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RECONFIGURATION OF SHIPBOARD POWER SYSTEMS USING A GENETIC ALGORITHM

By

Koteshwar Reddy Padamati

A Thesis
Submitted to the Faculty of
Mississippi State University
in Partial Fulfillment of the Requirements
for the Degree of Master of Science
in Electrical Engineering
in the Department of Electrical and Computer Engineering

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RECONFIGURATION OF SHIPBOARD POWER SYSTEMS USING A GENETIC ALGORITHM

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The shipboard power system supplies energy to sophisticated systems for weapons, communications, navigation, and operation. After a fault is encountered, reconfiguration of a shipboard power system becomes a critical activity that is required to either restore service to a lost load or to meet some operational requirements of the ship. Reconfiguration refers to changing the topology of the power system in order to isolate system damage and/or optimize certain characteristics of the system related to power efficiency. When finding the optimal state, it is important to have a method that finds the desired state within a short amount of time, in order to allow fast response for the system. Since the reconfiguration problem is highly nonlinear over a domain of discrete variables, the genetic algorithm method is a suitable candidate. In this thesis, a reconfiguration methodology, using a genetic algorithm, is presented that will reconfigure a network, satisfying the operational requirements and priorities of loads. Graph theory is utilized to represent the shipboard power system topology in matrices. The reconfiguration process

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and the genetic algorithm are implemented in MATLAB and tested on an 8-bus power system model and on larger power system with distributed generators by considering different fault scenarios. Each test system was reconfigured in three different ways: by considering load priority, without considering load priority, and by combining priority factor and magnitude factor. The test results accuracy was verified through hand checking.

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DEDICATION

I would like to dedicate this work to my family members.

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ACKNOWLEDGMENTS

I would like to express my sincere gratitude to my major professor, Dr. Noel N. Schulz, for her support, guidance, and encouragement throughout this research. I would also like to extend thanks to the other committee members, Dr. Herbert Ginn and Dr. Anurag K. Srivastava, for their willingness to serve on my graduate committee and more importantly for their support and valuable suggestions.

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المنارة للاستشارات

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TABLE OF CONTENTS

المنارة للاستشارات

www.manaraa.com

المنارة للاستشارات
www.manaraa.com

المنارة للاستشارات

www.manaraa.com

LIST OF TABLES

المنارة للاستشارات

www.manaraa.com

LIST OF FIGURES

المنارة للاستشارات

www.manaraa.com

www.manaraa.com

CHAPTER I

INTRODUCTION

1.1 Introduction

The shipboard power system (SPS) supplies energy to sophisticated systems for weapons, communications, navigation and operation. The reliability and survivability of SPS are critical, especially under battle conditions. When a fault occurs, the fault should be isolated immediately and there will be un-faulted sections that are left without supply. It is required to quickly restore supply to these un-faulted sections to increase the system survivability. This procedure is called service restoration. Restoration is achieved by reconfiguring the power system network.

This thesis will focus on reconfiguration for restoration of the shipboard power system. Reconfiguration refers to changing the topology of the power system in order to isolate system damage and/or optimize certain characteristics of the system related to power efficiency. When finding the optimal state, it is important to have a method that finds the desired state within a short amount of time, in order to allow fast response for the system. Since the reconfiguration problem is highly nonlinear over a domain of discrete variables, the genetic algorithm method is a good optimization candidate. In this thesis, a reconfiguration methodology, using a genetic algorithm, is presented that will reconfigure a given network, satisfying the operational requirements and priorities of

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loads. It also considers islanding to restore supply to critical loads after a fault is encountered.

1.2 Shipboard Power System Overview

Shipboard power systems consist of generators that are connected in a ring configuration through a generator switchboard. Shipboard power systems are very similar to isolated utility systems in that the available generators are the only source of supply for the system loads. There are, however, several differences between utility and shipboard power systems, such as ships have large dynamic loads relative to generator size and a larger portion of nonlinear loads relative to power generation capacity, and transmission lines are not nearly as significant as for utilities because of their short lengths [6]. The main characteristics of shipboard power systems are [10]:

- Generation is closely sized to the load demand (i.e., no significant spinning reserve).
- A small number of loads constitute most of the load demand (e.g., the propulsion motors).
- SPSs are geographically smaller than utility power systems; system level measurement is possible.
- Transmission lines are not nearly as significant as with a utility system; systems have short line segments with very low impedance.
- SPSs have a high impedance ground.
- SPSs need faster controls than the utilities to maintain the system stability and frequency.

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- There is a higher expectation to maintain loads for fight through and survivability.

As the shipboard power system has a relatively weak balance between the generator capacity and load demand, the large rotational load on the ship makes the power system vulnerable if power balance is not maintained all the time. The normal protection schemes only provide fault detection and isolation functions, but do not consider system stability or power balance after fault isolation. So reconfiguring a power system after a fault is a critical issue that needs to be addressed.

1.3 System Reconfiguration

Reconfiguration is the process of altering the configuration of the electrical power system by changing the status of the switches without violating operating constraints. Reconfiguration is mainly done for load restoration, loss minimization, and load balancing [13]. Reconfiguration for restoration involves redirecting power flow to the remaining loads in the event of a component failure, generator loss, or grid infraction. This research work deals with reconfiguration for restoration of shipboard power system.

The electric power system allows for reconfigurability. Faults can be detected quickly, and the system can be configured in order to isolate the fault. Instantaneous response to system damage prevents it from propagating, allowing as many loads as possible to function. Reconfiguration also allows power to be quickly diverted to high power applications for very small time frames, which is vital for next generation, high-power weapons. Furthermore, the system can be reconfigured in non-emergency situations in order to optimize power consumption. The optimization can be directed

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toward overall efficiency, power to the loads, or minimize power loss, or a combination of the same. Reconfiguration can also be performed in order to satisfy system constraints or criteria, such as desired load consumption or current ratings.

This thesis discusses system reconfiguration after a fault is encountered. The objective of the reconfiguration is to maintain power supply to unaffected loads to the maximum extent and supply power to high priority loads through load shedding if necessary. This optimization will be performed while considering the system constraints.

1.4 Thesis Objective

In today's shipboard power system generation is closely sized to load demand. When faults occur as a result of battle damage or equipment failure and are removed after isolation by protective devices, some critical loads are left without supply. Reconfiguration is critical to maintain the availability of energy to the connected loads and to interrupt the smallest portion of the system under any abnormal conditions. Reconfiguration is essential either to restore service to a section or to meet some operational requirements of the ship like to take some equipment for maintenance or to change from one mission to another. In order to make reconfiguration effective for the shipboard power system, it must be done intelligently and as fast as possible. By reconfiguring intelligently, the system is controlled without diverting manpower or requiring instant and vital decision making by a human. By performing reconfiguration quickly, the system can immediately respond to changing impedances of dynamic systems and also power system contingencies. Because of this need, it is desirable to find an accurate numerical method that solves the reconfiguration quickly.

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In this thesis a genetic algorithm was selected for the reconfiguration because of the fact that the algorithm can be applied irrespective of the objective function and topology, making it useful for functions that are highly nonlinear. Moreover the representation of the switch configuration is already modeled in a form suitable for the genetic algorithm, so no additional encoding and decoding is necessary to translate continuous variables into discrete variables. The genetic algorithm also has the advantage that it does not get struck on a local optimum which is the case for other global algorithms.

1.5 Thesis Organization

The organization of this thesis is as follows. Chapter 2 gives the background information related to shipboard power systems, graph theory and its application to power systems and briefly explains the genetic algorithm. The literature review is also covered in the second chapter. Chapter 3 explains the problem statement and proposed work. Chapter 4 explains in detail about the genetic algorithm, the genetic operators (selection, crossover, mutation) involved in the algorithm and constraint handling. It will define the mathematical problem formulation of the reconfiguration problem and the applicability of the algorithm to the reconfiguration problem. Chapter 5 is the main section of this thesis which explains the reconfiguration process for the 8-bus power system. Test cases and results are presented in Chapter 6. Chapter 7 provides the conclusions of this study and suggests some future work topics.

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CHAPTER II

BACKGROUND

This chapter gives a brief discussion of key topics related to the thesis subject. Shipboard power system topology and characteristics will be introduced based on the reviewed literature. A notional shipboard power system model is also presented. An overview of shipboard power system protection and zone-based protection scheme is presented. The zone selection differential protection is one possible protection solution for detecting and isolating various faults through identifying the differential current through current transformers and operating the breakers around the faulted area. Finally, graph theory and its application to power system representation and genetic algorithm will be outlined.

2.1 Shipboard Power System

2.1.1 Shipboard Power System Characteristics

Shipboard power systems are three-phase power systems, with the power transmitted and distributed to load and service centers through an ungrounded power network. Naval shipboard power systems have multiple AC generators to generate AC power. The power can be delivered directly to the load centers through AC transmission

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cables and distribution networks. The distribution systems may be pure AC or DC or a mixture of AC and DC power. This thesis focuses on the typical shipboard power system where three-phase AC power is generated and distributed. Shipboard power systems always require high survivability and stability since they supply power to sophisticated systems for weapons, communications, navigation, and operation. Shipboard power systems have special characteristics based on their structure. First of all, shipboard power systems are small in size. The cables connecting generators and loads are short and have small impedances. Any fault that occurs on the cable implies the fault is close to the generators and that may cause a severe impact on the generators. Secondly, shipboard power systems have large loads relative to the power generator capacity. Therefore, any generator fault may cause a significant generation deficiency, possibly even an entire system collapse. Finally, systems have a high impedance ground. Therefore, shipboard power systems require fast fault isolation and reconfiguration.

2.1.2 Shipboard Power Distribution System

Shipboard power distribution systems are designed to minimize the size and weight, save money, and improve the survivability of the vessel. Additionally, shipboard power distribution systems should possess the ability to continually transfer power to vital systems during and after fault conditions. There are two possible types of shipboard power distribution architecture: radial and zonal. In the next two sections, the typical radial and zonal distribution systems will be introduced.

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2.1.3 *Radial Electric Power Distribution*

In this type of configuration, the generators are connected in a ring configuration, which provides more flexibility in terms of generation, connection, and system configuration. The system is configured radially downstream of the generator switchboards [11]. There are load center switchboards, transformers, static loads, induction motors, power panels, circuit breakers (CB), and many three-phase and single-phase cables. A shipboard power system with radial electric power distribution system is shown in Figure 2.1. In this case, there are six generators: four generators providing power during normal operation and two generators serving as emergency back up. Power can be transferred from one generator switchboard to another through the connected tie circuit breakers. In this ring configuration power system, any generator can provide power to any load through load center switchboards. Load center switchboards, used under the generator switchboard level, are connected to the generator switchboards. Load centers are distributed as a radial configuration. The load center switchboards supply power to power panels or individual loads either directly or via automatic bus transfers (ABT) or manual bus transfers (MBT). The loads are designated as vital or nonvital. For vital loads, two sources of power (normal or alternate) are provided from separate paths via ABTs or MBTs. When vital loads lose supply through a normal path (for example,because of faults during battle), supply is restored through the alternate path provided via ABT or MBT. When the vital load is supplied via an ABT, switching to the alternate path occurs automatically. A vital load supplied via an MBT requires manual

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operation by an operator to switch to the alternate path. For an ABT, if the supply is restored to the alternate path, it automatically switches to the normal path.

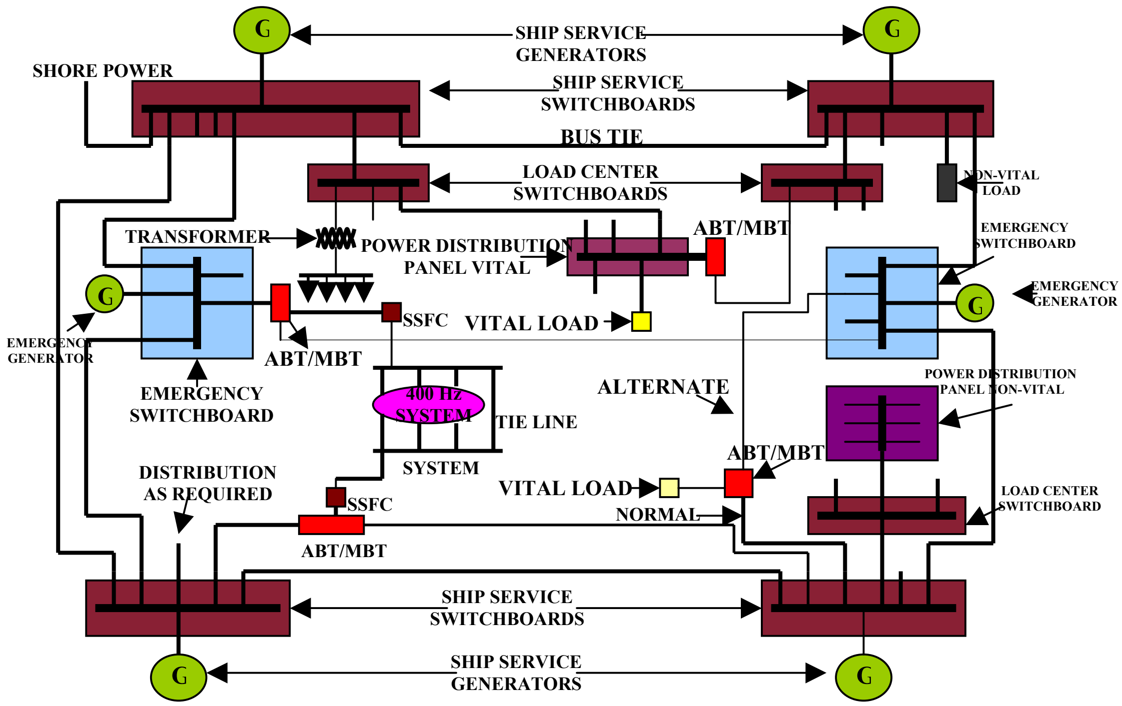

Figure 2.1 Radial Electric Power Distribution System

2.1.4 Zonal Electric Power Distribution

The zonal power distribution system consists of two main power distribution buses running longitudinally along the port and starboard side of the ship. One main bus would be positioned well above the waterline while the other would be located below the waterline, which maximizes the distance between buses and improves the survivability [14]. The effects of damage to the distributed system and other equipment should not disturb generators. Figure 2.2 shows zonal electric distribution system. This system is

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primarily designed around subdividing a ship into multiple zones typically five to eight zones – based on the layout of the usually transverse bulkheads. A high voltage ring runs around the inside perimeter of the ship and, hence, each bulkhead contains only two points where electric cables penetrate through – one on the port side and one on the starboard side of the ship [12]. Protective switches are located so as to electrically isolate each zone from adjacent zones. Within each zone are one or two switchboards or load centers known as Ship Service Converter Modules (SSCM). From these, loads are fed at 450V and 120V AC at either 60 Hz or 400 Hz and can also be fed at various DC voltage levels. Vital loads can be supplied from either the port switchboard or the starboard switchboard and can be switched via ABT. The zonal architecture is flexible and saves the cost for short switchboard feeder cables and elimination of distribution transformers.

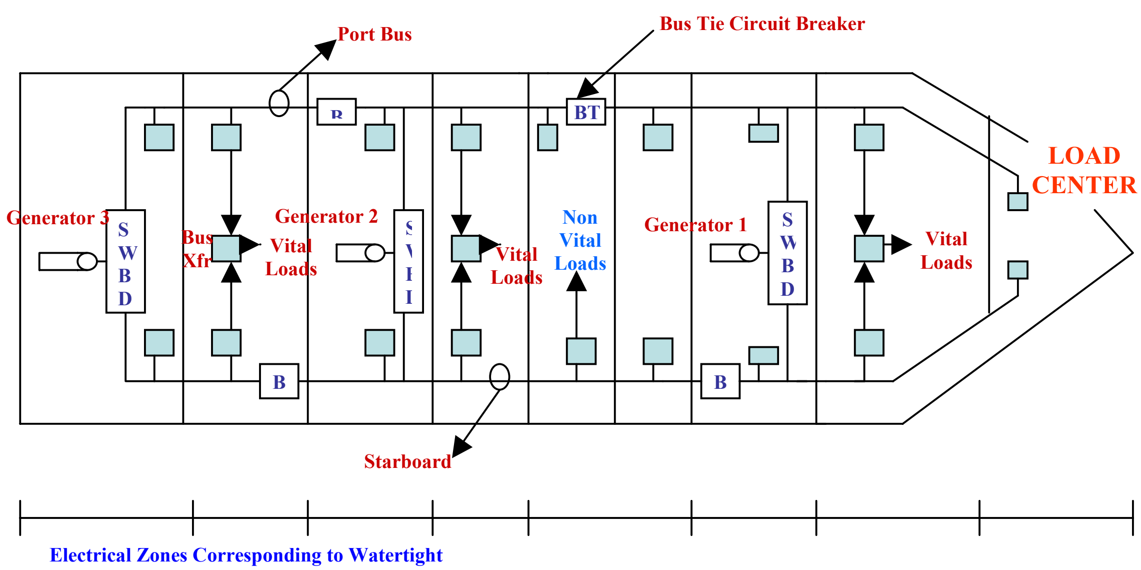

Figure 2.2 Zonal Electric Power Distribution System [14]

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2.2 DD(X) Shipboard Power System Model

The proposed DD(X) design for a ship is currently the only US Navy surface combatant using an Integrated Power System (IPS). The DD(X) architecture exhibits the Navy's new approach to integrate the power system and include electric propulsion. The Office of Naval Research (ONR) Program Officer for the Electric Ship Research and Development Consortium (ESRDC) effort suggested the DD(X) as the parent for this baseline model, which is indicative of the current development of surface combatant integrated power systems [10]. Figure 2.3 shows the typical DD(X) power system model.

The DD(X) power system is a 13.8 kV loop with four gas turbine generator sets. Two main turbine generators (MTGs) are rated at 36 MW each and two auxiliary turbine generators (ATGs) are rated at 4 MW each to provide a total installed generator power capacity of 80 MW [10]. Permanent magnet (PM) propulsion motors, each rated at 36.5 MW, support the propeller system. Each motor is controlled by an undefined advanced motor drive unit. Additionally, there is a 450 V system with seven main buses, which serve as load centers for the rest of the ship's load. These load centers are connected to two alternate 450 V auxiliary power units (APUs), rated at 0.5 MW each. The DD(X) total power requires 77.5 MW at a ship speed of 31.5 Knots and 2 MW at a ship speed of 0 Knots. Since the installed power of the generation plant is 80 MW and the two propulsion motors are totally rated at 73 MW, the main turbine generators provide power to the propulsion system and most of ship service electric loads consume power from the two small gas turbines [10].

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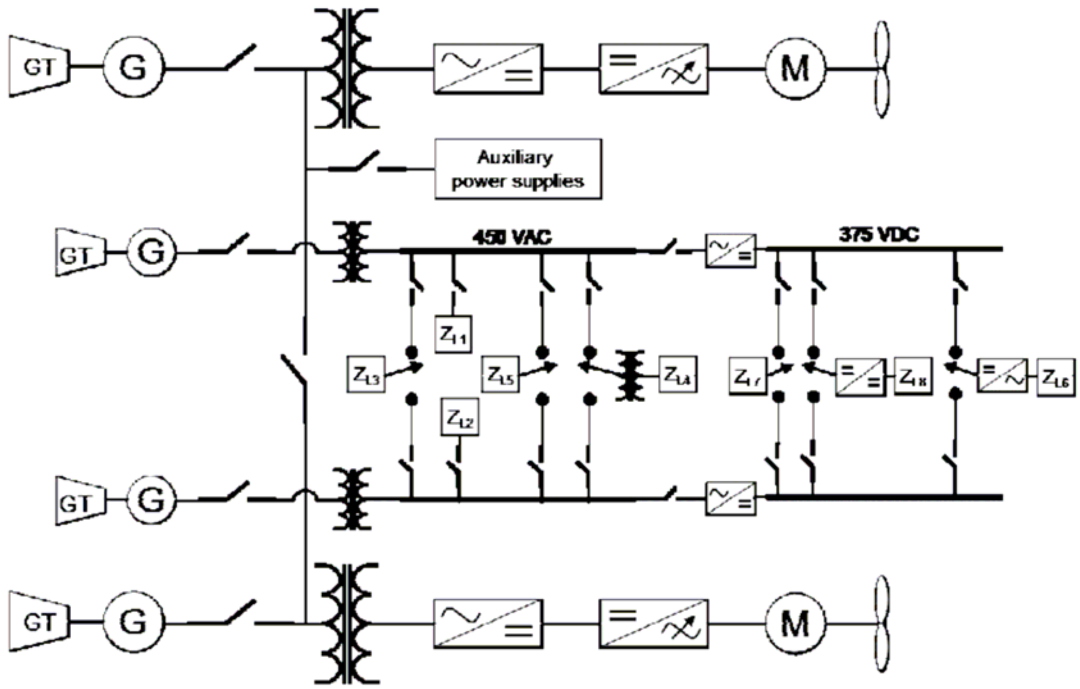

Figure 2.3 Typical DD(X) power system model [21]

2.3 Shipboard Power System Protection

Power system protection is designed to detect a fault, isolate the faulted part from the system, maintain system power balance, and keep the remaining system stable. Faults in a shipboard power system may occur due to material casualties of individual loads or a widespread fault due to battle damage. In addition to load faults, casualties can happen to cables, power generating equipment, or power distribution buses, which can lead to conditions of having inadequate power generation capacity for all attached loads [11]. After the fault has occurred, protective devices operate to isolate the faulted section. A

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zone based differential protection scheme will be used in this thesis as it offers a fast and efficient function to protect system stability and survivability [10].

2.3.1 Zone-Based Differential Protection Scheme

For complex configurations of a power system, zones can be defined for generators, transformers, buses, transmission and distribution lines, or motors [10]. If a fault occurs anywhere within a zone, action will be taken to isolate that zone from the rest of the system. Figure 2.4 illustrates the protective zone concept. A closed and dashed line shows each zone. Zone 1, for example, contains a generator and a connector leading to a transformer. In some cases, a zone may contain more than one component. For example, zone 4 contains a transformer and a line. Protective zones are overlapped to avoid the possibility of unprotected areas. For a fault anywhere in a zone, all circuit breakers in that zone open to isolate the fault.

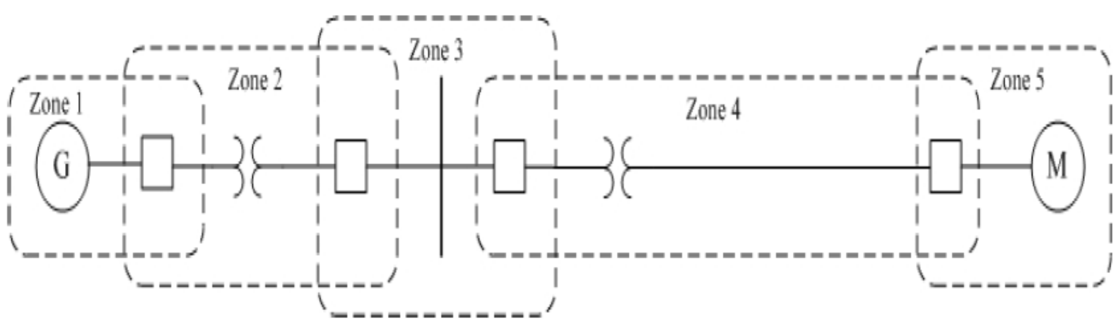

Figure 2.4 Illustration of Zone-Based Protection Scheme [10]

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2.4 Graph Theory and Its Application

Graph theory began in 1736 and one of the first people to experiment with graph theory was Leonhard Euler. He attempted to solve the problem of crossing seven bridges onto an island without using any of them more than once. From that point on, the study of graphs has been applied to a large number of real world problems. Today, graphs are all around us. They are used in many diverse industries, from urban planning, to shipping lanes, to computer networks such as the Internet [15]. They can represent physical networks, such as electrical circuits, or roadways. In the graph theory application to power system networks, graph theory can simplify power system representation, make system topology and operations visual, and represent all system topology changes as graph operations. This section introduces the fundamentals of graph theory.

2.4.1 Basic Graph Terminology

A graph consists of a nonempty set of points or vertices, and a set of edges that link together the vertices. A graph can take on many forms: directed or undirected. A directed graph is one in which the direction of any given edge is defined. Conversely, in an undirected graph the direction of the edge is not defined. Figure 2.5 represents an undirected graph and Figure 2.6 represents a directed graph. In the directed graph, edge *'2'* is connected by the source vertex *A* and target vertex *B*. The edges can also be weighted or un-weighted.

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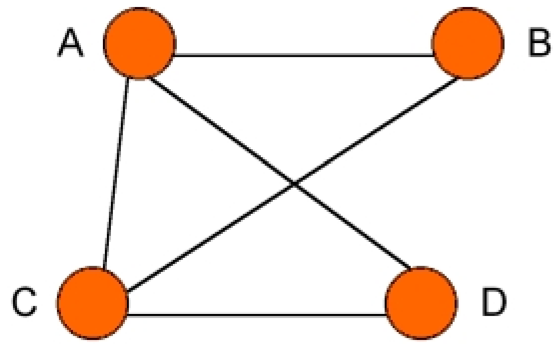

Figure 2.5 Undirected graph

The equivalent definition of the graph shown in Figure 2.5 is:

$G = (V,E)$

$V = \{A, B, C, D\}$
$E = \{(A, B), (A, C), (A, D), (B, C), (C, D)\}$

Where V is the set of vertices and E is the set of edges.

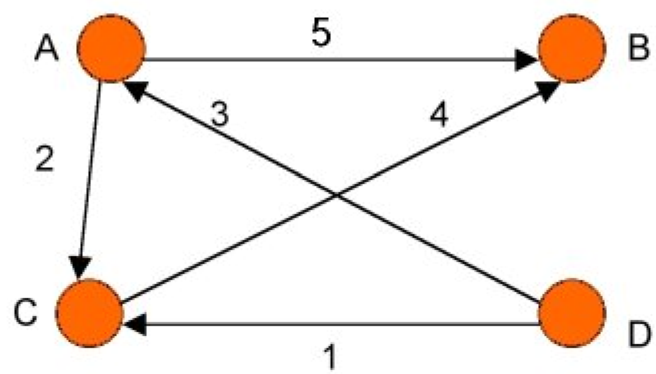

Figure 2.6 Directed graph

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The type of graph largely depends upon the features of its components, namely the attributes of the vertices and edges. A vertex within a graph may or may not have a label assigned to it. Similarly, an edge may have a label, weight, and/or direction associated with it. An edge in a graph that joins two vertices is said to be incident to both vertices. Furthermore, the degree of a vertex is determined by the number of distinct edges that are incident to it. More specifically, the indegree and outdegree of a vertex represent the number of edges those terminate in and originate from a vertex, respectively.

Two edges in a graph are termed *adjacent* if they connect to the same vertex. Similarly, two vertices are termed adjacent if they are connected by the same edge. A loop is an edge that links a vertex to itself. A *simple graph* is one that contains no loops or parallel edges, where more than one edge connects two given vertices, whereas a *multigraph* is a graph that contains multiple edges. Finally, a *complete graph* is a simple graph in which every pair of vertices is adjacent.

Other fundamental definitions and concepts of graph theory, which are used in this thesis, are briefly introduced below.

- A *path* through a graph is a traversal of consecutive vertices along a sequence of edges. By this definition, the vertex at the end of one edge in the sequence must also be the vertex at the beginning of the next edge in the sequence. The vertices that begin and end the path are termed the initial vertex and terminal vertex, respectively. With the exception of these initial and terminal vertices, each vertex within the path has two neighboring vertices that must also be

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adjacent to the vertex. The length of the path is the number of edges that are traversed along the path.

- If a vertex is *reachable* from another vertex then a path exists from the one vertex to the other vertex. It is assumed that every vertex is reachable from itself. Also, if vertex *b* is reachable from vertex *a* and vertex *c* is reachable from vertex *b*, then it follows that vertex *c* is reachable from vertex *a.*
- *Adjacency Matrix:* There are several different ways to represent a graph in a computer. Although graphs are usually shown diagrammatically, this is only possible when the number of vertices and edges is reasonably small. Graphs can also be represented in the form of matrices. The major advantage of matrix representation is that the calculation of paths and cycles can easily be performed using well known operations of matrices. An *adjacency matrix* is defined as follows: Let *G* be a graph with "n" vertices that are assumed to be ordered from v_1 to v_n. The n x n matrix A, in which

  $a_{ij} = 1$ if there exists a path from v_i to v_j

  $a_{ij} = 0$ otherwise

  is called an adjacency matrix.

  For example, an adjacency matrix for the graph shown in Figure 2.6 is:

$$A = \begin{vmatrix} 0\,1\,1\,0 \\ 0\,0\,0\,0 \\ 0\,1\,0\,0 \\ 1\,0\,1\,0 \end{vmatrix}$$

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- *Breadth-first search* (BFS) is a search through a graph that touches all of the vertices reachable from a particular source vertex. In addition, the order of the search is such that the algorithm will explore all of the children of a vertex before proceeding on to the children of its children [10]. When all of a vertex's children are explored, the vertex is finished. For example, if a breadth-first search is used in a graph shown in Figure 2.7. The search starts from vertex *a* and then the children of vertex *a*: vertices *b* and *c* are visited. Once both children (vertices *b, c*) of vertex *a* are visited, then vertices *d* and *e*, which are the children of vertex *b* are visited. Finally the children of *c*: vertices *f* and *g* are visited. Therefore, the order of discovery is: *abcdefg*. The order of finish is: *abcdefg*.

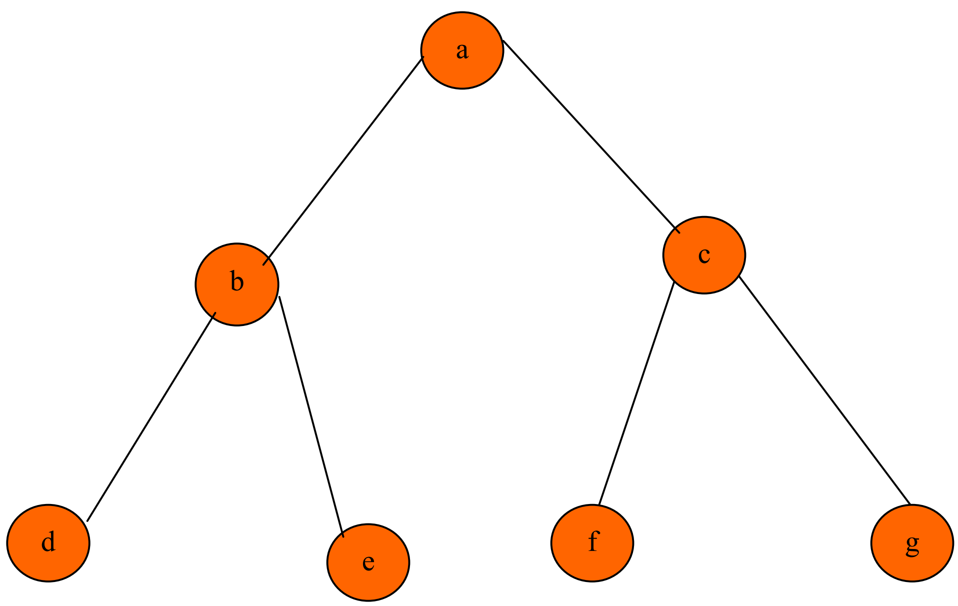

Figure 2.7 Illustration of Breadth-First Search

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2.5 Application of Graph Theory in Power Systems

Graph theory has been used in several applications of power system network representation, simulation, and analysis. The graph operation is a tool for step-by-step graph manipulation, providing a clear picture for analysis of power system operation. The associated matrix operation is suitable for computer implementation.

Graph theory is a powerful analytical tool in understanding and solving large, complex problems in electric network analysis. Graph theory applications in power networks can simplify the representation of switching procedures in a complex power system, convert various problems of power system analysis into graph-based problems, and develop system operations through graph-based numerical operations [10].

2.6 Application of Genetic Algorithm to Power Systems

Genetic algorithms (GAs) are search and optimization tools, which work differently, compared to classical search and optimization methods. Because of their broad applicability, ease of use, and global perspective, GAs have been increasingly applied to various search and optimization problems in the recent past. In reference [1], a genetic algorithm based method is proposed to decide the supply restoration and optimal load shedding strategy for distribution networks. The algorithm has been tested successfully on a practical system. In reference [2], genetic algorithm was successfully used to shipboard power system fault restoration and the superiority over the other methods was proved. RTDS fault restoration experiments indicated that the restoration algorithm based on the genetic algorithm can restore the fault in real time. In references [3] and [4], a genetic algorithm was applied for loss minimization and load balancing. In

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this thesis genetic algorithm is employed to find the post-fault optimal configuration so as to maintain power supply to unaffected loads to the maximum extent and supply power to the highest priority loads through load shedding if necessary. The detail explanation of genetic algorithm is given in chapter 4.

2.7 Summary

Shipboard power systems and their unique characteristics were discussed in this chapter. The characteristics of the DD(X) shipboard power systems were presented. An overview of shipboard power system protection and zone-based protection was presented. Based on the characteristics of shipboard power system, such as short cables and possible system-level measurements, a zone-based differential protection scheme is more flexible and more efficient for shipboard power protection. Basic concepts of graph theory and its applications were introduced. Finally genetic algorithm and its application to power systems were introduced.

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CHAPTER III

PROBLEM DESCRIPTION

The first part of this chapter presents the motivation and reasoning for developing a reconfiguration methodology for a shipboard power system using a genetic algorithm. Then the previous research work on shipboard power system reconfiguration is discussed. The problem statement and proposed work are provided at the end of this chapter.

3.1 Need for Reconfiguration

Faults in a shipboard power system may occur due to material casualties of individual loads or widespread fault due to battle damage. In addition to load faults, casualties can happen to cables, power generating equipment, or power distribution buses. If the fault is severe, such as a generator fault, it may cause a power deficiency to the remaining power system, system load generation unbalance, and even an entire system collapse. After the fault has occurred, protective devices operate to isolate the faulted section. But, this may lead to un-faulted sections that are not getting supplied. Therefore, it is required to restore supply automatically and quickly to these un-faulted sections of the shipboard power system to improve the system survivability. This can be achieved by changing the configuration of the system by opening and/or closing switches to restore supply to maximum load in the un-faulted sections of the shipboard power

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system. Reconfiguration can be aimed at supplying power to high priority loads and/or supplying power to maximum amount of loads depending upon the situation

3.2 Previous Work

Karen Butler, *et al* were the first to publish an intelligent approach to implementing a reconfiguration technique for shipboard power systems [5-8]. The papers they published established the foundation for intelligent reconfiguration for SPS. Briefly mentioned in the papers is an examination of commercial utility approaches to solving the restoration of service problem. In reference [5], a general reconfiguration method using heuristics reconfigured a given set of loads satisfying the operational requirements and load priorities. This method is very simple but has problems in restoration with an increasing number of loads. In the method of network flow approach [6, 7], the load priorities have not been considered during restoration. Reference [9] presents a shipboard power intelligent network reconfiguration method for service restoration using an expert system. The expert-system based method attempts to capture the knowledge and heuristic rules used by power system operators to determine switching sequences for supply restoration under a range of fault conditions. This information is typically stored in a knowledge base in the form of rules. The knowledge base is normally interpreted by an expert system shell in a way that seeks to mimic the decision-making process of human operators. However, the heuristic knowledge base is difficult and costly to gather and interpret. Since the resulting knowledge base is likely to be specific to a given system and its normal running configuration, a specific knowledge base may have to be built for each network to which the method was applied. In addition, there is no guarantee that, in a

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given case, the solution found will be close to the optimal solution under the prevailing conditions.

In this thesis, a reconfiguration methodology, using a genetic algorithm, is presented that will reconfigure a network, satisfying the operational requirements and priorities of loads. A genetic algorithm is selected because of its ability to find a global optimal solution for solving large-scale combinatorial optimization problems. Genetic algorithms have been found to be efficient methods for power system problems, including the supply restoration problem [1-4].

3.3 Problem Statement and Proposed Work

The need for reconfiguration for shipboard power systems has been stated and emphasized in preceding chapters and sections. Based on the studies and the requirements of the shipboard power system, it is valuable to develop a reconfiguration methodology to increase shipboard power system reliability and survivability.

The current shipboard power system has a relatively weak power balance since the generator capacity is closely sized to the load demand. The normal protection schemes only provide fault detection and isolation functions, but do not consider system stability or power balance after fault isolation. This research will focus on finding post-fault optimal configuration using a genetic algorithm, meeting designated objectives and system constraints.

The purpose of this research is to use a genetic algorithm to maintain the power balance of the remainder system after fault isolation and reduce the impact of the fault. The main objectives of the genetic algorithm are:

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- Maintain power supply to unaffected loads to the maximum extent.
- Supply power to high priority loads through load shedding if necessary.
- Serve largest amount of load.

The fitness function of the genetic algorithm is designed in such a way that the reconfiguration can be achieved by three different ways:

- Maximizing the power supplied to loads by considering load priority.
- Maximizing the power supplied to loads without considering load priority.
- Maximizing the power supplied to loads by combining priority factor and magnitude factor.

The overall research objectives include: representation of the shipboard power system topology using graph theory, fault isolation, finding post-fault configuration using a genetic algorithm. The reconfiguration process and the genetic algorithm were coded in MATLAB.

Reference [10] was used to represent the shipboard power system model using graph theory. The fitness function of the genetic algorithm for the reconfiguration of shipboard power system was designed to meet the defined objectives. The genetic algorithm was coded in MATLAB. The reconfiguration process has been tested on an 8-bus power system model and on larger power system with distributed generators. For each test system the genetic algorithm was run three times to reconfigure the system in three different ways and the results were compared for three cases.

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3.4 Summary

The reason for developing a reconfiguration methodology using a genetic algorithm for a shipboard power system was presented in this chapter. The previous research work related to shipboard power system reconfiguration was introduced. The problem statement and proposed research work were also provided in this chapter.

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CHAPTER IV

GENETIC ALGORITHM AND ITS APPLICATION TO RECONFIGURATION PROBLEM

This chapter describes in detail about the genetic algorithm, the genetic operators (selection, crossover, mutation) involved in the algorithm and constraint handling. It will define the mathematical problem formulation of the reconfiguration problem and the applicability of the algorithm to the reconfiguration problem.

4.1 Genetic Algorithm

Genetic algorithms [16] are based on evolutionary processes and Darwin's concept of natural selection. The study of genetic algorithms originated with John Holland in the mid-1970s. The genetic algorithm is a stochastic method designed to find a global optimum for a wide range of problems. The procedure can be applied irrespective of the objective function complexity, making it useful for functions that are highly nonlinear. The nature of the method is conducive to problems with discrete design variables, making it applicable to network reconfiguration problems. Before discussing the procedure, a review of terminology is needed.

- Each possible solution x is referred to as a chromosome. For the reconfiguration problem, x refers to the switch configuration.
- The content or value of the chromosome will be referred to as its genetic code. For instance, the genetic code of x can be [0,1,0,1,0,0].

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- Each position in the chromosome x is referred to as a gene, and its particular value, 0 or 1, is an allele.

- The population consists of a set of x values. The size of the population is often predefined and fixed throughout the course of the procedure.

- The term generation indicates a population at a specific point in time. For instance, another population, termed the second generation, replaces the population of the first generation.

- The fitness of a solution x, i.e. $f(x)$, concerns the performance index evaluated at x. For the problem studied here, the higher the value of $f(x)$, the higher the fitness of x. For minimization problems, fitness of x increases as $f(x)$ decreases.

- The terms selection, crossover and mutation are called genetic operators.

The terminology is depicted in Figure 4.1

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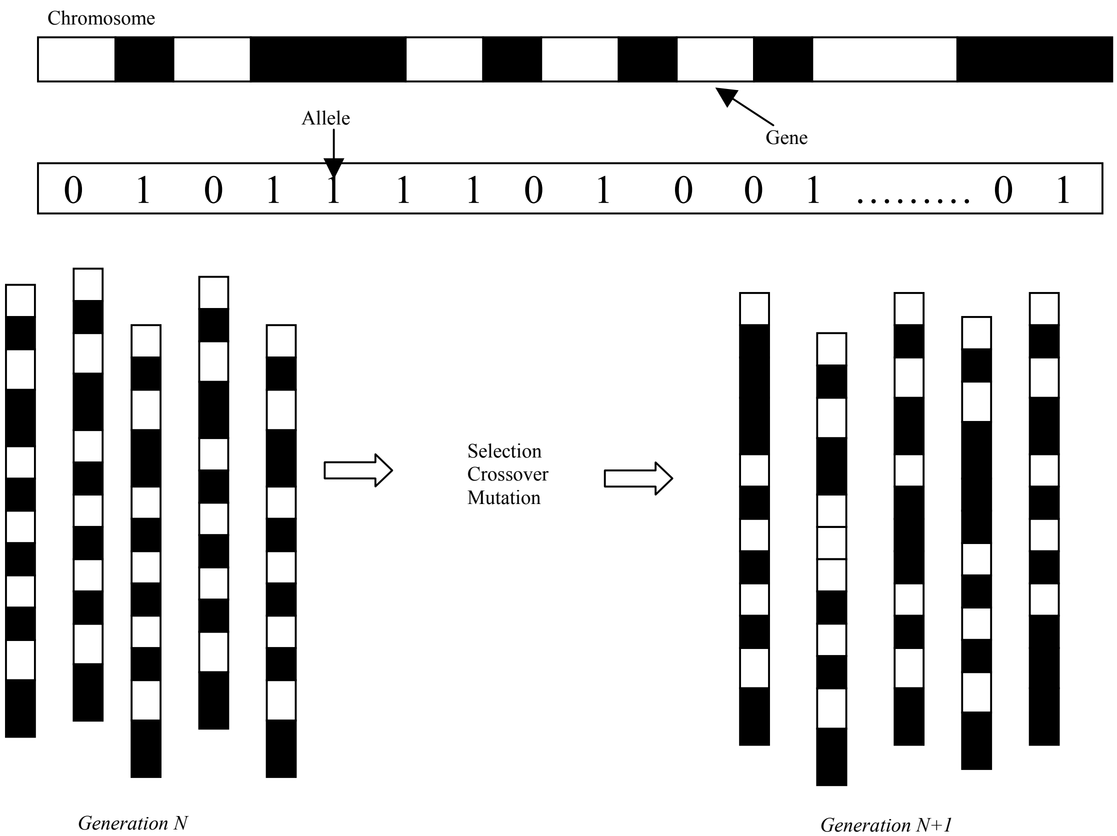

Figure 4.1 Genetic Algorithm Terminology [17]

4.2 Algorithm Description

A genetic algorithm is a search algorithm. It evolves a set of possible solutions until an optimum one is found. The basic idea is that a particular solution will pass its informational content on to its successors if it is a good solution. The better the solution, the higher is the probability of passing on its information - survival of the fittest. Figure 4.2 represents a simple function $f(x)$.

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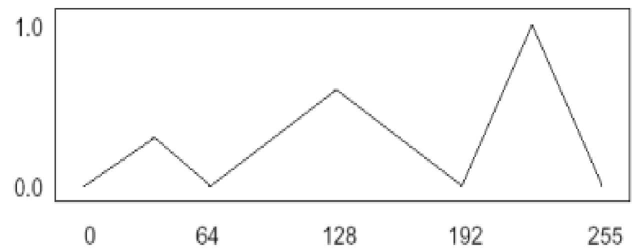

Figure 4.2 Simple function for Illustrating Random Search

A search algorithm should find the value in the domain that gives the maximum function value for $f(x)$ in Figure 4.2 that value is *224* since $f(224)$=1.0. Two search algorithms-random search and hill climbing [18] are described first in order to appreciate genetic algorithm.

4.2.1 Random Search

A random search would commence as follows:

- Solution =0.0
- While a satisfactory solution has not been found, repeat the following steps
- Pick a random point, x, in the domain. Evaluate $f(x)$ at that point; if $f(x)$> solution, save x as best solution found so far.
- End

Some problems can be solved with this approach. The most obvious is that this algorithm has *1/256* probability for $f(x)$ of finding the maximum on each iteration, and therefore may have to iterate for relatively long periods to find the maximum. Therefore the convergence of the solution is also not guaranteed in the random search.

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Random search does have one redeeming quality- it is exploratory, which means the search will look at many different areas of the function, given uniformly distributed samples. For example, it may pick *{56, 207, 93, 156}* as sample points. Note how these sample points are relatively spread out over the function. This spread-out nature is called exploratory.

4.2.2 Hill Climbing

Hill climbing is another search technique [18] and would work as follows on $f(x)$:

- Pick a random point, x, in the domain.
- If $f(x+1) > f(x)$ then increment x (move to the right) until $f(x+1) < f(x)$ goto last step.
- Else if $f(x-1) > f(x)$ then decrement x (move to the left) until $f(x-1) < f(x)$ goto last step.
- x is the solution.

The function $f(x)$ can be divided into three sections, each section corresponding to the small hills in $f(x)$ (roughly the first ¼, next *2/4* and then last ¼ of the domain). If the hill-climbing algorithm initially picked a random point in the first section, it will find itself moving along the function heading toward roughly 32, the highest point in the first section. If it picked a point in section 2, it would migrate toward 128 again the highest point in that section. Lastly, if it picked a point in section 3, it would find the global maximum at approximately 224. This search has a characteristic that random search does not: it's exploitive, which means the algorithm first picks a point and then slowly moves away from it if that is a profitable move. The key idea is that once the initial point is

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chosen, the search chooses a direction to move (based on the local information) to find the best solution. This use of local knowledge is the exploitive part of the hill-climbing algorithm. For hill climbing, the sections determine how effective the algorithm can be. If the function is not multimodal (i.e., it has one hill), then hill climbing will always find the optimal solution. If, however, the function is multimodal, then hill climbing cannot guarantee the optimal solution. In the example function, hill climbing has about a 25% chance of finding the optimal solution. This corresponds to the area in the domain covered by the third section, the section where the global maximum is located.

Random search and hill climbing provide other interesting contrasts. If $f(x)$ were not continuous, then hill climbing would have problems in that it would not know to skip over the noncontinuous areas. For example, we cannot determine if $f(x+1) > f(x)$, if $x+1$ is not in the domain of the function. Random search would not have such problems because if it picked a point where the function was not defined, it could just pick another point. Another issue is that although hill climbing moves away from low areas, random search may not. For example, if hill climbing were initiated at $x = 64$, it would quickly move away from it in the direction of $x = 128$. Once it had decided to move right, it would never try $x = 64$ again. Random search, however, would not remember that $x = 64$ was a low spot and would consider $x = 64$ as likely to be evaluated in future iterations as any other value of x. Both random search and hill climbing have their strengths and weaknesses, which are summarized in the following Table 4.1 [18].

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Table 4.1 Advantages and Disadvantages of Random Search and Hill Climbing

Search algorithm	Strengths	Weaknesses
Random Search	Exploration. Better with non-continuous functions.	Can reevaluate areas of low fitness many times. May run for long periods before finding a good solution.
Hill Climbing	Exploitation. More likely to find optimal solution with relatively low number of hills.	Can become locked into a potentially non-optimal hill.

From the above discussion it is obvious that random search and hill climbing are in a sense opposite approaches to the search problem. A reasonable goal would be to combine the good qualities from both in a single algorithm. A simple idea for an improved search would be to generate multiple random points and commence a hill-climbing search for each point.

Genetic algorithms behave much like the combined algorithm. It uses the exploration of random search and exploitation of hill climbing. Using an initially random distribution of sample points, they begin a modified hill climb on each point. The modified hill climb is fundamentally different, but has much the same feel. The major difference is that instead of moving right or left, the point mates with another point to become a new point to jump around the domain. The selection of mating partners is based on how large the point's function value is.

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4.3 Flowchart

The flowchart for the genetic algorithm is given in Figure 4.3. At the beginning of the procedure, chromosomes are generated at random and compose the first population, whose size is typically set by the user. Chromosomes are selected to be the parents for the new generation based on their fitness in relation to the other chromosomes. For the reconfiguration problem considered here, the fitness of chromosome x increases as $f(x)$ increases. The parents reproduce by a process called crossover, in which genetic information from two parents is combined to form two new offspring. Mutation can occur, in which the genetic code of the offspring is manipulated by a random process. Once selection, crossover, and mutation are complete, the new population is ready to reproduce, repeating the process.

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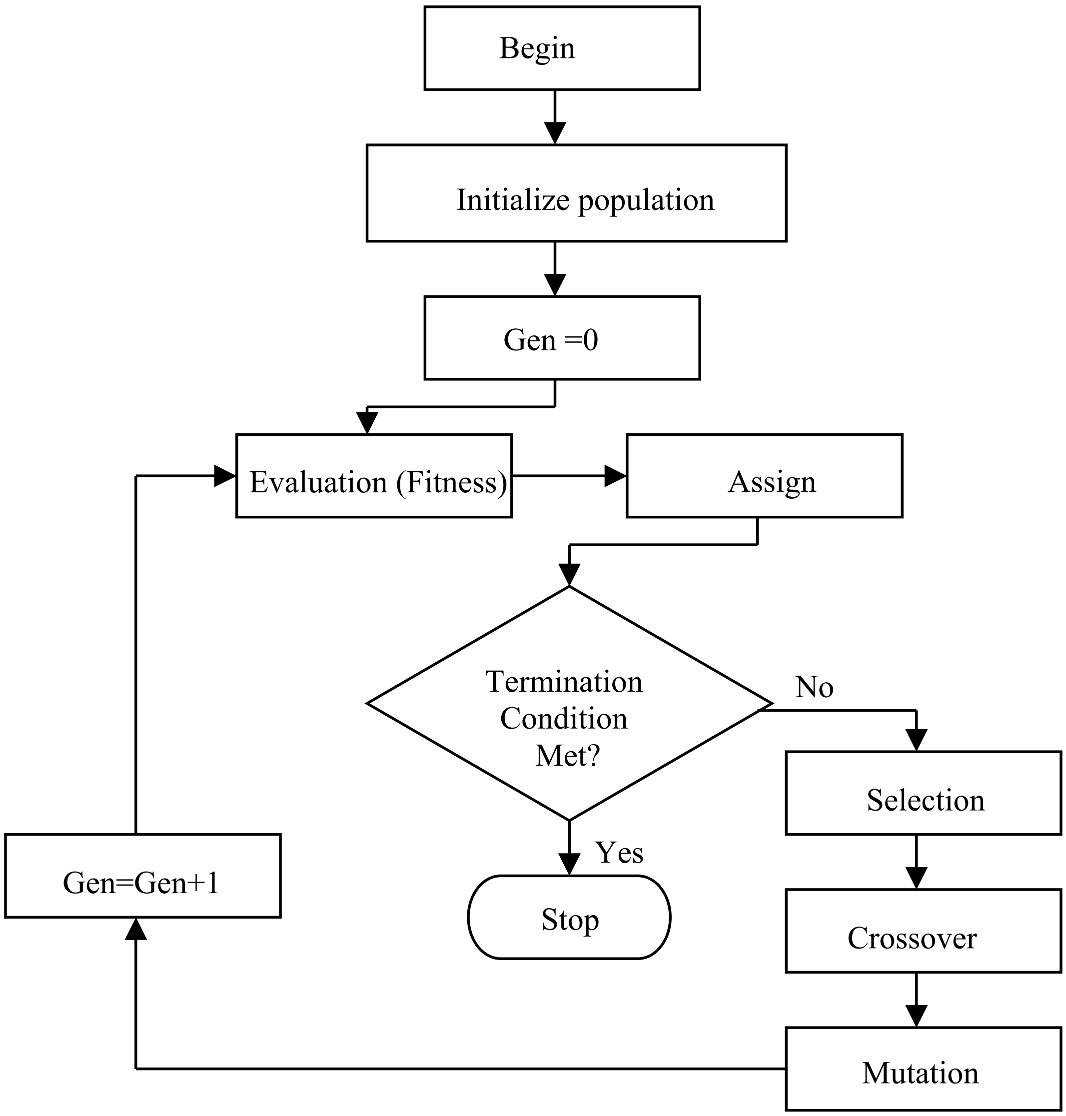

Figure 4.3 Flowchart showing the Genetic Algorithm

4.3.1 Initialization

A population of n solutions, or chromosomes, is created at random. The user typically specifies the population size. The fitness of each chromosome is determined by the objective function value $f(x)$. For maximization problems the fitness of a solution x increases as $f(x)$ increases and for minimization problems the fitness of x increases as

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$f(x)$ decreases.

4.3.2 Selection

The odds of reproduction for a chromosome increase as the fitness quality increases. One method for selecting chromosomes is called the “roulette wheel selection” scheme, and is illustrated in Figure 4.4. The main idea of this method is that the better individuals get higher chance. This is a way of choosing members from the population of chromosomes in a way that is proportional to their fitness. It does not guarantee that the fittest member goes through to the next generation but it has a very good chance of doing so.

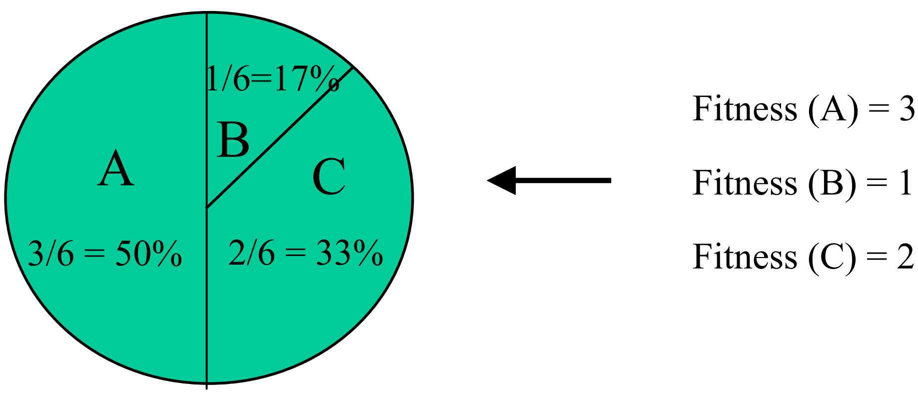

Figure 4.4 Roulette Wheel Selection

Let the population’s total fitness score be represented by a pie chart, or roulette wheel. Now a slice of the wheel is assigned to each member (chromosome) of the population. The size of the slice is proportional to the chromosomes fitness score. i.e., the fitter a member is the bigger the slice of pie it gets. A ball is spin around the wheel and a chromosome is selected at the point where the ball stops. In the example shown in Figure

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4.4, chromosome A has more fitness value and occupies 50% of the wheel, so the probability of being selected is more when compared to the other two chromosomes.

4.3.3 Crossover

Crossover is the process by which chromosomes of generation *N* combine their genetic material to produce members of generation *N+1*. This process mates two parent chromosomes to produce two child chromosomes. Crossover occurs at a rate specified by the user, and this rate is typically found in the range of 50 to 100% [19]. If crossover does not occur, the offspring are exact copies of the parents.

The most basic type of crossover is one-point crossover, which is illustrated in Figure 4.5. There are two parents, *A* and *B*, and two children, *A'* and *B'*. For the first child *A'*, a location between the chromosomes of parent *A* is randomly selected as the point of crossover. The bits before this point are exact copies of the corresponding genes of *A* and the rest of the bits come from the corresponding ones of *B*. For the child *B'*, the same process occurs; only the parent contributions are swapped.

As an illustration, in Figure 4.5, the crossover point is selected between bit 3 and 4. Bits 1 through 3 of *A'* are an exact copy of *A*, and the rest of the bits are copied from *B*. Likewise, bits 1 through 3 of *B*' are an exact copy of *B*, and the rest of the bits are copied from *A*.

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Parent *A*: 101 10000 → **Offspring *A'*: 101 11100**

Parent *B*: 100 11100 **Offspring *B'*: 100 10000**

Figure 4.5 Illustration of One-point Crossover

Note that the offspring contain parts of both parents and in a sense the parents have passed their "genes" on to their children. In the above example both parents had a leading *10* pattern and both offspring also have this same sub-pattern. It's entirely possible that this leading *10* pattern is a characteristic that gives a higher fitness. This passing of genetic information is how genetic algorithms get their exploitation aspects; they exploit the fact that a leading *10* is a good trait.

Two-point crossover operates on the same principle, except two crossover points are chosen, as illustrated in Figure 4.6.

Parent *A*: 101 10 000 → **Offspring *A'*: 101 11 000**

Parent *B*: 100 11 100 **Offspring *B'*: 100 10 100**

Figure 4.6 Illustration of Two-point Crossover

4.3.4 Mutation

Mutation in genetic algorithms is used when some random error is introduced during crossover. This is analogous to mutation in nature, which is where the term is borrowed. Mutation is sparingly used with a low probability p_m. If the probability of

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mutation is increased too much, the genetic algorithm is pushed more to the random search side. As mutation makes jumps in the domain, it hampers the exploitive nature of hill climbing. Mutation prevents premature convergence of the genetic algorithm and helps the GA procedure avoid local maxima.

The most common type of mutation is bit mutation. Each bit of a chromosome is inverted with a probability p_m. The parameter p_m is very small, typically less than 1%. The mutation rate p_m typically lies between *1/pop_size* and *1/chromosome_length*. The process is illustrated in Figure 4.7.

10110000 → **00100000**

Figure 4.7 Illustration of Bit Mutation

4.3.5 Repetition of algorithm

The old generation is replaced by the new one, and the fitness of each chromosome is evaluated. The algorithm is repeated; beginning until some convergence criteria is satisfied. The criterion is typically based on the history of the best solution throughout each generation. For instance, the program can terminate if the best fitness does not change after a certain number of iterations. This number must be large enough to prevent premature convergence to a local maximum, but small enough to avoid unnecessary iterations and to have a fast algorithm.

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4.4 Tunable Parameters

As with most stochastic methods, the operation of the genetic algorithm depends heavily on the tuning of multiple parameters whose optimal values can typically be found only through experiment. For the reconfiguration problem, we desire parameters that provide solution quality, while allowing the procedure to work quickly. The main parameters of interest are the crossover rate, mutation rate, and population size. A crossover rate between 50% and 100% [19] and a mutation rate between 0.5% and 5% [20] have been found to work well for a variety of problems, but the optimal set varies based on the problem at hand, and for the reconfiguration problem, may even depend on the particular configuration [20]. In this thesis a crossover rate of 95% and a mutation rate of 0.75% were considered.

The population size is usually affected by the length l of the chromosomes, since the length determines the size of the x domain. Large populations have the advantage of covering a larger subset of the x domain, but more function evaluations are needed, resulting in more computational time. A small population typically lends more importance to the genetic algorithm operators as opposed to a large population, which relies more on the exploration of the x domain. A population size of 40 was considered in this thesis.

4.5 Handling Constraints with the Genetic Algorithm

The genetic algorithm is designed for unconstrained optimization problems, but the network reconfiguration problem has constraints regarding load power and generator

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ratings. Therefore, either the objective function or the genetic algorithm must be modified.

One option for the genetic algorithm is to simply reject infeasible points when they are encountered. Rejection can be accomplished by adding a large static penalty to the objective function for constraint violations, which discourages the selection of the infeasible chromosome for future generations. The chromosome could also be modified until it is feasible. Complete rejection may be infeasible however, as infeasible points can sometimes lead to desirable feasible regions. Since the genetic algorithm works by operating with groups of genes, rather than complete genes exclusively, infeasible solutions may be usable, since portions of their gene code may actually be desirable.

Another option to deal with constraints is to implement a penalty function that is small enough to allow infeasible regions to be used in the genetic algorithm and prevents their complete rejection. The implementation of penalty functions is typically undesirable, as their effectiveness depends on user-defined coefficients. When choosing these coefficients, a balance must be maintained between encouraging convergence of a feasible solution and allowing the procedure to explore infeasible regions in order to reach feasible ones. These coefficients are typically problem dependent, and in the case of the reconfiguration problem, may even rely on the configuration at that time.

To overcome the difficulties mentioned above, a modified penalty function is used in the genetic algorithm. Modified penalty functions use coefficients that change throughout the genetic algorithm, and they do not suffer the disadvantages of user-defined functions. The new fitness function with the penalty incorporated is expressed as,

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$$F' = F + a.P$$

Where '*a*' is a constant and $P = P_G - P_L$ is a variable, which depends on the chromosome (switch configuration). When the load is greater than the generation, P is negative and thus decreases the fitness value of the corresponding switch configuration. The acceptance or rejection of that particular solution depends on the extent of constraint violation. With this method the algorithm sometimes accepts infeasible solutions in order to reach feasible ones.

4.6 Mathematical Formulation of Reconfiguration Problem

The problem statement can include objectives such as minimization of power loss, maximum power delivery to the loads, and maximum power delivery to a single load. The objective function considered here is to maximize the power supply to unaffected loads and supply power to high priority loads through load shedding if necessary. The loads are classified as non-vital, semi-vital and vital loads. These loads are multiplied by a weighting factor P. The weighting factor is selected so that the vital and semi-vital load contributions are greater than the largest non-vital load contribution. The objective function is defined as follows,

Maximize $L_1 + L_2 + L_3 + ... + L_n$

Subject to $P_{gen} \geq P_{load}$

The fitness function of the genetic algorithm was designed in such a way that the reconfiguration can be achieved by three different ways. The fitness function includes two objectives with different weighting factors. These weighting factors are

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selected depending on the situation whether to restore the loads based on priority or based on load magnitude. The magnitude of the fitness function depends on switch configuration $'x'$. The fitness function is defined as,

$$F = W_M\left[x(1)L_1 + x(2)L_2 + x(3)L_3 + \ldots + x(n)L_n\right] + W_p\left[P_1x(1)L_1 + P_2x(2)L_2 + P_3x(3)L_3 + \ldots + P_nx(n)L_n\right]$$

Where,

$'x'$ is the switch configuration.

$x(i) = 1$ indicates breaker closed for i = 1,2,…,n.

$x(i) = 0$ indicates breaker open for i = 1,2,…,n.

$L_1, L_2, L_3, \ldots, L_n$ are load values.

$P_1, P_2, P_3, \ldots, P_n$ are priorities of loads.

W_M is weighting factor for load selection based on magnitude only.

W_P is weighting factor for load selection by considering priority.

Parameters W_M and W_P determine the mode of load selection. If W_M is taken as 1 and W_P as zero, the reconfiguration will be done based on the load magnitude only. If W_M is zero and W_P is 1, prioritization of loads is implemented and high priority loads are selected untill the generation capacity is less than total load. If W_M is 1 and W_P is 1, the algorithm considers both the load priority factor and magnitude factor during the reconfiguration.

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4.7 Application of Genetic Algorithm to Reconfiguration Problem

The genetic algorithm is a stochastic method designed to find the global optimum for a wide range of problems. The algorithm can be applied irrespective of the objective function and topology, making it useful for functions that are highly nonlinear. Since the reconfiguration problem is highly nonlinear over a domain of discrete variables, the genetic algorithm is a good candidate procedure. This procedure does not use any special features of the objective function behavior; it works in spite of its behavior.

An appealing feature of the reconfiguration problem in relation to the genetic algorithm involves the x domain. The representation of the switch configuration is already represented in a form suitable for the genetic algorithm, so no additional encoding and decoding is necessary to translate continuous variables into discrete variables, and vice versa.

The genetic algorithm works on the assumption that parts of solutions can be combined to produce other solutions. This implies that if two solutions are effective, the combination of their genetic code will be effective as well.

4.8 Summary

Complete description of a genetic algorithm was given in this chapter. Mathematical problem formulation of the reconfiguration problem was presented. Application of genetic algorithm for the reconfiguration problem and the fitness function was explained.

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CHAPTER V

RECONFIGURATION PROCESS

This chapter explains the reconfiguration procedure for an 8-bus power system. Graph theory is used to represent the power system and then a genetic algorithm is implemented for the reconfiguration of a shipboard power system model.

5.1 Graph Representation of Power System

Graph theory has been used in several applications of power system network representation, simulation, and analysis. The graph operation is a tool for step-by-step graph manipulation, providing a clear picture for analysis of power system operation. The associated matrix operation is suitable for computer implementation. The shipboard power system model is shown in Figure 5.1 and corresponding graphical representation is shown below in Figure 5.2. Initial formulation of the representation of the SPS test system was done in [10] and part of it is repeated here as it relates to the genetic algorithm. The vertex represents the bus, cable, tie-bus, generator and load while circuit breakers are represented by edges in graphical model. The direction of the edge is related to the direction of flow of power through the breaker. Table 5.1 shows the relationship between the major components of a shipboard power system and the corresponding graphical elements.

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Table 5.1 Graph representation of shipboard power system model

Components In Power System	**Elements In Graph**
Generator, Bus bar, Cable, Load	Vertex
Circuit Breaker	Edge

The power system model consists of four generators (G1, G2, G3, G4), six switchboards (bus 1, bus2, bus 3, bus 5, bus 6 and bus 7), two cables (bus 4 and bus 8), six loads (Load1, Load2, Load3, Load4, Load5 and Load 6), and eighteen breakers.

In order to accommodate the power system reconfiguration and provide a continuous protection function, it is normally accompanied by protection zone selection function to determine the circuit breakers to be tripped to isolate the fault. Here, shipboard power system has been divided into 8 protection zones as shown in matrices from zone 1 to zone 8 containing the connectivity of the breakers. Each bus with directly connected breakers is defined as a zone in the differential protection scheme. In the corresponding system of graph representation, each vertex with the directly connected edges represents a protection zone.

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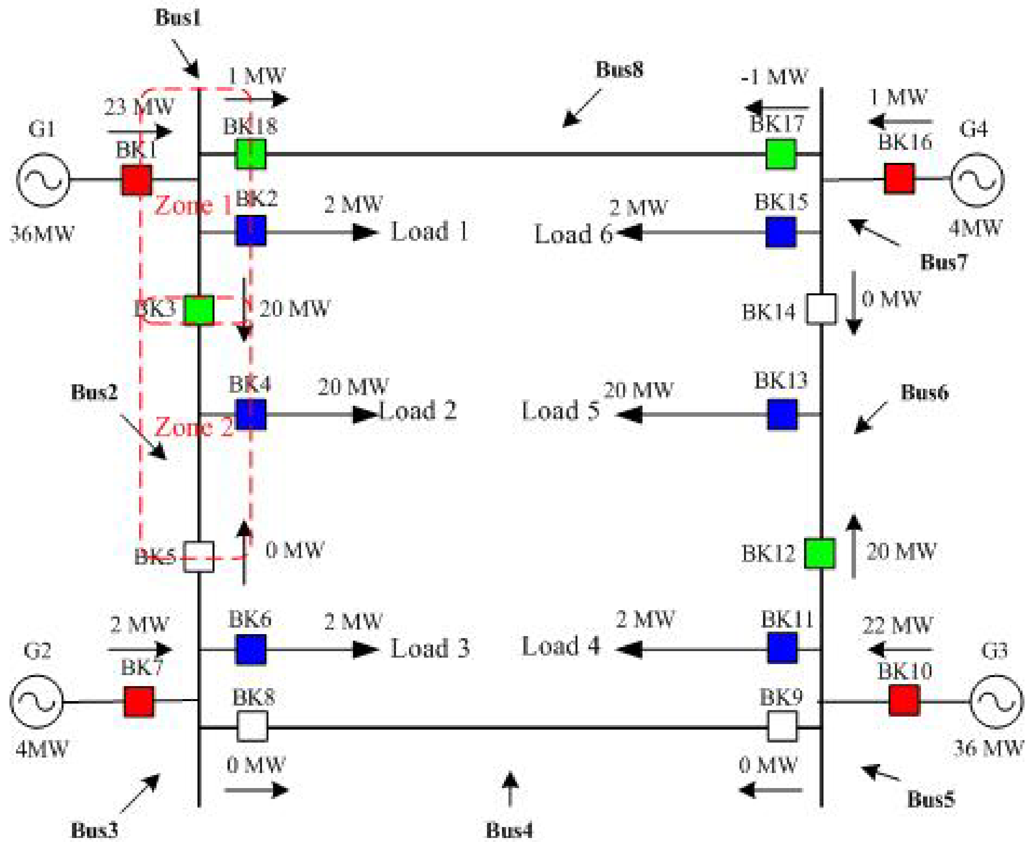

Figure 5.1 Shipboard Power System Model

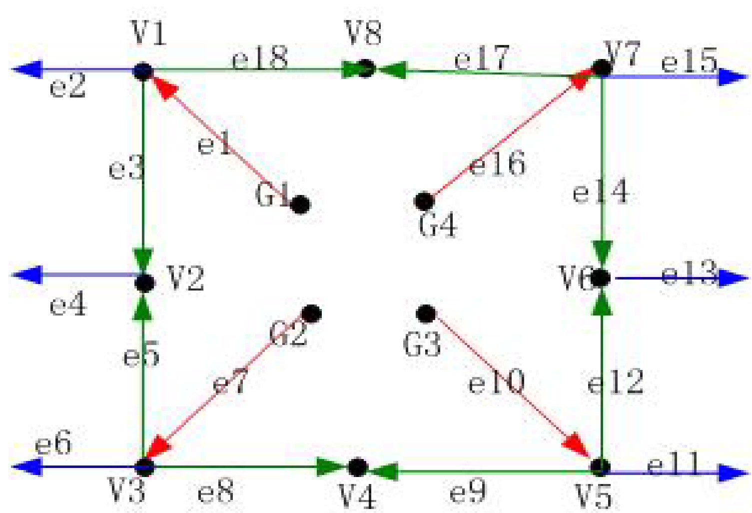

Figure 5.2 Graph representation of Shipboard Power System Model

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After simplifying a power system topology into a graph, the corresponding matrices can represent the graph mathematically for computer implementation. This matrix is called breaker-to-zone matrix or edge-to-vertex (EtoV) matrix. For the power system shown in Figure 5.1 the incidence vectors of the matrix EtoV are shown in Table 5.2. The EtoV matrix is an 8x18 matrix corresponding to eight zones and eighteen breakers. The positive sign represents the flow of power towards a zone and negative sign represents flow of power away from the zone. Additional data required for the system include the breaker type**,** breaker status, breaker flow, generator capacity, and load priority. These matrices are given in Table 5.2. There are three types of breaker: '1' refers to the generator breaker, which connects a generator with a zone, '2' refers to the load breaker, which connects a load feeder with a zone, and '3' refers to the tie breaker, which connects two zones.

Table 5.2 Input data 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 = [23, 2, 20, 20, 0, 2, 2, 0, 0, 22, 2, 20, 20, 0, 2, 1, -1, 1]
GEN_CAP = [1, 36; 7, 4; 10, 36; 16, 4]
LOADS = [2, 2; 4, 20; 6, 2; 11, 2; 13, 20; 15, 2]
LOAD_PRIORITY = [2, 1; 4, 150; 6, 12; 11, 1; 13, 1; 15, 150]

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The breaker status matrix represents the system breaker open/close status. A “1” means that the breaker is closed, and a “0” means that the breaker is open. The instantaneous power flow through each breaker can be obtained from the protection system. The generator capacity (GEN_CAPACITY) matrix is a two-column matrix. The first column contains the index of the generator breaker and the second column contains the corresponding generator capacity. The instantaneous power flow (BRK_FLOW) matrix and generator capacity matrix are also shown in Table 5.2 with the unit of MW. The load priority (LOAD_PRIORITY) matrix is another important piece of information that the reconfiguration algorithm needs when the system requires possible load shedding. In the load priority matrix shown in Table 5.2, the first column contains the index of the breaker; the second column contains the load priority, with larger numbers indicating the higher priority. In the power system model shown in Figure 5.1, loads 2, 3, and 6 have higher priority than loads 1, 4 and 5.

5.2 Reconfiguration Algorithm

5.2.1 Flow Chart

After simplifying a power system topology into a graph, the corresponding matrices can represent the graph mathematically. The input data to the reconfiguration algorithm includes an incident matrix (breaker-to-zone matrix), a generator capacity matrix, a breaker status matrix and an instantaneous power flow matrix. When the power system experiences fault(s), the fault detection functions will quickly locate the fault and

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issue a trip signal to the breakers surrounding the faulted zone to isolate the fault. Then the breaker-to-zone matrix will be updated by removing the isolated zones and tripped breakers. The zone balance matrix will be calculated to find out any negative zones. The path searching function is then activated to find out possible power supply paths for these negative zones. All the loads and generators are extracted along the path and then the genetic algorithm is used for restoration and load shedding if necessary. The flow chart of the reconfiguration process is shown in Figure 5.3.

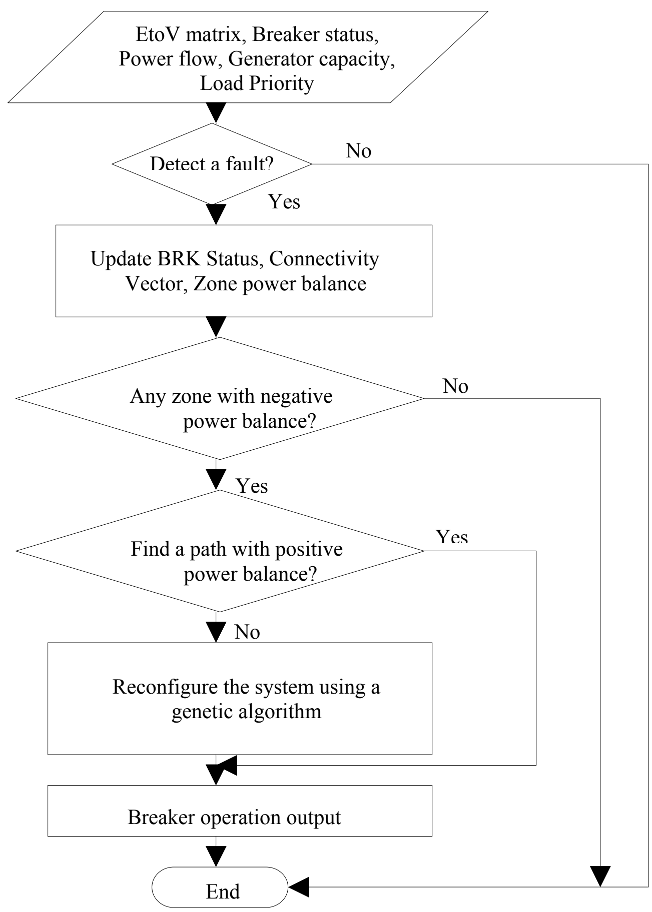

Figure 5.3 Flowchart of Reconfiguration Process

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The major steps involved in the reconfiguration process are: a graphical representation of power system, a matrix representation of system data, the system data update after fault(s), the search path(s) with positive power balance, and reconfiguration of the system using a genetic algorithm. The first two steps are explained above in section 5.1. The remaining steps are explained below by considering an 8-bus power system model shown in Figure 5.1.

5.2.2 Reconfiguration of an 8-bus power system model

Consider the 8-bus power system model shown in Figure 5.1. When a single or multiple faults happen on the shipboard power system, the zone-based differential fault detection function will quickly identify the faulted zone(s) and isolate the faulted zone(s). The corresponding tripped breaker status in the BRK_STATUS matrix will be updated to zero. Then a new connectivity matrix EtoV_new will be updated after fault isolation by removing the row(s) of the isolated zone(s) and the column(s) of the tripped breaker(s) for fault isolation. For example, in the power system shown in Figure 5.1, if a fault happens in zone 1, breakers 1, 2, 3, and 18 are tripped to isolate the fault. The updated BRK_STATUS matrix and updated EtoV matrix are shown in Table 5.3. Then, the BRK_FLOW matrix is updated after removing the column(s) of the tripped breaker and replacing the instantaneous power flow of generator breakers with the corresponding generator capacity. The updated BRK_FLOW matrix is also shown in Table 5.3.

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Table 5.3 Updated data after fault isolation

S(Zone2) = [-1, 1, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0]
S(Zone3) = [0, -1, -1, 1, -1, 0, 0, 0, 0, 0, 0, 0, 0, 0]
S(Zone4) = [0, 0, 0, 0, 1, 1, 0, 0, 0, 0, 0, 0, 0, 0]
S(Zone5) = [0, 0, 0, 0, 0, -1, 1, -1, -1, 0, 0, 0, 0, 0]
S(Zone6) = [0, 0, 0, 0, 0, 0, 0, 0, 1, -1, 1, 0, 0, 0]
S(Zone7) = [0, 0, 0, 0, 0, 0, 0, 0, 0, 0, -1, -1, 1, 1]
S(Zone8) = [0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, -1]
BRK_STATUS = [0, 0, 0, 1, 0, 1, 1, 0, 0, 1, 1, 1, 1, 0, 1, 1, 1, 0]
BRK_FLOW = [20, 0, 2, 2, 0, 0, 36, 2, 20, 20, 0, 2, 4, -1]

The Zone_Balance matrix can show whether power is balanced or not with any zone. It can be calculated by the below equation [10]:

$$\text{Zone\_Balance} = \text{EtoV} * [\text{BRK\_FLOW}]^T$$

After fault isolation, the Zone_Balance matrix also will be updated. The post-fault Zone_Balance matrix is shown in Table 5.4. In this case, zone 2 and zone 8 have negative power balances, which mean that zone 2 imported 20MW power and zone 8 imported 1MW power from faulted zone 1 before fault occurred.

Table 5.4 Zone Balance matrix for fault in zone 1

Zone Index	2	3	4	5	6	7	8
Power Balance(MW)	-20	2	0	14	0	3	-1

5.2.3 Path search for negative power zone

After calculating the zone balance matrix, a path searching function is used to find any possible power surplus path that may supply power to the zone(s) with a negative power balance. All the zones with the power deficit, if any, are stored in a priority queue, in which a larger power deficit means higher priority. For example, in the previous case,

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zone 2 has a 20 MW power deficit, which is larger than the 1 MW, the power deficit of zone 8. Therefore, the path-searching algorithm will start from zone 2. The first element of the priority queue is chosen as the first start node (vertex) for the search algorithm to find the shortest path with no power deficit in the tree space defined by the connectivity matrix EtoV. The shortest distance is the minimum number of breakers (edges) between the end node and the start node. The breadth-first search algorithm has been developed to solve this problem. The search function will return when it finds a path with non-negative power balance, as well as when the tree space is completely searched. During the search process, the connectivity matrix and power balance vector are properly updated to prepare for the path search of the next node in the priority queue. If any node stored in the priority queue is already included in the existing merged path, the corresponding node is excluded from the priority queue. The process continues until the priority queue is empty.

The output of the path searching function contains all possible paths for each negative zone including the sequence of the vertices, the corresponding sequence of breakers along the path, and the amount of power deficit, if this path has a negative power balance. For the example power system, the output is only one path, which is shown below:

Vertices along the path: [2, 3, 4, 5, 6, 7, 8]

Breakers along the path: [5, 8, 9, 12, 14, 17];

Power balance: [-2];

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The power system with the fault in zone 1 and possible power supply path is shown in Figure 5.4.

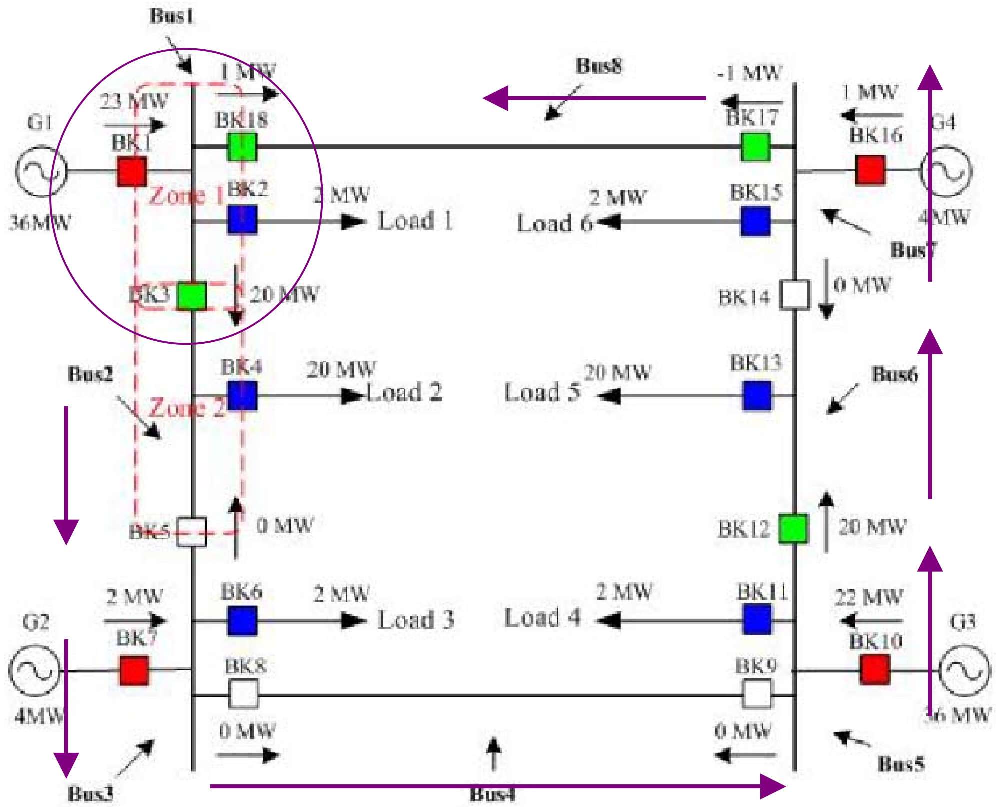

Figure 5.4 Power System with fault in zone 1

5.2.4 Reconfiguration using a genetic algorithm

If the path searching function cannot find a positive power supply path, then genetic algorithm is activated to reconfigure the power system by opening/closing the breakers. The input to the genetic algorithm includes generators along the path, loads

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along the path, and load priority. The output of the genetic algorithm consists of a vector of open signals to the load breakers, if load shedding is necessary. The genetic algorithm process is shown in Figure 5.5.

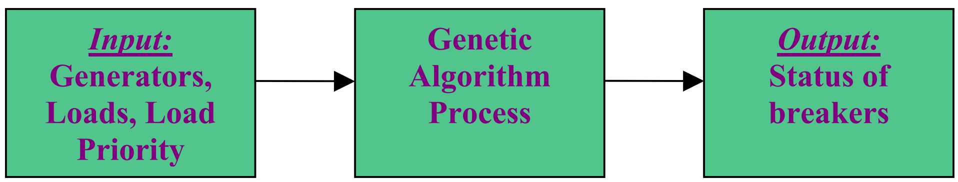

Figure 5.5 Genetic Algorithm Process

Initial population of solutions is randomly generated using a random number generator. The length of chromosome (solution) is equal to the number of loads along the path. The genetic operators: selection, crossover, and mutation are applied to this population of solutions to yield optimal status of load breakers. The initial population, population after selection, population after crossover, and population after mutation for one generation is shown in Figure 5.6.

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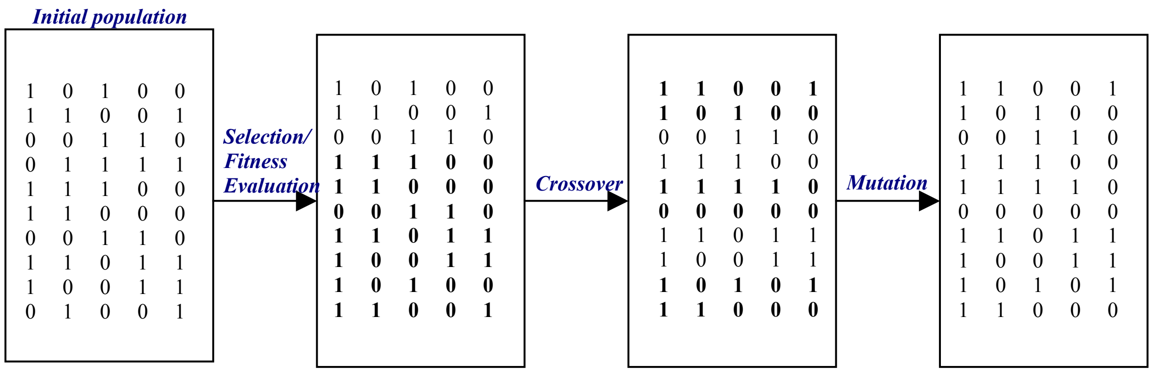

Figure 5.6 Genetic Algorithm Process for One generation

The fitness function considered here is to maximize the number of loads supplied based on the load priority. For the example power system, after isolating the fault, the total generation is 44 MW and total load is 46 MW. Load shedding is necessary in order to satisfy the constraint $P_{gen} \geq P_{load}$ (Total generation is greater than or equal to total load demand). For this test case, the load chosen by the genetic algorithm is service load 4, as it has the lowest priority. The output of the genetic algorithm is:

Genetic algorithm output: [1 1 0 1 1]

This implies that loads 2, 3, 5, 6 are supplied and load 4 is shed and the corresponding breaker BK11 is opened. The overall output of the reconfiguration algorithm consists of a vector of close signals to the breakers, if they are open, along the path and a vector of open signals to the load breakers, if load shedding is necessary.

Table 5.5 shows the test results of the eight scenarios on power system model shown in Figure 5.4. Case 1 through case 4 show that a fault happened on a single bus. Case 5 through case 8 show that two faults happened on different buses.

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In case 1, when the fault happened on bus 1 and protection system isolated bus 1 from the system, bus 2 had negative power balance of -20MW, which means that bus 2 imported 20MW power from faulted bus 1 before fault occurred. Then, the reconfiguration algorithm started to search possible paths with non-negative power balance for the negative power bus 2. The only possible path found was B2-B3-B4-B5-B6-B7-B8. All the loads and generators are extracted along this path and then the genetic algorithm was used to restore the loads based on the priority and the available generation. In this case the generation was found to be 44 MW and the total load was 46 MW. So load 4 (L4) was shed because it has lowest priority compared to other loads and the remaining loads are restored along the path.

In case 6, two faults happened on bus 1 and bus 5. After fault isolation, bus 2 and bus 6 both have a power deficit. In this case two islands were formed corresponding to two negative buses. These are B2-B3-B4 and B6-B7-B8. The Genetic algorithm was applied separately for each island and loads L2 and L5 were shed even though they have the highest priority because there was not enough power generation.

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Table 5.5 Reconfiguration of an 8-bus power system model

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)**	**44**
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)**	**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** **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)**	**2** **2**
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)**	**-**

5.3 Summary

Graph theory was used to represent shipboard power system model and then the reconfiguration procedure was explained by considering an 8-bus power system model. The genetic algorithm process of finding the breaker status was explained. Eight fault scenarios were considered and the system was reconfigured based on load priority. The test results accuracy was verified through hand checking.

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CHAPTER VI

TEST CASES AND RESULTS

The reconfiguration process has been developed and implemented in Matlab. The algorithm has been tested on an 8-bus power system model and on 13-bus power system model with distributed generators. The genetic algorithm was run three times for each test system to reconfigure the system in three different ways and the results were compared for three cases. The test results will be presented and analyzed in this chapter.

6.1 Test Case 1

Test case 1 is a symmetrical power system with four generators and is based on the shipboard DD(X) power system model. The power system topology is shown in Figure 6.1. There are two main generators (G1 and G3) and two auxiliary generators (G2 and G4). Based on the power system topology, the necessary data for fast reconfiguration is listed in Table 6.1. In this case, breakers 5, 8, 9, and 14 are usually open, and the system is run as a radial system. The total six loads have three priority levels: vital, semi-vital and, non-vital. The reconfiguration process has been tested on test case 1 with eight scenarios, which are that a fault/faults happened on different generation bus/buses. The genetic algorithm was run three times to reconfigure the system in three different ways.

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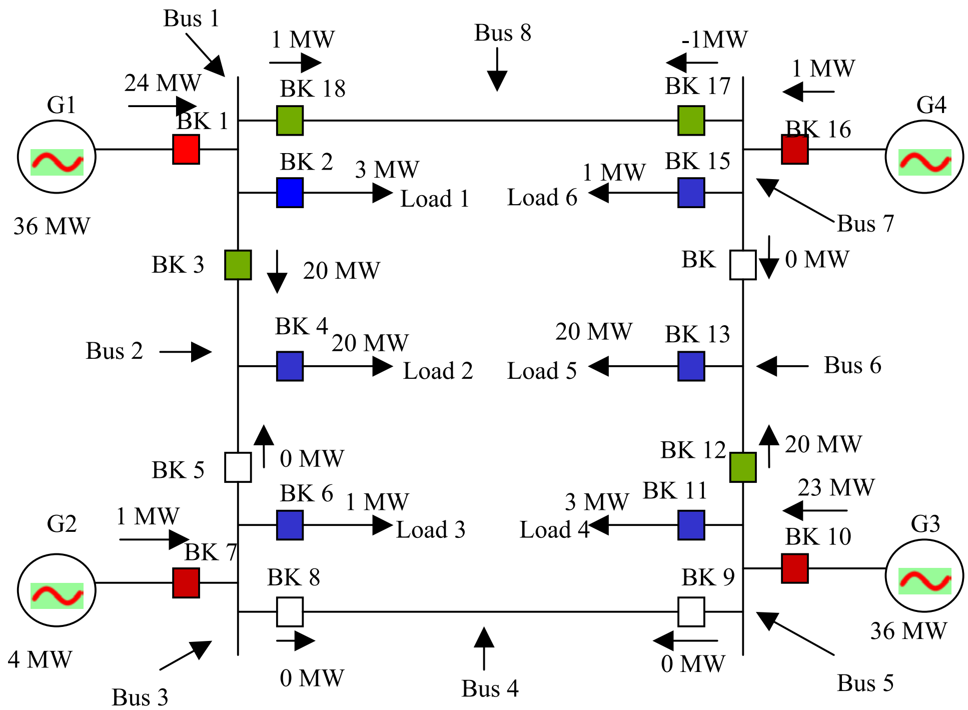

Figure 6.1 Test Case 1:8-bus power system model

Table 6.1 Power system topology matrices of Test Case 1

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]

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6.1.1 Reconfiguration based on load priority

In this case the objective of the reconfiguration is to maximize the power supplied to loads by considering load priority. Table 6.2 shows the test results of the eight scenarios on test case 1. Cases 1 through 4 show that a fault happened on a single bus. Cases 5 through 8 show that two faults happened on different buses.

Table 6.2 Reconfiguration of Test Case 1 based on 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**	**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)**	**-**

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In case 1, when the fault happened on bus 1 and protection system isolated bus 1 from the system, bus 2 had negative power balance of -20MW, which means that bus 2 imported 20MW power from faulted bus 1 before fault occurred. Then, the reconfiguration algorithm started to search possible paths with non-negative power balance for the negative power bus 2. The only possible path found was B2-B3-B4-B5-B6-B7-B8 and the power balance along this path was negative. That means there was not enough power generation and the system needs to be reconfigured. All the loads and generators are extracted along this path and then the genetic algorithm was used to restore the loads based on the priority and the available generation. The fitness of the genetic algorithm is,

$$F = W_M\left[x(1)L_1 + x(2)L_2 + x(3)L_3 + \ldots + x(n)L_n\right] + W_p\left[P_1x(1)L_1 + P_2x(2)L_2 + P_3x(3)L_3 + \ldots + P_nx(n)L_n\right]$$

Since the reconfiguration is done by considering load priority, W_M is set to zero and W_P is set to 1 and the fitness function reduces to:

$$F = \left[P_2x(2)L_2 + P_3x(3)L_3 + P_4x(4)L_4 + P_5x(5)L_5 + P_6x(6)L_6\right]$$

Where,

'x' is the switch configuration.

$x(i) = 1$ indicates breaker closed for $i = 1,2,\ldots,$n.

$x(i) = 0$ indicates breaker open for $i = 1,2,\ldots,$n.

$L_2, L_3, \ldots, L_6$ are load values.

$P_2, P_3, \ldots, P_6$ are priorities of loads.

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The output of the genetic algorithm consists of a vector of open signals to the load breakers, if load shedding is necessary and the amount of power served in MW.

In this case the generation was found to be 44 MW and the total load was 46 MW. So load 4 (L4) was shed because it the has lowest priority compared to other loads and the remaining loads are restored along the path. Table 6.2 shows the amount of MW served is only 42 MW even though the generation was found to be 44 MW. This is because the vital loads are served first and then semi-vital and non-vital loads follow.

In case 6, two faults happened on bus 1 and bus 5. After fault isolation, bus 2 and bus 6 both have a power deficit. In this case two islands were formed corresponding to two negative buses. These are B2-B3-B4 and B6-B7-B8. Genetic algorithm was applied separately for each island and loads L2 and L5 were shed even though they have the highest priority because there was not enough power generation.

6.1.2 Reconfiguration without considering load priority

In this case the objective of the reconfiguration is to maximize the power supplied to loads without considering load priority. Table 6.3 shows the test results of the eight scenarios on test case 1. Cases 1 through 4 show the results for a fault on a single bus. Cases 5 through 8 show the results for faults on different buses.

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Table 6.3 Reconfiguration of Test Case 1 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	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 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)	-

The fitness function for this case is:

$$F = \left[x(1)L_1 + x(2)L_2 + x(3)L_3 + ... + x(n)L_n \right]$$

Since the reconfiguration is based on load magnitude only, W_M is set to 1 and W_P is set to zero. In case 1, when the fault happened on bus 1, the generation was found to be 44 MW and the total load was 46 MW. In this case load 6 (L6) is shed to utilize the maximum available generation. Table 6.3 shows the amount of MW served is 44 MW.

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6.1.3 Reconfiguration by combining priority factor and magnitude factor

In this case the objective of the reconfiguration is to maximize the power supplied to loads by combining priority factor and magnitude factor. Table 6.4 shows the test results of the eight scenarios on test case 1. Cases 1 through 4 show that a fault happened on a single bus. Cases 5 through 8 show that two faults happened on different buses.

Table 6.4 Reconfiguration of Test Case 1 by combining 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 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)	-

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The fitness function for this case is:

$$F = \left[x(1)L_1 + x(2)L_2 + x(3)L_3 + ... + x(n)L_n\right] + \left[P_1x(1)L_1 + P_2x(2)L_2 + P_3x(3)L_3 + ... + P_nx(n)L_n\right]$$

Since the reconfiguration is done by combining priority factor and magnitude factor, W_M is set to 1 and W_P is set to 1.

This scenario behaves much like the reconfiguration based on load priority because the load priority factor contributes more to the fitness function than the load magnitude factor. The difference might be significant for large power systems. The comparison of results is shown in Table 6.5

Table 6.5 Comparison of results for Test Case 1

Test Case	$W_p = 1, W_M = 0$ **(Load Priority is considered)**	$W_p = 0, W_M = 1$ **(Load priority is not considered)**	$W_p = 1, W_M = 1$ **(Combining priority and magnitude factor)**
	MW Served	**MW Served**	**MW Served**
Case1	**42**	**44**	**42**
Case2	**-**	**-**	**-**
Case3	**42**	**44**	**42**
Case4	**-**	**-**	**-**
Case5	**-**	**-**	**-**
Case6	**1** **1**	**1** **1**	**1** **1**
Case7	**-**	**-**	**-**
Case8	**-**	**-**	**-**

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6.2 Test Case 2

Test case 2 is a larger power system with distributed generators. The system has five main generators and three distributed generators. The power system topology is shown in Figure 6.2. There are five main generators (G1, G2, G3, G4 and G5) and three distributed generators (DG1, DG2 and DG3). Based on the power system topology, the necessary data for reconfiguration is listed in Table 6.6 In this case, the distributed generators do not contribute to the power system at normal situations, and breakers 7, 15, 16, 17, 23, 28 and 30 are usually open. The distributed generators are switched ON only after a fault, if there is not enough power generation. The thirteen loads have three priority levels. The genetic algorithm was run three times to reconfigure the system in three different ways.

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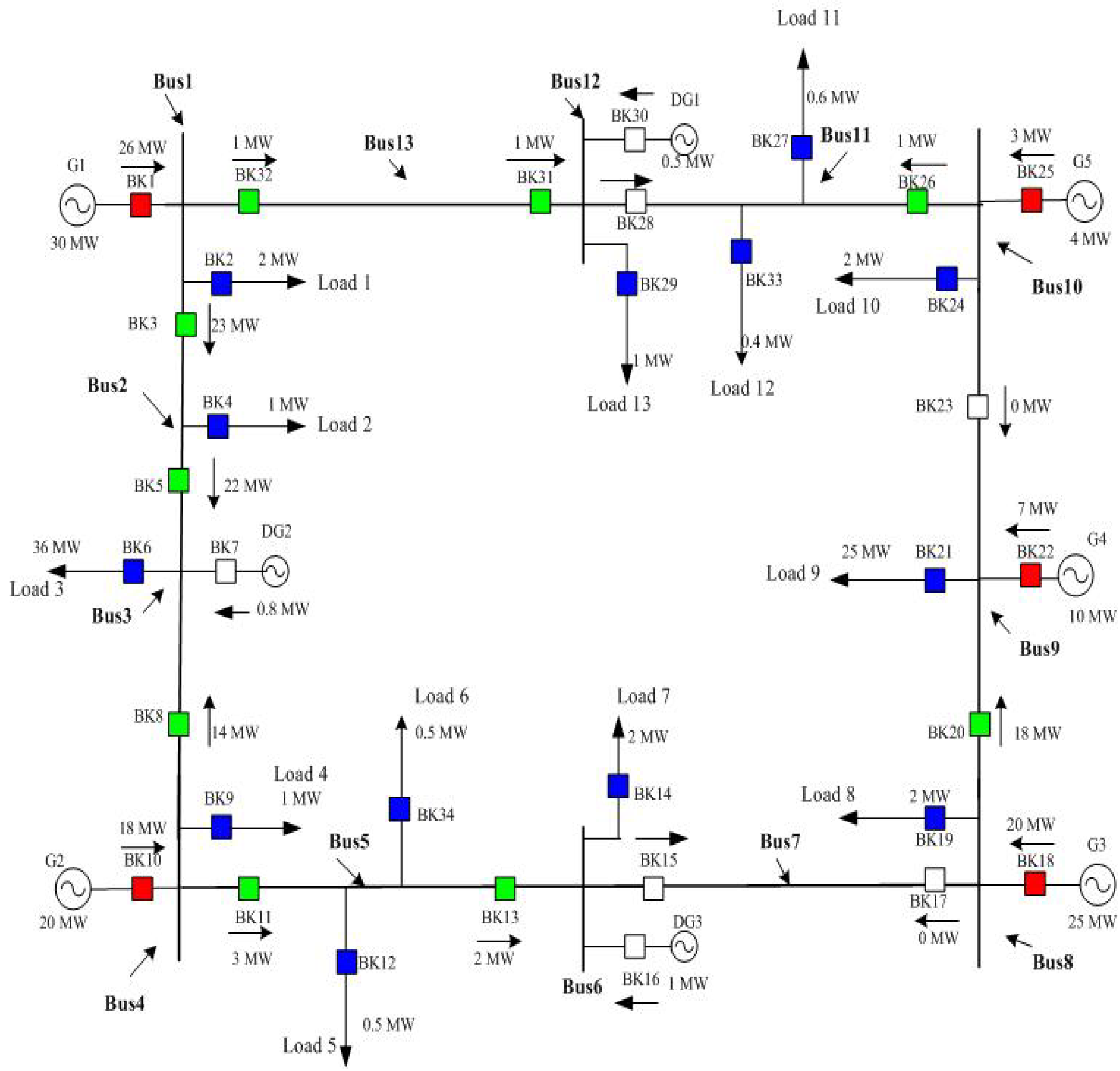

Figure 6.2 Test Case 2:13-bus power system

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Table 6.6 Power system topology matrices of Test Case 2

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 1 1 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]

6.2.1 Reconfiguration based on load priority

The reconfiguration process has been tested on test case 2 with eight scenarios. Table 6.7 shows the test results of the eight scenarios on test case 2. Cases 1 through 4 show that a fault happened on a single bus. Cases 5 through 6 show that two faults happened on different buses.

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Table 6.7 Reconfiguration of Test Case 2 based on 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-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**	**L2, L11, L13**	**BK *4, 27, 29*, 8, 9, 10, 11 (O) BK 28, 33, 17, 15, 7, 16, 30 (C)**	**70.4**
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**

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6.2.2 Reconfiguration without considering load priority

Table 6.8 shows the test results of the eight scenarios on test case 2 when only load magnitude is considered for reconfiguration. Results show that the amount of MW served is more when reconfiguration is done based on load magnitude.

Table 6.8 Reconfiguration of Test Case 2 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-B13	L9	BK *21*, 1, 2, 3, 32 (O) BK 15, 17, 23, 28, 7, 16, 30 (C)	47
Case 2	B4	B3, B5	B3-B2-B1-B13-B12-B11-B10-B9-B8-B7-B6-B5	L5, L6, L13	BK *19*, 8, 9, 10, 11 (O) BK 28, 33, 17, 15, 7, 16, 30 (C)	71
Case 3	B8	B9	B9-B10-B11-B12-B13-B1-B2-B3-B4-B5-B6-B7	L1, L4, L5, L7, L12	BK *2, 9, 12, 14, 33* , 18, 19, 20 (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-B12-B13	L3 L9	BK *6, 21*, 1, 2, 3, 32, 18, 19, 20 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

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6.2.3 Reconfiguration by combining priority factor and magnitude factor

Table 6.9 shows the test results of the eight scenarios on test case 2 where reconfiguration is done by combining priority factor and magnitude factor.

Table 6.9 Reconfiguration of Test Case 2 by combining 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)	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, 33, 17, 15, 7, 16, 30 (C)	71
Case 3	B8	B9	B9-B10-B11-B12-B13-B1-B2-B3-B4-B5-B6-B7	L1, L2, L4, L6,, L12,L13	BK *2, 4, 9, 34, 33, 29,* 18, 19, 20 (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-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

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This scenario behaves much like the reconfiguration based on load priority because the load priority factor contributes more to the fitness function than the load magnitude factor. The comparison of results is shown in Table 6.10.

Table 6.10 Comparison of results for Test Case 2

Test Case	$W_p = 1, W_M = 0$ (Load Priority is considered)	$W_p = 0, W_M = 1$ (Load priority is not considered)	$W_p = 1, W_M = 1$ (Combining priority and magnitude factor)
	MW Served	MW Served	MW Served
Case1	36	47	36
Case2	70.4	71	71
Case3	65.9	66.1	66.1
Case4	-	-	-
Case5	-	-	-
Case6	0	0	0
Case7	5 4	5 4	5 4
Case8	5	5	5

6.3 Summary

In this chapter, the reconfiguration process, which has been implemented in MATLAB, has been tested on two power system models with various fault scenarios. Detailed test results were presented and verified through hand-checking. The genetic algorithm was run three times for each test system to reconfigure the system in three different ways. The genetic algorithm accurately enforces the power generation-load

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balance of the un-faulted part of the power system. The results from the load shedding meet the defined rules.

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CHAPTER VII

CONCLUSIONS AND FUTURE WORK

7.1 Conclusions

As the electric power systems in U.S. Navy ships supply energy to sophisticated systems for weapons, communications, navigation, and operation, it is very important to maintain availability of power to the connected loads that keep systems operational. After the fault has occurred, protective devices operate to isolate the faulted section. But, this may lead to un-faulted sections that are not getting supply. Therefore, it is required to restore supply automatically and as fast as possible depending upon the impact of the fault, to these un-faulted sections of the shipboard power system to improve the system survivability. This research work focused on the development of a reconfiguration methodology using a genetic algorithm that will reconfigure a network, satisfying the operational requirements and priorities of loads. A genetic algorithm was selected because of its ability to find global optimal solution for solving large-scale combinatorial optimization problems. The main contributions of this research work are summarized as follows:

- A genetic algorithm was applied to a shipboard power system to maintain the power balance of the remainder system after fault isolation and reduce the impact of the fault. The main objectives of the genetic algorithm were:
  - Maintain power supply to unaffected loads to the maximum extent.
  - Supply power to high priority loads through load shedding if necessary.

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- Serve largest amount of load.

- The fitness function of the genetic algorithm was designed in such a way that the reconfiguration can be achieved by three different ways:
  - Maximizing the power supplied to loads by considering load priority.
  - Maximizing the power supplied to loads without considering load priority.
  - Maximizing the power supplied to loads by combining priority factor and magnitude factor.
- The reconfiguration process and the genetic algorithm were implemented in MATLAB.

The developed reconfiguration methodology has been tested on two different shipboard power system models for different fault scenarios. The test results verified the correctness of the algorithm.

The major disadvantage of the genetic algorithm is the tuning of parameters. And also, the initial population is randomly chosen. This random initial population may not cover the entire design space uniformly.

7.2 Future Work

At present, the genetic algorithm was applied for the reconfiguration of a shipboard power system without considering cable ratings and multiple paths. In the future these factors can be included as the constraints for the genetic algorithm. Also other types of faults like the generator fault and line faults can be considered for reconfiguration.

In the future, the performance of the genetic algorithm can be improved by investigating different ways of generating initial population.

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Another area of possible future work is to build the shipboard power system model in RTDS (Real Time Digital Simulator) and use genetic algorithm for the reconfiguration of SPS in real time to verify the shipboard power system real time fault isolation and restoration demand.

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