FAULT DETECTION AND SERVICE RESTORATION IN MEDIUM VOLTAGE DISTRIBUTION SYSTEM

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Approval of the thesis :

FAULT DETECTION AND SERVICE RESTORATION IN MEDIUM VOLTAGE DISTRIBUTION SYSTEM

submitted by **MÜFİT ALTIN** in partial fulfillment of the requirements for the **degree of Master of Science in Electrical and Electronics Engineering** by,

Prof. Dr. Canan Özgen
Dean, Graduate School of **Natural and Applied Sciences** __________

Prof. Dr. İsmet Erkmen
Head of Department, **Electrical and Electronics Engineering** __________

Prof. Dr. Nevzat Özay
Supervisor, **Electrical and Electronics Engineering Dept., METU** __________

Examining Committee Members:

Prof. Dr. A. Nezih Güven
Electrical and Electronics Engineering Dept., METU __________________

Prof. Dr. Nevzat Özay
Electrical and Electronics Engineering Dept., METU __________________

Prof. Dr. Ahmet Rumeli
Electrical and Electronics Engineering Dept., METU __________________

Prof. Dr. Arif Ertaş
Electrical and Electronics Engineering Dept., METU __________________

Abdullah Nadar
Head of Department, TÜBİTAK-UZAY __________________

Date: __________________

I hereby declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

Name, Last Name	:	Müfit ALTIN
Signature	:	

ABSTRACT

FAULT DETECTION AND SERVICE RESTORATION IN MEDIUM VOLTAGE DISTRIBUTION SYSTEM

Altın, Müfit

M.S., Department of Electrical and Electronics Engineering

Supervisor : Prof. Dr. Nevzat Özay

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This thesis proposes an algorithm and develops a program for fault detection and system restoration in medium voltage distribution systems.

In Turkey, TUBITAK-UZAY developed distribution automation system including fault detection and service restoration functions for Bogazici Electricity Distribution Company. By the time, expanding of distribution system with non-standardized infrastructure (for example more than one circuit breaker in the feeder, mesh and closed loop feeder structure), developed automation system have not properly worked under these unplanned situations.

Taking into consideration of previously utilized TUBITAK Distribution Automation System (TUDOSIS), fault isolation algorithm is improved to cope with practical problems as non-standardized infrastructure and selectivity issue in protection system, and the proposed isolation algorithm is simulated.

Further system restoration solution for mesh distribution systems is analyzed for distribution system in Turkey and expert system based algorithm is proposed.

Keywords –distribution automation system, fault detection, system restoration.

ÖZ

ORTA GERİLİM DAĞITIM SİSTEMLERİNDE
ARIZA İZOLASYONU VE TEKRAR ENERJİLENDİRME

Altın, Müfit

Yüksek Lisans, Elektrik-Elektronik Mühendisliği Bölümü

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Bu tez orta gerilim dağıtım sistemleri için arıza izolasyonu ve yeniden enerjilendirme algoritması önermekte olup bir program geliştirmektedir. Türkiye'de TÜBİTAK-UZAY tarafından Boğaziçi Elektrik Dağıtım Şirketi için arıza tespiti ve yeniden enerjilendirme fonksiyonlarını içeren bir dağıtım otomasyon sistemi geliştirilmiştir. Zamanla dağıtım sistemlerinde standart olmayan yapıların (örneğin fider üzerinde birden fazla kesici bulunması, *mesh* ve kapalı *ring* yapıları) sisteme dahil olmasıyla, geliştirilen dağıtım otomasyon sistemi bu planlanmayan durumlar karşısında gerektiği şekilde çalışamamaktadır.

Önceden kullanılan TÜBİTAK Dağıtım Otomasyon Sistemi (TÜDOSİS)'ni göz önünde bulundurarak arıza izolasyon algoritması standart olmayan yapılar ve koruma sistemindeki seçicilik konuları gibi pratikte karşılaşılan sorunların üstesinden gelmek için iyileştirilmiş ve önerilen izolasyon algoritması simüle edilmiştir. Bundan başka mesh dağıtım sistemleri için expert sistemlere dayanan yeniden enerjilendirme çözümleri önerilmektedir.

Keywords: Dağıtım Otomasyon Sistemi, Arıza İzolasyonu, Yeniden Enerjilendirme.

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My engineering career was started four and half years ago in Istanbul with TÜDOSİS project. I was a novice graduate from the telecommunication and computer area of the Electrical and Electronics Engineering Department and I did not realize my mistake for choosing wrong research area until come across our project advisor, Prof. Dr. Nevzat Özay. Then I decided to do my M.S. research in distribution systems under his supervision. For these great years, I would like to thank, first of all, to my supervisor for his guidance, invaluable advices concerning both life and practical engineering.

In Power System Group of TÜBİTAK-UZAY, I have had the chance to gain engineering experience in the field (in İstanbul) as a project manager. At this point I am grateful to Abdullah Nadar and Ulaş Karaağaç for supporting and believing in me about my project duty and M.S. study. Also, I cannot forget TUDOSIS Istanbul project team among whom I want to mention their names, Fatih Mehmet Yaşar, Fatih Koç, Abdullah Eker and Mehmet Barik for their cooperation and patience.

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Special thanks go to my friends Erkan Şentürk (a.k.a Sami) and Oğuz Öztürk for being an excellent housemates and indulging my whims. The hard times with this thesis would not be bearable without my intimate friends Osman, Raşid, Mevlüt, Serkan, Mert, Özge, Saygın, Nihan, Kantar, Hatice and also other members of Ankara Sosyete. Also I would like to thank Ahmet, Çiğdem, Bahadır, Merdim, Anıl and Kerem for their grate camaraderie.

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INTRODUCTION

1.1 Power Distribution System Automation

In last twenty years, electricity has been an important factor in the modern society. The electric equipments, such as air-conditioner, refrigerator, TV, and computer system, have penetrated into the modern life that it is impossible to live without them. Accordingly, the role of electricity that supports activities in such a highly electricity-dependent society is also becoming more important and customer awareness and intolerance for power system outages continues to intensify.

The separation of generation (supply), bulk transmission and distribution (delivery) into different companies has sharpened the focus of these organizations. Power distribution utilities have endeavored to implement and improve the control and management methods of distribution network. The driving force is the moves that include privatization, deregulation, and unbundling together with the other regulations for the trading and supply of energy. The owners of distribution network are being required to improve the reliability of power delivery through making the whole operating condition more efficient. In addition to reliability, power quality is another important key feature including voltage regulation and unbalance, sags, swells, and harmonic content.

Distribution automation (DA) is a complete solution to foregoing performance issues. DA concept covers the complete range of functions from protection to SCADA and associated information technology application. This concept melds together the ability to mix local automation, remote control of switching devices, and central decision making into cohesive, flexible, and cost-effective operating architecture for power distribution systems.

In practice, within DA concept there are two specific terms that are commonly used in the industry; Distribution Management System (DMS) and Distribution Automation System (DAS). DMS has an overview that provides operator the whole picture of the network regarding with the assistance of real-time functions and nonreal-time information.

The DAS fits below the DMS and includes all the remote-controlled devices at the substation and feeder levels (e.g., circuit breakers, load break switches), the local automation distributed at these devices and the communication infrastructure [1].

1.2 Fault Isolation and Service Restoration

DA functions briefly summarized as the following:

- Automatic bus sectionalizing
- Feeder deployment switching and automatic sectionalizing
- Integrated volt/var control
- Substation transformer load balancing
- Feeder load balancing
- Remote metering
- Load control

Complete DA functions are given in more detail in Appendix A. Fault isolation and service restoration which are the major focuses of this thesis, are automatic bus sectionalizing functions. Considering that distribution systems are usually operated as a set or sets of radial feeders supplied from one or more substations, a typical fault isolation, service restoration operation sequence is as follows:

Upon the occurrence of a fault, the feeder breaker will trip and automatically reclose a number of times if it is an overhead system. If the fault clears before the reclosure is complete, there is no further action required. However, for persistent faults, fault locating is based on the assumption that only the fault detectors between a faulted section and the substation circuit breaker have target set. Thus, the network is scanned until a section is found having a fault indicator set on one end, but not the other. With the faulted section specified, switches on either end of the faulted section will be opened. This is the fault isolation part. Transferring the remaining unfaulted and de-energized sections to another source or sources is the service restoration function of DA. Flow chart for fault isolation and service restoration is given in Figure 1.

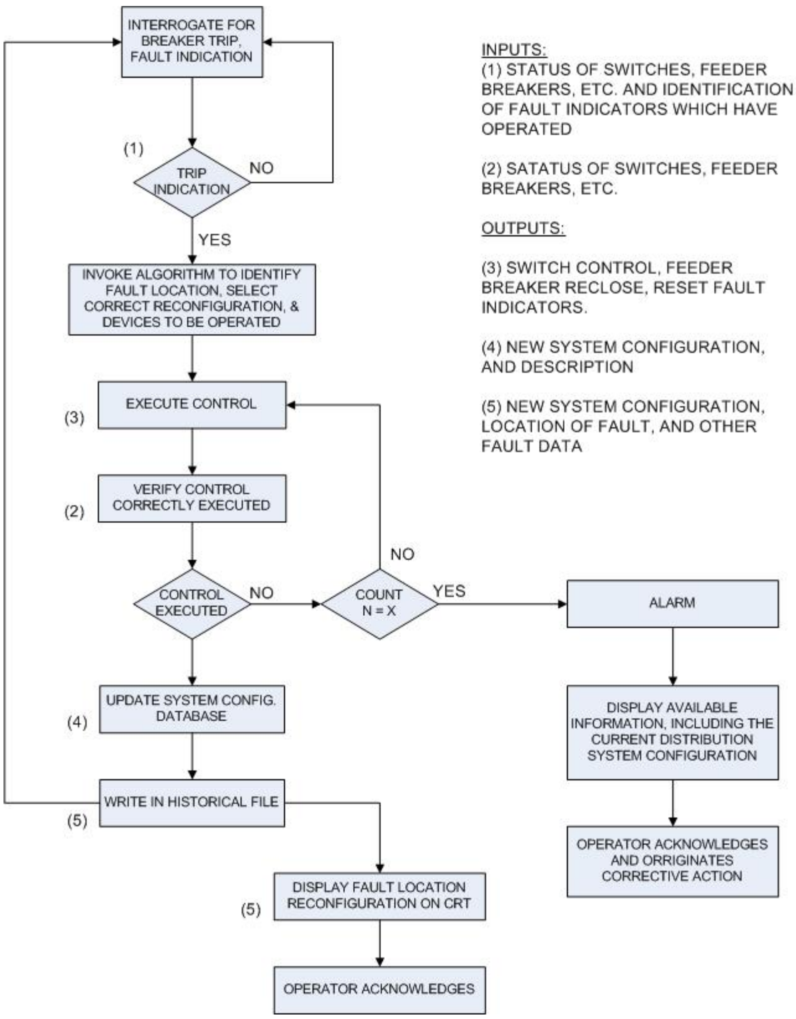

Figure 1 Flow chart for fault isolation and service restoration

1.3 TUBITAK Distribution Automation System

Turkish Electricity Distribution Company (TEDAS) had decided to uprate the primary distribution voltage level to 34.5 kV from 10.5 or 6 kV in big cities of Turkey. Therefore, more loads could be served by one feeder, as a result, reliability issue became more important. TUBITAK designed, implemented and integrated the distribution automation system, using the technology available complying with relevant international standards, is called TUDOSIS (TUBITAK Distribution Automation System) for the medium voltage distribution system of Istanbul. TUDOSIS project was carried out together with uprating distribution voltage level. As the 34.5 kV primary distribution system would start from fresh, then it would be easy to install automation system with its components such as hardware (remote terminal unit, RTU), automation prepared devices (e.g. protection relays, circuit breakers, load breaker switches) and communication medium (at the beginning fiber optic cable).

The 34.5 kV uprated distribution feeders are loop designed but radial operated network structure. In case of a fault, the fault current flows from the substation through the feeder up to the fault point. Hence, the determination of fault location is easily achieved through an RTU which is placed in the HV/MV power substation where the feeder breaker tripped, by interrogating RTUs along the feeder in the distribution transformers. Afterwards detection of fault location, fault is isolated by the opening related switches. This special RTU sends information to the control center software about fault isolation process. Control center software should restore the system according to coming information by closing the feeder circuit breaker and changing the normally open point location. TUDOSIS can allow service restoration process to execute manually, semi or full automatically by the choice of operator [3].

Unfortunately DAS could not keep up pace with the expansion of the distribution network in Istanbul, as a result non-standardized network structures (circuit breaker with protection relays along the feeder, mesh designed radial operated network structure, closed loop system) have appeared and these drawbacks have obstructed the development of TUDOSIS.

1.4 Contribution of the Thesis

In this thesis, a general solution of DAS that covers all variations of distribution network infrastructures in Turkey especially in big cities is proposed. In the literature there are two general approaches; SCADA-based and Model-based approach. In a model-based approach, all the distribution system is modeled and simulated in detail including distributed generation. However, it is not applicable to passive networks and in Turkey distributed generators are usually connected to MV buses in HV/MV substations. The proposed SCADA-based approach uses the current assets efficiently to improve reliability. The solution proposed in this thesis is inspired from previously implemented and tested system, TUDOSIS.

Contributions of the thesis are summarized as follows:

a) Improving fault isolation algorithm of TUDOSIS by implementing new RTU firmware with modifying the control center software.
b) Implementing service restoration algorithm based on expert system for mesh designed radial operated network structures.

1.5 Outline of the Thesis

In Chapter 2, a review of the previous distribution automation system, TUDOSIS, is provided with practical drawbacks of distribution system. Chapter 3 presents fault isolation solution for these drawbacks and discussion on essential concepts about protection and automation. Service restoration algorithm is proposed in Chapter 4. Finally the thesis is concluded in Chapter 5. Appendices provide detailed discussions on the material.

CHAPTER 2

TUBITAK DISTRIBUTION AUTOMATION SYSTEM

2.1 Conversion to 34.5 kV Voltage Level

In the Turkish electric distribution system, the voltage is stepped down from 400 kV or 154 kV transmission level to 34.5 kV at bulk power substations, and for rural and small-town distribution, this level is utilized without further transformation to supply the distribution transformers whose secondaries are at 400 V. The medium voltage feeders are radial and mainly composed of overhead lines.

Before uprating to a higher voltage level, the function of the 34.5kV feeders was to act as subtransmission circuits to load centers where the voltage was further stepped down to one of 6.3, 10.5 or 15 kV levels in big cities. The feeders from these secondary substations were the open-loop type and composed of underground cables. For Istanbul (European side), the 10.5 kV distribution networks were manually operated conventional underground systems with 6-8 distribution transformers per feeder. Most of the existing systems are heavily meshed with lateral branches to adjacent loops to increase the capacity from the 50 % level available from the form of a simple loop to approximately 80 % with five lateral branches to adjacent loops. In 10.5 kV distribution system, faulted location could be determined around 2 hours.

It is shown that 34.5 kV distribution voltage level minimizes the investments on the high voltage (HV) system and a new primary distribution system is provided [4]. The advantages of one primary distribution at 34.5 kV level, without involving a second MV level are; supplying higher installed capacity than 10.5 kV distribution level, eliminating double medium voltage (MV) transformation losses (154 to 34.5kV then 34.5 to 10.5 kV), simple operation manner in practice and implementing distribution automation covering remote fault isolation and service restoration for reliability.

2.2 Operation of Distribution Feeder in Uprated System

Uprating to 34.5 kV level for underground systems in big cities, medium voltage network becomes ring designed radial operated structure shown in Figure 2. In the development stage, it has been easy to operate and plan this kind of network. There are one or two source substation and two feeder circuit breakers. This feeder structure is similar to two radial feeders that are able to mutually support each other in the case of a cable fault. Feeder cable MVA capacity is selected with the idea that one branch should supply all distribution transformers.

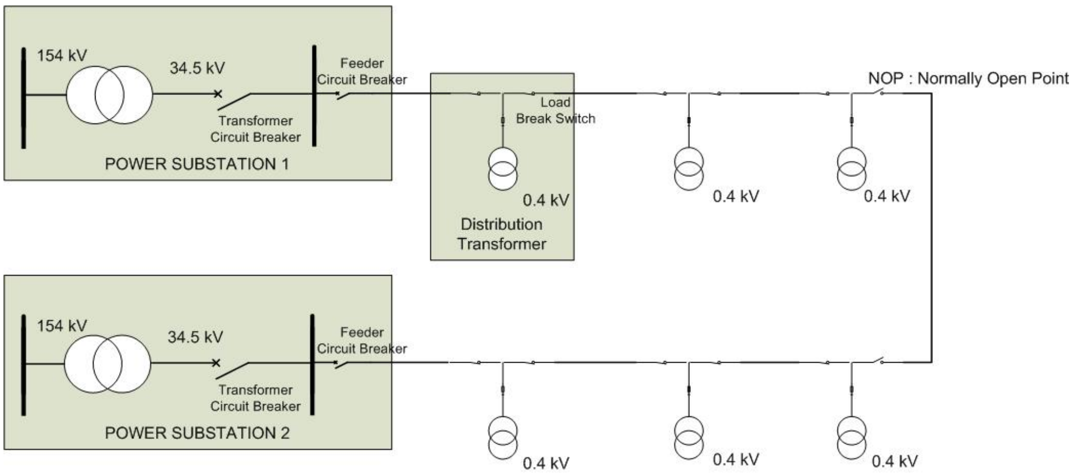

Figure 2 Ring designed Radial operated Distribution Network

For any cable fault, the customers downstream of that fault do not need to wait for repairs because they can be reconnected to supply by switching the network around. This will mean that, after downstream disconnection, the normally open point (NOP) switch between the two feeders will need to be closed, and it can be seen that each distribution transformers can be supplied from two directions. Another important point is that, there are only two circuit breakers (and protection relay groups) at the start of the feeders and load break switches are utilized to isolate the sections of faulted cable between the distribution transformers. Protection system will work such as, in the case of fault related protection relay (at the end of the feeder) senses the fault and circuit breaker should be tripped and fault will be cleared.

2.3 Functions of TUDOSIS

Whit the utilization of 34.5 kV level for supplying distribution transformers, the number of distribution transformers served was more than tripled (10.5 kV voltage level), the exposure length and therefore the number faults would also increase in the same proportion. These feeders could no longer be operated manually. Therefore, TUDOSIS was designed and implemented for the Istanbul (European side) distribution system and it had been operated by Bogazici Electric Distribution Company (BEDAS) since 1996.

The functions of TUDOSIS can be summarized as follows:

- <u>Data Acquisition:</u> Status of switchgears (i.e. circuit breakers, load break switches and fuses), protection relays' information, loads of the transformers and feeder currents and bus voltages etc.
- <u>Remote Control:</u> Controlling of switches.
- <u>Fault Isolation</u>
- <u>Service Restoration</u>

2.3.1 Fault Isolation

The line or the bus faults along the feeder are sensed by the protection relay (earth fault or overcurrent relay) and this information is acquired by special RTU called line end terminal unit (LETU). The feeder circuit breaker opens (trips) and its state is reported to control center software indicating the reason of tripping through LETU (Figure 3).

Fault isolation process has both centralized and distributed control approach. LETU performs fault location detection and isolation as a multi-agent device [5].

In normal communication condition (no communication failure between LETU and all the RTUs in distribution transformers along the feeder), LETU determines fault location by interrogating fault passage indicators (FPI) one by one until the end of the feeder. The faulted region is defined as the section just before the first no fault current indication. The switches that correspond to the last fault current indication and the one after this indicator are opened to isolate the section. Fault isolation is shown in Figure 4.

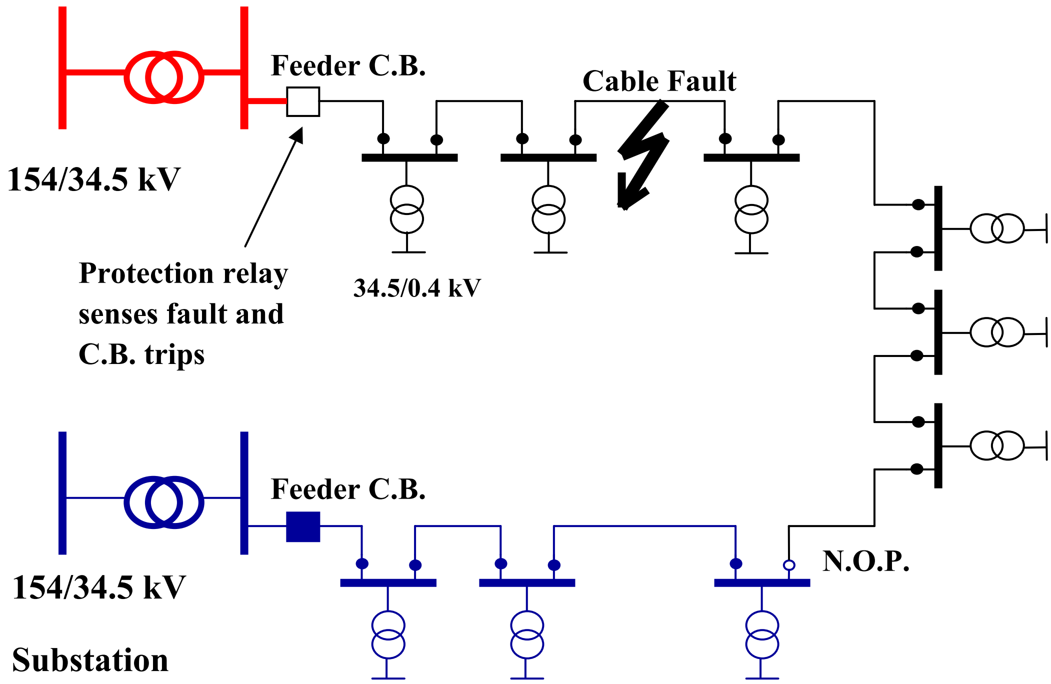

Figure 3 Feeder Line Fault and Protection System

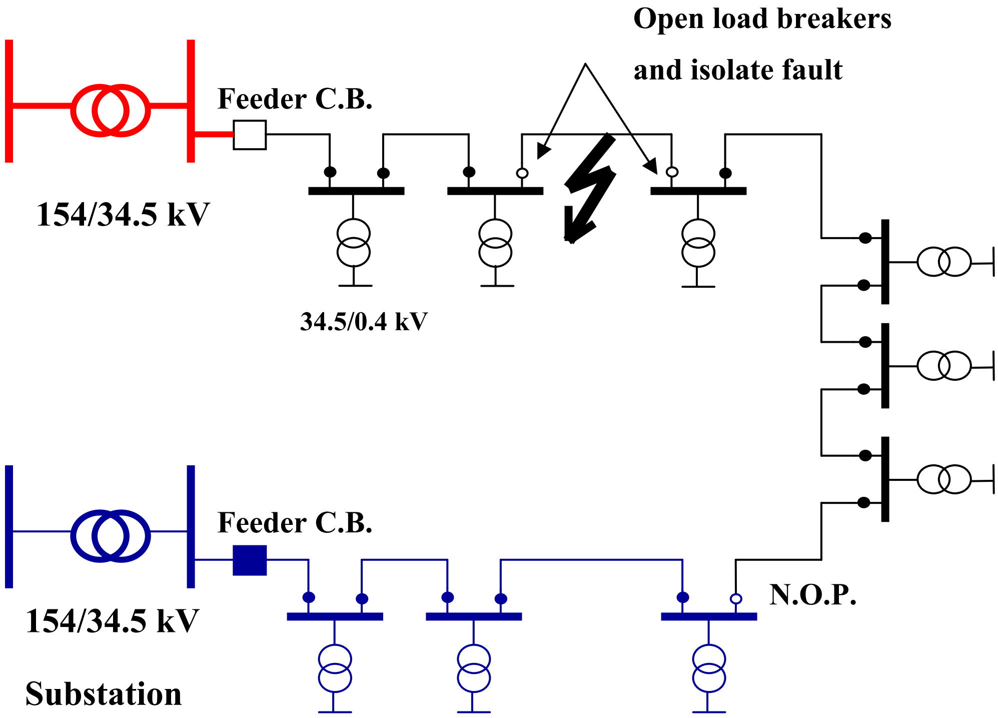

Figure 4 Fault Isolation System

The distributed approach of fault isolation is propounded by the need to minimize the interrupted duration and increase the efficiency. If there is a communication failure along the feeder, the LETU queries RTUs which it can reach and sends a message that includes fault passage indicator information of the reached region and leaves the isolation to the control center software. When control center software receives such a message, it isolates the minimal region indicated by the message without doing any analysis. In that case, centralized fault isolation system takes the control.

2.3.2 Service Restoration

After the isolation of the faulted section, service restoration system is a centralized approach that reenergizes downstream of the faulted section, and done by the control center software. The de-energized region between tripped feeder circuit breaker that has been opened by the feeder relays and the faulted location of the feeder will be supplied by closing the feeder circuit breaker. During restoration in order to eliminate in-rush currents, distribution transformers should be energized step by step. Since the feeders are operated as an open loop network, previously normally open switch is closed and rest of the de-energized portion of the feeder has been restored. This process is shown in Figure 5.

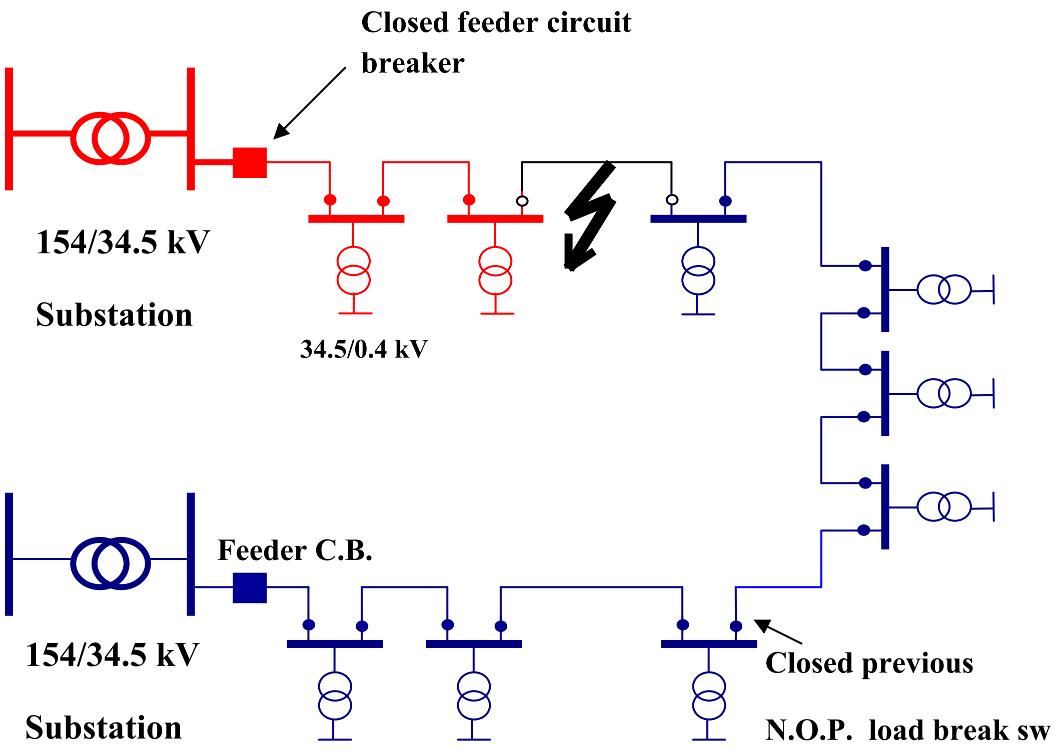

Figure 5 Service Restoration System

2.4 Components of TUDOSIS

The basic architecture of TUDOSIS comprises four main components: the device to control and acquire data from power system (Distribution transformer terminal), a communication system, distribution automation gateways and man-to-machine interface (MMI) software (i.e. control center software).

2.4.1 Remote Terminal Units of TUDOSIS

There are four types of RTUs; Control Station Terminal (CST), Substation Terminal (SST), Line End Terminal Unit (LETU) and Distribution Transformer Terminal (DTT).

- CST: CST is the communication interface between SST and control center.
- SST: ST is the communication interface between CST and LETU. They are gateways to route messages coming from control center to related RTU according to their communication roadmaps.
- LETU: LETU acquires information about circuit breakers on/off states, protection relays, feeder currents and bus voltages in the power substations. Also it is the communication link between the SST and DTT. It performs fault location detection and isolation even though the control center is not online in its responsibility region.
- DTT: DTT gathers all information in the distribution transformers.

Network of TUDOSIS is implemented in parallel architecture with distribution system. It is in hierarchical structure to easily adapt future expansion of the distribution system (Figure 6).

2.4.2 Communication System of TUDOSIS

TUDOSIS uses DNP for RTU-RTU and RTU-control center workstation communication. The DNP is based on the IEC 870-5 protocol which uses EPA (Enhanced Performance Architecture) as defined by OSI (Open System Interconnection) protocol [6].

TUDOSIS communication infrastructure is generally fiber optic cable. The reason is that, fiber optic cables were laid along with 34.5 kV power cables, and therefore, there would be no extra cost.

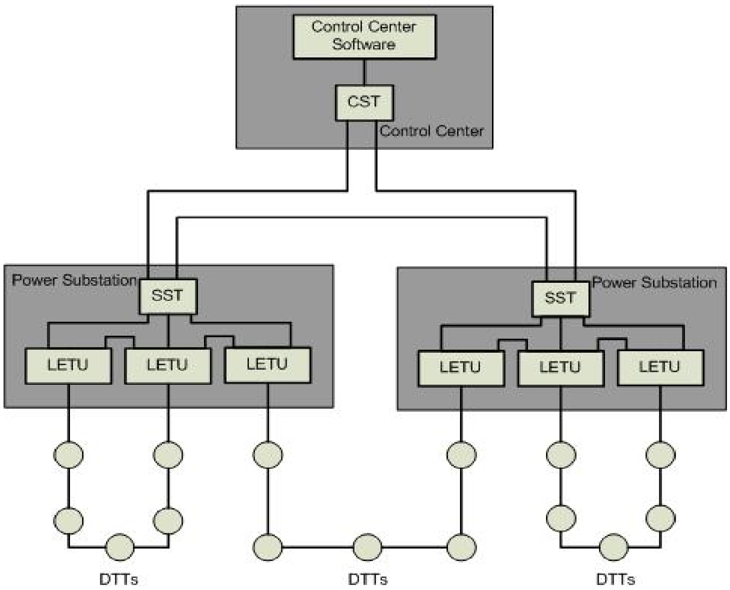

Figure 6 TUDOSIS Network Architecture

2.4.3 Control Center Software of TUDOSIS

UNIX-based control center software that runs on SUN workstations and Solaris 7 operating system was developed for TUDOSIS. In the design and implementation of the system, special care had been given to the usability and openness of the system. MMI was implemented in C++ which has an object oriented programming paradigm to cope with the complexity of the system and to enable easy maintenance [7].

TUDOSIS control center software has the following features:

- displaying one-line diagrams of the distribution system, with real-time switch states indicated (Figure 7),
- sending operator commands,
- isolating faults on feeders (centralized approach),
- restoring feeder de-energized sections,
- keeping historic logs of events and real-time data,
- handling alarms.

All of these components were implemented and integrated to the Istanbul (European Side) MV (34.5 kV) distribution system and TUSOSIS has been operated from 1996 till today.

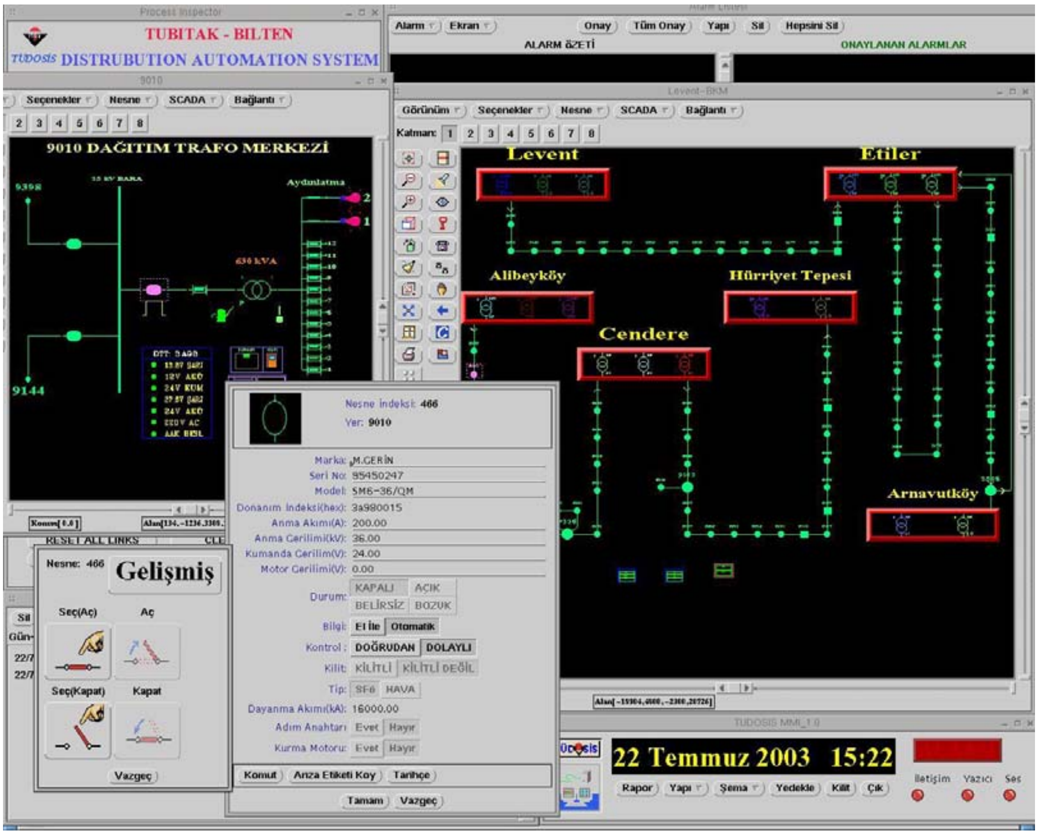

Figure 7 A Snapshot of Control Center Software of TUDOSIS

2.5 Practical Drawbacks in Integration of TUDOSIS

As mentioned before TUDOSIS was designed for ring designed, radial operated (open loop) MV cable distribution system. In this network structure, circuit breakers are located only at the upper ends of the feeder and load break switches are installed in distribution transformers (transformer switching is done by a load break switch in series with fuse). By itself, feeder circuit breaker cannot trip when fault occurs. However, suitable protection relays are arranged to detect a fault condition, initiate the automatic tripping of the breaker and LETU performs fault isolation.

Ideally, there should be a circuit breaker at the start of each cable section tripping for faults inside that particular section. However, as a result of equipment ratings (i.e. the fault current limited to flow for 1 seconds), and the need for an incremental time of 300 milliseconds (i.e. electronic relays) - 500 milliseconds (i.e. mechanical relays) for selective operation of protection system between successive circuit breakers, the maximum number of circuit breakers in series (along the feeder) cannot exceed three [8].

Because of design limitations for ensuring selectivity, a possible solution is shown in Figure 8. However the protective scheme has the disadvantage that NOP on the feeder directly affects the protective function since time grading settings are adjusted with respect to a constant normally open point. If the normally open circuit breaker is shifted, because of a fault or maintenance purposes, all of the relays have to be adjusted for the new configuration.

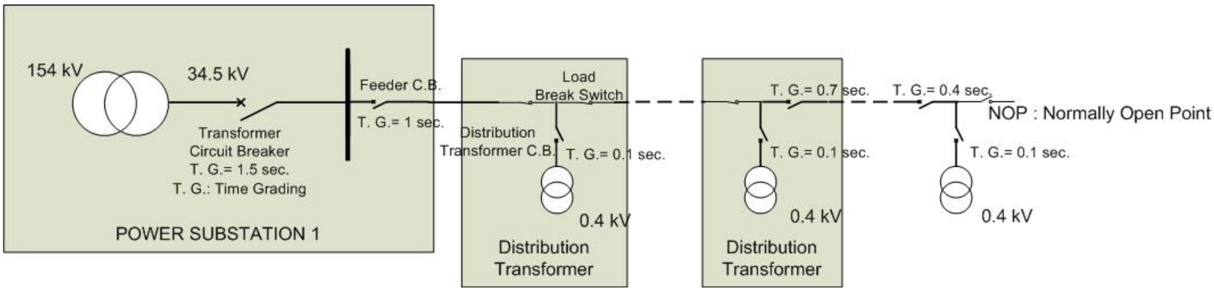

Figure 8 Sample Distribution System for Time Grading Selectivity

Besides, TUDOSIS cannot function properly in such a system for fault isolation and system restoration. If the feeder circuit breaker is not tripped in the case of fault, fault isolation algorithm will not be initialized and LETU will not determine fault location. Consequently the distribution automation system is not reliable anymore.

The open loop system described previously would eventually evolve into a radial operated ring system for economic reasons. Figure 9 illustrates simple mesh system with three lateral branches. TUDOSIS again cannot fulfill its functions with this type of network. LETU cannot be installed in the node distribution transformer because of both hardware and embedded software limitations. Service restoration algorithm was designed for two supply substation architecture which is not applicable in this case that has three supply points.

Closed ring distribution network is not feasible architecture for feeders which are supplied from two substations. Paralleling two different 154/34.5 kV substation transformer causes circulating currents and also short circuit currents roughly will be doubled. This situation will change whole protection system of distribution and transmission system.

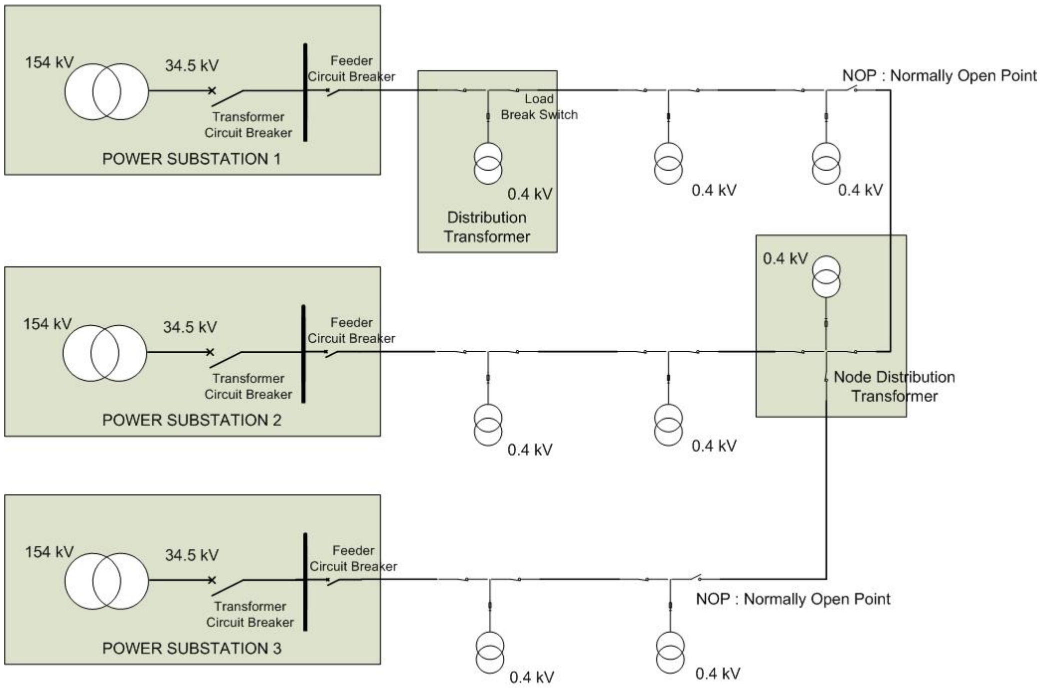

Figure 9 Sample Mesh Network System

CHAPTER 3

FAULT ISOLATION ALGORITHM

3.1 Literature Survey: Fault Isolation Algorithms

Numerous approaches have been proposed to solve the problem with fault detection and isolation in electrical power systems, and commonly used ones are briefly discussed below.

These are classified into two categories: SCADA-based and Model-based Fault Detection and Isolation.

3.1.1 SCADA-based Fault Detection and Isolation

In this approach, fault detection and isolation is performed using the alarms from the system. Protection system leads DA for fault detection and selectivity is accomplished by coordinated operation of protection relays. In large systems the number of alarms resulting from a fault event can be quite substantial, which increases the challenge of fault isolation for the system operator. At this point DA is usually implemented using either a centralized approach or a distributed approach.

An accepted example of distributed solution for fault isolation and service restoration is the IntelliTEAM II Automatic Restoration System which was introduced by S&C Electric Company in 2003 [9]. IntelliTEAM II can automate parts of a circuit in need of attention or an entire distribution system consisting of open-loop feeders with multiple normally open points to other feeders. “Team” and “coach” metaphors help to describe IntelliTEAM II operation. Each team is defined as a line segment bounded by two to eight automated switches and each team has a software coach.

When an outage or line fault occurs, local control logic determines if a switch is opened. The coach of each affected team then uses real-time data, including voltage and current data gathered prior to the system event to develop a restoration strategy for unfaulted sections. The coaches of adjacent teams then work together through shared controls to implement strategies that will maximize restoration of the network within the prioritization rules by the user. Figure 10 illustrates the team concept. The coach distributes data and coordinates the operation of automated switches and circuit breakers. The important issue is that, each team is responsible for isolating fault as well as restoring its load.

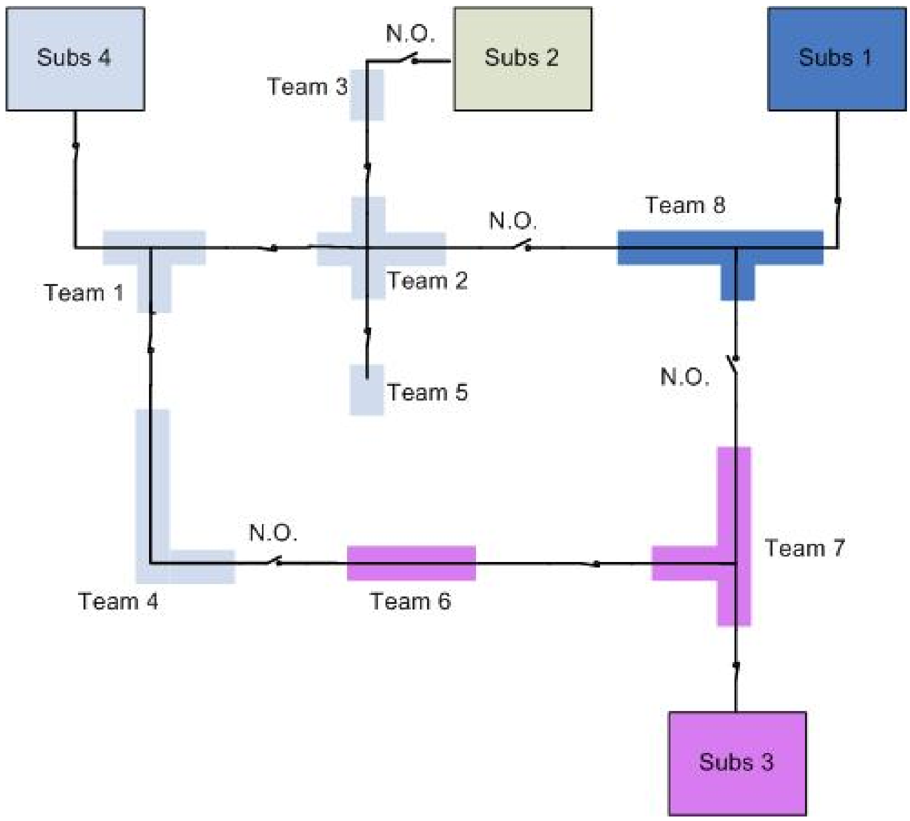

Figure 10 An example of IntelliTEAM II

Another implemented example using distributed approach is TUDOSIS which was mentioned in Chapter 2. The advantage of this approach is that it can properly isolate fault and restore de-energized region without requiring the knowledge of system topology and other network parameters.

In case of fault, when a breaker or its associated relays fail to operate, the fault is removed by backup protection. For large systems, in such cases, it is difficult for the dispatchers to estimate the fault location. Moreover, multiple faults may take place, with many breakers being tripped within a short time. In these circumstances, centralized solutions have been proposed to assist the system operator providing accurate fault location. Artificial neural networks (ANN) have been successfully applied to fault detection and isolation problems. For instance in [10], the method explores the fact that the identification of a faulted component requires only information from alarms originating from faulted region. A local strategy is followed to tackle the problem of dimension. Decision rules are presented in order to achieve accurate final diagnoses from the analysis of the ANN classifications. Alternative to ANN, expert systems are able to produce successful results for fault diagnosis [11]. In this thesis rule-based expert systems are discussed in Chapter 4 for service restoration. These solutions are fault tolerant and provide system wide approach.

3.1.2 Model-based Fault Detection and Isolation

In model-based fault detection the knowledge of the physical system is exploited, using well established relationships from power engineering to describe the behavior of the system. Observing contradictions, between the predicted behavior from the model and the behavior observed, conclude that the normal behavior of the system is violated, and hence that a fault has occurred. This general idea can be implemented in a number of ways, and only a couple of them is mentioned here.

3.1.2.1 Look-up Table Approach

This approach comprises protection scheme for distribution network including distributed generation (DG). The protection scheme is based on a complete short circuit analysis for every type of fault applied anywhere in the system, where the contributions to the faults from different supplies are stored in a database. Following a fault, the pattern of the realized flow from the sources is compared to the ones simulated to detect the fault and isolate the fault location. As the short circuit analysis is only valid for a specific configuration of network, generation and load, accurate detection requires that the analysis is updated after change in the distribution system [12]. The basis for this solution is that the contribution to the fault current from different supplies, constitute a unique fingerprint for type and location of the fault. A drawback with this method is that the protection scheme needs time to reconfigure following a significant change for next system state. During this period there is a reliability problem.

3.1.2.2 Dynamic Model Evaluation Approach

In [13], an on-line fault detection scheme is proposed, where faults are treated as unknown inputs to the power system model. Through the model, measurements contain information about fault type and related recordings, and in case a fault occurs, the fault detection and isolation is performed by an observer, where the unknown input is estimated. Once the system is modeled, the dynamics that described the faults are decoupled from the rest of the system, after which the unfaulted part of the system is used to design an observer that estimates the remaining part of the system, including the unknown faults.

3.2 Proposed Method: SCADA-Based Distributed Approach

In this thesis SCADA-based distributed approach is proposed for fault detection and isolation method which has originated from TUDOSIS fault isolation algorithm. Drawbacks concerning integration of TUDOSIS are discussed in Chapter 2. To answer these problems, a new fault isolation algorithm has been developed with novel remote terminal unit structures. The distribution system is represented in an object oriented programming (OOP) language, C#. Afterwards protection system and DA components (RTU) along with fault detection and isolation algorithm are implemented in this representation.

3.2.1 Representation of Distribution System

The basic components used in the distribution system can be classified as switching, conduction and protective components in representative point of view. Transformers and other measurement devices are out of scope elements for this study. The following table gives generally the specifications of these elements:

Table 1 Distribution System Elements

Type	**Explanation**
Circuit Breaker	Interrupting fault current Switching (on/off) under load
Load Break Switch	Only switching (on/off) under load
Bus	Conduction structure in substations
Cable	Conduction structure between substations

Before going a step further in distribution system modeling, OOP design and programming terminology are expressed.

3.2.1.1 OOP Design and Programming Concepts

- Objects and Methods

  Software executes when a data structure (of varying levels of complexity) is acted upon by one or more processes according to procedure defined by static algorithms or a group of dynamic commands. Therefore, OOP language must establish a mechanism to accomplish these functionalities [14]. The data elements and the available processes on those elements are encapsulated in a single programming element called "object". An object is the entity which corresponds to a real world component such as a machine, a file, an integer or an electrical signal. Software realization of objects consists of private (no access right is given to other objects) or public data structures that are also called attributes and processes manipulating those structures. These processes are called "methods". The only way of manipulating the object, is calling the object methods. In other words methods are interface of an object to the outer object space. Figure 11 gives an example of “switch” object which has a type (circuit breaker, load breaker or disconnect switch), location, rating, connection points and relays and also it can be opened and closed.

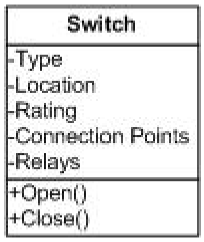

Figure 11 A Sample Object: Switch

- <u>Classes and Class Inheritance</u>

  One can group objects, having same characteristics and similar operations, into groups that are called classes. The data and interface design (attributes and methods) is defined in the class implementation.

  Classes having similar characteristics can be grouped under hierarchical graph. The hierarchy is constructed according to the coverage of generalized characteristics. Most generalized classes are at the top (parent) and traversing to the bottom, more specialized classes (children) are passed through. The children in the hierarchy inherit general characteristics of its parents. This mechanism is transitive; C is child of B and B is child of A means the characteristics of A is passed to C. This new-class generation from generic groups to specific ones (i.e. book to dictionary, animal to mammal) is accomplished by a mechanism, is called “inheritance”.

- Polymorphism
  Polymorphism is the ability to change into morphologic forms and in OOP, is the term to denote the ability to have different types of objects and structures to initiate a known pattern of interrelations through inheritance. This feature of OOP makes modular and extensible programming very easy and avoids code duplication. To achieve polymorphism, inheritance mechanism is used in a special form which enables an abstract class (A class which has no instances itself but uses its descending class instances as its own) to behave like its multiple forms of inheriting classes. This abstract class can change its behavior at run time by simple constructors defined in the program code [14].

3.2.1.2 Simulation Environment of Distribution System in C#

A simulation program is written which represents the distribution and its automation system for clearer understanding of the fault isolation algorithm. Using the OOP benefits, first an "EDeviceBase" class is created. EDeviceBase is the parent of the all electrical equipments in the simulation program, which inherits from UserControl class in C# library. EDeviceBase class properties and methods are given in Figure 12. "Bus", "Cable", "CircuitBreaker" and "LoadBreaker" are children classes of EDeviceBase class.

Bus object is located in the HV/MV substations and distribution transformer stations. It ties two or more switching device (circuit breaker or load break switch) to each other. Cable object connects only two switching device to each other or one bus to a switching device.

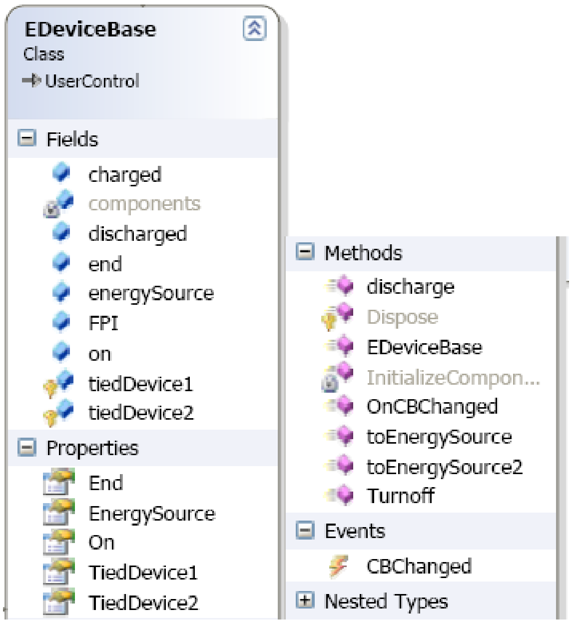

Figure 12 EDeviceBase Class Properties (and Fields) and Methods (and Events)

Circuit breaker object is a switching device which is opened (or tripped) in the case of a fault. However, load breaker object is a switching device which cannot be triggered by the discharge method (a method which is triggered by the faultset method). The class diagram of electric equipments is shown in Figure 13.

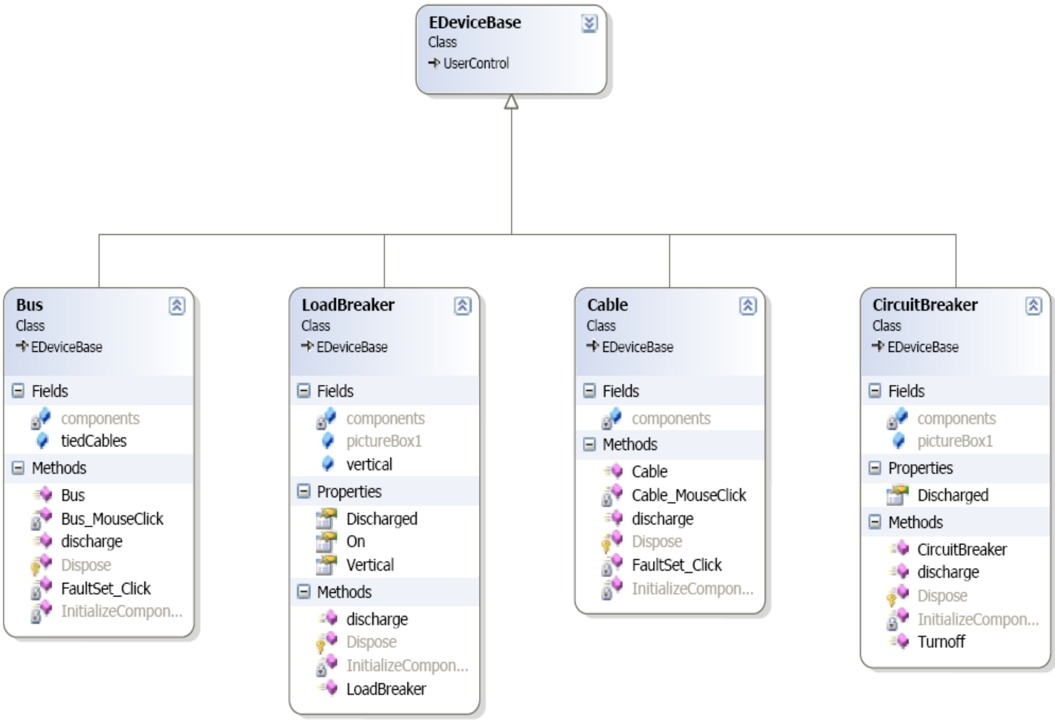

Figure 13 Class Diagram of Electric Equipments

In the same manner, RTU is the parent object of the other RTU structures; LETU, LITU, DTT and NDTT. RTU is connected to switching devices (circuit breakers or load break switches) in the substation or distribution transformer stations. When switching devices status is changed (tripping of circuit breaker), attached RTU will perceive the alteration and invoke the related method. Class diagram of RTU and its children is given in Figure 14.

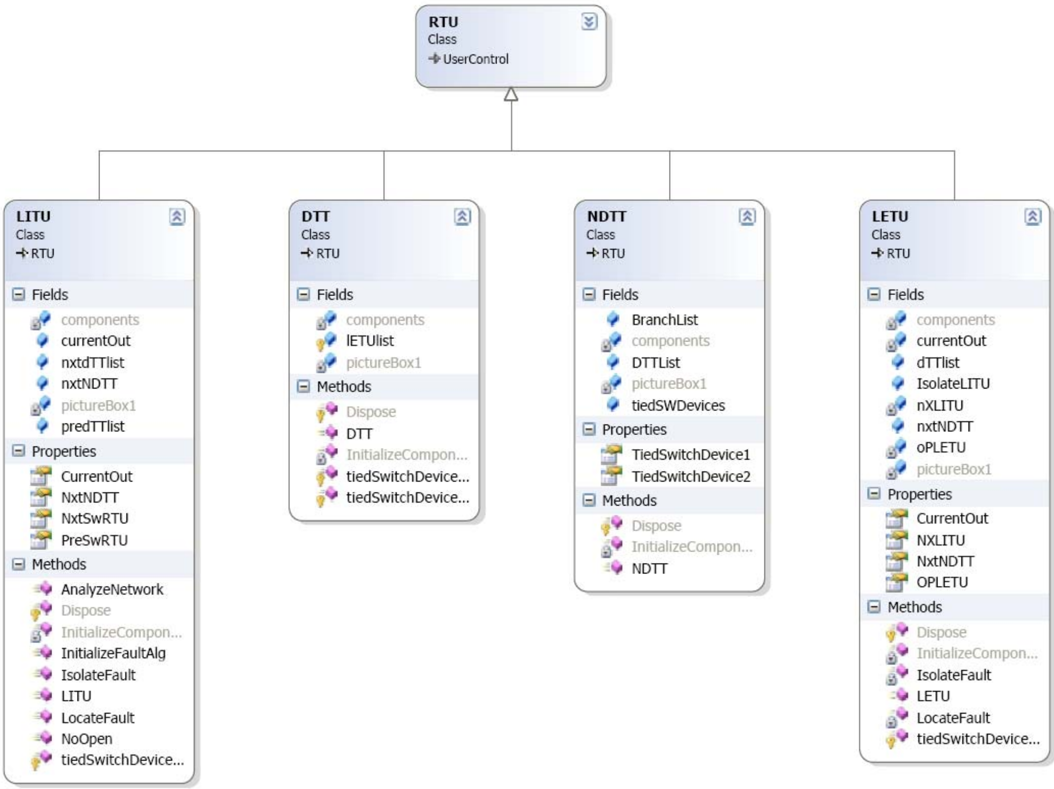

Figure 14 Class Diagram of RTU

In C# programming language environment, using these proposed objects a distribution network can be designed and implemented. It is an easy and flexible coding approach for the developer. When the project file is opened, both C# components and developed components can be dragged and dropped in to framework of the program (Figure 15). After constructing substructure of the distribution system, the program should be compiled and run to realize and simulate the fault isolation algorithm.

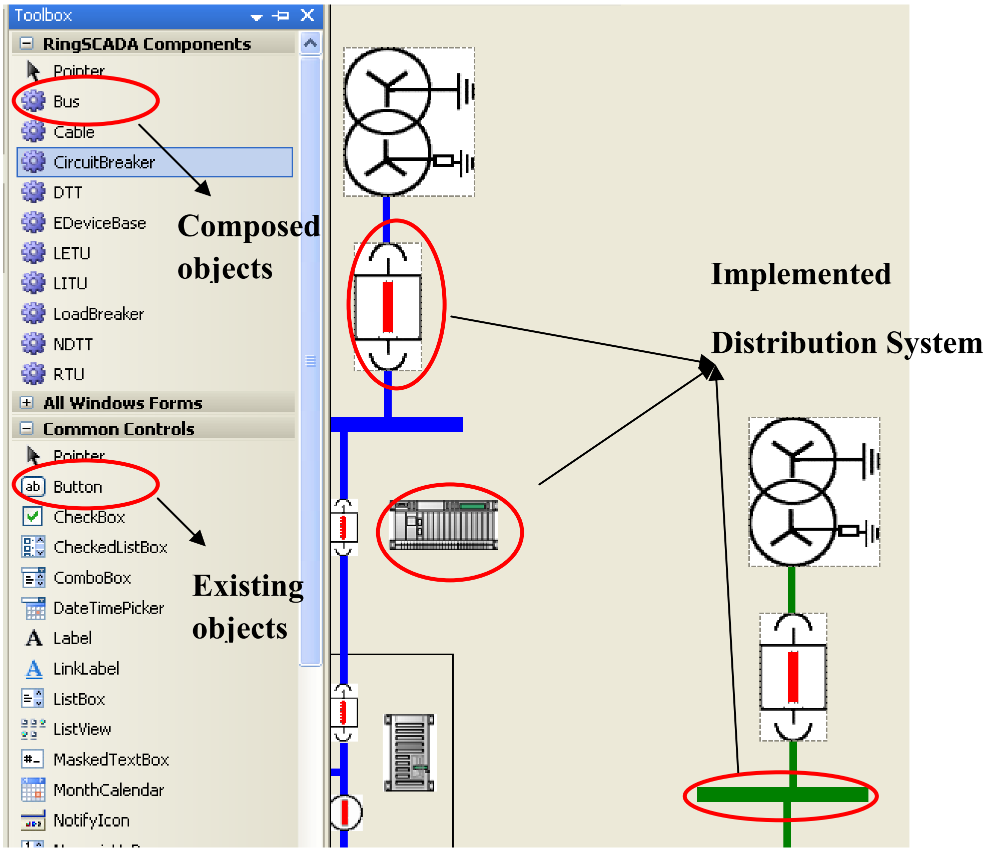

Figure 15 Graphical User Interface of the Simulation Program

3.2.2 Fault Isolation Algorithm

Starting point of this thesis is to overcome unplanned development of the distribution system. Effectiveness of the selectivity must be questioned and improved for installed circuit breakers with protection relays. Some of the relays have been made inoperative to satisfy selectivity limitations. For example, twenty distribution transformers in an open loop feeder, supplied by two power substations, two protection relays are set for one feeder and two for the other feeder. After coordination of protection scheme, novel RTU structures are proposed; one of them is for distribution transformer (LITU) with relays and another is for node distribution transformers (NDTT).

LETU has a DTT list which comprises DTTs from itself to next RTU with relays. This field of the LETU intends to decrease interrogation region. If associated circuit breaker trips, it will question all the DTTs in the list, and will find the fault location by analyzing last faulted passage indicator set value. When a breaker or is associated circuit breaker fails to operate, LETU will consider the faulted situation and assign the task to next RTU with relays (probably LITU).

For mesh network system it is difficult to track and keep the fault passage indicators' information. NDTT partakes in fault detection algorithm by having branch lists (incoming or outgoing feeders from node distribution transformer). Every branch list covers DTTs data and next RTU with relay information. In Figure 16, NDTT1 (NDTT object) has the information of next LITUs (LITU2 and LITU3) and also DTTs (DTT5 and DTT8) for every branch.

For instance, when a fault occurs at point A, fault current flows from Substation 1 to fault location. Upstream circuit breaker will trip and LITU2 will interrogate NDTT1 fault passage indicators (in this case FPI 2 and FPI 3). FPI 3 is set to 1, subsequently LITU2 will append feeder by adding DTT5 to its DTT list and LITU3 to its newt switching RTU with relay.

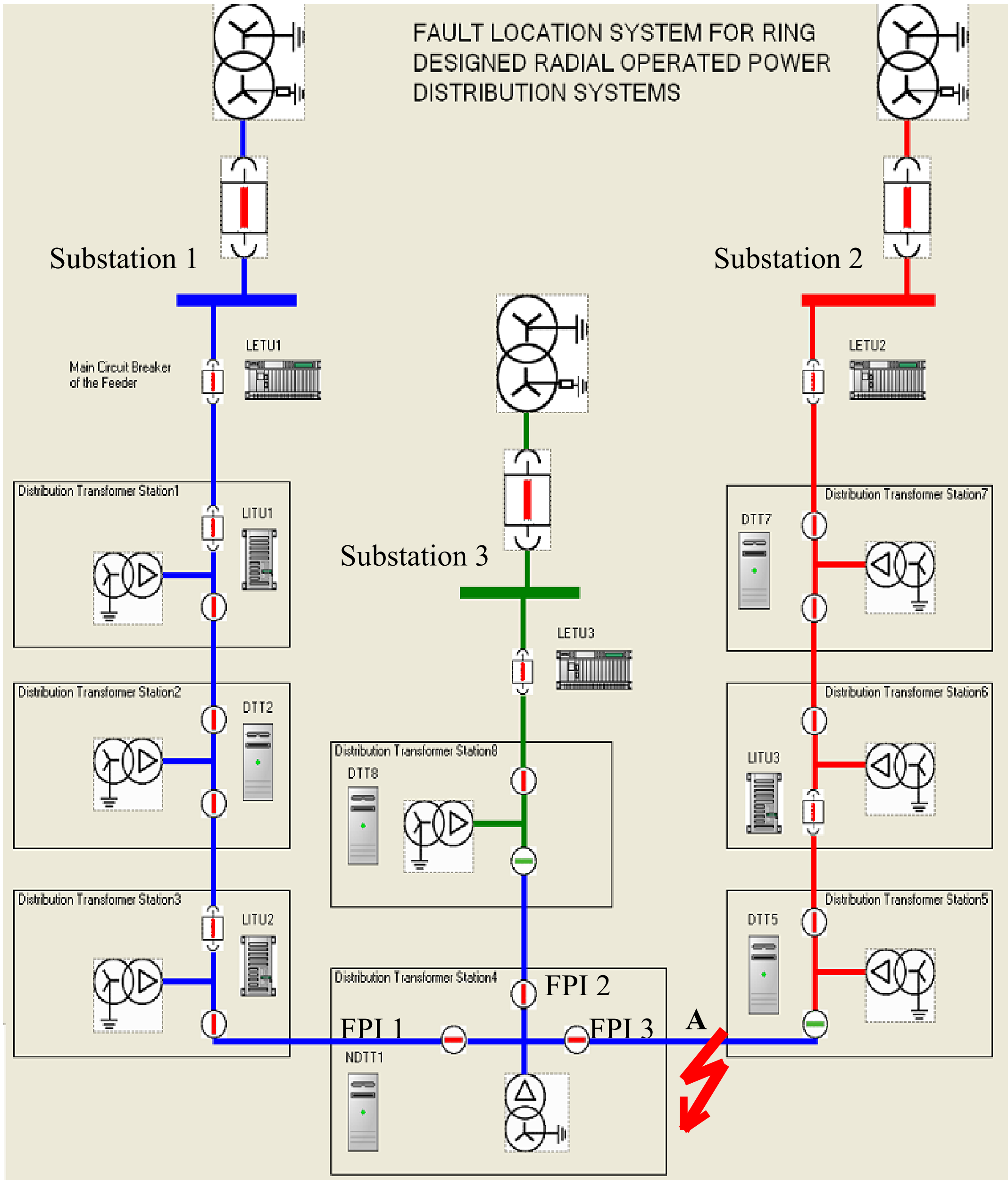

Figure 16 A Snapshot of Developed Program

As a result, in this fault case an open loop system is composed dynamically between Substation 1 and Substation 2 omitting Substation 3 feeder. It appears that mesh system turns into ring designed radial operated network during the fault isolation process.

LITU object is extended version of the LETU. LETU has only one DTT list but LITU has two DTT lists in case of changing current direction. DTT list selection is determined by recognizing the normally open point switch. Same understanding is exploited for NDTT case. Consequently, installed circuit breakers with relays in the feeder and also mesh distribution networks this novel SCADA-based approach is a solution for fault detection and isolation.

3.3 Closed Loop Distribution System Protection and DA System

In ring designed and ring operated (closed loop) distribution network's protection scheme is completely different from the open loop system. In an open loop system (described in Chapter 2) over-current and earth fault current relays are used and selectivity limitation determines the number of the relay in the feeder. In the case of a fault or a maintenance work, whenever normally open point of the feeder changes, selectivity is altered and reconfiguration is needed for new feeder structure. It can be done with remote programming of the relays.

However, closed loop system protection scheme is distinguished from open loop system because of fault current flow. For closed loop cable distribution systems there are two different solutions. One of them is directional over-current relays and the other is line differential relays.

3.3.1 Line Differential Protection

Line differential protection is a unit protection type (Figure 17). In normal condition (there is no fault between two distribution transformer stations) the sum of incoming and outgoing currents (I1+I2) equals to zero. When a fault occurs at the line, I1+I2 will not be zero and relays will generate trip signal reciprocally.

Afterwards circuit breakers will be opened and fault isolation eventuates. Therefore a fault isolation algorithm and service restoration algorithm in DA is inessential.

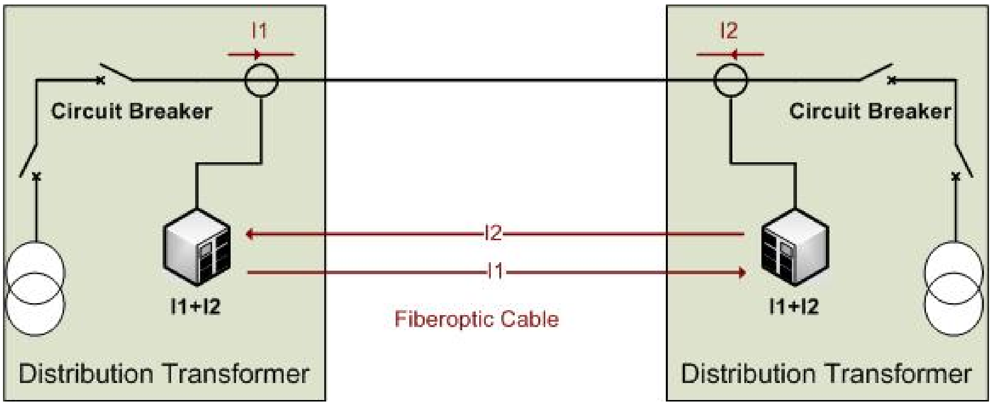

Figure 17 Line Differential Protection using Fiberoptic Cable

This protection system is fast, selective and accurate. The disadvantage of line differential protection is that bus protection cannot be achieved in the distribution transformer stations. Hence over-current relays must be added to protection system. Properly speaking, closed loop distribution system is operable only for the case where the two MV feeders are supplied from one MV bus in a HV/MV substation (Figure 18). Distribution system operators do not want to operate a closed loop system that is supplied from different source substations. Circulating currents and increased short circuit currents can cause trouble for existing transmission and distribution system.

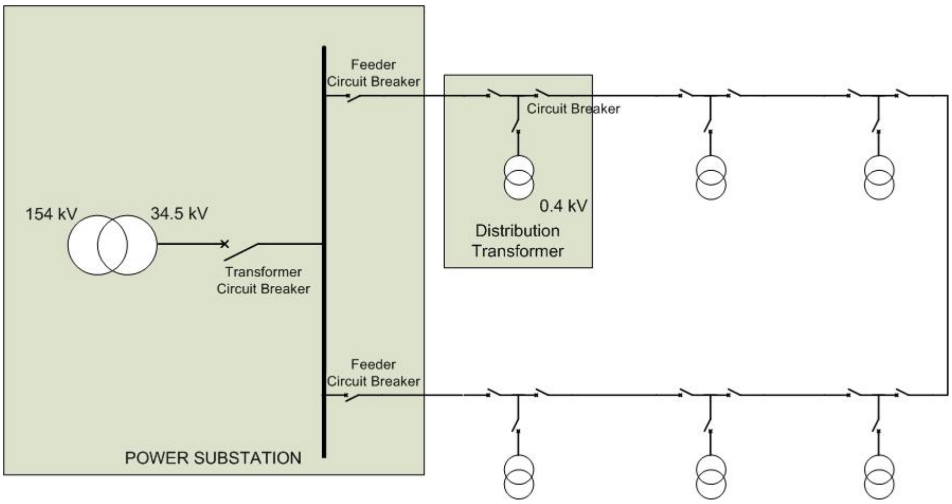

Figure 18 Ring Designed Ring Operated Distribution System

3.3.2 Directional Over-Current Protection

Directional over-current relays indicate whether the fault is in the upstream or the downstream direction from where they are located and trip the associated circuit breaker. For this purpose a directional protection relay needs a source of both current and voltage. The current source can be current transformer which is toroidal type or plastic moulded case. The voltage source might be a wound voltage transformer on a new cell or cubicle. Once more ensuring selectivity causes design limitation in protection system. Fault isolation algorithm considers the circuit breaker tripping and directional fault passage indicators information to determine exact fault location.

Ring designed, ring operated distribution system, for both approaches, requires additional equipments (voltage transformer, directional over-current relays, line differential protection relays etc.) that increase the operating cost of the system. Considering fault location statistics (faults at MV or LV), distribution system operator should make cost-benefit analysis. If number of LV faults is much more than MV faults, line differential protection system will be a luxury and therefore useless.

CHAPTER 4

SERVICE RESTORATION

4.1 Objectives and Constraints of Service Restoration

The main objective in service restoration procedure is to restore out-of-service areas by transferring de-energized loads to other adjacent distribution feeders as quickly as possible. Distribution system is usually designed in ring topology (and radial operated), but in some regions (i.e. Beyazit and Beyoglu; old city districts of Istanbul) it has mesh structure that allows for several operating configurations (Figure 9). Accordingly restoration of load through alternate routes is a combinatorial problem with predefined constraints.

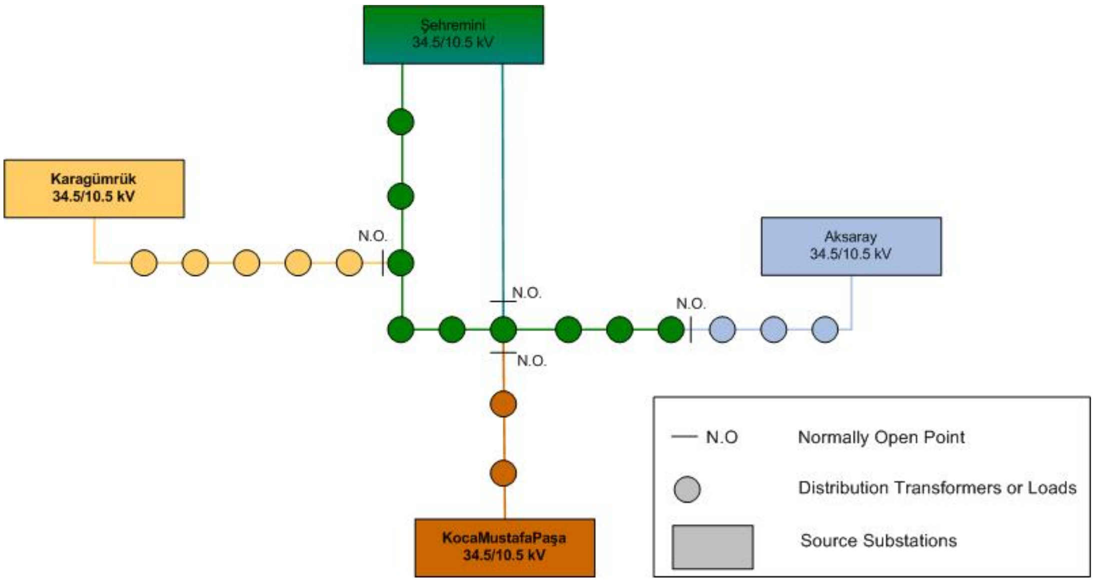

Figure 19 A Sample 10.5 kV Distribution Feeder in Beyazit (Istanbul)

Furthermore service restoration has to minimize expected energy not supplied (EENS) during restoration processes. This means the number of switching operations (open/close switches) is minimized, through switching sequence is considered. Another important issue is supplying energy to the largest number of loads as possible. After restoration to final configuration, total power losses have to be reduced.

All these objectives cannot be provided simultaneously, thus service restoration will assist the system operator by the control center software (Automatic service restoration is not recommended in practical manner).

Final configuration must not violate operational constraints. The constraints are summarized as following;

- During and after restoration process, distribution system must retain radial topology.
- Source substation and line loadings must not exceed the capacity limit.
- Voltages at the load buses must stay between the limits ($0.95 < V_{bus} < 1.05$)

4.2 Methodology

An effective service restoration strategy for distribution systems plays a key role in improving system reliability. As a result there has been considerable research efforts focused on restoration problem. The problem has been addressed with methods such as integer programming, ANN, genetic algorithm, rule-based expert systems and hybrid systems.

4.2.1 Integer (Mathematical) Programming

Integer programming as given in [16], proposes a non-combinatorial, systematic and procedural algorithm. From the view point of this method, the loads in the "isolated island" must be energized by transferring them to "support feeders". In this case, there are radial feeders along with the faulted feeder and a group of de-energized loads with connections to these feeders. Constraints of approach are line/transformer capacity and voltage drop at the end of the line.

As a first step, solution algorithm determines the “main support feeder”. This feeder is chosen by connecting isolated island to every adjacent feeder and deciding minimum constraint violation among these feeders. If there is no constraint violation, service restoration is completed. Otherwise, algorithm moves on to the first support stage. Tie switches that can be used to transfer loads from feeder that has caused constraint violation to the adjacent feeders are identified, then a tie switch and the associated feeder are chosen to transfer loads one-by-one. Again if there is violation constraint, second stage support feeders are determined by tolerating some violations in the first support feeder. Now the first stage support feeder is treated as a main support feeder with constraint violation.

After second stage support, if there are still violations, load curtailment is performed. There may be some possibilities in restoring the curtailed loads by load transfer among former violation feeders (main, first and second support feeders). Therefore tolerating some violations, loads are tried to be supplied from the former feeders.

4.2.2 Artificial Neural Network (ANN)

In [17], ANN approach is developed to determine the service restoration plan for a distribution system within the service area of Taiwan Power Company. A typical underground distribution network is shown in Figure 20. It is observed that feeder coming from S/S 2 can supply power to feeder S/S 1 in the case of fault. In addition, three laterals (LAT1-3) are connected with supporting laterals. Also, there may exist some laterals (LAT 4) without supporting laterals.

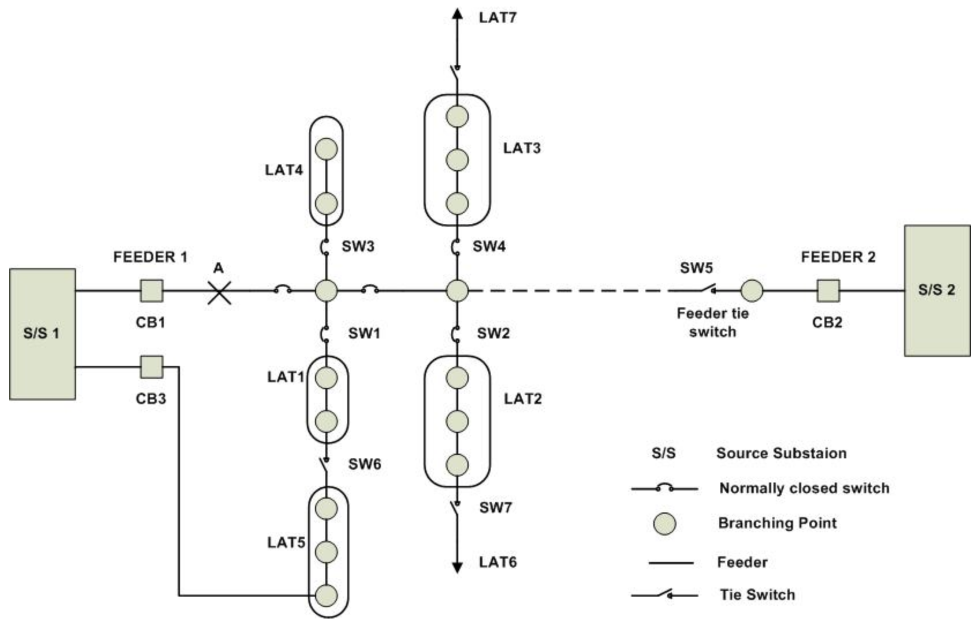

Figure 20 One-line diagram of the studied system

For example, after the fault at point A on Feeder 1 has been isolated, LAT1-4 is de-energized. To restore service to these laterals, Feeder 2 can be used by closing the SW 5. If the supporting feeder does not have enough spare capacity to LAT1-4, ANN algorithm must select some additional supporting laterals. One of the requirements of this method is only the switches which are in the near vicinity to out-of-service area may be operated. According to this requirement, reconfiguration of supporting laterals is not considered.

The ANN employed in this approach is multilayer feed forward neural network. In general, an ANN is made up of neurons connected together via links. ANN solves a complicated problem very efficiently because the knowledge about the problem is distributed in the neurons and connection weights of links between neurons and information are processed in parallel. ANN inputs are the capacity of the supporting laterals and supporting feeder and the outputs are these supporting laterals' (or feeder) switch positions.

4.2.3 Evolutionary Algorithm (EA)

The common underlying idea behind evolutionary algorithm techniques is the same: given a population of individuals, the environmental pressure causes natural selection (survival of fittest) and this causes a rise in the fitness of the population. Given a quality function to be maximized, a set of candidate solutions, i.e., elements of the function's domain, is randomly created and the quality function is applied as an abstract fitness measure – the higher the better. Based on this fitness, some of the better candidates are chosen to seed the next generation by applying *recombination* and/or *mutation* to them. Recombination is an operator applied to two or more selected (from current generation) candidates, and results in one or more new candidates. Mutation is applied to one candidate and results in one new candidate. Executing recombination and mutation leads to a set of new candidates that compete – based on their fitness – with the old ones for a place in the next generation [18].

One of the implementations of EA to service restoration problem is proposed in [19]. In this approach first of all distribution network is represented as a graph. A graph consists of nodes, which represent loads (distribution transformer) and edges which are branches (lines) between two distribution transformers (Figure 21). Edges are unidirectional that means current flow direction may change according to feeder configuration. Every feeder is represented as a data structure called tree, thus graph is a forest of these trees. For example, in Figure 21 the nodes starting with 1 (root of tree) and through the nodes 4, 5, 9, 13, 8, 12 compose a tree (feeder) with connection edges.

After representation of distribution network, EA needs operators (recombination or mutation) to generate new candidates. Mentioned approach has two operators that changes two trees and makes up a new forest. Both operators can transfer a subtree from a tree to another tree. Only difference is operator1 keeps root of the subtree unchanged, but operator2 changes the root and also configuration of the subtree.

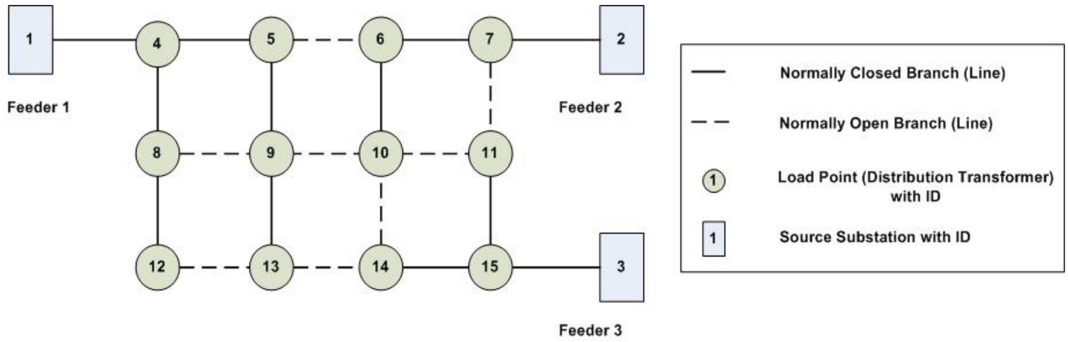

Figure 21 Mesh Distribution System with three feeders

Loads (or nodes) are defined as a constant current model; the load flow can be easily calculated for currents from terminal loads to substation and then from substation to terminal nodes for voltages. Constraints can be summarized as follows; radial network structure, line capacity, source substation capacity and voltage drop.

At this point, proposed method has distribution system structure, load flow algorithm and EA operators. After fault isolation, out-of-service area can be considered as a subtree. Using operators (1 or 2), de-energized area is connected to another feeder (tree). This first configuration (individual) can violate one or more constraints, so it is necessary to find a better configuration. Starting from this individual, stochastically EA can produce other configurations by applying operators. For this process the parameters are population size (how many individuals must remain for the next generation) and maximum generation number (how many individual must be generated). Pseudo-code for the proposed EA is given in Figure 22. Finally after running of the proposed algorithm or other EA approaches offline, system operator has a group of restoration procedure according to operational constraints.

```
ALGORITHM proposed EA (F0 : initial network with isolated loads)

//start generation counter
g: = 0;

//generate an initial network configuration (population) connecting isolated region
P (g):= INTIAL_POP (P (g0, F0));

//evaluate the feeders (individuals) of the initial configuration (population)
EVAULATE (P (g));

//test for termination criterion (a generation gmax)
WHILE stop criterion not reached DO

//stochastically select a feeder (individual, Fs) in the network (population)
Fs: = STOCHASTICALLY-SELECT (P (g));

//stochastically select the operator1 or operator2
OP: = SELECT_OPERATOR (op1, op2);

//apply OP to produce a new individual Fg from Fs
Fg: = OP (Fs);

//evaluate the new individual Fg
EVAULATE (Fg);

//deterministically select the survivors from P (g) and Fg
P (g+1):= ALTER_POP (P (g), Fg);

//increase the generation counter
g := g+1;

END
```

Figure 22 Pseudo-code for the proposed EA

4.2.4 Rule-based Expert System

In general, rule-based expert systems use human expert knowledge to solve real-world problems that normally would require human intelligence. Expert knowledge is often represented in the form of rules (or as data within the computer). A rule is a kind of instruction or command that applies in certain situations. For example “No chewing gum in school” is a school rule. Rules are like if-then statements in traditional manner. For school rule example, its pseudo-code can be implemented:

IF

I am in school.

AND

I am a chewing gum.

THEN

Spit out the gum

END

Using this very general definition, it might be concluded that all the knowledge available about the world can be encoded as rules. For a problem, if facts (environment, i.e. distribution network) and rules are encoded, a rule-based system will use these rules to derive conclusions. According to this structure, important advantages are:

- ability to capture and preserve human experience,
- minimize human expertise needed at a number of locations at the same time,
- solutions can be developed faster. Rule-expert system has a general structure shown in Figure 23. Programmer or developer can use the interface to encode the real life problem. Knowledge base stores rules and facts that are entered by the user concerning the problem. Then inference engine controls the whole process of applying the rules to the facts to obtain the outputs of the system.

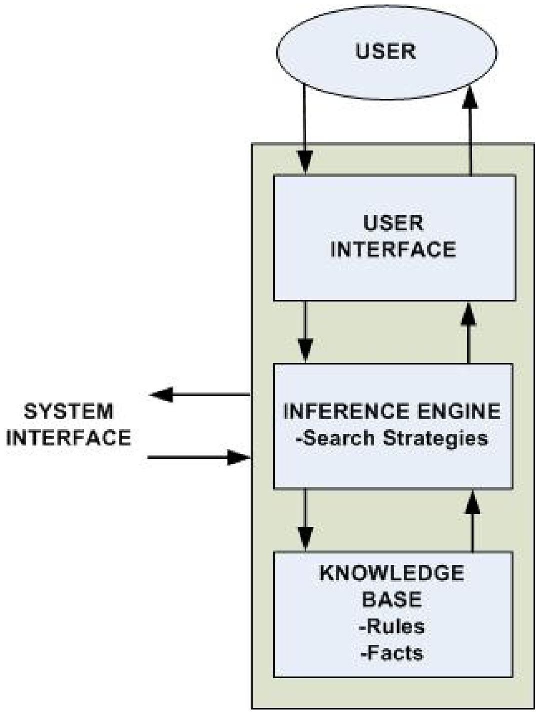

Figure 23 General structure of rule-based Expert System

After brief introduction to expert systems, can rule-based expert system be a remedy to service restoration problem? Several investigations have been carried out in the past [20]-[21] exploiting expert systems. The algorithm acquired from literature and side experiences are discussed in 4.2.6.

4.2.5 Hybrid Systems (Expert System with Genetic Algorithm)

Hybrid systems combine expert systems with genetic algorithm (or other approaches) to solve service restoration problem. Service restoration is a combinatorial and constrained optimization problem. Some approaches that have been mentioned before deal with restoring the out-of-service area as soon as possible. But in [22], the starting point is the total power source capacity may not be enough to restore the whole de-energized region and supply margins of supporting power sources have to be increased. In such a situation, expert system determines configuration of the network to increase supply limits. After providing sufficient supply capacity, genetic algorithm determines switch operations by disintegrating out-of-service region into smaller region for each available power sources. Therefore, high reliability can be realized by both expert system and genetic algorithm. The general flow chart of the system is shown in Figure 24.

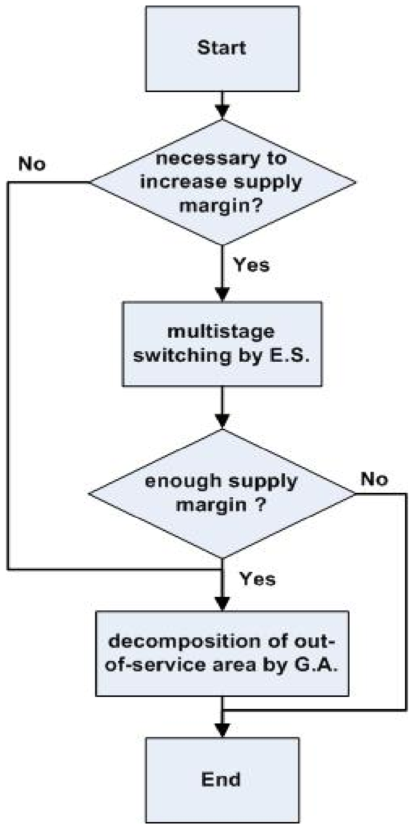

Figure 24 General flow chart of the hybrid system

4.2.6 Proposed Approach

Taking above approaches and distribution system (in Turkey) requirements into consideration, expert systems seems to be a good choice for service restoration. Expert Systems is a well proven technology for Energy Management Systems (EMS), having decades of application in this area [23]. Beside, expert systems solutions are fully explainable, can be easily documented and incorporate previous knowledge which are the abilities that ANN lack. Mathematical programming approach does not include human expert thought process and concerning changes in the distribution network structure, therefore service restoration algorithm must be modified. Because of the loss of experts in power distribution companies, due to privatization and retirement, expert systems can preserve corporate intelligence and memory. Also it will be possible to use the knowledge database (rules in expert systems) in the future to train the novice specialists.

First of all the main purpose of proposed service restoration algorithm is to minimize the number of the switching operations. It is same as minimization of expected energy not supplied (EENS) during service restoration, because the most valuable energy is the unsold energy for distribution companies. The assumptions of the proposed approach are listed below:

- Fault isolation is performed,
- Distribution feeders are in radial structure, (in ring or mesh design)
- Fault related information and load information are obtained through the DA, (Distribution Automation)
- There is no priority of load zones,
- The loads are balanced,
- Load currents are used to determine if feeders are operated within their ampacity,

During and after the service restoration following constraints must be satisfied:

- Radial network structure must remain.
- Source substation transformer capacity limit cannot be exceeded.
- The voltage drop at the end of the feeder must lie between the limits ($0.95<V<1.05$ pu)

For radial distribution system, it is adequate to use the constant current model and the nodes are sorted in the terminal substation order (TSO). Thus, the load flow can calculate the current flows from terminal nodes to substation and then the voltages from substation to terminal nodes. A model of load flow can be seen in [24].

OOP is applied in order to represent the components of distribution system as in fault isolation case, but proposed service restoration algorithm runs on the control center software and not in the RTU's hardware. The expert system reasoning process is designed to be in hierarchical structure in the following sequence:

- the group restoration is performed.
- if there are still de-energized customers after group restoration, zone restoration will be executed.
- load transfer stage is used for remaining out-of-service loads after second stage.
- if some customers are still out of service after third stage, maximum load zone restoration is used to restore the maximum number of customers.

4.2.6.1 Group Restoration

In this stage, all of the connection lines (tie lines) in the de-energized region to the neighbor feeders are searched. The neighbor feeder associated with each tie line is the back-up feeder. For line faults (not at the branch point) all the outage loads are clustered as one group and will be tried to transfer to the back-up feeders. For example in Figure 25, a fault occurs on L2 (as Fault 1). Z2, Z3, Z4, Z5, Z6, Z7 and Z13, Z14, Z15, Z16 form a single group. F2, F3, F4 are the back-up feeders through L8, L12 and L20 (tie lines) respectively.

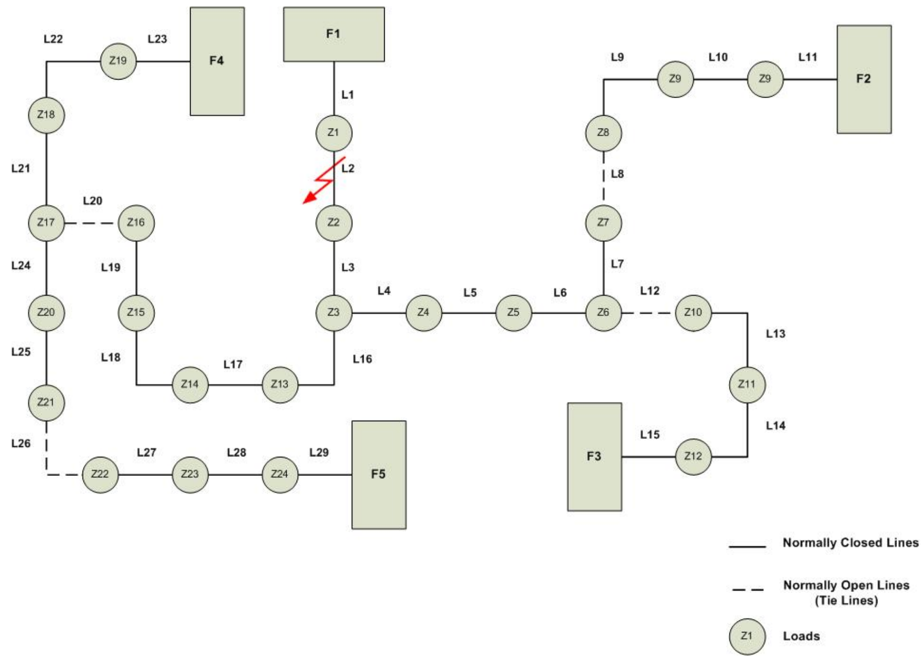

Figure 25 Sample system for proposed approach

After deciding the group and available tie lines, algorithm starts to transfer the entire group to a back-up feeder. If the load current of the connected group exceeds the ampacity of back-up feeder (any overload at the lines of the back-up feeder) and voltage drop constraint is violated, then the tie line is excluded for first stage restoration. If a fault takes place in the Z3 (bus fault at distribution transformer), there will be three groups; (Z2, Z3), (Z4, Z5, Z6, Z7) and (Z13, Z14, Z15, Z16).

4.2.6.2 Zone Restoration

If group restoration stage is unsuccessful, the zone restoration will take place. In this step, the algorithm investigates if there is a branch (node distribution transformer) point in the outage area. If the answer is “no”, zone restoration cannot be performed. Otherwise, zones will be determined according to first branch point. Loads up to the branch point and loads beyond that point can be considered as different zones. Tie lines are searched again for every zone. Then they have to be restored in the same manner as in group restoration. This process is illustrated in Figure 26.

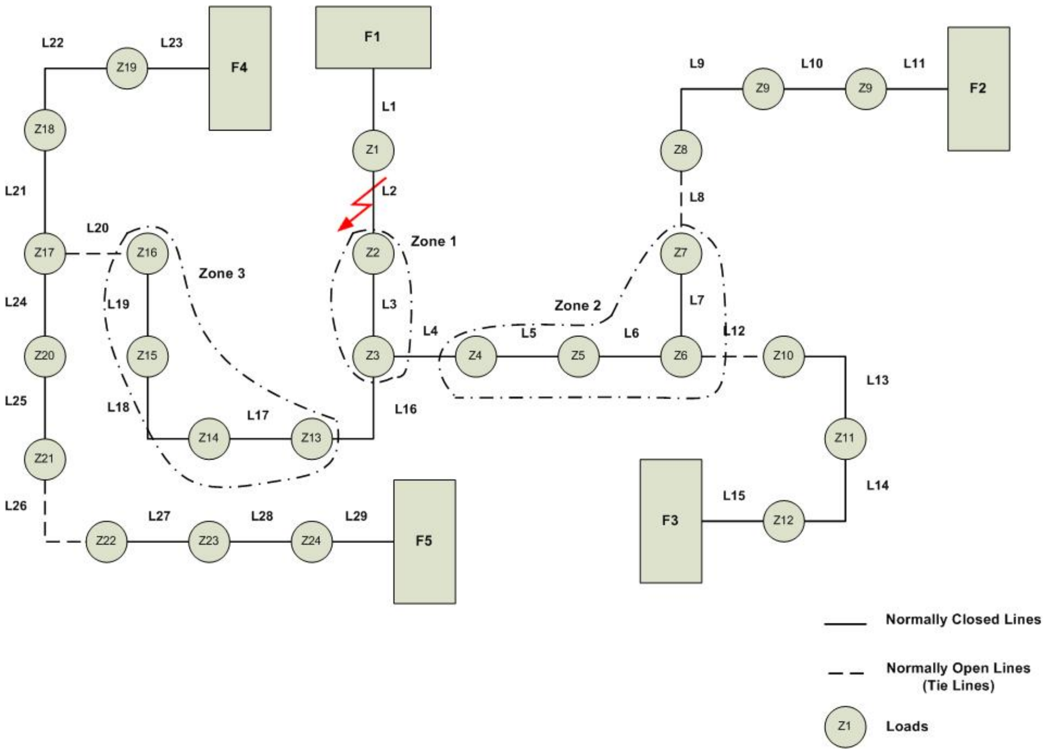

Figure 26 Zone restoration inference

4.2.6.3 Load Transfer

After group and zone restoration stage, if de-energized loads exist, load transfer will be considered. Transferring loads from the associated back-up feeder to its adjacent support feeder (in Figure F5 is support feeder) increases the load margin of the back-up feeder. For example in Figure 27, Z20 and Z21 may be transferred in the case that there is not enough ampacity of F4 feeder.

4.2.6.4 Maximum Load Restoration

Finally when all above stages cannot restore outage region, maximum load restoration will be performed. Loads will be tried to transfer through the tie lines to back-up zone one-by-one that are still in the de-energized zone (clustered by the zone restoration stage). The process is demonstrated in Figure 27. Some of the loads in F4 feeder are transferred to F5 feeder but it is not sufficient for all the loads in Zone 3 (Z13, Z14, Z15, and Z16). Then some of the loads in Zone3 are transferred to F4 feeder according to its ampacity. After maximum load restoration, unrestored loads are marked as failure zone. At every stage constraints are checked for system reliability.

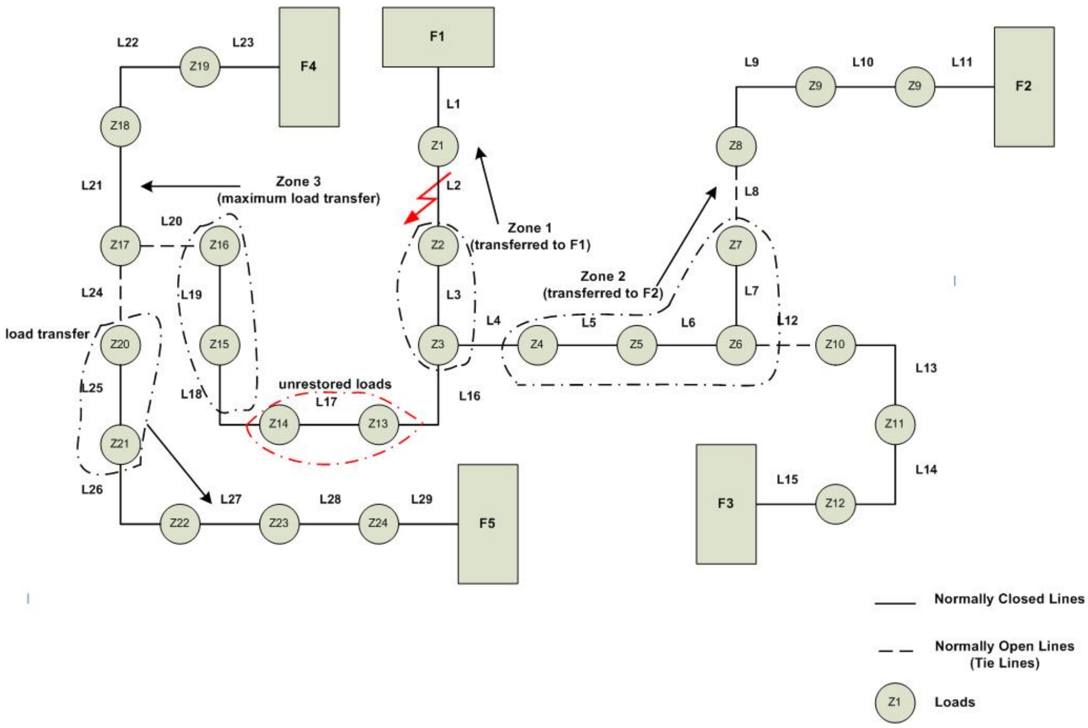

Figure 27 Maximum load transfer process

4.2.7 JESS (Rule Based Systems in Java)

After discussing proposed method, now it is time to briefly introduce an example of expert system engine, Jess. Proposed service restoration algorithm is written in Jess. Jess is a rule engine and scripting language which is written in Java, so it is an ideal tool for adding rules technology to Java-based software systems. The CLIPS expert system shell an open-source rule engine written in C, was the original inspiration for Jess.

Jess rule engine contains:

- An inference engine
- A rule base
- A working memory

Also interference engine consists of:

- A pattern matcher
- An agenda
- An execution engine

These components are shown schematically in Figure 28.

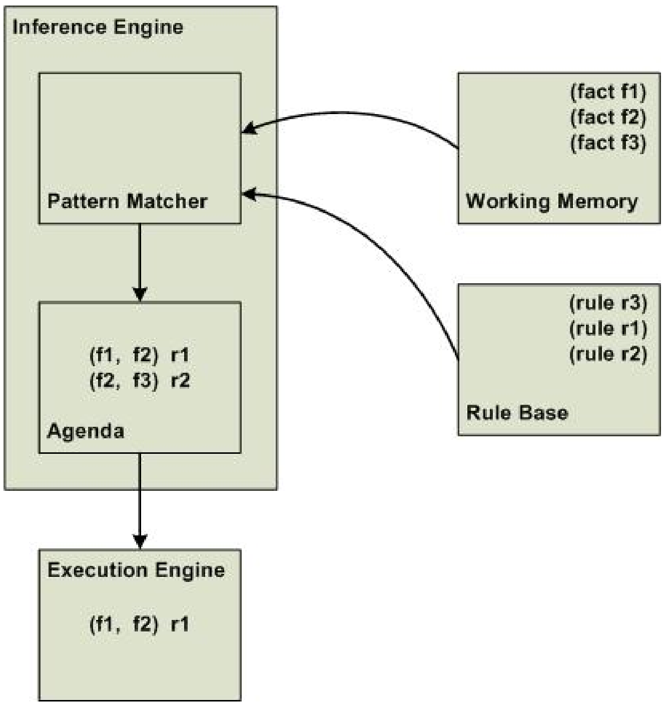

Figure 28 The architecture of Jess rule-based system

The main job of a rule engine is to apply rules to data. The inference engine controls the whole process of applying the rules to the working memory to obtain the outputs of the system. In inference engine, all the rules are compared to working memory (using pattern matching) to decide which ones should be activated at each cycle. The list of rules whose right-hand sides (action parts) will be executed, forms an agenda. The process of ordering the agenda strategy for a given rule engine will depend on different factors. Also the rule base contains all the rules that system knows and working memory contains all the pieces of information that the rule-system is working with. Finally, once rule engine decides what rule to fire, it has to execute rule's action part. The execution engine is the component of the rule engine that gives the output of the rules and facts.

The key point of the Jess (and also CLIPS) is the pattern matching algorithm. An inefficient solution would be to keep a list of the rules and simply check each one's action parts in turn against the working memory, forming a set of activation records for any of that match. After choosing one rule and executing it, it will be discarded and started again. It is obvious that it is not very efficient and does not scale well. After firing each rule, the system must recheck each fact against each rule. Doubling the number of facts or the number of rules roughly halves the performance of the system.

Briefly, the Rete algorithm which is an optimization algorithm in pattern matching, eliminates the inefficiency in the simple pattern matcher by remembering past test results across iterations of the rule loop. The Rete algorithm is implemented by building a network of interconnected nodes. For example some facts and rules are described as, Facts:

x (slot a)

y (slot b)

z (slot c)

Rules:

Rule name : example-1

(x (a ?v1))

(y (b ?v1))   =>)

Rule name : example-2

(x (a ?v2))

(y (b ?v2))

(z) =>)

The above rules might be compiled into the network shown in Figure 29.

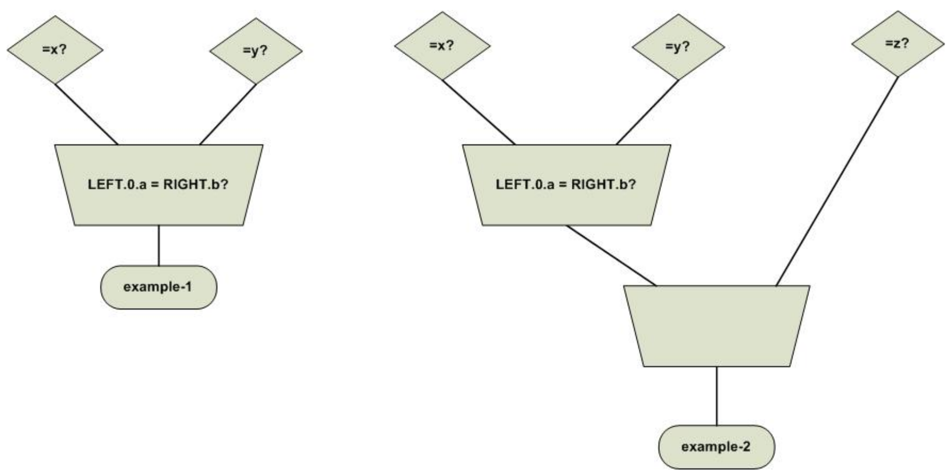

Figure 29 An unoptimized Rete network example

There are many optimizations for Rete algorithm. The pattern and join networks in Figure 30 are collectively only half the size they were in the first version. This kind of sharing comes up frequently in real systems and is significant performance booster.

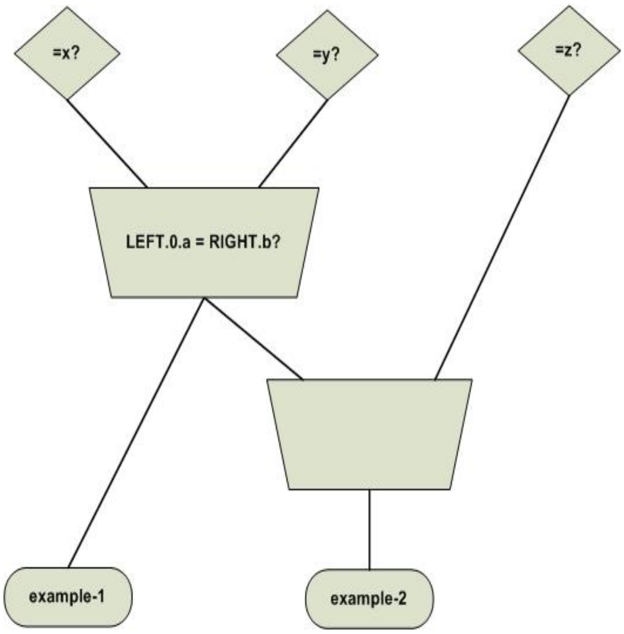

Figure 30 A Rete network that shares both pattern and join nodes

CHAPTER 5

CONCLUSION AND FUTURE WORK

In this thesis, fault isolation and service restoration algorithms based on expert system are presented for medium voltage cable distribution system. In Turkey, especially in big cities, electric distribution system has been uprating from 10.5 kV (or 6kV, 15 kV) voltage level to 34.5 kV voltage level for reducing distribution system losses, robust planning and simple power system operation since 90's. Ensuring reliability of sustainable energy was the next goal and TUBITAK developed a distribution automation system named TUDOSIS. This system has been implemented and working successfully for about more than ten years in Istanbul. But during of ten years time, distribution system has expanded without distribution automation because of lack of funds. The unplanned growth of power system endangered TUDOSIS unable to work properly. This was the starting point for the thesis and a new fault isolation algorithm for distribution automation is proposed.

Proposed fault isolation algorithm has a SCADA based approach that uses the alarms originating from the protection systems (relays and circuit breakers) and fault passage indicators through SCADA system. In the core of fault isolation algorithm, there is a distributed control approach which means automation system delivers the isolation task between novel RTUs. These RTUs are placed in the substation that has circuit breaker and relays, are responsible for possible faults in the manner of an agent based framework (simply every team which is consisted of distribution transformers has a coach). When a fault occurs, related circuit breaker will trip and special RTU for this substation will interrogate connected RTUs. After finding the fault location, it is cleared by opening both side switching devices and after that, control center software will be informed of the fault isolation process. In the case of communication problem between RTUs in the feeder and substation, the coach RTUs will hand over the isolation process to control center software.

Furthermore service restoration is mandatory for sustainable energy quality and system reliability. In Turkish distribution system for mesh networks expert system based service restoration algorithm is the right choice. One reason is expert system solution is fully explainable and consists of operator knowledge. The other reason is that this approach can preserve specialists' knowledge to train novice operators. Proposed approach consists of four steps which are from the related literature and the operators' knowledge. These steps are; group restoration (outage area is considered as whole group), zone restoration (outage area is divided according to branch points), load transfer (support feeder transfers their loads to adjacent feeders to increase their load margin) and maximum load restoration (number of the de-energized loads is minimized).

In the light of these proposed methods, a new distribution automation system will be designed within two subgroups. First flexible RTU hardware and software should be implemented considering presented fault isolation approach and new information and communication technology (ICT) infrastructures. Therefore, flexible ICT infrastructures should be low-cost, secure, open and reliable to lead management of smart electricity distribution which is next generation of distribution concept. Accordingly control center software should be designed taking into account proposed fault isolation and service restoration functions and open for ICT hardware solutions (i.e. not only one type of RTU). On the other hand protection system of the current distribution system will be reconfigured considering dispersed generation and penetration level of the generation.

Finally ultimate goal of the future project to build a distribution management system covering distribution automation, demand side management and distributed generation management.

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APPENDIX A

DISTRIBUTION AUTOMATION SYSTEM FUNCTIONS

	FUNCTION	MANAGEMENT AREAS				
		Information	System Reliability	System Efficiency	Voltage	Customer Loads
A	AUTOMATIC CONTROL:					
	Automatic Bus Sectionalizing	X	X	X		
	--Fault Isolation	X	X			
	--Service Restoration	X	X			
	--Overload Protection	X	X	X		
	Feeder Deployment Switching and Automatic Sectionalizing	X	X			
	--Fault Location	X	X			
	--Fault Isolation	X	X			
	--Service Restoration	X	X	X		
	--Feeder Reconfiguration	X				
	Integrated Volt/VAR Control	X		X	X	
	--Bus Voltage Control	X			X	
	--Substation Transformer Circulating Current Control	X		X		
	--Line Drop Compensation	X			X	
	Feeder Reactive Power Control	X			X	
	--Substation Transformer Load Balancing	X		X		
	-- Substation Reactive Power Control	X		X		
	Substation Transformer Load Balancing	X		X		
	--Reduce Transformer Load Loss	X		X		
	--Minimize Overloads	X	X			
B	MANUAL CONTROL:					
	Distribution Dispatch Center/ SCADA Interface	X	X	X	X	X

FUNCTION		MANAGEMENT AREAS				
		Information	System Reliability	System Efficiency	Voltage	Customer Loads
C	DATA ACQUISTION AND PROCESSING:					
	Analog Data Freeze	X				
	Data Monitoring	X				
	Data Logging	X				
D	INTERFACE:					
	Distribution	X				
	--Distribution Line Carrier	X	X	X	X	X
	--Radio	X	X	X	X	X
	--Telephone	X				
E	PROTECTION:					
	Automatic Reclosing	X	X			
	Bus Fault	X	X			
	Instantaneous Overcurrent	X	X			
	Substation Transformer	X	X			
	Time Overcurrent	X	X			
	Under Frequency	X	X			
F	LOAD MANAGEMENT:					
	Load Control	X				X
	Remote Service	X				X
	Pass-Through Commands	X				X
	--Load Shedding	X				X
	--Time-of-Use Signal	X				X
G	REMOTE METERING:					
	Load Survey	X				X
	Peak Demand Metering	X				X
	Remote Meter Reading	X				X
	Remote Programming of Meter	X				X
	Tamper Detection	X				X