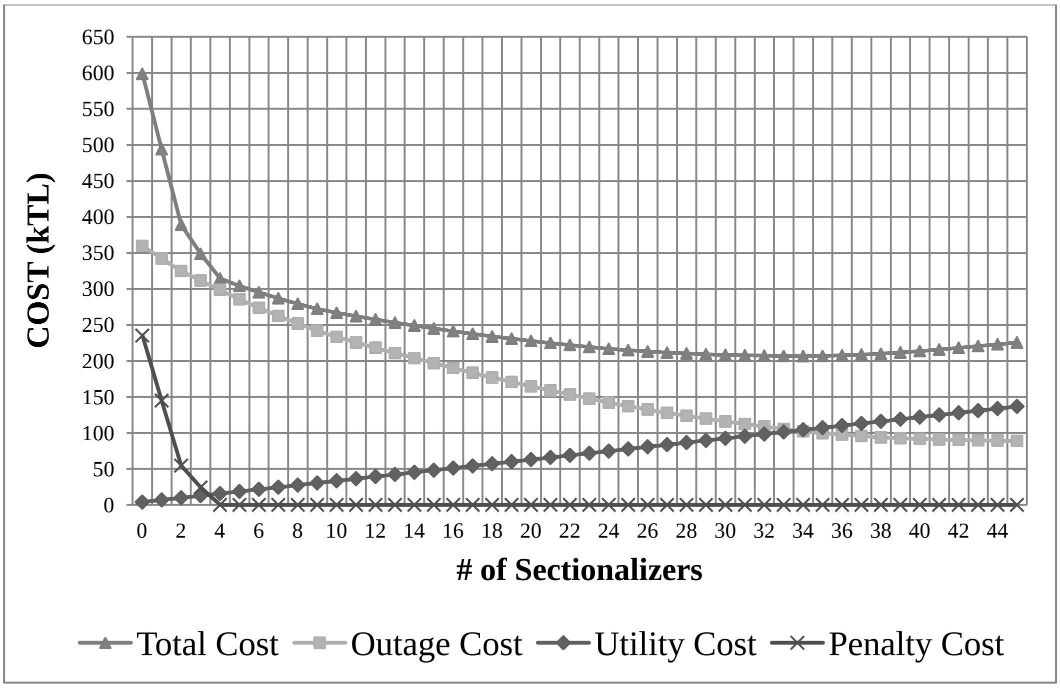

Figure 53 Case5: Line per km failure duration 3pu

In Case5 the per km overhead line failure duration is set to 3pu. Since the per km failure duration is increased, the *Outage Cost* component effect on the *Total Cost* is higher compared to Base Case.

In Case5 the highest value of the *Outage Cost* is 359.569TL while it was 182.282TL in Base Case. As it is expected that in Case5 the *Outage Cost* is the dominant component in *Total Cost* which forces the sectionalizing switch installations. Therefore the optimization algorithm tends to allocate much more sectionalizing switches compared to Base Case. As it is seen in Figure 53 at the minimum point of *Total Cost* which gives the optimal switch allocation configuration, 34 sectionalizing switches are installed among 45 possible locations. At the optimal switch allocation configuration of Case5 the calculated values are as given in Table 28.

Table 28 Failure duration variation case5 results

# of Sect Installed	**Outage Cost (TL)**	**Utility Cost (TL)**	**Penalty Cost (TL)**	**Total Cost (TL)**	**SAIDI (hours/ year)**	**SAIFI (1/ year)**	**CAIDI (hours)**
0	359.569	3.935	235.120	598.624	89,65	10,50	8,54
34	102.317	104.264	0	206.582	34,12	4,95	6,89

Table 28 also illustrates the reliability indices values when there is no sectionalizing switch is installed on the system and with the optimal allocation of sectionalizing switches the average interruption duration in the network (SAIDI) is decreased from 84,65 hours to 34,12 hours and the average interruption duration in the network (SAIFI) is decreased from 10,50 to 4,95.

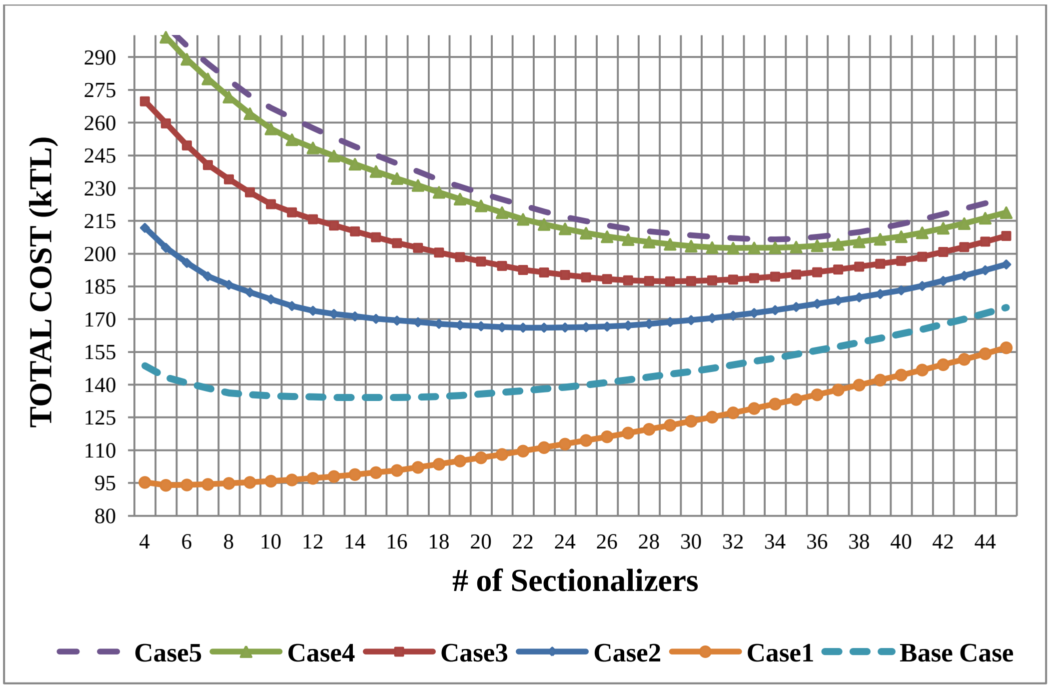

Figure 54 Total cost behavior with failure duration variation

In Figure 54 the *Total Cost* behavior for 6 cases (including Base Case) are presented. As the per km failure duration of overhead line is increased, naturally the *Total Cost* level of the network increases because of the *Outage Cost* component effect. As it can be seen from the Figure 54 the optimization algorithm tends to allocate more sectionalizing switches with the increasing failure duration. *Outage Cost* is a function of outage duration. When more sectionalizing switches installed on the network the total duration of the outages subjected by the customers is decreased. Therefore the optimization algorithm tends to reduce the *Outage Cost* by the installation of more sectionalizing switches.

It should also be noticed that (see Figure 51, Figure 52 and Figure 53) when the failure duration in the network increases the Penalty Cost component also becomes one of the contributor term in *Total Cost*. Penalty Cost component never exists in loading cases because it is a function of outage duration and frequency.

Optimization algorithm successfully eliminates the *Penalty Cost* component at the beginning of the iterations by allocating the sectionalizing switches on the most effective locations.

The decreasing behavior of *Outage Cost* with sectionalizing switch installations can be seen in Figure 55. Figure 55 also shows that the increasing outage durations also increase the *Outage Cost* level. For example *Outage Cost* of Case1 which simulates the lowest overhead line per km failure duration case moves along the bottom level while *Outage Cost* of Case5 which simulates the highest overhead line per km failure duration case moves along at the top level in Figure 55.

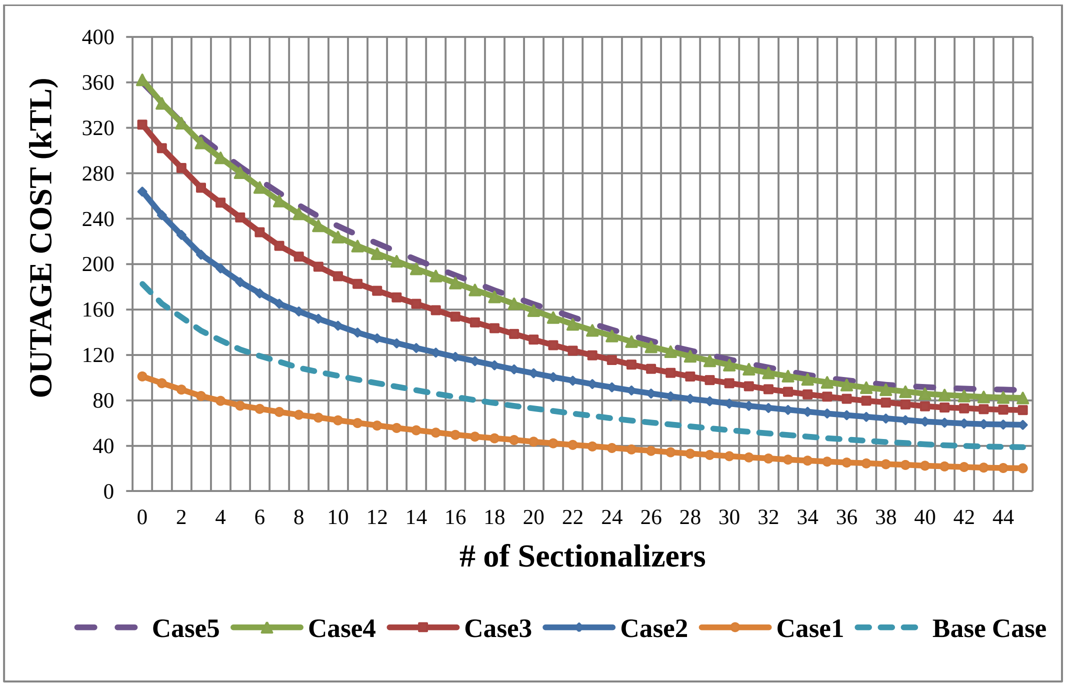

Figure 55 Outage cost behavior with failure duration variation

As a summary the calculated results of the costs and reliability indices for analyzed 6 cases are given in Table 29. The results presented in Table 29 are for the optimal sectionalizing switch allocation configurations which give the minimum *Total Cost*.

Table 29 Failure duration variation cases optimal sectionalizing switch allocation results

Cases	**OHL per km Failure Duration (pu)**	**# of Sect Installed**	**OTC (TL)**	**UTC (TL)**	**PNC (TL)**	**TC (TL)**	**SAIDI (hours/ year)**	**SAIFI (1/ year)**	**CAIDI (hours)**
Base Case	1	16	82.954	51.149	0	134.103	16,988	6,818	2,492
Case1	0,5	7	69.809	24.591	0	94.400	14,582	8,328	1,751
Case2	1,5	23	94.361	71.805	0	166.166	18,545	5,791	3,203
Case3	2	29	97.862	89.510	0	187.372	19,718	5,103	3,864
Case4	2,5	32	104.195	98.363	0	202.558	22,137	4,809	4,603
Case5	3	34	102.317	104.264	0	206.582	34,119	4,949	6,894

5.4.4. Failure Frequency Variation Cases

In that chapter optimization is carried out for different failure frequency schemes. The results of different failure frequency scenarios are presented and the effect of the MV/LV distribution transformer and overhead line per km failure frequencies on optimization results is analyzed. During the analysis MV/LV distribution transformer and overhead line per km failure frequencies are changed while all other parameters are kept same with the base case parameters. The cases analyzed are given in Table 30.

Table 30 Failure frequency variation scenarios

Cases	Line per km Failure Frequency (pu)	TR Failure Frequency (pu)
Base Case	1,00	1,00
Case 1	0,50	0,50
Case 2	1,50	1,50
Case 3	2,00	2,00
Case 4	2,50	2,50
Case 5	3,00	3,00

Failure Frequency Variation – Case1

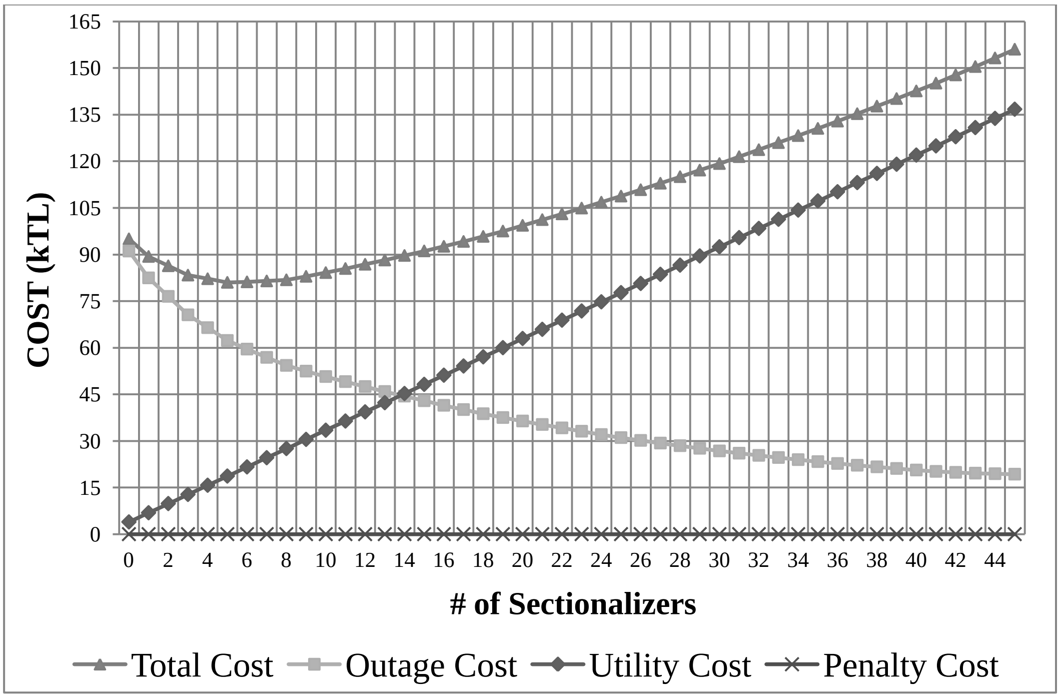

Figure 56 Case1: Failure frequency rates 0,5pu

The Base Case failure frequency values for MV/LV distribution transformers and per km overhead line are taken as the base value and in Case1 the failure frequency values for both elements are set to 0,5pu.

Since the failure frequency is decreased, the *Outage Cost* component effect on the *Total Cost* is relatively small compared to Base Case. In Case1 the highest value of the *Outage Cost* is 91.085TL while it was 182.282TL in Base Case. As it is expected that in Case1 the *Utility Cost* is the dominant component in *Total Cost* which prevents the sectionalizing switch installations. Therefore the optimization algorithm tends to allocate less sectionalizing switches compared to Base Case. As it is seen in Figure 56 at the minimum point of *Total Cost* which gives the optimal switch allocation configuration, only 5 sectionalizing switches are installed among 45 possible locations. At the optimal switch allocation configuration of Case1 the calculated values are as given in Table 31.

Table 31 Failure frequency variation case1 results

# of Sect Installed	**Outage Cost (TL)**	**Utility Cost (TL)**	**Penalty Cost (TL)**	**Total Cost (TL)**	**SAIDI (hours/ year)**	**SAIFI (1/ year)**	**CAIDI (hours)**
0	91.086	3.935	0	95.020	17,38	5,25	3,31
5	62.321	18.689	0	81.010	12,58	4,42	2,85

Table 31 also illustrates the reliability indices values when there is no sectionalizing switch is installed on the system and with the optimal allocation of sectionalizing switches the average interruption duration in the network (SAIDI) is decreased from 17,38 hours to 12,58 hours and the average interruption duration in the network (SAIFI) is decreased from 5,25 to 4,42.

Failure Frequency Variation – Case2

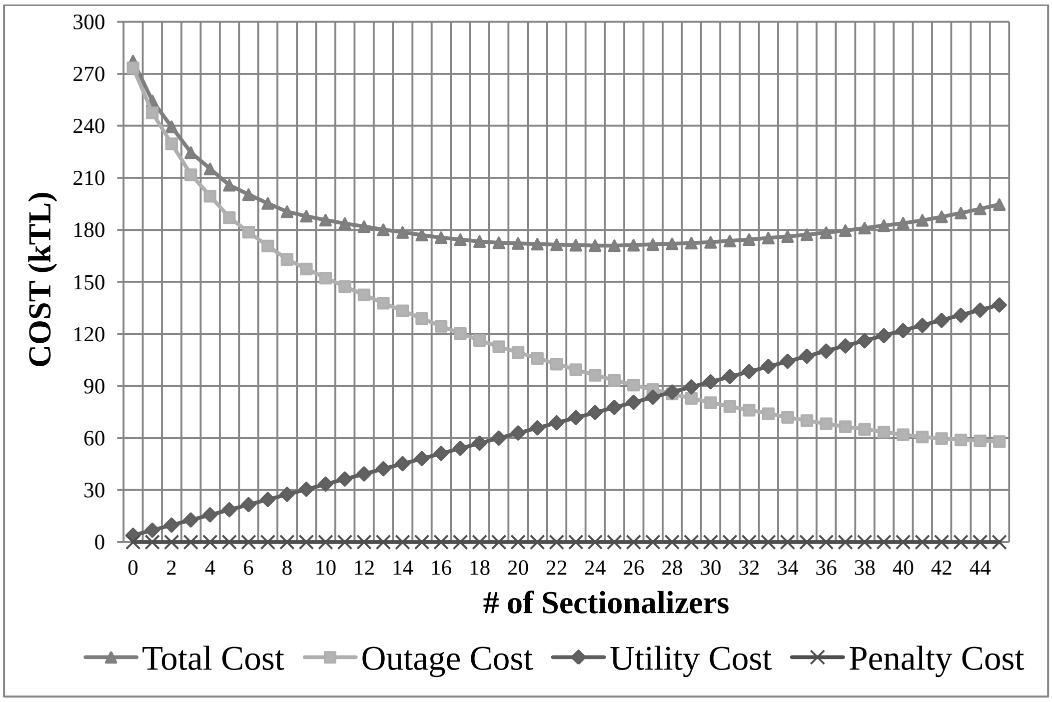

Figure 57 Case2: Failure frequency rates 1,5pu

In Case2 the failure frequency for overhead line and distribution transformers is set to 1,5pu. Since failure frequency of the network elements is increased, the *Outage Cost* component effect on the *Total Cost* is higher compared to Base Case. In Case2 the highest value of the *Outage Cost* is 273.479TL while it was 182.282TL in Base Case. As it is expected that in Case2 the *Outage Cost* is the dominant component in *Total Cost* which forces the sectionalizing switch installations. Therefore the optimization algorithm tends to allocate more sectionalizing switches compared to Base Case. As it is seen in Figure 57 at the minimum point of *Total Cost* which gives the optimal switch allocation configuration, 25 sectionalizing switches are installed among 45 possible locations. At the optimal switch allocation configuration of Case2 the calculated values are as given in Table 32.

Table 32 Failure frequency variation case2 results

# of Sect Installed	Outage Cost (TL)	Utility Cost (TL)	Penalty Cost (TL)	Total Cost (TL)	SAIDI (hours/ year)	SAIFI (1/ year)	CAIDI (hours)
0	273.480	3.935	0	277.414	52,18	15,75	3,31
25	93.254	77.707	0	170.960	19,11	8,27	2,31

Table 32 also illustrates the reliability indices values when there is no sectionalizing switch is installed on the system and with the optimal allocation of sectionalizing switches the average interruption duration in the network (SAIDI) is decreased from 52,18 hours to 19,11 hours and the average interruption duration in the network (SAIFI) is decreased from 15,75 to 8,27.

<u>Failure Frequency Variation – Case3</u>

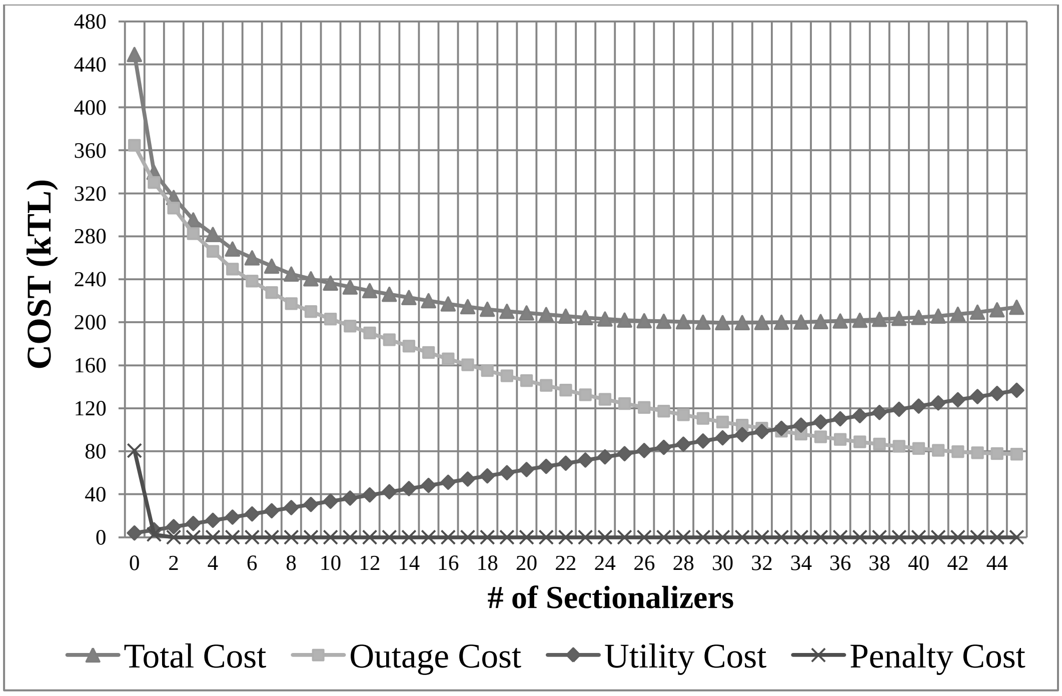

Figure 58 Case3: Failure frequency rates 2pu

In Case3 the failure frequency for overhead line and distribution transformers is set to 2pu. Since failure frequency of the network elements is increased, the *Outage Cost* component effect on the *Total Cost* is higher compared to Base Case. In Case3 the highest value of the *Outage Cost* is 364.565TL while it was 182.282TL in Base Case. As it is expected that in Case3 the *Outage Cost* is the dominant component in *Total Cost* which forces the sectionalizing switch installations. Therefore the optimization algorithm tends to allocate more sectionalizing switches compared to Base Case. As it is seen in Figure 58 at the minimum point of *Total Cost* which gives the optimal switch allocation configuration, 30 sectionalizing switches are installed among 45 possible locations. At the optimal switch allocation configuration of Case3 the calculated values are as given in Table 33.

Table 33 Failure frequency variation case3 results

# of Sect Installed	Outage Cost (TL)	Utility Cost (TL)	Penalty Cost (TL)	Total Cost (TL)	SAIDI (hours/ year)	SAIFI (1/ year)	CAIDI (hours)
0	364.566	3.935	80.587	449.087	69,56	21,00	3,31
30	107.184	92.461	0	199.644	21,97	9,98	2,20

Table 33 also illustrates the reliability indices values when there is no sectionalizing switch is installed on the system and with the optimal allocation of sectionalizing switches the average interruption duration in the network (SAIDI) is decreased from 69,56 hours to 21,97 hours and the average interruption duration in the network (SAIFI) is decreased from 21,00 to 9,98.

<u>Failure Frequency Variation – Case4</u>

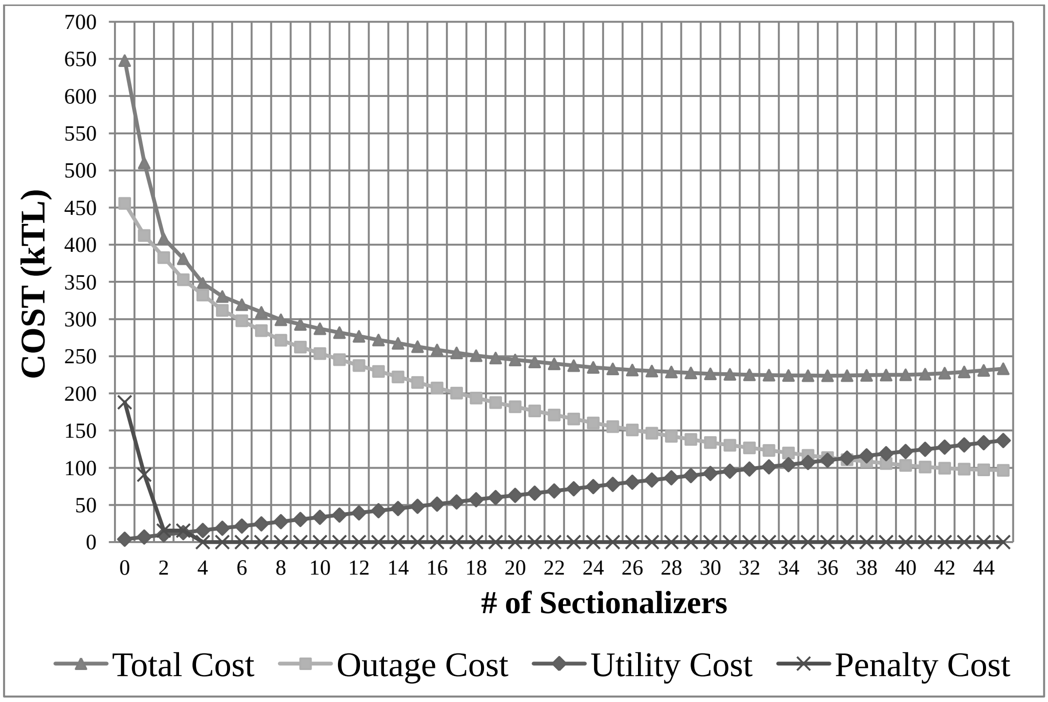

Figure 59 Case4: Failure frequency rates 2,5pu

In Case4 the failure frequency for overhead line and distribution transformers is set to 2,5pu. Since failure frequency of the network elements is increased, the *Outage Cost* component effect on the *Total Cost* is higher compared to Base Case. In Case4 the highest value of the *Outage Cost* is 455.762TL while it was 182.282TL in Base Case. As it is expected that in Case4 the *Outage Cost* is the dominant component in *Total Cost* which forces the sectionalizing switch installations. Therefore the optimization algorithm tends to allocate much more sectionalizing switches compared to Base Case. As it is seen in Figure 59 at the minimum point of *Total Cost* which gives the optimal switch allocation configuration, 36 sectionalizing switches are installed among 45 possible locations. At the optimal switch allocation configuration of Case4 the calculated values are as given in Table 34.

Table 34 Failure frequency variation case4 results

# of Sect Installed	Outage Cost (TL)	Utility Cost (TL)	Penalty Cost (TL)	Total Cost (TL)	SAIDI (hours/ year)	SAIFI (1/ year)	CAIDI (hours)
0	455.763	3.935	188.204	647.901	86,96	26,25	3,31
36	113.756	110.166	0	223.922	23,48	11,08	2,12

Table 34 also illustrates the reliability indices values when there is no sectionalizing switch is installed on the system and with the optimal allocation of sectionalizing switches the average interruption duration in the network (SAIDI) is decreased from 86,96 hours to 23,48 hours and the average interruption duration in the network (SAIFI) is decreased from 26,25 to 11,08.

Failure Frequency Variation – Case5

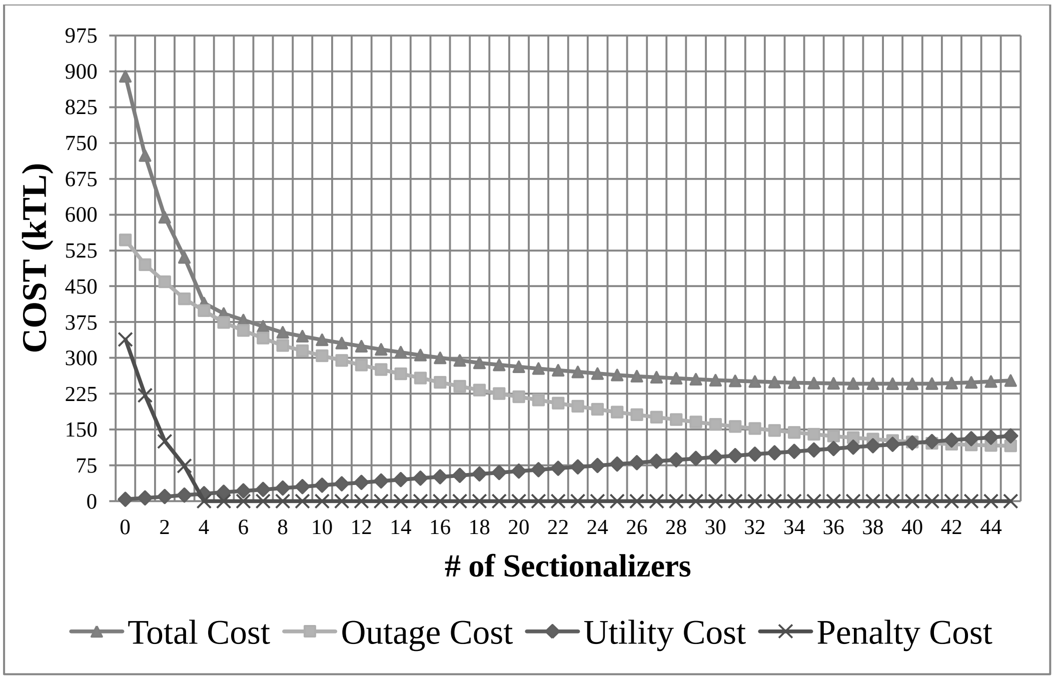

Figure 60 Case5: Failure frequency rates 3pu

In Case5 the failure frequency for overhead line and distribution transformers is set to 3pu.

Since failure frequency of the network elements is increased substantially, the *Outage Cost* component effect on the *Total Cost* is higher compared to Base Case. In Case5 the highest value of the *Outage Cost* is 546.848TL while it was 182.282TL in Base Case. As it is expected that in Case5 the *Outage Cost* is the dominant component in *Total Cost* which forces the sectionalizing switch installations. Therefore the optimization algorithm tends to allocate much more sectionalizing switches compared to Base Case. As it is seen in Figure 60 at the minimum point of *Total Cost* which gives the optimal switch allocation configuration, 40 sectionalizing switches are installed among 45 possible locations. At the optimal switch allocation configuration of Case5 the calculated values are as given in Table 35.

Table 35 Failure frequency variation case5 results

# of Sect Installed	**Outage Cost (TL)**	**Utility Cost (TL)**	**Penalty Cost (TL)**	**Total Cost (TL)**	**SAIDI (hours/ year)**	**SAIFI (1/ year)**	**CAIDI (hours)**
0	546.848	3.935	338.528	889.310	104,34	31,50	3,31
40	123.869	121.970	0	245.839	25,59	12,26	2,09

Table 35 also illustrates the reliability indices values when there is no sectionalizing switch is installed on the system and with the optimal allocation of sectionalizing switches the average interruption duration in the network (SAIDI) is decreased from 104,34 hours to 25,59 hours and the average interruption duration in the network (SAIFI) is decreased from 31,50 to 12,26.

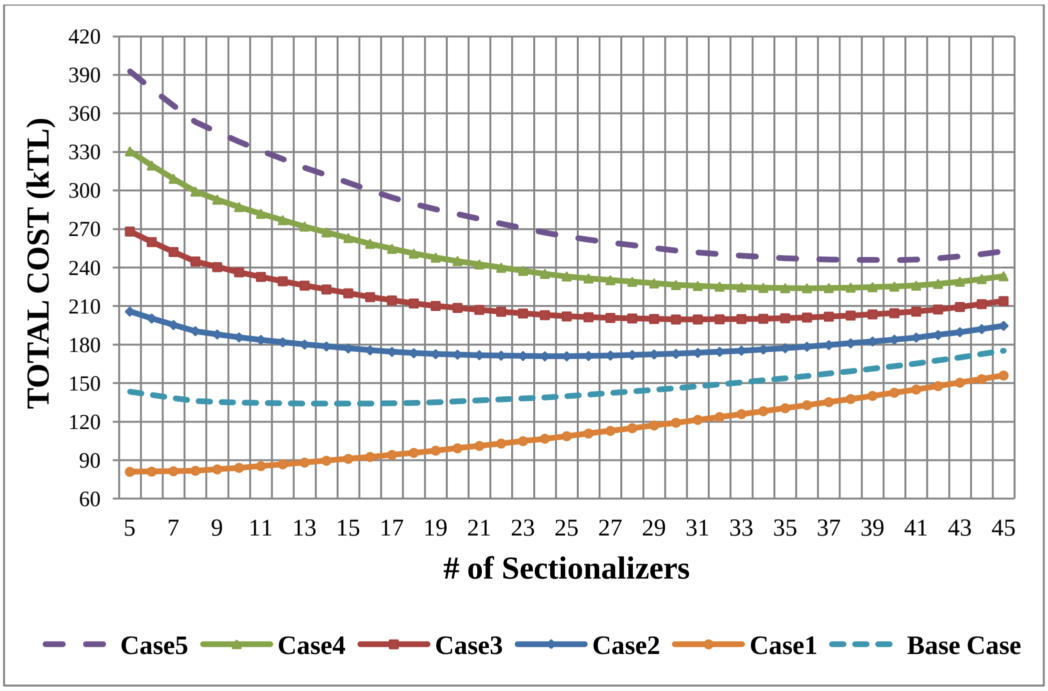

Figure 61 Total cost behavior with failure frequency variation

In Figure 61 the *Total Cost* behavior for 6 cases (including Base Case) are presented. As the failure frequency of the network elements is increased, naturally the *Total Cost* level of the network increases because of the *Outage Cost* component effect. As it can be seen from the Figure 61 the optimization algorithm tends to allocate more sectionalizing switches with the increasing failure frequency. *Outage Cost* is a function of outage duration and outage frequency accordingly. When more sectionalizing switches installed on the network the total frequency of the outages subjected by the customers is decreased. Therefore the optimization algorithm tends to reduce the *Outage Cost* by the installation of more sectionalizing switches. It should also be noticed that (see Figure 58, Figure 59 and Figure 60) when the failure frequency in the network increases the *Penalty Cost* component also becomes one of the contributor term in *Total Cost*. *Penalty Cost* component never exists in loading variation cases because it is a function of outage duration and frequency.

Optimization algorithm successfully eliminates the *Penalty Cost* component at the beginning of the iterations by allocating the sectionalizing switches on the most effective locations.

When the total frequency of the outages increases, the total duration of the outages in the network increases accordingly. Figure 62 shows that the increasing outage frequency also increases the *Outage Cost* level. For example *Outage Cost* of Case1 which simulates the lowest failure frequency case moves along the bottom level while *Outage Cost* of Case5 which simulates the highest failure frequency case moves along at the top level in Figure 62.

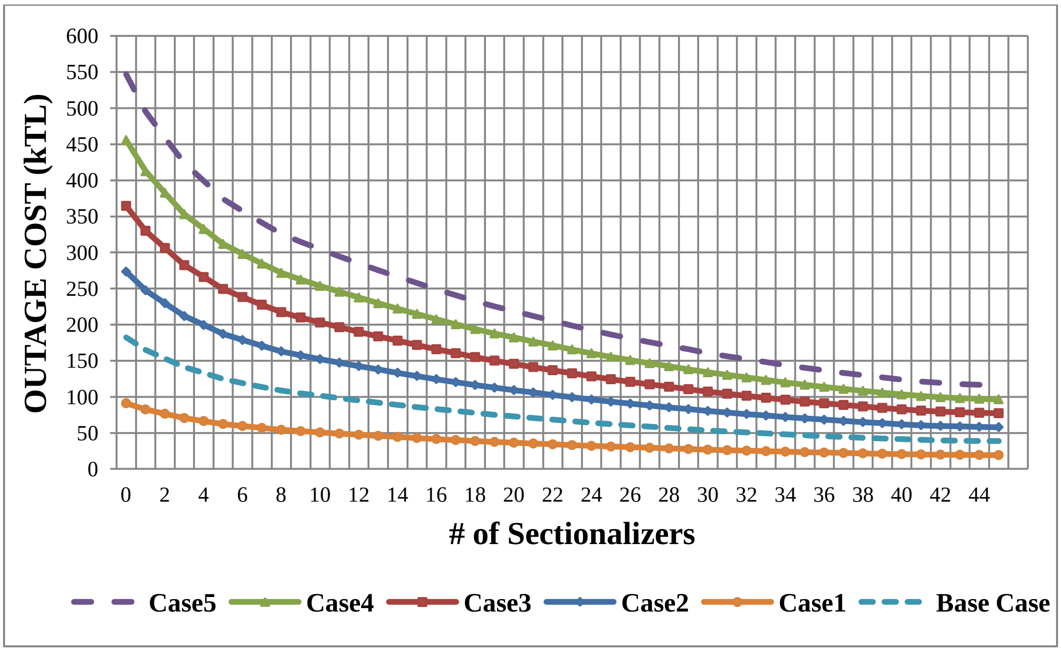

Figure 62 Outage cost behavior with failure frequency variation

As a summary the calculated results of the costs and reliability indices for analyzed 6 cases are given in Table 36. The presented results in Table 36 are the optimal sectionalizing switch allocation configurations which give the minimum *Total Cost*.

Table 36 Failure frequency variation cases optimal sectionalizing switch allocation results

Cases	OHL per km Failure Freq. (pu)	# of Sect Installed	OTC (TL)	UTC (TL)	PNC (TL)	TC (TL)	SAIDI (hours/ year)	SAIFI (1/ year)	CAIDI (hours)
Base Case	1	16	82.954	51.149	0	134.103	16,988	6,818	2,492
Case1	0,5	5	62.321	18.689	0	81.010	12,577	4,416	2,848
Case2	1,5	25	93.254	77.707	0	170.960	19,107	8,273	2,310
Case3	2	30	107.184	92.461	0	199.644	21,970	9,985	2,200
Case4	2,5	36	113.756	110.166	0	223.922	23,480	11,079	2,119
Case5	3	40	123.869	121.970	0	245.839	25,595	12,258	2,088

5.4.5. Switch Price Variation Cases

In that chapter optimization is carried out for different switch price schemes. The results of different switch unit price scenarios are presented and the effect on optimization results is analyzed. During the analysis different price scenarios are created while all other parameters are kept same with the base case parameters. The unit price cases analyzed are given in Table 37.

Table 37 Switch unit price variation scenarios

Cases	Recloser Unit Price	Sectionalizing switch Unit Price
Base Case	40kTL	30kTL
Case 1	32kTL	24kTL
Case 2	24kTL	18kTL
Case 3	20kTL	15kTL
Case 4	10kTL	7,5kTL

<u>Switch Price Variation – Case1</u>

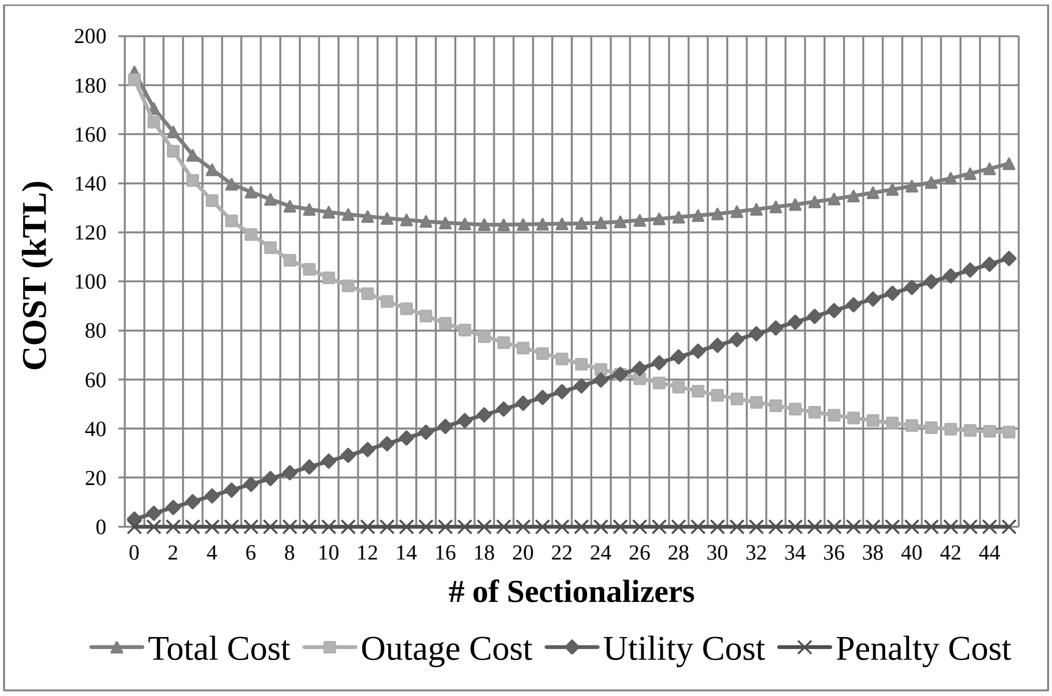

Figure 63 Case1: Rec unit price 32kTL, sect unit price 24kTL

In Case1 the unit prices of the recloser and sectionalizing switch are set to 32kTL and 24kTL respectively. Since the unit prices of the switches are decreased 20%, the *Utility Cost* component effect on the *Total Cost* is relatively small compared to Base Case. As it is expected that in Case1 the *Outage Cost* is the dominant component in *Total Cost* which forces the sectionalizing switch installations. Therefore the optimization algorithm tends to allocate slightly more sectionalizing switches compared to Base Case. As it is seen in Figure 63 at the minimum point of *Total Cost* which gives the optimal switch allocation configuration, 19 sectionalizing switches are installed among 45 possible locations. At the optimal switch allocation configuration of Case1 the calculated values are as given in Table 38.

Table 38 Switch Unit Price Variation Case1 Results

# of Sect Installed	Outage Cost (TL)	Utility Cost (TL)	Penalty Cost (TL)	Total Cost (TL)	SAIDI (hours/ year)	SAIFI (1/ year)	CAIDI (hours)
0	182.283	3.148	0	185.430	34,78	10,50	3,31
19	75.091	48.001	0	123.092	15,42	6,36	2,43

Table 38 also illustrates the reliability indices values when there is no sectionalizing switch is installed on the system and with the optimal allocation of sectionalizing switches the average interruption duration in the network (SAIDI) is decreased from 34,78 hours to 15,42 hours and the average interruption duration in the network (SAIFI) is decreased from 10,50 to 6,36.

Switch Price Variation – Case2

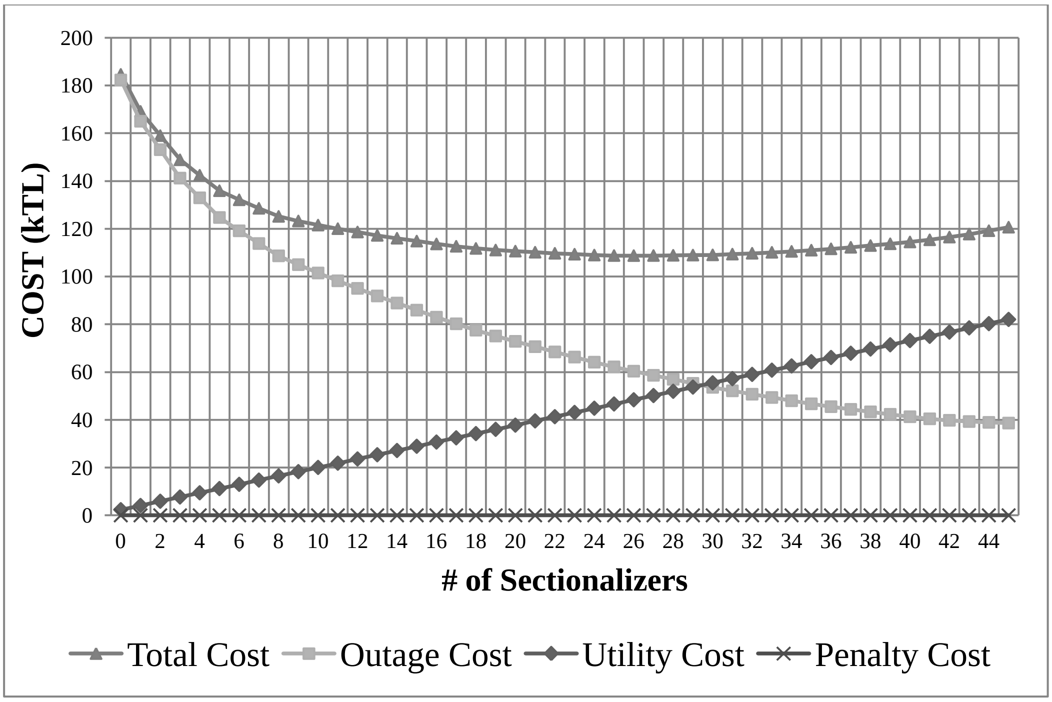

Figure 64 Case2: Rec Unit Price 24kTL, Sect Unit Price 18kTL

In Case2 the unit prices of the recloser and sectionalizing switch are set to 24kTL and 18kTL respectively.

Since the unit prices of the switches are decreased 40%, the *Utility Cost* component effect on the *Total Cost* is relatively small compared to Base Case. As it is expected that in Case2 the *Outage Cost* is the dominant component in *Total Cost* which forces the sectionalizing switch installations. Therefore the optimization algorithm tends to allocate more sectionalizing switches compared to Base Case. As it is seen in Figure 64 at the minimum point of *Total Cost* which gives the optimal switch allocation configuration, 26 sectionalizing switches are installed among 45 possible locations. At the optimal switch allocation configuration of Case2 the calculated values are as given in Table 39.

Table 39 Switch unit price variation case2 results

# of Sect Installed	Outage Cost (TL)	Utility Cost (TL)	Penalty Cost (TL)	Total Cost (TL)	SAIDI (hours/ year)	SAIFI (1/ year)	CAIDI (hours)
0	182.283	2.361	0	184.643	34,78	10,50	3,31
26	60.364	48.394	0	108.759	12,30	5,39	2,28

Table 39 also illustrates the reliability indices values when there is no sectionalizing switch is installed on the system and with the optimal allocation of sectionalizing switches the average interruption duration in the network (SAIDI) is decreased from 34,78 hours to 12,30 hours and the average interruption duration in the network (SAIFI) is decreased from 10,50 to 5,39.

Switch Price Variation – Case3

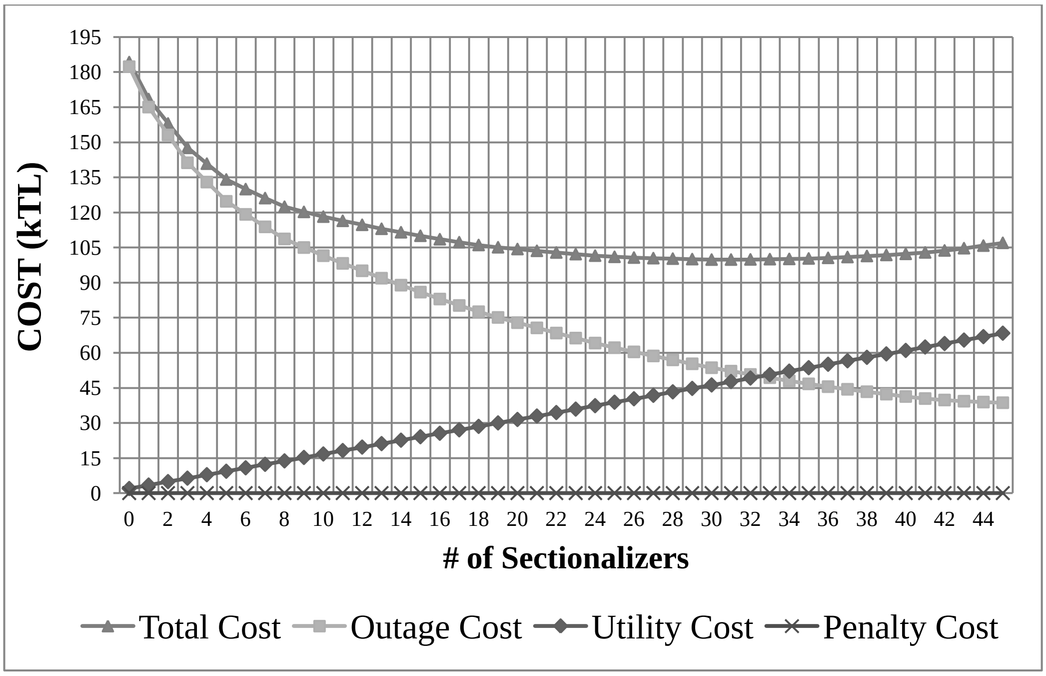

Figure 65 Case3: Rec unit price 20kTL, sect unit price 15kTL

In Case3 the unit prices of the recloser and sectionalizing switch are set to 20kTL and 15kTL respectively. Since the unit prices of the switches are decreased 50%, the *Utility Cost* component effect on the *Total Cost* is relatively small compared to Base Case. As it is expected that in Case3 the *Outage Cost* is the dominant component in *Total Cost* which forces the sectionalizing switch installations. Therefore the optimization algorithm tends to allocate much more sectionalizing switches compared to Base Case. As it is seen in Figure 65 at the minimum point of *Total Cost* which gives the optimal switch allocation configuration, 30 sectionalizing switches are installed among 45 possible locations. At the optimal switch allocation configuration of Case3 the calculated values are as given in Table 40.

Table 40 Switch unit price variation case3 results

# of Sect Installed	Outage Cost (TL)	Utility Cost (TL)	Penalty Cost (TL)	Total Cost (TL)	SAIDI (hours/ year)	SAIFI (1/ year)	CAIDI (hours)
0	182.283	1.967	0	184.250	34,78	10,50	3,31
30	53.592	46.230	0	99.822	10,98	4,99	2,20

Table 40 also illustrates the reliability indices values when there is no sectionalizing switch is installed on the system and with the optimal allocation of sectionalizing switches the average interruption duration in the network (SAIDI) is decreased from 34,78 hours to 10,98 hours and the average interruption duration in the network (SAIFI) is decreased from 10,50 to 4,99.

Switch Price Variation – Case4

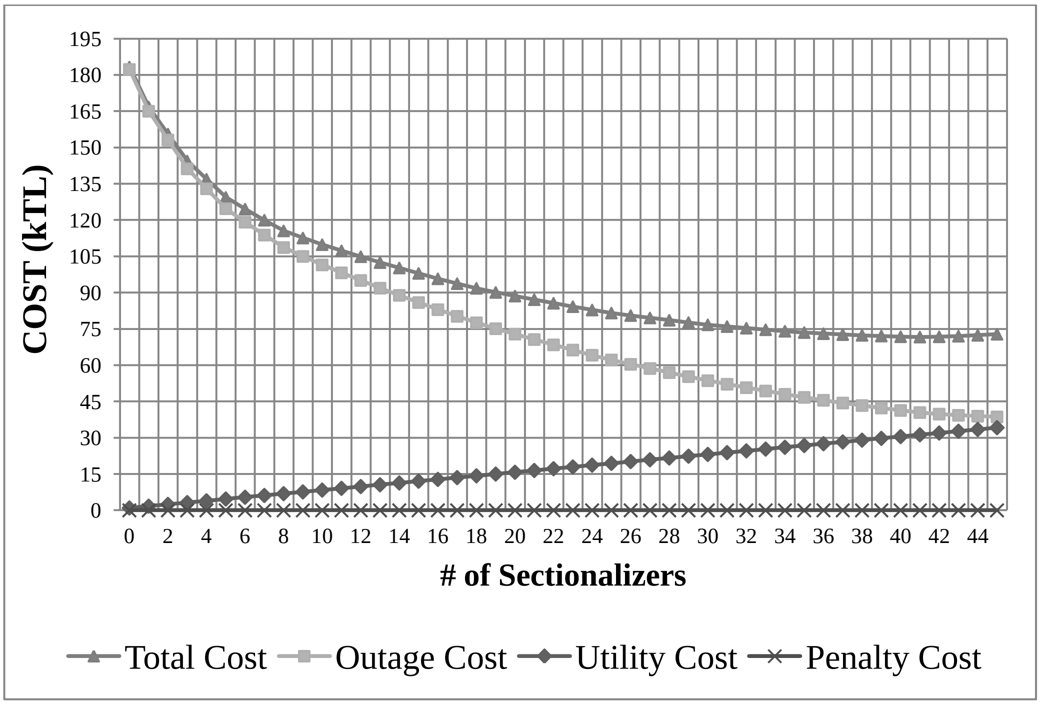

Figure 66 Case4: Rec unit price 10kTL, sect unit price 7,5kTL

In Case4 the unit prices of the recloser and sectionalizing switch are set to 10kTL and 7,5kTL respectively. Since the unit prices of the switches are decreased substantially, the *Utility Cost* component effect on the *Total Cost* is very small compared to Base Case. As it is expected that in Case4 the *Outage Cost* becomes the dominant component in *Total Cost* which forces the sectionalizing switch installations. Therefore the optimization algorithm tends to allocate sectionalizing switches nearly at all possible locations. As it is seen in Figure 66 at the minimum point of *Total Cost* which gives the optimal switch allocation configuration, 41 sectionalizing switches are installed among 45 possible locations.

At the optimal switch allocation configuration of Case4 the calculated values are as given in Table 41.

Table 41 Switch unit price variation case4 results

# of Sect Installed	**Outage Cost (TL)**	**Utility Cost (TL)**	**Penalty Cost (TL)**	**Total Cost (TL)**	**SAIDI (hours/ year)**	**SAIFI (1/ year)**	**CAIDI (hours)**
0	182.283	984	0	183.266	34,78	10,50	3,31
41	40.419	31.230	0	71.649	8,37	4,03	2,08

Table 41 also illustrates the reliability indices values when there is no sectionalizing switch is installed on the system and with the optimal allocation of sectionalizing switches the average interruption duration in the network (SAIDI) is decreased from 34,78 hours to 8,37 hours and the average interruption duration in the network (SAIFI) is decreased from 10,50 to 4,03.

In Figure 67 the *Total Cost* behavior for 5 cases (including Base Case) are presented.

As the unit price of the switches decreases, naturally the *Total Cost* level of the network decreases because of the reducing *Utility Cost* component effect. As it can be seen from the Figure 67 the optimization algorithm tends to allocate more sectionalizing switches with lower switch prices.

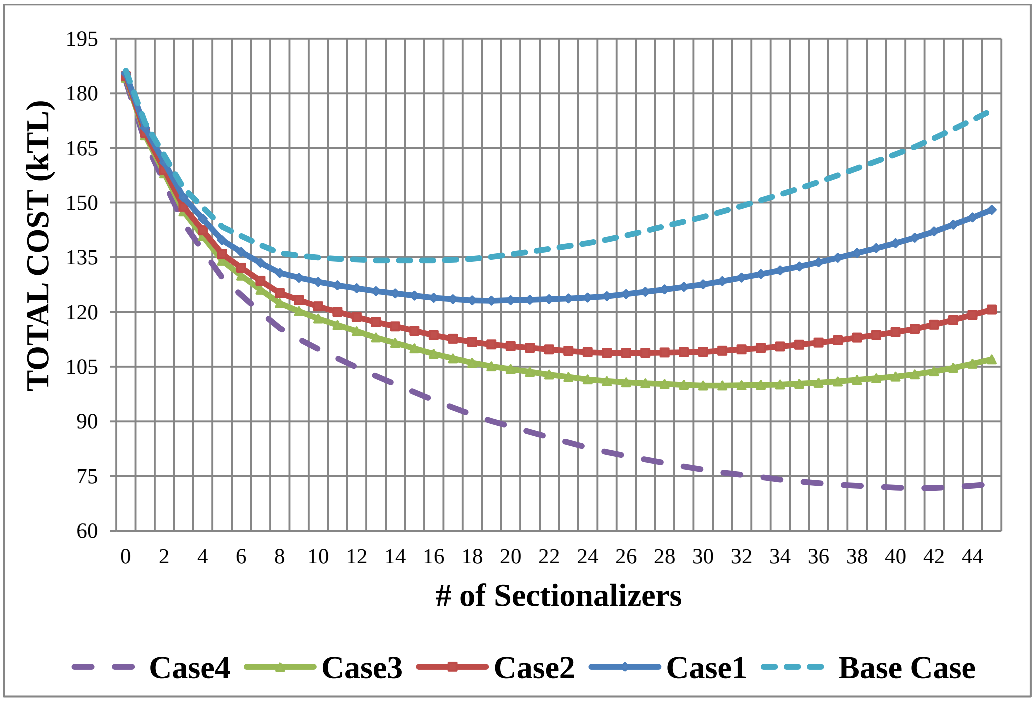

Figure 67 Total cost behavior with switch price variation

As a summary the calculated results of the costs and reliability indices for analyzed 5 cases are given in Table 42. The results presented in Table 42 are for the optimal sectionalizing switch allocation configurations which give the minimum *Total Cost*.

Table 42 Switch unit price variation cases optimal sectionalizing switch allocation results

Cases	Switch Unit Price (pu)	# of Sect Installed	OTC (TL)	UTC (TL)	PNC (TL)	TC (TL)	SAIDI (hours/ year)	SAIFI (1/ year)	CAIDI (hours)
Base Case	1	16	82.954	51.149	0	134.103	16,988	6,818	2,492
Case1	0,8	19	75.091	48.001	0	123.092	15,423	6,358	2,426
Case2	0,6	26	60.364	48.394	0	108.759	12,304	5,387	2,284
Case3	0,5	30	53.592	46.230	0	99.822	10,985	4,993	2,200
Case4	0,25	41	40.419	31.230	0	71.649	8,370	4,028	2,078

5.4.6. Penalty Threshold Variation Cases

In that chapter optimization is carried out for three penalty threshold schemes with the increased failure parameters. The results of three penalty threshold scenarios are presented and the effect on optimization results is analyzed.

During the analysis in order to show the *Penalty Cost* effect on the *Total Cost* structure the failure frequency and duration parameters are doubled. The cases analyzed are given in Table 43.

Table 43 Penalty threshold variation scenarios

Cases	Duration Penalty Threshold (hours/year)	Frequency Penalty Threshold (1/year)	Line per km failure frequency (pu)	TR Failure Frequency (pu)	Line per km failure duration (pu)
Base Case	96	72	1	1	1
Case 1	48	36	2	2	2
Case 2	32	24	2	2	2
Case 3	24	18	2	2	2

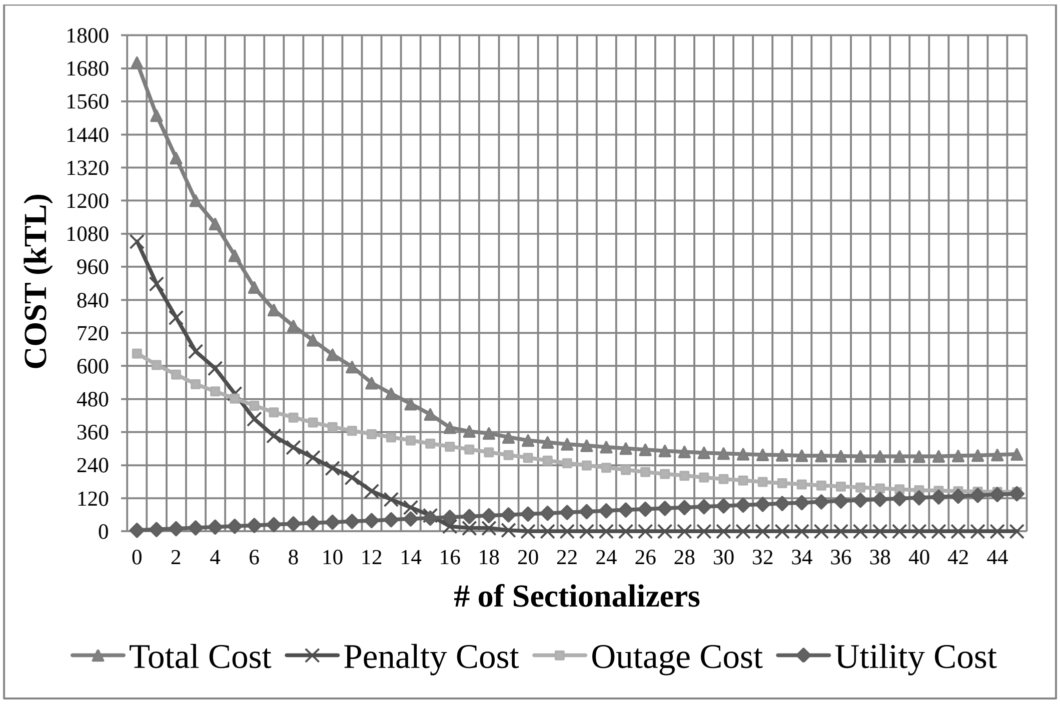

Figure 68 Case1: Penalty threshold limits are decreased 50%

In Figure 68 results of the Case1 where the penalty threshold limits are decreased 50% is presented. Figure 68 reveals the effect of the *Penalty Cost* component on the *Total Cost* structure. When the threshold limits are reduced the effect of the *Penalty Cost* is seen clearly since the maximum value of the *Total Cost* reaches to the level of millions. Until the *Penalty Cost* is diminished, it is the dominant component which determines the structure of the *Total Cost*. With the installation of sectionalizing switch since the outage durations subjected by the customers are decreased and the *Penalty Cost* decreases accordingly and sharply. Thereby it can be said that the decrease on the penalty thresholds forces the improvement of the continuity of supply quality of the network since the distribution feeders are more probable to exceed the penalty limits with lower penalty threshold values. It should be noticed that in the Base Case when the outage frequency and duration was 1pu and the penalty threshold limits are high the *Penalty Cost* component has no effect on the *Total Cost* structure since none of the feeders exceeds the penalty limits.

Thereby it can be said that the penalty threshold limits set by the continuity of supply regulation is scot free and with these threshold limits the necessary motivation for enhancing the continuity of supply quality in rural regions might not be encouraged.

And Figure 69 illustrates the behaviour of the *Total Cost* with decreasing penalty threshold limits. As expected when the penalty threshold is decreased, the *Total Cost* reaches higher levels due to the *Penalty Cost* contribution. As seen in the figure the optimization algorithm succesfully reduces the *Penalty Cost* contribution with decreasing the outage durations by allocation of the sectionalizing switches on the most effective locations.

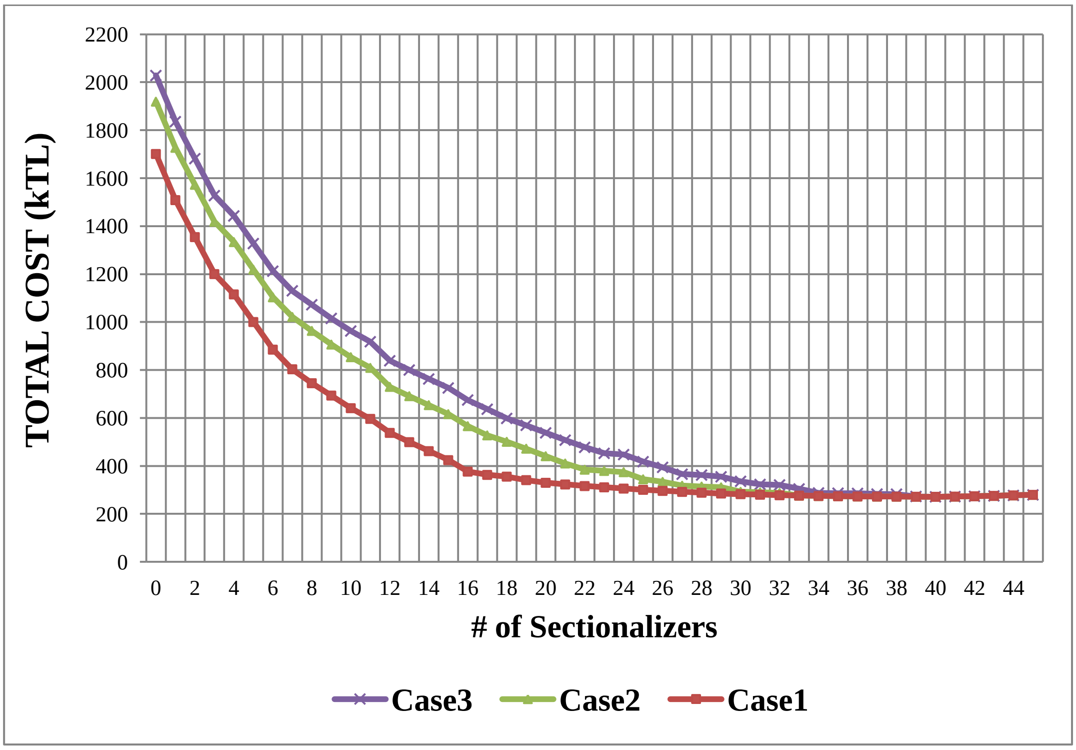

Figure 69 Total cost behavior with penalty threshold limits variation

The iteration results of the optimization algorithm till the elimination of *Penalty Cost* component for Case1 analysis is presentedin Table 44.

Table 44 Penalty variation case1 iteration results for penalty cost elimination

# of Sect Installed	Outage Cost (TL)	Utility Cost (TL)	Penalty Cost (TL)	Total Cost (TL)	SAIDI (hours/ year)	SAIFI (1/ year)	CAIDI (hours)
0	645.451	3.935	1.051.703	1.701.089	124,427	20,999	5,925
1	603.999	6.885	897.874	1.508.758	113,595	20,150	5,638
2	569.187	9.836	775.472	1.354.495	105,749	19,438	5,440
3	534.375	12.787	653.070	1.200.233	97,903	18,726	5,228
4	508.134	15.738	591.719	1.115.591	93,583	18,189	5,145
5	482.043	18.689	499.684	1.000.416	88,626	17,664	5,017
6	455.952	21.640	407.649	885.242	83,669	17,138	4,882
7	432.080	24.591	346.667	803.338	79,784	16,655	4,790
8	413.104	27.542	304.587	745.232	76,715	16,187	4,739
9	395.308	30.492	267.918	693.719	73,885	15,755	4,689
10	378.553	33.443	229.075	641.071	71,201	15,346	4,640
11	365.143	36.394	194.925	596.462	68,978	15,070	4,577
12	352.936	39.345	145.770	538.051	65,882	14,821	4,445
13	341.274	42.296	115.848	499.418	63,877	14,471	4,414
14	330.000	45.247	86.716	461.963	62,110	14,202	4,373
15	318.727	48.198	57.583	424.508	60,343	13,932	4,331
16	307.457	51.149	18.032	376.637	58,568	13,692	4,278
17	297.249	54.099	11.566	362.914	56,841	13,386	4,246
18	287.041	57.050	11.566	355.657	55,114	13,080	4,213
19	276.950	60.001	4.210	341.161	53,471	12,828	4,168
20	267.027	62.952	0	329.980	51,765	12,497	4,142

As it is shown in Table 44 optimization algorithm eliminates the *Penalty Cost* with 20 sectionalizing switch installations among 45 possible locations. The improvement of the continuity of supply can be observed by the enhancement of SAIDI and SAIFI indices thorought the iterations. When the system average interruption duration (SAIDI) enhances 59%, the system average interruption frequency (SAIFI) enhances 40% with the allocation of Sectionalizing switches to the first 20 most effective locations among 45 possible locations.

CHAPTER 6

CONCLUSIONS AND FUTURE WORK

In this thesis study an algorithm is presented in order to determine the optimum number and locations of the sectionalizing switches on rural distribution systems.

In rural regions, conventionally, electrical distribution system has a radial topology following an arborescent structure with many branch lines. The rural distribution network consists of long radial overhead lines and continuity of supply is a major problem due to the high failure rates. Since the ring design is not feasible in rural regions due to the high investment cost, sectionalizing the network with the implementation of automated switches becomes the most applicable solution in order to enhance the continuity of supply. In this study in order to analyze the system reliability, a reliability model for the radial distribution systems is created and the significant positive effect of the sectionalizing switches and reclosers are presented with the results of reliability analysis.

As the continuity of supply quality of the distribution system enhances with the sectionalizing switch installations, investment cost also increases. However, low system reliability causes higher outage frequency and duration which will increase the damage of these outages to customers and also increases cost of the distribution company as a result of the penalty payments. This tradeoff between *Outage Cost* and *Utility Cost* requires an optimization when determining the optimal number of sectionalizing switches and their locations.

In this study an optimization algorithm is implemented which successfully determines the optimal number and locations for the sectionalizing switches in rural distribution systems. With the optimization algorithm when the *Outage Cost* due to the interruption duration is decreased, the *Utility Cost* due to the switch investment and cost due to the penalty payments are kept at optimal levels.

The main conclusions reached throughout this study can be stated by the following;

- With the implementation of reclosers continuity of supply in the the rural distribution systems can be enhanced substantially by the elimination of transient nature faults effect,

- With the implementation of sectionalizing switches the faulted parts in the rural distribution network can be isolated in case of sustained faults and the cost due to the outage durations can be decreased substaintially,

- It is possible to determine optimal allocation of sectionalizing switches for the radial networks where the possible number of installation locations is high by use of an optimization algorithm which reduces the volume of the solution space,

- The failure frequency and duration data should be recorded by the DSOs precisely and carrefully. Such information is critical for the reliability assesment of the electrical distribution systems. The failure data shared in this thesis is a first in Turkey however it can not be claimed to be 100% true,

- The penalty threshold limits set for the rural regions in Turkey by the regulations on quality of supply is scot free and should be reviewed. With these threshold limits the necessary motivation for enhancing the continuity of supply quality in rural regions might not be encouraged. However this conclusion is based on the results of the analysis performed with the gathered data which can not be claimed to be 100% true. In case of higher failure rates *Penalty Cost* might reach to levels of millions as analyzed in failure duration and frequency variation cases. As analyzed in these cases with the optimal allocation of sectionalizing switches *Penalty Cost* can be reduced gradually with an optimum investment,

- The feeder definition for the EKSÜREG (Equivalent Annual Interruption Duration Index) and EKSIKG (Equivalent Annual Interruption Frequency Index) indices should be restructured. If the feeder based threshold limits maintain in the regulations, there should be spesific threshold limit definitions for the feeders of different length. Even if the customers connected to feeders with a short line legth are subjected to long outage durations in a year, since the annual total durations of the outages on the feeder might not exceed the annaul outage duration threshold limit there will not be enforcement to enhance continuity of supply for these feeders,

- The *Outage Cost* which is the incurred cost due to the durations during which the electricity cannot be supplied to the connected customers of the network is the main motivator which forces the sectionalizing switch investment on rural distribution systems in order to reduce the customer interruption durations.

And the work for the future investigation can be summarized by the following;

- A study for the development of a *Sector Customer Damage Function (SCDF)* which is a function of customer class and outage duration should be carried out by the DSOs in Turkey. The *SCDF* is critical in order to estimate monetary loss (damage) incurred by customers due to power outages,

- In this study the monetary cost incurred by the customers *(Outage Cost)* is calculated with the assumption of an average load on load points. By including the load variations on the load points (MV/LV distribution transformers) more precise results for *Outage Cost* can be achieved,

- The cost and reliability indices formulations in the scope of this study is derived for the distribution systems with radial topology. By enhancing the formulations of the cost and reliability indices for the loop designed systems, the optimal allocation of automated switches or RTUs (remote terminal unit) for urban regions where conventionally the electrical distribution network is loop desinged can be achieved.

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APPENDIX A

THRESHOLD VALUES FOR RELIABILITY INDICES

The threshold values for the continuity of supply indices are as given below in Table 47, Table 46 and Table 47.

Table 45 OKSUREG threshold values

Municipality Type	2007	2008	2009	2010
High Density (Urban)	8 h	7 h	6 h	5 h
Low Density (Rural)	20 h	18 h	16 h	15 h

Table 46 OKSIKG threshold values

Municipality Type	2007	2008	2009	2010
High Density (Urban)	4 times last more than 6 h	4 times last more than 6 h	3 times last more than 5 h	3 times last more than 5 h
Low Density (Rural)	6 times lasted more than 9 h	6 times lasted more than 9 h	5 times lasted more than 8 h	5 times lasted more than 8 h

Table 47 EKSIKG and EKSÜREG threshold values

Municipality Type	Threshold Values
MD_{dur} High Density (Urban)	72 h
MD_{freq} High Density (Urban)	56 times
MD_{dur} Low Density (Rural)	96 h
MD_{freq} Low Density (Rural)	72 times

APPENDIX B

INPUT DATA OF THE KÖK FEEDERS ANALYZED

In Numerical Analysis chapter optimized algorithm results are presented for a KÖK which consists of 6 feeders and 45 clusters in total. The input data of the network is as given in Table 48.

Table 48 Input data of the KÖK

Feeder Name	Cluster/ Main Line	Length (km)	# of TR	Load Type	Load (kW)	Number of Connected Customers
F1	**Cluster1**	5,0	3	Res	19,2	120
F1	**Cluster2**	7,0	3	Res	19,2	120
F1	**Cluster3**	4,0	3	Res	19,2	120
F1	**Cluster4**	3,0	6	Agr	38,4	24
F1	**Cluster5**	10,0	6	Res	38,4	240
F1	**Cluster6**	6,0	6	Agr	38,4	24
F1	**Cluster7**	4,0	9	Res	57,6	360
F1	**Cluster8**	12,0	15	Res	96,0	600
F1	**Cluster9**	4,0	9	Res	57,6	360
F1	**Cluster10**	12,0	15	Res	96,0	600
F1	**Mainline Seg1**	3,0	-	-	-	-
F1	**Mainline Seg2**	3,0	-	-	-	-
F1	**Mainline Seg3**	3,0	-	-	-	-
F1	**Mainline Seg4**	3,0	-	-	-	-
F1	**Mainline Seg5**	3,0	-	-	-	-
F1	**Mainline Seg6**	3,0	-	-	-	-
F1	**Mainline Seg7**	3,0	-	-	-	-
F1	**Mainline Seg8**	3,0	-	-	-	-
F1	**Mainline Seg9**	3,0	-	-	-	-

Feeder Name	Cluster/ Main Line	Length (km)	# of TR	Load Type	Load (kW)	Number of Connected Customers
F1	**Mainline Seg10**	3,0	-	-	-	-
F2	**Cluster1**	6,0	3	Res	19,2	120
F2	**Cluster2**	14,0	9	Res	57,6	360
F2	**Cluster3**	8,0	6	Agr	38,4	24
F2	**Cluster4**	5,0	18	Res	115,2	720
F2	**Cluster5**	10,0	3	Res	19,2	120
F2	**Cluster6**	16,0	3	Res	19,2	120
F2	**Cluster7**	14,0	9	Res	57,6	360
F2	**Cluster8**	8,0	6	Res	38,4	240
F2	**Cluster9**	5,0	18	Res	115,2	720
F2	**Cluster10**	6,0	3	Agr	19,2	12
F2	**Mainline Seg1**	2,5	-	-	-	-
F2	**Mainline Seg2**	2,5	-	-	-	-
F2	**Mainline Seg3**	2,5	-	-	-	-
F2	**Mainline Seg4**	2,5	-	-	-	-
F2	**Mainline Seg5**	2,5	-	-	-	-
F2	**Mainline Seg6**	2,5	-	-	-	-
F2	**Mainline Seg7**	2,5	-	-	-	-
F2	**Mainline Seg8**	2,5	-	-	-	-
F2	**Mainline Seg9**	2,5	-	-	-	-
F2	**Mainline Seg10**	2,5	-	-	-	-
F3	**Cluster1**	1,8	3	Agr	19,2	12
F3	**Cluster2**	2,6	9	Res	57,6	360
F3	**Cluster3**	8,0	6	Res	38,4	240
F3	**Cluster4**	6,0	18	Res	115,2	720
F3	**Cluster5**	2,0	3	Agr	19,2	12
F3	**Cluster6**	2,6	9	Res	57,6	360
F3	**Cluster7**	1,8	6	Res	38,4	240
F3	**Cluster8**	6,0	18	Res	115,2	720
F3	**Mainline Seg1**	3,2	-	-	-	-
F3	**Mainline Seg2**	3,2	-	-	-	-
F3	**Mainline Seg3**	3,2	-	-	-	-
F3	**Mainline Seg4**	3,2	-	-	-	-
F3	**Mainline Seg5**	3,2	-	-	-	-
F3	**Mainline Seg6**	3,2	-	-	-	-
F3	**Mainline Seg7**	3,2	-	-	-	-

Feeder Name	Cluster/ Main Line	Length (km)	# of TR	Load Type	Load (kW)	Number of Connected Customers
F3	**Mainline Seg8**	3,2	-	-	-	-
F4	**Cluster1**	6,0	3	Res	19,2	120
F4	**Cluster2**	7,0	9	Res	57,6	360
F4	**Cluster3**	8,0	6	Res	38,4	240
F4	**Cluster4**	9,0	18	Res	115,2	720
F4	**Cluster5**	5,0	3	Res	19,2	120
F4	**Cluster6**	6,0	9	Agr	57,6	36
F4	**Cluster7**	8,0	6	Res	38,4	240
F4	**Mainline Seg1**	3,0	-	-	-	-
F4	**Mainline Seg2**	3,0	-	-	-	-
F4	**Mainline Seg3**	3,0	-	-	-	-
F4	**Mainline Seg4**	3,0	-	-	-	-
F4	**Mainline Seg5**	3,0	-	-	-	-
F4	**Mainline Seg6**	3,0	-	-	-	-
F4	**Mainline Seg7**	3,0	-	-	-	-
F5	**Cluster1**	10,0	6	Res	38,4	240
F5	**Cluster2**	7,0	9	Res	57,6	360
F5	**Cluster3**	6,0	6	Res	38,4	240
F5	**Cluster4**	8,0	18	Res	115,2	720
F5	**Cluster5**	8,0	3	Agr	19,2	12
F5	**Mainline Seg1**	1,5	-	-	-	-
F5	**Mainline Seg2**	1,5	-	-	-	-
F5	**Mainline Seg3**	1,5	-	-	-	-
F5	**Mainline Seg4**	1,5	-	-	-	-
F5	**Mainline Seg5**	1,5	-	-	-	-
F6	**Cluster1**	7,0	3	Res	19,2	120
F6	**Cluster2**	6,0	9	Res	57,6	360
F6	**Cluster3**	1,8	6	Res	38,4	240
F6	**Cluster4**	16,0	13	Res	83,2	520
F6	**Cluster5**	2,0	3	Agr	19,2	12
F6	**Mainline Seg1**	3,0	-	-	-	-
F6	**Mainline Seg2**	3,0	-	-	-	-
F6	**Mainline Seg3**	3,0	-	-	-	-
F6	**Mainline Seg4**	3,0	-	-	-	-
F6	**Mainline Seg5**	3,0	-	-	-	-

APPENDIX C

MOD 3 BUILDING LAYOUT PLANS

C.1. Mod 3 Type Kiosk Layout Plan

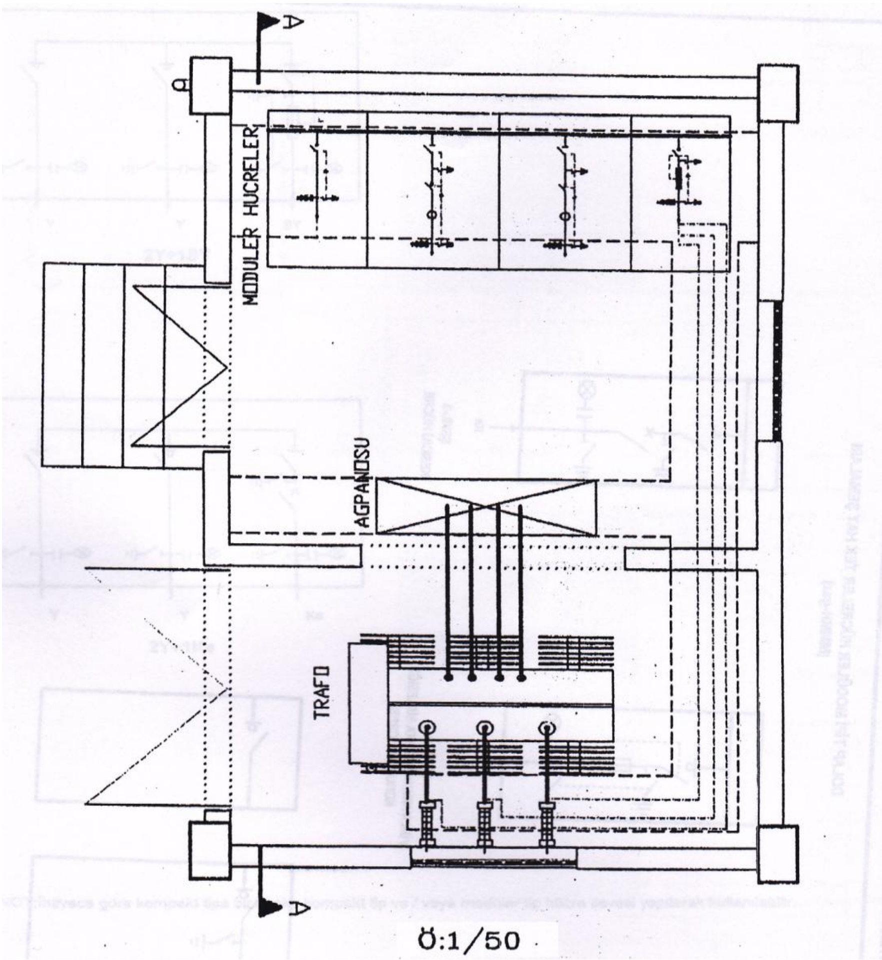

Figure 70 MOD3 type kiosk layout plan

C.2. Mod 3 Type Kiosk Detailed Layout Plan

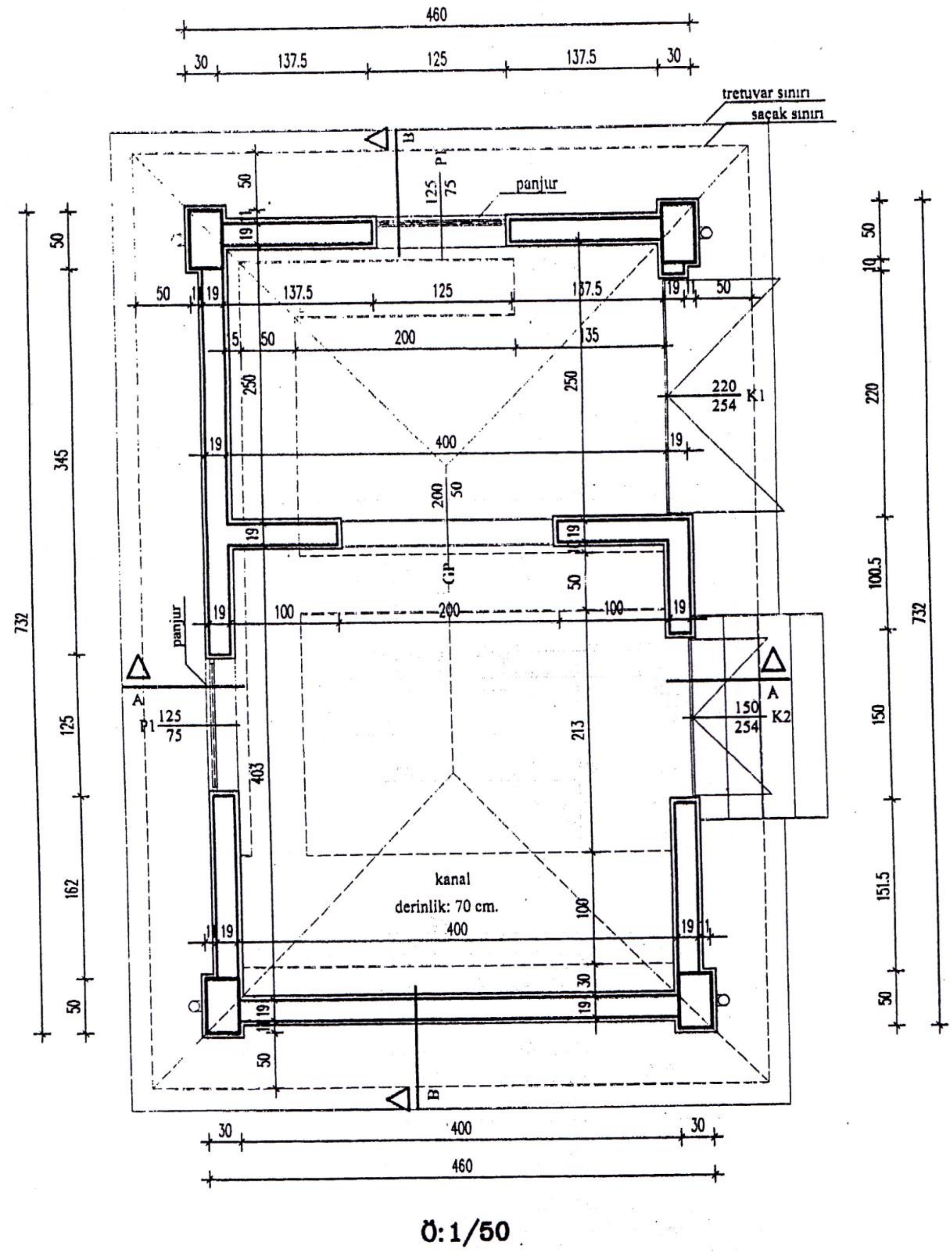

Figure 71 MOD3 type kiosk detailed layout plan