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UNCERTAINTY IN MEASUREMENTS AND COGNITIVE ENGINEERING ANALYSIS OF A DECISION SUPPORT SYSTEM FOR POWER SYSTEM RECONFIGURATION

By

Venkata Krishna Pendurthi

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UNCERTAINTY IN MEASUREMENTS AND COGNITIVE ENGINEERING ANALYSIS OF A DECISION SUPPORT SYSTEM FOR POWER SYSTEM RECONFIGURATION

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Accuracy of the measurement data used for the decision making process or for shipboard operations and control is very important to ensure the reliability and survivability. The uncertainties present in measurement data need to be minimized for reliable system operation. In this work, a fuzzy logic based model is developed to deal with uncertainty in the meter data. Operational and historical parameters of the meters were used to determine a 'trust' value of individual meter. A fuzzy correction system for measurement data was used to generate an input dataset for a genetic algorithm based reconfiguration system. Additionally, with the goal of optimizing the performance of power system operator, the effects of Decision Support System (DSS) on the quality of decisions taken by the operator were examined. Unaided and aided interface prototypes were developed and usability tests were carried out on interface prototypes with users having knowledge of power systems.

DEDICATION

I would like to dedicate this thesis to my family

ACKNOWLEDGEMENTS

I would like to gratefully thank my advisor Dr. Noel N Schulz, for her guidance, motivation, constant encouragement and support throughout my research work. Her high levels of energy fuelled my motivation all the times. I experienced at most pleasure working with Power and Energy Research Lab (PERL) at Mississippi State. I am thankful to Dr. Anurag K Srivastava, for accepting to be my co-advisor and for his excellent guidance in every important step of my research. Special thanks to Dr. Stephanie Doane for guiding and supporting me throughout the research work. Her vast technical knowledge and experience helped me to develop both professionally and personally. I consider the time that I spent with Skill Acquisition Lab (SAL) at Mississippi State University as the most fruitful part of my professional development.

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CHAPTER 1

INTRODUCTION

1.1 Introduction

Shipboard power system design for naval operations is a complex task. With the goal of increasing affordability and military capability, this requires the ship design to ensure reliable and safer operations even during adverse and unforeseen conditions. The U.S. Office of Naval Research has focused on developing the technologies of the all-electric war ship [1] to optimize size and performance of the ship. This provided an option of using an electrical propulsion system instead of a conventional mechanical propulsion system. This idea has opened or facilitated the opportunity to think of installing new kinds of loads which can use electrical energy, when the propulsion system is not using it. The all electric war ship will have increased complexity of power system and needs high-end automation to act fast enough with operational situations. Accuracy of sensor measurements is an important parameter of consideration to ensure reliability and survivability of the system. Uncertainty present in the data is the limiting factor of the accuracy of shipboard operations. Any analysis or operational decision taken by the operator depends on the data measured at the component level of the power system. Any uncertainty present at the meter readings will result in unwanted or faulty operations. So it is very important to plan accordingly by better understanding the uncertainty present in meter data. In this research work we focused on dealing with the uncertainty present in meter data. Results of the findings are tested on a reconfiguration algorithm developed for shipboard power systems.

Additionally with the goal of high end automation and reducing the personnel on the ship, we need to design the best Human Computer Interaction (HCI) system to support monitoring, control and operational tasks. When humans collaborate with technology to accomplish tasks, the human system interface must be designed to support optimal system performance. Navy operational environments require processing of power system information from sailors, and real time power system reconfiguration through use of human systems. Developing design principles for human systems that facilitate sailor power systems management has direct relevance to the Navy.

Design of human systems interfaces that support optimal performance requires consideration of -

1) Capabilities and limitations of technology and humans,

2) Task constraints, operational system performance constraints, and

3) How interface design features interact with 1) to impact performance.

Another purpose of this research is to directly examine the impact of Decision Support Systems (DSS) on the quality of real time power system reconfigurations made using a human system interface for the optimum performance of human.

1.2 Thesis objective

Towards the goal of developing better systems which can support the overarching outcome of an all-electric warship, objectives for this research work are:

- Develop a model which can deal with uncertainty present in meter data

- Integrating an uncertainty model with a genetic algorithm based reconfiguration algorithm to refine the reconfiguration recommendations
- Examine the effect of DSS on the quality of reconfiguration decisions taken by the sailors
- Performing usability studies on power system reconfiguration user interface to identify niche improvements in the interface.

1.3 Thesis organization

Organization of thesis chapters is presented in this section to provide an overview of presented topics in this work. The second chapter consists of background and literature review related to power system reconfiguration, uncertainty, HCI and their related topics. Tools used for this work are also briefly outlined in this chapter. Chapter 3 explains the motivation behind human system interface work and approach chosen to reach the objectives. Interface designs, DSS, experimental setup, and usability studies are discussed in the context of the work. Chapter 4 presents the motivation behind the power systems engineering work and the approach chosen to achieve these objectives is explained. Fuzzy evaluation of meters, a genetic algorithm based reconfiguration technique, and 8 bus and 13 bus shipboard power system test cases are discussed as a part of the approach. Chapters 5 and 6 present the results on human system interaction and power system engineering respectively. Discussions and analysis were presented on the basis of results obtained. Chapter 7 concludes the research work and suggests future work on the topic.

CHAPTER 2

BACKGROUND AND LITERATURE REVIEW

2.1 Introduction

This chapter gives a brief discussion and background of important topics related to the thesis subject. Basics of Human Computer Interaction, Decision Support System, usability studies, and cognitive walk through studies are explained in relevance to the research work with the help of reviewed literature. Causes of uncertainty, effect of uncertainty on power systems, methods to deal with uncertainty are explained with the help of reviewed literature. Power system reconfiguration, in general, and in particular related to shipboard power system is explained. Tools used in the research work are also introduced in this chapter.

2.2 Human computer interaction

Human Computer Interaction (HCI) is a study of how people interact with computers and to improve computers/interfaces for successful interaction with humans [2]. It is a multidisciplinary concept involving several fields like, computer science, cognitive psychology, neuroscience, human factors, engineering, design, philosophy, artificial intelligence, and sociology. Basic goal of HCI is to improve the interaction between humans and computers by making interface more user friendly. Design of any interface is a complex task and developed interface should be capable of interacting with humans for optimal performance. Several methods were present in the literature for the design of interface. Two important methods that are in relevance to current work are User Centered Design (UCD) and rapid prototyping. UCD is a design philosophy that gives extensive importance to human/user needs, wants and limitations in each step of interface design. The main difference between conventional design philosophies to UCD is that conventional methods force users to change according to the developed interface where as UCD allows users to optimize their performance by designing the interface around how users can, and want to work. A work product based UCD methodology is a best practice because the ultimate focus is on tangible outputs and successful outcomes rather than on process and activity [3].

To build an effective interface, it should undergo a series of tests by its intended users. Building of real interface for the purpose of testing a design is very costly and demands a large amount of time and effort. To deal with this problem, designers can make use of rapid prototype models [4]. User interface prototype is a simulation of a user interface for a system or application with which a user can interact [5]. In rapid prototyping interface prototypes were developed which can be modified easily as per the feedback received from testing of the prototype.

A general procedure for design, development and testing of rapid prototype is listed below.

1) Create the prototype design based on interface design and use.
2) Assemble the necessary equipment to make the prototype interactive.
3) Develop the prototype.

4) Select the users to test the prototype. User selection is very important and feedback received to modify the interface depends on them. Generally users should those who intend to use the interface.
5) Create tasks for users that need to be done by interacting with interface prototype.
6) Form the evaluation procedure and make sure that prototype can be used to solve the tasks created.
7) Make arrangements to record user actions.
8) Conduct the experiment with users on prototype and record their actions.
9) If necessary interview the users for their opinion on the interface prototype.
10) Analyze user data to identify problems with interface.
11) Suggest the design modifications to design team to solve the identified problems.
12) If necessary refine the prototype and conduct the experiment again.

2.2.1 Cognitive engineering

Cognitive engineering applies knowledge of cognitive psychology to the design and development of systems that support the cognitive process of users. Fig 2.1 shows the human information processing for better understanding of how cognitive resources are utilized for HCI.

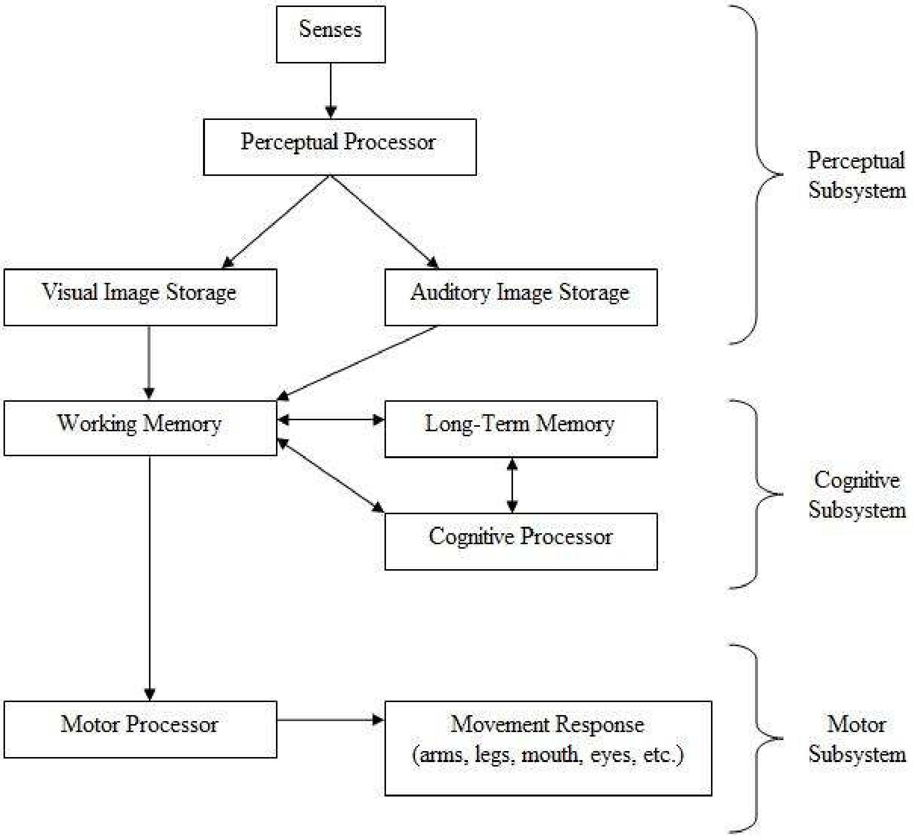


Figure 2.1 Human information processing [6]

2.2.2 Decision support system

DSS is a computerized aid, model or information system that supports the decision making process for users. Many DSS researchers acknowledged the importance of decision aiding for users taking decisions in complex and dynamic environment [7]. Decisions are embedded in task cycles that include problem definition, visualizing a reasonable solution, taking actions to reach the goal and evaluating the effects of that action [8]. A DSS should be designed so as to capitalize individual's strengths and compensate for their inherent weaknesses [9]. A well designed DSS shall be an interactive system helps in taking decisions by compiling or comprehending the useful information from raw data, personal knowledge, models, and documents. Fig 2.2 shows the top level architecture of DSS. The model in the architecture manipulates data to create a meaningful inference specific to the situation.

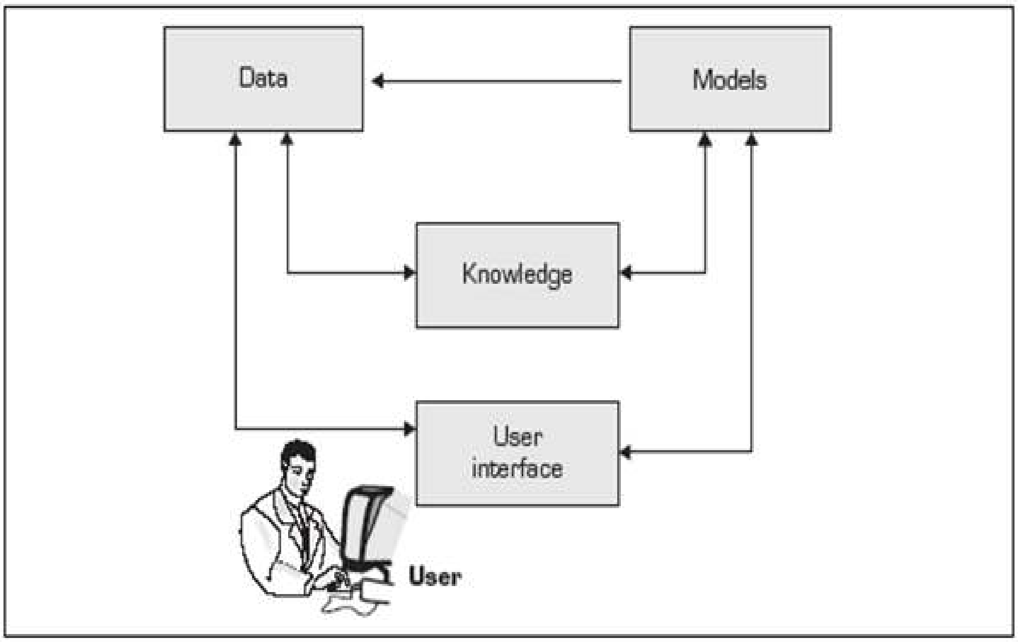


Figure 2.2 Architecture of decision support system

2.2.3 Decision support system

Usability testing is a method of evaluating a product by testing it on users. It is a systematic evaluation under controlled conditions [10]. In usability testing there are two types of data that can be collected from users.

- Performance data: This data represents what actually happened. It includes the responses given by the user or the data stored in the system while they are interacting with interface. Effectiveness and efficiency of the product can be measured by capturing data on task completion rate, completion time, navigation path towards the goal and selection of action to accomplish the goal

- Preference data: This is the data about what users thought while solving or to solve the tasks. By capturing the data like, whether users enjoy working with product, whether users are confused or frustrated with product, whether users prefer one design upon other design etc., user's satisfaction on that particular design can be found.

2.2.4 Cognitive walkthrough

Based on cognitive model (CE+ model), exploratory learning contains a problem-solving component, a learning component and an execution component [11]. The problem solving component says that user will choose among alternative actions based on the relativity between the user's expectation of the consequence of an action and the user's current goal. After, the selected option has been processed; the user checks the response given by the system and makes a decision as to whether or not progress is being made toward the goal. If a mismatch is detected, the user will attempt to do 'undo' the just taken action. User learns from the action taken, if it leads a positive response. Previous action will be stored in the form of a rule. The execution component of CE+ models the user by first attempting to fire an applicable rule that matches with the current context. If none is found, the problem solving component described above is invoked and the model attempts to discover an action that leads to a positive evaluation of progress. Now based on these guidelines a cognitive walkthrough procedure was developed. It is a theoretically structured evaluation process that takes the form of a list of questions.

"Cognitive walkthrough" was defined as the procedure for systematically evaluating features of an interface in the context of theory [12].

The use of cognitive models in Human Computer Interaction in design and applying them to practical problems is very difficult. In cognitive walkthrough method, list of theoretically motivated questions pertaining to user interface are framed by using the theory of exploratory learning proposed by Lewis and Polson [13]. All the questions focus on the interface between users and computer in performing specified task. Questions with positive responses indicate the steps that can be learned easily in the interface and questions with negative response indicate the steps that are difficult to learn in the interface. Using these steps, potential source of problems in interaction can be identified early in the design.

2.2.5 Tools

Tools that were used in design of the interface prototypes for this research are Adobe-Authorware, Power world simulator, and Visual Basic. An unaided interface prototype was developed by using Powerworld and Visual Basic script and the Aided interface was developed using Adobe-Authorware.

2.2.5.1 Adobe-Authorware

Authorware is an interpreted flowchart based graphical programming language and this can be used to create user interactive programs [14]. The Authorware program starts with a flow line and it indicates how the program navigates the user from starting to ending. In Authorware, a program can be constructed by arranging the icons in a logical flow and this determines the flow of the program. Software is capable of navigating the user through different modules or pages and can record the data of user actions in a controlled manner. This makes this product more useful for experiments that need to analyze user actions. The latest version available in Authorware is Authorware 7.0.2. Adobe announced the end of future developments to Authorware. Fig 2.3 shows the screen shot of the Authorware program developed for the aided interface prototype.

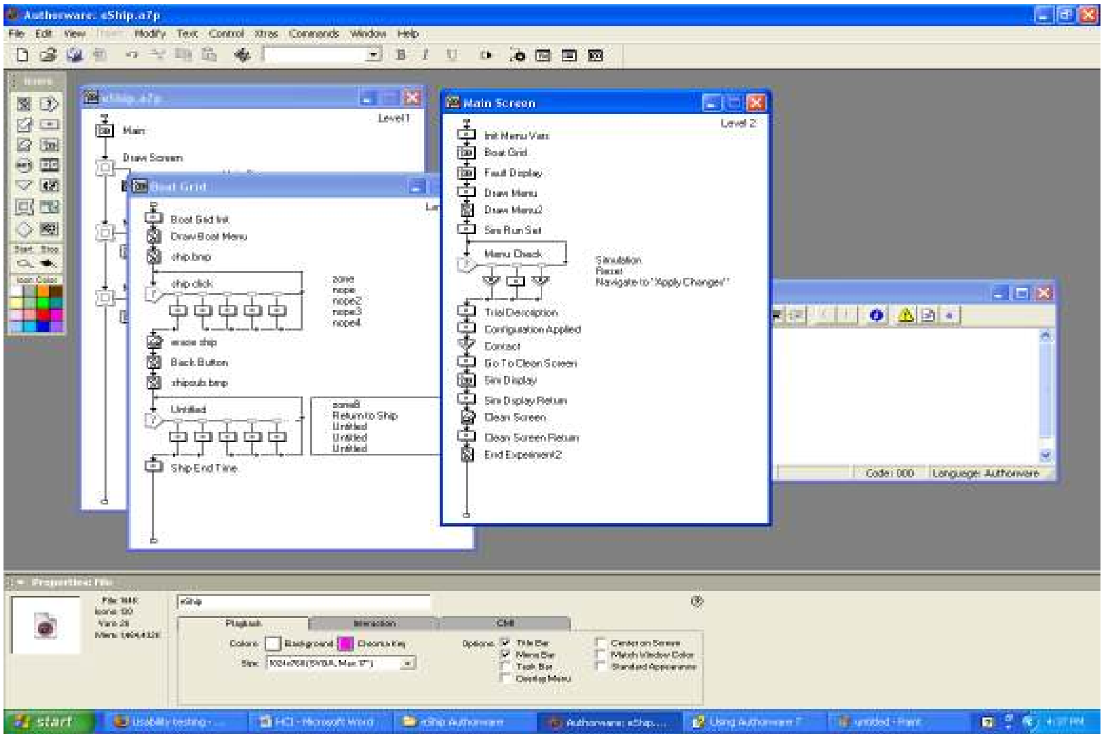


Figure 2.3 Screenshot of Authorware program window

2.2.5.2 Powerworld

Powerworld is a simulation tool used for analysis and visualization of power system. The Powerworld simulator allows the user to run a wide variety of simulations on complex power system networks. Some of them include optimal power flow, security constrained optimal power flow, ATC calculations, and transmission line parameter calculations [15]. Powerworld allows users to build their system in it and performs different analysis tasks. Powerworld has two distinct modes of operation 'edit' mode and 'run' mode. In Edit mode, the user can create or modify the system. In run mode software allows only simulation of the built system and user cannot modify the system architecture. However, one can change the status of circuit breakers and ratings of any of the power system components dynamically in 'run' mode. Powerworld implements these changes in the next simulation iteration. Fig 2.4 shows the shipboard power system built for one of the user tasks.

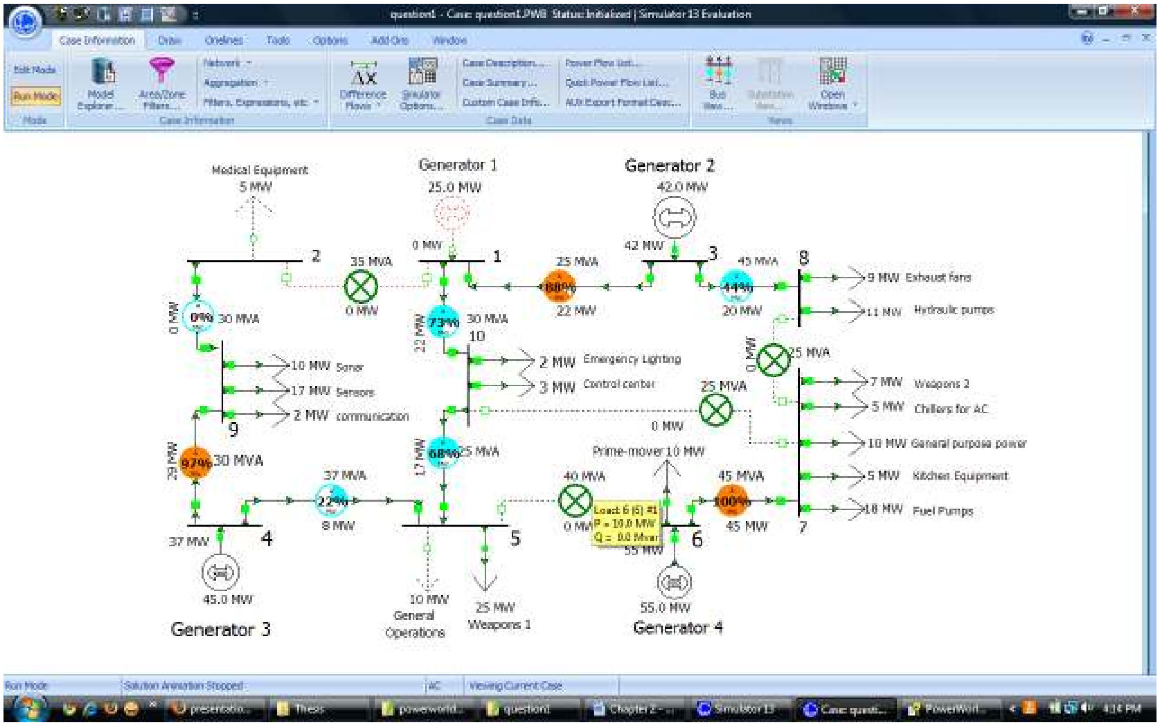


Figure 2.4 Screenshot of Powerworld simulator in 'Run' mode

2.3 Power system engineering

2.3.1 Uncertainty

Uncertainty is a term used in wide variety of contexts. In general this is used to represent the vagueness or inexactness of any particular attribute. For example let us say if "we don't know the type of the food at tomorrow's party", then this situation can be called as uncertain. However this uncertainty can be quantified with some probability or by using some other mathematical technique. There are different types of uncertainty [16] based on the state of operation. These are:

Measurement uncertainty: it is the result of errors in measured values.

Process uncertainty: It is due to randomness in dynamic systems.

Model uncertainty: It is due to approximations or negligence of parameters.

Estimate uncertainty: It is the one that appears due to uncertainties in its dependencies

Implementation uncertainty: It is due to the failure in reaching the exact strategic objective.

Measurement uncertainty can be defined as "A parameter associated with the result of a measurement that characterizes the dispersion of the values that could reasonably be attributed to the measurand" [16]. Measurement of a variable is influenced by many elemental error sources. These errors are due to:

- errors in standardization or calibration process,
- variations in ambient conditions,
- Dynamic changes in the steady of steady state phenomena,

- undesired interaction of the equipment with environment, and
- Imperfect installations.

Fig. 2.5 shows the measurement system making N measurements and having six elemental error sources. The output of measurement system measurand X depends on all the elemental sources and true value of the measurand.

$X_{measured}=X_{true}+E1+E2+E3+E4+E5+E6$

E1, E2, E3, E4, E5, and E6 changes for every individual measurement

$X_{measured} = X_{true} \pm u_x$

Where u_x is the uncertainty in measurement X

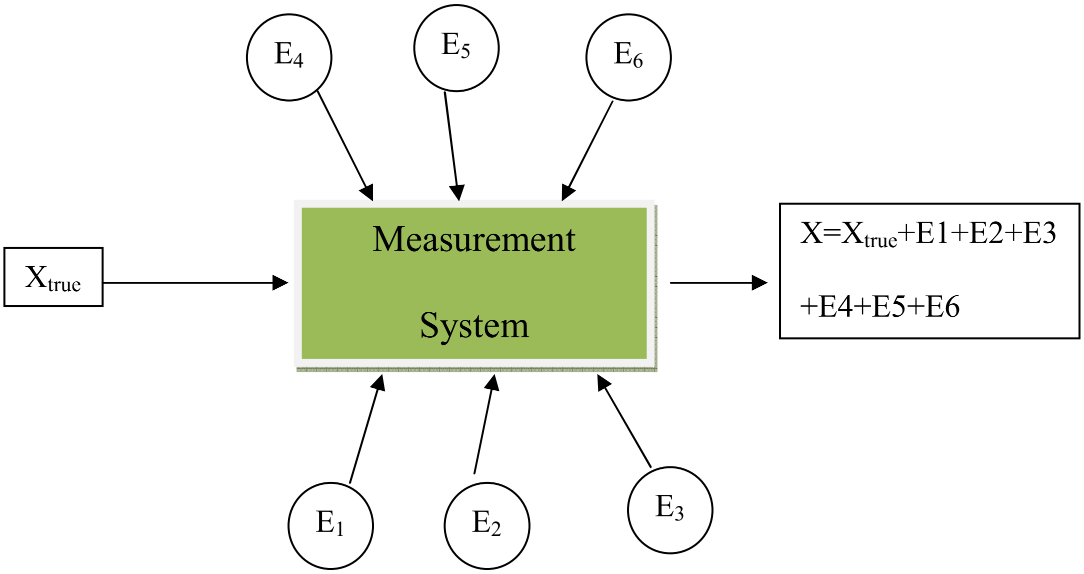


Figure 2.5 Measurement system with elemental error sources

If we have a confidence of C% to say that true value of X lies within the interval $X_{best} \pm u_x$, then it is called as expanded uncertainty U_X. For example, if we are 99%

confident that the estimate of X lies between $X_{best} \pm U_{X,}$ then about 99 times out of 100, X_{true} would be in that interval [16].

2.3.1.1 Uncertainty in power systems

The uncertainty analysis in power systems is a well known research problem and the literature present is extensive [17]-[20]. Uncertainty in power system operation can be caused due to uncertainty in meter data or due to parameter uncertainty i.e. due to aging, temperature, or operating conditions. For operational security and better planning it is very important to analyze uncertainties in power system and develop methods to mitigate their effect on the system. Operation parameters of power system models are seldom known exactly. It is obvious that the analysis methods that are based on these models produce inexact results. In power system operation and control it is very important to know exact values of load data. Many researchers recognized the importance of load characteristics on dynamic properties of power systems [21]-[24]. The Tokyo power system collapse in 1987 was partially attributed to improper estimation of load demand [25].

Literature on uncertainty presents different ways of dealing with uncertainty. Methods include techniques from mathematical, heuristic, intelligent techniques, probability, index based, and Monte-Carlo methods. Traditionally the Monte-Carlo method was used to solve problems associated with uncertainty. But it requires simulation parameters for every randomly generated set. Doing this is time consuming and causes computational challenges.

Papers [26]-[27] explained the mathematical model of trajectory sensitivities method to estimate uncertain models of the power system. Uncertainty due to a disturbance was addressed in [28] [29]. Uncertainty in power system parameters was explained in [30] and was estimated by deriving the relation between output and uncertain parameters. Other papers explaining the parameter uncertainty included [31]-[34]. Probabilistic based analysis of uncertainty is very popular and most of the research work has been done in many fields on probabilistic methods in dealing with uncertainty. In recent times focus has been shifted to intelligent based techniques due to their capabilities. In the present study, a fuzzy logic based technique is used to model the uncertainty present in meter data. In the fuzzy system it is very easy to represent vague data and linguistic expressions in a fuzzy variable form. Apart from this, fuzzy logic can be applied independent of system, and can provide solutions to non linear problems.

2.3.2 Fuzzy logic systems

Fuzzy sets were introduced by Zadeh in 1965 to represent the data with vagueness. A fuzzy set is defined as a set containing elements that have varying degree of membership in set. This explanation is different from crisp set. In crisp sets, members of crisp set would not become members unless their membership becomes full or 1.

Say, **X** represents a fundamental set and x are the elements of fundamental set, then the set

$$\tilde{A} = \left\{ (x, \mu_A(x)) \mid x \in \mathbf{X} \right\}$$

is referred to as the uncertain set or fuzzy set (A) on X. $\mu_A(X)$ is called as membership function of fuzzy set. Below fig. 2.6 shows the comparison of fuzzy set representation with crisp set representation.

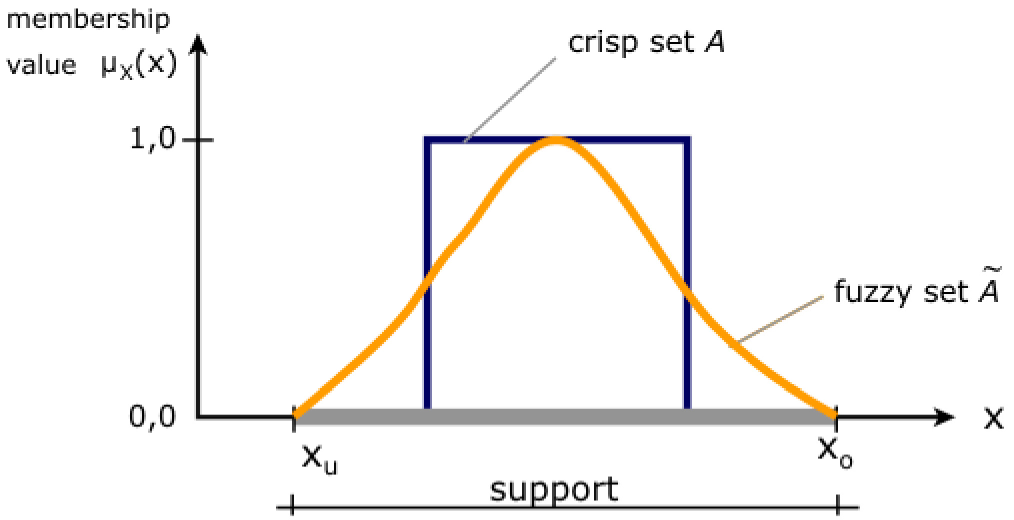


Figure 2.6 Fuzzy membership function Vs crisp membership function

Fuzzy logic is about reasoning which is approximate rather than exact. Fuzzy set and fuzzy logic are the base for fuzzy systems. Operations like union, intersection, and complement can also be performed with fuzzy sets as they were in crisp sets. Membership function μ(x) of a fuzzy variable defines the relationship to express the distribution of truth of a variable. In any fuzzy logic system, it consists of fuzzifier, inference engine, If-Then rules, and defuzzifier. Fig 2.7 shows the basic working of fuzzy logic system. Fuzzifier is responsible in converting the crisp inputs in to fuzzy variables. A knowledge base consists of If-Then rules specifying the relationship between input fuzzy variables to fuzzy outputs. A fuzzy inference system is a reasoning process which activates the fuzzy rules relevant to the inputs. Defuzzifier converts the set of fuzzy inputs into a single crisp value based on the type of defuzzifier used.

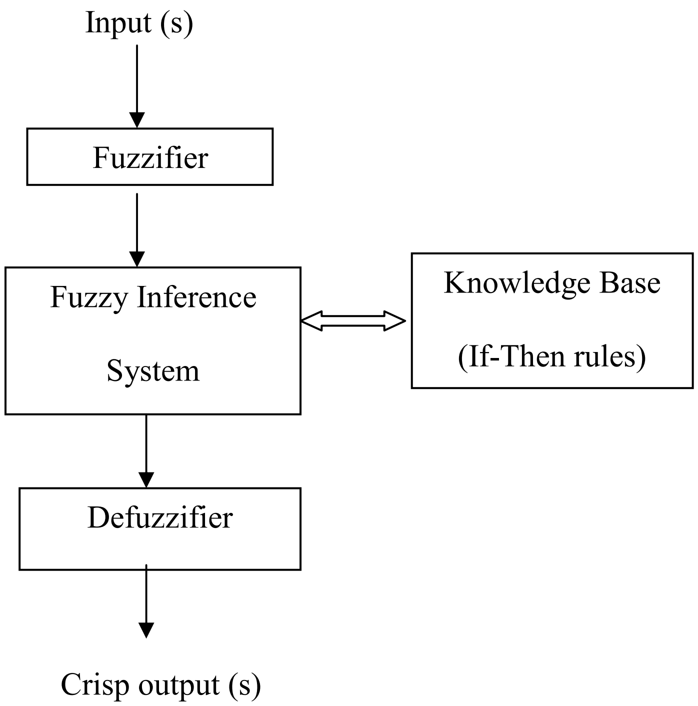


Figure 2.7 Different components in fuzzy logic system

Linguistic expressions can be formed as fuzzy rules by arranging them in a form of "If-Then". An example fuzzy rule is

If (Weight is Medium) AND (Height is High) Then (Person is Athletic)

This rule is a self explanatory. These fuzzy rules are very important because all the outputs are the results of these rules. One should be careful in forming the rules for accurate results.

Several de-fuzzification methods were explained in the literature [35]. They are:

- *Max-membership principle*: In this method a value which forms the peak of the function is selected as the output. This method is limited to peaked functions.
- *Centroid method*: This method is proposed by Sugeno and it is the most popularly used de-fuzzification method. In this method a center of the area is considered as the output.
- *Weighted average*: As the name suggests it weights the maximum of each membership function and produces the average of those values. This method is used only for symmetrical membership functions.
- *Mean-Max membership*: This method is also called middle of the maxima. This selects the middle value of the maxima of the membership functions [36].

We used the centroid method of de-fuzzification in this work.

2.3.3 Shipboard power system

A Shipboard Power System (SPS) is a complex three-phase AC network. One of the SPS examples is shown in fig. 2.8. It consists of two main generators and two auxiliary generators generating AC power. Distribution system can be a combination of AC and DC. The shipboard power system consists of all latest technologies embedded to make them more reliable, flexible, survivable, low weight and robust. In this thesis work, we considered the AC system. The shipboard power system is different to terrestrial power system. Below are the few differences apart from operational diversity:

- Small sized compared to terrestrial systems.
- Generators are closely sized to load requirement.
- Cable lengths for distribution or transmission are small, therefore impedance is small.
- Severities of the faults are high.
- Failure of any generator will pose serious challenges as it makes load greater than generation.
- Consists of non linear and pulsed loads.

Due to these differences and operational cause, shipboard power systems demand fast isolation of the fault and reconfiguration of the power system to support ship's ongoing operations.

An integrated Power System (IPS) model was proposed by US Navy for current ship developments. Office of Naval Research (ONR) and Electric Ship Research and Development

Consortium (ESRDC) suggested considering the DD(X) model as the base model for IPS model. Fig 2.8 shows the DD(X) model of SPS. This model consists of two main turbine generators (MTG) rated 36MW each and two auxiliary turbine generators (ATG) rated 4MW each, two propulsion motors of 36.5MW each, and two auxiliary power units of 0.5MW each. The MTGs provide power to the propulsion system and two small gas turbines provide power to ship service loads.

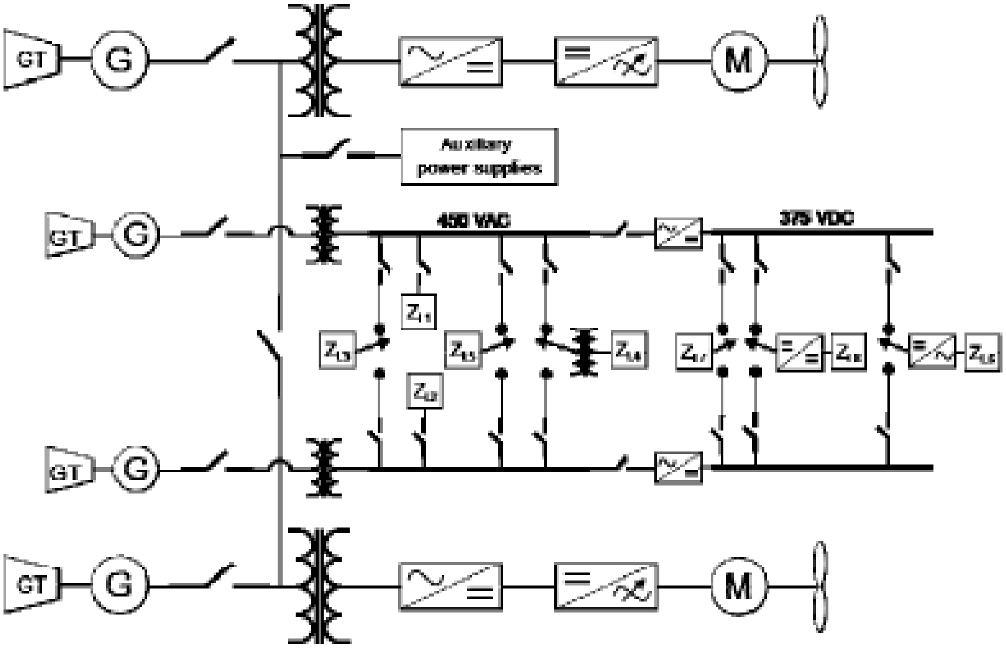


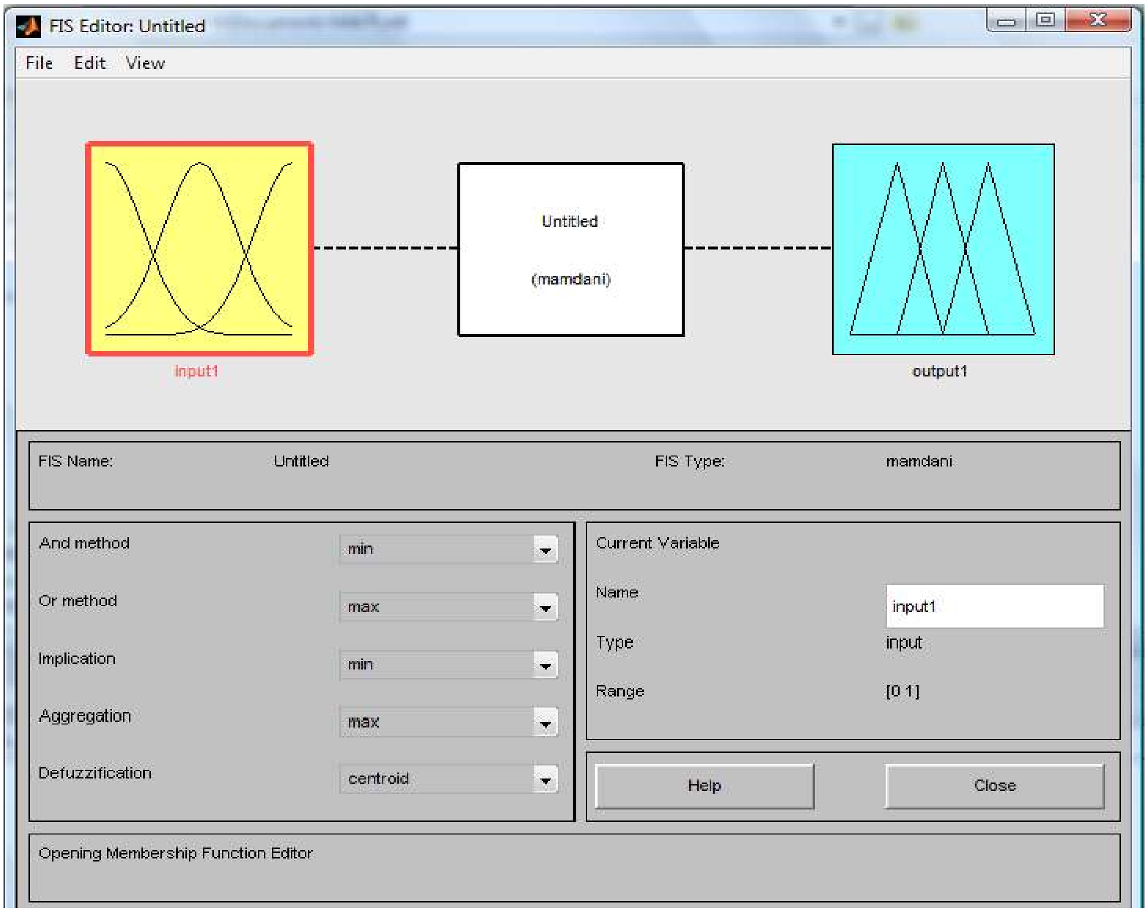
Figure 2.8   DD(X) shipboard integrated power system (IPS) model [37]

2.3.4 Reconfiguration (Restoration)

Reconfiguration of power system can be defined as “after fault isolation of a power system reconfiguration is to restore power to unaffected zones of the power system based on certain objective function” [38]. Faults in the ship may be cause due to the damage by the attack or due to material causalities. Faults may happen to generators, cables, equipments, or distribution buses .In this system a fault on generator can be considered very severe and may lead entire system collapse due to the imbalance of load generation ratio. The objective functions for reconfiguration may vary based on the operational goals of the power system. They can be to reduce losses in the system, to restore the loads based on their priority or to operate the power system more economically [39] [40] [41]. In a shipboard power system it is very important to feed critical loads under all conditions. In this thesis work, we considered reconfiguration in the context of ensuring supply to loads based on their priority and weight factors associated with them. Several methods were present in the literature for the reconfiguration of shipboard power system. Butler etc all introduced intelligent techniques for the reconfiguration of shipboard power systems in [42]. Heuristic based approach [41], network flow approach [43], knowledge model approach [44], genetic algorithm based [45], and fuzzy are some of the techniques presented in the literature. In knowledge based approach, model needs rules to operate up on a system and creating rules for every system separately makes it a difficult process. Though network flow approach was simple, it doesn't take care of priorities of the load. In most of the literature work, researchers did not consider the effect of uncertainty in meter data or neglected the presence of uncertainty. However, uncertainty exists in the system and needs to be considered for a better reliable and robust system. In this work, we considered a genetic algorithm based [46] reconfiguration techniques in conjunction with a fuzzy logic system. Review of [46] will provide all necessary background required for understating of "the genetic algorithm based reconfiguration techniques" used in this work.

2.3.4.1 Tools – Matlab fuzzy logic tool box

We used MATLAB's fuzzy Graphical User Interface (FGUI) to build a fuzzy correction system to deal with uncertainty in meter data. It consists of FIS Editor, which enables the user to build his/her fuzzy inference system. Fig. 2.9 shows the typical FIS editor. It lets the researcher define fuzzy sets, fuzzy rules, and operations of fuzzy sets based on fuzzy rules. FIS fires rules on each fuzzy input set to determine fuzzy outputs. Based on de-fuzzification method selected, a crisp output will be generated by FIS [47].



FIS Name: Untitled

FIS Type: mamdani

And method: min

Or method: max

Implication: min

Aggregation: max

Defuzzification: centroid

Current Variable

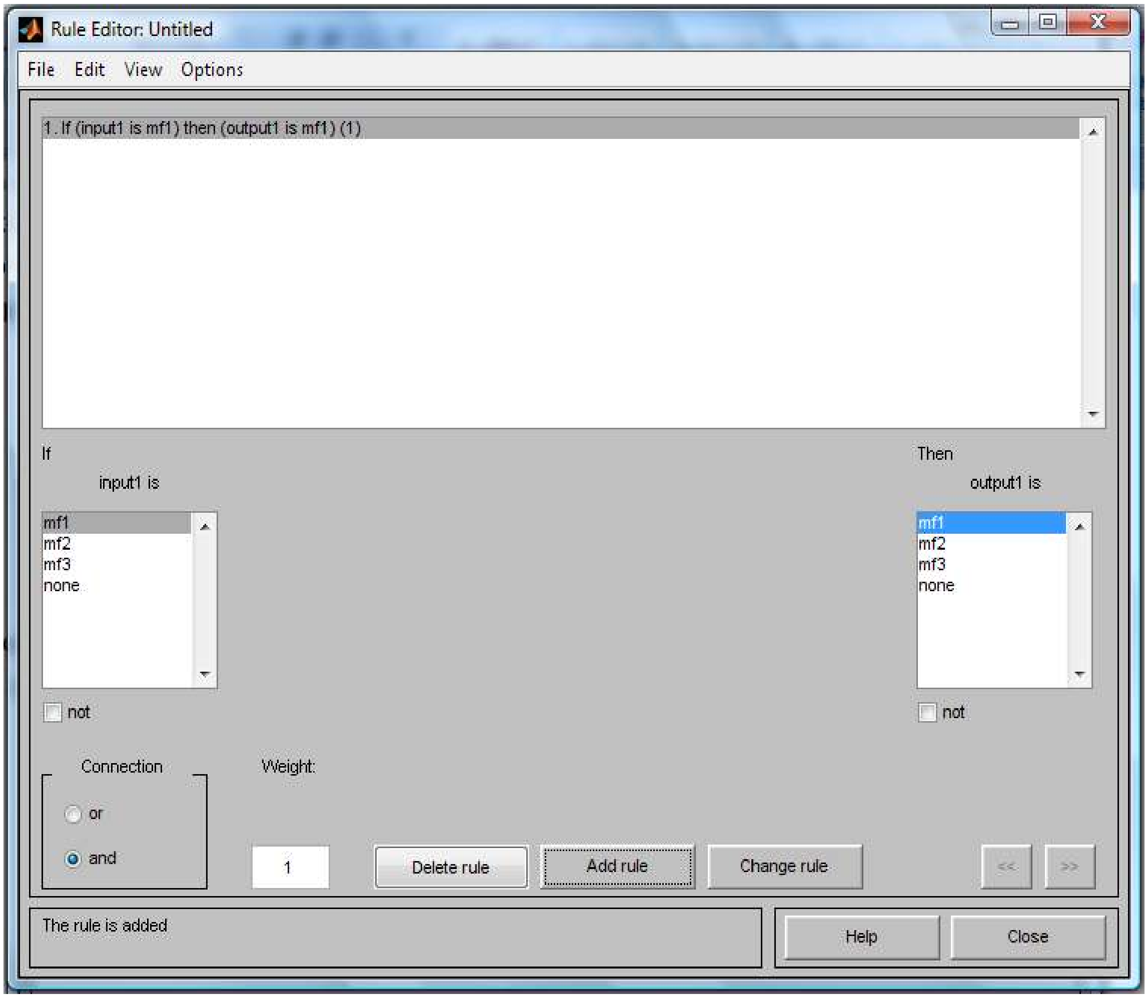
Name: input1

Type: input

Range: [0 1]

Opening Membership Function Editor

Figure 2.9 MATLAB fuzzy inference system: editor



```
1. If (input1 is mf1) then (output1 is mf1) (1)
```

Weight: 1

```
The rule is added
```

Figure 2.10 MATLAB fuzzy GUI: fuzzy rule editor

2.4 Summary

This chapter introduced all the basics and background information necessary for the thesis work. Literature was reviewed for previous work on Decision Support System (DSS) in Human Computer Interaction (HCI), different usability studies, uncertainty and reconfiguration in shipboard power system. All tools used in this work are also introduced.

CHAPTER 3

PROBLEM STATEMENT AND SOLUTION APPROACH FOR HUMAN SYSTEMS INTERACTION

3.1 Introduction

This chapter explains the motivation behind the development of the Decision Support System (DSS) for an operator making decisions in a complex and dynamic environment with the help of HCI. This chapter also explains the approach chosen for the design, development and analysis of the Human Computer Interaction in ship board power systems.

3.2 Motivation

Design of an all-electric warship poses unprecedented levels of system complexity and operational diversity including the need for robustness to damage through control and dynamic reconfiguration. It also minimizes the manpower required to serve in the ship by making use of latest technologies and automation to a greater extent. Because of this the operational tasks for individual become more critical. So, the human systems interface must be designed to support optimal system performance. The design of the Decision Support System intended for aiding the system operator in making complex decisions is an important task with the Human Computer Interaction. Part of this research work is focused on quantitative cognitive engineering of a decision support system (DSS) designed to augment the quality of real-time reconfiguration decisions made by human operators in managing the power system. The DSS is an integral component of graphical human interface that allows users to monitor power system status. The interface enables use of the DSS to run simulations that calculate the impact of alternative reconfiguration decisions on system performance, with the goal of optimizing the speed and quality of operator reconfigurations.

3.3 Approach

This research approach includes rapid prototyping of the human systems interface with and without DSS and performing usability studies that allow quantitative measurement of human systems performance for both kinds of interfaces. Usability studies use the cognitive walkthrough methodology developed by Lewis et al., [12] to quantify the user's ability to accomplish goals using the interface. Decision quality analysis will quantify differences between optimal and user reconfigurations and the time required to complete reconfigurations in supported and non-supported conditions. Based on the usability studies, design recommendations were made for an aided interface for optimal operation of the interface.

3.4 Interface design

In the effort focused on decision support for real time power system reconfiguration, an unaided and aided human systems interface were developed to enable quantitative measurement of reconfiguration decisions by experimental subjects. These interfaces should be capable of interacting with humans in solving reconfiguration problems and should be able to record users' responses to the problems. The unaided interface, as the name suggests will not be providing decision support system which can help the user in making decisions. In contrast, the aided interface will have a built-in decision support system. The interfaces were not time restricted; users can spend any amount of time in solving the problem. However the time taken to complete the task was noted for each problem.

3.4.1 Unaided interface

The prototype of unaided interface was designed with the help of Powerworld and Visual Basic. Powerworld is an efficient and powerful tool in analysis and visualization of power system network. So we used Powerworld to showcse the power system network along with power flows and faults. It can also respond to dynamic changes in the power system. Since Powerworld itself cannot track the user actions and save the users responses, a Visual Basic program intended to store users actions was also run along with Powerworld. Users were restricted to access any of the Powerworld tools, so that there won't be any chance for users in changing any of the power system parameters. A screenshot of the unaided interface can be seen in fig. 3.1. In the figure, the part showing the ship board power system was running in power world.

The part shown in blue color with 'Save' and 'Reset' buttons was programmed in Visual Basic. This serves two purposes, one to hide the Powerworld tools from the user and to save or reset the power system. Users can click on the circuit breakers to reconfigure the power system. The save button saves the configuration on the screen as the user's response to the problem. The Reset button will take back the user to original system so that he/she can start again.

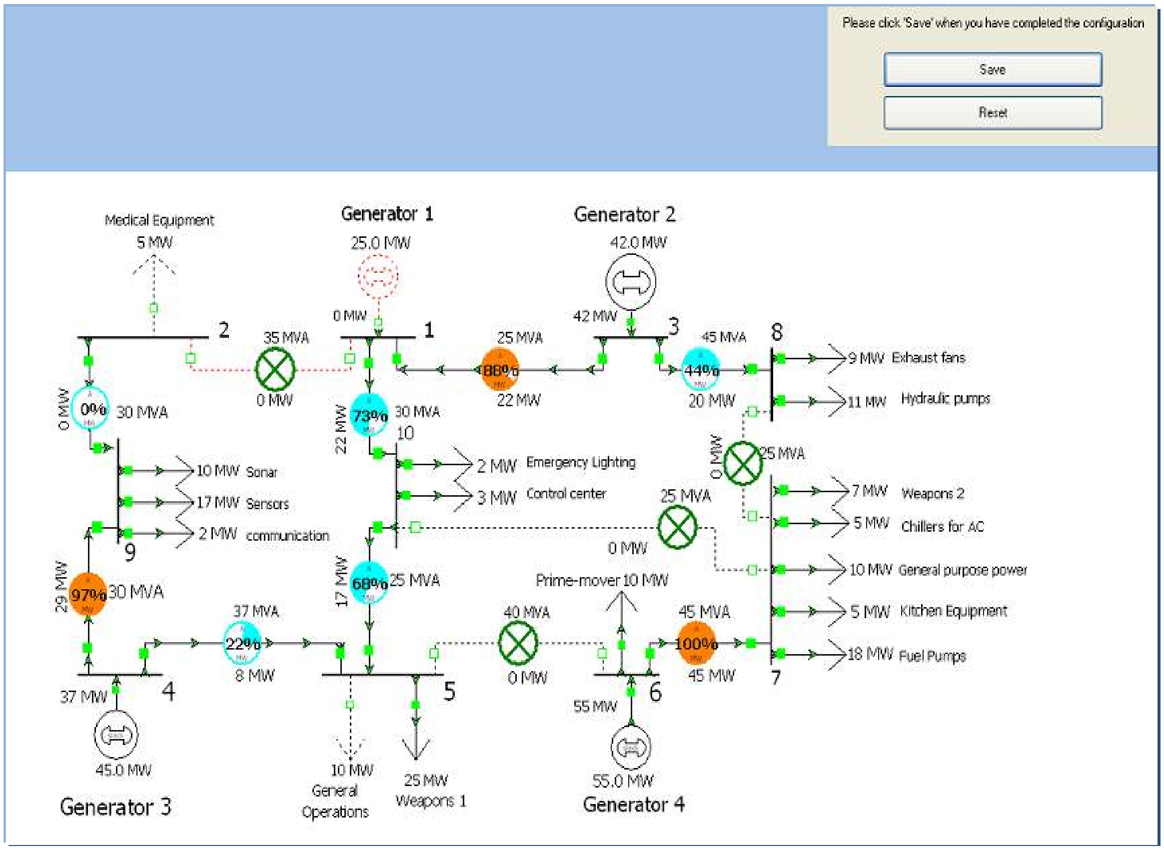
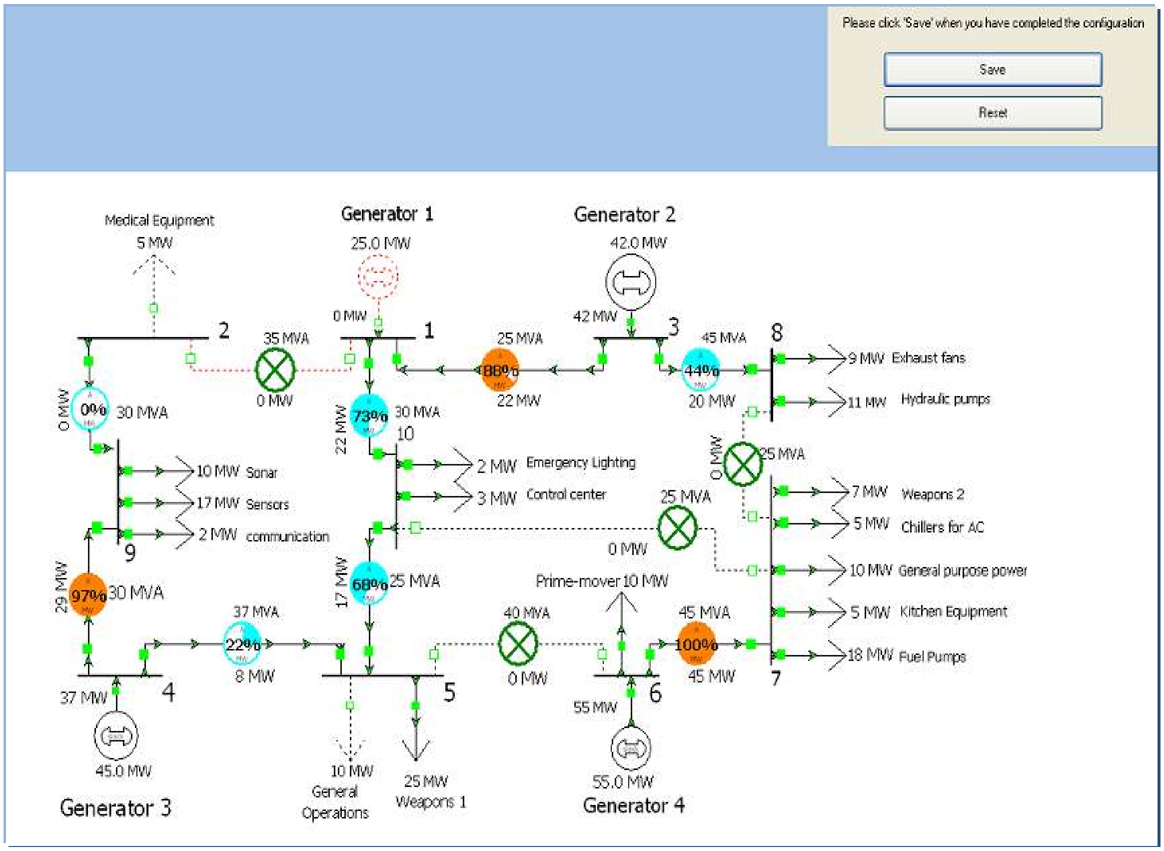

Please click 'Save' when you have completed the configuration

Figure 3.1 Un-aided interface

3.4.2 Aided interface

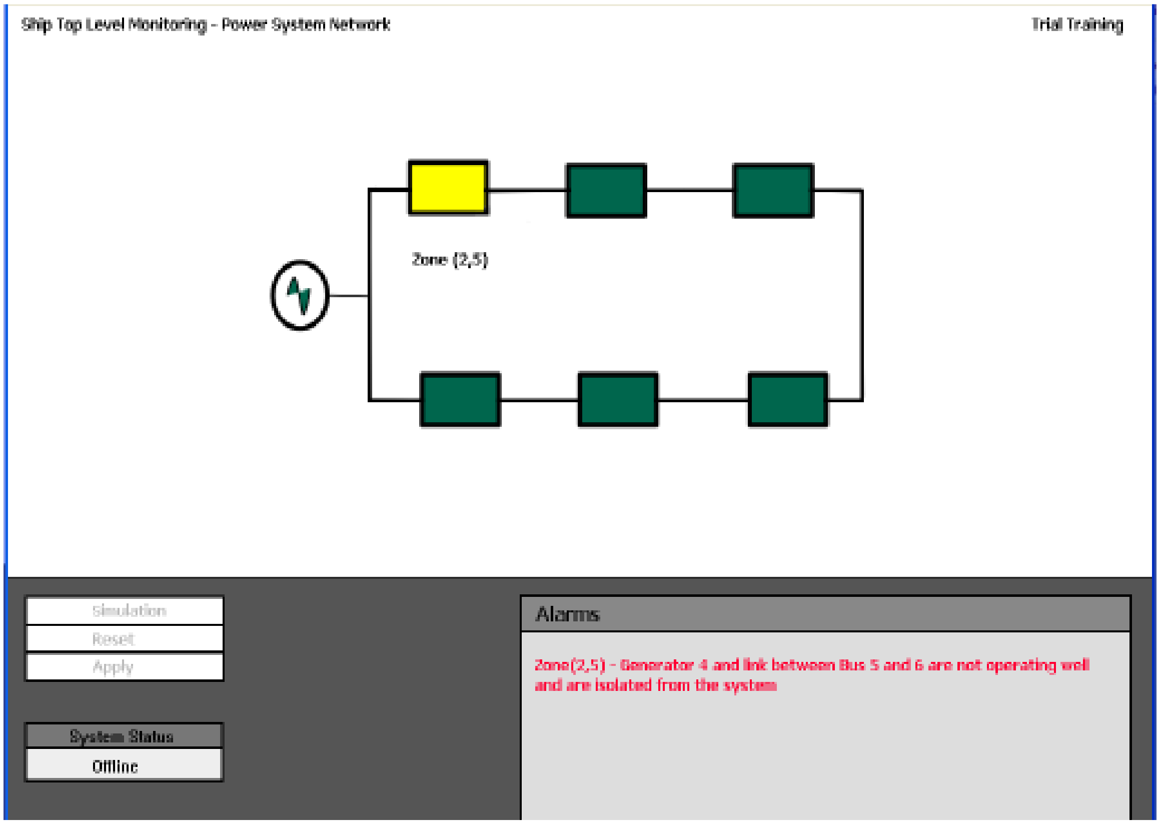
The prototype of aided interface was developed using Authorware. The Aided interface was a three level interface showing from top level monitoring of the ship down to ship's component level. Fig. 3.2 shows the first level of interaction with the operator. This shows the top level monitoring of the ship. For the flexibility in operation and to identify different parts in ship, it was divided into 5x8=40 zones. If any problem occurs in any part of the ship, the zone representing that area changes its color from normal (green) to either yellow or red based on the severity of the fault. All the zones shown on the ship are active. By clicking any particular zone will take the operator to the next visual level of the ship. For example by clicking on the alarmed zone (2, 5), the interface will take the operator to next lower level of ship to deal with the fault. The alarms window shows the messages representing the problems in the ship. Simulation, Reset and Apply buttons are inactive because they are the operations associated with the component level of ship monitoring.



Please click 'Save' when you have completed the configuration

Figure 3.2 Aided interface - first level

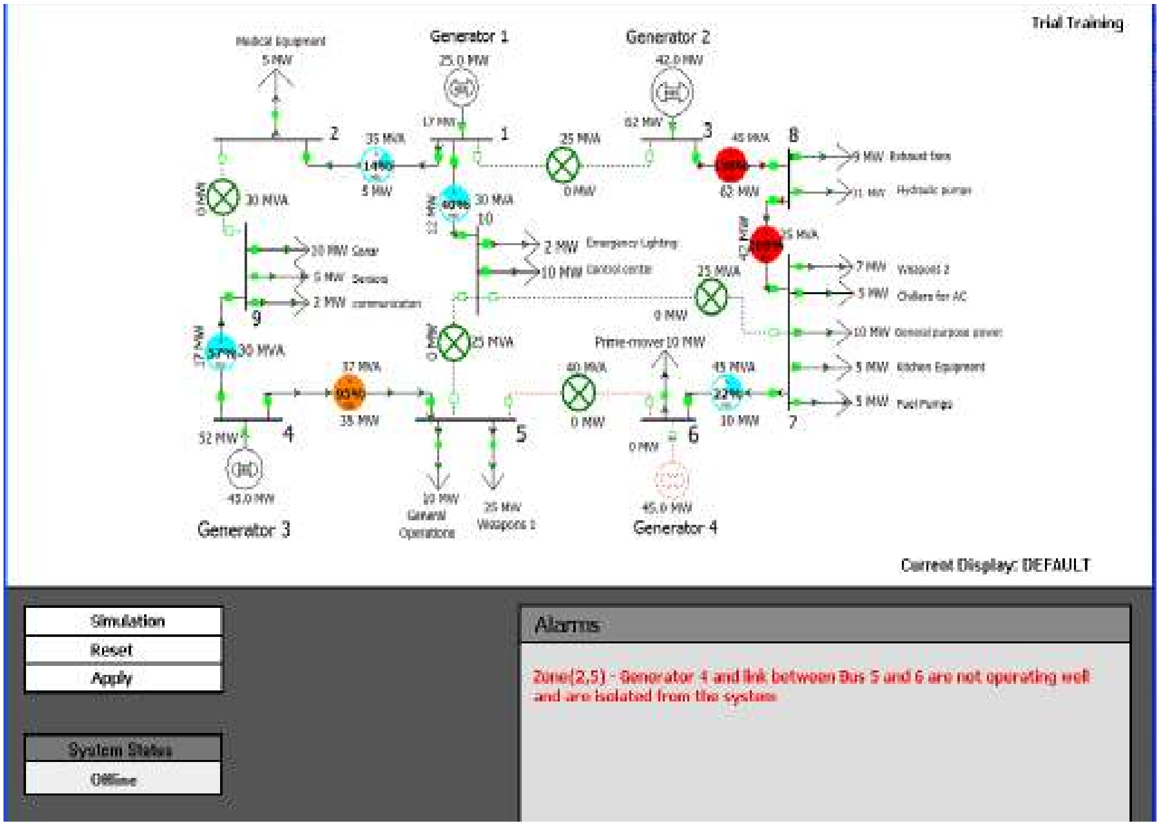
Fig. 3.3 shows the second level of ship monitoring. The screen shot shown in the fig. 3.3 is a result of clicking on the zone (2, 5) in the first level of ship monitoring fig. 3.2. Since the problem occurred in the zone (2, 5) was due to the fault in power systems network, the second level of interface shows the top level view of power system. Like the first level of monitoring, here also users can click on any zone to navigate to that particular area to look into the problem.



Zone(2,5) - Generator 4 and link between Bus 5 and 6 are not operating well and are isolated from the system

Figure 3.3 Aided interface - second level

For example assume that we clicked on zone (2, 5) to monitor the root cause of the alarm given. That results in component level view of the power system. Fig 3.4 shows the third level of ship monitoring. The circuit breakers were not active as they were in unaided interface i.e. users cannot click on any circuit breakers to toggle their status. In this level each power system component in the ship and their connections can be seen. Problems that need component level attention should be identified and solved in this level. The affected areas are shown in red color. From the fig 3.4 we can see the Generator 4, line connecting Bus5 and Bus6, link between Bus 3 and Bus 8 and link between Bus 7 and Bus 8 are shown in red color. Also, the Generator 4 and line between Bus 5 and Bus 6 are shown with dotted red lines, which mean that these were isolated from the system to protect the entire system from the fault. At this point the user can solve the problem with the help of simulation options available. Simulation, Reset and Apply buttons are active in this level. At this point user can solve the problem with the help of simulation options available. These simulation options provide the user required decision aid.

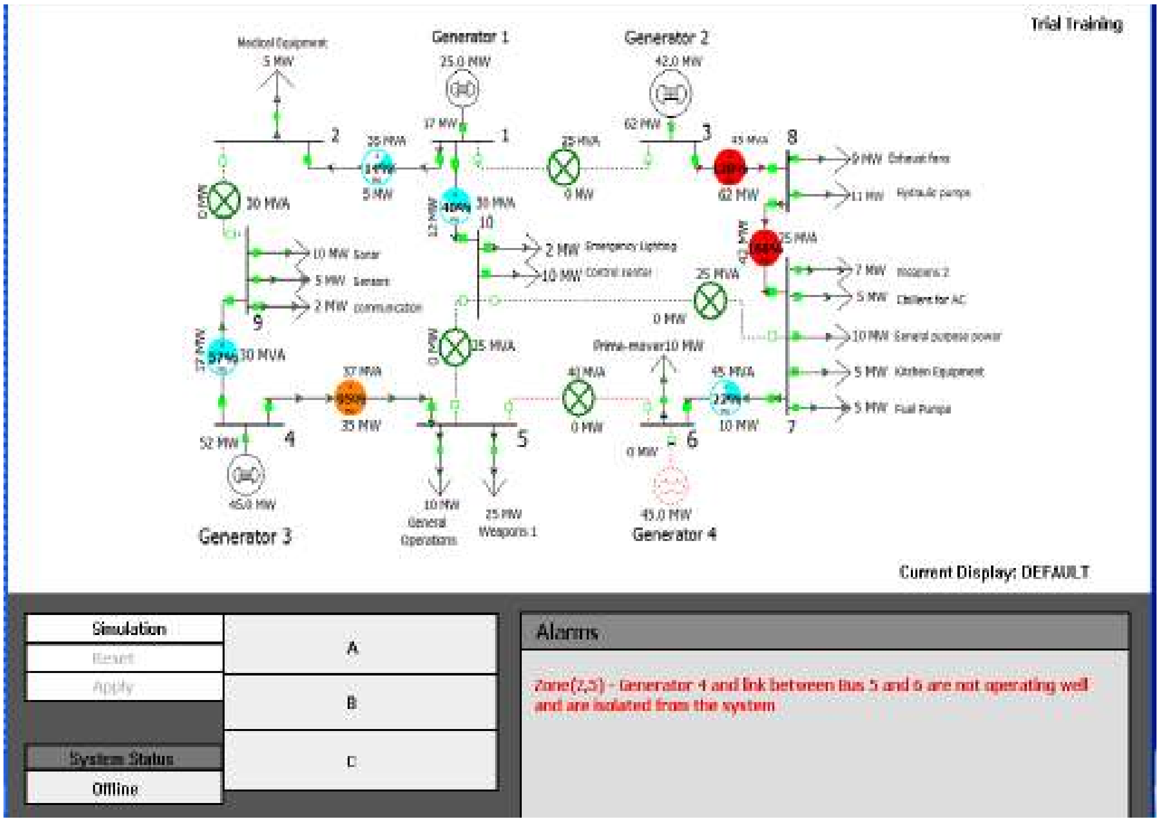


Zone(2,5) - Generator 4 and link between Bus 5 and 6 are not operating well and are isolated from the system

Figure 3.4 Aided interface - third level

Decision support system:

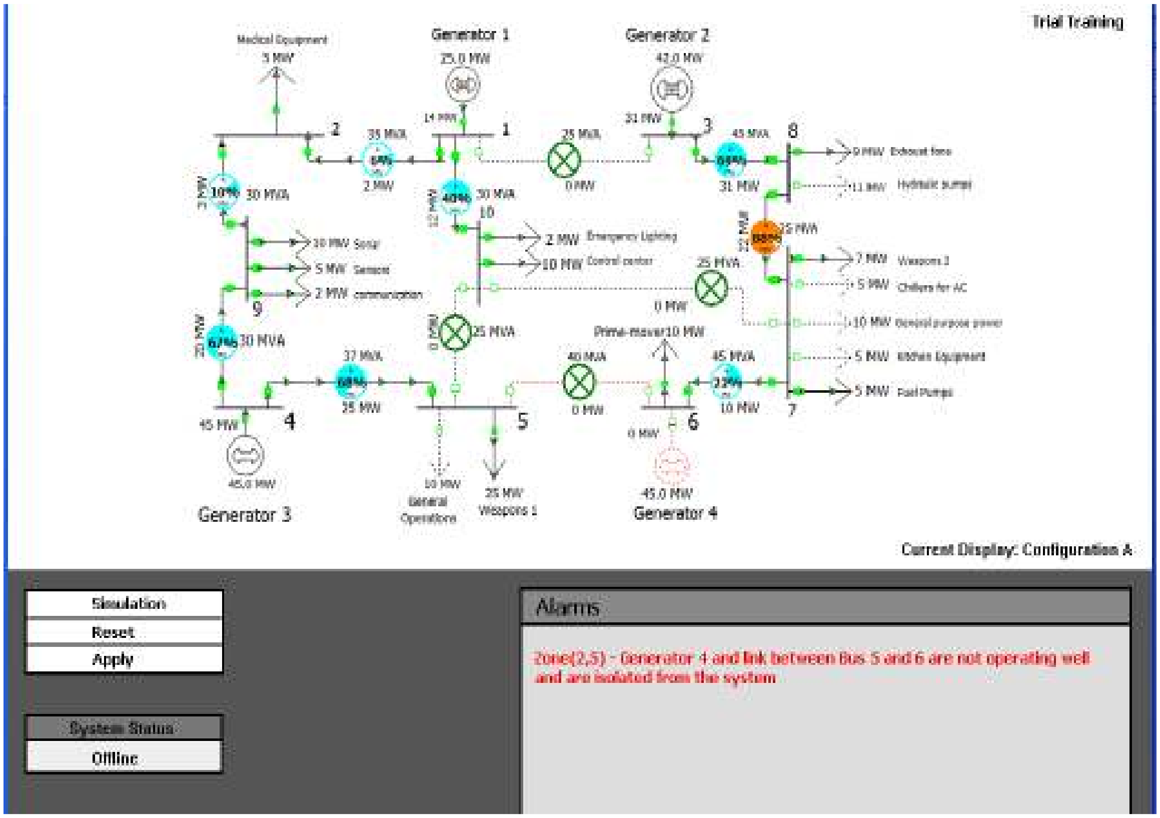
As mentioned earlier DSS should build on existing knowledge of user, and it should be able evaluate different possible options in advance and showcase them to user for decision making [48]. Also while designing the DSS a key consideration would be to concentrate on decision elements of the problem and how they contribute to problem [49]. Working memory demands are the central point of user performance limitation. Literature suggests that performance deficits can be overcome by prompts and graphical aids that reduce working memory demands [50]. Based on these findings a good DSS should be built based on previous knowledge of the users, take care of the most common errors that may occur in decision making, and should reduce the working memory demands. In our case DSS was all built in 'Simulation' option. This shows different simulations available in decision support system. In this project, we considered three simulation options A, B, and C. These options show the reconfiguration schemes simulated by following priority of the loads, maximizing the load served and considering both priority and magnitude of the loads respectively. These simulation options simulate the system in advance and provide the user with necessary information to take required action. Users can click on these simulation options any number of times and in any order.



Zone(2,5) - Generator 4 and link between bus 5 and 6 are not operating well and are isolated from the system

Figure 3.5 Aided interface showing simulation options

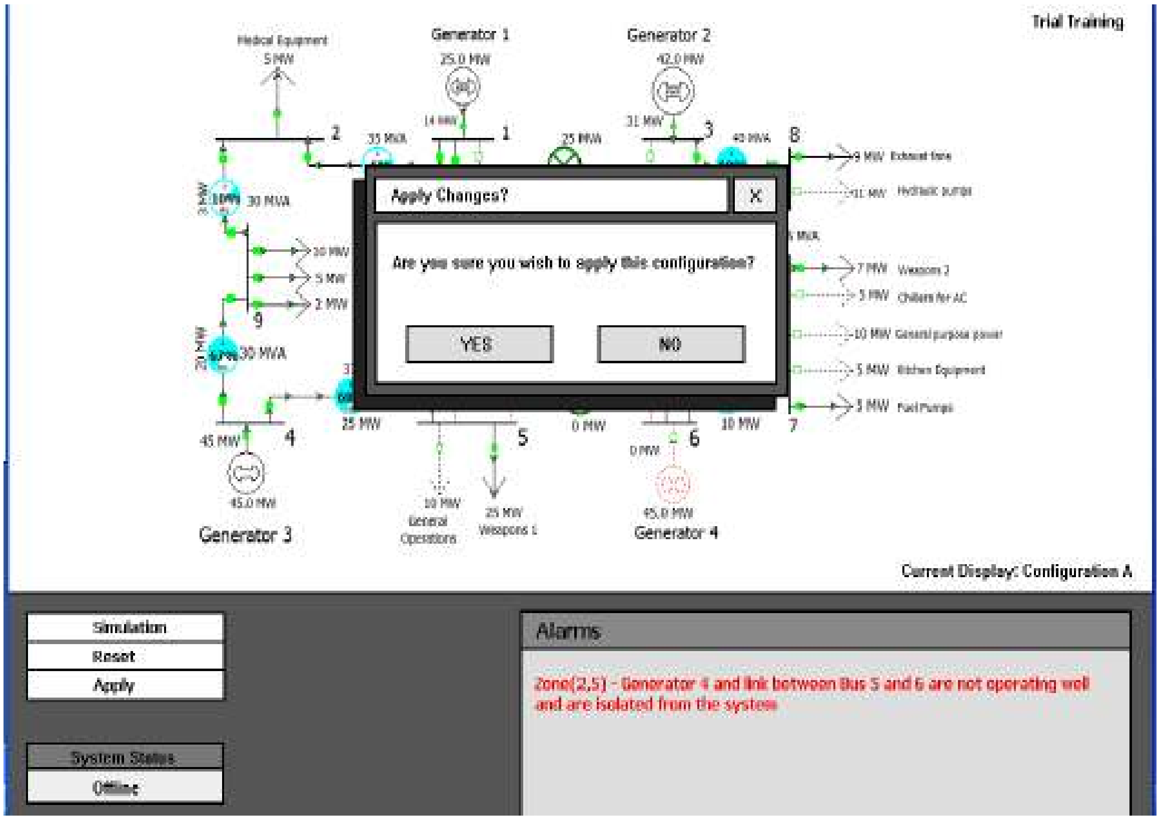
By clicking on ‘A’ shows the scheme simulated based on priority of the loads. Based on the situation and fault conditions, the user has to decide on simulation option that best suits for the problem. The user can click on ‘Apply’ button when he/she thinks the current displayed simulation option was the best solution for the given problem.



Zone(2,5) - Generator 4 and link between Bus 5 and 6 are not operating well and are isolated from the system

Figure 3.6 Aided interface showing simulation result of A

Fig 3.7 shows the interface with a confirmation window for confirming the changes made by the operator. By clicking on ‘Yes’, all the changes will be applied to the power system network, i.e. the scheme selected will be stored as the reconfiguration decision taken by the user for given problem. Instead, by clicking on 'No', interface will just undo the 'Apply' action taken by the user.



Are you sure you wish to apply this configuration?

Zone(2,5) - Generator 4 and link between Bus 5 and 6 are not operating well and are isolated from the system

Figure 3.7 Aided interface after clicking on 'Apply' button

3.5 Power system models used for the experiment

We designed twelve network configurations for 12 tasks and no two configurations were identical. Every network has four generators and sixteen loads, and the ratings of the loads, generators and topological connection of power system were varied depending on the task. The sixteen loads of each circuit fall into one of the four types. They are critical loads, tactical loads, service loads and general loads. Specifically critical loads include prime-mover and fuel pump; tactical loads includes sonar, sensor, communication, control room, emergency lighting, weapons1 and weapons2; service loads include exhaust, medical equipment, Heating Ventilation and Air Conditioning (HVAC) and kitchen and general loads include hydraulic pumps, general operations and general purpose power. The purpose of each load is explained here.

Critical Loads:

- Prime mover –enables the ship movements
- Fuel Pumps – These pumps are intended to supply fuel continuously to generators.

Tactical Loads:

- Sonar – Sonar will detect the underwater vessels (enemy ships or any other objects) based on sound navigation
- Sensor – Used to detect temperature surrounding the ship. This is useful to detect possible attacks and attacked portions of the ship.
- Communication – This load enables all communication devices to communicate between different parts of the ship.
- Control center – This load is connected to all the computer and critical control equipments in the control room
- Emergency lighting – This is the minimum lighting required to figure out any given objective.
- Weapons 1 – Missile launchers, bombs, etc
- Weapons 2 – Laser guns, etc.

Human Service Loads:

- Exhaust – Fans used to maintain air quality in the ship
- Medical equipment – Medical equipment and medical room load
- Chillers – For air conditioning
- Kitchen equipment – Kitchen equipment like freezers, cookers, food storage equipment

General Loads:

- Hydraulic pumps – used to move heavy objects on the ship (can be assumed of limited use)
- General operations – These are the loads for normal lighting, conference rooms, and dry cleaners.
- General purpose power – loads like corridor power sockets, room maintenance and loads.

Components in the interfaces were color coded to represent the operational states of that particular component or part of the circuit. In both interfaces red signifies that immediate attention required, yellow/orange signifies warning and green signifies normal/safe operation. The MW values and power flow limitations on the line are all assumptions and don't directly represent actual systems. Fig 3.8 shows the ship board power system having problems represented in red color.

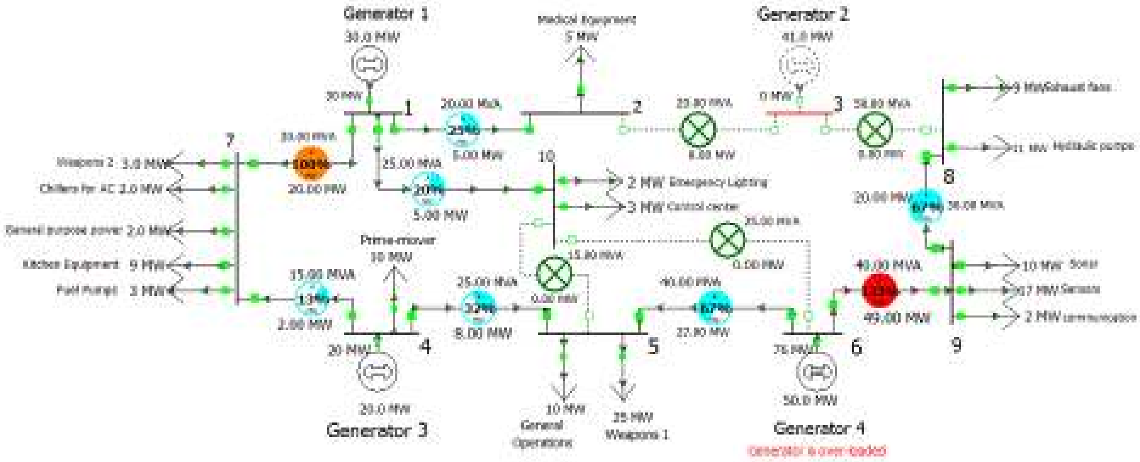


Figure 3.8 Power system network with fault

The dotted links or components indicate that they are removed from the system or not powered and dark links or components indicate that they are well connected to the power system or powered. In unaided interface users can reconfigure the power system by clicking the circuit breakers. For aided interface, the decision support system, with the help of simulations suggests possible options of solution. By using Powerworld, these simulation options A, B and C are created in advance by following the reconfiguration algorithm which works on priority of the loads or maximization of the loads or using both priority and maximization, respectively. When the user clicks on simulation A or B or C, the aided interface brings up these pre-calculated options on the screen as if they were simulated in real time. Figs 3.9, 3.10, and 3.11 show the simulation options A, B, and C, respectively for the problem shown in fig 3.8.

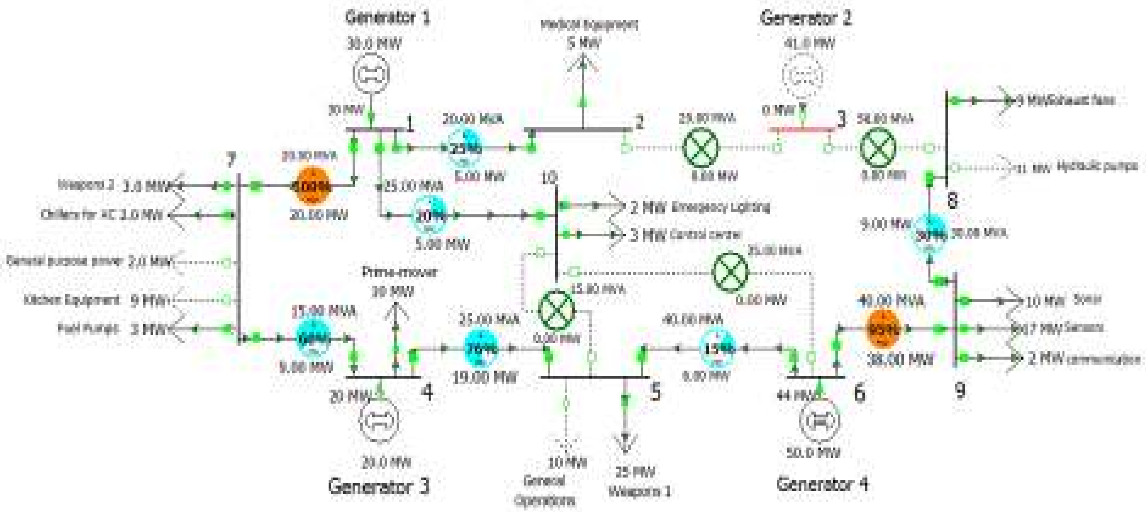


Figure 3.9 Power system network reconfigured based on priority of the loads

The above fig 3.9 is the reconfigured network based on priority of the loads. By assuming that the ship was in a battle situation, all the loads supporting communication activities and weaponry systems were given higher priority followed by service loads and general purpose loads. Now by following the priority of the loads and to not violate any constraints of power system, the low priority loads, such as general operations, general purpose power and kitchen equipment, are disconnected from the system. With this the power to high priority loads was maintained.

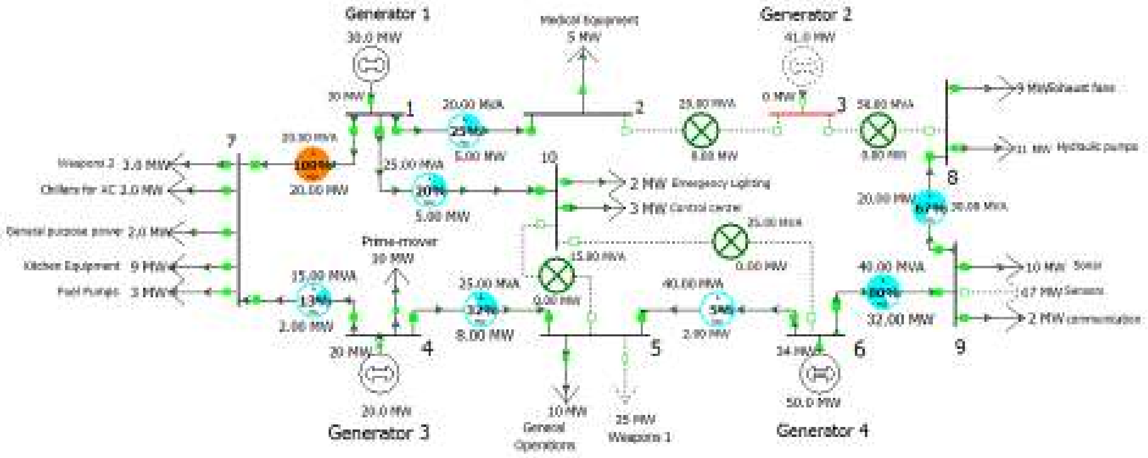


Figure 3.10 Power system network reconfigured based on maximization of the loads

Fig 3.10 shows the reconfigured network based on maximization of the loads. To make maximum number of loads connected in the system, the loads with the highest denomination should be disconnected until the available generation can feed all the connected loads. So the loads named weapons1 was disconnected from the system. All the loads in this method are considered with equal priority.

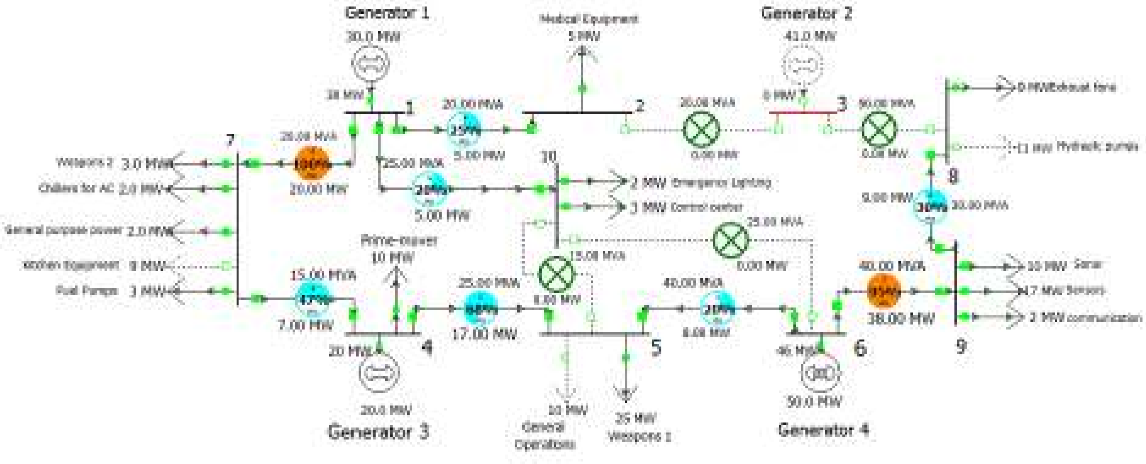


Figure 3.11 Power system network reconfigured based on both priority and maximization of the loads

Fig 3.11 shows the reconfigured network based on both priority and maximization of the loads i.e. loads with higher denomination and lower priorities were disconnected from the system. This process continues until the available generation can feed all the connected loads in the system. Now from the fig we can see that the loads named, general purpose and kitchen equipment are disconnected because they are the loads with the high denomination and low priority.

3.6 Experimental setup

3.6.1 Participants

Subject selection was very important for this kind of experiment. Every subject should possess good knowledge of power systems to tackle or understand power system reconfiguration problems. For any kind of subject, researchers expected maximum duration of two hours to complete the test. Subjects were run individually and sessions were lasting two hours or less. Each subject was paid $20 for one participation period. Ten subjects completed the experiment and all were graduate students in Electrical and Computer Engineering Department at Mississippi State University.

3.6.2 Tasks

Total twelve problems were formed, six for the aided interface and six for the unaided interface. The six problems in aided interface are similar to unaided interface in terms of their complexity and type of problem presented in the task. These problems were named as “matched sets”. It is essential that the problems should be matched to compare the quality of decision taken by the users.

3.6.3 Apparatus

Two computers were used as the testing station, one computer was running unaided and other was running an aided interface. We also made a booklet available for the user, which describes the current situation of the ship pertaining to the problem that user was working on and a load sheet explaining the use of each load connected in the ship.

3.6.4 Operating conditions of the ship

The operating criteria of ship varies based the situation or mission profile. For example it can be a battle situation, simply patrolling or a normal situation. The operational criteria, usage of resources, strategies taken are highly dependent on the situation of the ship. We formulated twelve situations for twelve problems, six for unaided and six for aided interface. Situations were explained in text so that user can read and understand. Of the created twelve situations, four referred to priority of the loads, four referred to maximizing the loads, and four referred to both and they are divided equally between unaided and aided interface. Users were asked to solve the problem based on the situation and problems shown in the interface of the ship. The twelve situations used for twelve tasks of the experiment.

- The ship is in the middle of battle and a short circuit fault has caused a power system to fail. Please reconfigure the loads to fight back the enemy and fulfill the captain's wishes to make the generators work fully.
- All of the ship's operations and power systems are operating at full capacity. Suddenly the ship is blindsided by an enemy attack. The captain has ordered all systems be returned to their previous state and the ship be prepared for battle conditions. Please reconfigure the power system to meet the captain's demands.
- The ship is sailing across the Atlantic Ocean. The Captain wanted to test all the ship systems work at optimal performance. Although it is not expected, the captain orders the crew to be on alert. All of the sudden an enemy vessel approaches and attacks the ship causing substantial damage. Please reconfigure the power system for the given situation.
- The ship is returning home and sustained major damage to the structure and the internal power systems from a battle with an enemy vessel. Many were critically injured during the attack and seek immediate medical attentions. The captain has just issued a warning that another enemy vessel

has been spotted along the ships current plotted course. Please reconfigure the power system to handle the current situation.

- The ship has been damaged due to an ongoing enemy attack. The captain has ordered that all offensive systems remain available. Please reconfigure the system given the current condition.
- A warship is patrolling, but an attack is not expected. The captain wants to test the entire power system, but unfortunately a fault has occurred and the power system is not working as expected. Please reconfigure the power system in the best possible way to meet the captain's expectations.
- You are in the middle of the Atlantic Ocean and an enemy missile hits your ship. The power system has been damaged. Reconfigure the loads to prepare for a counter attack.
- The ship was damaged in battle and is now returning home. An attack is not expected during this trip. The captain would like the system to run at full capacity. Please reconfigure the system to comply with the captain's wishes.
- The ship is operating at full capacity and conditions around the ship are normal. For no apparent reason a fault has occurred in the power system. Please reconfigure the system to return the ship to normal operating conditions.
- The captain has ordered a war situation drill in which the ship runs on limited resources. To keep you on your toes the captain has ordered one of

your team members create an intentional fault in the system. Please reconfigure the system given the condition.

- The ship is operating under normal peacetime conditions and the captain of the ship tasks you with making sure the ship uses its power resources as economically as possible given that generators are efficient at their full rating. While completing this task you detect a fault in one of the systems. Please reconfigure the power system to resolve the problem and while following the captains wishes.
- A new warship is constructed and its maiden voyage the commander in chief wishes to dine with the ship commanders. An inefficient power system design has resulted in a fault. Reconfigure the power system to support this important event.

3.6.5 Procedure

Each subject follows randomized order of the tasks. Initially subjects were trained on the interfaces, once the training was complete then they were allowed to solve the 12 problems. Users have to switch between the computers based on sequence of tasks that they encounter. Each subject solved 6 problems using the "aided" interface and 6 using the "unaided" interface, where the 12 problems were presented in a randomized order. The problems used in the aided and unaided interfaces were matched for complexity. Complexity was defined by total number of buses in the system, interconnections between them, flow limits on the lines between the buses, and available capacity of the generators and load requirements. The terms aided and unaided were not used during the experiment to ensure no prior bias in subject response. Load types were explained verbally to each subject at the beginning of the experiment and also provided on a printed sheet so that they can refer during the experiment.

Users will be provided with a scenario which explains the ship’s current situation like we may say “you are in middle of Atlantic and a sudden war alert is issued please reconfigure the power system to address the specific needs of the task.” After reading the situation they can look into the power system network. Power system network will have a fault and users will be asked to reconfigure the power system to restore the loads based on the given situation. While doing this they should not violate any constraints posed on the power system, like lines and generators should not be overloaded, faulted system should not be kept back into the healthy system and the reconfigured network should have minimum switching operations [51].

When subjects performed six problems using the unaided interface, they manually manipulated the power network. Subjects could reconfigure the circuit by clicking on the circuit breakers. One click toggles the breaker between ON and OFF. Circuit breakers are represented by green squares in the screen shot below. When a subject determined that they were finished with their reconfiguration, they could select the ‘SAVE’ button to commit the new configuration. The unaided interface also provided an option to ‘RESET’ the configuration to its original if the subject decided to restart their solution.

When using the aided interface, subjects solved six problems that were matched in complexity to those solved using the unaided system. Subjects began the task just as for the unaided system – they read the scenario and then reviewed the current configuration on the screen. Rather than reconfiguring manually, subjects were asked to select buttons A, B, or C to view possible solutions. Their task was to choose the configuration that best fit the optimal solution for the scenario provided. Selecting button “A” resulted in the display of a configuration based on priority of the loads, “B” showed a configuration based on maximum load and “C” displayed a configuration for priority and maximization of loads combined. When the subject decided on the best solution given the provided scenario and power system state, they selected “Apply” to save their solution.

3.7 Scoring the responses

Subject responses were scored using a logical decision quality metric with a scale of 1 to 10. User responses were credited based on the quality of their decision. Best responses were given 10 points, satisfactory responses were given 5 points and responses with many violations that were not suitable for the scenario were given 0 points. The best scores (10) were given for solutions that a) were optimal for the given task constraints, and b) included no violations, such as critical loads shutdown, and/or more than the minimum number of switching operations and or violating any limits. Both unaided and aided responses were scored based on the same rules so, that the quality of the decisions made in unaided and aided interfaces could be compared quantitatively.

3.8 User data

For each problem solved in unaided interface, final reconfiguration scheme set by the user, total time taken by the user to complete the task and each atomic action taken by the user are stored in a file named with user identification number. For each problem solved in aided interface, the reconfiguration scheme selected by the user, total time taken to solve the problem, and the data related to the sequence of simulations that user selected is saved under the name of user’s identification number.

3.8.1 User performance for unaided and aided interfaces

From the final reconfiguration scheme selected by the user and with the use of scoring rules explained above, the quality of the decision made by the user for aided and unaided interface was determined. For each user and for each problem solved in aided and unaided interfaces, the reconfiguration response was credited on a scale of 1 to 10. Higher the value of the score, higher was the quality of decision taken. Comparison of scores of unaided interface with aided interface decides the superiority of the one interface on other.

3.8.2 Error analysis

Errors in the cognitive process are the causes for poor performance in the decision making. Reconfiguration error analyses were performed to determine the origins of reconfiguration solution failures. All the errors made by the users are classified into few fundamental errors so that it will be easy to identify the cognitive reasons behind those errors.

3.8.3 Cognitive walkthrough studies

As explained in Chapter II, Cognitive walkthrough is a methodology or a procedure to systematically evaluate the features of an interface [12].

Below shows the cognitive walk through evaluation form for a single action

---

CE+ Design Walkthrough Date:
Interface: **Aided Interface**
Evaluator: **Venkata K. Pendurthi**
Task:
Step # - 1

Actions/choices should be ranked according to what percentage of potential users are expected to have problems: 0 = none; 1 = some; 2 = more than half; 3 = most.

1. Description of user's immediate goal:

2. (First/next) atomic action user should take:

   2a. Obvious that action is available? Why/why not?

   2b. Obvious that action is appropriate to goal? Why/Why not?

3. How will user access description of action?

   3a. Problem accessing? Why/Why not?

4. How will user associate description with action?

   4a. Problem associating? Why/why not?

5. All other available actions less appropriate? For each, why/why not?

6. How will user execute the action?

   6a. Problems? Why/why not?

7. If timeouts, time for user to decide before timeout? Why/why not?

8. Execute the action. Describe system response:

   8a. Obvious progress has been made toward goal? Why/why not?

   8b. User can access needed info. in system response? Why/why not?

9. Describe appropriate modified goal, if any:

   9a. Obvious that goal should change? Why/why not?

   9b. If task completed, is it obvious? Why/why not?

The questions are framed in such a way that each individual aspect of the interface should be included. These are framed as per the CE+ theory of problem solving and learning process.

First, the designer specifies a series of individual tasks to complete one big task. The interface design was evaluated based on these tasks. Next, the sequence of user actions that will successfully perform the given task was specified by the designer. The main part of cognitive walk through is problem solving and evaluation of the feedback using CE+ to know the ease of learning for the evaluated task. The designer has to defend his assumptions, for expecting or not expecting any problem.

In the above questions, questions 1 and 2 describe the user's immediate goal and action. Questions from 2a to 7 evaluate the ease with which user correctly selects and execute the action. Question 8 evaluates the response of the system. Finally question 9 evaluates whether the user recognizes the next goal of action or detects that the goal was achieved. After going through all actions for all tasks, all the information can be summarized with the following cognitive walkthrough summary sheet. The cognitive walkthrough evaluation form can be used as a designer walkthrough and also user walkthrough. The designer walk through sheet should be filled by designer on what he thinks are the potential problems in the interface. User walkthrough sheet should be filled at the time of experiment as per the user's comments and actions.

A typical cognitive walk through summary sheet is shown in table 3.1. This sheet contains all the actions required to complete the goal and designers assessment of the problems particular to each goal. The designer should also need to explain the reasons behind his assumptions.

Table 3.1 Cognitive walkthrough summary sheet

Action/sub-goal: Actions taken to achieve overall goal and sub-goals	Expected # of users who will have problems. 0 = none; 1=one ; 2=two, N=n users	Why problems may occur
1. Follow the instructions to navigate to another screen	1=one	Problem: Instructions may not be salient enough for users to find Possible solution: Instructions could be flashing
2. .. 3. … 4. … 5. …. 6. …		Problem: Possible solution:

The cognitive walk through helps in making important design decisions for the interface and it also helps in its implications on the effectiveness of the user. The process of learning any system or interface involves complex interaction between cognitive process of the user, characteristics of the tasks, and the details of particular interface. Cognitive walk through, since being a hand simulation of the interface and user actions, the development of full user interface is not required and because of this it can be considered very cost effective.

3.9 Summary

This chapter explained the part of research work related to cognitive engineering and approach chosen in realizing the goal. Method of designing prototypes for aided and unaided interfaces for performing usability testing was explained. Different scenarios coupled with power system problems were explained. Method of scoring the user responses, and cognitive walkthrough methodology were introduced.

CHAPTER 4

PROBLEM DESCRIPTION AND SOLUTION APPROACH FOR POWER SYSTEM ENGINEERING

4.1 Introduction

The first part of this chapter presents the motivation and reasoning for developing a fuzzy based evaluation system to deal with uncertainty present in meter data. As the chapter proceeds, the problem description, solution approach, fuzzy correction system, genetic algorithm based reconfiguration technique and test cases used for the analysis are explained.

4.2 Motivation

Using uncertain data for any kind of analysis has higher chances of producing inappropriate or erroneous results. In power system operation and control, the data coming from meters is used for all types of calculations and analysis. For example power flow and voltage values are measured at strategic locations of the power system network and they are used for state estimation, power flow analysis, dynamic and short circuit analysis. For all these types of analyses the data given by the meters are pivotal and everything interlinked to those metered values. It is known that measurements have different types of inaccuracies and certain amount of errors is associated with those measurements. There can be errors in the calibration process, differences in ambient conditions, assumptions made in mathematical modeling, electro-magnetic influences, imperfect installations and others. Using erroneous data will restrict the optimal operation and control of power systems. In a shipboard environment, it is very important to deal with such errors to ensure reliable and optimal operation and control of the power system at all times. This research focuses on dealing with measurement uncertainty for optimal shipboard power system reconfiguration.

4.3 Approach

A fuzzy based meter correction system was proposed to take care of the errors in the data. Fuzzy logic was selected due to its superiority in representing uncertain data and flexibility to adapt any kind of system. A rule driven fuzzy knowledge base was created based on a meter's historical performance and operational parameters. The meter data treated with fuzzy correction system was used to reconfigure the power system network using a genetic algorithm based technique [46]. To identify the effect of fuzzy correction system on reconfiguration results, we compared the simulations on the basis of three types of data listed below.

- Data with actual power flow values (Type A)
- Data after introducing errors into the load data (Type B)
- Data after correcting the error with fuzzy logic system (Type C)

The data with actual power flow values i.e. Type A scenario, can be considered as actual or true values of the system. In Type B, we introduced errors into the data of Type A to simulation conditions such as data coming from meters. In Type C test scenario, the data used in Type B was treated/corrected using a fuzzy correction system. All three kinds of data were used in GA based reconfiguration technique as depicted in the fig. 4.1.

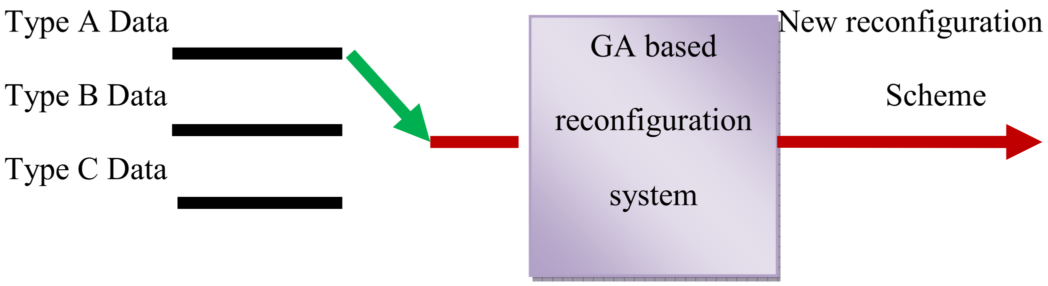


Figure 4.1 Picture depiction of reconfiguration using different kinds of data

4.4 Fuzzy evaluation method

An algorithm designed to evaluate the meters and rank them as per the trust on meter data was named as the fuzzy evaluation method. Based on the meter's 'trust' value, all its measurements can be corrected close to the actual value. This method works based on a meter's operational and historical behavior. Consideration of a meter's historical data along with operational specifications makes the method more accurate and reliable. Since the meter parameters and working rules of the system have to be created by the operator, this method will produce different results for different systems. The rules and the parameters are highly dependent on the system and the designer; a rule based fuzzy correction system developed for one system may not work accurately for the other system.

4.4.1 Meter parameters

The true value of the measurement (X) always lies between $X_{best} \pm U_X$, where U_X is the uncertainty in X that corresponds to our estimate with C% confidence of the effects of the combination of the systematic and random errors. Generally we assume X_{best} as the average value of N measurements and U_X contains magnitude of the combination of all errors affecting measured value X [16]. With meter parameters, such as standard error (E%), degree of confidence on meter data (C%), reliability and age the meter can be validated and a measurement of the uncertainty developed by making use of rule based fuzzy logic system. The user's interpretation/expression of 'low', 'medium' or 'high' on any variable of the meter was highly contextual and clear boundaries with crisp values cannot be drawn between them. Always a vague partition of these parameters can be done by experienced operators. So these parameters were converted into fuzzy variables and were fuzzified to apply fuzzy rules at later stage. All the four fuzzy variables are characterized by Low, Medium, and High fuzzy sets. Fuzzy numbers may have a variety of shapes bounded by conditions. For simplicity we assumed trapezoidal shapes and triangular shapes in special conditions. The meter parameters, error% and degree of confidence can be determined from the manufacturer's specifications sheet, but reliability and age require historical data. These values vary as time goes.

- *Standard Error (E%)*: Error percentage is the maximum percentage deviation that any measurement goes beyond its true value. In this work, we assumed a maximum of 6% error for any given meter. Fig. 4.2 shows membership function of Meter % Error. The membership function explains the variation of fuzzy sets Low, Medium, and High on the X-axis.

Low was defined from 0 to 2.5% error, Medium was defined from 2% to 4% error and any value higher than 3.5% was defined as High.

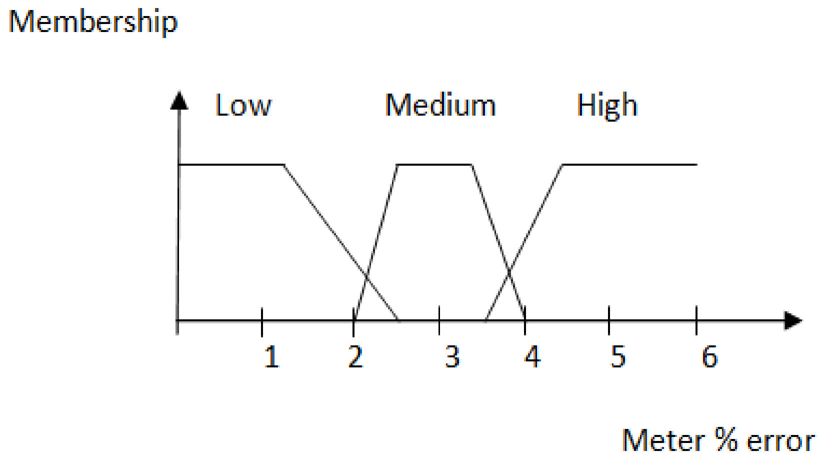


Figure 4.2 Fuzzy membership function of %error

- *Degree of Confidence (C%)*: It is not 100% true that the measured variable will always lie between $X_{best} \pm U_X$, we can attach probability for X to lie between these limits and this is called as degree of confidence C%. For this work, for any meter, we assumed degree of confidence to lie between 94% and 99%. Higher the C%, higher the probability that the meter show values within the error limits. Fig. 4.3 shows the fuzzy membership function of the degree of confidence C%. Fuzzy sets Low was defined from 0.94 to 0.965, Medium was defined from 0.955 to 0.985 and High was defined from 0.975 to 1.

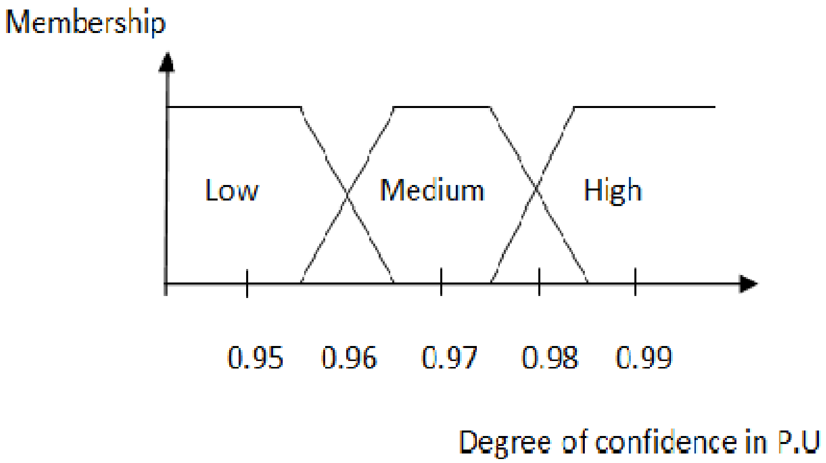


Figure 4.3 Fuzzy membership function of degree of confidence %C

- *Reliability:* Reliability is defined as the outages that the meter has per year (outages/year). This has to be calculated from historical performance of the meter. If outages/year is more the reliability of the meter is less and vice versa. Fig. 4.4 shows the membership function of the fuzzy variable reliability. Reliability was modeled to vary from 0 to 1. Fuzzy sets Low was defined from 0 to 0.25, Medium was defined from 0.2 to 0.5, and High was defined from 0.45 to 1.

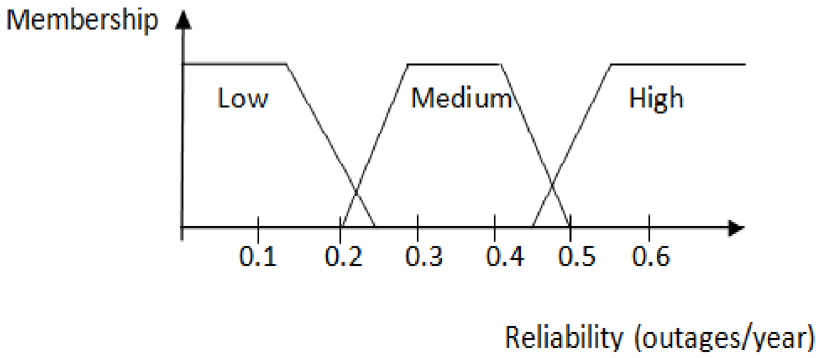


Figure 4.4 Fuzzy membership function of reliability

- *Age*: age is a relative age and is the ratio of current age to the total expected operation period of the meter. Fig. 4.5 shows the membership function of the Age varying from 0 to 1. Fuzz sets Low was defined from 0 to 0.3, Medium was defined from 0.2 to 0.7, and High was defined from 0.6 to 1.

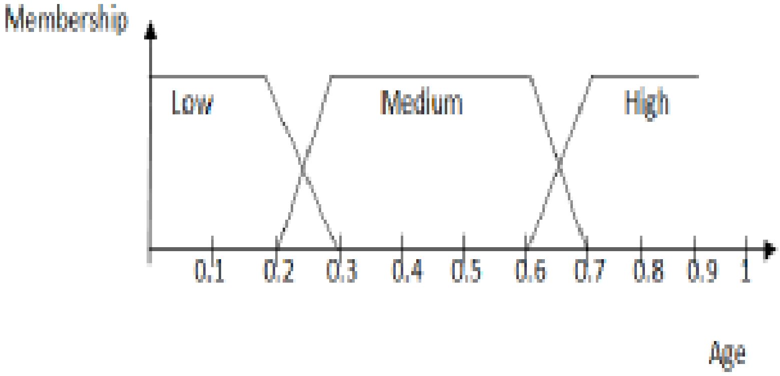


Figure 4.5 Fuzzy membership function of reliability

4.4.2 Flow chart

Fig. 4.6 shows the flow chart of fuzzy evaluation system designed to deal with meter uncertainty. The fuzzy variables standard error, reliability, degree of confidence and age will act as inputs to rule based fuzzy information system (FIS). Fuzzy system consists of fuzzifier, knowledge base, fuzzy inference system and defuzzifier. Fuzzy inference system is like a heart of the system which interacts with the fuzzy rules and fuzzy variables. We used Mamdani's implication or classical implication for obtaining the fuzzy relation R based on the rule if X, then Y. Based on the input to FIS it fires the rules to come out with a crisp value. We used centroid method of de-fuzzification for this purpose. Output of the fuzzy evaluation system was named as 'trust' and it directly represents the trust on that particular meter.

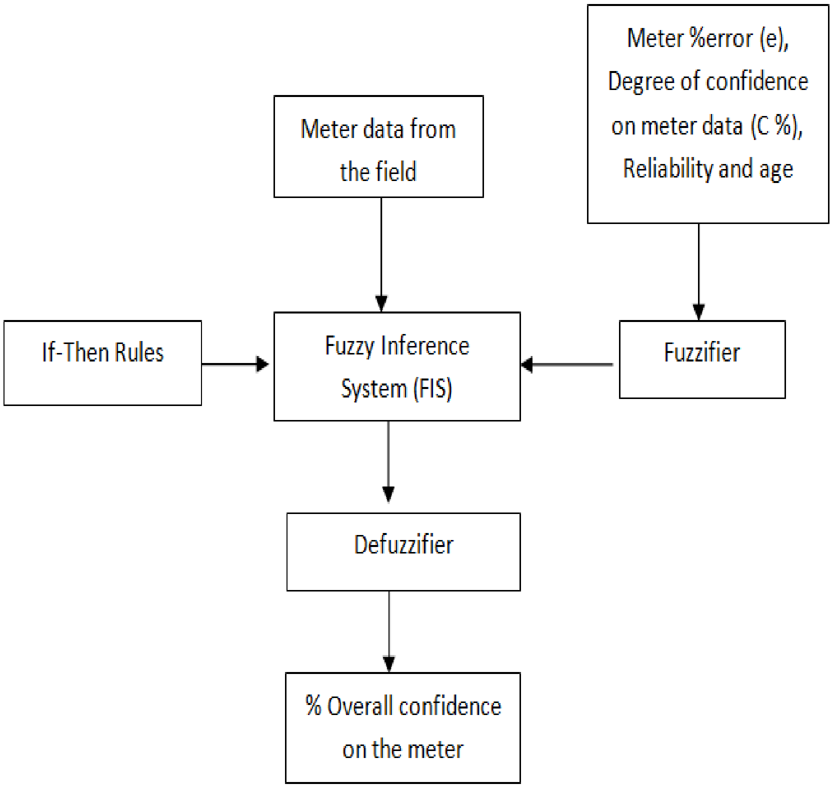


Figure 4.6 Flow chart of fuzzy evaluation system

Based on the output ‘trust’ meters can be classified as low trust meter, medium trust meter or high trust meter. Fig. 4.7 shows the fuzzy representation of variable ‘trust’ and it is varied from 0 to 1. The trust was divided into three fuzzy sets Low, Medium, and High. The value of ‘trust’ depends on fuzzy inputs, fuzzy rules and fuzzy inference system. All these variables and methods explained in the algorithm were implemented in MATLAB fuzzy GUI. Fig. 4.8 shows the screen shot of the design.

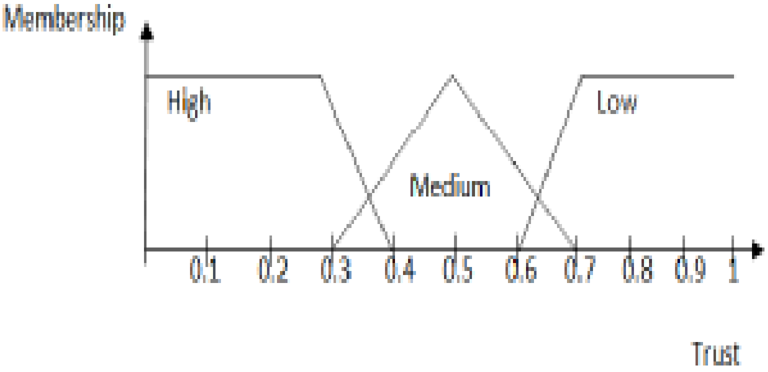
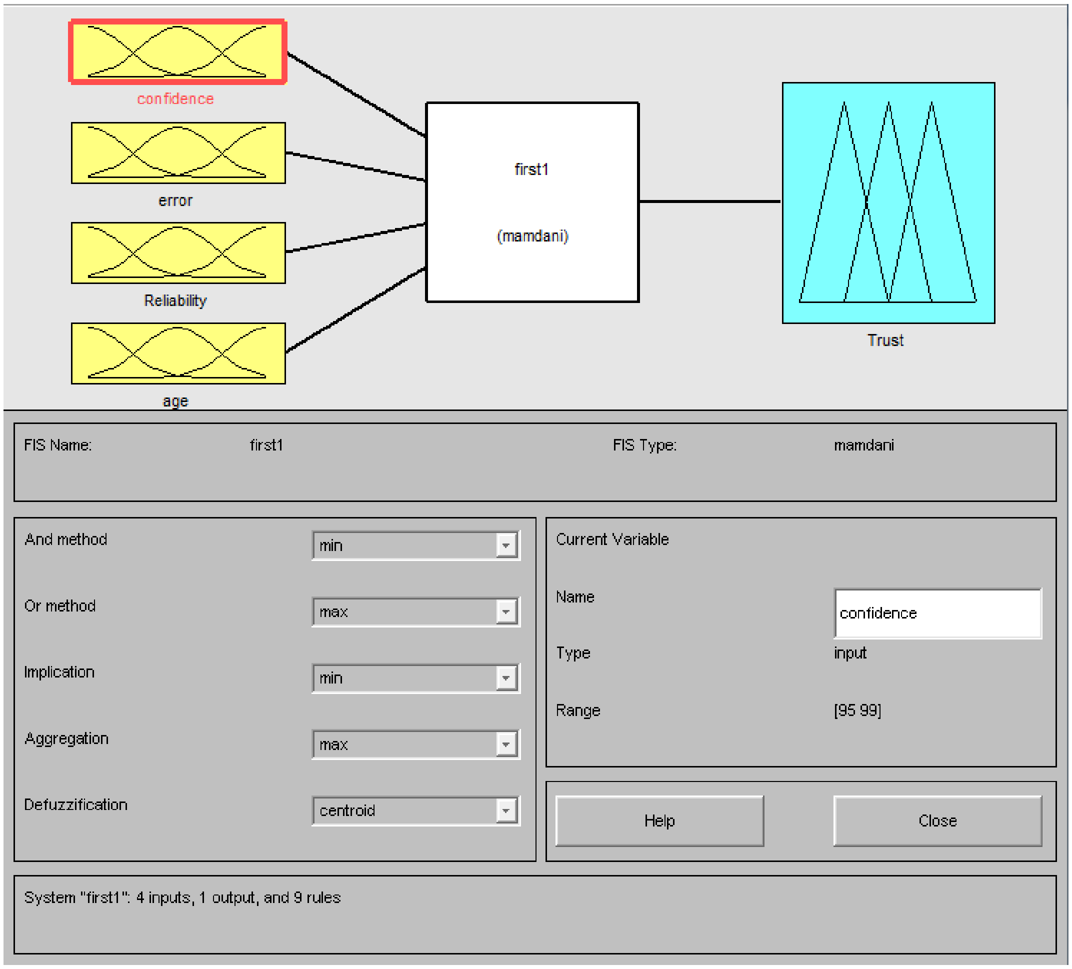


Figure 4.7 Fuzzy membership function of trust



FIS Name: first1

FIS Type: mamdani

And method: min

Or method: max

Implication: min

Aggregation: max

Defuzzification: centroid

Current Variable

Name: confidence

Type: input

Range: [95 99]

System "first1": 4 inputs, 1 output, and 9 rules

Figure 4.8 Screen shot fuzzy GUI in MATLAB for the proposed system

4.4.3 Fuzzy rules

FIS consists of a set of rules which contain knowledge and logical evaluation of inputs. For example a rule can be formed as below.

If (error% is low) and (degree of confidence is high) or (reliability is high) and (age is low) then (output is high)

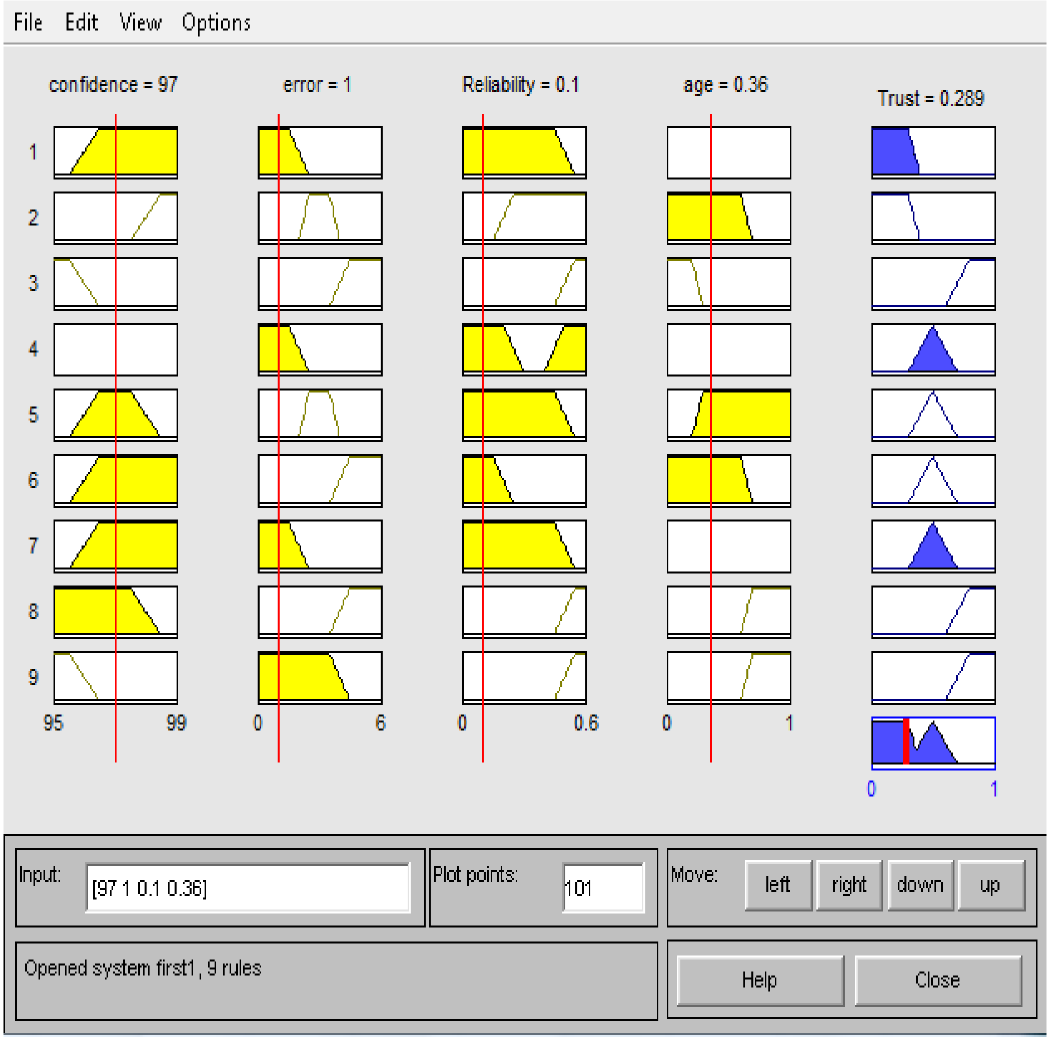
Considering the above four parameters as the inputs for fuzzy information system, the rules shown in table 4.1 are formed for the evaluation of the meter data. Fuzzy rules were formed for different varieties of fuzzy inputs. First rule in the table 4.1 says that *IF (% error is Low) and (Degree of confidence is NOT Low) and (Reliability is NOT Low) THEN (trust is High)*. This rule is built in with many rules. In this rule, Degree of confidence is specified as NOT Low, i.e. it works for the combination of (Degree of confidence is Medium) or (degree of confidence is High), similarly for Reliability. First rule states that (Age is None), it means that if the first three inputs meets the conditions of the rule then value of the 'Age' doesn't influence the output 'Trust'. With this none rules all the combinations of the fuzzy conditions for the four inputs were achieved.

Table 4.1 Fuzzy rules

% error	Degree of confidence	Reliability	Age	Output (trust on meter)
Low	Not Low	Not Low	None	High
Medium	High	High	Not High	High
High	Low	Low	Low	Low
Low	None	Medium	None	Medium
Medium	Medium	Not Low	Not Low	medium
High	Not Low	High	Not High	Medium
High	Not High	Low	High	Low
Low	Low	Not Low	None	Medium
Not High	Low	Low	High	Low

Fig. 4.9 shows the screen shot of implementation of the rules in the simulation design. This shows the evaluation of inputs (confidence 97%, standard error 1, reliability 0.1, and age 0.36) with fuzzy rules mentioned in table. Algorithm fires all nine rules one at a time and it will produce nine output values each according to the rule. All these values are combined and will be de-fuzzified using centroid method. With these values

FIS evaluated the final ‘trust’ to be 0.289, i.e. it falls in the range of High fuzzy set of trust fuzzy membership function.



Input: [97 1 0.1 0.36]

Plot points: 101

Opened system first1, 9 rules

Figure 4.9 Screen shot showing the firing of fuzzy rules on the inputs

For example consider that we have five meters named M1, M2, M3, M4 and M5 with their parameters given. Table 4.2 shows the five meters and values of their Standard error, Reliability, Degree of confidence and Age. Now by giving these data to fuzzy evaluation system, it gives the trust on each meter.

4.4.4 Measurement correction

The value ‘trust’ represents the amount of uncertainty in believing the data given by the meter and this trust is a result of its historical behavior and its operational parameters. In this work, we assumed that the total uncertainty present in the data was only because of the error present in the meter data. The de-fuzzified ‘trust’ obtained from fuzzy evaluation system was used to correct the maximum ‘%error’ of that meter. The maximum error was multiplied with de-fuzzified ‘trust’ to get modified or more accurate values of the meter. De-fuzzified trust can be viewed as a weighting factor for the average error.

Table 4.2 table showing error adjustment using fuzzy correction technique

Meter ID	Error %	Degree of confidence	Reliability	Age	De fuzzified Trust	Trust on meter data	**Power flow values (in MW)**	error adjustment	**Readings with error adjustments (in MW)**
M1	±5	96	0.11	0.2	0.735	Low	**2**	3.675	**2.0735**
M2	±1	96	0.12	0.55	0.323	Medium	**20**	0.323	**20.0646**
M3	±2	99	0.3	0.3	0.323	Medium	**2**	0.646	**2.01292**
M4	±1	97	0.1	0.36	0.289	High	**2**	0.289	**2.00578**
M5	±3	96	0.25	0.45	0.5	Medium	**20**	1.5	**20.3**
M6	±4	98	0.4	0.77	0.826	Low	**2**	3.304	**2.06608**

In this table 4.2, meters were named either low trust meters, Medium trust meters or High trust meters. Assume that the meters M1, M2, M3, M4 and M5 measures 2, 20, 2, 2, 20, and 2, respectively. Now, for M1, the trust was 0.735. It was a result of its inputs %error 5, %C 96%, Reliability 0.11 and Age 0.2 as well as fired fuzzy rules. The trust is the representation of the total uncertainty due to the error 5%. This error can be reduced by multiplying the error with the trust. The new modified error defines the maximum possible value of that meter for any true measurement. For the measurement of 2MW which was considered to be the true value, the maximum possible measurement by the meter was 2*(1+0.735*5/100) = 2.0735MW. All the other measurements were modified accordingly.

4.5 Measurement correction

With the concept of Darwin's natural selection, genetic algorithm was proposed in mid 1970s by John Holland [53]. It is a stochastic method and can yield global optimum for a wide variety of problems. A genetic algorithm based reconfiguration scheme was selected because; the algorithm can be used to solve nonlinear problems irrespective of objective function and type of system.

The three important steps for any genetic algorithm are 'Selection', 'Crossover' and 'Mutation'. In selection, the selection of chromosome is proportional to fitness of the chromosomes in the population. Higher the fitness higher is the chances of selecting the chromosome. The working of the selection can be associated with a roulette wheel selection. In crossover, chromosomes of one generation combine their genetic material to produce other chromosomes of next generation. Mutation is used when some random error is introduced during crossover. This process is repeated until a new generation satisfying the convergence criteria is evaluated. For this work a population size of 40, crossover rate of 95% and mutation rate of 0.75% were considered [46].

The objective function considered for the reconfiguration was to maximize the power supplied to unaffected loads by following either priority of the loads, magnitude of the loads or by both priority and magnitude of the loads.

i.e max $\{L1+L2+L3+\ldots..Ln\}$

Subject to $Pgen > Pload$

The fitness function was defined as

$$F=W_M[x(1)L1+x(2)L2+\ldots.+x(n)Ln]+W_P[P1x(1)L1+P2x(2)L2+\ldots\ldots..+Pnx(n)Ln]$$

Where, x(n) indicates switch status for nth switch

L1, L2…..Ln indicates load values

P1, P2, ….Pn indicates priorities of the loads

W_M - weighting factor for reconfiguration based on load

W_P – Weighting factor for reconfiguration based on priority

W_P and W_M determine the type of reconfiguration. If $W_P=1$ and $W_M=0$, reconfiguration follows priority of the loads. If $W_P=0$ and $W_M=1$, reconfiguration follows load magnitude. If $W_P=1$ and $W_M=1$, reconfiguration follows both priority and load magnitude.

The GA based reconfiguration is explained with the help of ship board power system test case shown in fig 4.10. A graph model was developed for the system shown in fig. 4.10 by considering generator, bus bar, cable and load as Vertex and Circuit breaker as Edge [52].

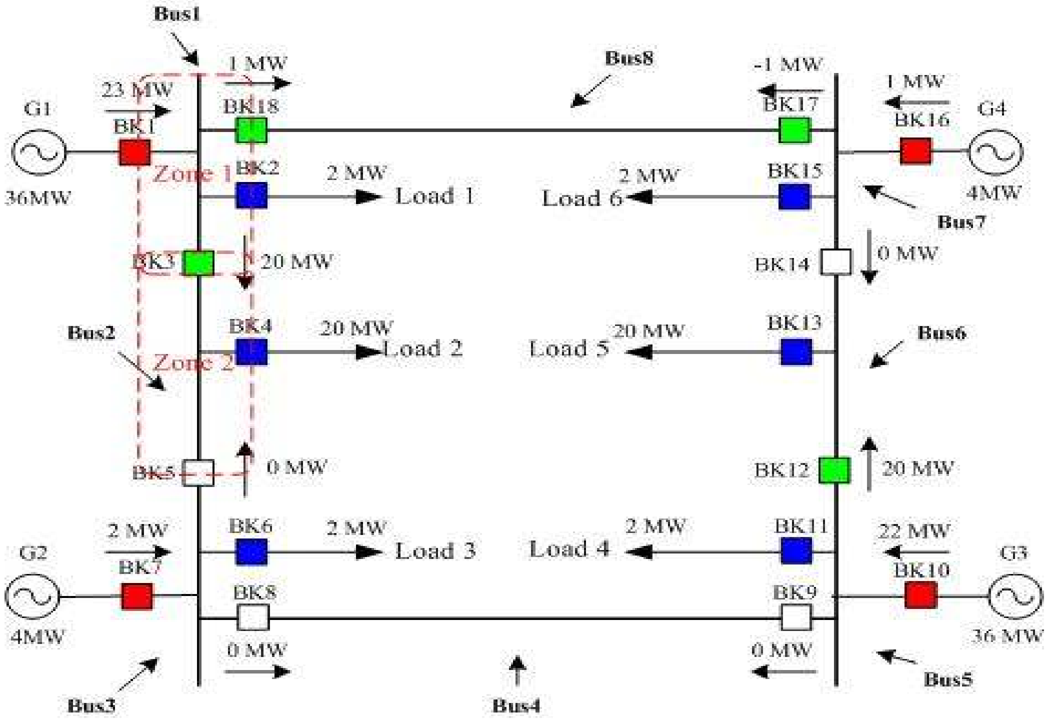


Figure 4.10 8-bus power system used for demonstration [46]

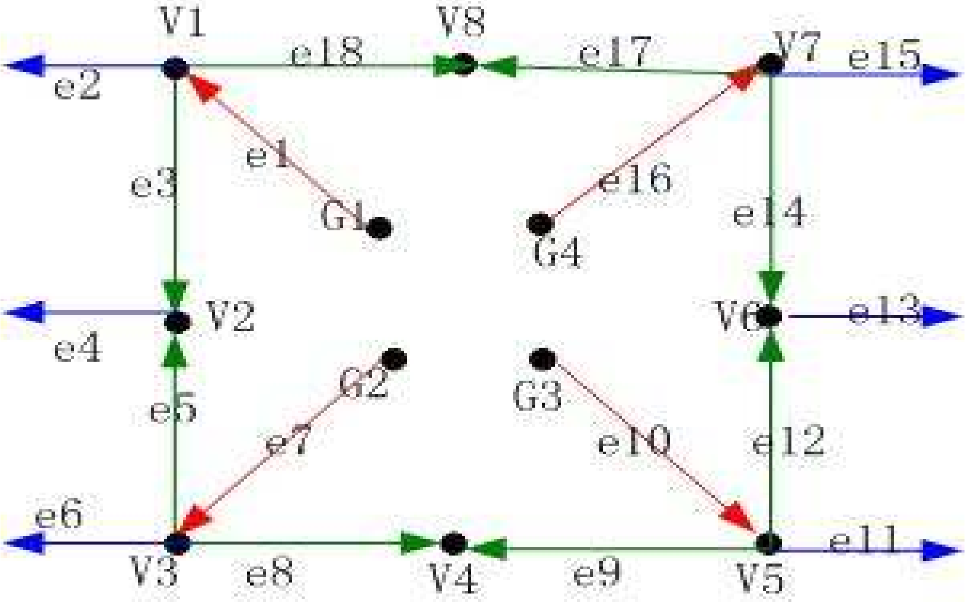


Figure 4.11 Graph model of power system shown in fig. 4.10 [46]

The SPS model consists of four generators, eight buses and eight breakers. This model was divided into eight protection zones. Each vertex with directly connected edges was called as a zone. Now the graph can be represented in matrix form to evaluate the system mathematically. Breaker-to-zone matrix or edge-to-vertex matrix represents the topology and power flow of the system. In the matrix (EtoV) with size of 8x18, 8 rows are corresponding to eight zones and 18 columns are corresponding to eighteen circuit breakers. Power flow from edge to vertex was represented with +1, power flow from vertex to edge was represented with -1 and zero power flow or breaker with OFF status is represented with 0.

S(Zone1) = [1, -1, –1, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, -1]

S(Zone2) = [0, 0, 1, -1, 1, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0]

S(Zone3) = [0, 0, 0, 0, -1, -1, 1, -1, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0]

S(Zone4) = [0, 0, 0, 0, 0, 0, 0, 1, 1, 0, 0, 0, 0, 0, 0, 0, 0, 0]

S(Zone5) = [0, 0, 0, 0, 0, 0, 0, 0, -1, 1, -1, -1, 0, 0, 0, 0, 0, 0]

S(Zone6) = [0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 1, -1, 1, 0, 0, 0, 0]

S(Zone7) = [0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, -1, -1, 1, 1, 0]

S(Zone8) = [0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, -1, 1]

The matrix BRK_TYPE gives the information on type of breaker. The breakers connected to generators are given number 1, the breakers connected to load breaker are given number 2, and the breakers connected to tie line or tie breakers are given number 3.

BRK_TYPE = [1, 3, 2, 3, 2, 3, 1, 2, 2, 1, 3, 2, 3, 2, 3, 1, 2, 2]

In the matrix BRK_STATUS, The breakers in ON status are represented with 1 and the breakers in OFF status are represented with 0.

BRK_STATUS = [1, 1, 1, 1, 0, 1, 1, 0, 0, 1, 1, 1, 1, 0, 1, 1, 1, 1]

BRK_FLOW represents the flow of power through different circuit breakers.

BRK_FLOW = [23, 2, 20, 20, 0, 2, 2, 0, 0, 22, 2, 20, 20, 0, 2, 1, -1, 1]

The matrix GEN_CAP gives the information about generator capacity.

GEN_CAP = [1, 36; 7, 4; 10, 36; 16, 4]

The matrix LOADS represents load connected to system with the circuit breaker number.

LOADS = [2, 2; 4, 20; 6, 2; 11, 2; 13, 20; 15, 2]

The matrix LOAD_PRIORITY represents priority of the load connected to particular breaker. In the below matrix first element represents the breaker number and second element represents its priority.

LOAD_PRIORITY = [2, 1; 4, 150; 6, 12; 11, 1; 13, 1; 15, 150]

Fig 4.12 shows the flow chart of GA based reconfiguration system. EtoV matrix, breaker status, power flow, generator capacity and load priority acts as inputs to algorithm. The algorithm allows us to put a fault on any of the buses. Now with the fault applied on a particular bus/buses all the breakers connected in the faulted zone are disconnected, BRK_STATUS matrix and breaker zone matrix will be modified accordingly. After fault isolation the Zone_Balance matrix will also be updated and this will help in finding any unbalance in the power flows.

Zone_Balance=EtoV*$[\mathrm{BRK\_FLOW}]^T$

After finding the zone_Balance a search function looks for a positive power flow path for all the loads in the un-faulted part of the power system. If the search algorithm cannot find positive paths for all loads, it means that the generation capacity is less than the load requirement and in this case some of loads should be shut down to accommodate the available power. GA based optimization technique will help in finding the possible paths of power flows by shutting down the loads based on the type of reconfiguration. For further details on this GA based reconfiguration is available in [46].

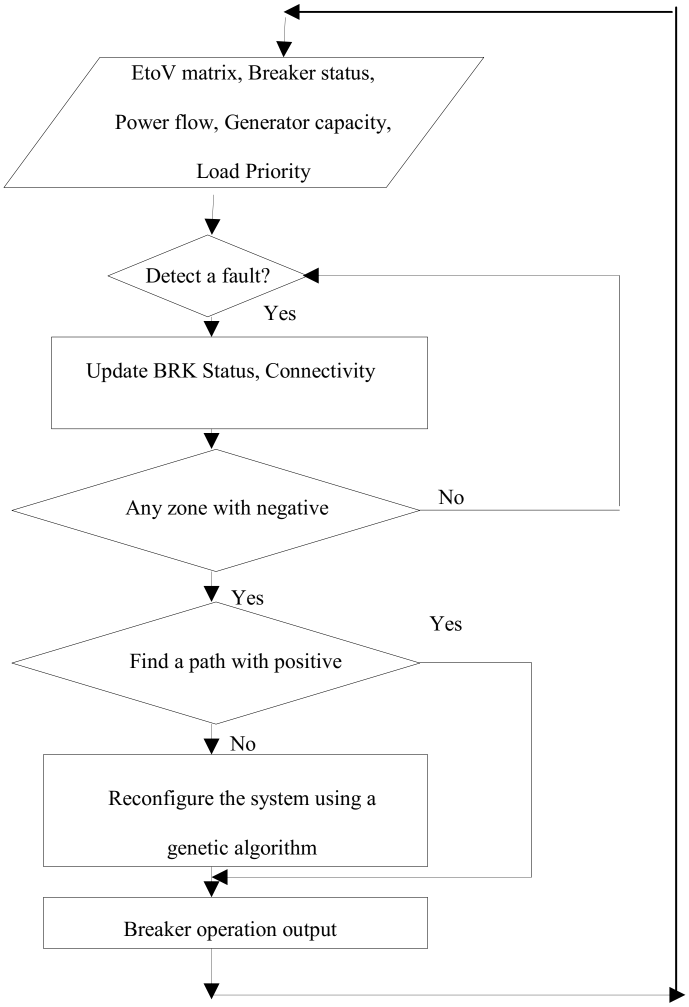


Figure 4.12 Flow chart of GA based reconfiguration [46]

4.5.1 Reconfiguration using actual power flow values (Type A)

For the system shown in fig. 4.10, the power flow program was run and all values of MW flows were noted. These values were considered the true values. The data set shown on the demonstration system in Fig. 4.10 is the actual power flow values of the network. This data set was applied to the GA based reconfiguration technique explained in fig. 4.12. Based on these power flow values all the input matrices for the reconfiguration algorithm were calculated. The fitness function also has to be modified based on the type of reconfiguration. For example, to restore the power based on priority of the loads the fitness function has to be simplified by substituting $W_P = 1$ and $W_M = 0$, to restore the loads based on load maximization $W_P=0$ and $W_M=1$, and to restore the loads based on both priority and load maximization $W_P=1$ and $W_M=1$.

4.5.2 Reconfiguration with errors introduced (Type B)

Since the real data coming from meters will always have a certain amount of error associated with it, we added errors for each load value by assuming that a meter is connected at each load. Table 4.3 shows the metered value, error associated with that meter and reading with full error. Reading with full error is the meter reading after adding the positive maximum % error to it. By taking these values into consideration new power flow values were calculated. Inputs calculated based on these power flow values were applied to the reconfiguration algorithm. These details will be explained in detail in Chapter 6.

Table 4.3 Meter readings with errors introduced

Meter ID	Error %	**Power flow values (in MW)**	**Readings with full error (in MW)**
M1	±5	**2**	**2.1**
M2	±1	**20**	**20.2**
M3	±2	**2**	**2.04**
M4	±1	**2**	**2.02**
M5	±3	**20**	**20.6**
M6	±4	**2**	**2.08**

4.5.3 Reconfiguration with fuzzy correction of meter data (Type C)

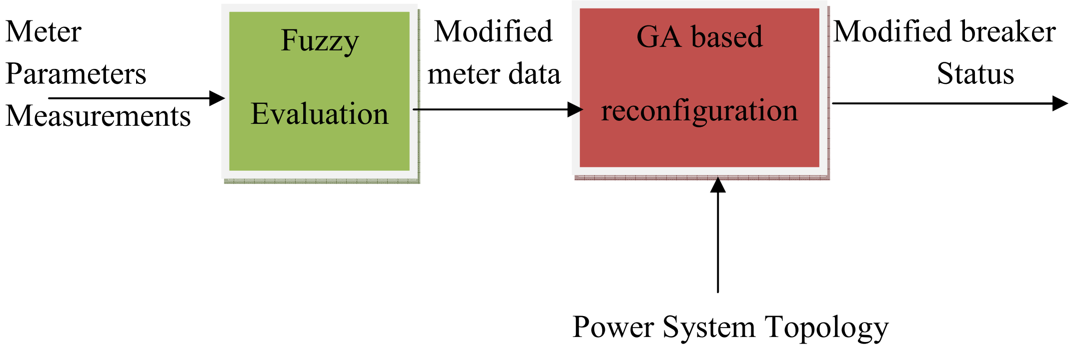


Figure 4.13 Block diagram of reconfiguration after fuzzy correction

Fig 4.13 shows the block diagram of ‘GA based reconfiguration using fuzzy correction’ for uncertain meter data. The data corrected (table 4.2) using fuzzy correction system was used to calculate the new reconfiguration schemes for different fault cases.

Results were noted for 8 bus and 13 bus test cases. These details will be explained in detail in Chapter 6.

4.6 Test cases

Two shipboard power system test cases of 8-bus and 13-bus were used. These test cases were chosen similar to those used in [46], so that the comparison of reconfiguration results with and without correcting the meter data will be easier. These models were designed based on DD(X) power system model.

4.6.1 8 bus test system [46]

This model consists of 4 generators out of which two generators G1 and G3 acts as main generators and other two generators G2 and G4 acts as auxiliary generators. In this case at base conditions breakers 5, 8, 9, 14 are open and all other breakers are closed.

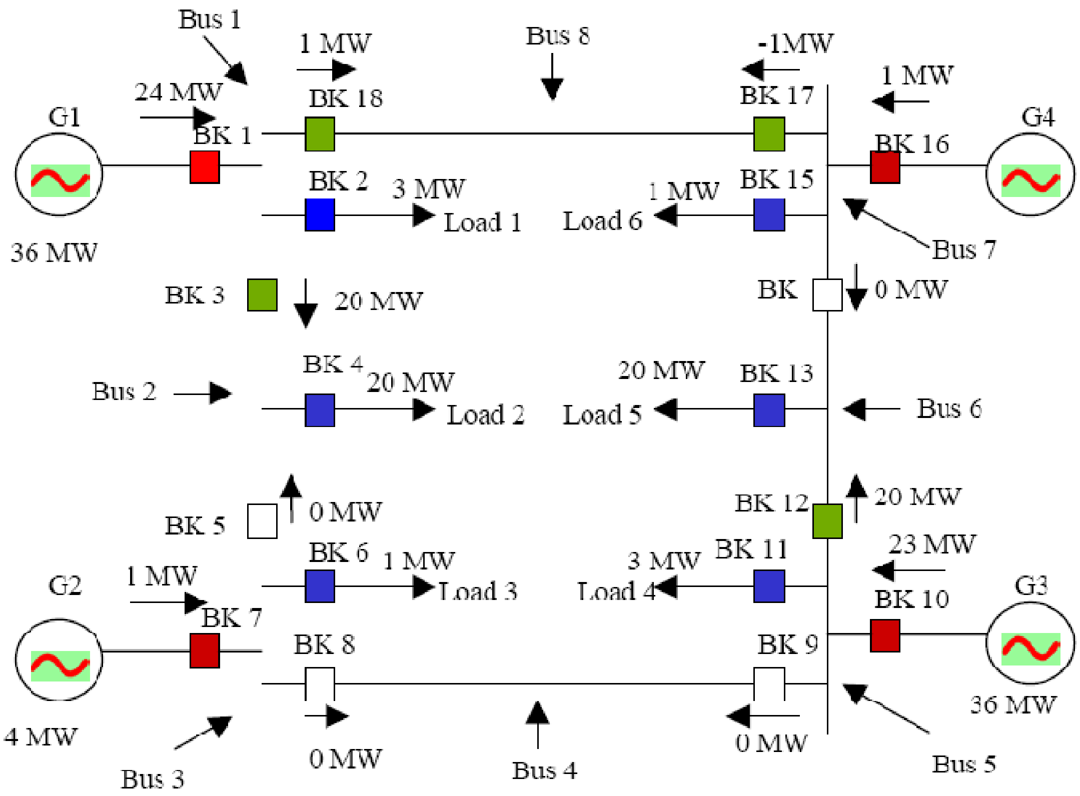


Figure 4.14 8-bus shipboard power system test case

Now by using the graph theory explained, the matrices representing the topology of the model were formulated.

S(Zone1) = [1, -1, –1, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, -1]
S(Zone2) = [0, 0, 1, -1, 1, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0]
S(Zone3) = [0, 0, 0, 0, -1, -1, 1, -1, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0]
S(Zone4) = [0, 0, 0, 0, 0, 0, 0, 1, 1, 0, 0, 0, 0, 0, 0, 0, 0, 0]
S(Zone5) = [0, 0, 0, 0, 0, 0, 0, 0, -1, 1, -1, -1, 0, 0, 0, 0, 0, 0]
S(Zone6) = [0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 1, -1, 1, 0, 0, 0, 0]
S(Zone7) = [0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, -1, -1, 1, -1, 0]
S(Zone8) = [0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 1, 1]

BRK_TYPE = [1, 3, 2, 3, 2, 3, 1, 2, 2, 1, 3, 2, 3, 2, 3, 1, 2, 2]
BRK_STATUS = [1, 1, 1, 1, 0, 1, 1, 0, 0, 1, 1, 1, 1, 0, 1, 1, 1, 1]

BRK_FLOW = [24, 3, 20, 20, 0, 1, 1, 0, 0, 23, 3, 20, 20, 0, 1, 1, -1, 1]

GEN_CAP = [1, 36; 7, 4; 10, 36; 16, 4]
LOADS = [2, 3; 4, 20; 6, 1; 11, 3; 13, 20; 15, 1]
LOAD_PRIORITY = [2, 1; 4, 150; 6, 30; 11, 1; 13, 1; 15, 150]

4.6.2 13 bus test system [46]

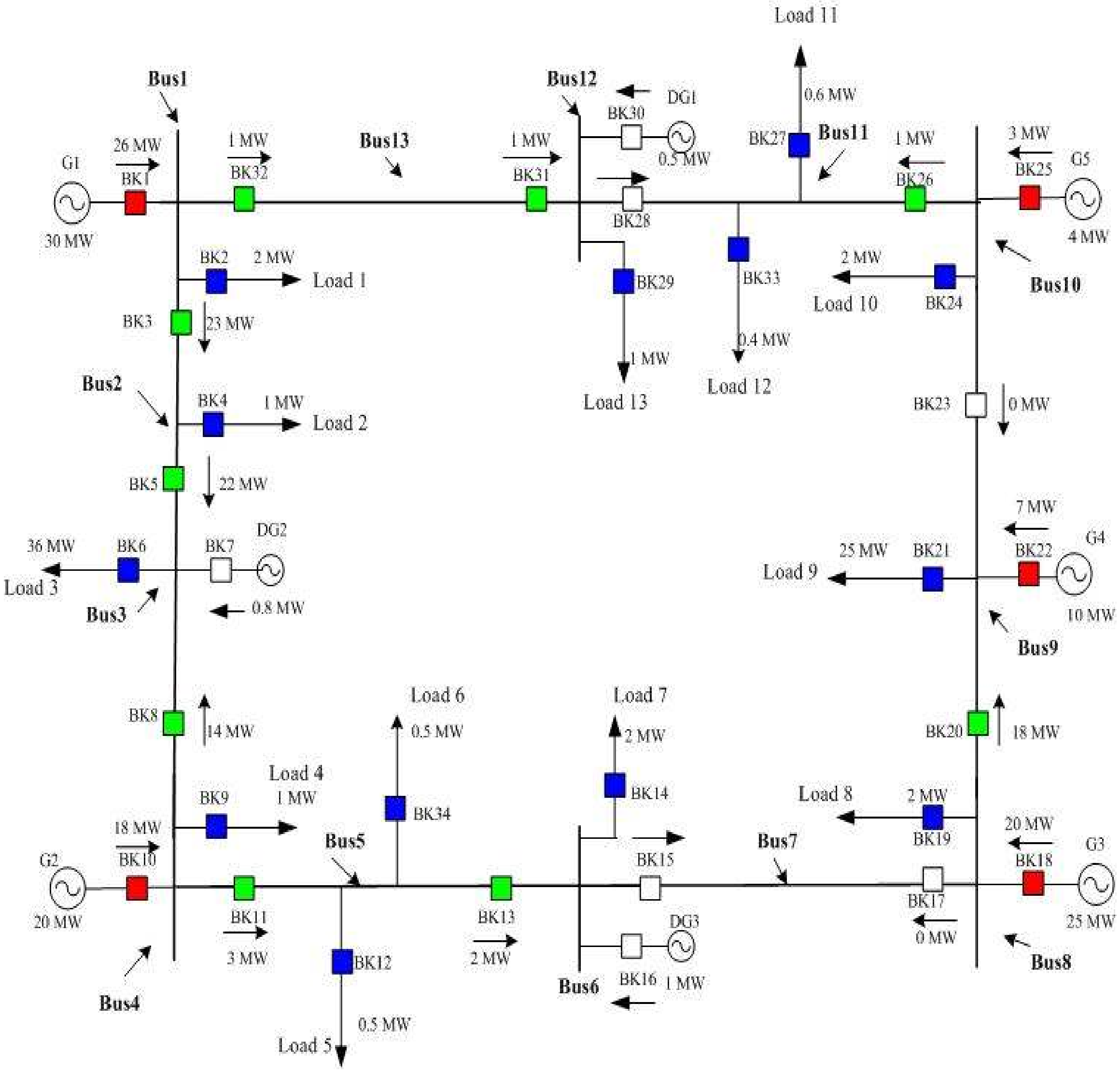


Figure 4.15 13-bus shipboard power system test case

Fig. 4.15 shows a 13 bus test system which also includes distributed generators. This system totally contains 8 generators, in these 5 generators G1, G2, G3, G4, G5 acts as main generators and three generators DG1, DG2 and DG3 acts as distributed generators. Under normal circumstances the distributed generators will be in OFF position. When there is a fault and the generation capacity from the main generation is less than load requirements then distributed generators will be switched ON. In this case at base conditions breakers 7, 15, 16, 17, 23, 28 and 30 are usually open and all other breakers were closed. By using the graph theory the 13 bus test system was formulated in matrix form as shown below.

S(Zone1) = [1 -1 -1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 -1 0 0]
S(Zone2) = [0 0 1 -1 -1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0]
S(Zone3) = [0 0 0 0 1 -1 1 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0]
S(Zone4) = [0 0 0 0 0 0 0 -1 -1 1 -1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0]
S(Zone5) = [0 0 0 0 0 0 0 0 0 0 1 -1 -1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 -1]
S(Zone6) = [0 0 0 0 0 0 0 0 0 0 0 0 1 -1 -1 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0]
S(Zone7) = [0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0]
S(Zone8) = [0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 -1 1 -1 -1 0 0 0 0 0 0 0 0 0 0 0 0 0 0]
S(Zone9) = [0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 -1 1 1 0 0 0 0 0 0 0 0 0 0 0]
S(Zone10) = [0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 -1 -1 1 -1 0 0 0 0 0 0 0 0]
S(Zone11) = [0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 -1 1 0 0 0 0 -1 0]
S(Zone12) = [0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 -1 -1 1 1 0 0 0]
S(Zone13) = [0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 -1 1 0 0 0 0 0]

Based on the actual power flow values and ratings of the machines below matrices were formed.

BRK_TYPE = [1, 3, 2, 3, 2, 3, 1, 2, 3, 1, 2, 3, 2, 3, 2, 1, 2, 1, 3, 2, 3, 1, 2, 3, 1, 2, 3, 2, 3, 1, 2, 2, 3, 3]

BRK_STATUS = [1 ,1, 1, 1, 1, 1, 0, 1, 1, 1, 1, 1, 1, 1, 0, 0, 0, 1, 1, 1, 1, 1, 0, 1, 1, 1, 1, 0, 1, 0, 1, 1, 1, 1]

BRK_FLOW = [26, 2, 23, 1, 22, 36, 0, 14, 1, 18, 3, 0.5, 2, 2, 0, 0, 0, 20, 2, 18, 25, 7, 0, 2, 3, 1, 0.6, 0, 1, 0,1, 1, 0.4, 0.5]

GEN_CAP = [1 30; 7 0.8; 10 20; 16 1;18 25;22 10;25 4;30 0.5]

LOADS = [2, 2;4, 1;6, 36;9, 1;12, 0.5;34, 0.5;14, 2;19, 2;21, 25;24, 2;27, 0.6;33, 0.4;29, 1]

LOAD_PRIORITY = [2, 95; 4, 1; 6, 95; 9, 1; 12, 95;34,1; 14, 9000;19, 1;21, 9000;24, 95;27,1;33 95;29,1]

4.7 Summary

In this chapter the description of research problem and the approach chosen were discussed. The rule based fuzzy correction of meter data coupled with GA technique was explained with examples. The 8-bus test case and 13-bus test case, their basic structure, and matrix formulation with the help of graph representation were also explained in this chapter.

CHAPTER 5

RESULTS AND DISCUSSIONS FOR HUMAN SYSTEMS INTERACTION

5.1 Introduction

This chapter describes quantitative analysis of the quality of decision making in aided and unaided interfaces. Furthermore cognitive walkthrough and error analysis in the interest of improving aided interface are explained.

5.2 Unaided interface Vs aided interface

For each user, scoring was given for his/her response, i.e. 12 scores were given for 12 problems. These scores for 10 users are analyzed in two ways, one by looking at the quality of decision taken for each individual problem by all the users for unaided and aided problem, and two by looking at the quality of decision taken by each user for all the problems in unaided and aided interface. Errors made by users in unaided and aided interfaces were also discussed in this section.

As explained in Chapter 3, users are scored based on their responses to the tasks. For example let us consider a task in unaided interface in which the scenario states that "The ship has been damaged due to an ongoing enemy attack. The captain has ordered that all offensive systems remain available. Please reconfigure the system given the current condition" and the power system given to the users was shown in fig 5.1. Generator 4 got damaged due to enemy attack and due to this some of the lines shown in red color got overloaded as well. Now the user has to solve the problem based on the given scenario and power system.

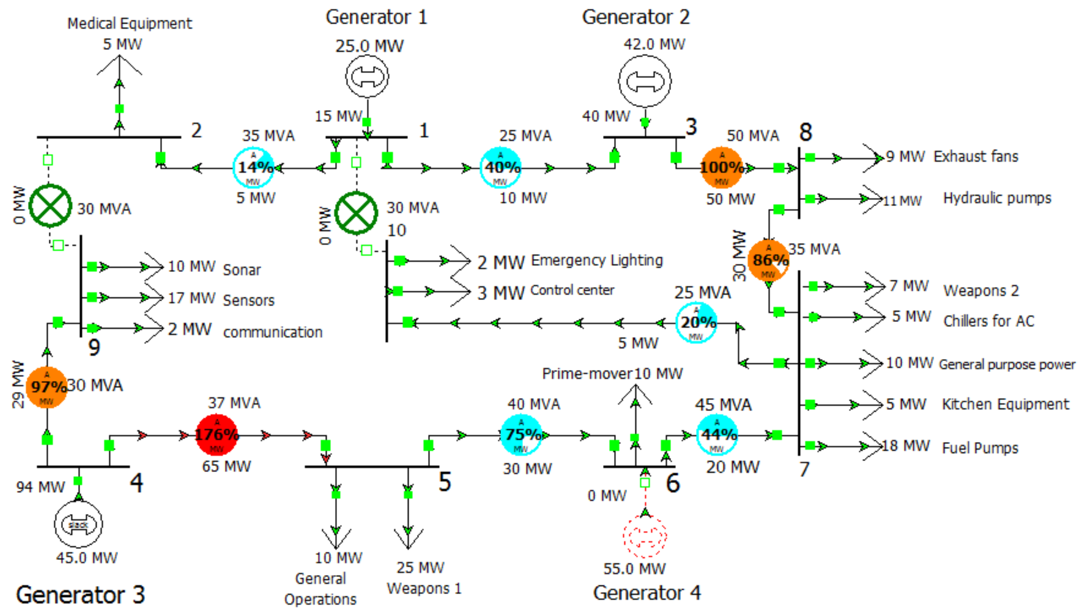


Figure 5.1 Power system network before reconfiguration

For the problem an optimal solution should take care of the important loads so that they remain powered and should avoid any overloading problems. One of the users had given below response shown in fig 5.2 as the solution for the problem. In this response, we can see most of the important loads like sonar, communications, weapons, fuel pumps and prime mover loads were fed. But line between Bus 7 and Bus 8 was overloaded and load sonar connected to Bus 9 was not fed. This response was given a score of 5 out of 10. Responses that don’t violate any constraints were given a score of 10 and responses that violate most of the constraints are given zero. All the responses for all the users were scored using this approach. Scores of all responses were summed up and normalized on scale of 10. The same method was followed to score aided interface responses.

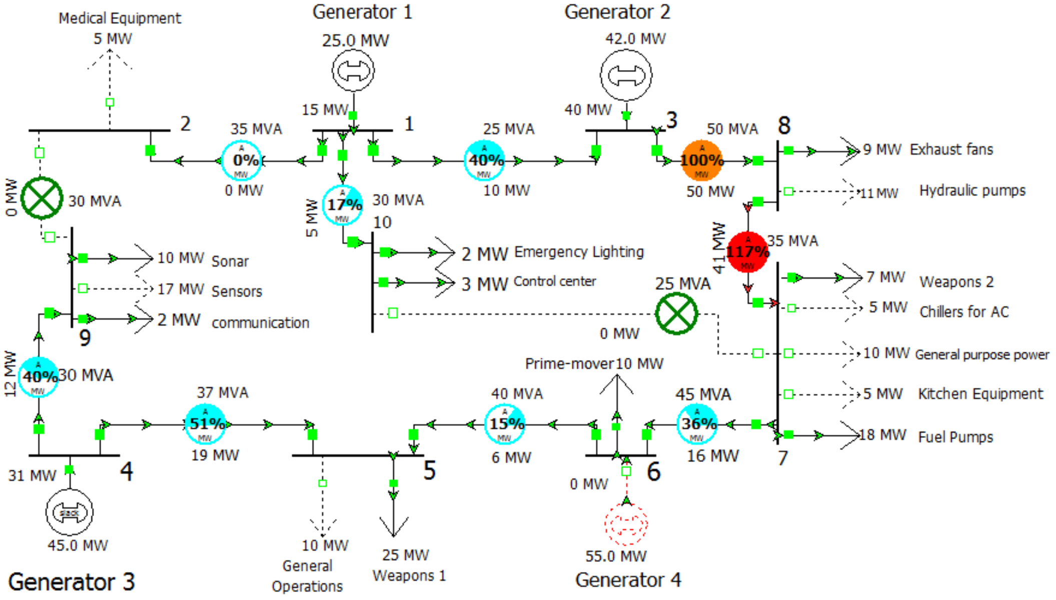


Figure 5.2 Power system network as the reconfiguration solution given by a user

5.2.1 Decision quality

Table 5.1 shows the mean and standard deviation of the decision quality scores for the six matched problem sets when using the aided and the unaided systems across 10 subjects. As indicated in the Table 5.1, the mean decision quality score when using the aided interface was 6.8, higher than when using the unaided interface 3.4. Overall, then, the quality of reconfiguration decisions made by trained electrical engineers doubled when using the aided interface. The results are depicted graphically in fig 5.3. It can also be observed that for each individual problem, the quality of decision taken for aided interface was superior to unaided interface.

Table 5.1 Decision quality for aided and unaided interfaces for matched problems

Matched problems	Mean Aided	S.D Aided	Mean Unaided	S.D Un aided
1	8.0	2.6	5.5	2.8
2	5.0	5.3	1.4	2.3
3	4.0	4.6	3.5	3.4
4	6.5	3.4	3.0	2.6
5	8.0	4.2	2.2	2.5
6	9.5	1.6	5.0	2.4
Total	41.0	21.6	20.6	15.9
Mean	6.8	3.6	3.4	2.7

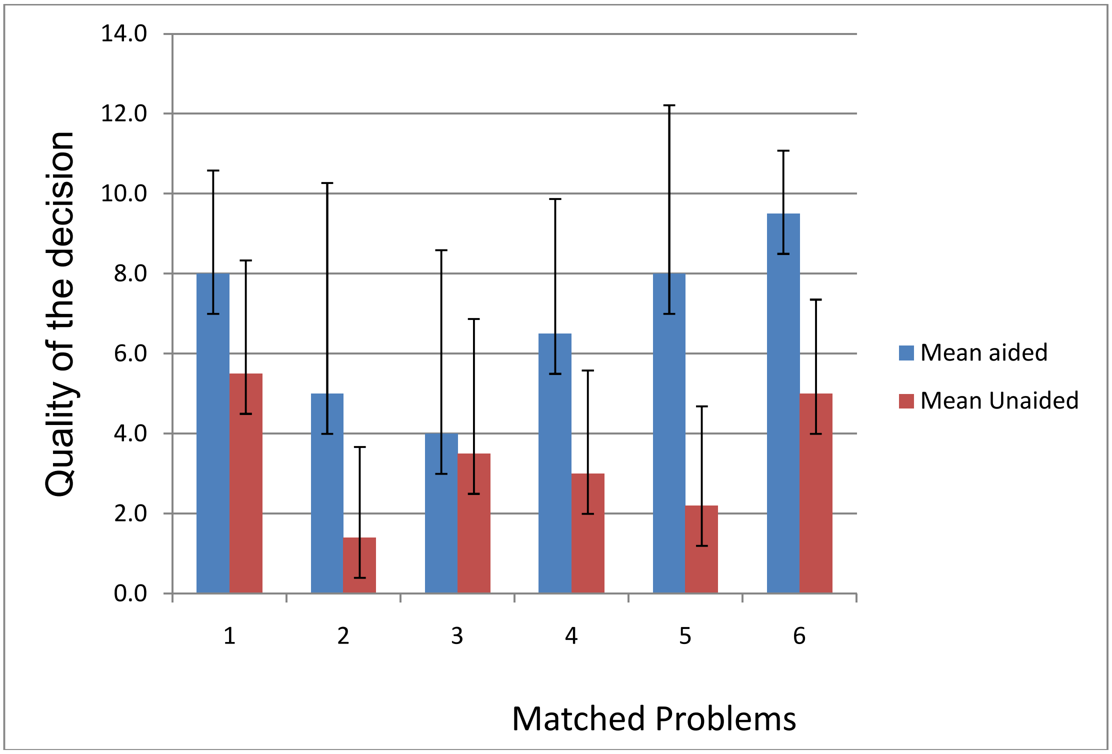


Figure 5.3 Quality of decision compared for aided and unaided interfaces for matched problems

Table 5.2 shows the scoring of each individual user for all 12 tasks compared between aided and unaided interfaces. From the table we can say that on an average user performed superior in aided interface when compared with unaided interface. Also from the table each individual user for all the problems performed superior to unaided interface. Fig. 5.4 shows the graphical view of scoring of each individual user for all 12 tasks compared between aided and unaided interfaces.

Table 5.2 Decision quality for aided and unaided interfaces for different subjects

User Number	Mean Aided	S.D Aided	Mean Un aided	S.D Un aided
User 1	8.3	2.6	1.7	2.6
User 2	7.5	4.2	3.3	2.6
User 3	9.2	2.0	5.0	3.2
User4	5.8	4.9	2.5	4.2
User 5	7.5	4.2	4.2	3.8
User 6	7.5	4.2	4.3	1.2
User 7	5.8	4.9	2.5	2.7
User 8	2.5	4.1	1.7	2.7
User 9	8.3	4.1	5.8	2.0
User 10	5.0	4.5	2.5	2.7
Total	67.5	39.6	33.5	27.7
Mean	6.8	4.0	3.4	2.8

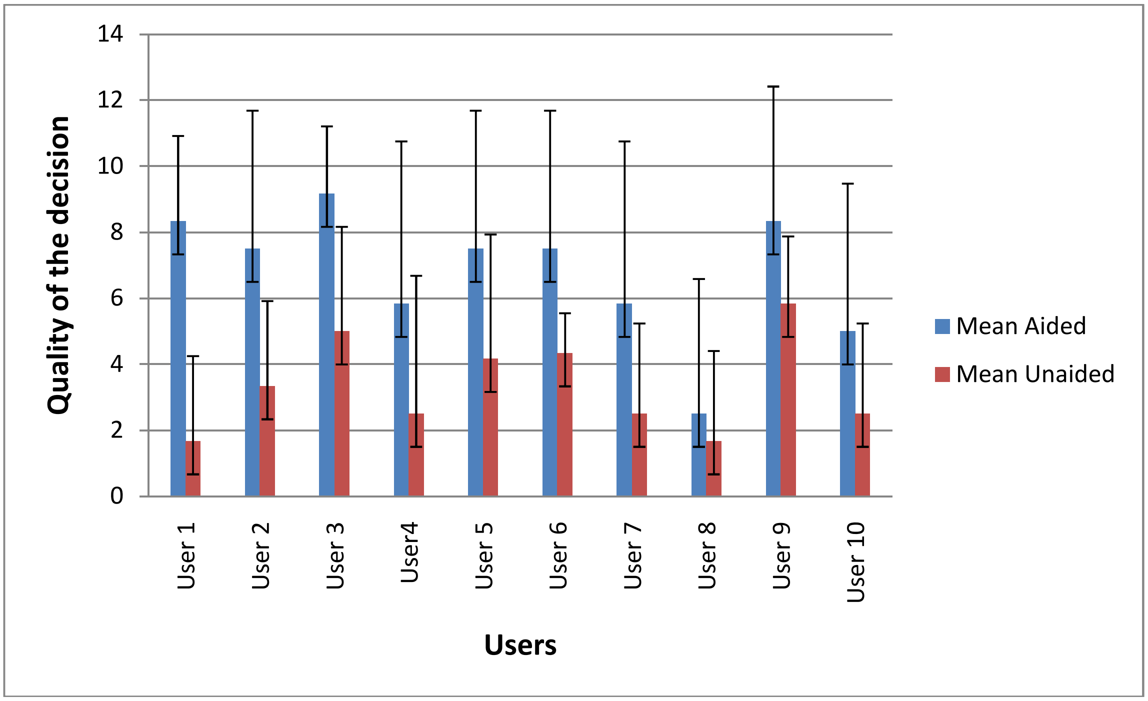


Figure 5.4 Quality of decision compared for aided and unaided interfaces for different users

5.2.2 Decision quality

User responses were analyzed in the context of 'what errors made them to not come up with the optimum solution for a task'. Different errors made by users in the interaction were, either important loads were not fed or the solution contains violations on the constraints posed. Each violation of a constraint or load requirement was counted as one error. Table 5.3 shows the error count for each user for aided and unaided interfaces. Taking average of the errors for ten users, each user committed 6.7 errors in unaided interface where as only 1.2 errors were made in aided interface.

Table 5.3 Errors made by users in unaided and aided interfaces

	error type	User 1	User 2	User 3	User 4	User 5	User 6	User 7	User 8	User 9	User 10	**Total**	
Unaided	Important loads were not fed	3	4	2	4	3	4	4	4	4	4	**36**	**67**
	Constraints were not met	2	3	4	2	4	4	2	2	5	3	**31**	
Aided	Important loads were not fed	0	0	0	0	0	0	1	0	1	0	**2**	**12**
	Constraints were not met	2	1	1	1	1	0	1	2	0	1	**10**	

With the unaided interface, the user must continuously make notes of the different loads and their intended use in the ship, constraints on the power system network and reconfiguration based on the situation of the ship. The above mentioned errors can be counted against working memory problems because users may forget that the lines and generators should not be overloaded, while trying to keep the important loads in the system. It is also possible to forget to maintain power for the important loads while trying to meet other constraints.

The aided interface inherently takes care of most of the user’s memory requirements and routine errors. Here the chance of missing a load or overloading a line or generator was very minimal because these routine problems were taken care while designing the interface with DSS. With this the number of errors that we can see in the unaided interface was greatly reduced in the aided interface. The problems belonging to working memory problem are reduced to great extent in aided interface. This is evident from the error table. From this table it can be observed that working memory problems were mostly eliminated from aided interface and also the scope of making has been reduced significantly.

5.3 Cognitive walkthrough studies

Cognitive walkthrough studies were carried out for the aided interface. The user's overall goal of reconfiguring the power system network using the aided interface was divided into below seven intermediate tasks.

1) *Read the scenario*: This is the first step of the user to read and understand the ship conditions and machine of operation that the ship is in.
2) *Select the alarm zone in top level ship monitor*: Now as per the feedback in alarm window, user has to select the appropriate zone of the ship to diagnose the problem in that particular zone.
3) *Select the alarmed zone in power system network*: As per the problem, interface takes the user to next lower level of the ship to look into the problem.
4) *Select the simulation*: At this stage user can look into the component level of the ship monitoring interface. After looking into the problem, user has to select the simulation button to see the different solution options available.
5) Go-*through/evaluate the simulations*: Compare different solution suggested by simulation and evaluate them to come up with best possible solution.
6) *Select the best suitable configuration as the reconfiguration solution*: At this stage user selects the best simulation option as the solution for the problem.
7) *Confirm the action taken*: here user has to confirm the action just taken.

Each task contains 9 atomic actions explained on the designer walkthrough sheet. For each atomic action and for each task designer a walkthrough sheet will be prepared. For each user, 9*7=63 walkthrough sheets were prepared. Now the designer has to interact with an interface and fill in the designer walkthrough sheet. All tasks and each atomic action should be checked by the designer. In the designer walkthrough, the designer will come up with the list of problems that he/she is expecting in the interface. Below table 5.4 shows the summary of designer walkthrough for aided interface. All the user reactions while interacting with the interface should be documented in user walkthrough sheet as shown in table 5.5. The User walkthrough sheet typically looks similar to the Designer walkthrough sheet but it should be filled by the experimenter while the user interacting with the system.

Table 5.4 Designer walkthrough sheet

Action/subgoal	Expected # of users, who will have problems 0=none, 1=some, 2=more than half, 3=most	Why problems may occur and solution
1) Read Through the scenario	0	
2) Select the alarmed zone in ship	1	Problem: Alarmed zone color, and alarm color should have been matching Solution: make alarm and ship zone sin same color
3) Select the alarmed zone in power system network	1	Problem: Alarmed zone color, and alarm color should have been matching Solution: make alarm and power system zone sin same color
4) Select the simulation	0	
5) Check the three simulation options available	0	
6) Select the best for given scenario	0	
7) Confirmation on action taken	0	

For task 1, one user expressed that the explanation of a scenario has to be more elaborate. The user requested to define the words such as war situation, normal situation, and safe operation which were used in explaining the scenario. Experimenters/designers assumed the meanings of the words were obvious. Making the scenarios more informative will solve this problem.

For tasks 2, 3 and 4 users did not report any problems. For task 5, two users reported problems in comparing the three simulation options. Since the interface doesn't provide any flexibility in placing the three simulation options side by side, comparing the options in smaller details demands higher cognitive memory resources and consumes time. To solve this problem, interface can be modified to allow the user to place three simulation options side by side.

For task 6, two users reported problems in identifying the load types. It was observed that users were consuming more time in identifying the loads as per their intended usage. Color coding of loads as per their type will resolve this problem and enables the user to act fast on the problem. Also improving of size of the text for loads shall help them in acting fast.

For task 7 users did not report any problems.

Table 5.5 User cognitive walkthrough sheet

Action/subgoal	Actual # of users, who will have problems 0=none, 1=some, 2=more than half, 3=most	Why problems may occur and solution
1) Read Through the scenario	1 person	Problem: Explanation of the given scenario is not well enough Solution: Make scenario more narrative and informative (what is war situation, what is normal situation, different loads that need not to be on all time)
2) Select the alarmed zone in ship	**0**	
3) Select the alarmed zone in power system network	**0**	
4) Select the simulation	0	
5) check the three simulation options available	2 person	Problem: Red color is not highly prominent/visible Solution: Increase the intensity of red color Problem: Ability to not keep all three option side by side, made it difficult to compare the simulations options Solution: Interface design should be changed to make all three options to view side by side.
6) Select the best for given scenario	2 persons	Problem: Text is not big enough, Identifying loads was difficult, Comparing the options was difficult Solution: Put all 3 options side by side to compare easily, increase text size and loads should be color coded
7) Confirmation on action taken	0	

Below table 5.6 shows the comparison of problems that were predicted by the designer to the problems that the user really has.

Table 5.6 Walkthrough summary sheet for actual Vs predicted

Action/Sub goal	Actual/predicted
1) Read Through the scenario	1/0
2) Select the alarmed zone in ship	0/1
3) Select the alarmed zone in power system network	0/1
4) Select the simulation	0/0
5) check the three simulation options available	2/0
6) Select the best for given scenario	2/0
7) Confirmation on action taken	0/0

From the table 5.6, it can be observed that overall six users reported problems at three actions or subtasks. Though the designer also predicted two problems at two different cognitive tasks, the users didn't report them as problems. However, combination of prototype testing on users and designers expectation of the problems allowed the interface to overcome a wide variety of problems.

5.4 Design recommendations for aided interface

Based on the cognitive walkthrough and error analysis these are possible design recommendations made for the redesign of the interface. This is not an exhaust list and some are speculative but rational comparison of the data.

1) Place the three simulation options side by side for users to compare them easily.

   Explanation: Since the interface doesn't allow the user to place all three simulation options side by side, the user has to click each action one after other and remember the old option to compare with the active option. To click each one and possibly make mental comparisons between them, it takes time. On an average each user is viewing a total of twelve simulation option screens per problem.

2) Increase the thickness of red color to differentiate easily from other normal components.

   Explanation: Identifying the red colored objects is an important task before reconfiguring the system. This process possibly can be made faster by making the red color more prominent or visible compared with other. This can be changed with new screen shots having richer red color.

3) Remove "go offline" button.

   Explanation: From the user walkthrough studies we find that some users are clicking on "go offline" button in the interface. While looking at the simulation options we assume that the system is in offline mode and no separate selection is required to go to offline mode. So this button can be removed or faded to avoid confusion for the users. Further analysis on user intentions on clicking on this button will be useful to draw firm conclusion on this issue.

4) Number each load according to the load group (essential loads, tactical loads, general loads etc.) it belongs to.

   Explanation: Identification of each load and the type of load is very important to reconfigure the power system. In the interface irrespective of its type, all loads were shown in same color and in same manner. Any modifications in the interface to make users identify the type of loads easily are required. Numbering the loads as per their type is one way to differentiate the loads.

5) Show a different fault zone for each different problem.

   Explanation: Since we kept the same zone as faulted zone for all problems, users are not looking into the alarm at all. Change in the alarming zone in the problems may bind them to look into the alarm message in the interface.

6) Modify the text of scenario to easily understand the situation that the ship is in.

   Explanation: Text in the scenario sheet was not clear for all. Some users want explanation of war situation, normal condition and other words used in the text.

5.5 Summary

In this chapter it was demonstrated that the decision quality resulting from user of the aided interface was superior to unaided interface. Affect of aided interface (with DSS) in the performance of users was quantitatively analyzed. With the help of error analysis and cognitive walkthrough analysis, possible design recommendations are made for improving the aided interface.

CHAPTER 6

RESULTS AND DISCUSSION FOR POWER SYSTEM RECONFIGURATION

6.1 Introduction

In this chapter the reconfiguration results with and without correcting uncertainty in meter data are explained for the 8 bus and 13 bus test cases. To demonstrate the effect of uncertainty and fuzzy correction system on reconfiguration results, results were compared and analyzed case by case. The genetic algorithm based reconfiguration was used for all types of data and for both test cases.

6.2 Test Case I – 8 bus SPS

The 8 bus test system explained in Chapter 4 was tested using the GA based reconfiguration technique for three kinds of data Type A, Type B and Type C.

6.2.1 Reconfiguration with actual power flow values (Type A)

By using the actual power flow values for the test system, input matrix can be formed. This work is similar to [46], and is repeated in this chapter for the flexibility of the reader.

S(Zone1) = [1, -1, –1, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, -1]
S(Zone2) = [0, 0, 1, -1, 1, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0]
S(Zone3) = [0, 0, 0, 0, -1, -1, 1, -1, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0]
S(Zone4) = [0, 0, 0, 0, 0, 0, 0, 1, 1, 0, 0, 0, 0, 0, 0, 0, 0, 0]
S(Zone5) = [0, 0, 0, 0, 0, 0, 0, 0, -1, 1, -1, -1, 0, 0, 0, 0, 0, 0]
S(Zone6) = [0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 1, -1, 1, 0, 0, 0, 0]
S(Zone7) = [0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, -1, -1, 1, -1, 0]
S(Zone8) = [0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 1, 1]

BRK_TYPE = [1, 3, 2, 3, 2, 3, 1, 2, 2, 1, 3, 2, 3, 2, 3, 1, 2, 2]
BRK_STATUS = [1, 1, 1, 1, 0, 1, 1, 0, 0, 1, 1, 1, 1, 0, 1, 1, 1, 1]

BRK_FLOW = [24, 3, 20, 20, 0, 1, 1, 0, 0, 23, 3, 20, 20, 0, 1, 1, -1, 1]
GEN_CAP = [1, 36; 7, 4; 10, 36; 16, 4]
LOADS = [2, 3; 4, 20; 6, 1; 11, 3; 13, 20; 15, 1]
LOAD_PRIORITY = [2, 1; 4, 150; 6, 30; 11, 1; 13, 1; 15, 150]

We created faults on Bus 1, Bus 3, Bus 5, Bus 7, Buses 1and 3, Buses 1 and 5, and Buses 5 and 7 separately for all three kinds of objective functions of reconfiguration.

- *Reconfiguration based on load priority:*

  In this case objective function of the reconfiguration is to reconfigure the power system by following the priority of the loads. Reconfiguration results were included in APPENDIX A in table A.1.1 for different fault cases.

- *Reconfiguration without considering load priority*

  In this case objective function of reconfiguration is to maximize the power served to loads by following equal priority to all the loads. Reconfiguration results were included in APPENDIX A in table A.1.2 for different fault cases.

- *Reconfiguration using both priority and magnitude factor*

  In this case the objective function of the reconfiguration algorithm is to follow both priority and magnitude factor of the loads. Reconfiguration results were included in APPENDIX A in table A.1.3 for different fault cases.

6.2.2 Reconfiguration with errors introduced (Type B)

Based on the errors introduced in meter readings, see Table 4.3, new power flow values are calculated. Inputs to the GA based reconfiguration algorithm are changed accordingly. Below are the inputs for reconfiguration algorithm.

S(Zone1) = [1, -1, –1, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, -1]
S(Zone2) = [0, 0, 1, -1, 1, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0]
S(Zone3) = [0, 0, 0, 0, -1, -1, 1, -1, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0]
S(Zone4) = [0, 0, 0, 0, 0, 0, 0, 1, 1, 0, 0, 0, 0, 0, 0, 0, 0, 0]
S(Zone5) = [0, 0, 0, 0, 0, 0, 0, 0, -1, 1, -1, -1, 0, 0, 0, 0, 0, 0]
S(Zone6) = [0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 1, -1, 1, 0, 0, 0, 0]
S(Zone7) = [0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, -1, -1, 1, -1, 0]
S(Zone8) = [0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 1, 1]

BRK_TYPE = [1, 3, 2, 3, 2, 3, 1, 2, 2, 1, 3, 2, 3, 2, 3, 1, 2, 2]
BRK_STATUS = [1, 1, 1, 1, 0, 1, 1, 0, 0, 1, 1, 1, 1, 0, 1, 1, 1, 1]

BRK_FLOW = [24.35, 3.15, 20.2, 20.2, 0, 1.02, 1.02, 0, 0, 23.63, 3.03, 20.6, 20.6, 0, 1.04, 1.04, -1, 1];
GEN_CAP = [1, 36; 7, 4; 10, 36; 16, 4]
LOADS = [2, 3; 4, 20; 6, 1; 11, 3; 13, 20; 15, 1]
LOAD_PRIORITY = [2, 1; 4, 150; 6, 30; 11, 1; 13, 1; 15, 150]

Section A.2 of APPENDIX shows the reconfiguration results with full error values and considering priority of the loads in table A.2.1, without considering priority of the loads in table A.2.2 and considering both priority and magnitude factor in table A.2.3.

6.2.3 Reconfiguration with fuzzy correction of meter data (Type C)

Table 6.1 shows the error adjustment of six meters based on fuzzy correction system. Error% for all the meters is readjusted with de-fuzzified trust value. Last column in table, ‘readings after error adjustment’ indicate the new meter data after fuzzy correction. By using these values new power flow values were calculated and accordingly input matrices for the reconfiguration program are modified.

Table 6.1 8-bus system-meter data along with fuzzy corrected readings

Meter ID	Error %	Degree of confidence	Reliability	Age	de fuzzified Trust	output	**Power flow values (in MW)**	error adjustment	**Readings after error adjustment (in MW)**
M1	5	96	0.11	0.2	0.735	Low	**3**	3.675	**3.11025**
M2	1	96	0.12	0.55	0.323	Medium	**20**	0.323	**20.0646**
M3	2	99	0.3	0.3	0.323	Medium	**1**	0.646	**1.00646**
M4	1	97	0.1	0.36	0.289	High	**3**	0.289	**3.00867**
M5	3	96	0.25	0.45	0.5	Medium	**20**	1.5	**20.3**
M6	4	98	0.4	0.77	0.826	Low	**1**	3.304	**1.03304**

Input matrices:

S(Zone1) = [1, -1, –1, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, -1]
S(Zone2) = [0, 0, 1, -1, 1, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0]
S(Zone3) = [0, 0, 0, 0, -1, -1, 1, -1, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0]
S(Zone4) = [0, 0, 0, 0, 0, 0, 0, 1, 1, 0, 0, 0, 0, 0, 0, 0, 0, 0]
S(Zone5) = [0, 0, 0, 0, 0, 0, 0, 0, -1, 1, -1, -1, 0, 0, 0, 0, 0, 0]
S(Zone6) = [0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 1, -1, 1, 0, 0, 0, 0]
S(Zone7) = [0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, -1, -1, 1, -1, 0]
S(Zone8) = [0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 1, 1]

BRK_TYPE = [1, 3, 2, 3, 2, 3, 1, 2, 2, 1, 3, 2, 3, 2, 3, 1, 2, 2]
BRK_STATUS = [1, 1, 1, 1, 0, 1, 1, 0, 0, 1, 1, 1, 1, 0, 1, 1, 1, 1]

BRK_FLOW = [24.17485, 3.11025, 20.0646, 20.0646, 0, 1.00646, 1.00646, 0, 0, 23.300867, 3.00867, 20.3, 20.3, 0, 1.00304, 1.00304, -1, 1];
GEN_CAP = [1, 36; 7, 4; 10, 36; 16, 4]
LOADS = [2, 3; 4, 20; 6, 1; 11, 3; 13, 20; 15, 1]
LOAD_PRIORITY = [2, 1; 4, 150; 6, 30; 11, 1; 13, 1; 15, 150]

Section A.3 of APPENDIX shows the reconfiguration results using fuzzy correction of meter data and considering priority of the loads in table A.3.1, without considering priority of the loads in table A.3.2, and considering both priority and magnitude factor in table A.3.3.

6.2.4 Comparison of Type A, Type B and Type C

Reconfiguration results presented in section A of Appendix are compared for three objective functions of reconfiguration. The Norm_2 is defined as the 'square root of the sum of the squares of the variable'. We used Norm_2 in this study to look at the difference between three types of reconfiguration results. Norm_2 is also known as Euclidean norm.

- *Reconfiguration based on priority of the loads*

Table 6.2 shows the comparison of reconfiguration results by following priority of the loads and reconfigured based on actual power flow values, with errors introduced and with the data corrected with fuzzy correction system. The results obtained in Type A are considered as the actual or best results because in Type A actual power flow values are used.

In case 1, we created a fault on Bus 1 and run the reconfiguration program for three types of data. In type A, algorithm isolated bus 1 and all those connected to bus 1. Breaker status in the table indicates the circuit breakers that need to be opened and closed. In Type A breakers 11, 1, 2, 3, 18 are opened and breakers 5, 9, 14 are closed. Breakers 1, 2, 3, and 18 are directly connected to bus 1 and load 4 was shut down by opening the breaker 11. By the isolation of breaker 1, source G1 was out of the system. Now to match the supply with demand some of the loads have to be disconnected. The reconfiguration algorithm by following its objective function, i.e. priority of the loads, shuts down the low priority load/loads. The MW served indicates the total MW supplied by the generators after reconfiguration. In the same manner the test system was tested for different faults.

D1 in the table represents the square of the difference of MW served between Type A and Type B reconfiguration schemes and D2 represents the square of the difference of MW served between Type A and Type C. Now Norm2 for reconfiguration results of Type A and Type B is √D1 and for Type A and Type C is √D2. From the table Norm2 for D1 is higher than D2, i.e. the results obtained in Type C are closer to Type A results. This indicates that the fuzzy correction system is helping in reducing the effect of uncertainty present in meter data.

Table 6.2 8-bus system-comparison of reconfiguration results based on priority of the loads

CASE	Faulted Bus	With Power flow values (Type A)			Reconfiguration with error introduced (Type B)			With corrected errors using Fuzzy evaluation (Type C)			Square of the difference	
		Breaker Status	**Load shedding**	**MW served**	**Breaker Status**	**Load shedding**	**MW served**	**Breaker Status**	**Load shedding**	**MW served**	D1	D2
Case 1	**B1**	BK *11,* 1, 2, 3, 18 (O); BK 5, 9, 14 ('C)	L4	42	BK *11,* 1, 2, 3, 18 (O) BK 5, 8, 9, 14 (C)	L4	42.86	BK *11,* 1, 2, 3, 18 (O) BK 5, 8, 9, 14 (C)	L4	42.37 41	0.73 96	0.139 95
Case 2	**B3**	BK 6,7 (O)	No	Zero	BK 6,7 (O)	No		BK 6,7 (O)	No	Zero	0	0
Case 3	**B5**	BK *2* , 10, 11, 12 (O); BK 14, 5,8 (C)	L1	42	BK *6* ,15, 10, 11, 12 (O) BK 14, 5,8 (C)	L3, L6	43.95	BK *6* ,15, 10, 11, 12 (O) BK 14, 5,8 (C)	L3, L6	43.47 49	3.80 25	2.175 1825
Case 4	**B7**	BK 15, 16, 17 (O)	No	Zero	BK 15, 16, 17 (O)	No	Zero	BK 15, 16, 17 (O)	No	Zero	0	0
Case 5	**B1, B3**	BK *4,* 1, 2, 3, 18, 6, 7 (O)	No	Zero	BK *4,* 1, 2, 3, 18, 6, 7 (O)	L2	Zero	BK *4,* 1, 2, 3, 18, 6, 7 (O)	No	Zero	0	0
Case 6	**B1, B5**	BK *4, 13* , 1, 2 ,3 ,18, 10, 11, 12(O); BK 5, 8, 14 (C)	L2 L5	1 1	BK *4, 13* , 1, 2 ,3 ,18, 10, 11, 12(O) BK 5, 8, 14 (C)	L2 L5	1.02 1.04	BK *4, 13* , 1, 2 ,3 ,18, 10, 11, 12(O) BK 5, 8, 14 (C)	L2 L5	1.003 04; 1.006 46	0.00 04 0.00 16	9.242 E-06 4.173 E-05
Case 7	**B3, B7**	BK 6,7 15, 16, 17 (O)	No	Zero	BK 6,7 15, 16, 17 (O)	No	Zero	BK 6,7 15, 16, 17 (O)	No	Zero	0	0
Case 8	**B5, B7**	BK *13,* 10, 11, 12, 15, 16, 17 (O)	No	Zero	BK *13,* 10, 11, 12, 15, 16, 17 (O)	L5	Zero	BK *13,* 10, 11, 12, 15, 16, 17 (O)	No	Zero	0	0
									Total		4.54 41	2.315 18
									Norm 2		**2.13 16**	**1.521 57**

From the table in Case 5, in type B reconfiguration it suggests to shut down the load 2 while type A and type C doesn't recommend any load be disconnected. This indicates the misoperation of the power system due to uncertainty in the data. Except the MW served and Case 5 all reconfiguration data looks similar for Type A, Type B and Type C data.

- *Reconfiguration without considering load priority*

Table 6.3 shows the comparison of reconfiguration results without following priority of the loads and reconfigured based on actual power flow values, with errors introduced and with the data corrected with fuzzy correction system. From the table Norm2 for D1 is much higher than D2, i.e. the results obtained in Type C are closer to Type A results.

Table 6.3 8-bus system-Comparison of reconfiguration results without considering priority of the loads

CASE	**Faulted Bus**	**With Power flow values (Type A)**			**Reconfiguration with error introduced (Type B)**			**With corrected errors using Fuzzy evaluation (Type C)**			**Square of the difference**	
		Breaker Status	**Load shedding**	**MW served**	**Breaker Status**	**Load shedding**	**MW served**	**Breaker Status**	**Load shedding**	**MW served**	D1	D2
Case 1	**B1**	BK 15, 1, 2, 3, 18 (O) ; BK 5, 8, 9, 14 ©	L6	44	BK 11, 1, 2, 3, 18 (O) BK 5, 8, 9, 14 (C)	L4	42.86	BK *15*, 6, 1, 2, 3, 18 (O) BK 5, 8, 9, 14 (C)	L3, L6	43.3733	1.2996	0.39279
Case 2	**B3**	BK 6,7 (O)	No	zero	BK 6,7 (O)	No	Zero	BK 6,7 (O)	No	Zero	0	0
Case 3	**B5**	BK 15, 10, 11, 12 (O); BK 14, 5,8 ©	L6	44	BK *2*, 10, 11, 12 (O) BK 14, 5,8 (C)	L1	42.86	BK *15*, 10, 11, 12 (O) BK 14, 5,8 (C)	L3, L6	43.4748	1.2996	0.27583
Case 4	**B7**	BK 15, 16, 17 (O)	No	zero	BK 15, 16, 17 (O)	No	Zero	BK 15, 16, 17 (O)	No	Zero	0	0
Case 5	**B1,B3**	BK *4*, 1, 2, 3, 18, 6, 7(O)	No	zero	BK *4*, 1, 2, 3, 18, 6, 7(O)	L2	Zero	BK *4*, 1, 2, 3, 18, 6, 7(O)	L2	Zero	0	0
Case 6	**B1,B5**	BK *4, 13*, 1, 2 ,3 ,18, 10, 11, 12(O); BK 5, 8, 14 ©	L2 L5	1 1	BK *4, 13*, 1, 2 ,3 ,18, 10, 11, 12(O) BK 5, 8, 14 (C)	L2 L5	1.02 1.04	BK *4, 13*, 1, 2 ,3 ,18, 10, 11, 12(O) BK 5, 8, 14 (C)	L2 L5	1.00646 1.00304	0.0004 0.0016	4.173 E-05 9.242 E-06
Case 7	**B3, B7**	BK 6,7 15, 16, 17 (O)	No	zero	BK 6,7 15, 16, 17 (O)	No	Zero	BK 6,7 15, 16, 17 (O)	no	Zero	0	0
Case 8	**B5,B7**	BK *13*, 10, 11, 12, 15, 16, 17 (O)	No	zero	BK *13*, 10, 11, 12, 15, 16, 17 (O)	L5	Zero	BK *13*, 10, 11, 12, 15, 16, 17 (O)	L5	Zero	0	0
									Total		2.6012	0.66867
									Norm 2		**1.6128**	**0.81772**

In case 1 and case 3, though type C reconfiguration algorithm suggests to disconnect more loads than in Type A and Type B, the MW served by Type C is higher than Type B and is closer to Type A. In this case, the objective of reconfiguration is to maximize the load served without considering any priority to the loads. So as per the objective function MW served is more important than the number of loads shedding. From the table 6.3 it can be observed that Type C results were as line with the objective function. From cases 4 to 8 reconfiguration results are similar.

- *Reconfiguration considering both priority and magnitude factor*

Table 6.4 shows the comparison of reconfiguration results by following both priority and magnitude factor of the loads and reconfigured based on actual power flow values, with errors introduced and with the data corrected with a fuzzy correction system. From the table it can be observed that Norm2 for D1 is higher than D2.

In case 1, the loads shed in Type A and Type C are similar but Type B suggests shedding a larger number of loads. This also shows shedding of important loads, L3 and L6, instead shedding down of low priority load L4. Except MW served the results for all other cases were similar.

Table 6.4 8-bus system - Comparison of reconfiguration results based on both priority and magnitude factor

CASE	**Faulted Bus**	**With Power flow values (Type A)**			**Reconfiguration with error introduced (Type B)**			**With corrected errors using Fuzzy evaluation (Type C)**			**Square of the difference**	
		Breaker Status	**Load shedding**	**MW served**	**Breaker Status**	**Load shedding**	**MW served**	**Breaker Status**	**Load shedding**	**MW served**	D1	D2
Case 1	**B1**	BK *11,* 1, 2, 3, 18 (O); BK 5, 8, 9, 14 (C)	L4	42	BK 6, 15, 1, 2, 3, 18 (O) BK 5, 8, 9, 14 (C)	L3, L6	43.83	BK *11,* 1, 2, 3, 18 (O) BK 5, 8, 9, 14 (C)	L4	42.3735	3.3489	0.1395023
Case 2	**B3**	BK 6,7 (O)	No	Zero	BK 6,7 (O)	No	Zero	BK 6,7 (O)	No	Zero	0	0
Case 3	**B5**	BK *2* , 10, 11, 12 (O); BK 14, 5,8 (C)	L1	42	BK 2, 15 , 10, 11, 12 (O) BK 14, 5,8 (C)	L1	42.86	BK 6, 15 , 10, 11, 12 (O) BK 14, 5,8 (C)	L3, L6	43.4749	0.7396	2.17533
Case 4	**B7**	BK 15, 16, 17 (O)	No	zero	BK 15, 16, 17 (O)	No	Zero	BK 15, 16, 17 (O)	No	Zero	0	0
Case 5	**B1, B3**	BK *4,* 1, 2, 3, 18, 6, 7 (O)	No	zero	BK *4,* 1, 2, 3, 18, 6, 7 (O)	L2		BK *4,* 1, 2, 3, 18, 6, 7 (O)	L2	Zero	0	0
Case 6	**B1, B5**	BK *4, 13* , 1, 2 ,3 ,18, 10, 11, 12(O); BK 5, 8, 14 (C)	L2 L5	1 1	BK *4, 13* , 1, 2 ,3 ,18, 10, 11, 12(O) BK 5, 8, 14 (C)	L2 L5	1.02 1.04	BK *4, 13* , 1, 2 ,3 ,18, 10, 11, 12(O) BK 5, 8, 14 (C)	L2 L5	1.00646 1.0033	0.0004 0.0016	4.173E-05 1.092E-05
Case 7	**B3, B7**	BK 6,7 15, 16, 17 (O)	No	zero	BK 6,7 15, 16, 17 (O)	No	Zero	BK 6,7 15, 16, 17 (O)	No	Zero	0	0
Case 8	**B5, B7**	BK *13,* 10, 11, 12, 15, 16, 17 (O)	No	zero	BK *13,* 10, 11, 12, 15, 16, 17 (O)	L5	Zero	BK *13,* 10, 11, 12, 15, 16, 17 (O)	L5	Zero	0	0
									Total		**4.0905**	**2.314884**
									Norm 2		**2.02249**	**1.521474**

6.3 Test case II – 13 bus SPS

The 13 bus test system explained in Chapter 4 was tested on GA based reconfiguration technique for three kinds of data Type A, Type B and Type C. The 13 bus test system is bigger compared to 8 bus test system and also contains more number of loads, main and auxiliary generators along with distributed generators. Due to the increase in complexity of the system, the variation in reconfiguration results can be observed.

6.3.1 Reconfiguration with actual power flow values (Type A)

By using the actual power flow values for the test system, below input matrix for 13 bus test system can be formed. This work is similar to [46], and is repeated in this chapter for the flexibility of the reader.

S(Zone1) = [1 -1 -1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 -1 0 0]
S(Zone2) = [0 0 1 -1 -1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0]
S(Zone3) = [0 0 0 0 1 -1 1 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0]
S(Zone4) = [0 0 0 0 0 0 0 -1 -1 1 -1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0]
S(Zone5) = [0 0 0 0 0 0 0 0 0 0 1 -1 -1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 -1]
S(Zone6) = [0 0 0 0 0 0 0 0 0 0 0 0 1 -1 -1 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0]
S(Zone7) = [0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0]
S(Zone8) = [0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 -1 1 -1 -1 0 0 0 0 0 0 0 0 0 0 0 0 0 0]
S(Zone9) = [0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 -1 1 1 0 0 0 0 0 0 0 0 0 0 0]
S(Zone10) = [0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 -1 -1 1 -1 0 0 0 0 0 0 0 0]
S(Zone11) = [0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 -1 1 0 0 0 0 -1 0]
S(Zone12) = [0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 -1 -1 1 1 0 0 0]
S(Zone13) = [0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 -1 1 0 0 0 0 0]
BRK_TYPE = [1, 3, 2, 3, 2, 3, 1, 2, 3, 1, 2, 3, 2, 3, 2, 1, 2, 1, 3, 2, 3, 1, 2, 3, 1, 2, 3, 2, 3, 1, 2, 2, 3, 3]
BRK_STATUS = [1 ,1, 1, 1, 1, 1, 0, 1, 1, 1, 1, 1, 1, 1, 0, 0, 0, 1, 1, 1, 1, 1, 0, 1, 1, 1, 1, 0, 1, 0, 1, 1, 1, 1]
BRK_FLOW = [26, 2, 23, 1, 22, 36, 0, 14, 1, 18, 3, 0.5, 2, 2, 0, 0, 0, 20, 2, 18, 25, 7, 0, 2, 3, 1, 0.6, 0, 1, 0,1, 1, 0.4, 0.5]
GEN_CAP = [1 30; 7 0.8; 10 20; 16 1;18 25;22 10;25 4;30 0.5]
LOADS = [2, 2;4, 1;6, 36;9, 1;12, 0.5;34, 0.5;14, 2;19, 2;21, 25;24, 2;27, 0.6;33, 0.4;29, 1]
LOAD_PRIORITY = [2, 95; 4, 1; 6, 95; 9, 1; 12, 95;34,1; 14, 9000;19, 1;21, 9000;24, 95;27,1;33 95;29,1]

With these input matrices reconfiguration algorithm was run for different reconfiguration objectives. Section B.1 of APPENDIX shows the reconfiguration results for actual power flow values considering priority of the loads in table B.1.1, without considering priority of the loads in table B.1.2 and considering both priority and magnitude factor in table B.1.3.

6.3.2 Reconfiguration with errors introduced (Type B)

Table 6.5 shows the meter readings and errors introduced in to each meter reading. Meters M1 to M13 are assumed to be connected to Load 1 to Load 13 in sequence. Each meter was associated with some error. Reading with full error is the maximum possible reading of the meter considering positive error maximum.

Table 6.5 13-bus system-meter readings along with errors

Meter ID	**meter readings (in MW)**	error %	**Reading with full error (in MW)**
M1	2	±3	2.06
M2	1	±1	1.01
M3	36	±2	36.72
M4	1	±1	1.01
M5	0.5	±3	0.515
M6	0.5	±1	0.505
M7	2	±4	2.08
M8	2	±5	2.1
M9	25	±5	26.25
M10	2	±1	2.02
M11	0.6	±4	0.624
M12	0.4	±3	0.412
M13	1	±2	1.02

By considering the above values, new power flows were calculated for the test system. Accordingly input matrices for the reconfiguration program were modified. Input matrices used for this case are shown here.

S(Zone1) = [1 -1 -1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 -1 0 0]
S(Zone2) = [0 0 1 -1 -1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0]
S(Zone3) = [0 0 0 0 1 -1 1 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0]
S(Zone4) = [0 0 0 0 0 0 0 -1 -1 1 -1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0]
S(Zone5) = [0 0 0 0 0 0 0 0 0 0 1 -1 -1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 -1]
S(Zone6) = [0 0 0 0 0 0 0 0 0 0 0 0 1 -1 -1 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0]
S(Zone7) = [0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0]
S(Zone8) = [0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 -1 1 -1 -1 0 0 0 0 0 0 0 0 0 0 0 0 0 0]
S(Zone9) = [0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 -1 1 1 0 0 0 0 0 0 0 0 0 0 0]
S(Zone10) = [0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 -1 -1 1 -1 0 0 0 0 0 0 0 0]
S(Zone11) = [0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 -1 1 0 0 0 0 -1 0]
S(Zone12) = [0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 -1 -1 1 1 0 0 0]
S(Zone13) = [0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 -1 1 0 0 0 0 0]

BRK_TYPE = [1, 3, 2, 3, 2, 3, 1, 2, 3, 1, 2, 3, 2, 3, 2, 1, 2, 1, 3, 2, 3, 1, 2, 3, 1, 2, 3, 2, 3, 1, 2, 2, 3, 3]
BRK_STATUS = [1 ,1, 1, 1, 1, 1, 0, 1, 1, 1, 1, 1, 1, 1, 0, 0, 0, 1, 1, 1, 1, 1, 0, 1, 1, 1, 1, 0, 1, 0, 1, 1, 1, 1]
BRK_FLOW = [26.81, 2.06, 23.73, 1.01, 22.72, 36.72, 0, 14, 1.01, 18.11, 3.1, 0.515, 2.08, 2.08, 0, 0, 0, 20.1, 2.1, 18, 26.25, 8.25, 0, 2.02, 3.056, 1.036, 0.624, 0, 1.02, 0,1.02, 1.02, 0.412, 0.505]

GEN_CAP = [1 30; 7 0.8; 10 20; 16 1;18 25;22 10;25 4;30 0.5]
LOADS = [2, 2.06;4, 1.01;6, 36.72;9, 1.01;12, 0.515;34, 0.505;14, 2.08;19, 2.1;21, 26.25;24, 2.02;27, 0.624;33, 0.412;29, 1.02]
LOAD_PRIORITY = [2, 95; 4, 1; 6, 95; 9, 1; 12, 95;34,1; 14, 9000;19, 1;21, 9000;24, 95;27,1;33 95;29,1]

By using above matrices, reconfiguration program was run and results were noted. Section B.2 of APPENDIX shows the reconfiguration results with full error values and considering priority of the loads table B.2.1, without considering priority of the loads table B.2.2 and considering both priority and magnitude factor table B.2.3.

6.3.3 Reconfiguration with fuzzy correction of meter data (Type C)

An error associated with each meter was corrected using the fuzzy correction system. Table 6.6 shows the meter parameters and corrected meter readings with fuzzy correction system. ‘Readings after error adjustments’ was used to calculate new power flows in the system.

Table 6.6 13-bus system - meter data along with fuzzy corrected readings

Meter ID	Error %	Degree of confidence	Reliability	Age	de fuzzified Trust	Trust on meter data	**Power flow values (in MW)**	%error adjustment	**Readings after error adjustment (in MW)**
M1	3	99	0.11	0.5	0.5	MED	2	1.5	2.03
M2	1	99	0.55	0.2	0.5	MED	1	0.5	1.005
M3	2	96	0.4	0.7	0.323	HIGH	36	0.646	36.23256
M4	1	96	0.2	0.7	0.346	HIGH	1	0.346	1.00346
M5	3	96	0.1	0.8	0.5	MED	0.5	1.5	0.5075
M6	1	99	0.1	0.1	0.289	HIGH	0.5	0.289	0.501445
M7	4	97	0.29	0.22	0.5	MED	2	2	2.04
M8	5	97	0.5	0.7	0.826	LOW	2	4.13	2.0826
M9	5	98	0.55	0.11	0.5	MED	25	2.5	25.625
M10	1	98	0.1	0.1	0.289	HIGH	2	0.289	2.00578
M11	4	98	0.26	0.4	0.5	MED	0.6	2	0.612
M12	3	96	0.6	0.9	0.826	LOW	0.4	2.478	0.409912
M13	2	96	0.7	0.68	0.678	LOW	1	1.356	1.01356

New input matrices were formed based on the new power flow values. Below shows the input matrices used for this case. Section B.3 of APPENDIX shows the reconfiguration results using fuzzy correction of meter data and considering priority of the loads in table B.3.1, without considering priority of the loads in table B.3.2 and considering both priority and magnitude factor in table B.3.3.

S(Zone1) = [1 -1 -1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 -1 0 0]
S(Zone2) = [0 0 1 -1 -1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0]
S(Zone3) = [0 0 0 0 1 -1 1 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0]
S(Zone4) = [0 0 0 0 0 0 0 -1 -1 1 -1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0]
S(Zone5) = [0 0 0 0 0 0 0 0 0 0 1 -1 -1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 -1]
S(Zone6) = [0 0 0 0 0 0 0 0 0 0 0 0 1 -1 -1 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0]
S(Zone7) = [0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0]
S(Zone8) = [0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 -1 1 -1 -1 0 0 0 0 0 0 0 0 0 0 0 0 0 0]
S(Zone9) = [0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 -1 1 1 0 0 0 0 0 0 0 0 0 0 0]
S(Zone10) = [0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 -1 -1 1 -1 0 0 0 0 0 0 0 0]
S(Zone11) = [0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 -1 1 0 0 0 0 -1 0]
S(Zone12) = [0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 -1 -1 1 1 0 0 0]
S(Zone13) = [0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 -1 1 0 0 0 0 0]

BRK_TYPE = [1, 3, 2, 3, 2, 3, 1, 2, 3, 1, 2, 3, 2, 3, 2, 1, 2, 1, 3, 2, 3, 1, 2, 3, 1, 2, 3, 2, 3, 1, 2, 2, 3, 3]
BRK_STATUS = [1 ,1, 1, 1, 1, 1, 0, 1, 1, 1, 1, 1, 1, 1, 0, 0, 0, 1, 1, 1, 1, 1, 0, 1, 1, 1, 1, 0, 1, 0, 1, 1, 1, 1]
BRK_FLOW = [26.28112, 2.03, 23.23756, 1.005, 22.23256, 36.23256, 0, 14, 1.00346, 18.0524, 3.048945, 0.5075, 2.04, 2.04, 0, 0, 0, 20.0826, 2.0826, 18, 25.625, 7.625, 0, 2.00578, 3.0277, 1.022, 0.612, 0, 1.01356, 0,1.01356, 1.01356, 0.41, 0.5014]

GEN_CAP = [1 30; 7 0.8; 10 20; 16 1;18 25;22 10;25 4;30 0.5]
LOADS = [2, 2.03;4, 1.005;6, 36.23256;9, 1.00346;12, 0.5075;34, 0.501445;14, 2.04;19, 2.0826;21, 25.625;24, 2.00578;27, 0.612;33, 0.41;29, 1.01356]
LOAD_PRIORITY = [2, 95; 4, 1; 6, 95; 9, 1; 12, 95;34,1; 14, 9000;19, 1;21, 9000;24, 95;27,1;33 95;29,1]

6.3.4 Comparison of Type A, Type B and Type C

Reconfiguration results presented in section B of Appendix are compared for three objective functions of reconfiguration.

- *Reconfiguration based on priority of the loads*

Table 6.7 shows the comparison of reconfiguration results by following priority of the loads and reconfigured based on actual power flow values, with errors introduced and with the data corrected with fuzzy correction system for 13 bus test system. From the table Norm2 for D1 is higher than D2, i.e. the results obtained in Type C are closer to Type A results.

Table 6.7 13-bus system- comparison of reconfiguration results based on priority of the loads

		Reconfiguration with Power flow values (Type A)			Reconfiguration with error introduced (Type B)			Reconfiguration with fuzzy correction (Type C)			Square of the difference	
Test case	**fault Bus**	**Load Shedding**	**Breaker reconfiguration**	**MW Served**	**Load Shedding**	**Breaker reconfiguration**	**MW Served**	**Load Shedding**	**Breaker reconfiguration**	**MW Served**	**D1**	**D2**
Case 1	**B1**	L3	BK *6*, 1, 2, 3, 32 (O) BK 15, 17, 23, 28, 7, 16, 30 (C)	36	L3, L6	BK *6*, 34, 1, 2, 3, 32 (O) BK 15, 17, 23, 28, 7, 16, 30 (C)	37.54	L3, L13	BK *6*, 29, 1, 2, 3, 32 (O) BK 15, 17, 23, 28, 7, 16, 30 (C)	36.304	2.3716	0.0929
Case 2	**B4**	L8	BK 19, 8, 9, 10, 11 (O) BK 28, 23, 17, 15, 7, 16, 30 (C)	71	L2, L6, L8, L11	BK 4, 34, 19*, 27,* 8, 9, 10, 11 (O) BK 28, 23, 17, 15, 7, 16, 30 (C)	71.077	L2, L8	BK 4, 19, 8, 9, 10, 11 (O) BK 28, 23, 17, 15, 7, 16, 30 (C)	70.977	0.00592	0.0005
Case 3	**B8**	L2, L4, L6, L10, L11,L13	BK *4, 9, 34, 24, 27, 29,* 18, 19, 20 (O) BK 23, 28, 15, 7, 16, 30 (C)	65.9	L1,L2, L4, L6, L10, L11, L13	BK 2, 4, 9, 34, 24, 27, 29, 18, 19, 20(O) BK 23, 28, 15, 7, 16, 30 (C)	65.977	L2, L4,L5, L6, L11, L12, L13	BK 4, 9, 12, 34, 24, 27, 33, 29, 18, 19, 20(O) BK 23, 28, 15, 7, 16, 30 (C)	65.9	0.00592	0
Case 4	**B9**	No	BK 20, 21, 22 (O)	0	No	BK 20, 21, 22 (O)	0	No	BK 20, 21, 22 (O)	0	0	0
Case 5	**B10**	No	BK 24, 25, 26 (O)	0	No	BK 24, 25, 26 (O) BK 28 ('C)	0	No	BK 24, 25, 26 (O) BK 28 ('C)	0	0	0
Case 6	**B1, B4**	L2,L3	BK *4, 6*, 1, 2, 3, 32, 8, 9, 10, 11 (O) BK 15, 17, 28, 7 (C)	0	L2,L3	BK *4, 6*, 1, 2, 3, 32, 8, 9, 10, 11 (O) BK 15, 17, 28, 23, 7 (C)	0	L2,L3	BK *4, 6*, 1, 2, 3, 32, 8, 9, 10, 11 (O) BK 15, 17, 28, 23, 7 (C)	0	0	0

Table 6.7 (continued)

Case 7	**B1, B8**	L3	BK *6, 21*, 1, 2, 3, 32, 18, 19, 20 (O)	5	L3, L9	BK *6, 21*, 1, 2, 3, 32, 18, 19, 20 (O)	4.076	L3, L9	BK *6, 21*, 1, 2, 3, 32, 18, 19, 20 (O)	4.0413	0.853776	0.919106
		L9	BK 7, 15, 16, 23, 28, 30 (C)	4	L9	BK 7, 15, 16, 23, 28, 30 (C)	5.12	L9	BK 7, 15, 16, 23, 28, 30 (C)	5.057	1.2544	1.117249
Case 8	**B4, B10**	L3	BK *6*, 8, 9, 10, 11 , 24, 25, 26 (O) BK 7, 15, 16, 28, 30 (C)	5	L3	BK *6*, 8, 9, 10, 11 , 24, 25, 26 (O) BK 7, 15, 17, 28, 30 (C)	5.126	L3	BK *6*, 8, 9, 10, 11 , 24, 25, 26 (O) BK 7, 15, 17, 28, 30 (C)	5.07	0.01587	0.0049
									Total		**4.5075**	**2.1347**
									Norm 2		**2.1230**	**1.4610**

For Case 1, Type B sheds loads L3 and L6, and Type C sheds the loads L3 and L13. L6 is the load with higher priority compared with L13 therefore it should not be shed by the reconfiguration algorithm. This case reports mal-operation of the switches for the power system reconfiguration, by using the algorithm without correcting the error data.

For Case 2, reconfiguration with full error sheds the loads L2, L6, L8, and L11 and reconfiguration with fuzzy correction sheds loads L2 and L8. By considering the reconfiguration scheme given by the actual power flow values, i.e. without any errors, it suggests to shed load L8, as the optimal solution of reconfiguration. Reconfiguration results by using data introduced with errors shows a lot of deviation from the optimal solution, whereas the reconfiguration solution given by using fuzzy corrected data is closer to the optimal solution. From this case, unnecessary load shedding of L6 and L11 can be observed because of the use of erroneous data. For other cases the results were more or less similar.

- *Reconfiguration without considering load priority*

Table 6.8 shows the comparison of reconfiguration results without following priority of the loads and reconfigured based on actual power flow values, with errors introduced and with the data corrected with fuzzy correction system for 13 bus test system. From the table Norm2 for D1 is higher than D2 i.e. the results obtained in Type C are closer to optimal solution Type A. For cases 1, 2 and 3, the MW served in Type C was closer to Type A. Case 2 also shows a higher number of loads shed in Type B reconfiguration.

Table 6.8 13-bus system- comparison of reconfiguration results without considering priority of loads

		Reconfiguration with Power flow values (Type A)			Reconfiguration with error introduced (Type B)			Reconfiguration with fuzzy correction (Type C)			Square of the difference	
Test case	**Fault Bus**	**Load Shedding**	**Breaker reconfiguration**	**MW Served**	**Load Shedding**	**Breaker reconfiguration**	**MW Served**	**Load Shedding**	**Breaker reconfiguration**	**MW Served**	**D1**	**D2**
Case 1	**B1**	**L5, L9**	BK 12, *21,* 1, 2, 3, 32 (O) BK 15, 17, 23, 28, 7, 16, 30 (C)	46.5	L9, L11	BK 21, 27, 1, 2, 3, 32 (O) BK 15, 17, 23, 28, 7, 16, 30 (C)	47.39	L6, L9, L11	BK 34, 21, 27, 1, 2, 3, 32 (O) BK 15, 17, 23, 28, 7, 16, 30 (C)	46.3	0.7921	0.04

Table 6.8 (continued)

Case 2	**B4**	**L5, L12, L13**	BK *12, 33, 29,* 8, 9, 10, 11 (O) BK 28, 23, 17, 15, 7, 16, 30 (C)	71.1	L2, L5, L7, L12	BK 4, 12, 14, 33, 8, 9, 10, 11 (O) BK 28, 23, 17, 15, 7, 16, 30 (C)	71.148	L6, L10, L12	BK 34, 24, 33, 8, 9, 10, 11 (O) BK 28, 23, 17, 15, 7, 16, 30 (C)	71.148	0.00230	0.00230
Case 3	**B8**	**L2, L4, L6, L7, L12, L13**	BK 4*, 9, 14, 33, 34,* 18, 19, 20, 29 (O) BK 23, 28, 15, 7, 16, 30 (C)	66.1	L1, L2, L4, L10, L12, L13	BK *2, 4, 9, 34, 24, 33, 29, 18, 19, 20* (O) BK 23, 28, 15, 7, 16, 30 (C)	66.189	L4, L6, L7, L10, L12, L13	BK *9,34, 14, 24, 33, 29, 18, 19, 20* (O) BK 23, 28, 15, 7, 16, 30 (C)	66.01	0.00792	0.0081
Case 4	**B9**	**No**	BK 20, 21, 22 (O)	0	No	BK 20, 21, 22 (O)	0	No	BK 20, 21, 22 (O)	0	0	0
Case 5	**B10**	**No**	BK 24, 25, 26 (O)	0	No	BK 24, 25, 26 (O) BK 28 (C)	0	No	BK 24, 25, 26 (O) BK 28 (C)	0	0	0
Case 6	**B1, B4**	**L2, L3**	BK *4, 6*, 1, 2, 3, 32, 8, 9, 10, 11 (O) BK 15, 17, 28, 7 (C)	0	L2, L3	BK *4, 6*, 1, 2, 3, 32, 8, 9, 10, 11 (O) BK 15, 17, 28,23, 7 (C)	0	L2, L3	BK *4, 6*, 1, 2, 3, 32, 8, 9, 10, 11 (O) BK 15, 17, 28,23, 7 (C)	0	0	0
Case 7	**B1, B8**	**L3**	BK *6, 21*, 1, 2, 3, 32, 18, 19, 20	5	L3,L9	BK *6, 21*, 1, 2, 3, 32, 18, 19, 20	4.07	L3,L9	BK *6, 21*, 1, 2, 3, 32, 18, 19, 20	4.04	0.8649	0.9216
		L9	BK 7, 15, 16, 23, 28, 30 (C)	4	L9	BK 7, 15, 16, 23, 28, 30 (C)	5.12	L9	BK 7, 15, 16, 23, 28, 30 (C)	5.05	1.2544	1.1025
Case 8	**B4, B10**	**L3**	BK *6*, 8, 9, 10, 11 , 24, 25, 26 (O) BK 7, 15, 17, 28, 30 (C)	5	L3	BK *6*, 8, 9, 10, 11 , 24, 25, 26 (O) BK 7, 15, 17, 28, 30 (C)	5.12	L3	BK *6*, 8, 9, 10, 11 , 24, 25, 26 (O) BK 7, 15, 17, 28, 30 (C)	5.07	0.0144	0.0049
									Total		**2.93602**	**2.0794**
									Norm 2		**1.71348**	**1.4420**

- *Reconfiguration considering both priority and magnitude factor*

Table 6.9 shows the comparison of reconfiguration results by following both priority and magnitude factor of the loads and reconfigured based on actual power flow values, with errors introduced and with the data corrected with fuzzy correction system for 13 bus test system. From the table Norm2 for D1 (2.56) is much higher than D2 (1.77), i.e. the results obtained in Type C are closer to optimal solution Type A. For cases 2 and 3 shedding of more number of loads can be observed in Type C compared with Type B. For the cases having multiple bus faults, the results were similar.

Table 6.9 13-bus system- comparison of reconfiguration results considering both priority and magnitude factor of the loads

		Reconfiguration with Power flow values (Type A)			Reconfiguration with error introduced (Type B)			Reconfiguration with fuzzy correction (Type C)			Square of the difference	
Test case	**Fault Bus**	**Load Shedding**	**Breaker reconfiguration**	**MW Served**	**Load Shedding**	**Breaker reconfiguration**	**MW Served**	**Load Shedding**	**Breaker reconfiguration**	**MW Served**	**D1**	**D2**
Case 1	**B1**	L3, L11	BK *6*, 27, 1, 2, 3, 32 (O) BK 15, 17, 23, 28, 7, 16, 30 (C)	35.4	L3	BK 6, 1, 2, 3, 32 (O) BK 15, 17, 23, 28, 7, 16, 30 (C)	37.5	L3, L6	BK *6*, 34, 1, 2, 3, 32 (O) BK 15, 17, 23, 28, 7, 16, 30 (C)	36.304	4.41	0.8188
Case 2	**B4**	L2, L11, L6	BK 4, 34, 27, 8, 9, 10, 11 (O) BK 28, 23, 17, 15, 7, 16, 30 (C)	71	L2, L6, L8, L12	BK 4, 34, 19, 33, 8, 9, 10, 11 (O) BK 28, 23, 17, 15, 7, 16, 30 (C)	71.289	L2, L6, L8	BK 4, 34, 19, 8, 9,*10, 11* (O) BK 28, 23, 17, 15, 7, 16, 30 (C)	70.476	0.08352	0.2745

Table 6.9 (continued)

Case 3	**B8**	L1, L2, L4, L6,, L11,L13	BK *2, 4, 9, 34, 27, 29,* 18, 19, 20 (O) BK 23, 28, 15, 7, 16, 30 (C)	66.1	L2, L4, L5, L6, L10, L11 L12,L13	BK 2,*4, 9,12, 34, 24, 29,* 18, 19, 20 (O) BK 23, 28, 15, 7, 16, 30 (C)	65.927	L4, L5, L6, L10, L11 L12,L13	BK *4, 9,12, 34, 24, 27, 33, 29,* 18, 19, 20 (O) BK 23, 28, 15, 7, 16, 30 (C)	65.927	0.02992	0.0299
Case 4	**B9**	No	BK 20, 21, 22 (O)	0	No	BK 20, 21, 22 (O)	0	No	BK 20, 21, 22 (O)	0	0	0
Case 5	**B10**	No	BK 24, 25, 26 (O)	0	No	BK 24, 25, 26 (O) BK 28 (C)	0	No	BK 24, 25, 26 (O) BK 28 (C)	0	0	0
Case 6	**B1, B4**	L2,L3	BK *4, 6*, 1, 2, 3, 32, 8, 9, 10, 11 (O) BK 15, 17, 28, 7 (C)	0	L2,L3	BK *4, 6*, 1, 2, 3, 32, 8, 9, 10, 11 (O) BK 15, 17, 28, 23, 7 (C)	0	L2,L3	BK *4, 6*, 1, 2, 3, 32, 8, 9, 10, 11 (O) BK 15, 17, 28, 23, 7 (C)	0	0	0
Case 7	**B1, B8**	L3	BK *6, 21*, 1, 2, 3, 32, 18, 19, 20 (O)	5	L3, L9	BK *6, 21*, 1, 2, 3, 32, 18, 19, 20 (O)	4.041	L3, L9	BK *6, 21*, 1, 2, 3, 32, 18, 19, 20 (O)	4.041	0.91968	0.9196
		L9	BK 7, 15, 16, 23, 28, 30 (C)	4	L3	BK 7, 15, 16, 23, 28, 30 (C)	5.0574	L3	BK 7, 15, 16, 23, 28, 30 (C)	5.0574	1.11809	1.1180
Case 8	**B4, B10**	L3	BK *6*, 8, 9, 10, 11 , 24, 25, 26 (O) BK 7, 15, 16, 28, 30 (C)	5	L3	BK *6*, 8, 9, 10, 11 , 24, 25, 26 (O) BK 7, 15, 17, 28, 30 (C)	5.07	L3	BK *6*, 8, 9, 10, 11 , 24, 25, 26 (O) BK 7, 15, 17, 28, 30 (C)	5.07	0.0049	0.0049
									Total		**6.56612**	**3.1660**
									Norm 2		**2.56244**	**1.7793**

6.4 Summary

Fuzzy correction system was successfully used along with GA based reconfiguration program to minimize the effect of uncertainty in reconfiguration results. Comparison of reconfiguration results also shows that the results of Type C (reconfiguration with fuzzy correction system) are closer to Type A (reconfiguration with actual power flow values), which are optimal. The effect of the fuzzy correction system becomes more and more critical as the size of the system increases.

CHAPTER 7

CONCLUSIONS AND FUTURE WORK

7.1 Introduction

Reliability of the operation and control of power system are limited by uncertainties present in meter data. Also the data used for making decisions in shipboard power system operations is very critical and any errors associated with them may lead to undesired operations or decisions. In this research work a fuzzy rule based algorithm to deal with uncertainties present in meter data was proposed and the same was tested on the genetic algorithm based reconfiguration. Fuzzy logic was selected due to its superiority and flexibility in representing vague data. Test cases of 8 bus and 13 bus shipboard power system cases were considered.

When humans need to use computers to take decisions, user interface has to be designed with the aim of optimizing the performance of human computer interaction (HCI). Decision Support System (DSS) is an integral part of HCI and very crucial in aiding the operator's decision making process. In this research work, an impact of DSS on decision quality was quantitatively analyzed by performing experiments on unaided (without DSS) and aided (with DSS) interfaces. Usability studies were carried out and design recommendations were made to improve the aided interface.

This research work has made significant contributions in the area of power system reconfiguration and human systems interface design of all-electric war ship.

Work done as a part of this thesis was:

- A fuzzy correction system was developed to deal with uncertainty present in meter data and was tested using a genetic algorithm based reconfiguration technique. Results of the research work show an improvement in the reconfiguration results with the use of fuzzy correction system. Different intermediate steps/achievements were listed below:
    - A rule oriented fuzzy evaluation system was developed based on meter's historical and operational parameters.
    - Meter data was corrected based on the fuzzy evaluation of meters.
    - Successfully integrated fuzzy correction system with genetic algorithm based reconfiguration algorithm.
    - Reconfiguration results were compared on example 8 bus and 13 bus shipboard power system test cases.
- Effect of Decision Support System on user performance was quantitatively analyzed and usability studies were performed on the interfaces. Decision

quality analysis results were in line with our expectations. Different intermediate steps/achievements are listed below:

- Unaided and aided interface prototypes for power system reconfiguration were developed.
- DSS was designed based on the reconfiguration algorithm which takes care of the priority of the loads, maximization of the loads or both.
- Cognitive walkthrough analysis and error analysis were done to identify improvements in the design.
- Design recommendations were made for the aided interface design.

7.2 Future work

Present work can be extended to follow identified fields in the future.

In Human Systems Interaction:

- Aided interface may be improved by implementing design recommendations proposed in this work.
- After implementing the design changes, usability tests can be performed to measure the improvement in the usability of the interface.

In Power system studies:

- Use of fuzzy correction system can be extended to deal with uncertainty for operations and planning in real-time market and wide area monitoring and control.

- By using fuzzy meter evaluation, a new meter weight matrix vector for state estimation can be formed. Efficacy of this can be compared with conventional weight matrix vector.

In the present work we assumed that all system states were known, hence no state estimation algorithm was run. In future developments to make this model complete, state estimation algorithm can be included feeding data to power flow tool.

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APPENDIX A

TEST CASE 1 – 8 BUS

A.1 Reconfiguration with actual power flow values (Type A)

A.1.1: Reconfiguration based on priority of the loads

Test case	Faulted Bus Number	Negative power bus	Possible power supply path	Load Shedding	Breaker reconfiguration	MW Served
Case1	B1	B2	B2-B3-B4-B5-B6-B7-B8	L4	BK *11*, 1, 2, 3, 18 (O) BK 5, 8, 9, 14 (C)	42
Case2	B3	No	No	No	BK 6,7 (O)	-
Case3	B5	B6	B6-B7-B8-B1-B2-B3-B4	L1	BK *2* , 10, 11, 12 (O) BK 14, 5,8 (C)	42
Case4	B7	No	No	No	BK 15, 16, 17 (O)	-
Case5	B1, B3	B2	No possible generation	L2	BK *4*, 1, 2, 3, 18, 6, 7 (O)	-
Case6	B1, B5	B6 B2	B6-B7-B8 B2-B3-B4	L2 L5	BK *4*, *13* , 1, 2 ,3 ,18, 10, 11, 12(O) BK 5, 8, 14 (C)	1 1
Case7	B3, B7	No	No	No	BK 6,7 15, 16, 17 (O)	-
Case8	B5, B7	B6	No possible generation	L5	BK *13*, 10, 11, 12, 15, 16, 17 (O)	-

A.1.2: Reconfiguration without considering priority of the loads

Test case	Faulted Bus Number	Negative power bus	Possible power supply path	Load Shedding	Breaker reconfiguration	MW Served
Case1	B1	B2	B2-B3-B4-B5-B6-B7-B8	L6	BK *15*, 1, 2, 3, 18 (O) BK 5, 8, 9, 14 (C)	44
Case2	B3	No	No	No	BK 6,7 (O)	-
Case3	B5	B6	B6-B7-B8-B1-B2-B3-B4	L6	BK *15*, 10, 11, 12 (O) BK 14, 5,8 (C)	44
Case4	B7	No	No	No	BK 15, 16, 17 (O)	-
Case5	B1, B3	B2	No possible generation	L2	BK *4*, 1, 2, 3, 18, 6, 7(O)	-
Case6	B1, B5	B6	B6-B7-B8	L2	BK *4, 13*, 1, 2 ,3 ,18, 10, 11, 12(O) BK 5, 8, 14 (C)	1
		B2	B2-B3-B4	L5		1
Case7	B3, B7	No	No	No	BK 6,7 15, 16, 17 (O)	-
Case8	B5, B7	B6	No possible generation	L5	BK *13*, 10, 11, 12, 15, 16, 17 (O)	-

A.1.3: Reconfiguration considering both priority and magnitude factor

Test case	Faulted Bus Number	Negative power bus	Possible power supply path	Load Shedding	Breaker reconfiguration	MW Served
Case1	B1	B2	B2-B3-B4-B5-B6-B7-B8	L4	BK *11*, 1, 2, 3, 18 (O) BK 5, 8, 9, 14 (C)	42
Case2	B3	No	No	No	BK 6,7 (O)	-
Case3	B5	B6	B6-B7-B8-B1-B2-B3-B4	L1	BK *2* , 10, 11, 12 (O) BK 14, 5,8 (C)	42
Case4	B7	No	No	No	BK 15, 16, 17 (O)	-
Case5	B1, B3	B2	No possible generation	L2	BK *4*, 1, 2, 3, 18, 6, 7 (O)	-
Case6	B1, B5	B6	B6-B7-B8	L2	BK *4*, *13* , 1, 2 ,3 ,18, 10, 11, 12(O) BK 5, 8, 14 (C)	1
		B2	B2-B3-B4	L5		1
Case7	B3, B7	No	No	No	BK 6,7 15, 16, 17 (O)	-
Case8	B5, B7	B6	No possible generation	L5	BK *13*, 10, 11, 12, 15, 16, 17 (O)	-

A.2 Reconfiguration with errors introduced (Type B)

A.2.1: Reconfiguration considering priority of the loads

Test case	Faulted Bus Number	Negative power bus	Possible power supply path	Load Shedding	Breaker reconfiguration	MW Served
Case1	B1	B2	B2-B3-B4-B5-B6-B7-B8	L4	BK *11,* 1, 2, 3, 18 (O) BK 5, 8, 9, 14 (C)	42.86
Case2	B3	No	No	No	BK 6,7 (O)	-
Case3	B5	B6	B6-B7-B8-B1-B2-B3-B4	L3, L6	BK *6* ,15, 10, 11, 12 (O) BK 14, 5,8 (C)	43.95
Case4	B7	No	No	No	BK 15, 16, 17 (O)	-
Case5	B1, B3	B2	No possible generation	L2	BK *4,* 1, 2, 3, 18, 6, 7 (O)	-
Case6	B1, B5	B6	B6-B7-B8	L2	BK *4, 13* , 1, 2 ,3 ,18, 10, 11, 12(O) BK 5, 8, 14 (C)	1.02
		B2	B2-B3-B4	L5		1.04
Case7	B3, B7	No	No	No	BK 6,7 15, 16,	-

					17 (O)	
Case8	B5, B7	B6	No possible generation	L5	BK *13,* 10, 11, 12, 15, 16, 17 (O)	-

A.2.2: Reconfiguration without considering priority of the loads

Test case	Faulted Bus Number	Negative power bus	Possible power supply path	Load Shedding	Breaker reconfiguration	MW Served
Case1	B1	B2	B2-B3-B4-B5-B6-B7-B8	L4	BK 11, 1, 2, 3, 18 (O) BK 5, 8, 9, 14 (C)	42.86
Case2	B3	No	No	No	BK 6,7 (O)	-
Case3	B5	B6	B6-B7-B8-B1-B2-B3-B4	L1	BK *2*, 10, 11, 12 (O) BK 14, 5,8 (C)	42.86
Case4	B7	No	No	No	BK 15, 16, 17 (O)	-
Case5	B1, B3	B2	No possible generation	L2	BK *4*, 1, 2, 3, 18, 6, 7(O)	-

Case6	B1, B5	B6 B2	B6-B7-B8 B2-B3-B4	L2 L5	BK *4, 13*, 1, 2 ,3 ,18, 10, 11, 12(O) BK 5, 8, 14 (C)	1.02 1.04
Case7	B3, B7	No	No	No	BK 6,7 15, 16, 17 (O)	-
Case8	B5, B7	B6	No possible generation	L5	BK *13*, 10, 11, 12, 15, 16, 17 (O)	-

A.2.3: Reconfiguration considering both priority and magnitude factor

Test case	Faulted Bus Number	Negative power bus	Possible power supply path	Load Shedding	Breaker reconfiguration	MW Served
Case1	B1	B2	B2-B3-B4-B5-B6-B7-B8	L3, L6	BK 6, 15, 1, 2, 3, 18 (O) BK 5, 8, 9, 14 (C)	43.83
Case2	B3	No	No	No	BK 6,7 (O)	-
Case3	B5	B6	B6-B7-B8-B1-B2-B3-B4	L1	BK 2, 15 , 10, 11, 12 (O) BK 14, 5,8 (C)	42.86

Case4	**B7**	**No**	**No**	**No**	**BK 15, 16, 17 (O)**	**-**
Case5	**B1, B3**	**B2**	**No possible generation**	**L2**	**BK *4,* 1, 2, 3, 18, 6, 7 (O)**	**-**
Case6	**B1, B5**	**B6** **B2**	**B6-B7-B8** **B2-B3-B4**	**L2** **L5**	**BK *4, 13 ,* 1, 2 ,3 ,18, 10, 11, 12(O)** **BK 5, 8, 14 (C)**	**1.02** **1.04**
Case7	**B3, B7**	**No**	**No**	**No**	**BK 6,7 15, 16, 17 (O)**	**-**
Case8	**B5, B7**	**B6**	**No possible generation**	**L5**	**BK *13,* 10, 11, 12, 15, 16, 17 (O)**	**-**

A.3 Reconfiguration with fuzzy correction of meter data (Type C)

A.3.1: Reconfiguration considering priority of the loads

Test case	**Faulted Bus Number**	**Negative power bus**	**Possible power supply path**	**Load Shedding**	**Breaker reconfiguration**	**MW Served**
Case1	**B1**	**B2**	**B2-B3-B4-**	**L4**	**BK *11,* 1, 2, 3,**	**42.3741**

			B5-B6-B7-B8		**18 (O) BK 5, 8, 9, 14 (C)**	
Case2	**B3**	**No**	**No**	**No**	**BK 6,7 (O)**	**-**
Case3	**B5**	**B6**	**B6-B7-B8-B1-B2-B3-B4**	**L3, L6**	**BK *6* ,15, 10, 11, 12 (O) BK 14, 5,8 (C)**	**43.47485**
Case4	**B7**	**No**	**No**	**No**	**BK 15, 16, 17 (O)**	**-**
Case5	**B1, B3**	**B2**	**No possible generation**	**L2**	**BK *4,* 1, 2, 3, 18, 6, 7 (O)**	**-**
Case6	**B1, B5**	**B6 B2**	**B6-B7-B8 B2-B3-B4**	**L2 L5**	**BK *4, 13 ,* 1, 2 ,3 ,18, 10, 11, 12(O) BK 5, 8, 14 (C)**	**1.00304 1.00646**
Case7	**B3, B7**	**No**	**No**	**No**	**BK 6,7 15, 16, 17 (O)**	**-**
Case8	**B5, B7**	**B6**	**No possible generation**	**L5**	**BK *13,* 10, 11, 12, 15, 16, 17 (O)**	**-**

A.3.2: Reconfiguration without considering load priority

Test case	**Faulted Bus Number**	**Negative power bus**	**Possible power supply path**	**Load Shedding**	**Breaker reconfiguration**	**MW Served**
Case1	**B1**	**B2**	**B2-B3-B4-B5-B6-B7-B8**	**L3,L6**	**BK *15*, 6, 1, 2, 3, 18 (O)** **BK 5, 8, 9, 14 (C)**	**43.37327**
Case2	**B3**	**No**	**No**	**No**	**BK 6,7 (O)**	**-**
Case3	**B5**	**B6**	**B6-B7-B8-B1-B2-B3-B4**	**L6, L3**	**BK *15*, 10, 11, 12 (O)** **BK 14, 5,8 (C)**	**43.4748**
Case4	**B7**	**No**	**No**	**No**	**BK 15, 16, 17 (O)**	**-**
Case5	**B1, B3**	**B2**	**No possible generation**	**L2**	**BK *4*, 1, 2, 3, 18, 6, 7(O)**	**-**
Case6	**B1, B5**	**B6** **B2**	**B6-B7-B8** **B2-B3-B4**	**L2** **L5**	**BK *4*, *13*, 1, 2 ,3 ,18, 10, 11, 12(O)** **BK 5, 8, 14 (C)**	**1.00646** **1.00304**
Case7	**B3, B7**	**No**	**No**	**No**	**BK 6,7 15, 16, 17 (O)**	**-**

Case8	B5, B7	B6	No possible generation	L5	BK *13*, 10, 11, 12, 15, 16, 17 (O)	-

A.3.3: Reconfiguration considering both priority and magnitude factor

Test case	Faulted Bus Number	Negative power bus	Possible power supply path	Load Shedding	Breaker reconfiguration	MW Served
Case1	B1	B2	B2-B3-B4-B5-B6-B7-B8	L4	BK *11,* 1, 2, 3, 18 (O) BK 5, 8, 9, 14 (C)	42.3735
Case2	B3	No	No	No	BK 6,7 (O)	-
Case3	B5	B6	B6-B7-B8-B1-B2-B3-B4	L3, L6	BK 6, 15 , 10, 11, 12 (O) BK 14, 5,8 (C)	43.4749
Case4	B7	No	No	No	BK 15, 16, 17 (O)	-
Case5	B1, B3	B2	No possible generation	L2	BK *4,* 1, 2, 3, 18, 6, 7 (O)	-
Case6	B1, B5	B6	B6-B7-B8	L2	BK *4, 13* , 1, 2 ,3	1.00646

		B2	B2-B3-B4	L5	,18, 10, 11, 12(O) BK 5, 8, 14 (C)	1.003304
Case7	B3, B7	No	No	No	BK 6,7 15, 16, 17 (O)	-
Case8	B5, B7	B6	No possible generation	L5	BK *13,* 10, 11, 12, 15, 16, 17 (O)	-

APPENDIX B

TEST CASE 2 – 13 BUS

B.1 Reconfiguration with actual power flow values (Type A)

B.1.1: Reconfiguration based on priority of the loads

Test case	Faulted Bus Number	Negative power bus	Possible power supply path	Load Shedding	Breaker reconfiguration	MW Served
Case 1	B1	B2, B13	B2-B3-B4-B5-B6-B7-B8-B9-B10-B11-B12-B13	L3	BK *6*, 1, 2, 3, 32 (O) BK 15, 17, 23, 28, 7, 16, 30 (C)	36
Case 2	B4	B3, B5	B3-B2-B1-B13-B12-B11-B10-B9-B8-B7-B6-B5	L8	BK 19, 8, 9, 10, 11 (O) BK 28, 23, 17, 15, 7, 16, 30 (C)	71
Case 3	B8	B9	B9-B10-B11-B12-B13-B1-B2-B3-B4-B5-B6-B7	L2, L4, L6, L10, L11,L13	BK *4, 9, 34, 24, 27, 29,* 18, 19, 20 (O) BK 23, 28, 15, 7, 16, 30 (C)	65.9
Case 4	B9	No	No	No	BK 20, 21, 22 (O)	-
Case 5	B10	B11	B11-B12-B13-B1	No	BK 24, 25, 26 (O)	-

Case 6	B1, B4	B2 B3 B5 B13	B2-B3 B5-B6-B7-B8 B13-B12-B11-B10	L2,L3	BK *4, 6*, 1, 2, 3, 32, 8, 9, 10, 11 (O) BK 15, 17, 28, 7 (C)	0
Case 7	B1, B8	B2 B9 B13	B2-B3-B4-B5-B6-B7 B9-B10-B11-B12-B13	L3 L9	BK *6, 21*, 1, 2, 3, 32, 18, 19, 20 (O) BK 7, 15, 16, 23, 28, 30 (C)	5 4
Case 8	B4, B10	B3 B5 B11	B3-B2-B1-B13-B12-B11 B5-B6-B7-B8	L3	BK *6*, 8, 9, 10, 11, 24, 25, 26 (O) BK 7, 15, 16, 28, 30 (C)	5

B.1.2: Reconfiguration without considering priority of the loads

Test case	Faulted Bus Number	Negative power bus	Possible power supply path	Load Shedding	Breaker reconfiguration	MW Served
Case 1	B1	B2, B13	B2-B3-B4-B5-B6-B7-B8-B9-	L5, L9	BK 12, *21*, 1, 2, 3, 32 (O)	46.5

			B10-B11-B12-B13		BK 15, 17, 23, 28, 7, 16, 30 (C)	
Case 2	B4	B3, B5	B3-B2-B1-B13-B12-B11-B10-B9-B8-B7-B6-B5	L5, L12, L13	BK *12, 33, 29,* 8, 9, 10, 11 (O) BK 28, 23, 17, 15, 7, 16, 30 (C)	71.1
Case 3	B8	B9	B9-B10-B11-B12-B13-B1-B2-B3-B4-B5-B6-B7	L2, L4, L6, L7, L12, L13	BK 4, *9, 14, 33, 34,* 18, 19, 20, 29 (O) BK 23, 28, 15, 7, 16, 30 (C)	66.1
Case 4	B9	No	No	No	BK 20, 21, 22 (O)	-
Case 5	B10	B11	B11-B12-B13-B1	No	BK 24, 25, 26 (O)	-
Case 6	B1, B4	B2 B3 B5 B13	B2-B3 B5-B6-B7-B8 B13-B12-B11-B10	L2, L3	BK *4, 6,* 1, 2, 3, 32, 8, 9, 10, 11 (O) BK 15, 17, 28, 7 (C)	0
Case 7	B1, B8	B2 B9 B13	B2-B3-B4-B5-B6-B7 B9-B10-B11-	L3 L9	BK *6, 21*, 1, 2, 3, 32, 18, 19, 20 BK 7, 15, 16, 23,	5 4

			B12-B13		28, 30 (C)	
Case 8	**B4, B10**	**B3** **B5** **B11**	**B3-B2-B1-B13-B12-B11** **B5-B6-B7-B8**	**L3**	**BK *6*, 8, 9, 10, 11, 24, 25, 26 (O)** **BK 7, 15, 17, 28, 30 (C)**	**5**

B.1.3: Reconfiguration considering both priority and magnitude factor

Test case	**Faulted Bus Number**	**Negative power bus**	**Possible power supply path**	**Load Shedding**	**Breaker reconfiguration**	**MW Served**
Case 1	**B1**	**B2, B13**	**B2-B3-B4-B5-B6-B7-B8-B9-B10-B11-B12-B13**	**L3, L11**	**BK *6*, 27, 1, 2, 3, 32 (O)** **BK 15, 17, 23, 28, 7, 16, 30 (C)**	**35.4**
Case 2	**B4**	**B3, B5**	**B3-B2-B1-B13-B12-B11-B10-B9-B8-B7-B6-B5**	**L2, L11, L6**	**BK 4, 34, 27, 8, 9, 10, 11 (O)** **BK 28, 23, 17, 15, 7, 16, 30 (C)**	**71**
Case 3	**B8**	**B9**	**B9-B10-B11-B12-B13-B1-B2-**	**L1, L2, L4, L6,,**	**BK *2, 4, 9, 34, 27, 29,* 18, 19, 20 (O)**	**66.1**

			B3-B4-B5-B6-B7	**L11,L13**	**BK 23, 28, 15, 7, 16, 30 (C)**	
Case 4	**B9**	**No**	**No**	**No**	**BK 20, 21, 22 (O)**	**-**
Case 5	**B10**	**B11**	**B11-B12-B13-B1**	**No**	**BK 24, 25, 26 (O)**	**-**
Case 6	**B1, B4**	**B2** **B3** **B5** **B13**	**B2-B3** **B5-B6-B7-B8** **B13-B12-B11-B10**	**L2,L3**	**BK *4, 6*, 1, 2, 3, 32, 8, 9, 10, 11 (O)** **BK 15, 17, 28, 7 (C)**	**0**
Case 7	**B1, B8**	**B2** **B9** **B13**	**B2-B3-B4-B5-B6-B7** **B9-B10-B11-B12-B13**	**L3** **L9**	**BK *6, 21*, 1, 2, 3, 32, 18, 19, 20 (O)** **BK 7, 15, 16, 23, 28, 30 (C)**	**5** **4**
Case 8	**B4, B10**	**B3** **B5** **B11**	**B3-B2-B1-B13-B12-B11** **B5-B6-B7-B8**	**L3**	**BK *6*, 8, 9, 10, 11 , 24, 25, 26 (O)** **BK 7, 15, 16, 28, 30 (C)**	**5**

B.2 Reconfiguration with errors introduced (Type B)

B.2.1: Reconfiguration considering priority of the loads

Test case	Faulted Bus Number	Negative power bus	Possible power supply path	Load Shedding	Breaker reconfiguration	MW Served
Case 1	B1	B2, B13	B2-B3-B4-B5-B6-B7-B8-B9-B10-B11-B12-B13	L3, L6	BK *6*, 34, 1, 2, 3, 32 (O) BK 15, 17, 23, 28, 7, 16, 30 (C)	37.54
Case 2	B4	B3, B5	B3-B2-B1-B13-B12-B11-B10-B9-B8-B7-B6-B5	L2, L6, L8, L11	BK 4, 34, 19, *27,* 8, 9, 10, 11 (O) BK 28, 23, 17, 15, 7, 16, 30 (C)	71.077
Case 3	B8	B9	B9-B10-B11-B12-B13-B1-B2-B3-B4-B5-B6-B7	L1,L2, L4, L6, L10, L11, L13	BK 2, 4, 9, 34, 24, 27, 29, 18, 19, 20(O) BK 23, 28, 15, 7, 16, 30 (C)	65.977
Case 4	B9	No	No	No	BK 20, 21, 22 (O)	-
Case 5	B10	B11	B11-B12-B13-B1	No	BK 24, 25, 26 (O)	-

					BK 28	
Case 6	B1, B4	B2 B3 B5 B13	B2-B3 B5-B6-B7-B8 B13-B12-B11-B10	L2,L3	BK *4, 6*, 1, 2, 3, 32, 8, 9, 10, 11 (O) BK 15, 17, 28, 23, 7 (C)	0
Case 7	B1, B8	B2 B9 B13	B2-B3-B4-B5-B6-B7 B9-B10-B11-B12-B13	L3, L9 L9	BK *6, 21*, 1, 2, 3, 32, 18, 19, 20 (O) BK 7, 15, 16, 23, 28, 30 (C)	4.076 5.12
Case 8	B4, B10	B3 B5 B11	B3-B2-B1-B13-B12-B11 B5-B6-B7-B8	L3	BK *6*, 8, 9, 10, 11 , 24, 25, 26 (O) BK 7, 15, 17, 28, 30 (C)	5.126

B.2.2: Reconfiguration without considering priority of the loads

Test case	Faulted Bus Number	Negative power bus	Possible power supply path	Load Shedding	Breaker reconfiguration	MW Served
Case 1	B1	B2, B13	B2-B3-B4-B5-B6-B7-B8-B9-	L9, L11	BK 21, 27, 1, 2, 3, 32 (O)	47.39

			B10-B11-B12-B13		BK 15, 17, 23, 28, 7, 16, 30 (C)	
Case 2	B4	B3, B5	B3-B2-B1-B13-B12-B11-B10-B9-B8-B7-B6-B5	L2, L5, L7, L12	BK 4, 12, 14, 33, 8, 9, 10, 11 (O) BK 28, 23, 17, 15, 7, 16, 30 (C)	71.148
Case 3	B8	B9	B9-B10-B11-B12-B13-B1-B2-B3-B4-B5-B6-B7	L1, L2, L4, L10, L12, L13	BK *2, 4, 9, 34, 24, 33, 29, 18, 19, 20* (O) BK 23, 28, 15, 7, 16, 30 (C)	66.189
Case 4	B9	No	No	No	BK 20, 21, 22 (O)	-
Case 5	B10	B11	B11-B12-B13-B1	No	BK 24, 25, 26 (O) BK 28 (C)	-
Case 6	B1, B4	B2 B3 B5 B13	B2-B3 B5-B6-B7-B8 B13-B12-B11-B10	L2, L3	BK *4, 6*, 1, 2, 3, 32, 8, 9, 10, 11 (O) BK 15, 17, 28,23, 7 (C)	0
Case 7	B1, B8	B2 B9 B13	B2-B3-B4-B5-B6-B7 B9-B10-B11-	L3,L9 L9	BK *6, 21*, 1, 2, 3, 32, 18, 19, 20 BK 7, 15, 16, 23,	4.07 5.12

			B12-B13		**28, 30 (C)**	
Case 8	**B4, B10**	**B3** **B5** **B11**	**B3-B2-B1-B13-B12-B11** **B5-B6-B7-B8**	**L3**	**BK *6*, 8, 9, 10, 11 , 24, 25, 26 (O)** **BK 7, 15, 17, 28, 30 (C)**	**5.12**

B.2.3: Reconfiguration considering both priority and magnitude factor

Test case	**Faulted Bus Number**	**Negative power bus**	**Possible power supply path**	**Load Shedding**	**Breaker reconfiguration**	**MW Served**
Case 1	**B1**	**B2, B13**	**B2-B3-B4-B5-B6-B7-B8-B9-B10-B11-B12-B13**	**L3**	**BK 6, 1, 2, 3, 32 (O)** **BK 15, 17, 23, 28, 7, 16, 30 (C)**	**37.5**
Case 2	**B4**	**B3, B5**	**B3-B2-B1-B13-B12-B11-B10-B9-B8-B7-B6-B5**	**L2, L6, L8, L12**	**BK 4, 34, 19, 33, 8, 9, 10, 11 (O)** **BK 28, 23, 17, 15, 7, 16, 30 (C)**	**71.289**
Case 3	**B8**	**B9**	**B9-B10-B11-B12-B13-B1-B2-B3-B4-B5-B6-**	**L2, L4, L5, L6, L10, L11**	**BK 2,*4, 9,12, 34, 24, 29,* 18, 19, 20 (O)**	**65.927**

			B7	L12,L13	BK 23, 28, 15, 7, 16, 30 (C)	
Case 4	B9	No	No	No	BK 20, 21, 22 (O)	-
Case 5	B10	B11	B11-B12-B13-B1	No	BK 24, 25, 26 (O) BK 28 (C)	-
Case 6	B1, B4	B2 B3 B5 B13	B2-B3 B5-B6-B7-B8 B13-B12-B11-B10	L2,L3	BK *4, 6*, 1, 2, 3, 32, 8, 9, 10, 11 (O) BK 15, 17, 28, 23, 7 (C)	0
Case 7	B1, B8	B2 B9 B13	B2-B3-B4-B5-B6-B7 B9-B10-B11-B12-B13	L3, L9 L3	BK *6, 21*, 1, 2, 3, 32, 18, 19, 20 (O) BK 7, 15, 16, 23, 28, 30 (C)	4.041 5.0574
Case 8	B4, B10	B3 B5 B11	B3-B2-B1-B13-B12-B11 B5-B6-B7-B8	L3	BK *6*, 8, 9, 10, 11 , 24, 25, 26 (O) BK 7, 15, 17, 28, 30 (C)	5.07

B.3 Reconfiguration with fuzzy correction of meter data (Type C)

B.3.1: Reconfiguration considering priority of the loads

Test case	Faulted Bus Number	Negative power bus	Possible power supply path	Load Shedding	Breaker reconfiguration	MW Served
Case 1	B1	B2, B13	B2-B3-B4-B5-B6-B7-B8-B9-B10-B11-B12-B13	L3, L13	BK 6, 29, 1, 2, 3, 32 (O) BK 15, 17, 23, 28, 7, 16, 30 (C)	36.3049
Case 2	B4	B3, B5	B3-B2-B1-B13-B12-B11-B10-B9-B8-B7-B6-B5	L2, L8	BK 4, 19, 8, 9, 10, 11 (O) BK 28, 23, 17, 15, 7, 16, 30 (C)	70.977
Case 3	B8	B9	B9-B10-B11-B12-B13-B1-B2-B3-B4-B5-B6-B7	L1,L2, L4,L5, L6, L11, L12, L13	BK 2, 4, 9, 12, 34, 27, 33, 29, 18, 19, 20(O) BK 23, 28, 15, 7, 16, 30 (C)	65.9
Case 4	B9	No	No	No	BK 20, 21, 22 (O)	-
Case 5	B10	B11	B11-B12-B13-B1	No	BK 24, 25, 26 (O) BK 28	-

Case 6	B1, B4	B2 B3 B5 B13	B2-B3 B5-B6-B7-B8 B13-B12-B11-B10	L2,L3	BK *4, 6*, 1, 2, 3, 32, 8, 9, 10, 11 (O) BK 15, 17, 28, 23, 7 (C)	0
Case 7	B1, B8	B2 B9 B13	B2-B3-B4-B5-B6-B7 B9-B10-B11-B12-B13	L3, L9 L9	BK *6, 21*, 1, 2, 3, 32, 18, 19, 20 (O) BK 7, 15, 16, 23, 28, 30 (C)	4.0413 5.057
Case 8	B4, B10	B3 B5 B11	B3-B2-B1-B13-B12-B11 B5-B6-B7-B8	L3	BK *6*, 8, 9, 10, 11 , 24, 25, 26 (O) BK 7, 15, 17, 28, 30 (C)	5.07

B.3.2: Reconfiguration without considering load priority

Test case	Faulted Bus Number	Negative power bus	Possible power supply path	Load Shedding	Breaker reconfiguration	MW Served
Case 1	B1	B2, B13	B2-B3-B4-B5-B6-B7-B8-B9-B10-B11-B12-	L6, L9, L11	BK 34, 21, 27, 1, 2, 3, 32 (O) BK 15, 17, 23, 28,	46.3

			B13		7, 16, 30 (C)	
Case 2	B4	B3, B5	B3-B2-B1-B13-B12-B11-B10-B9-B8-B7-B6-B5	L6, L10, L12	BK 34, 24, 33, 8, 9, 10, 11 (O) BK 28, 23, 17, 15, 7, 16, 30 (C)	71.148
Case 3	B8	B9	B9-B10-B11-B12-B13-B1-B2-B3-B4-B5-B6-B7	L4, L6, L7, L10, L12, L13	BK *9,34, 14, 24, 33, 29, 18, 19, 20* (O) BK 23, 28, 15, 7, 16, 30 (C)	66.01
Case 4	B9	No	No	No	BK 20, 21, 22 (O)	-
Case 5	B10	B11	B11-B12-B13-B1	No	BK 24, 25, 26 (O) BK 28 (C)	-
Case 6	B1, B4	B2 B3 B5 B13	B2-B3 B5-B6-B7-B8 B13-B12-B11-B10	L2, L3	BK *4, 6*, 1, 2, 3, 32, 8, 9, 10, 11 (O) BK 15, 17, 28,23, 7 (C)	0
Case 7	B1, B8	B2 B9 B13	B2-B3-B4-B5-B6-B7 B9-B10-B11-B12-B13	L3,L9 L9	BK *6, 21*, 1, 2, 3, 32, 18, 19, 20 BK 7, 15, 16, 23, 28, 30 (C)	4.04 5.05

Case 8	B4, B10	B3 B5 B11	B3-B2-B1-B13-B12-B11 B5-B6-B7-B8	L3	BK *6*, 8, 9, 10, 11 , 24, 25, 26 (O) BK 7, 15, 17, 28, 30 (C)	5.07

B.3.3: Reconfiguration considering both priority and magnitude factor

Test case	Faulted Bus Number	Negative power bus	Possible power supply path	Load Shedding	Breaker reconfiguration	MW Served
Case 1	B1	B2, B13	B2-B3-B4-B5-B6-B7-B8-B9-B10-B11-B12-B13	L3, L6	BK *6*, 34, 1, 2, 3, 32 (O) BK 15, 17, 23, 28, 7, 16, 30 (C)	36.3049
Case 2	B4	B3, B5	B3-B2-B1-B13-B12-B11-B10-B9-B8-B7-B6-B5	L2, L6, L8	BK 4, 34, 19, 8, 9,*10, 11* (O) BK 28, 23, 17, 15, 7, 16, 30 (C)	70.476
Case 3	B8	B9	B9-B10-B11-B12-B13-B1-B2-B3-B4-B5-	L2, L4, L5, L6, L10, L11	BK *4, 9,12, 34, 24, 27, 33, 29,* 18, 19, 20 (O)	65.927

			B6-B7	L12,L13	BK 23, 28, 15, 7, 16, 30 (C)	
Case 4	B9	No	No	No	BK 20, 21, 22 (O)	-
Case 5	B10	B11	B11-B12-B13-B1	No	BK 24, 25, 26 (O) BK 28 (C)	-
Case 6	B1, B4	B2 B3 B5 B13	B2-B3 B5-B6-B7-B8 B13-B12-B11-B10	L2,L3	BK *4, 6*, 1, 2, 3, 32, 8, 9, 10, 11 (O) BK 15, 17, 28, 23, 7 (C)	0
Case 7	B1, B8	B2 B9 B13	B2-B3-B4-B5-B6-B7 B9-B10-B11-B12-B13	L3, L9 L3	BK *6, 21*, 1, 2, 3, 32, 18, 19, 20 (O) BK 7, 15, 16, 23, 28, 30 (C)	4.041 5.0574
Case 8	B4, B10	B3 B5 B11	B3-B2-B1-B13-B12-B11 B5-B6-B7-B8	L3	BK *6*, 8, 9, 10, 11 , 24, 25, 26 (O) BK 7, 15, 17, 28, 30 (C)	5.07