Arab Academy for Science and Technology and Maritime Transport
College of Engineering & Technology
Electrical and Control Engineering Department

A Novel Fuzzy Cause-and-Effect-Networks Based Methodology for a Distribution Substation's Fault Diagnosis

M.Sc. thesis

By:

Eng. Muhammad Mustafa Ismael

A thesis submitted to the Faculty of Engineering – Arab Academy for Science and Technology and Maritime Transport in partial fulfillments of the requirements for the M.Sc. degree in Electrical and Control Engineering

Supervised by:

Prof Dr. Yasser Galal

Electrical and Control Department
Faculty of Engineering
Arab Academy for Science and Technology and Maritime Transport

Dr. Walid Aly El-Khattam

Electrical power and machines Department
Faculty of Engineering, Ain Shams University

Cairo 2014

Arab Academy for Science and Technology and Maritime Transport
College of Engineering & Technology
Electrical and Control Engineering Department

A Novel Fuzzy Cause-and-Effect-Networks Based Methodology for a Distribution Substation's Fault Diagnosis

M.Sc. thesis

By:

Eng. Muhammad Mustafa Ismael

A thesis submitted to the Faculty of Engineering – Arab Academy for Science and Technology and Maritime Transport in partial fulfillments of the requirements for the M.Sc. degree in Electrical and Control Engineering

Prof. Dr. Yasser Galal
Supervisor

Dr. Walid Aly El Khattam
Supervisor

Prof. Dr. Hussien El Desoki
Examiner

Prof. Dr. Waheed Sabry
Examiner

Cairo 2014

STATEMENT

This thesis is submitted to Arab Academy for Science and Technology and Maritime Transport in partial fulfillment of the requirement for M.Sc. degree in Electrical and Control Engineering. The included work in this thesis has been carried out by the author at the Electrical and Control department, Arab Academy. No part of this thesis has been submitted for a degree or a qualification at other university or institute.

Name: Muhammad Mustafa Ismael

Signature:

Date: / /2014

ACKNOWLEDGEMENTS

First of all I thank Allah for helping me finish thesis and I pray that Allah will accept it from me.

I owe my sincere thanks and gratitude to Prof. Mohamed Mansour a father and a teacher may Allah bless his soul.

I am extremely grateful and thankful to my parents, my wife Shaimaa and my brother Abd Al-Rahman for giving me their love, support, encouragement and their patience.

I would like to express my sincere gratitude to Dr. Walid El-Khattam for his support, valuable advice and great help.

My deep appreciation and thanks also goes to Prof. Yasser Galal whose passionate spirit is a constant source of inspiration.

Last but not least, thanks for all my dearest friends and colleagues who are always giving me the need support.

الاكاديمية العربية للعلوم والتكنولوجيا والنقل البحري
كلية الهندسة و التكنولوجيا
قسم الهندسة الكهربية والتحكم

طريقة مستحدثة لتحديد موقع ونوع الاخطاء في محطات التوزيع الفرعية باستخدام المنطق الغامض والشبكات السببية

رسالة الماجستير

مقدمة من:
مهندس/ محمد مصطفي اسماعيل

للحصول على درجة الماجستير في الهندسة الكهربية والتحكم

تحت إشراف:

أستاذ دكتور/ ياسر جلال
قسم القوى الكهرباء والتحكم
كلية الهندسة
الاكاديمية العربية للعلوم والتكنولوجيا والنقل البحري

دكتور/ وليد على الختام
قسم القوى الكهربية والالات
كلية الهندسة
جامعة عين شمس

القاهرة 2014

ملخص الرسالة

تكتسب انظمة الطاقة الكهربية اهمية بالغة لتاثيرها الكبير في حياتنا اليومية ، ولذا فان استمرارية الامداد بالطاقة الكهربية للمستهلكين دون انقطاع تعد رغبة اساسية و هدف منشود سواء للمستهلك او للقائمين على المنظومة.وانطلاقا من هذه الاهداف الملحة تم تقديم ابحاث متعددة للتغلب علي ما قد يؤثر علي ثبات عملية التزود والامداد بالطاقة ، وتقديم الحلول لتجنب اي عراقيل من شانها تهديد هذا الثبات المنشود. وقدمت هذه المجهودات البحثية نتائج طيبة ولكن شابها بعض المشكلات المتعلقة بتعقيدات التكوين وبطء الاستجابة في التعامل مع حالات حدوث الاخطاء في انظمة الطاقة.

ولذا في هذا البحث تم تقديم اطروحة لتحديد الخطأ ونوعه في محطات التوزيع الفرعية ، تتلافي عيوب الانظمة الاخري لتحقيق نتائج افضل.كما تم مراعاة الضغط الذي يتعرض له عامل التشغيل اثناء حدوث اخطاء في محطات التوزيع الفرعية لتجنب ما قد يؤثر بالسلب علي قراراته في التعامل مع هذه الاخطاء ، فتم مراعاة الدقة في تحديد الخطأ ونوعه بسرعة فائقة لمساعدة عامل التشغيل علي التعامل مع حالات الاخطاء دون تكبد اي اعباء مالية في تجهيز المحطة باجهزة مكلفة ، بل تم الاعتماد علي المعلومات المتوفرة من انظمة التحكم اسكادا -SCADA– عن حالة المحطة وبيانات اعراض حدوث الاخطاء.

ارتكزت الاطروحة المقدمة لتحديد الاخطاء وانواعها علي تقنية الشبكات السببية الغائمة FUZZY Cause – Networks and Effect _ لتحديد الاخطاء ، والمنطق الغيمي _ FUZZY Logic _ لتحديد انواعها، وتم توضيح وتقديم التكوين الرياضي وقواعد البيانات للطريقة المقترحة.

وقد تم تقييم اطروحة البحث باختبارها علي انظمة محطات توزيع فرعية فعلية ومقارنة نتائج الاختبارات مع طريقتين تم طرحهما في ابحاث سابقة. اثبتت النتائج تفوق الطريقة المطروحة وتبينت قدراتها العالية في التعامل مع اي حالة من حالات الاخطاء. ولزيادة التاكيد علي مميزات الطريقة المقترحة في هذا البحث تم اختبارها علي نظام قائم لاستبيان مميزات اضافية عند التعامل مع سيناريوهات اكثر تعقيدا وصعوبة.

تبين بعد هذه الاختبارات الاتي:

1- الدقة العالية في التعامل مع اي حالة من حالات حدوث الاخطاء.
2- القدرة الفائقة للطريقة المطروحة في التعامل مع حالات الشك في اسباب الاعراض الناجمة من حدوث اخطاء في المحطة.
3- قدرة الطريقة المطروحة في التعامل مع اي تكوين للمحطات الفرعية.
4- مرونة التكوين الرياضي للطريقة المقترحة.
5- سهولة التكوين والتعديل في قاعدة بيانات الطريقة المقترحة.
6- سرعة الاستجابة الفائقة اهلت الطريقة المقترحة لتكون اداة تحديد للاخطاء ونوعها وقت حدوثها.
7- ظهرت كحل اقتصادي للتعامل مع حالات الاخطاء مستندة علي المعلومات المتوفرة في انظمة التحكم الخاصة بالمحطة دون اللجوء لشراء اجهزة مكلفة عالية التقنية لتديد الاخطاء وانواعها.

تم استخدام برامج الماث لاب Mat lab— لبرمجة الطريقة المقترحة في هذا البحث وعمل محاكاة لسيناريوهات الاختبارات المتعددة، كما تم طرح أعمال للبحث المستقبلي ومناقشتها.

وتتكون هذة الرسالة من ستة فصول كما يلى:

- الفصل الاول: المقدمة ويعرض هذا الفصل مقدمة لموضوع البحث. كما يعرض اهداف الرسالة و مكوناتها و الخطوط العريضة لها.

- الفصل الثانى: بعنوان انظمة الاسكادا ، وفيه يوضح مكونات ومهام نظام الاسكادا باعتبارها بيئة الحدث لهذا البحث. كما يتم تسليط الضوء علي دور المشغل في غرفة التحكم والحاجة لطريقة معاونة له لتحدد صفات الخطأ عند حدوثه لتلافي الوقوع في كوارث.

- الفصل الثالث: بعنوان الطريقة المقترحة لتحديد الخطا ، وفيه يتم عرض صفات الطريقة المقترحة ومكوناتها الرياضية و الخوارزميات المستخدمة في هذه العملية.

- الفصل الرابع: بعنوان الطريقة المقترحة لتحديد نوع الخطأ ، وفيه يتم عرض الشق الثاني من الطريقة المقدمة في هذا البحث وهي تحديد نوع الخطأ وصفاته. تم ابراز التاصيل الرياضي للطريقة ومكوناتها.

- الفصل الخامس : بعنوان التطبيقات وفيه تم عمل مقارنة لنتائج الطريقة المقدمة مع طرق مستخدمة اخري علي انظمة واقعية في سيناريوهات مختلفة وتبين كفاءة وقدرة الطريقة المقترحة علي التعامل مع اي نوع او عدد للاخطاء في اي تكوين لمحطات التوزيع.

- الفصل السادس: الاستنتاج ويناقش هذا الفصل الاستنتاجات العامة للرسالة و التوصيات المستقبلية المقترحة للبحث فى هذا المجال.

الاكاديمية العربية للعلوم والتكنولوجيا والنقل البحري
كلية الهندسة و التكنولوجيا
قسم الهندسة الكهربية والتحكم

طريقة مستحدثة لتحديد موقع ونوع الاخطاء في محطات التوزيع باستخدام المنطق الغامض والشبكات السببية

رسالة الماجستير

مقدمة من:
مهندس/ محمد مصطفي اسماعيل

للحصول على درجة الماجستير في الهندسة الكهربية والتحكم

استاذ دكتور / ياسر جلال
مشرف

دكتور / وليد على الختام
مشرف

استاذ دكتور / حسين الدسوقي
ممتحن

استاذ دكتور / وحيد صبري
ممتحن

القاهرة 2014

Abstract

Power systems gained their importance due to proximity to huge numbers of consumers. Sound distribution system operation is essential for consumers and equipment safety. In case of abnormal events, accurate and fast fault diagnosis (identifying fault and fault type) is a vital issue to retrieve a sound distribution systems' operation.

This thesis presents a fault diagnosis methodology for substations, using Fuzzy Cause and Effect-Networks (FCE-Nets) and fuzzy logic. Both, fault detecting and estimating fault's type are identified using simple matrix operations, Fuzzy logic data base, and if-then-rules. Four case studies are carried out to evaluate the proposed methodology. The obtained results are compared with two different methods: Expert System (ES) with Artificial Neural Networks (ANNs) and Cause and Effect-Network (CE-NETs) to verify the proposed method. The comparison results are discussed and conclusions are reported. Finally, conclusions and recommendations are presented and discussed.

Table of Contents

List of Tables

List of Figures

List of Symbols and Abbreviations

$\wedge$	Fuzzy minimum operator
$\otimes$	Fuzzy multiplication operator
$3^{\emptyset}$ fault	Symmetrical fault
ANNs	Artificial Neural Networks
B	Backup node vector
CBs	Circuit Breakers
CE-Net	Cause and Effect Network
CF	Certainty Factor
CO	Over current relay
EFS	Estimated Fault Section
ES	Expert Systems
F	Fault node vector
FCE-Nets	Fuzzy Cause and Effect-Networks
GPS	Global Positioning System
H	High set of the fault type's membership function
I/O	Input/Output
L	Low set of the fault type's membership function
DL	Line to line fault
DLG	Double line to ground fault
$\mu\ (x)$	Membership function
MMI	Man Machine Interface
MTU	Master Terminal Unit
N	Normal set of the fault type's membership function
NCC	National Control Center
NRLDC	Northern Regional Load Dispatch Centre
PDC	Phasor Data Concentrators
PGCIL	Power Grid Corporation of India Limited
PLC	Power-Line Carrier
PMUs	Phasor Measurement Units
PN	Petri-Nets
PTC	Public Telephone Communication
$\widetilde{R}$	Rule matrix
RTUs	Remote terminal units
SCADA	Supervisory Control And Data Acquisition
SLG	Single line to ground fault
T	Truth State Vector
T^{*}	The updated transformation vector
TV	Transformation Vector
WAMS	Wide Area Monitoring System

** Additional symbols are defined locally.

Chapter 1: Introduction

The main objective of power systems is to provide a reliable and continuous supply for their consumers. In the event of fault occurrence, the operator/dispatcher aims to minimize the damages to equipment in faulted areas, isolate faulted equipment and components, and restore the system as soon as possible. However, the operator/dispatcher may find it difficult and time consuming to provide the right decisions. This mission becomes more complex if multiple faults occurred or some equipment malfunctioned. Therefore, a successful decision will be achieved after recognizing and identifying the fault's location, characteristics, and type, which are the basic tasks of the fault diagnosis in power systems.

1.1Motivations

Researchers investigating fault diagnosis are concerned with the data to be used for fault diagnosis and the implemented identification methodologies to improve their accuracy and speed. The most widely used data are the status of Circuit Breakers (CBs) and protective relays. This data is obtained from the Supervisory Control And Data Acquisition (SCADA) systems to improve and facilitate monitoring and operating processes.

A fault diagnosis methodology is proposed based on a Fuzzy Cause and Effect-Networks (FCE-Nets) technique to assist the operator/dispatcher when he faces alarm attacks due to faults in distribution systems' substations. This methodology is concerned with fault diagnosis using the status of protective devices as it is commonly available in existing SCADA systems.

1.2Objectives

The objectives of this thesis are:

1) Proposing effective real time decentralized fault diagnosis (location, type) methodology to help operators in the control rooms of substations to make right decisions when they face fault alarms attack.
2) Implementing this proposed methodology as a tool box. The implementation shall be accurate, easy in establishing and forming its database, suitable for real time detection, economical and able to deal with uncertainty events.
3) Testing this methodology on existing systems and compare results with other methods to analyze and proof its strengths and the abilities.

1.3Thesis outline

This thesis is composed of five chapters other than this introductory chapter. It is organized as follows:

Chapter 2

The construction, main functions and the stages of the state estimation of the SCADA as the environment of events of this thesis are introduced. The need of methodologies, functions and techniques of fault diagnosis are presented by discussing the main tasks of operators /dispatchers.

Chapter3

Furthermore, literature reviews of fault allocation estimation methods and techniques are reported showing their strength and weakness. The concepts, construction and the mathematical operations of the proposed methodology are presented. The proposed fault allocation estimation process is described in details.

Chapter 4

General view over fault types is introduced. The mathematical forming and the rules construction of the proposed fault type identification process are reported in details.

Chapter 5

The procedures and the steps of the proposed methodology are presented using the of Matlab Fuzzy toolbox. To proof the ability, accuracy and the effectiveness of the proposed method; the obtained results from the proposed method were compared with other methods on existing systems. The ability of the proposed methodology was tested to deal with uncertainty situations as a real time fault diagnosis tool box.

Chapter 6

In this chapter, summary of the achievements of this work are presented. Conclusions and recommendations are evaluated and discussed. In addition, future work is suggested.

Appendix

Finally, the published research is introduced in the appendix.

Chapter 2: Supervisory Control and Data Acquisition (SCADA)

In this chapter, SCADA as the environment of this research will be discussed showing the different components of the system and the stages of the state estimation process. Then, the rule of the operator will be presented to focus mainly on the dangerous sequence of the wrong decisions. The main purpose of this chapter is clarifying the need of methodologies, functions and techniques to help the operator in making right decisions during the complex fault situations of the system.

2.1SCADA architecture

The SCADA system is a set of computational tools used to monitor, control, and optimize the performance of a power system. Initially, power systems were overseen only by supervisory control systems. These were control systems which monitored the status of Circuit Breakers (CBs) at substations along with generator outputs and the overall system frequency. Later, supervisory control systems were enhanced by adding an interconnection-wide real-time data acquisition function giving rise to the first SCADA system [1].

Figure 2.1 shows the basic architecture of a typical power SCADA system with centralized fault diagnosis functions. In SCADA systems, all of the field data is collected by Remote Terminal Units (RTUs). Then the RTU transmits the collected data to the control center through communication networks [2].

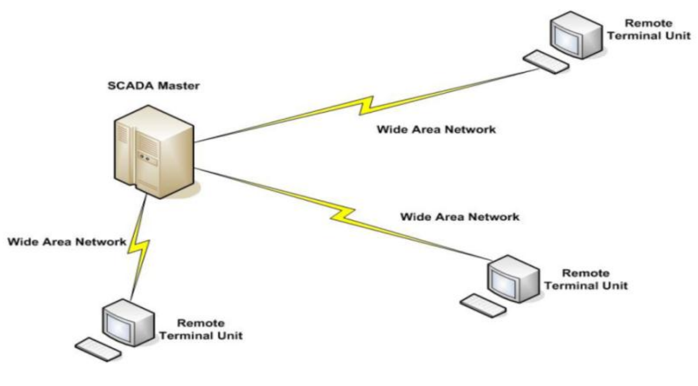


Fig. 2.1 Simple SCADA System Components [2]

A SCADA system is a centralized control and monitoring system that typically consists of a master station, communication networks, and RTUs [1]. Figure 2.2 shows the stages of the SCADA interface.

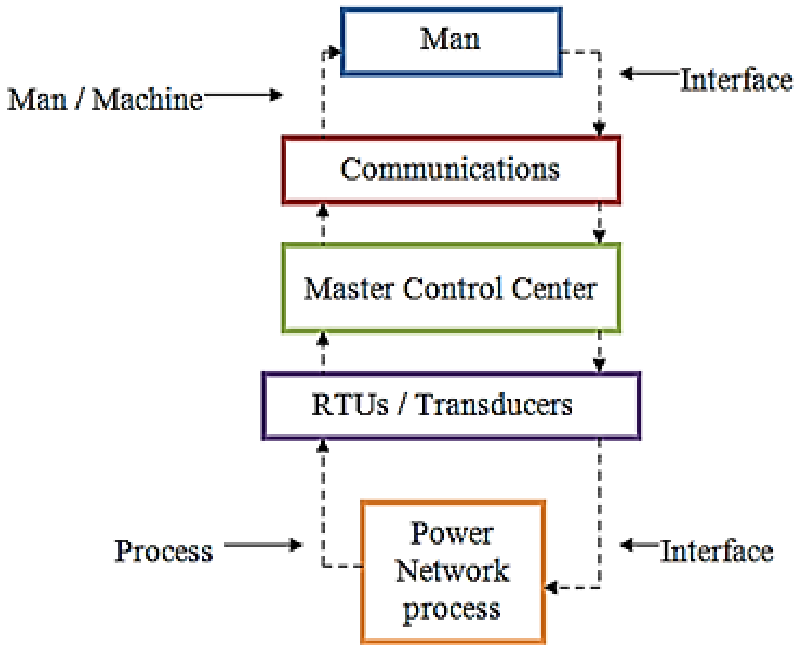


Fig. 2.2 The stages of the SCADA interface [1]

2.1.1 Man Machine Interface (MMI)

It is an interface between man and technology for control of the technical process.
The computer system at Master Control Center is connected with RTU over the communication link.

2.1.2 Master Terminal Unit (MTU)

The MTU initiates all communication, gathers data, stores information, sends information to other systems, and interfaces with operators. The major difference between the MTU and RTU is that the MTU initiates virtually all communications between the two. The MTU also communicates with other peripheral devices in the facility like monitors, printers, and other information systems [3]. The primary interface to the operator is the monitor that portrays a representation of relays, breakers, etc.

2.1.3 Communication

There are many communication methods available. Evaluation of different communication systems for data communication among the system elements is required at the planning stage. The communication methods may be used individually or combined [3]. The communication methods include the following:

a. Public Telephone Communication (PTC)

b. Power-Line Carrier (PLC)

c. Radio Communication

d. Fiber Optics

e. Satellite Communication

2.1.4 Remote Terminal Units (RTUs)

Modern RTUs are microprocessor based devices and are designed to acquire data and transfer the same to the Master Station through a communication link.

The RTU is usually designed to monitor parameters such as: Bus-line volts, current, active power, reactive power, status of circuit breakers, switches and isolators, fault detection temperature, level, pressure, flow etc. [3].

RTUs collect data packets which includes any block of data sent over a network. Each pack contains information about the sender, receiver and error control information, in addition to the actual message [4]. The process of collecting data packets is carried out by using the following devices:

a. Transducer

This is a measuring element that senses the external action. It gathers parameters and supplies through remote telecommunication capabilities [3].

b. Transmitter

This provides output (transmittable) signals after converting and amplifying low level signals of basic sensor elements [3].

Then RTUs perform analogue/digital conversions, check data-scaling and corrections (typically at I/O card level). Finally RTUs carry out pre-processing tasks and send/receive messages from/to master station(s) via interfaces [3].

2.1.5 Programs

The operation of a microprocessor is affected by sequential application of a number of instructions. Such a sequence of instructions is called a program. There are three categories of programming:

a. Machine code
b. Assembly language
c. High level language

The computer operator, who controls the microprocessor by means of a keyboard, will use a high level language with the help of a compiler, and assembly language with the help of an assembler [4].

2.1.6 Protocol

It allows two computers to understand each other while transferring information between themselves. In networking and communications, it is the specification that defines the procedures to follow when transmitting data [4].

2.2State estimation

During normal operation, the power system is either in a secure or insecure state. The power system is said to be in a secure state if disturbances within the power grid do not impair system performance. State estimation is a vital component of the SCADA and it is used to analyze the security of the power system and take corrective or preventive action when necessary [5]. Figure 2.3 shows the relation between state estimation process and different elements of a SCADA system.

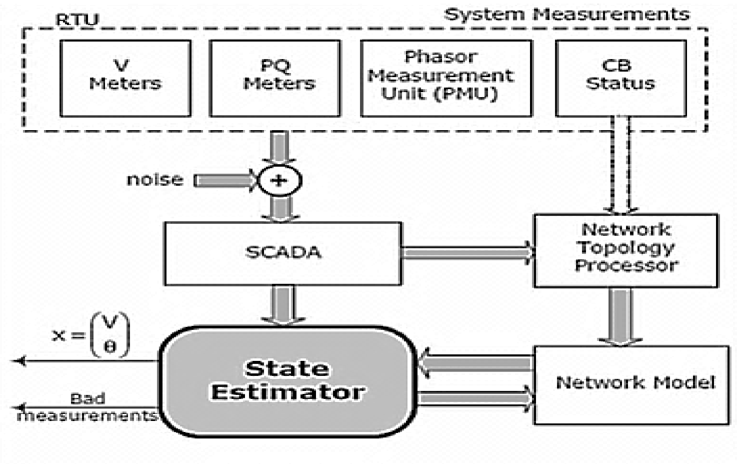


Fig. 2.3 Relationship between the different elements of a SCADA system [5]

2.2.1 The Processes of the state estimation

The data acquisition system obtains real-time measurement from devices like RTUs and, more recently, Phasor Data Concentrators (PDC) scattered throughout the system. The state estimator calculates the system state and provides the necessary information to the supervisory control system which then takes action by sending control signals to the switchgear [6].

The conventional state estimator built into the SCADA consists of four main processes are shown in Figure 2.4.

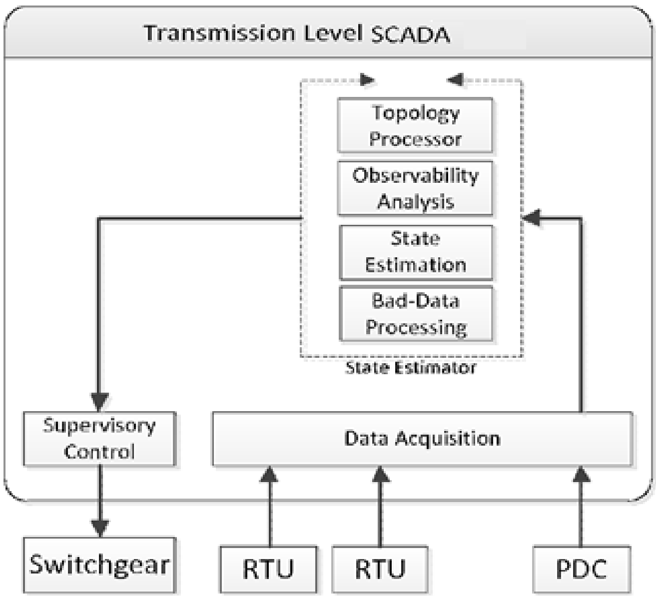


Fig. 2.4 State Estimation Block Diagram [6]

2.2.2 Topology Processing

It is the process that tracks the network topology and maintains a real-time database of the network model. This is done by analyzing the position of CBs and other switchgear in the substations [6].

2.2.3 Observability Analysis

This process is carried out to ensure that the measurement set is sufficient to perform state estimation [6].

2.2.4 State Estimator

This process is run by using some kind of algorithms on the operating measurement sets to estimate the system state [5].

2.2.5 Bad-Data Processing

This process identifies any gross errors in the measurement set and eliminates bad measurements [6].

2.3Operator rule

A fault can cause a large number of alarm messages in a short period of time in a power SCADA system. This will impose heavy stress on operator in the control center and hamper his decision-making during the restoration process. In [7], Figure 2.5 shows the relation between the control center and the fields of operation:

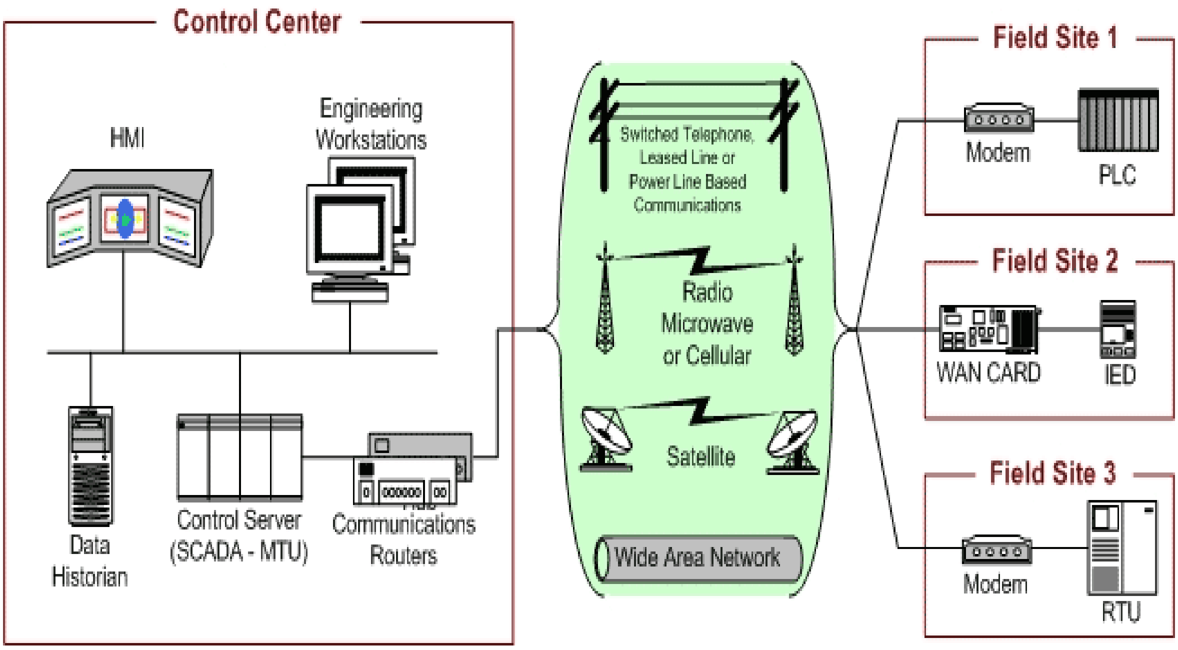


Fig. 2.5 Connection between Control Center and the field of operations [7]

If a SCADA system does not have a fault diagnosis function, the operator needs to use his operation experience to estimate possible fault sections according to a large number of alarm messages. If the operator makes a wrong decision, this may cause serious damage to power equipment leading to a large area blackout [5].

Fault diagnosis also becomes increasing complex if some pieces of equipment fail to operate correctly. Therefore, it is necessary to develop fault analysis tools to assist operator in power system operation. That will be discussed in the following chapters.

2.4Literature survey on applications and functions of SCADA system

In [8], an existing application of a SCADA system was discussed of power system network of Dhaka city, Bangladesh. The author presented SCADA in overall operation, control and monitoring of transmission and distribution systems. The monitoring of the daily operation, load management and system faults by a SCADA and how the advantages of SCADA help in improving the performance of overall system operations were presented. RTUs were considered as the back-bone of the SCADA system, as they are placed in every substation of the electrical power system network. The focus was on the RTUs role which is gathering operational information of switchgears of the substation and transfers that to the central database through microwave linkage. Furthermore, the main functions of the SCADA system was presented as; data acquisition, data communication, data presentation and control.

Finally, a recommendation was made to implement the SCADA system for controlling the whole electricity network of Bangladesh to improve the overall system performance, reliability, and stability of the whole system.

In [9], the author discussed the existing SCADA system with Wide Area Monitoring System (WAMS) at the Power Grid Corporation of India Limited (PGCIL) Northern Regional Load Dispatch Centre (NRLDC). The communications infrastructure that WAMS used and the tools to monitor and archive the time-synchronized data were discussed.

The main focus was on the problem of the slow process of retrieving data from the devices. The cause of this problem was the asynchronous nature of the data which did not provide accurate angle difference information from two nodes on the network. Figure 2.6 shows the SCADA system performing an asynchronous scan of RTUs.

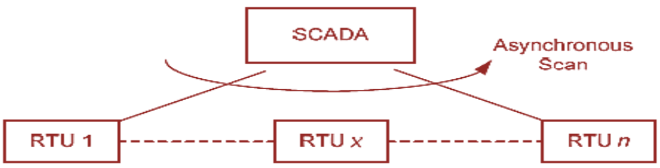


Fig. 2.6 SCADA system performing an asynchronous scan of RTUs [9]

Using Phasor Measurement Units (PMUs) was recommended because they provide a time- stamp samples of voltage and current accurately. Furthermore, it was mentioned that this technology can be used to provide high-speed and coherent real-time information of the power system and improve the ability of the SCADA system functions. Figure 2.7 shows the proposed improvements on SCADA system.

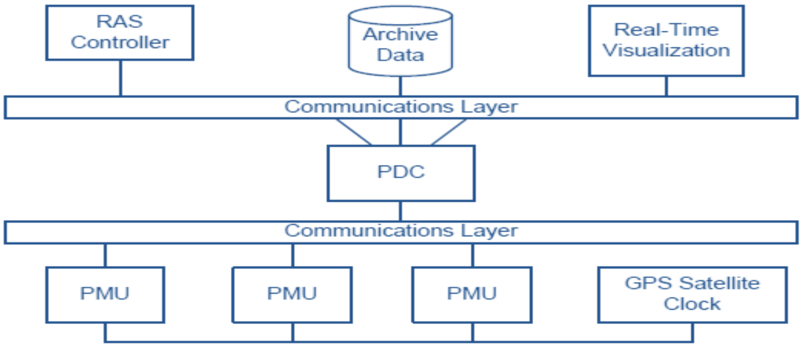


Fig .2.7 Building blocks of a synchrophasor-based system [9]

In [10], the author focused on the requirements from the SCADA system to keep the power systems stable.

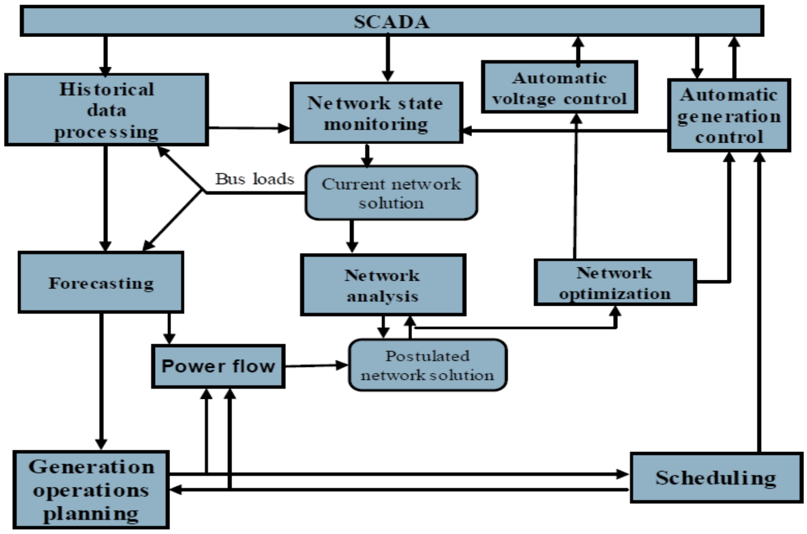


Fig. 2.8 Required functions from SCADA system [10]

The author also gave a detailed view of these functions and sorted them as follows:

a. Supervisory control and data acquisition

It supervises the status or the changes of breakers, connectors, and protective relays; induces of charged/uncharged status of lines and buses; supervises active/reactive power against operational/emergency limit; judges network faults.

b. State estimation and scheduling

It estimates most likely numerical data set to represent current network.

c. Load forecasting

It anticipates hourly total loads for a few days ahead based on the weather forecast, type of day, etc. utilizing historical data about weather and load.

d. Power flow control

It supports operators to provide effective power flow control by evaluating network reliability, considering anticipated total load, network configuration, load flow, and contingencies.

e. Data maintenance

It enables operator to modify the database of power device status and network topology by defining parameters.

f. Voltage/reliability monitoring

It monitors present voltage reliability and transient stability and predicts future status some hours ahead.

2.5Conclusions

In this chapter, SCADA system was focused on as the environment of the proposed methodology to show the following:

1- The construction and main functions of the SCADA system.
2- The stages of the state estimation process.
3- The main duty of operator in the control center of the SCADA system was illustrated. Thus to improve the state estimation function of SCADA needs to improve.

Also a literature review was presented to show the great and complex duties and functions of SCADA system and how to improve the ability of the SCADA system to keep the power system stable.

Chapter 3: Fault Identification Using fuzzy Cause and Effect Networks

In this chapter various fault diagnosis methods and techniques used in fault diagnosis were discussed briefly. Although these methods offer powerful solutions, they still suffers from some imperfections such as slow response time and difficulty in database maintenance, slow convergence in the training process, and determination of the network parameters like hidden units, layers [11]. Because of the last mentioned problems, a new method for fault identification in substations is proposed. This proposed method based on the Fuzzy Cause-Effect Networks (FCE-Nets), the fuzzy rule matrix and Boolean rule matrix transformations. Since the proposed reasoning methods require only simple matrix operations in a parallel manner, it is well suitable for on-line applications.

3.1Literature survey on fault diagnosis and section estimation

3.1.1 Expert Systems (ES)

Expert systems were the earliest attempt in applications of power system fault diagnosis. In rule-based expert systems, knowledge of the power system is represented as rules stored in the database via if-then-else form.

Although the rule-based ES offers a useful method for fault diagnosis in [12], common drawbacks of ES-based fault diagnosis involve knowledge-based maintenance and slow response time due to conventional knowledge representation and inference mechanism.

3.1.2 Artificial Neural Networks (ANNs)

The main advantages of ANN for fault diagnosis are its flexibility with noisy data and fast response time. No explicit rules are required to precisely define the power system configuration and protective schemes [13].

However, as in [14] it needs an additional training process and takes time to derive the required network weights.

When power systems become more complicated, the convergence of the training slows down and sometimes falls in a local optimum. In addition, when the changes in power networks occur, neural networks should be trained again in response to each change.

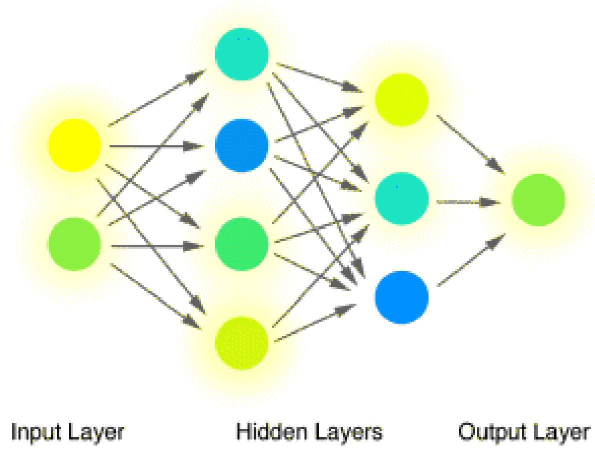


Fig 3.1 Simple Neural Network [14]

3.1.3 Petri-Nets (PN)

The major features of the Petri net (PN)-based methods are the abilities of graphical knowledge representation and parallel information processing [15].

- A basic PN consists of four basic elements:

A) Places

B) Arcs

C) Transitions

D) Tokens

In [16], the incidence matrix becomes large in dimension for a complex power system, leading to the difficulty in analysis.

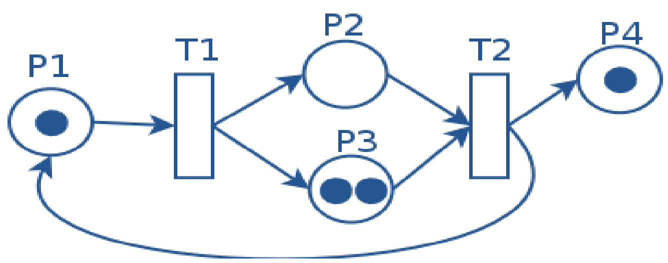


Fig 3.2 A Petri-Net Model [16]

3.1.4 Cause and Effect Network

The CE-Net is a graphical tool for knowledge representation. It is easier for human operators to understand and maintain the knowledge base in graphical representation and as in [17] the difficulties of the knowledge acquisition from operators in terms of detailed rules are avoided. Since CE-Nets can be easily represented by matrices, the parallel information processing can be achieved with fast inference speed. Compared to PNs, the CE-Nets are easier for operators to draw and model objects. In addition, the inference procedures of CE-Nets are more concise and need less computation in the inference process, but it has a poor ability in dealing with uncertainty situations [18]

3.2Main concepts of the proposed fault section estimation process

After the previous survey over the used techniques and methods in fault diagnosis, the main concepts and techniques on which the proposed fault allocation process is based; will be explained in detail as follows:

3.2.1 Fuzzy Logic

Fuzzy logic is a convenient way to express incomplete or uncertain information. It has been successfully applied in various fields. Many approaches hybrid with fuzzy logic have been proposed for fault diagnosis to solve information inexactness and uncertainties. All of the aforementioned approaches can couple with fuzzy logic to gain the advantage in dealing with information uncertainty [19].

A. Fuzzy Data Base & Rule Base

Fuzzy sets provide a mathematical way based on the concept of possibility and defined by a number between one and zero. In another words, for crisp sets an element x in the universe X is either belong to the set or it is not, whereas elements of a fuzzy set may have various degrees of belonging.

The key issue of fuzzy logic lies in the definition of membership functions which are usually defined on a trial-and-error basis [20].

a. Membership function

A fuzzy set can be defined as follows:

An element of a fuzzy set is an ordered pair containing a Se element and the degree of membership in the fuzzy set. A membership function is a mapping:

$$\boldsymbol{\mu}: \boldsymbol{x} \rightarrow [\mathbf{0}, \mathbf{1}] \tag{3.1}$$

And for fuzzy set *A:*

$$\boldsymbol{A} = \{(\boldsymbol{x} \,.\, \boldsymbol{\mu}_{\boldsymbol{A}}(\boldsymbol{x})) \parallel \boldsymbol{x} \in \boldsymbol{X} \tag{3.2}$$

The membership function describes the degree that the element $\boldsymbol{x}$ belongs to the fuzzy set *A*. A higher value of $\boldsymbol{\mu}_{\boldsymbol{A}}(\boldsymbol{x})$ means a greater degree of membership. The underlying power of fuzzy set theory is that it uses linguistic variables, rather than quantitative variables, to represent imprecise concepts.

A linguistic variable differs from a numerical variable in that its values are not numbers but words or sentences in a natural or artificial language. For instance, instead of describing the value of the faulted currents or voltages in terms of their exact magnitude we could just say that the currents or voltages are *high* or *low*, which is more uncertain and less precise but more useful [21].

b. Fuzzy rule base

A rule consists of prior parts describing causes and the resultant parts describing effects. The general formulation of a fuzzy implication rule can be denoted as:

$$\boldsymbol{R}_{\boldsymbol{i}} : \boldsymbol{IFC}_{\boldsymbol{j}}\boldsymbol{ThenC}_{\boldsymbol{i}}\ (\ \boldsymbol{CF} = \ \boldsymbol{\mu}_{\boldsymbol{i}}) \tag{3.3}$$

This infers that the truth of condition $\boldsymbol{C}_{\boldsymbol{j}}$ implies the truth of condition $\boldsymbol{C}_{\boldsymbol{i}}$ with a certainty factor $\boldsymbol{CF} = \boldsymbol{\mu}_{\boldsymbol{i}}$. So the larger the value of a certainty factor is, the more reliable the rule is [22]. Figure 3.3, shows the fuzzy rule base inference as follows:

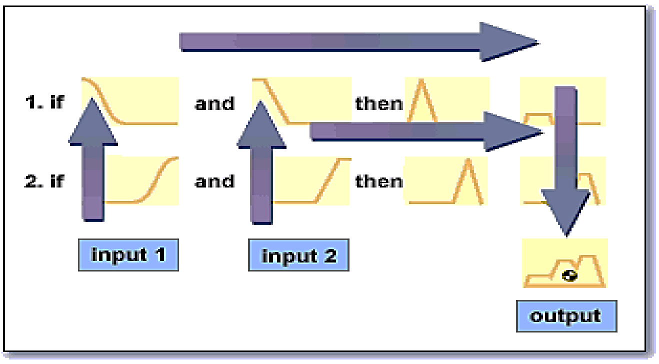


Fig. 3.3 Fuzzy Inference Diagram

3.2.2 Fuzzy Cause-Effect Networks (FCE-Nets)

Since operator knowledge can contain expressions and terms with some degree of uncertainty, the proposed method used the advantages of the fuzzy logic and the CE-nets to express the degree of certainty of a rule as a real number between 0 and 1 and to represent it in graphical way. The use of certainty factor (CF) is a good way to describe the uncertainty in numerical expression which facilitate the usage of certainty factor to represent the uncertain characteristic in conditions and rules [22].

FCE-Nets can easily represent causality between faults and actions of protective relays and circuit breakers by the following three kinds of nodes:

- **a)** Fault section node: This node represents a section hit by a fault.
- **b)** Relay node: This node indicates the action of a protective relay.
- **c)** Circuit breaker (CB) node: This node means the action of a circuit breaker.

In addition, there are three kinds of arcs show the relation between the mentioned nodes, they are as following:

- **a)** Protected-by: Means that the fault of section A causes the action of relay B.
- **b)** Cause: Means that the action of relay A causes the trip of circuit breaker B.
- **c)** Backup-by: Means that the failure of circuit breaker A causes the action of relay

Figure 3.4, shows relations between the nodes and the arcs in FCE-Nets.

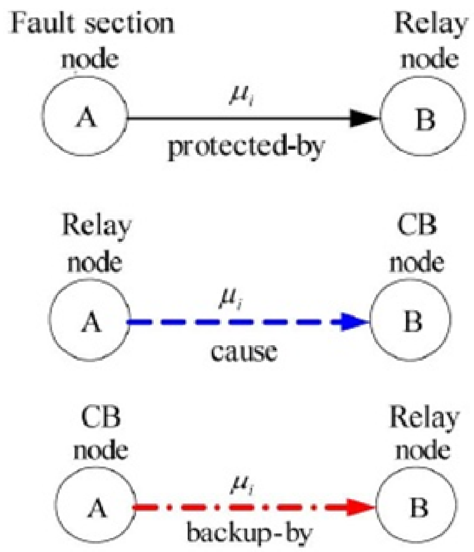


Fig. 3.4 Basic node-arc relations in FCE-Nets [22]

3.3The properties of the proposed fault identification process

In this part, the components, the mathematical reasoning and the theoretical representation of the proposed fault section estimation process are presented as follows:

3.3.1 Membership Function

The proposed approach utilizes fuzzy membership functions to represent system state's data which is derived from SCADA systems instead of specifying a fixed value, and use fuzzy inference techniques to perform reasoning in the proposed inference algorithm. The trapezoidal fuzzy Membership *M* was used in the proposed method. It is characterized by four points (a, b, c, d), where (bc) denotes the core in which the membership value is equal to 1 and (ab and cd) indicate the left and right boundaries of the trapezoidal distribution. Figure 3.5, shows a trapezoidal fuzzy membership function *M* parameterized by (a, b, c, d).

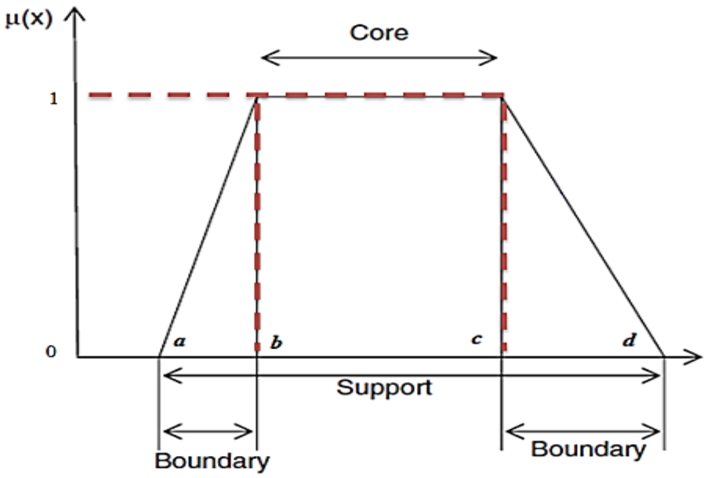


Fig. 3.5 :Trapezoidal fuzzy membership function [21]

3.3.2 Fuzzy Rules of the FCE-Net

The challenge when the Eqn. 3.3 used is to define membership function with Certainty factor (CF) can achieve the accuracy in defining the location state of faulted buses or branches when any fault occurs. Figure 3.6 shows the graph association for the rules.

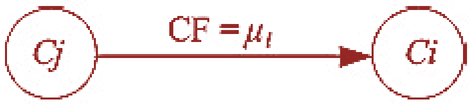


Fig 3.6 Associated graph for fuzzy implication rules [22]

Since operators' knowledge can contain some degree of uncertainty, a rule can be described as the following statement:

IF (a fault at $\boldsymbol{F_n}$) THEN (relay $\boldsymbol{CO_n}$ operates) (CF= $\boldsymbol{\mu_i}$)

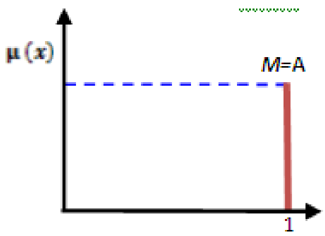
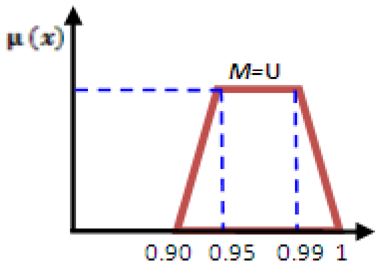
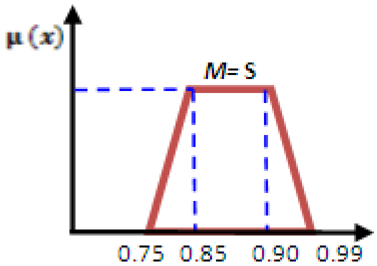
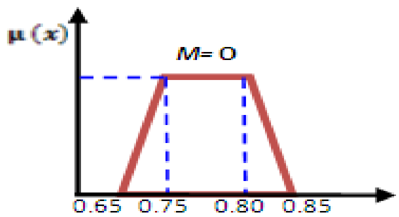
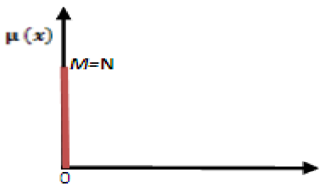
For different occasions, the CF of the same rule may change to another value. So with no doubt the choice of a good certainty factor needs some expertise. In order to avoid a bias in assigning the certainty factors, in the proposed method historical data from some operators in the National Control Center (NCC) was used. This data which contains historical records of relays COs and CBs behaviors when dealing with fault situations were used to identify certainty factors as shown in table 3.1.

Table 3.1 Historical records of the protection elements' behaviors with faults and their corresponding (CF)

Action	# of occurrence	CF
Feeder fault cause local relay operating	9:10 / 10	0.95
Circuit breaker tripped because of relay operating	7:9 / 10	0.80
Backup relay operates when the local relay fails	9:10 /10	0.95

Table 3.2 lists the linguistic terms and their corresponding fuzzy numbers as follows:

Table 3.2: The linguistic terms and their corresponding fuzzy number and membership functions

Uncertain terms	Fuzzification	Membership representation
Always (A)	[1.00 1.00 1.00 1.00]	
Usually (U)	[0.90 0.95 0.99 1.00]	
Some times (S)	[0.75 0.85 0.90 0.99]	
Often (O)	[0.65 0.75 0.80 0.85]	
Never (N)	(0.00, 0.00, 0.00, 0.00)	

3.3.3 Matrix Representation of FCE-Nets

The rules with linguistic certainty factors can be represented as the fuzzy rule matrix $\widetilde{R}$. This matrix describes the relations between causes and effects of FCE-Nets. Once the fuzzy rule matrix is established, the diagnosis algorithm can then be performed by matrix operations. A fuzzy rule matrix associated with K conditions is a k by k matrix with all ones on the diagonal by reflexivity because each condition implies itself [22]. The entry $\tilde{R}[i,j] = \mu_i$ means that condition C_j implies condition C_i with the certainty factor μ_i, and $\tilde{R}[i,j] = 0$ indicates that there is no implication between C_j and C_i.

$$R[i,j] = \begin{cases} \mu_i, & if\ C_j \rightarrow C_i \\ 0\ , & otherwise \end{cases}$$

A fuzzy value in the entry of the fuzzy rule matrix gives the degree of confidence in how condition C_j implies the truth of condition C_i.

The following matrix D is employed to represent the presence or absence of a specified relation between pairs of nodes. *The* entry of this matrix in position (i,j) n is μ_i if two nodes n_j and n_i are related. As shown in Figure 3.4 the transpose of a binary matrix corresponds to the reversal of all arrows in the associated digraph.

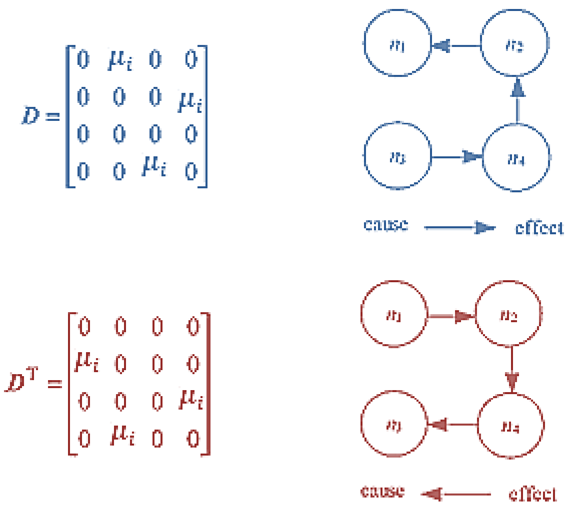


Fig 3.7 The transpose of a binary matrix corresponds to the reversal of all arrows in the associated digraph

3.3.4 Reasoning with Fuzzy Rule Matrices

Assume that a FCE-Net contains a set of k conditions. Each condition contains a high level of linguistic expression for humans to use. However, this string expression is inconvenient and inefficient for computers to process.

Therefore, some vectors were defined to transform string based conditions into numerical vectors for reasoning and computation as follows:

A. Truth State Vector (T)

The truth state vector (T) is employed to represent the fault symptom with the status of protective devices. This vector contains the truth values for a set of k conditions, $C_1, C_2 \dots \dots C_k$. Each component is defined by T[i] =λ_i , where $\boldsymbol{\lambda_i}$ is the truth value of condition C_i, [22].

B. Fault Node Vector (F):

The fault node vector F is defined to represent the fault section nodes in a given FCE-Net. This vector contains k Boolean valued components for a set of k conditions. If node condition $\boldsymbol{C_i}$, is associated with a fault section node, the value of F[i] is assigned to 1, otherwise F[i] is 0 [23].

$$F[i] = \begin{cases} 1, & if\ C_i \in fault\ section\ node \\ 0, & otherwise \end{cases}$$

This vector is defined for extracting the nodes that belong to the fault section node through fuzzy intersection operation.

C. Backup Node Vector (B):

The backup node vector B is employed to represent the backup relay nodes in a given FCE Net. This vector contains k Boolean valued components for a set of conditions.

If node condition $\boldsymbol{C_i}$ is associated with a backup relay node, the value of B[i] is assigned to 1, otherwise B[i] is 0 [22].

$$B[i] = \begin{cases} 1, & if\ C_i \in backup\ relay\ node \\ 0, & otherwise \end{cases}$$

This vector is defined for extracting operated backup relays through fuzzy intersection operation.

D. Transformation vector (TV):

The meaning of this transformation is to propagate the truth state of given fault symptoms leading backward into the fault cause. The TV vector contains information that causes the fault symptoms.

$$\boldsymbol{TV} = \widetilde{\boldsymbol{R}}^{\boldsymbol{T}} \otimes \boldsymbol{T} \tag{3. 4}$$

Where "$\otimes$" is the *fuzzy multiplication operator*, by which row-by-column matrix product is performed by replacing multiplication and addition with the min and max operations, respectively. Also the fuzzy multiplication operator is used for performing truth state transformation on the transpose of the fuzzy rule matrix and a truth state vector that contains the degree of truth in its entries. The entry of a fuzzy rule matrix represents an implication between two conditions. As truth state contains information of fault symptoms, the function of this operator is to perform a composition transformation that propagates the truth state leading backward into the fault cause [22].

The TV transformation is calculated to compare it with T with to check if there was a device failure. If they equal each other this means that there was no failure operation at feeder protection; otherwise, failures did occur.

E. The updated transformation vector T^*

If TV don't equal with T, the process went to update TV and assign it to $\boldsymbol{T}^*$using the following formula; otherwise, TV assigned toT^*.

$$\boldsymbol{T}^* \equiv \boldsymbol{TV} - \left[\widetilde{\boldsymbol{R}}^{\boldsymbol{T}} \otimes (\boldsymbol{B} \wedge \boldsymbol{T})\right] \tag{3. 5}$$

- Where "$\wedge$"the fuzzy min-operatorwhich is is used to remove the status of operated backup relays in the truth state vector when the action of the backup relays is caused by a main relay failure [24]. The fuzzy multiplication operator is used for performing truth state transformation on the transpose of the fuzzy rule matrix and the truth state vector operated on a backup relay node by fuzzy min-operator [22].

- The fuzzy multiplication operator is used for performing truth state transformation on the transpose of the fuzzy rule matrix and the truth state vector operated on a backup relay node by fuzzy min-operator.

As such, the updated transformation vector using (3.5) is to remove the status of backup relays from fault section candidates.

F. Estimated Fault Section (EFS)

As the vector T^*contained information about fault causes, we selected only fault section nodes with the entry value greater than a threshold as estimated fault sections [22]. The selection of fault section nodes from T^*can be achieved by the following:

$$\boldsymbol{EFS} = \boldsymbol{T}^* \wedge \boldsymbol{F} \qquad (3.6)$$

3.4Conclusions

Mainly in this chapter, the proposed fault identification method based on FCE-Nets was presented.

1- A literature review on some used fault diagnosis methods and techniques was presented to show the parameters, construction, advantages and dis-advantages of each one.
2- The proposed method of fault identification which is based on fuzzy logic and FCE-Nets were presented.
3- The main advantage of the fuzzy logic which is the ability of dealing with uncertainty situations was focused on.
4- The properties of the proposed FCE-Nets were presented.
5- It was discussed that by transforming the established FCE-Nets into matrix forms, the possible fault identification can be done through simple matrix operations.
6- Some operators and vectors to transform string based conditions to numerical expression for reasoning and computation.
7- The knowledge representation with the FCE-Nets model is based on graphical methodology, so it is easy to understand the relationship between the rules and conditions.
8- Furthermore, it is possible to predict the inference results in advance by observing the flow of truth state in the FCE-Nets when some conditions are specified.
9- Also the proposed method is capable of representing uncertain knowledge and performing fuzzy reasoning through matrix based transformation.

Chapter 4: Fault Types Identification using Fuzzy Data Base and Rule Base

In order to protect the system from damage due to a fault, the fault type has to be identified as well. Therefore, in this chapter a proposed method based on fuzzy data and rule base is presented to identify different fault types in substations. Thus, it will be easier for the operator to estimate the volume of damages or the suitable way to follow to keep the system balanced. Literature review on some famous techniques and their applications in fault type identifying is presented to show advantages and dis advantages of each one.

4.1Literature survey on fault classification methods and techniques

Among the various techniques of the fault classification, the most widely used techniques are Neural Network systems, Fuzzy systems and Expert systems. Some of these efforts is discussed briefly as follows:

In [23], a fault classification technique was proposed based on fuzzy Logic. The fault classification algorithm is based on the angular differences among the sequence components of the fundamental fault current (FFC) as well as on their relative magnitudes.

In [24], a comparison between two neural networks (ANN) models for fault diagnosis of power systems was performed. Radial basis function and back-propagation networks are compared with reference to generalization, training time and number of training patterns needed for each model. Although the capabilities of ANN in online fault diagnosis was presented, there were clearly unsolved problems, such as slow convergence in the training process, and determination of the network parameters like hidden units, layers, learning rate and momentum value . In addition, when any configuration of the system changes, the related neural network needs to be re-trained. In practical use, the needs of a great number of patterns to train the ANN and the slow training process often make the users hesitate to accept the ANN approach in the fault diagnosis.

In [25], fault type identification is achieved using a simple and numerically efficient algorithm based on Park's transformations. The algorithm uses two transformation matrices. The first matrix is used to filter out the dc offset and harmonics that contaminate the three-phase voltage signal. The second transformation is used to estimate the positive and negative sequence components.

The zero sequence components can easily be estimated from the first transformation matrix. Results based on detailed system models are presented A detailed synchronous machine model-based power system was used in MATLAB was used to test the proposed technique by conducting a series of faults and then identify the type of fault given a minimum number of fault current cycles. Finally the author recommended his proposed technique to systems that contain harmonics because of the inherent filtering capability of the park transform.

In [26], the capabilities of the expert system in identifying bus faults were discussed. Also the expansion of expert system to include real-time measurements of current and voltage phasors to classify the type of fault that the faulted section was reported.

Although the ES based approach offers powerful solutions to the fault diagnosis, but the response time of the ES is usually not applicable to a real-time environment due to the conventional knowledge representation and inference steps. Also, There is the always sufferance of the procedure of knowledge acquisition and knowledge base revision or maintenance.

4.2Fault types

Faults in certain important equipment can affect stability of power system. Estimating fault types when the fault hits any feeder in the substations will help the operator to make the right decisions and will make avoidance to severe effects due to faults.

4.2.1 Symmetrical Faults

A fault involving all three phases is known as a symmetrical (balanced) fault.

4.2.2 Unsymmetrical Faults

A fault involving one or two phases is known as an unsymmetrical (unbalanced) fault.

A) Single line to ground (SLG)
B) Line to line (DL)
C) Double line to ground (DLG)

4.3The properties of the proposed fault types identification process

Generally, when faults occur, feeders current increase in magnitude and bus voltages go down and that changes from phase to another depending on the fault type. So the proposed approach will depend on the behavior of the voltage and current during fault situations to identify fault types.

4.3.1 Fuzzy Data Base & Rule Base

The values of faulted currents and voltages are highly depending on the location between the source and faulted location as well as load characteristics. So the Fuzzy if then rules identify the fault types based on feeder currents and bus voltages through the data which is provided to SCADA from RTUs and measurement devices.

4.3.2 Membership function

All measurements, in root mean square value, are described with the use among three fuzzy sets: Low (L), Normal (N) and High (H). The related linguistic variables and membership functions are defined in fuzzy data base.

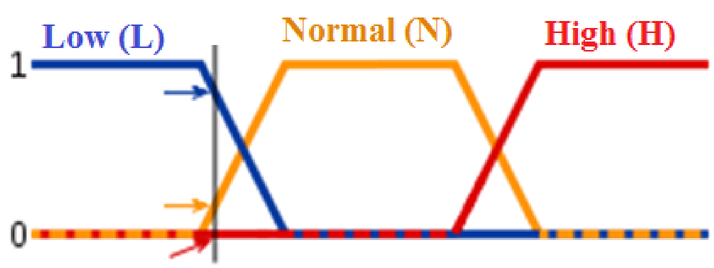


Fig. 4.1. The proposed Membership Sets for current and voltage ranges

4.3.3 Fuzzy rule base

The Fuzzy Rule Base is formed by rules which are elicited from all types of fault. In order to define these rules, behavior of analogue signal has to be well understood. In [27], table 4.1 shows the summary of proposed rules for identifying fault types as follows:

Table 4.1 Summary of rules for identifying fault types

Rule #	I_A	I_B	I_C	I_N	V_A	V_B	V_C	Type
R1	H	N	N	H	L	N	N	SLG A
R2	N	H	N	H	N	L	N	SLG B
R3	N	N	H	H	N	N	L	SLG C
R4	H	H	N	N	L	L	N	DL AB
R5	N	H	H	N	N	L	L	DL BC
R6	H	N	H	N	L	N	L	DL AC
R7	H	H	N	H	L	L	N	DLG AB
R8	N	H	H	H	N	L	L	DLG BC
R9	H	N	H	H	L	N	L	DLG AC
R10	H	H	H	N	L	L	L	$3^{\emptyset}$ fault

Where, Single Line to Ground fault (SLG), Double Line fault (DL) Double Line to Ground fault (DLG), Symmetrical Fault ($3^{\emptyset}$).

For example:

IF I_A = (N) I_B = (H) I_C=(N) I_N = (H) V_A = (N) V_B = (L) V_C = (N) , Then fault type SLG-B.

4.3.4 Fault type analysis procedures

The process of the fault type fuzzy reasoning consists of four stages as shown in Figure 4.6 of the fuzzy logic scheme (FLS) for fault classification. First, at (P) measurements of the feeder currents and bus voltages must be taken from SCADA system. Next, these values must be translated into fuzzy linguistic terms; these terms (Q) are specified by the membership functions of the fuzzy sets, which are defined in the appropriate universe of discourse. These linguistic terms are then used in the evaluation of the fuzzy rules. Fuzzy rules are evaluated by means of the compositional rule of inference. The maximum membership grade in rules stands for the dominant rule and is selected as the final result (R). To determine the crisp fault type (S) correctly these fuzzy outputs need to be defuzzified.

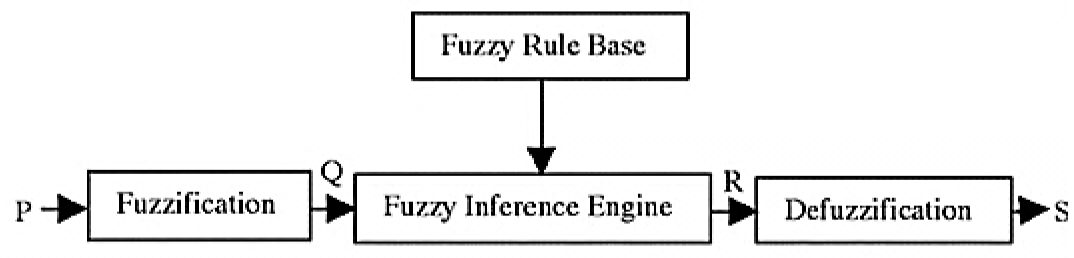


Fig. 4.2 FLS for fault classification [23]

4.4Conclusions

In this chapter, the proposed fault type identification method based on fuzzy logic was presented and the following main points were discussed in details.

1- Some efforts of researchers in the field of fault type classification were discussed.
2- The proposed method identifies the fault types from the known data from SCADA system which is provided by the measurement devices of current and voltages.
3- The constructions of the database and rule base of the proposed method were presented.
4- The procedure of fault type estimating the was presented.

Chapter 5: Applications

In this chapter the proposal methodology and procedures of fault diagnosis process will be presented. Also the data base, the rule base and the graphical networks of the proposed methodology will be presented and discussed in details. To evaluate the proposed methodology two cases of study will be done on existing systems against other methods and the results will be compared and discussed. Furthermore, two challengeable scenarios will be done on existing system, to obtain more advantages and test the abilities of the proposed methodology. All the tests and evaluations will be done by using Mat-lab fuzzy tool-box.

5.1Inference and procedures of proposed method

The proposed fault diagnosis method consist of two processes , the first one is to estimate the fault identifying by using FCE-Nets and the second process is estimating fault type using fuzzy data base and IF-Then rule.

In the last chapters the methodology and the main concepts of each process where discussed in details. The procedures and inferences of each process will be presented as follow:

5.1.1 Inference of Fault identification by FCE-Nets

The inference procedures are described step by step as follows:

1) From the information of the system in SCADA, the fuzzy cause and effect relations diagraph of the system will be defined to build a k -by- k fuzzy rule matrix $\widetilde{R}$ according to the given FCE-Nets, with rows and columns indexed by nodes.

If an arc (C_j, C_i) presented, the certainty factor in cell $\widetilde{R}[i,j]$ got value; otherwise $\widetilde{R}[i,j]$ is zero. (C_j, C_i) denotes a directed arc from node to node. Also the values of the vectors F and B will be received from SCADA.

2) According to fault symptoms, the truth value of each condition will be defined in the entry $T[i]$ to derive the truth state vector.

3) Calculate transformation vector TV, using (3.2).

4) Compare the two vectors $\tilde{R}^T \otimes T$ and T. if they are equal, assign TV to T^*; otherwise the inference procedure goes to update the fuzzy truth state transformation using (3.4).

5) The vector T^*contains information about fault causes, the fault sections can be retrieved by selecting fault section nodes from T^* by determining the value of EFS from (3.5), and then selecting the entry value greater than the threshold value for selecting fault sections $\leftthreetimes$ as estimated fault sections.

Figure 5.2, shows the flow chart of defining the fault location.

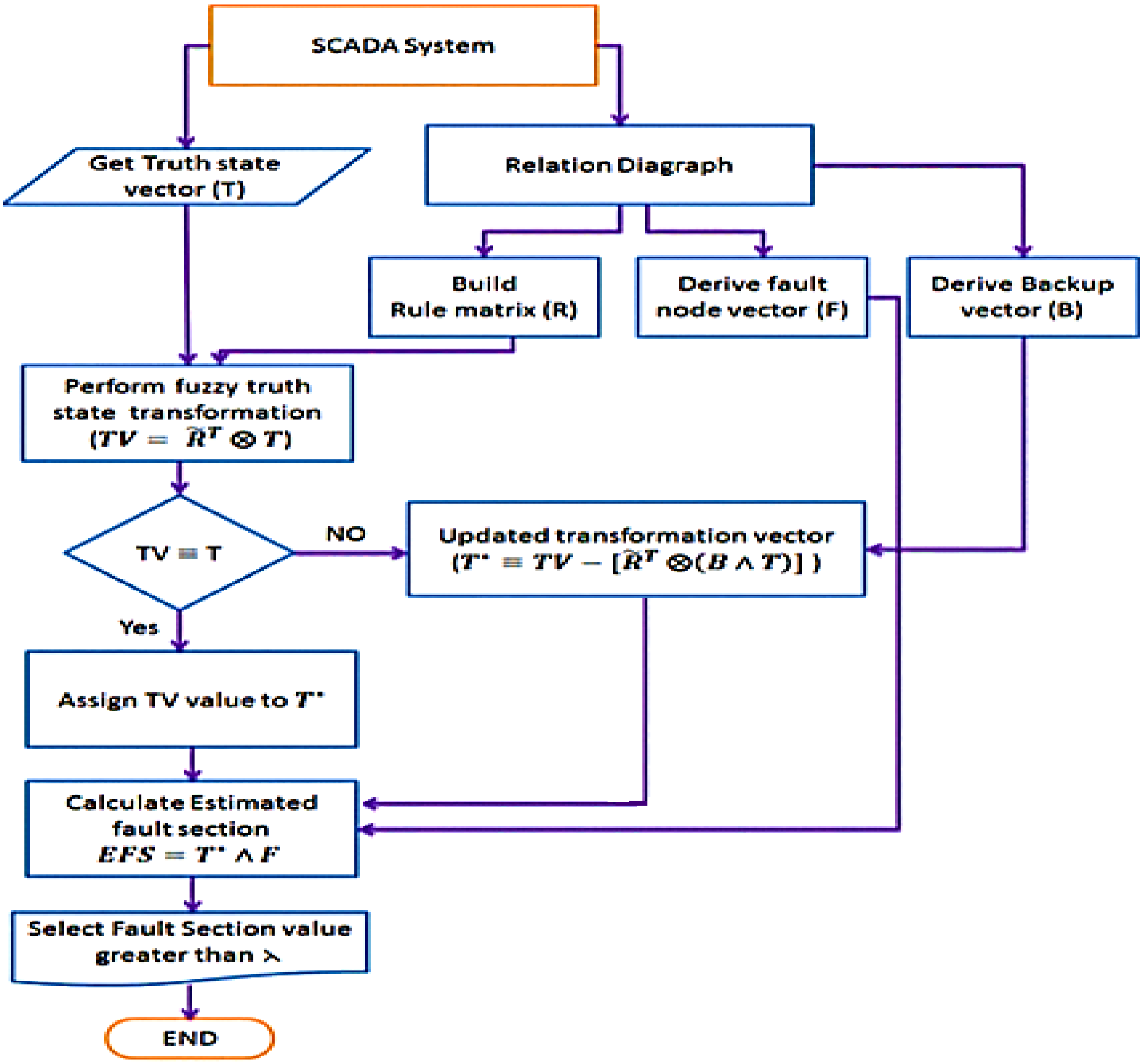


Fig. 5.1 The flow chart of fault Identification

5.1.2 Fault type analysis procedures

The process of the fault type fuzzy reasoning consists of four stages as follows:

1) Measurements of the feeder currents and bus voltages must be taken from SCADA system.

2) These values must be translated into fuzzy linguistic terms; these terms are specified by the membership functions of the fuzzy sets, which are defined in the appropriate universe of discourse. The following figures showing the memberships of feeder current, bus voltage and neutral current also the defining of the ranges of the sets High (H), Normal (N) and low (L) for every membership function. Figures 5.3-5, shows the membership functions for the current, voltage and neutral current of the feeders.

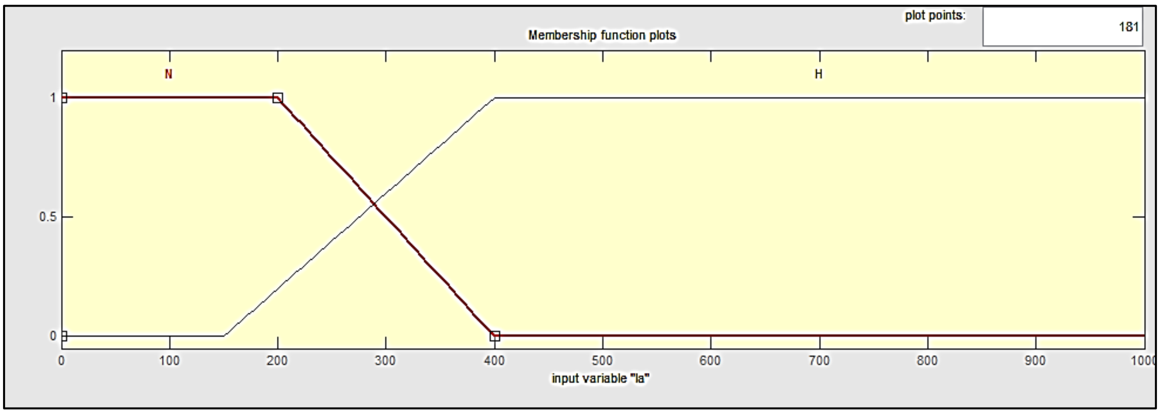


Fig.5. 2 Membership function for the fuzzy set feeder current

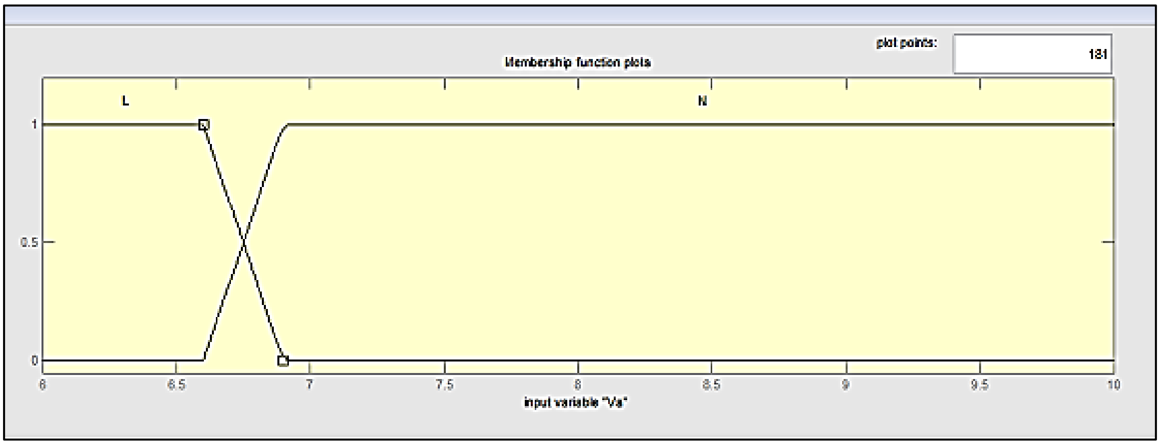


Fig.5. 3 Membership function for the fuzzy set Bus Voltage

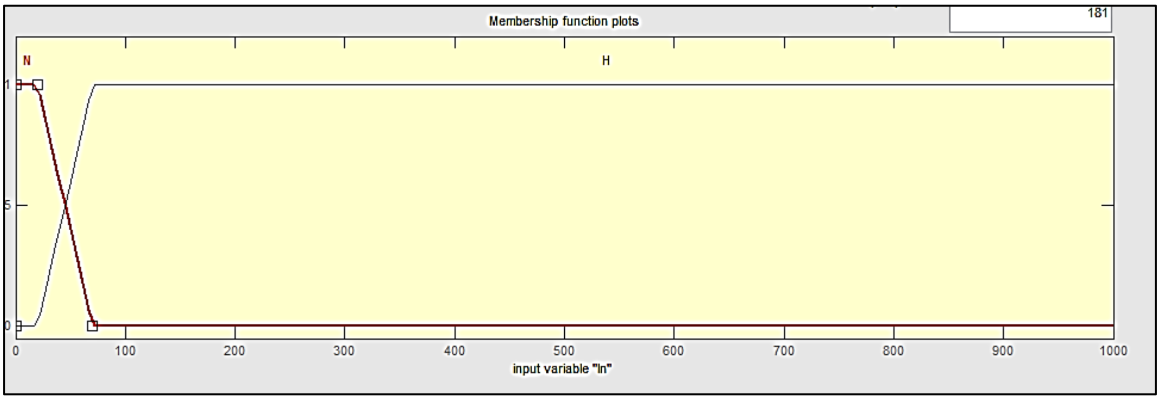


Fig. 5.4 Membership function for the fuzzy set Neutral Current

2) These linguistic terms are then used in the evaluation of the fuzzy rules. Fuzzy rules are evaluated by means of the compositional rule of inference. Table 5.1, shows the summary of rules for identifying fault types which was discussed in chapter 4.

Table 5. 1 Summary of rules for identifying fault types

Rule #	I_A	I_B	I_C	I_N	V_A	V_B	V_C	Type
R1	H	N	N	H	L	N	N	SLG A
R2	N	H	N	H	N	L	N	SLG B
R3	N	N	H	H	N	N	L	SLG C
R4	H	H	N	N	L	L	N	DL AB
R5	N	H	H	N	N	L	L	DL BC
R6	H	N	H	N	L	N	L	DL AC
R7	H	H	N	H	L	L	N	DLG AB
R8	N	H	H	H	N	L	L	DLG BC
R9	H	N	H	H	L	N	L	DLG AC
R10	H	H	H	N	L	L	L	$3^{\emptyset}$ fault

Figure 5.6, shows the rules in the Rule Editor in Matlab.

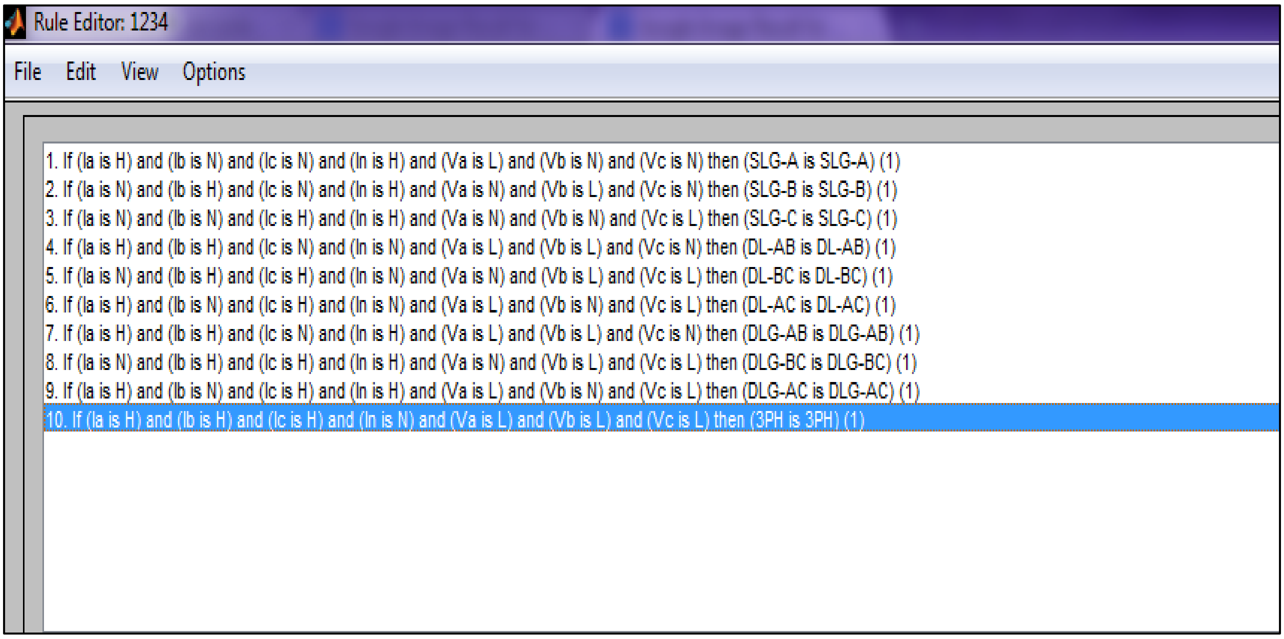


Fig. 5.5 Rule Editor in Matlab

4) The maximum membership grade in rules stands for the dominant rule and is selected as the final result. Figure 5.7, shows the rule viewer in Matlab fuzzy toolbox.

Fig. 5.6 Rule Viewer in Matlab

- Figure 5.8 shows the flow chart of defining the fault type.

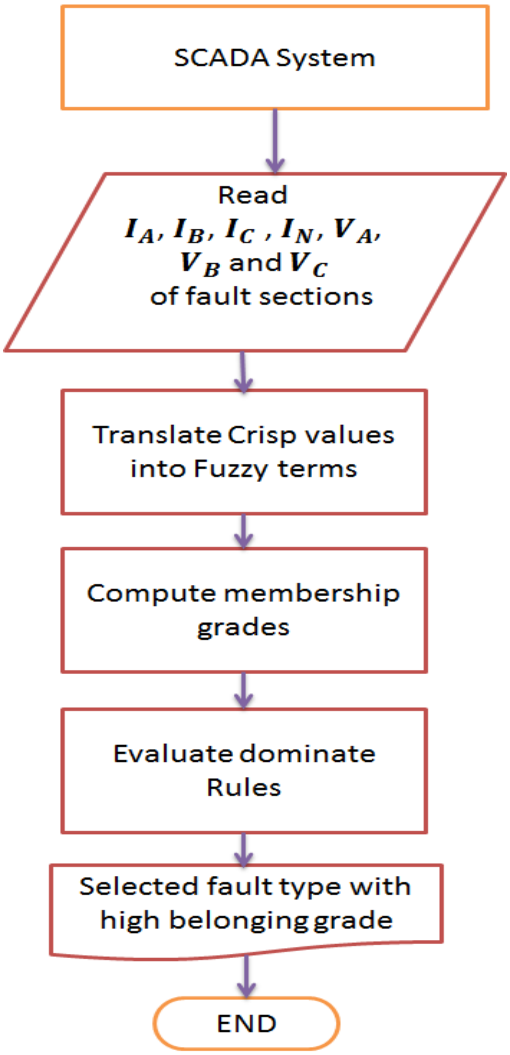


Fig. 5.7 The flow chart of fault type identification

- Figure 5.9 shows the flow chart of the proposed method of the fault diagnosis with the two missions of identifying fault location and type.

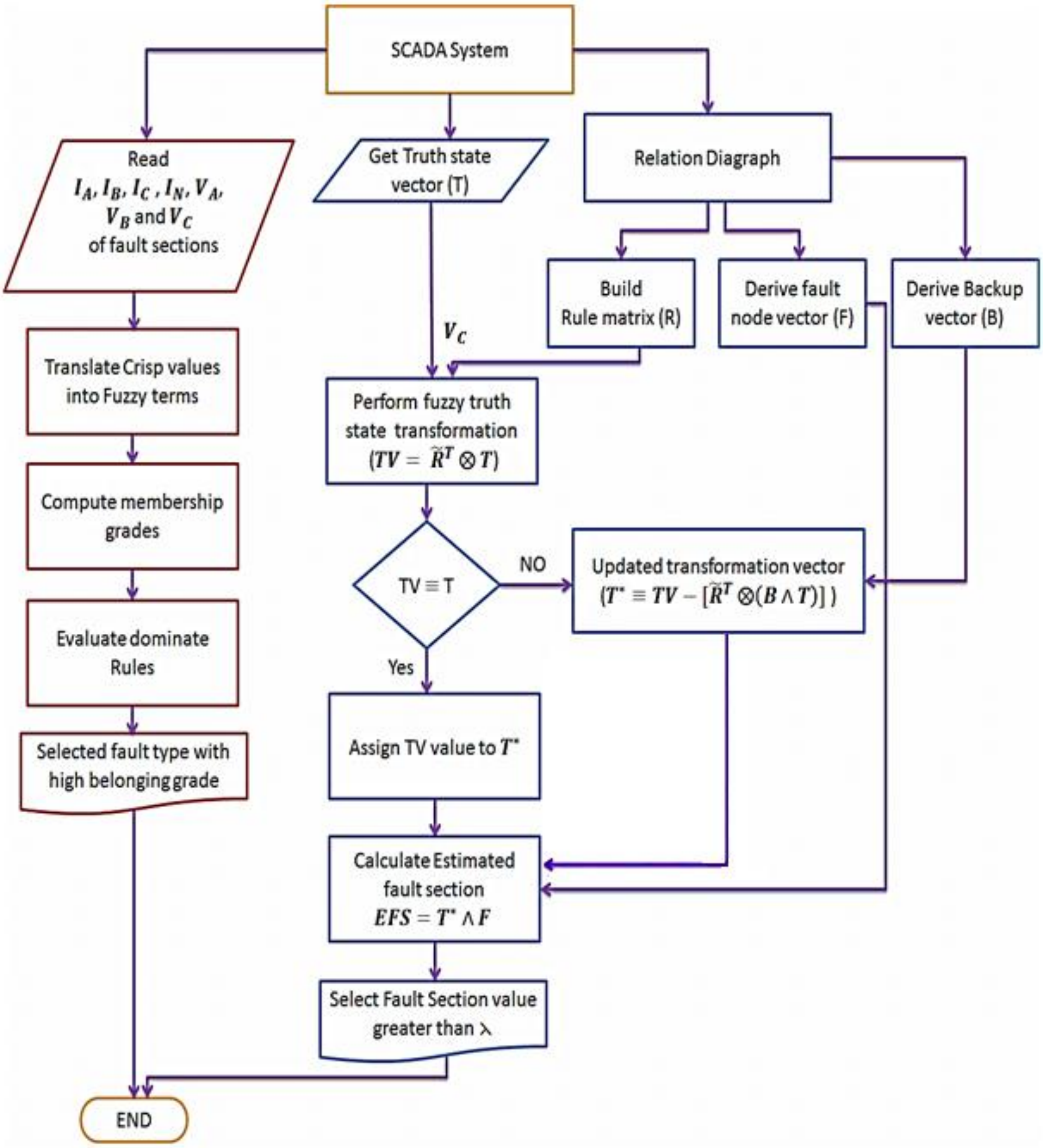


Fig. 5.8 The flow chart of the proposed method

5.2 Testing and evaluating the proposed methodology

A. CASE 1

As it was mentioned in the introduction of this chapter, a comparison between the proposed method and the other one in [28] will take place to test effectiveness, accuracy and simplicity in construction. The author proposed a new method based on Expert System (ES) with connection with Artificial Neural Network (ANN) and recommended this method for online fault diagnosis of power substations.

The author used an existing system, considering that there aren't transmission errors assumed in the cases he presented.

A single line-to-ground fault occurs at phase A of feeder 1. CO relay "C03A" operates and trips breaker "CB3", but the LCO relay "LC03" fails. The fault situation is shown in figure 5.10.

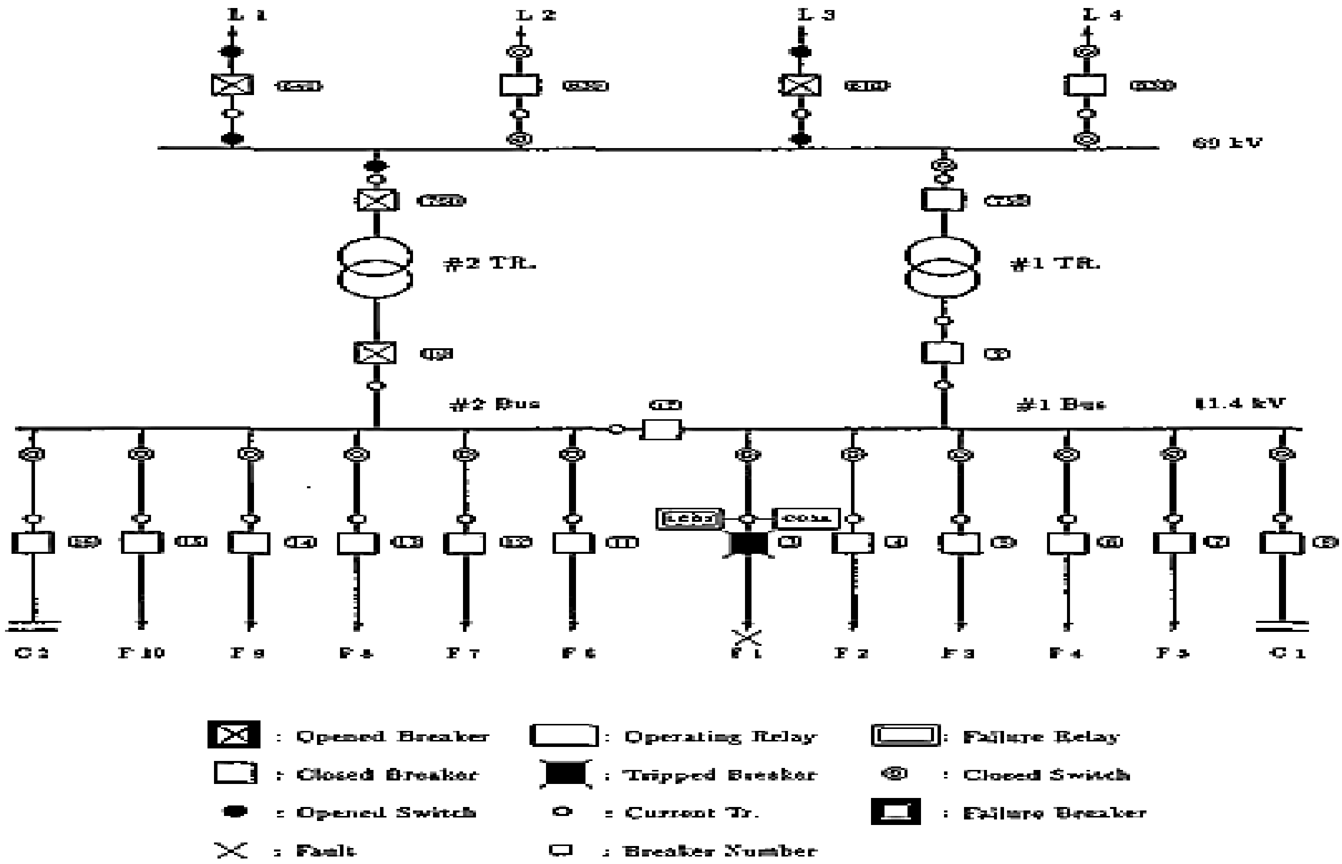


Fig. 5.9 Distribution system of case 1

Table 5.2 ,shows the pre-fault values of the branch F1 and the voltage of #1 BUS as follow:

Table 5. 2 Pre- Fault Values of Case 1

Phases	F1	Bus #1
Phase A	230.2 (A)	9536.1 (V)
Phase B	234.5 (A)	9617.6 (V)
Phase C	236.3 (A)	9626.4 (V)
Neutral	20 (A)	

The author's final results is as shown in Table 5.3, where the corresponding peak bus voltages and feeder currents at the fault are appended for reference.

Table 5. 3 The author's final results of case 1

Fault section	Phase A of feeder 1 (11.4KV)	
Fault type	Single line to ground	
Peak values of BUS Voltage at (#1 Bus)	Phase A	8923 V
	Phase B	9468 V
	Phase C	9843 V
Peak values of feeder current (Feeder 1)	Phase A	506 A
	Phase B	282 A
	Phase C	293 A
	Neutral	25 A

- The proposed method and procedures were done on the mentioned case above and the results were as following

A) Fault identification process :

Step 1: Figure 5.11, shows the relation diagraph of this system. Tables (5.4-6), present the defining of the node of conditions and the developing of the rule matrix of the system and the fault vector.

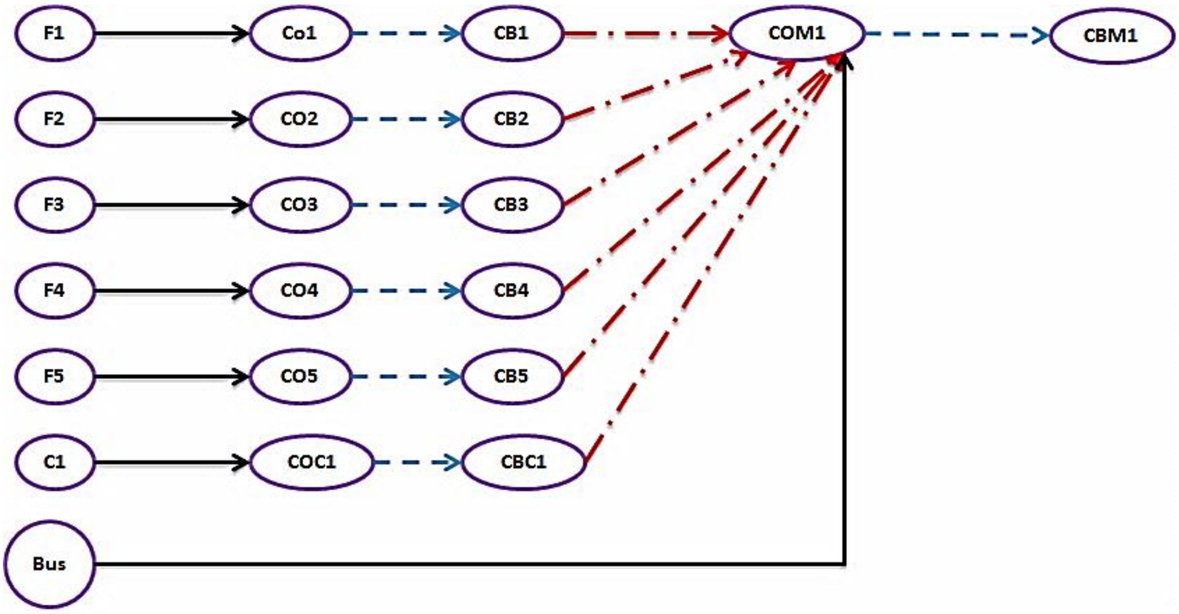


Fig. 5. 10 FCE-Net of Case1

Table 5. 4 Set of node conditions of Case 1

Node	Description	Node	Description
C1	A fault occurs at feeder F1	C15	A fault occurs at feeder F4
C2	Relay CO1 operates	C16	Relay CO4 operates
C3	Circuit breaker CB1 tripped	C17	Circuit breaker CB4 tripped
C4	CO1 operates but CB1 fails	C18	CO4 operates but CB4 fails
C5	Relay COM1 operates	C19	A fault occurs at feeder F5
C6	Circuit breaker CBM1 tripped	C20	Relay CO5 operates
C7	A fault occurs at feeder F2	C21	Circuit breaker CB5 tripped
C8	Relay CO2 operates	C22	CO5 operates but CB5 fails
C9	Circuit breaker CB2 tripped	C23	A fault occurs at feeder C1
C10	CO2 operates but CB2 fails	C24	Relay COC1 operates
C11	A fault occurs at feeder F3	C25	Circuit breaker CBC1 tripped
C12	Relay CO3 operates	C26	COC1 operates but CBC1 fails
C13	Circuit breaker CB3 tripped	C27	A fault occurs at section BUS1
C14	CO3 operates but CB3 fails		

The rule matrix describes the relations between causes and effects of FCE-Nets. Table 5.4 , shows the non-zero entries of rule matrix of this system.

Table 5. 5 Nonzero Entries of Rule Matrix of Case 1

R[i]	Value	R[i]	Value	R[i]	Value
R [1,1]	1	R[2,1]	0.95	R[2,2]	1
R[3,2]	0.8	R[3,3]	1	R[4,4]	1
R[5,4]	0.95	R[5,5]	1	R[5,10]	0.95
R[5,14]	0.95	R[5,18]	0.95	R[5,22]	0.95
R[5,26]	0.95	R[5,27]	0.95	R[6,5]	0.8
R[6,6]	1	R[7,7]	1	R[8,7]	0.95
R[8,8]	1	R[9,8]	0.8	R[9,9]	1
R[10,10]	1	R[11,11]	1	R[12,11]	0.95
R[12,12]	1	R[13,12]	0.8	R[13,13]	1
R[14,14]	1	R[15,15]	1	R[R16,15]	0.95
R[16,16]	1	R[17,16]	0.8	R[17,17]	1
R[18,18]	1	R[19,19]	1	R[20,19]	0.95
R[20,20]	1	R[21,20]	0.8	R[21,21]	1
R[22,22]	1	R[23,23]	1	R[24,23]	0.95
R[24,24]	1	R[25,24]	0.8	R[25,25]	1
R[26,26]	1	R[27,27]	1		

The fault node vector (F) is defined to represent the fault section nodes in a given FCE-Net. Table 5.6 , shows the non-zero entries of Fault vector (F) of this system.

Table 5. 6 Nonzero entries of Fault vector (F) of Case 1

F[i]	Value	Description
F[1]	1	F1
F[7]	1	F2
F[11]	1	F3
F[15]	1	F4
F[19]	1	F5
F[23]	1	C1
F[27]	1	BUS 1

Step2: Get the truth state vector entries from SCADA and as the author mentioned that there is no backup protection, we didn't give any values for the backup process. The truth vector values are as shown in Table 5.7.

Table 5. 7 Nonzero entries of truth vector (T) of Case 1

T[i]	Value	Description
T[2]	0.95	Degree of 'Relay CO1 operates'
T[3]	0.8	Degree of ‘Circuit breaker CB1 tripped’

Step 3: Calculating (TV) vector to propagate the truth state of given fault symptoms leading backward into the fault cause. The (TV) vector contains information that causes the fault symptoms. Table 5.8 , presents the entries of the vector (TV) of this system.

Table 5. 8 The entries of the vector (TV)

TV[i]	Value	TV[i]	Value	TV[i]	Value
TV[1]	0.95	TV[10]	0	TV[19]	0
TV[2]	0.95	TV[11]	0	TV[20]	0
TV[3]	0.8	TV[12]	0	TV[21]	0
TV[4]	0	TV[13]	0	TV[22]	0
TV[5]	0	TV[14]	0	TV[23]	0
TV[6]	0	TV[15]	0	TV[24]	0
TV[7]	0	TV[16]	0	TV[25]	0
TV[8]	0	TV[17]	0	TV[26]	0
TV[9]	0	TV[18]	0	TV[27]	0

Step4: Although the T vector and TV vector aren’t equal, the $\boldsymbol{T}^{*}$ is equal to TV and that because of the author mention in this example that there is no backup protection.

Step 5: the fault section determined from the EFS vector according to (3.6) is F1 as shown in Table 5.9:

Table 5. 9 The fault section estimated of Case 1

Faults	Node#	EFS
F1	C1	0.95
F2	C7	0
F3	C11	0
F4	C15	0
F5	C19	0
C1	C23	0
BUS 1	C27	0

B) Fault type estimation process :

Step1: Define the membership function ranges as shown in Figures 5.12-14:

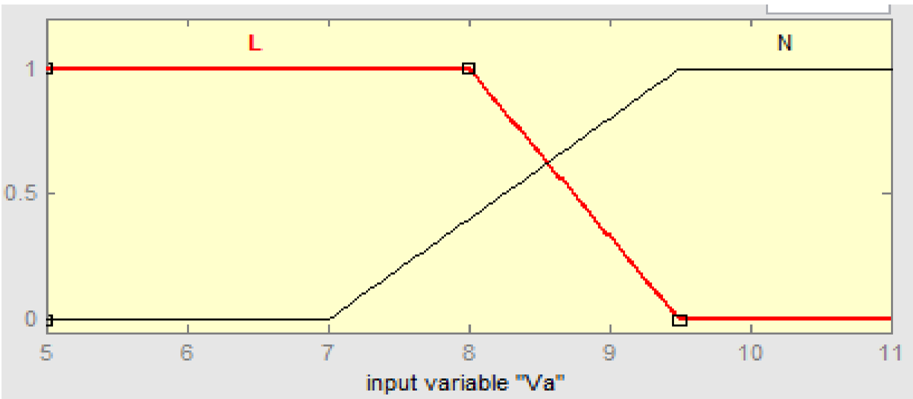


Fig.5. 11 Membership function of the Bus Voltages of Case 1

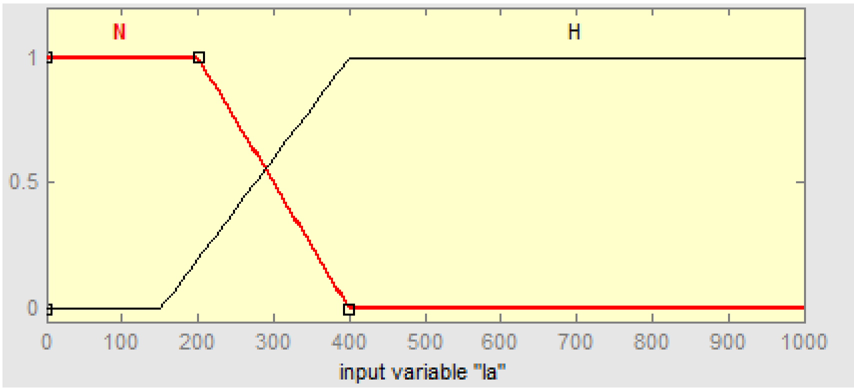


Fig.5. 12 Membership function of the Feeder currents of Case 1

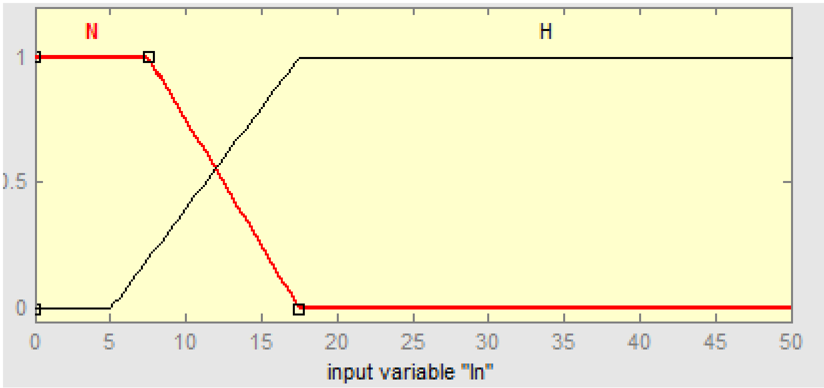


Fig.5. 13 Membership function of the neutral current of Case 1

Step2: Get the reads of Current and voltage measurement devices from SCADA as it is reported by the author.

Step3: By using the rules, the result will be as shown in Table 5.10:

Table 5. 10 Fault data from SCADA and the suitable rule base of Case 1

Rule #	I_A	I_B	I_C	I_N	V_A	V_B	V_C	Fault Type	Degree of belonging
R1	506	282	293	25	8.9	9.4	9.8	SLG-A	0.620
	H	N	N	H	L	N	N		

After this case the proposed methodology can be evaluated as follow :

1- By this case not only the accuracy of the proposed method were shown but also the simplicity of the knowledge base and ability to modify this base were shown if it compared to the ES-ANN system discussed in [28] and shown in Figure 5.15.

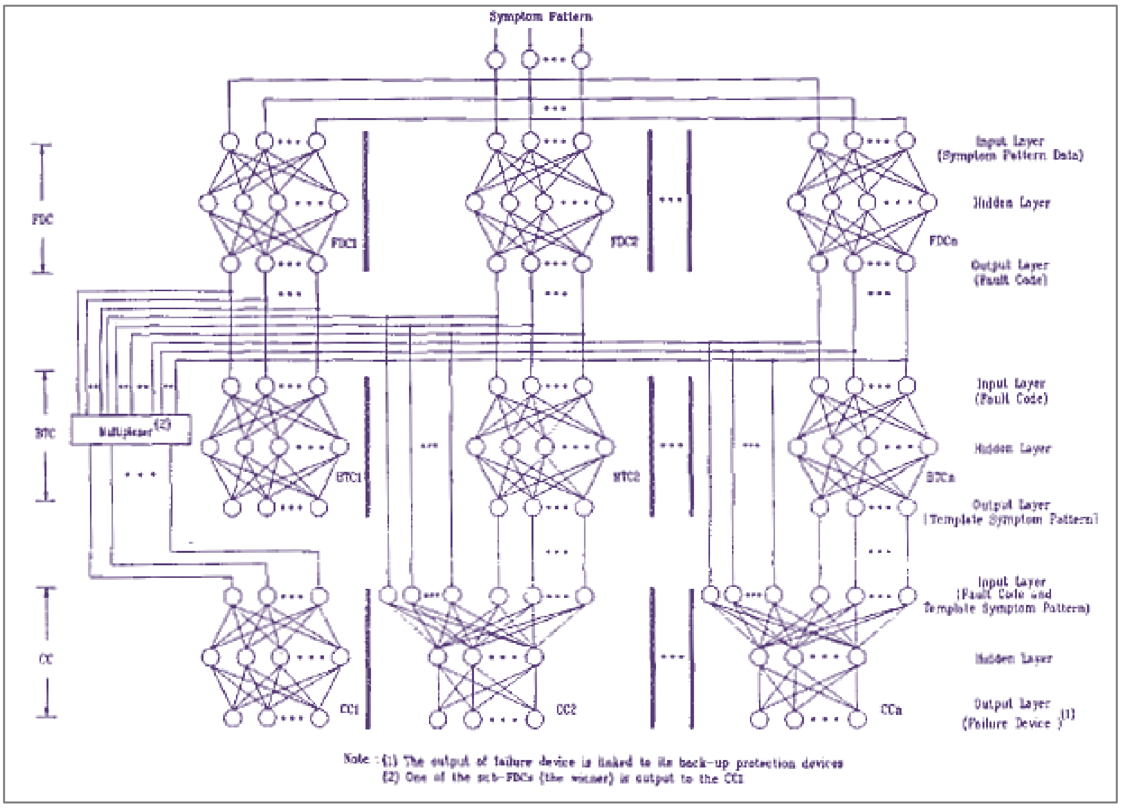


Fig. 5. 14 Hierarchical Architecture of the Connectionist-type Knowledge Base [28]

2- The proposed method does not need to be trained for every modification so it is very applicable for online diagnosis.

B. Case 2

In this case the accuracy of fault section estimation process of the proposed method will be tested by comparing the results with the method in [29] to show the difference between the main concept of FCE-Nets and the classical cause and effect networks (CE-Nets).

A realistic Taipower's secondary substation was used to demonstrate the proposed method in [29] as shown in Figure (5.16). The substation is composed of three sub-transmission lines, three main transformers, two tie circuit breakers, one 69KV primary bus bar and three 11.4KV secondary bus bars. Each secondary bus contains five radial distribution feeders which are protected by CO relays, LCO relays and re-closers. The main transformers are protected by differential relays. The bus bars are protected by CO and LCO relays and as the back-up protection for each feeder. The three phase, four-wire distribution system is solidly grounded at substation, with the neutral wire also grounded at each distribution transformer location.

The author work with almost the same steps of our proposed method but he defined a vector called Elimination vector (E) to identify the cause of fault so he can get the faulted section as shown in (5.1)

$$E \equiv T \wedge B \qquad (5.1)$$

A three-phase fault occurs at the feeder F1. Relay CO1 operates correctly while the circuit breaker CB-1 fails to trip. Owing to the tripping failure of CB-1, the backup breaker CBM1 is tripped by the relays COM1. Meanwhile, a double-line to ground fault at phases B and C happens at feeder F2, which causes CO2 operating to trip CB-2. However, the status of relay CO2 is missing, considering this missing signal to complicate the studied case so the entries of vector T are changed as shown in table 5.12.

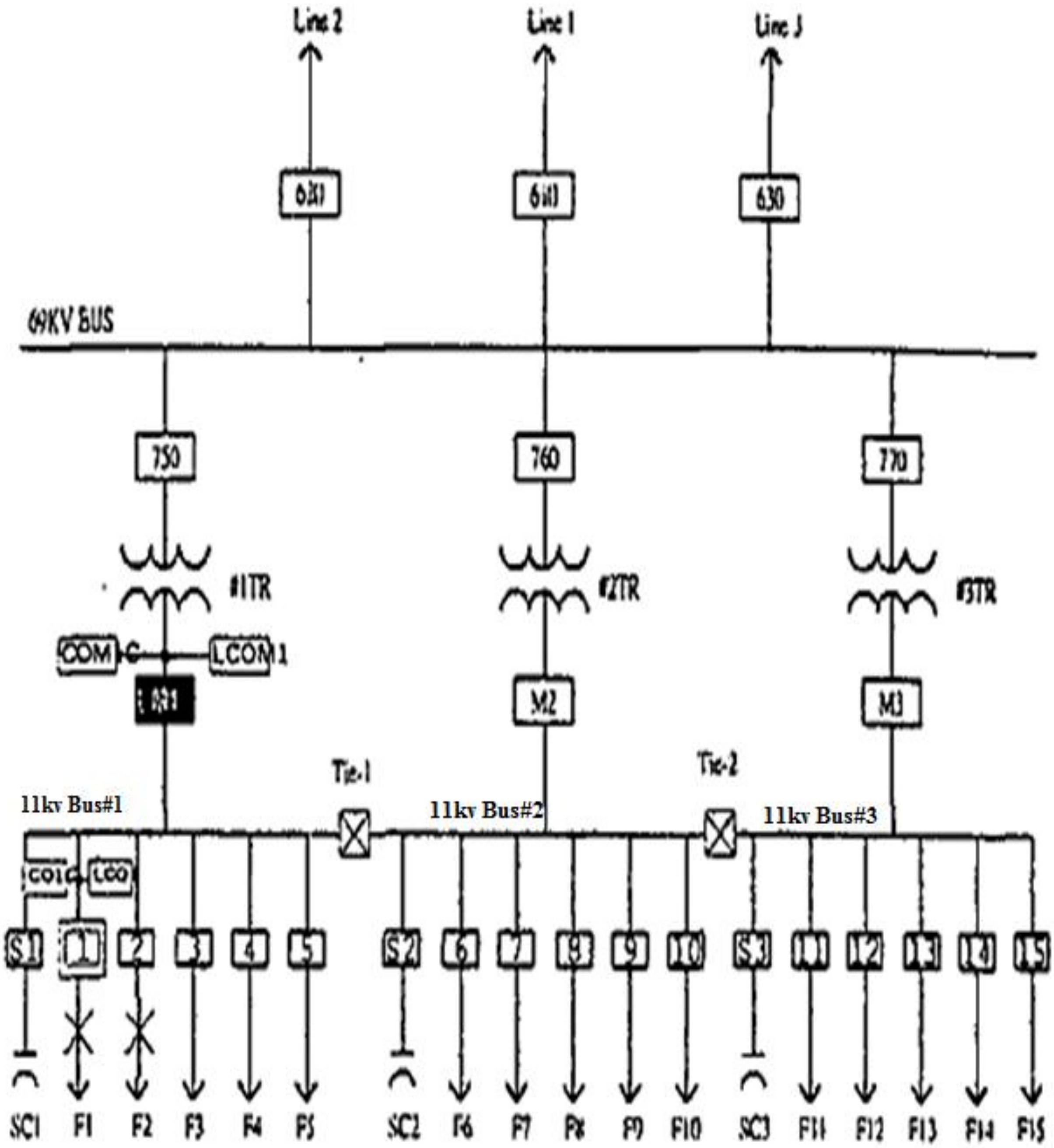


Fig.5. 15 Fault situation of Case 2 [30]

Procedures of Fault diagnosis:

A) Fault identification process :

Step 1: The construction of the system is the same of the construction of case 1, so the FCE-Net in will be the same of the one was presented in Figure 5.11. Also the same node of conditions in table 5.2, the same entries of rule matrix in Table 5.3 and the same fault vector values will be used. In this case there is a backup protection the backup vector of the system will be as shown in Table 5.11.

Table 5.11 Values of the backup vector (B) Case 2

B[i]	Value
B[4]	1
B[10]	1
B[14]	1
B[18]	1
B[22]	1
B[26]	1

Step2: The truth state vector (T) is employed to represent the fault symptom with the status of protective devices. Table 5.12 , shows the non-zero entries of (T) vector of this system.

Table 5. 12 Nonzero entries of truth state vector (T) of Case 2

T[i]	Value	Description
T[2]	0.98	Relay CO1 operates
T[4]	0.98	CO1 operates but CB1 fails
T[5]	0.84	Relay COM1 operates
T[6]	0.84	Circuit breaker CBM1 tripped
T[8]	0.88	Degree of 'Relay CO2 operates'
T[9]	0.88	Circuit breaker CB2 tripped

Step 3: Calculating (TV) vector to propagate the truth state of given fault symptoms leading backward into the fault cause. The (TV) vector contains information that causes the fault symptoms. Table 5.12 , presents the entries of the vector (TV) of this system.

Table 5. 13 Values of the vector (TV) of Case 2

TV[i]	Value	TV[i]	Value	TV[i]	Value
TV[1]	0.95	TV[10]	0.84	TV[19]	0
TV[2]	0.98	TV[11]	0	TV[20]	0
TV[3]	0	TV[12]	0	TV[21]	0
TV[4]	0.98	TV[13]	0	TV[22]	0
TV[5]	0.84	TV[14]	0	TV[23]	0
TV[6]	0.84	TV[15]	0	TV[24]	0
TV[7]	0.88	TV[16]	0	TV[25]	0
TV[8]	0.88	TV[17]	0	TV[26]	0
TV[9]	0.88	TV[18]	0	TV[27]	0.84

Step4: The TV transformation is calculated to compare it with T with to check if there was a device failure. If they equal each other this means that there was no failure operation at feeder protection; otherwise, failures did occur. Because TV don’t equal with T, the process went to update TV and assign it to $\boldsymbol{T}^*$using the following formula; otherwise, TV assigned toT^*. Table 5.14 , presents the entries of the vector T^* of this system.

Table 5. 14 Values of the vector T* of Case 2

$\boldsymbol{T}^*$ $[\boldsymbol{i}]$	Value	$\boldsymbol{T}^*$ $[\boldsymbol{i}]$	Value	$\boldsymbol{T}^*$ $[\boldsymbol{i}]$	Value
$\boldsymbol{T}^*$ $[\mathbf{1}]$	0.95	$\boldsymbol{T}^*$ $[\mathbf{10}]$	0.84	$\boldsymbol{T}^*$ $[\mathbf{19}]$	0
$\boldsymbol{T}^*$ $[\mathbf{2}]$	0.98	$\boldsymbol{T}^*$ $[\mathbf{11}]$	0	$\boldsymbol{T}^*$ $[\mathbf{20}]$	0
$\boldsymbol{T}^*$ $[\mathbf{3}]$	0	$\boldsymbol{T}^*$ $[\mathbf{12}]$	0	$\boldsymbol{T}^*$ $[\mathbf{21}]$	0
$\boldsymbol{T}^*$ $[\mathbf{4}]$	0	$\boldsymbol{T}^*$ $[\mathbf{13}]$	0	$\boldsymbol{T}^*$ $[\mathbf{22}]$	0
$\boldsymbol{T}^*$ $[\mathbf{5}]$	0.84	$\boldsymbol{T}^*$ $[\mathbf{14}]$	0	$\boldsymbol{T}^*$ $[\mathbf{23}]$	0
$\boldsymbol{T}^*$ $[\mathbf{6}]$	0.84	$\boldsymbol{T}^*$ $[\mathbf{15}]$	0	$\boldsymbol{T}^*$ $[\mathbf{24}]$	0
$\boldsymbol{T}^*$ $[\mathbf{7}]$	0.88	$\boldsymbol{T}^*$ $[\mathbf{16}]$	0	$\boldsymbol{T}^*$ $[\mathbf{25}]$	0
$\boldsymbol{T}^*$ $[\mathbf{8}]$	0.88	$\boldsymbol{T}^*$ $[\mathbf{17}]$	0	$\boldsymbol{T}^*$ $[\mathbf{26}]$	0
$\boldsymbol{T}^*$ $[\mathbf{9}]$	0.88	$\boldsymbol{T}^*$ $[\mathbf{18}]$	0	$\boldsymbol{T}^*$ $[\mathbf{27}]$	0.84

Step 5: the fault sections determined from the EFS vector according to (3.6) and E according to (5.1) as shown in Table 5.14:

Table 5. 15 Comparison between values of the vectors (EFS) and (E)

Faults	Node#	EFS	E
F1	C1	0.95	E[4]= 0.98
F2	C7	0.88	0
F3	C11	0	0
F4	C15	0	0
F5	C19	0	0
C1	C23	0	0
BUS 1	C27	0.84	0

By this case it was shown that :

1- When the information is complete, FCE-Nets and CE-Nets inference can obtain the correct results. But if a status signal is missing, CE-Nets can't find the fault sections.
2- The proposed method has the ability to identify multiple fault sections even when a failure device and incomplete or missing information happen.

5.3System under study

A typical unit in Cairo West Planet as shown in Figure 5.17 is employed to illustrate the reasoning process of the FCE-Net technique. The unit is composed of one sub transmission line , one main transformer and one auxiliary transformer feeds two 6.6KV bus bars each one of the protected by 2500 A, 40 kA for 1 sec, 6.6KV switch gear (SWG). Bus1 feeds three radial feeders each one of them protected by 3 relays CO and 1250A CB.Bus2 feeds five radial feeders each one of them protected by 3 relays CO and 1250A CB. The protective relays of the 6.6KV buses serve as the backup protection for their connected feeders. Two challengeable scenarios were took place on this system to prove the accuracy, ease in construction , the ability in dealing with uncertainty situations and with any construction of substations of the proposed methodology.

A. The First scenario

A three phase fault hit feeder (F1) and protective relay CO1 operates and give a signal to circuit breaker CB1 to trip. Although CO1 operates, CB1 failed to trip. So the protective Relay of the Bus1 operates as a backup and CBM1 tripped. Also a single line to ground fault hit feeder (F5) and protective relay CO5 operates and give a signal to circuit breaker CB5 to trip.CB5 tripped with no failure. Table 5.16, shows the pre-fault values of feeder current of F1 and F5 also the bus voltage of Bus#1 and Bus#2.

Table 5. 16 Pre-Fault values of Scenario 1

Phases	F1	F5	Bus #1	Bus #2
A	500 (A)	420 (A)	9.2 (V)	9.3 (V)
B	360 (A)	380 (A)	9.4 (V)	9.2 (V)
C	390 (A)	370 (A)	8.7 (V)	10.1 (V)
Neutral	45(A)	62(A)		

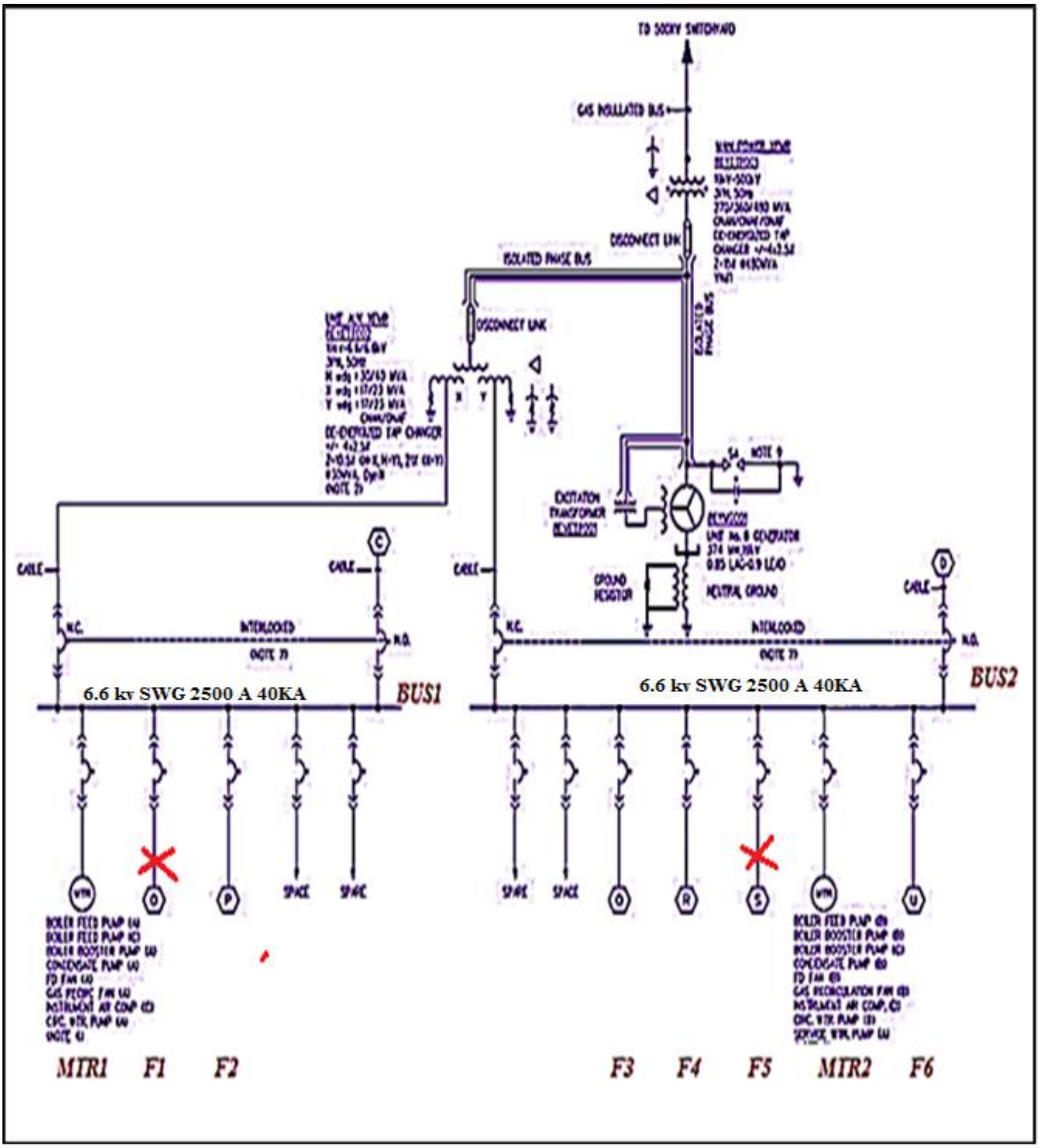


Fig.5. 16 A typical unit in Cairo West Planet – Scenario 1

-Procedures of Fault diagnosis:

A) Fault identification process :

Step 1: To perform the reasoning process with the fuzzy rule matrix, the associated FCE-Net for the model system is shown in Figure 5.18. Tables (5.17-20), shows the defining of the node conditions and the developing of the rule matrix (R), the fault vector (F) and backup vector (B) as follows:

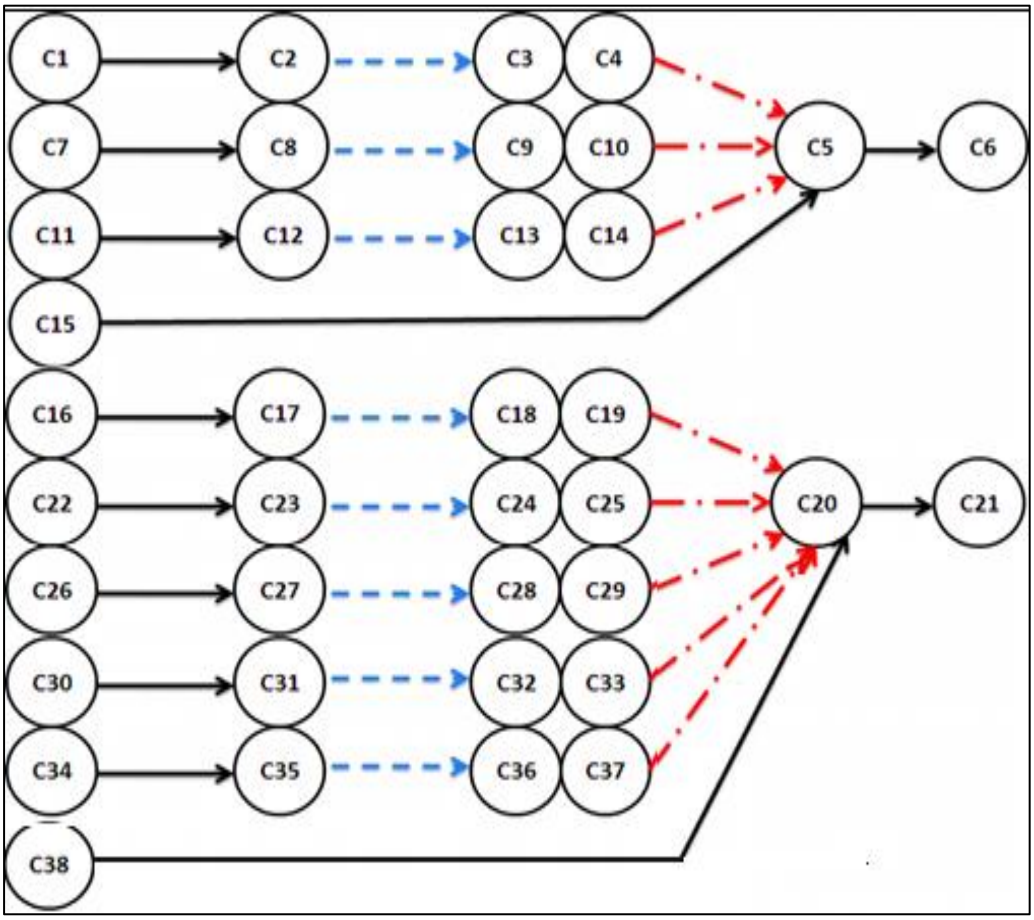


Fig.5. 17 The associated FCE_Net for the model System - Scenario 1

- The set of conditions of the system is listed in the following table:

Table 5. 17 The set of conditions of the system – Scenario 1

Node	Description	Node	Description
C1	A fault occurs at feeder F1	C20	Relay COM3 operates
C2	Relay CO1 operates	C21	Circuit breaker CBM3 tripped
C3	Circuit breaker CB1 tripped	C22	A fault occurs at feeder F4
C4	CO1 operates but CB1 fails	C23	Relay CO4 operates
C5	Relay COM1 operates	C24	Circuit breaker CB4 tripped
C6	Circuit breaker CBM1 tripped	C25	CO4 operates but CB4 fails
C7	A fault occurs at feeder F2	C26	A fault occurs at feeder F5
C8	Relay CO2 operates	C27	Relay CO5 operates
C9	Circuit breaker CB2 tripped	C28	Circuit breaker CB5 tripped
C10	CO2 operates but CB2 fails	C29	CO5 operates but CB5 fails
C11	A fault occurs at feeder MTR1	C30	A fault occurs at feeder F6
C12	Relay COMTR1 operates	C31	Relay CO6 operates
C13	Circuit breaker CBMTR1 tripped	C32	Circuit breaker CB6 tripped
C14	COMTR1 operates but CBMTR1 fails	C33	CO6 operates but CB6 fails
C15	A fault occurs at section BUS1	C34	A fault occurs at feeder MTR2
C16	A fault occurs at feeder F3	C35	Relay COMTR2 operates
C17	Relay CO3 operates	C36	Circuit breaker CBMTR21 tripped
C18	Circuit breaker CB3 tripped	C37	COMTR1 operates but CBMTR2 fails
C19	CO3 operates but CB3 fails	C38	A fault occurs at section BUS2

The rule matrix describes the relations between causes and effects of FCE-Nets. Table 5.18 , shows the non-zero entries of rule matrix of this system.

Table 5. 18 Nonzero Entries of Rule Matrix of Scenario 1

R[i]	Value	R[i]	Value	R[i]	Value
R [1,1]	1	R[2,1]	0.95	R[2,2]	1
R[3,2]	0.8	R[3,3]	1	R[4,4]	1
R[5,4]	0.95	R[5,5]	1	R[6,5]	0.8
R[6,6]	1	R[7,7]	1	R[8,7]	0.95
R[8,8]	0.95	R[9,8]	0.8	R[9,9]	1
R[5,10]	0.95	R[5,14]	0.95	R[5,15]	0.95
R[10,10]	1	R[11,11]	1	R[12,11]	0.95
R[12,12]	1	R[13,12]	0.8	R[13,13]	1
R[14,14]	1	R[15,15]	1	R[16,16]	1
R[17,16]	0.95	R[17,17]	1	R[R18,17]	0.8
R[18,18]	1	R[19,19]	1	R[20,19]	0.95
R[20,20]	1	R[20,25]	0.95	R[21,20]	0.8
R[21,21]	1	R[22,22]	1	R[23,22]	0.95
R[23,23]	1	R[24,23]	0.8	R[24,24]	1
R[25,25]	1	R[26,26]	0.8	R[27,26]	0.95
R[27,27]	1	R[28,27]	0.8	R[28,28]	1
R[20,29]	0.95	R[20,33]	0.95	R[29,29]	1
R[30,30]	1	R[31,30]	0.95	R[31,31]	1
R[32,31]	0.8	R[32,32]	1	R[33,33]	1
R[34,34]	1	R[35,34]	0.95	R[35,35]	1
R[36,35]	0.8	R[36,36]	1	R[20,37]	0.95
R[20,38]	0.95	R[37,37]	1	R[38,38]	1

Once the fuzzy rule matrix is established, the diagnosis algorithm can then be performed by matrix operations

The fault node vector (F) is defined to represent the fault section nodes in a given FCE-Net. Table 5.19 , shows the non-zero entries of Fault vector (F) of this system.

Table 5. 19 Values of the fault vector of Scenario 1

F[i]	Value	Description
F[1]	1	F1
F[7]	1	F2
F[11]	1	MTR1
F[15]	1	BUS1
F[16]	1	F3
F[22]	1	F4
F[26]	1	F5
F[30]	1	F6
F[34]	1	MTR2
F[38]	1	BUS2

The backup node vector B is employed to represent the backup relay nodes in a given FCE Net. Table 5.20 , shows the (B) vector of this system.

Table 5. 20 Values of Backup vector (B) of Scenario 1

B[i]	Value
B[4]	1
B[10]	1
B[14]	1
B[19]	1
B[25]	1
B[29]	1
B[33]	1
B[37]	1

Step 2: The informed data from SCADA of the truth state vector is listed as follow:

Table 5. 21 Nonzero entries of the truth state vector (T) of Scenario 1

T[i]	Value	Description
T[5]	0.95	Degree of 'Relay COM1 operates'
T[6]	0.8	Degree of 'CBM1 tripped'
T[2]	0.95	Degree of 'Relay CO1 operates'
T[4]	0.8	Degree of 'Relay CO1 operates but CB1 fails'
T[27]	0.95	Degree of 'Relay CO5 operates'
T[28]	0.95	Degree of 'Circuit breaker CB5 tripped'

Step3: Calculating TV Vector to propagate the truth state of given fault symptoms leading backward into the fault cause. The (TV) vector contains information that causes the fault symptoms. Table 5.22 , presents the entries of the vector (TV) of this system.

Table 5. 22 Calculated values of the (TV) vector of Scenario 1

TV[i]	Value	TV[i]	Value	TV[i]	Value
TV[1]	0.95	TV[14]	0.95	TV[27]	0.95
TV[2]	0.95	TV[15]	0.95	TV[28]	0.95
TV[3]	0	TV[16]	0	TV[29]	0
TV[4]	0.95	TV[17]	0	TV[30]	0
TV[5]	0.95	TV[18]	0	TV[31]	0
TV[6]	0.8	TV[19]	0	TV[32]	0
TV[7]	0	TV[20]	0	TV[33]	0
TV[8]	0	TV[21]	0	TV[34]	0
TV[9]	0	TV[22]	0	TV[35]	0
TV[10]	0.95	TV[23]	0	TV[36]	0
TV[11]	0	TV[24]	0	TV[37]	0
TV[12]	0	TV[25]	0	TV[38]	0
TV[13]	0	TV[26]	0.95		

Step4: The T vector and TV vector aren't equal, the process went to update TV and assign it to $\boldsymbol{T}^{*}$. Table 5.23, presents the entries of the vector T^{*} of this system.

Table 5. 23 Calculated values of the (T*) Vector of Scenario 1

T^* [i]	Value	T^* [i]	Value	T^* [i]	Value
$\boldsymbol{T^*}$ [**1**]	0.95	$\boldsymbol{T^*}$ [**14**]	0.95	$\boldsymbol{T^*}$ [**27**	0.95
$\boldsymbol{T^*}$ [**2**]	0.95	$\boldsymbol{T^*}$ [**15**]	0.95	$\boldsymbol{T^*}$ [**28**]	0.95
$\boldsymbol{T^*}$ [**3**]	0	$\boldsymbol{T^*}$ [**16**]	0	$\boldsymbol{T^*}$ [**29**]	0
$\boldsymbol{T^*}$ [**4**]	0.15	$\boldsymbol{T^*}$ [**17**]	0	$\boldsymbol{T^*}$ [**30**]	0
$\boldsymbol{T^*}$ [**5**]	0.95	$\boldsymbol{T^*}$ [**18**]	0	$\boldsymbol{T^*}$ [**31**]	0
$\boldsymbol{T^*}$ [**6**]	0.80	$\boldsymbol{T^*}$ [**19**]	0	$\boldsymbol{T^*}$ [**32**]	0
$\boldsymbol{T^*}$ [**7**]	0.95	$\boldsymbol{T^*}$ [**20**]	0	$\boldsymbol{T^*}$ [**33**]	0
$\boldsymbol{T^*}$ [**8**]	0.95	$\boldsymbol{T^*}$ [**21**]	0	$\boldsymbol{T^*}$ [**34**]	0
$\boldsymbol{T^*}$ [**9**]	0.80	$\boldsymbol{T^*}$ [**22**]	0	$\boldsymbol{T^*}$ [**35**]	0
$\boldsymbol{T^*}$ [**10**]	0.95	$\boldsymbol{T^*}$ [**23**]	0	$\boldsymbol{T^*}$ [**36**]	0
$\boldsymbol{T^*}$ [**11**]	0	$\boldsymbol{T^*}$ [**24**]	0	$\boldsymbol{T^*}$ [**37**]	0
$\boldsymbol{T^*}$ [**12**]	0	$\boldsymbol{T^*}$ [**25**]	0	$\boldsymbol{T^*}$ [**38**]	0
$\boldsymbol{T^*}$ [**13**]	0	$\boldsymbol{T^*}$ [**26**]	0.95		

Step 5: the fault section determined from the EFS vector according to (3.6) is F1 as the following table:

Table 5. 24 Calculated Values of the EFS vector of Scenario 1

F[i]	Description	Value
F[1]	F1	0.95
F[7]	F2	0
F[11]	MTR1	0
F[15]	BUS1	0.95
F[16]	F3	0
F[22]	F4	0
F[26]	F5	0.95
F[30]	F6	0
F[34]	MTR2	0
F[38]	BUS2	0

The Faulted sections are F1, Bus1 and F5.

B) Fault type estimation process :

Step1: Define the membership function ranges as following:

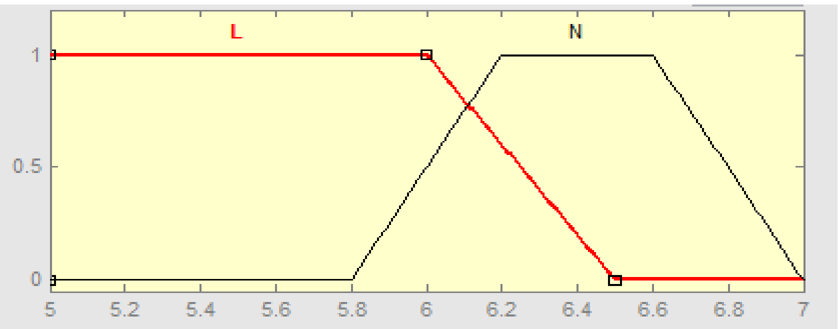


Fig.5. 18 Membership function of the Bus Voltages of Scenario 1

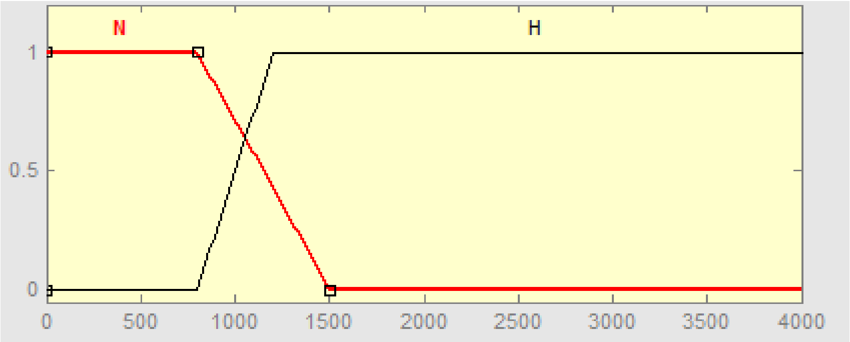


Fig.5. 19 Membership function of the Feeder currents of Scenario 1

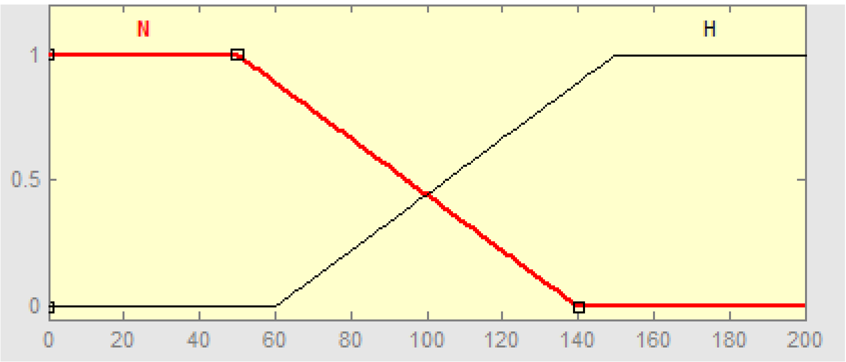


Fig.5. 20 Membership function of the neutral current of Scenario 1

Step2: Get the reads of Current and voltage measurement devices from SCADA.

Step3: By using the rules, the result will be as follows:

Table 5. 25 Fault data from SCADA and the suitable rule base of Scenario 1

Rule #	F#	I_A	I_B	I_C	I_N	V_A	V_B	V_C	*Fault Type*	*Degree of belonging*
R10	F1	3000	3000	2500	40	5.4	5.6	6.2	*3∅ fAULT*	0.76
		H	H	H	N	L	L	L		
R1	F5	1250	400	380	100	6.3	9	9.8	*SLG-A*	0.69
		H	N	N	H	L	N	N		

In this case:

1- The proposed method shows high flexibility in dealing with any system construction.
2- The graphical construction of the nodes and arrows of the used system was very ease in construction and understanding.
3- The memberships cover the database very well.

These results reflect the great abilities and advantages of the proposed methodology.

B. Scenario 2

To increase the challenge in this scenario we increase the number of faults to show the accuracy and the ability of the proposed method in dealing with any number of faults occur in the same time.

A double line to ground fault hit feeder (F2), so protective relay CO2 operates and gives a signal to circuit breaker CB2 to trip. Although CO2 operates, CB2 failed to trip. So the protective Relay of the Bus1 operates as a backup and CBM1 tripped.

Also a single line to ground fault hit feeder (F3) and protective relay CO3 operates and give a signal to circuit breaker CB3 to trip; CB3 tripped with no failure.

A line to line fault hit feeder (F4), so protective relay CO4 operates and gives a signal to circuit breaker CB2 to trip. Although CO4 operates, CB4 failed to trip. So the protective Relay of the Bus2 operates as a backup and CBM2 tripped.

A three phase fault hit feeder (F5), so protective relay CO5 operates and gives a signal to circuit breaker CB2 to trip. Although CO5 operates, CB5 failed to trip; CB3 tripped with no failure. Figure 5.22, shows the faulted distributed system of case 4. Table 5.26 , shows the pre fault values of the faulted feeders curren and the voltage of Bus#1 and Bus #2.

Table 5. 26 Pre-Fault values of Scenario 2

Phases	F2	F3	F4	F5	Bus #1	Bus #2
A	650 (A)	500 (A)	580 (A)	530 (A)	9.2 (V)	8.3 (V)
B	690 (A)	550 (A)	498 (A)	550 (A)	8.6 (V)	7.6 (V)
C	682 (A)	496 (A)	420 (A)	510 (A)	8.4 (V)	9.5 (V)
Neutral	80(A)	75(A)	60(A)	85(A)		

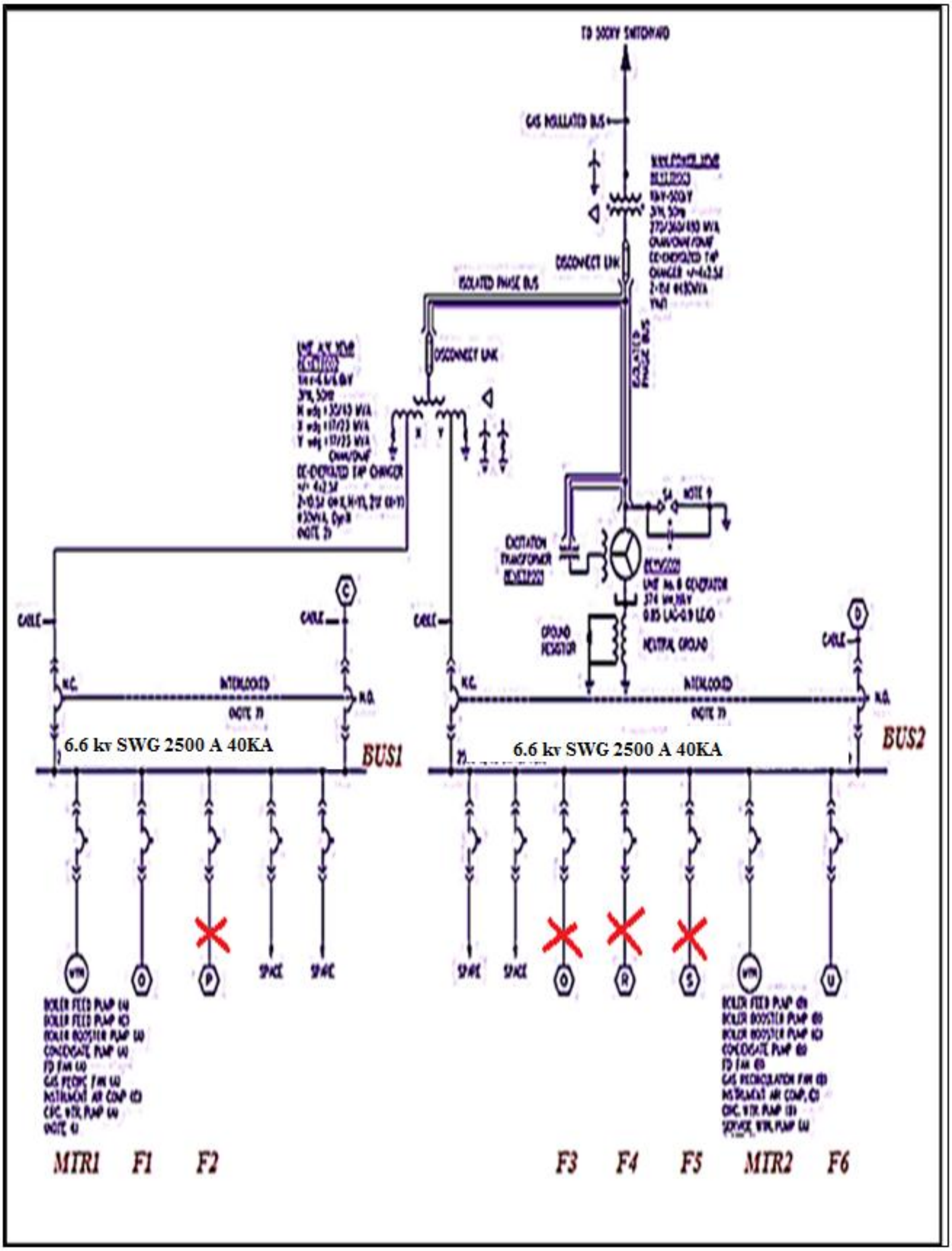


Fig.5. 21 Faulted Distribution System of Scenario 2

- Procedures of Fault diagnosis:

A) Fault identification process :

Step 1: As the previous case.

Step 2: The truth state vector (T) is employed to represent the fault symptom with the status of protective devices. Table 5.27 , shows the non-zero entries of (T) vector of this system.

Table 5. 27 Nonzero entries of the truth state vector (T) of Scenario 2

T[i]	Value	Description
T[5]	0.95	Degree of 'Relay COM1 operates'
T[6]	0.8	Degree of 'CBM1 tripped'
T[8]	0.95	Degree of Relay CO2 operates
T[9]	0.80	Degree of Circuit breaker CB2 tripped
T[10]	0.80	Degree of CO2 operates but CB2 fails
T[17]	0.95	Degree of Relay CO3 operates
T[18]	0.80	Degree of Circuit breaker CB3 tripped
T[20]	0.95	Degree of Relay COM3 operates
T[21]	0.80	Degree of Circuit breaker CBM3 tripped
T[23]	0.95	Degree of Relay CO4 operates
T[24]	0.80	Degree of Circuit breaker CB4 tripped
T[25]	0.80	Degree of CO4 operates but CB4 fails
T[27]	0.95	Degree of Relay CO5 operates
T[28]	0.80	Degree of Circuit breaker CB5 tripped

Step3: Calculating (TV) vector to propagate the truth state of given fault symptoms leading backward into the fault cause. The (TV) vector contains information that causes the fault symptoms. Table 5.28 , presents the entries of the vector (TV) of this system.

Table 5. 28 The calculated entries of the TV vector of Scenario 2

TV[i]	Value	TV[i]	Value	TV[i]	Value
TV[1]	0	TV[14]	0.95	TV[27]	0.95
TV[2]	0	TV[15]	0.95	TV[28]	0.80
TV[3]	0	TV[16]	0.95	TV[29]	0.95
TV[4]	0.95	TV[17]	0.95	TV[30]	0
TV[5]	0.95	TV[18]	0.80	TV[31]	0
TV[6]	0.80	TV[19]	0.95	TV[32]	0
TV[7]	0.95	TV[20]	0.95	TV[33]	0.95
TV[8]	0.95	TV[21]	0.80	TV[34]	0
TV[9]	0.80	TV[22]	0.95	TV[35]	0
TV[10]	0.95	TV[23]	0.95	TV[36]	0
TV[11]	0	TV[24]	0.80	TV[37]	0.95
TV[12]	0	TV[25]	0.95	TV[38]	0.95
TV[13]	0	TV[26]	0.95		

Step4: Because TV don't equal with T, the process went to update TV and assign it to $\boldsymbol{T}^*$using the following formula; otherwise, TV assigned toT^*. Table 5.26 , presents the entries of the vector T^* of this system.

Table 5. 29 The calculated values of the T*vector of Scenario 2

$\boldsymbol{T}^*$ $[\boldsymbol{i}]$	Value	$\boldsymbol{T}^*$ $[\boldsymbol{i}]$	Value	$\boldsymbol{T}^*$ $[\boldsymbol{i}]$	Value
$\boldsymbol{T}^*$ $[\mathbf{1}]$	0	$\boldsymbol{T}^*$ $[\mathbf{14}]$	0.95	$\boldsymbol{T}^*$ $[\mathbf{27}$	0.95
$\boldsymbol{T}^*$ $[\mathbf{2}]$	0	$\boldsymbol{T}^*$ $[\mathbf{15}]$	0.95	$\boldsymbol{T}^*$ $[\mathbf{28}]$	0.80
$\boldsymbol{T}^*$ $[\mathbf{3}]$	0	$\boldsymbol{T}^*$ $[\mathbf{16}]$	0.95	$\boldsymbol{T}^*$ $[\mathbf{29}$	0.95
$\boldsymbol{T}^*$ $[\mathbf{4}]$	0.95	T^* [17]	0.95	T^* [30]	0
T^* [5]	0.95	T^* [18]	0.80	T^* [31]	0
T^* [6]	0.80	T^* [19]	0.95	T^* [32]	0
T^* [7]	0.95	T^* [20]	0.95	T^* [33]	0.95
T^* [8]	0.95	T^* [21]	0.80	T^* [34]	0
T^* [9]	0.80	T^* [22]	0.95	T^* [35]	0
T^* [10]	0.15	T^* [23]	0.95	T^* [36]	0
T^* [11]	0	T^* [24]	0.80	T^* [37]	0.95
T^* [12]	0	T^* [25]	015	T^* [38]	0.95
T^* [13]	0	T^* [26]	0.95		

Step 5: the fault sections determined from the EFS vector according to (3.6) as the following table:

Table 5. 30 The estimated fault sections of Scenario 2

F[i]	Description	Value
F[1]	F1	0
F[7]	F2	0.95
F[11]	MTR1	0
F[15]	BUS1	0.95
F[16]	F3	0.95
F[22]	F4	0.95
F[26]	F5	0.95
F[30]	F6	0
F[34]	MTR2	0
F[38]	BUS2	0.95

The Faulted sections are F2, Bus1, F3, F4, F5 and Bus2.

B) Fault type estimation process :

Step1: Define the membership function ranges as the previous case.

Step2: Get the reads of Current and voltage measurement devices from SCADA.

Step3: By using the rules, the result will be as follows:

Table 5. 31 Fault data from SCADA and the suitable rule base of Scenario 2

Rule #	F#	I_A	I_B	I_C	I_N	V_A	V_B	V_C	*Fault Type*	*Degree of belonging*
R7	F2	2000	2000	700	130	4.5	4.7	7	*DLG AB*	*0.623*
		H	H	N	H	L	L	N		
R3	F3	550	600	2500	121	7.2	8.1	5.9	*SLG-C*	*0.69*
		N	N	H	H	N	N	L		
R5	F4	590	1400	2500	121	9	6	5.9	*DL-BC*	*0.74*
		N	H	H	N	N	L	L		
R10	F5	2600	1660	2300	50	4.4	4.7	4.9	*3∅ fAULT*	*0.87*
		H	H	H	N	L	L	L		

By this case:

1- The great ability of the proposed case in dealing with any number of faults was approved.
2- The high accuracy of the proposed method in defining fault types when dealing with almost similar types was shown, that was very clear in the fault type of (F2). Although the degree of belonging was very close between the DL-AB and the DLG-AB, the high accuracy of the proposed method in selecting the fault type of this state was approved. Figure 5.23, shows the degree of belonging of the two close types in Fault (F2).

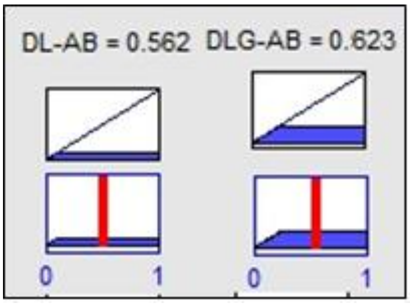


Fig.5. 22 The degree of belonging of fault types of Scenario 2

5.4Conclusions

In this chapter, by using Mat-lab fuzzy toolbox the proposed approaches of the fault diagnosis were presented.

Four cases of study of existing substations were taken place to evaluate and test the proposed methodology; two of them were done and by comparing the results of the tests with another two methods based on ES-ANN and CE-Nets techniques. After comparing the results and discussing them, it was obtained that the proposed methodology got the advantages of:

1- High accuracy and fast response.
2- Great ability to deal with uncertain situations.
3- Easy in construction and maintenance.
4- Suitability for on-line operation and no need for training.

By these tests, evaluations and according to the great results, it is proofed that the proposed method improves the technique that was presented in [22] by the following:

1- More than one bus with more than one backup were added in the same graphical network to decrease the processing time which was leaked when dealing with every bus individually.
2- The flexibility in forming the graphical networks with any substation construction reflected on the mathematical structure of the proposed method and its data base and this improvement make the construction of the proposed method suits any substation construction with any number of busses and feeders.
3- Historical records of number of occurrence of the fault symptoms were used in constructing the memberships and the data base of the proposed methodology.
4- The fault type estimating process based on fuzzy logic was added and it runs in parallel with the fault identification process to complete the fault diagnosis processes.

Finally, the proposed methodology can be recommended to be integrated into existing SCADA systems like a tool box with no need for extra devices.

Chapter 6: Conclusion and Recommendations

At the beginning, the construction and functions of SCADA system as the environment of the events of the proposed methodology were presented. Also the duties of the operator/dispatcher which include analyzing the information and data received from all the components of SCADA representing current state of the fields and to recognize possible threats to them were discussed; to represent how complex and risky these duties are. The need of methodology to reduce or avoid the risk of making wrong decisions under stresses to keep the power system stable was very necessary. So some fault diagnosis methods and techniques were discussed generally showing the construction, advantages and dis-advantages of every one.

Then the proposed method was presented showing the main concepts and basis that form it. This method is based on FCE-Nets as graphical tool and matrix-based operations to identify fault location. In the meanwhile, the fuzzy logic database and rule-base is implemented to identify the fault type. The construction, matrixes and operators were presented in details. The advantages of the proposed method were discussed, mainly capability of representing and dealing with uncertain knowledge and terms thanks to the fuzzy logic abilities, ease in understanding the relationship between the rules and conditions and the possibility to predict the inference results in advance by observing the flow of truth state in the FCE-Nets when some conditions are specified.

So the challenge was to test and compare the results of this methodology with another techniques and methods on existing systems to proof the abilities of the proposed methodology in dealing with any system and giving accurate results.

6.1General discussion on the results

By using Mat-lab fuzzy tool box, the comparing of the results obtained from the proposed methodology with ES-ANN based and CE-Nets techniques and the applying of the proposed methodology on existing systems with hard scenarios shows ;

1- The high accuracy
2- Great ability to deal with un-certainty situations
3- Quick response.
4- Suitability for on-line operation, no need for training, and simplicity in establishing the model of the proposed methodology.
5- The great ability of the proposed methodology in dealing with any construction of the systems and with any number of faults
6- The proposed methodology can be considered as an economical solution as it can be integrated to existing SCADA system like a tool box with no need to extra devices.
7- The proposed technique will help the operator to make right decisions when he faces fault events.

6.2Future work

In [30], a proposed hardware-implemented fault diagnosis system for SCADA-based substations, which has its merits of fast inference speed and low cost. In addition, it is easily integrated into existing systems, and is adaptive to network reconfiguration.

- The author also recommend his proposed feature to achieve the following:

1) Fast Inference Speed

Since the proposed fault diagnosis approach has fast inference speed, it is suitable for real-time applications.

2) Decentralized Fault Diagnosis Framework:

Traditional fault diagnosis has problems when the host computer in the control center fails to obtain accurate data from remote sites due to communication problems.

The proposed decentralized system performs fault analysis in the field site, which has less of an influence on communication failure since the data for analysis is obtained directly from RTUs.

3) Feasibility for Power Utilities:

The proposed system can be easily integrated with the existing SCADA systems, which makes it feasible for power utilities.

4) Adaptive to Network Reconfiguration:

Since FPGAs are reprogrammable silicon chips, the proposed approach can deal with the changes of network configuration, which is effective in power system operation.

- Finally we suggest this promising proposal of implementing hardware device based on cause and effect concept which is mainly consist of simple logic gates doing the operates and calculations in the fault diagnosis process, can replace the PMUs devices as an economical solution with less accuracy.

References

[1] M. K. Khedkar and G. M. Dhole , A Textbook of Electric Power Distribution Automation , University science press, 2010, pp. 26-36.

[2] A. Pabla, “Electronic Power Distribution System, TATA McGraw-Hill , 11th edition 2008 , pp. 228-248 .

[3] Peng Zhang , Industrial Control Technology: A Handbook for Engineers and Researchers, William Andrew Inc., 2008, pp. 496-506.

[4] Stephen Doyle, Understanding Information Technology, Stanley Thornes, 2000, pp. 307-308.

[5] Zhao Yang Dong and Pei Zhang , Emerging Techniques in Power System Analysis, Springer, 2010, pp. 151-167

[6] Joseph Weiss, Protecting Industrial Control Systems from Electronic Threats, Momentum press , 2010 , pp. 130-138.

[7] Keith Stouffer, Joe Falco and Karen Scarfone, Guide to Industrial Control Systems (ICS) Security, National Institute of Standards and Technology,June2011 , pp. 21-22

[8] Mangapathirao V. Mynam, Ala Harikrishna, and Vivek Singh, Synchrophasors Redefining SCADA Systems, Schweitzer Engineering Laboratories, Inc.

[9] Rajib Baran Roy,” Controlling of Electrical Power System Network by using SCADA,” International Journal of Scientific & Engineering Research Volume 3, Issue 10 , October-2012

[10] Nicoleta Arghira, Daniela Hossu, Ioana Făgărăşan, Sergiu Stelian Iliescu and Daniel Răzvan Costianu ,” MODERN SCADA PHILOSOPHY IN POWER SYSTEM OPERATION – A SURVEY,” U.P.B. Sci. Bull., series C, vol. 73, Issue 2, 2011.

[11] C. Fukui , and J. Kawakami, “An expert system for fault section estimation using information from protective relays and circuit breakers,” IEEE Transaction Power Delivery, vol. 1, no. 4, pp. 83–90, Oct. 1986.

[12] Y. L. Zhu, Y. H. Yang, B. W. Hogg, W. Q. Zhang, and S. Gao, “An expert system for power systems fault analysis,” IEEE Transaction Power Systems, vol. 9, no. 1, pp. 503–509, Feb. 1994.

[13] G. Cardoso, J. G. Rolim, and H. H. Zurn, “Application of neural-network modules to electric power system fault section estimation,” IEEE Transaction Power Delivery, vol. 19, no. 3, pp. 1034–1041, Jul. 2004.

[14] T. Bi, Z. Yan, F. Wen, Y. Ni, C. M. Shen, F. F. Wu, and Q. Yang, “On-line fault section estimation in power systems with radial basis function neural network,” International Journal of Electric Power Energy Systems, vol. 24, no. 4, pp. 321–328, May 2002.

[15] C. L. Yang, A. Yokoyama, and Y. Sekine, “Fault section estimation of power system using colored and timed Petri nets,” Electerical Engineering Japan., vol. 115, no. 2, pp. 89–101, 1995.

[16] K. L. Lo, H. S. Ng, D. M. Grant, and J. Trecat, “Extended Petri net models for fault diagnosis for substation automation,” Generation, Transmission and Distribution, IEE Proceedings, vol. 146, no. 3, pp. 229–234, May 1999.

[17] Wen-Hui Chen, Shun-Hung Tsai, and Hsien-I. Lin, “Fault Section Estimation for Power Networks Using Logic Cause-Effect Models,” IEEE Transactions on Power Delivery, vol. 26, no. 2, pp. 963 – 971, April 2011.

[18] Wen-Hui Chen ,Chih-Wen Liu ,Men-Shen Tsai,” Fault Diagnosis in Distribution Substations Using CE-Nets via Boolean Rule Matrix Transformations,”, Power Engineering Society Summer Meeting IEEE , vol. 1, pp. 416 – 420 , Jul 2000.

[19] S. W. Min, J. M. Sohn, J. K. Park, and K. H. Kim, “Adaptive fault section estimation using matrix representation with fuzzy relations,” IEEE transactions on power systems, vol. 19, no. 2, pp. 842–848, May 2004.

[20] H. J. Cho and J. K. Park, “An expert system for fault section diagnosis of power systems using fuzzy relations,” IEEE Transaction Power Systems, vol. 12, no. 1, pp. 342–348, Feb. 1997.

[21] Wen-Hui Chen, Chih-Wen Liu, and Men-Shen Tsai,” On-Line Fault Diagnosis of Distribution Substations Using Hybrid Cause-Effect Network and Fuzzy Rule-Based Method”, IEEE Transactions on Power Delivery, VOL. 15, NO. 2, April.2000.

[22] Wen-Hui Chen,” Fault Section Estimation Using Fuzzy Matrix-Based Reasoning Methods,” IEEE Transactions on Power Delivery, vol. 26, no. 1, Jan. 2011.

[23] Biswarup Das, ” Fuzzy Logic-Based Fault-Type Identification in Unbalanced Radial Power Distribution System,”IEEE Transactions on Power Delivery, vol. 21, NO. 1, pp. 278 - 285 , January 2006.

[24] D. K. Ranaweera, “Comparison of neural network models for fault diagnosis of power system,” Electrical Power Systems, pp. 99–104, 1994.

[25] S. A. Soliman, and M. Belkhayat,” Power Systems Fault Type Identification Based on Park's Transformation Algorithm,” Power Engineering, 2006 Large Engineering Systems, pp. 141-145, 2006 IEEE.

[26] A. A. Girgis, and M. B. Johns, “A hybrid expert system for faulted section identification, fault type classification and selection of fault location algorithms,” IEEE Transaction Power Delivery, vol. 4, no. 2, pp. 978–985, April 1989.

[27] Onojo Ondoma James, Ononiwu Gordon Chiagozie,” Fault detection on radial power distribution systems using fuzzy logic,” Asian journal of natural & applied sciences, Vol.1, No.2, pp. 38-52 ,June 2012.

[28] Hong-TzerYang, Wen-YeauChang, Ching-LienHuang, ” on-line fault diagnosis of power substation using connectionist expert system,” IEEE Transactions on Power Systems, Vol. 10, No. 1, pp. 323-331, February 1995.

[29] Wen-Hui Chen, Chih-Wen Liu, and Men-Shen Tsai, “Fast Fault Section Estimation in Distribution Substations Using Matrix-Based Cause–Effect," Networks IEEE transactions on power delivery, vol. 16, no. 4, pp. 522 - 527 ,October 2001.

[30] Wen-Hui Chen, “Decentralized Fault Diagnosis and Its Hardware Implementation for Distribution Substations”, IEEE Transactions on Power Delivery, Vol. 27, Issue. 2 , pp. 902-909, 2012 IEEE.

Appendix: Published Paper of the Thesis