MULTI-AGENT SYSTEM FOR PREDICTIVE RECONFIGURATION OF SHIPBOARD POWER SYSTEMS

A Dissertation

by

SANJEEV KUMAR SRIVASTAVA

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

December 2003

Major Subject: Electrical Engineering

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ABSTRACT

Multi-Agent System for Predictive Reconfiguration
of Shipboard Power Systems. (December 2003)
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The electric power systems in U.S. Navy ships supply energy to sophisticated systems for weapons, communications, navigation and operation. The reliability and survivability of the Shipboard Power System (SPS) are critical to the mission of a surface combatant ship, especially under battle conditions. In the event of battle, various weapons might attack a ship. When a weapon hits the ship it can cause severe damage to the electrical system on the ship. This damage can lead to de-energization of critical loads on a ship that can eventually decrease a ship's ability to survive the attack. It is very important, therefore, to maintain availability of energy to the connected loads that keep the power systems operational. Technology exists that enables the detection of an incoming weapon and prediction of the geographic area where the incoming weapon will hit the ship. This information can then be used to take reconfiguration actions before the actual hit so that the actual damage caused by the weapon hit is reduced.

The Power System Automation Lab (PSAL) has proposed a unique concept called "Predictive Reconfiguration" which refers to performing reconfiguration of a ship's power system before a weapon hit to reduce the potential damage to the electrical system caused by the impending weapon hit. The concept also includes reconfiguring the electrical system to restore power to as much of the healthy system as possible after the weapon hit.

This dissertation presents a new methodology for Predictive Reconfiguration of a Shipboard Power System (SPS). This probabilistic approach includes a method to assess the damage that will be caused by a weapon hit. This method calculates the expected probability of damage for each electrical component on the ship. Also a heuristic method is included, which uses the expected probability of damage to determine reconfiguration steps to reconfigure the ship’s electrical network to reduce the damage caused by a weapon hit. This dissertation also presents a modified approach for performing a reconfiguration for restoration after the weapon hits the system. In this modified approach, an expert system based restoration method restores power to loads de-energized due to the weapon hit. These de-energized loads are restored in a priority order. The methods were implemented using multi-agent technology.

A test SPS model based on the electrical layout of a non-nuclear surface combatant ship was presented. Complex scenarios representing electrical casualties caused due to a weapon hit, on the test SPS model, were presented. The results of the Predictive Reconfiguration methodology for complex scenarios were presented to illustrate the effectiveness of the developed methodology.

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CHAPTER I
INTRODUCTION

1.1 INTRODUCTION

The electric power systems in U.S. Navy surface combatant ships supply energy to sophisticated systems for weapons, communications, navigation and operation. The reliability and survivability of a Shipboard Power System (SPS) are critical to the mission of a surface combatant ship, especially under battle conditions. In the event of battle, various weapons might attack a ship. When a weapon hits the ship it can cause severe damage to the electrical system on the ship. This damage can lead to de-energization of critical loads on a ship that can eventually decrease a ship's ability to survive the attack. It is very important to maintain availability of energy to the connected loads that keep the power system operational.

There exist technology that enables the detection of an incoming weapon and prediction of the geographic area where the incoming weapon will hit a ship. This information can be used to perform reconfiguration actions, before the hit, so that the damage caused to the power system by the weapon hit is reduced. In the literature no methodology, which can perform such task, was found. Therefore there is a need is to develop a new methodology, which can perform such a task.

Researchers in Power System Automation Laboratory (PSAL) at Texas A&M University have developed two methods for performing reconfiguration of SPS for load restoration. In one of these methods, an optimization based approach is used to reconfigure loads, de-energized from battle damage induced faults, satisfying the operational requirements [1]. In the other method, an expert system based approach for reconfiguration for load restoration of SPS restores loads de-energized due to fault in a SPS, considering the priorities of loads and satisfying the system constraints [2]. Both of these methods were developed to reconfigure the SPS after weapon induced faults occur.

This dissertation follows the style and format of *IEEE Transactions on Power Systems.*

Further, researchers in the PSAL have proposed a unique concept called "Predictive Reconfiguration" which refers to performing reconfiguration of the ship's power system before or after a particular action (e.g. missile hit). Five methodologies were defined to address the various aspect of the Predictive Reconfiguration problem.

Reconfiguration to meet operational needs – The objective of this methodology is to reconfigure from one system configuration to another to meet operational demands.

Pre-hit reconfiguration for damage reduction – The objective of this methodology is to reconfigure the ship's electrical system, before a weapon hit, to reduce the potential damage to the power system caused by a weapon hit.

Pre-hit reconfiguration (restoration) – The objective of this methodology is to quickly reconfigure (restore) loads de-energized due to a weapon hit. In this case when an incoming weapon is detected analysis is begun in order to determine the restoration actions so that the reconfiguration (restoration) of the system can be performed as quickly as possible after the hit.

Post-hit reconfiguration for load restoration – The objective of this methodology is to reconfigure the power system to restore power to as much of the healthy system as possible after failure(s) have occurred due to a weapon hit.

Predetermined reconfiguration (restoration) of failure(s) – The objective of this methodology is to compute and save reconfiguration strategies for a selected set of severe (catastrophic) fault scenarios. If one of the scenarios occurs, the predetermined reconfiguration actions could be implemented immediately.

A methodology which addresses the "Pre-hit Reconfiguration for damage reduction" aspect of the Predictive Reconfiguration methodology must assess the damage that will be caused by a weapon hit. In the literature, various discussions can be found on the different types of weapons used in an attack. The effectiveness of these weapons against a specified target is described in terms of "probability of kill". This value determines the probability of destroying a specified target for a given set of conditions. The accuracy of a type of weapon is also described in terms of the "miss distance". This value describes the distance by which a weapon might miss the target. Various factors can affect the accuracy and effectiveness of a weapon. This leads to indeterminacy in assessing the damage that will be caused by a weapon hit. Therefore the weapon hit damage assessment is undeterministic or probabilistic. This undeterministic or probabilistic information should then form the basis of determining the reconfiguration control actions. But performing reconfiguration, using the undeterministic or probabilistic information, is a challenge. In this dissertation, the author presents a new methodology to perform Predictive Reconfiguration of SPS to reconfigure the SPS before a weapon hit such that damage that will be caused by the actual weapon hit is reduced. The author has addressed the pre-hit reconfiguration for damage reduction aspect of the Predictive Reconfiguration.

The major contributions in this dissertation are in four areas. First, a probabilistic method to assess the damage that will be caused by the hit of an incoming weapon was developed to obtain the expected probability of damage for each electrical component of the ship. Secondly, a probabilistic methodology to perform the reconfiguration of SPS, before a weapon hit, was developed. This methodology uses the expected probability of damage for each component to determine control actions to reconfigure the SPS, before a weapon hit, such that the damage that will be caused to that SPS is reduced. This approach addresses the second methodology of the Predictive Reconfiguration problem presented earlier.

Thirdly, multi-agent technology was used to implement the Predictive Reconfiguration method. A Multi-Agent System was developed to implement Pre-hit Probabilistic Reconfiguration methodology for a SPS. In the Multi-Agent System various agents were developed to perform different tasks.

Finally, the methodology was illustrated using a test SPS model. This test SPS model was based on the electric power network found on a non-nuclear surface combatant ship. In the illustration the methodology results were compared with the results without Pre-hit Probabilistic Reconfiguration. These results are presented and discussed.

1.2 ORGANIZATION

This dissertation consists of five chapters. Chapter I give an overview of this work and an outline of the dissertation. In Chapter II, the problem of Predictive Reconfiguration will be formulated. In this chapter, information obtained in the literature regarding various aspects of weapon and its damage will be discussed. A methodology to assess the damage, to a SPS, caused by a weapon hit will also be presented in this chapter. This chapter further presents a methodology to perform Predictive Reconfiguration of SPS. Chapter III will present the implementation of Predictive Reconfiguration method using the Multi-Agent System approach. In Chapter IV an illustration of the method will be presented. Test cases will be illustrated and the methodology will be compared with the case in which no Pre-hit Probabilistic Reconfiguration was performed. Finally, in Chapter V, conclusions will be drawn and remarks about future work will be presented.

CHAPTER II

PREDICTIVE RECONFIGURATION PROBLEM FORMULATION AND METHODOLOGY

2.1 INTRODUCTION

Providing continuous mobility, power, and thermal management for shipboard combat systems in the presence of major interruptions involving cascading failures is a critical mission within the U.S. defense infrastructure [3]. The electrical layout of a typical shipboard power system (SPS) found on a surface combatant ship is shown in Fig. 2.1. It consists of various components such as generators, protective devices, and cables [4]. The three phase generators are delta connected in a ring configuration using generator switchboards. Bus tie circuit breakers interconnect the generator switchboards that allow for the transfer of power from one switchboard to another. Load centers and some loads are supplied power from generator switchboards. Further, load centers supply power to some loads directly and supply power to power-panels to which some loads are connected. Feeders supplying power to load centers, power-panels and loads are radial in nature, meaning that each load is supplied by a single source at any given time. The radial nature of the system is important for ease of fault location and isolation, and coordination of the protective devices.

Loads are categorized as either vital or non-vital and are either three phases or single phase. For vital loads, power is available through two separate paths (normal and alternate supply paths) via automatic bus transfers (ABTs) or manual bus transfers (MBTs). The ABTs are normal path seeking and the alternate path is used only when the normal path is not available. The electric motors are also protected from low voltage conditions by protective devices called low voltage release (LVR) and low voltage protection (LVP). The main coil of the LVR/LVP de-energizes when a low voltage condition is present causing the main circuit contacts to open thereby de-energizing the load. When the low voltage condition is cleared, LVRs are automatically switched back to power again whereas LVPs require an operator to manually restart it and restore load. There are also transformers that step-down the voltage from 450 to 120 volts, to supply the single-phase loads.

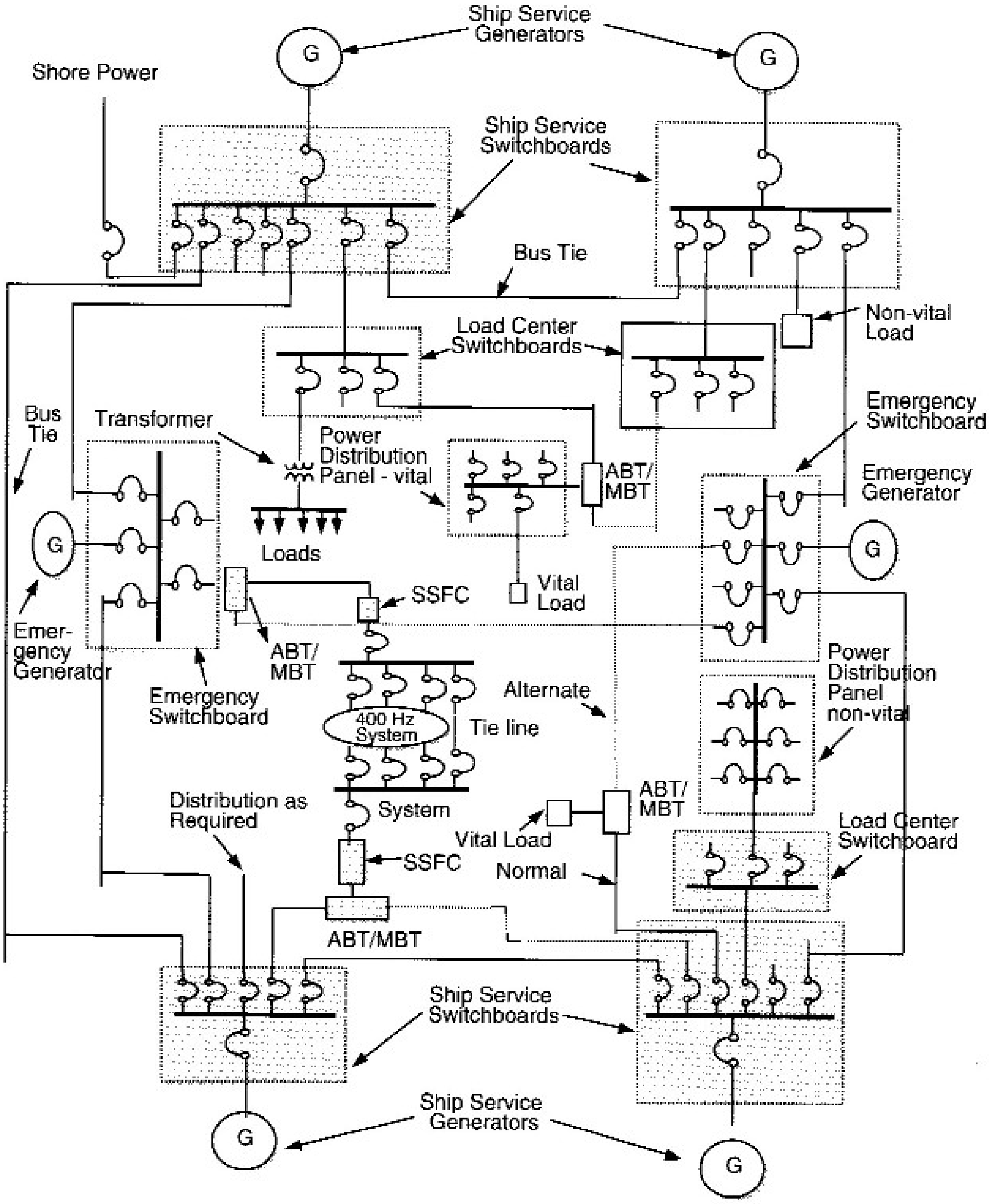

Fig. 2.1: Electrical Layout of an SPS [4]

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 energy to the connected loads that keep systems operational [2]. In the event of battle, various weapons might attack the ship. There exist technology that enables the detection of an incoming weapon and prediction of the geographic area where the incoming weapon will hit the ship. When a weapon hits the ship it can cause severe damage to the electrical system on the ship. These damages can lead to faults in the electrical system, cascading faults in the electrical system, and interruption of power supply to the loads.

The interruption of power supply to critical loads can reduce the ship's ability to survive the attack. The existing technology that provides information regarding an incoming weapon and predicts the location of its hit provides a source of information for reconfigure the power system, before the actual hit, to reduce the damage to the power system. In order to reduce the effects of the weapon damage to the power network, the electrical components of the ship that are predicted to be damaged by the weapon hit need to be determined. Then the effect of these damaged components on the power network needs to be assessed, and finally reconfiguration actions to reduce the effect of the damaged components to the operation of the power system need to be determined.

The prediction of future events, which in this case is prediction of the location of a weapon hit and subsequent damaged components, means that an undeterministic or probabilistic methodology is needed to assess the weapon damage and determine steps to perform reconfiguration to reduce the damage that will be caused by the weapon hit. This methodology has been termed, Pre-hit Probabilistic Reconfiguration for damage reduction, by this author.

Once the weapon hits the ship and causes damage to the power network on the ship, a methodology is needed to assess the actual damage to the SPS and perform reconfiguration to restore de-energized loads that have healthy paths available. This methodology is termed, Post-hit Reconfiguration for restoration by this author. Together Pre-hit Probabilistic Reconfiguration for damage reduction and Post-hit Reconfiguration for restoration perform the function of Predictive Reconfiguration.

In this dissertation, a methodology developed to perform Pre-hit Probabilistic Reconfiguration for damage reduction, before a weapon hit, is discussed. In this methodology, first, the probability that an electrical component will be damaged, due to the weapon hit, is computed for all the electrical components in the system. Then the heuristics of a probabilistic method developed to determine the reconfiguration steps required to reduce the damage that will be caused by the eventual hit, are presented. The dissertation also discusses a modified Post-hit Reconfiguration for restoration method, originally developed at PSAL [2]. In the method developed at PSAL, the restoration method restores load without violating any constraints. This method does not include a load shedding feature for situations when generation capacity is not available and critical loads need to be restored. In the modified Post-hit Reconfiguration for restoration method, a module to perform load-shedding was added. Details of the Pre-hit Probabilistic Reconfiguration for damage reduction method are presented in section 2.2. Section 2.3 gives the details of the modified Post-hit Reconfiguration for restoration method. A black box model of the Predictive Reconfiguration methodology has been presented in section 2.4. In section 2.5, a summary of this chapter has been presented.

2.2 PRE-HIT PROBABILISTIC RECONFIGURATION FOR DAMAGE REDUCTION

As stated earlier, the first function in probabilistic reconfiguration for damage reduction is to assess the damage that will be caused by a weapon hit. In this dissertation, the author has assumed that the "damage" to an electrical component, due to a weapon-hit, means improper functioning of that electrical component caused by the weapon hit. In that sense the effect of "damage" to electrical components on the ship, as addressed in this work, is presented below:

Circuit breaker – The "damage" to the circuit breaker leads to an open circuit condition on it.

Components other than circuit breakers – The "damage" to these components leads to a short circuit on them.

After damage assessment, the next function is to use the probabilistic information determined by damage assessment to determine steps for reconfiguring the electrical system such that the actual damage to it is reduced. In this section, first the approach for weapon hit damage assessment is presented, and then the methodology to determine steps for probabilistic reconfiguration is discussed.

2.2.1 Weapon-hit Damage Assessment

The main purpose of a weapon (e.g. missile) is to deliver a warhead to a target. A warhead is basically a device that is situated in the forward part of the armament system of a weapon, such as missile, and contains explosive charge. The function of the warhead is to destroy the target so that it cannot perform its mission [5]. The missile is a transporting vehicle for the warhead. The warhead essentially consists of a payload, a fuse and a safety and arming mechanism. It is the payload that directly causes damage to the enemy, and achieves the aim of the weapon.

Warhead devices can generally be separated into two categories: chemical energy warheads and kinetic energy warheads. A chemical energy warhead is a device that contains explosives that on detonation create blast and fragmentation effects. The metal fragments are quickly accelerated to hypervelocity. However, a device that contains a high-density penetrator that is accelerated by propellant toward a target is a kinetic energy weapon [5].

Warheads may also be classified based on manner in which energy and material travel through the environment on detonation. If it is uniform in all directions, it is known as an isotropic warhead, but a payload may be designed to release more energy in a particular direction. Such a warhead is known as a non-isotropic or directional warhead. Both chemical energy and kinetic energy high-explosive warhead types can be designed as isotropic or non-isotropic warhead [5].

Depending on the number of munitions, warheads may also be divided into two categories - unitary warhead and cluster/sub-munitions warhead. As the name indicates unitary warheads consist of a single warhead. The payload in the warhead may be of blast type or fragmentation type. In blast type, the payload is designed to achieve its effect and damage level primarily from blast. The payload is basically high explosive. A fragmentation payload consists of an explosive charge surrounded by a casing.

A cluster warhead consists of a large cased warhead containing sub-munitions (in bomblets) that can be ejected or dispensed to cause maximum effect at a moment decided by a fusing mechanism. The weapon (missile) delivers the main warhead to the target area where the outer skin maybe removed explosively or by aerodynamic forces before the sub-munitions are released. The sub-munitions may be blast, fragmentation type or filled with chemical, biological or incendiary material.

Ships are relatively hard targets and usually require a kinetic energy penetrating warhead, followed by blast fragmentation after the penetration of the hull. The most common weapons used against ships are anti-ship missiles. The anti-ship missiles are generally large in size and have a large warhead. They are designed to survive ship's defenses, relying on either speed or flying at low altitude in clutter to survive.

A weapon's effectiveness is its ability to destroy an intended target. In the case of a missile, it depends upon the distance from the warhead to the target at the instant of the warhead explosion; the missile-velocity and the target-velocity vectors; structural, geometrical, and physical characteristics of the target; atmosphere density; and the warhead itself. Some parameters, which define a missile's effectiveness are miss distance, lethal radius, circular error probability and single shot kill probability.

In random situations, when many missiles are fired against a target, all the missiles may not hit the target. Due to large number of random factors, the missile will display a tendency to miss the target at various distances related to probabilities. It can be said that the missile obeys a miss-distance probability distribution [6]. The miss distance of a weapon is defined as the distance by which a weapon misses the aimed location. The miss distance is calculated from the target intercept plane, and a vector r represents the closest point of approach [7]. This vector is normal to the weapon trajectory, and X and Y represents the errors of not impacting the target, as shown in Fig. 2.2, for a two dimensional case.

If there is no correlation between the X and Y miss distance, and the means in X and Y direction are equal to 0, and the standard deviation in X and Y direction are equal, then the miss distance frequency distribution is expressed by the circular normal distribution, given by (2.1) [5].

$$\rho(r) = \frac{1}{2\pi\sigma^2} e^{-r^2 / 2\sigma^2} \tag{2.1}$$

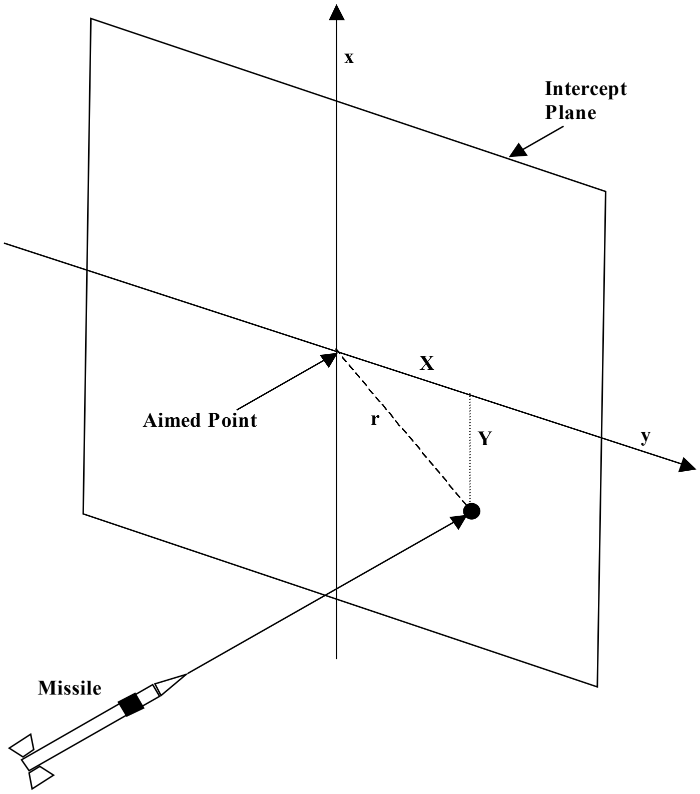

Fig. 2.2: Miss Distance Intercept Plane

Where, r is the radial miss distance taken from the target aim location. The circular standard deviation is σ. The U.S. military uses a calculation known as circular error probability (CEP) to determine weapon accuracy. A circular error probability number is the radius of the circle in which a weapon will land at least half of the time. This CEP is modeled as equation (2.2) [5].

$$\text{CEP} = 1.177\sigma \tag{2.2}$$

This CEP equation will model that half of the weapon flights lie inside the specified CEP. The other half will lie outside.

If a large number of identical missiles were fired to destroy a target, then the plot of miss distance would be a normal distribution, as shown in Fig. 2.3. This phenomenon is known as dispersion and it will happen even in the case of a guided missile. If the target is taking an evasive action, then the resulting dispersion will decrease for a guided missile than for an unguided missile under the same conditions [8].

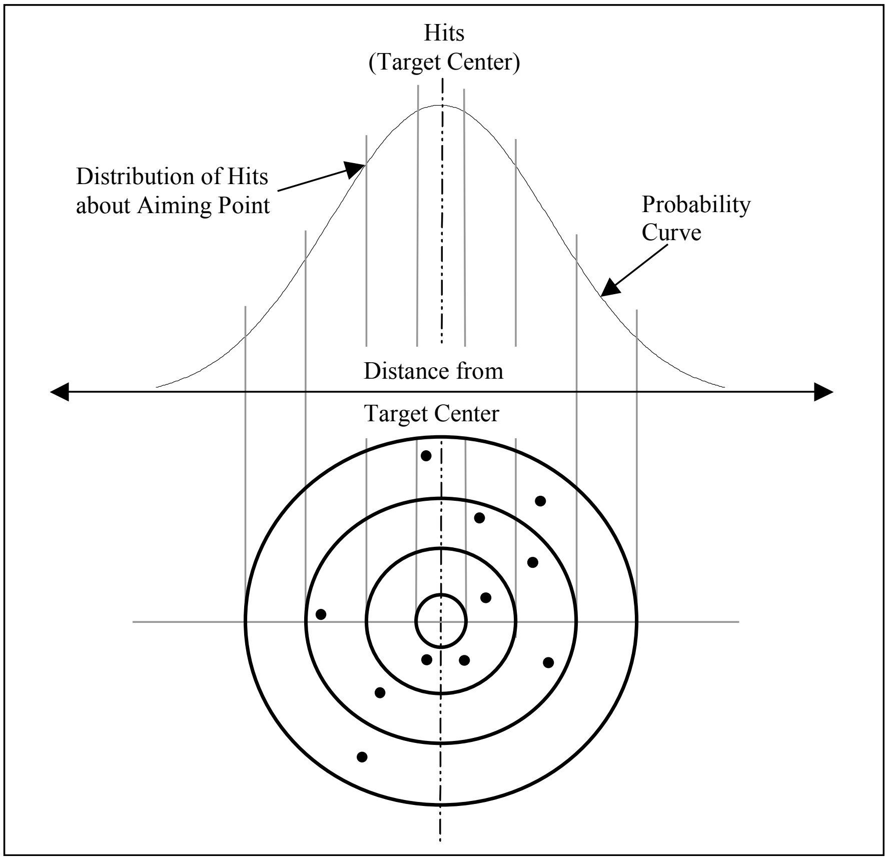

Fig. 2.3: Plot of Miss Distance [8]

A single-shot kill probability of the missile and warhead combination, against specified targets, is defined as the probability with which a given single missile and its warhead, when fired against a single target of specified type, will destroy the target. If the single-shot kill probability is 0.9, this means that, if a large number of specified missiles are individually fired at a specified target, 90 percent of the missiles will destroy the target [6]. The probability that weapon aimed at point target will hit it depends upon the lethal radius, accuracy, and number of attacking weapons. If n enemy weapons are fired to hit a target, then the probability of target destruction/kill is given by (2.3) [9].

$$P = 1 - \left(\tfrac{1}{2}\right)^{-R^2 n / C^2} \tag{2.3}$$

where, R = Lethal radius.

C = Circular probable error (CEP) of the attacking weapon.

For $n = 1$, the probability of target destruction would represent single-shot kill probability, given by (2.4).

$$P = 1 - \left(\tfrac{1}{2}\right)^{-R^2 / C^2} \tag{2.4}$$

Lethal radius or radius of destruction can be defined as the radius of a damage sphere/circle such that anything coming inside that sphere/circle will be destroyed. In other words the probability of kill inside that sphere/circle will be 1. In case of a nuclear warhead if the nuclear warhead explodes at the surface of ship, then (2.5) gives the lethal radius of the damage sphere/circle [9].

$$\text{Lethal radius, } R = \frac{6W^{1/3}}{H^{1/2}} \tag{2.5}$$

where,

R = lethal radius in nautical miles

W = weapon yield in megatons

H = target hardness in pounds/sq. inch

Factors such as weapon yield and the target hardness are responsible for intensity and size of explosion, radiation, pressure wave, shock waves and secondary explosion. These factors create difficulty in accurately estimating the lethal radius for a given missile. First of all, the hull of a ship is made of multiple materials. Secondly if the weapon (for e.g. missile) penetrates the hull of a ship then it can possibly come into contact with various other kinds of materials, which have different target hardness. Hence to calculate the lethal radius, target hardness of all materials with which the weapon comes in contact during explosion needs to be considered. But the task of considering the target hardness of all the materials can be practically infeasible. Thus it is very difficult to accurately calculate the lethal radius of damage sphere/circle.

No publicly available literature was found which discusses the details of calculation of lethal radius. In some literature where lethal radius was used in the assessment of damage caused by the missile hit, it was either assumed to be of fixed length or some model, which varies the probability of kill inside the lethal sphere/circle, was used. In [10], a special modification of Rand's Airbase Damage Assessment (AIDA) computer model – TSARINA has been described. The purpose of this model is to examine conventional air attacks against targets and to assess losses and damages to various resources. To estimate the effectiveness of a point-impact weapon, the basic mathematical representation used by this model was called a cookie-cutter representation. In this representation, a uniform probability of kill over a circle of specified radius was assumed. In an attempt to provide greater flexibility for the approximate weapon effect representation, different representations were developed. In one representation, for example, two-level cookie-cutter representation was used. In this representation, an inner circle with a specified probability of kill, and an outer circle defined such that the average probability of kill was just one fourth of that for the inner circle, was used.

From the weapon's effectiveness point of view, the most effective weapon against the ships is an anti-ship missile. It is the most common and widely used weapon against the ship's defenses. Although a lot has been discussed in literature regarding the missile's design, its trajectory, type of warhead/payload used and target kill probabilities; no de-classified information is available regarding the process of extensively assessing the damage caused by it.

In order to assess the damage caused by a weapon hit to a ship, it is necessary to know the location of weapon hit and the extent of damage the weapon warhead will cause on explosion around the hit location.

The existing technology on board ships detects and identifies an incoming weapon. Also it predicts the location where the weapon will hit the ship. Although it is known that such technology exist onboard a ship, no literature, which discusses this technology, was publicly available. A lot of information, though, was available in literature from the attacker's point of view. In this research work, in order to develop a method for assessing the damage caused due to a weapon hit, information that is available to attacker is assumed. The problem then is how to use this information to assess the actual damage that will be caused due to the eventual hit. From the various discussion made earlier its clear that various information available to the attacker is probabilistic in nature. It is impossible, therefore, to develop a deterministic solution for the problem of weapon damage assessment. The probabilistic information, available to attacker, models various uncertainties. It is important, therefore, first to identify and briefly discuss the various causes of uncertainties, which affect any deterministic approach. These factors are discussed below.

2.2.1.1 Uncertainty in Location of Weapon Hit

One possible source of uncertainty is the predicted location where the weapon will hit the ship. The exact location of the weapon hit is very difficult to determine. The weapon is always aimed to hit at a certain location and its ability to hit that location is defined in terms of probabilistic values. The miss distance of a weapon, discussed earlier, is defined as the distance by which a weapon misses the aimed location.

When a weapon is fired, the attacker's ability to accurately track and guide (in case of a guided weapon) the weapon to the aim location determines the weapon miss distance relative to the target. If there is an error in the accuracy of the target position, then the miss distance will grow. The miss distance is directly related to guidance and track accuracy. The prediction of actual hit location is therefore a source of uncertainty.

2.2.1.2 Uncertainty Introduced Due to Ship's Movement

Uncertainty discussed in previous section was uncertainty introduced due to inaccuracy of the incoming weapon. This section discusses another source, which causes the uncertainty in the determination of location where the weapon will the hit the ship, and that source is the ship's movements in the seawater. The reason for this uncertainty is the ship's motions in the seawater and effect of waves on the ship's motions. Ships are designed to float upright in calm waters. However, ships rarely sail in calm water. Waves, which are the main source of the ship's motions in a seaway, affect the performance of a ship considerably [11]. When the ship moves in a seaway, it makes random and simple harmonic motions along three axes – longitudinal, transverse and vertical, as shown in Fig. 2.4.

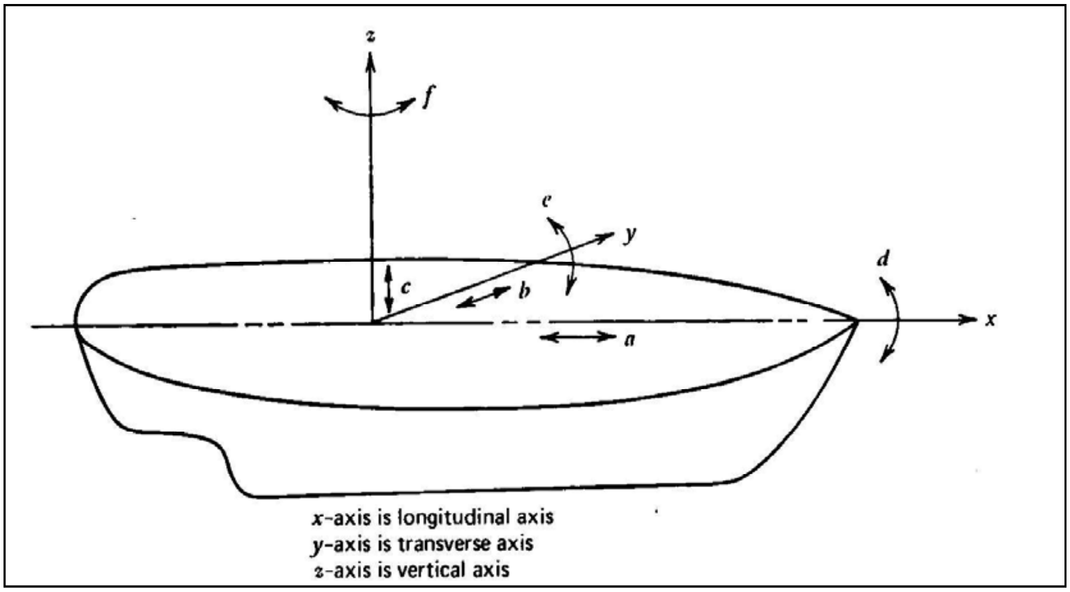

Fig. 2.4: Ship's Motion Along the x, y and z Axes of Ship

Basically a ship in seawater can have six different kinds of motions. It has three linear motions, surging, swaying, and heaving. Apart from linear motions it also has three rotational motions, rolling, pitching and yawing. Accordingly,

a = surging motion backwards and forwards in the direction of ship travel.
b = swaying athwartship motion of ship.
c = heaving motion vertically up and down.
d = rolling angular motion about the longitudinal axis. When the ship rolls, it lists alternately from starboard to port and then back to starboard.
e = pitching motion about the transverse axis. When a ship pitches, it trims alternately by the bow and by the stern.
f = yawing angular motion about the vertical axis.

The intensity of these motions depends upon the nature of waves. Due to these motions the location of impact of weapon would not be the same as determined earlier at the time when the weapon was fired, leading to further uncertainty in predicted location of weapon hit.

2.2.1.3 Uncertainty in Assessment of Extent of Weapon Damage

When a weapon hits a target, it explodes. This explosion can be accompanied by hot gases, fragments traveling at very high velocities, thermal radiation, pressure waves, shock waves or other secondary explosions. Extent of damage caused by the weapon hit depends on various factors. In the case of a nuclear weapon, as discussed earlier, these factors will be the weapon yield and target hardness. It has been already discussed that the exact determination of the target hardness is extremely difficult. Hence this can cause an inaccurate calculation of lethal radius, leading to the uncertainty in the determination of actual damage that will be caused by the weapon hit.

2.2.1.4 Probabilistic Approach for Damage Assessment

As mentioned earlier, in this research work an attempt is being made to develop a method to assess the damage that will be caused by a weapon hit, using the information available to the attacker. As this information is probabilistic in nature so the developed methodology will also be probabilistic in nature. Also, the developed methodology should model the various uncertainties mentioned in the earlier sections.

In this section, a probability based mathematical approach is presented which calculates the probability of damage due to a weapon hit, for a point on a ship. In order to develop the probability based mathematical approach some assumptions were made that basically addresses the various uncertainties mentioned earlier. In the work presented in this dissertation, the uncertainty introduced due to the motion of ship in rough water has been neglected. The assumptions made in this work are stated below.

a) It is assumed that the Probability Density Function representing the probability of actual hit of weapon at various locations on ship, is known. As shown in Fig. 2.3, the plot of miss distance for a series of identical missiles can be defined as a normal distribution. A point on the curve of Fig. 2.3 gives the probability by which a missile would miss the target for a given "miss distance". This probability can also be interpreted as the probability of hitting a location, which is at a distance of given "miss distance" from the location of intended hit. This information is from the point of view of entity that is attacking. Since the miss distance distribution is a normal distribution, as shown in Fig. 2.3, for the purpose of the work presented here, probability density function for the predicted location of the weapon hit has also been assumed to be a normal distribution [12]. The normal distribution of the predicted hit location of the weapon, with respect to the ship's coordinate axes, is given by (2.6).

$$p(x, y, z) = \frac{1}{(2\pi)^{3/2}\sigma^3} e^{-\left[(x-\mu_x)^2+(y-\mu_y)^2+(z-\mu_z)^2\right]/2\sigma^2} \tag{2.6}$$

where σ = standard deviation

μ_x = mean in x direction

μ_y = mean in y direction.

μ_z = mean in z direction.

The probability of predicted hit will be greatest, at the location represented by coordinate points (μ_x, μ_y, μ_z), with respect to the ship's coordinate axes. Therefore the means (μ_x, μ_y, μ_z) represent the predicted hit location. If the coordinate axes on the ship are moved to the mean (μ_x, μ_y, μ_z), then (2.6) can be simplified to (2.7), a normal distribution with zero mean, with respect to the shifted coordinate axes.

$$p(x, y, z) = \frac{1}{(2\pi)^{3/2}\sigma^3} e^{-(x^2+y^2+z^2)/2\sigma^2} \tag{2.7}$$

This assumption models the uncertainty involved in the prediction of the location of weapon hit.

b) It is assumed that a function that describes the probability of kill for a point, at a given distance from the location of actual hit, is known. This function is referred to as the Weapon Damage Function in this dissertation. As discussed earlier in section 2.2.1, a flexible cookie cutter representation has been used to assess the damage [10]. In that approach, variable values for probability of kill, distributed inside the lethal sphere, were assumed. Using the rationale of that approach, in the present work, a continuous function that gives the probability of kill for a point, as a function of distance from the location of actual hit, has been assumed. This function has also been assumed as a normal function with zero mean and origin at the location of the actual hit, and is given by (2.8). This assumption addresses the uncertainty involved in the assessment of extent of damage caused by a weapon hit.

$$f(x, y, z) = \frac{1}{(2\pi)^{3/2}\sigma_0^3} e^{-(x^2+y^2+z^2)/2\sigma_0^2} \tag{2.8}$$

where σ_0 = effectiveness factor

This function is normalized such that the probability of kill at the actual hit location is 1, as shown in Fig. 2.5. For normalization, (2.8) was multiplied by factor $(2\pi)^{3/2}\sigma_0^3$, which resulted in the normalized function given by (2.9).

$$F(x,y,z)=e^{-\left(x^2+y^2+z^2\right)/2\sigma_0^2} \tag{2.9}$$

The effectiveness factor, σ_0, represents a weapon's effectiveness in destroying a target and causing widespread damage. It is discussed in detail, later in this section. When the weapon hits the ship, it will explode which will cause primary damage to the ship. The explosion due to the weapon hit can also result in secondary effects like electromagnetic pulse (EMP), fallout radiation, thermal radiation, nuclear radiation, etc. These effects can cause damage to communication systems and physical damage to various components. In this dissertation, the weapon damage function represents the final damage caused, whether due to primary or secondary damage, to the electrical components.

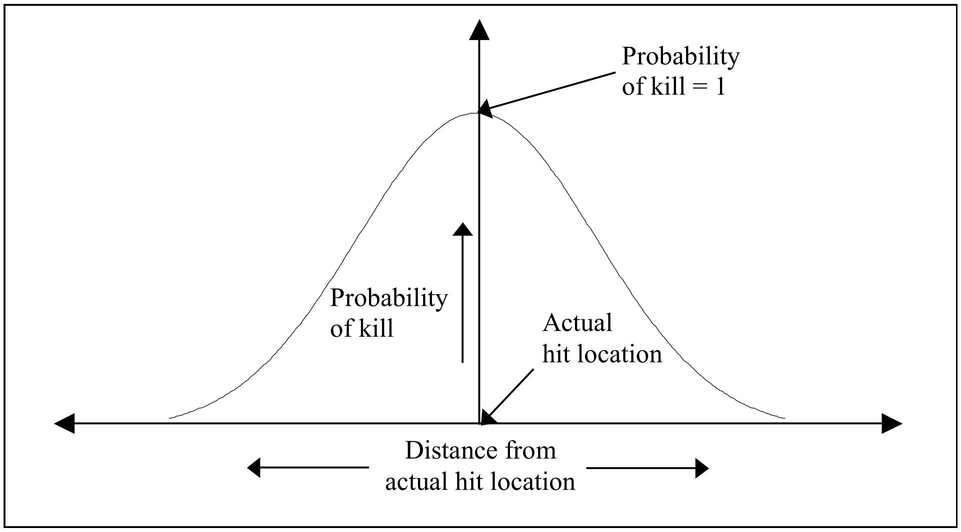

Fig. 2.5: Plot of Probability of Kill versus Distance from the Actual Hit Location

In the literature, probability of kill has been used to address the probability of complete destruction of a target. In the work presented in this dissertation, attempt has been made to compute the probability of destruction of an electrical component. During the attack on a ship, the actual target is typically not a single electrical component, and probability of kill for a ship can also be computed. Hence, in order to avoid any confusion, in this work the "probability of kill" for a point has been referred to as "probability of damage" for a point.

If a continuous random variable X has a probability distribution function $p(X)$, then a random variable, which is a continuous function of X and is denoted by $g(X)$, has the expected value given by (2.10) [13].

$$E = \int\int\int_{-\infty}^{+\infty} g(X) \cdot p(X) \cdot dX \tag{2.10}$$

The expected value of function $F(x, y, z)$ defined in (2.9) can be calculated using (2.10). This expected value will represent the expected probability of damage (*EPOD*) for a given point. Then the *EPOD* for a point P at (x_0, y_0, z_0), with respect to the shifted coordinate axes, is given by (2.11).

$$EPOD = \int\int\int_{-\infty}^{+\infty} p(x, y, z) \cdot F(x - x_0, y - y_0, z - z_0) \cdot dx \cdot dy \cdot dz \tag{2.11}$$

Next substituting the values of $p(x, y, z)$ and $F(x - x_0, y - y_0, z - z_0)$ from (2.7) and (2.9), respectively, in (2.11), gives (2.12).

$$EPOD = \int\int\int_{-\infty}^{+\infty} \frac{1}{(2\pi)^{3/2}\sigma^3} e^{-(x^2+y^2+z^2)/2\sigma^2} \cdot e^{-\left[(x-x_o)^2+(y-y_o)^2+(z-z_o)^2\right]/2\sigma_0^2} \cdot dx \cdot dy \cdot dz \tag{2.12}$$

Equation (2.12) can be rewritten as (2.13).

$$EPOD =$$

$$\frac{1}{(2\pi)^{3/2}\sigma^3}\int\int_{-\infty}^{+\infty}\int e^{-\left[x^2\left(\sigma_0^2+\sigma^2\right)+y^2\left(\sigma_0^2+\sigma^2\right)+z^2\left(\sigma_0^2+\sigma^2\right)+\sigma^2\left(x_0^2+y_0^2+z_0^2\right)-2xx_o\sigma^2-2yy_o\sigma^2-2zz_o\sigma^2\right]/2\sigma^2\sigma_0^2}\cdot dx\cdot dy\cdot dz \tag{2.13}$$

Next, (2.13) can be rewritten as (2.14).

$$EPOD =$$

$$\frac{e^{-\left(x_0^2+y_0^2+z_0^2\right)/2\sigma_0^2}}{(2\pi)^{3/2}\sigma^3}\int\int_{-\infty}^{+\infty}\int e^{-\left[y^2\left(\sigma_0^2+\sigma^2\right)+z^2\left(\sigma_0^2+\sigma^2\right)-2yy_o\sigma^2-2zz_o\sigma^2\right]/2\sigma^2\sigma_0^2}\cdot e^{-\left[x^2\left(\sigma_0^2+\sigma^2\right)-2xx_o\sigma^2\right]/2\sigma^2\sigma_0^2}\cdot dx\cdot dy\cdot dz \tag{2.14}$$

Separating the exponential with " x " variable as a separate integrand gives (2.15).

$$EPOD =$$

$$\frac{e^{-\left(x_0^2+y_0^2+z_0^2\right)/2\sigma_0^2}}{(2\pi)^{3/2}\sigma^3}\int\int_{-\infty}^{+\infty} e^{-\left(\sigma_0^2+\sigma^2\right)\left[y^2+z^2-\frac{2yy_0\sigma^2}{\left(\sigma_0^2+\sigma^2\right)}-\frac{2zz_0\sigma^2}{\left(\sigma_0^2+\sigma^2\right)}\right]/2\sigma^2\sigma_0^2}\cdot\left(\int_{-\infty}^{+\infty} e^{-\left(\sigma_0^2+\sigma^2\right)\left[x^2-\frac{2xx_0\sigma^2}{\left(\sigma_0^2+\sigma^2\right)}\right]/2\sigma^2\sigma_0^2}.dx\right)dy\cdot dz \tag{2.15}$$

Next let,

$$k=\frac{e^{-\left(x_0^2+y_0^2+z_0^2\right)/2\sigma_0^2}}{(2\pi)^{3/2}\sigma^3}; \qquad k_1=\frac{2x_0\sigma^2}{\left(\sigma_0^2+\sigma^2\right)}; \qquad k_2=\frac{2y_0\sigma^2}{\left(\sigma_0^2+\sigma^2\right)}; \qquad k_3=\frac{2z_0\sigma^2}{\left(\sigma_0^2+\sigma^2\right)}$$

and $k_4=\dfrac{\left(\sigma_0^2+\sigma^2\right)}{2\sigma_0^2\sigma^2}$

Then substituting k, k_1, k_2, k_3 and k_4 in (2.15) gives (2.16).

$$EPOD = k\cdot\int\int_{-\infty}^{+\infty} e^{-k_4\left(y^2-k_2y\right)}\cdot e^{-k_4\left(z^2-k_3z\right)}\cdot\left(\int_{-\infty}^{+\infty} e^{-k_4\left(x^2-k_1x\right)}.dx\right)\cdot dy\cdot dz \tag{2.16}$$

Next let,

$$I_1=\int_{-\infty}^{+\infty} e^{-k_4\left(x^2-k_1x\right)}\cdot dx \tag{2.17}$$

Substituting I_1 in (2.16) gives (2.18).

$$EPOD = k \cdot \int \int_{-\infty}^{+\infty} e^{-k_4\left(y^2 - k_2 y\right)} \cdot e^{-k_4\left(z^2 - k_3 z\right)} \cdot I_1 \cdot dy \cdot dz \tag{2.18}$$

We can write (2.17) as (2.19)

$$I_1 = \int_{-\infty}^{+\infty} e^{-k_4 x\left(x - k_1\right)} \cdot dx \tag{2.19}$$

Next using substitution,

$x = t + \frac{k_1}{2}$, then $dx = dt$

Substituting the values of "x" and "dx" in (2.19) gives (2.20).

$$I_1 = \int_{-\infty}^{+\infty} e^{-k_4\left(t + \frac{k_1}{2}\right)\left(t - \frac{k_1}{2}\right)} \cdot dt = \int_{-\infty}^{+\infty} e^{-k_4\left(t^2 + \frac{k_1^2}{4}\right)} \cdot dt = e^{\frac{k_4 k_1^2}{4}} \cdot \int_{-\infty}^{+\infty} e^{-k_4 t^2} \cdot dt \tag{2.20}$$

Solving (2.20) gives (2.21).

$$I_1 = e^{\frac{k_4 k_1^2}{4}} \cdot \sqrt{\frac{\pi}{k_4}} \tag{2.21}$$

Substituting the value of I_1 in (2.18) gives (2.22).

$$EPOD = k \cdot e^{\frac{k_4 k_1^2}{4}} \cdot \sqrt{\frac{\pi}{k_4}} \cdot \int \int_{-\infty}^{+\infty} e^{-k_4\left(y^2 - k_2 y\right)} \cdot e^{-k_4\left(z^2 - k_3 z\right)} dy \cdot dz \tag{2.22}$$

Separating the exponential with "y" variable as a separate integrand gives (2.23).

$$EPOD = k \cdot e^{\frac{k_4 k_1^2}{4}} \cdot \sqrt{\frac{\pi}{k_4}} \cdot \int_{-\infty}^{+\infty} e^{-k_4\left(z^2 - k_3 z\right)} \cdot \left(\int_{-\infty}^{+\infty} e^{-k_4\left(y^2 - k_2 y\right)} \cdot dy \right) dz \tag{2.23}$$

Using (2.17) and (2.21), (2.23) can be rewritten as (2.24).

$$EPOD = k \cdot e^{\frac{k_4 k_1^2}{4}} \cdot \sqrt{\frac{\pi}{k_4}} \cdot e^{\frac{k_4 k_2^2}{4}} \cdot \sqrt{\frac{\pi}{k_4}} \cdot \int_{-\infty}^{+\infty} e^{-k_4\left(z^2 - k_3 z\right)} \cdot dz \tag{2.24}$$

Again, using (2.17) and (2.21), (2.24) can be rewritten as (2.25).

$$EPOD = k \cdot e^{\frac{k_4 k_1^2}{4}} \cdot \sqrt{\frac{\pi}{k_4}} \cdot e^{\frac{k_4 k_2^2}{4}} \cdot \sqrt{\frac{\pi}{k_4}} \cdot e^{\frac{k_4 k_3^2}{4}} \cdot \sqrt{\frac{\pi}{k_4}} \tag{2.25}$$

Solving (2.25) we get (2.26).

$$EPOD = k \cdot \left(\frac{\pi}{k_4}\right)^{3/2} \cdot e^{\frac{k_4\left(k_1^2 + k_2^2 + k_3^2\right)}{4}} \tag{2.26}$$

Substituting the values of k, k_1, k_2, k_3 and k_4 in (2.26) gives (2.27).

$$EPOD = \frac{1}{\left[1 + \left(\sigma/\sigma_0\right)^2\right]^{3/2}} \cdot e^{-\frac{\left(x_0^2 + y_0^2 + z_0^2\right)}{2\left(\sigma_0^2 + \sigma^2\right)}} \tag{2.27}$$

The standard deviation, σ, for the probability distribution function for the location of weapon-hit, represents the accuracy of the weapon in hitting the aimed target. The smaller the value of, σ, the lesser will be the deviation from the mean value. This means that if a weapon is fired, the probability of hitting close to the aimed target will be higher. Hence, the smaller the value of σ, the more accurate will be the weapon.

Suppose a weapon is fired at the ship, and the main aim of that weapon is to destroy a target *T*. Since the aim is to destroy the target *T*, the coordinates of location of target *T* will become (0,0,0) after transferring the coordinate axes. Then the *EPOD* for target *T* would be given by (2.27). Now from the logical deduction it can be said the more accurate a weapon is the higher is the probability that it will destroy the target *T*. As explained above, the accuracy of the weapon is defined by σ. So lets examine two cases with different values of σ. One case with σ = 2 and the other σ = 8. In each of these cases, σ_0 is taken as 5.

Case 1: σ = 2

For this case, we compute the value of *EPOD* given by (2.27).

$$EPOD_{\sigma=2} = \frac{1}{\left[1+\left(\sigma/\sigma_0\right)^2\right]^{3/2}} = 0.8$$

Case 2: $\sigma = 8$

For this case, also we compute the value of *EPOD* given by (2.27).

$$EPOD_{\sigma=8} = \frac{1}{\left[1+\left(\sigma/\sigma_0\right)^2\right]^{3/2}} = 0.15$$

Since $EPOD_{\sigma=2} > EPOD_{\sigma=8}$, the weapon with σ = 2 will have a greater probability of destroying the target. The results of these cases are the same as obtained from logical deduction and i.e., the more accurate weapon will have the greater probability of destroying the target.

The effectiveness factor, σ_0, represents the spread of damage caused by the weapon hit. In other words, it represents the measure of a weapon's effectiveness. The larger the value of σ_0, the larger will be the damage caused by the weapon hit. Now, suppose a weapon is fired at a ship, and the main aim of that weapon is to destroy a target *T*. Since the aim is to destroy the target *T*, the coordinates of location of target *T* will become (0,0,0) after transferring the coordinate axes. Then the *EPOD* for target *T* would be given by (2.27). Now the more effective a weapon is in causing damage, the greater is the probability to destroy the target *T*. As explained above, the effectiveness of the weapon is defined by σ. So lets examine two cases with different values of σ_0. One case with σ_0 = 2 and in the other with σ_0 = 8. In each of these cases σ is taken as 3.

Case 1: $\sigma_0 = 2$

For this case, we compute the value of *EPOD* given by (2.27).

$$EPOD_{\sigma_0=2} = \frac{1}{\left[1+\left(\sigma/\sigma_0\right)^2\right]^{3/2}} = 0.17$$

Case 2: σ_0 = 8

For this case, also we compute the value of *EPOD* given by (2.27).

$$EPOD_{\sigma_0=8} = \frac{1}{\left[1+\left(\sigma/\sigma_0\right)^2\right]^{3/2}} = 0.82$$

Since $EPOD_{\sigma_0=8} > EPOD_{\sigma_0=2}$, the weapon with σ_0 = 8 will have a greater probability of destroying the target. The results of these cases are the same as obtained logically i.e., a more effective weapon will have the greater probability of destroying the target.

For a weapon with a given accuracy, defined by σ, and a given effectiveness, defined by σ_0, the probability of damage at a point, should decrease with the increase in distance from the aimed hit location. Consider two targets *T1* and *T2* at locations (x_1, y_1, z_1) and (x_2, y_2, z_2), respectively. The distance of these targets from the aimed point is given by (2.28) and (2.29), respectively.

$$r_1 = \left(x_1^2 + y_1^2 + z_1^2\right)^{1/2} \tag{2.28}$$

$$r_2 = \left(x_2^2 + y_2^2 + z_2^2\right)^{1/2} \tag{2.29}$$

It is assumed that target *T1* is closer to the aimed point than target *T2*. It implies that $r_2 > r_1$. The *EPOD* for each of these targets can be calculated using (2.27), and are given by (2.30) and (2.31), respectively. In each of these cases, the same σ and σ_0 values are assumed.

$$EPOD_{T1} = \frac{1}{\left[1+\left(\sigma/\sigma_0\right)^2\right]^{3/2}} \cdot e^{-\frac{r_1^2}{2\left(\sigma_0^2+\sigma^2\right)}} \tag{2.30}$$

$$EPOD_{T2} = \frac{1}{\left[1+\left(\sigma/\sigma_0\right)^2\right]^{3/2}} \cdot e^{-\frac{r_2^2}{2\left(\sigma_0^2+\sigma^2\right)}} \tag{2.31}$$

Since $r_2 > r_1$, then for a given σ and σ_0, $EPOD_{T1} > EPOD_{T2}$. This result is the same as obtained logically that for a given accuracy and effectiveness the probability of damage for a location which is closer to the aimed target will be higher than the probability of damage for the location which is farther from the aimed target.

Suppose an ideal weapon is fired to destroy a target *T*. Since the weapon has been assumed to be ideal, it will hit directly at the target location, (0,0,0). The probability distribution function of location of hit for such an ideal weapon would be represented by a normal distribution function with σ = 0. The EPOD for target T, in this case, can be calculated using (2.27), and the calculation for that is given by (2.32).

$$EPOD_T = \frac{1}{\left[1+\left(0/\sigma_0\right)^2\right]^{3/2}} = \frac{1}{\left[1+0^2\right]^{3/2}} = 1 \tag{2.32}$$

$EPOD_T = 1$, means that the target would certainly be destroyed. This result also is the same as obtained logically that for an ideal weapon, if fired directly at a target, will certainly destroy the target. These results show that the *EPOD* calculated by using (2.27), can be deduced logically. None of the cases, discussed above, gave inexplicable results.

The main goal of the Weapon Damage Assessment method is to compute the *EPOD* for electrical components. The *EPOD* given by (2.27) can be used to compute damage probability for each component in the electrical system on the ship. During the computation, each electrical component is divided into very small cubes. Let a component *C* be divided into "*n*" cubes, C_1, C_2,.., C_n. Let the point where the diagonals of the cuboids meet be P_{C1} ,P_{C2} ,.., P_{Cn}. Then using (2.27), *EPOD* for each point, where the diagonals meet, for all cubes can be calculated. Let these *EPOD* be represented by

$EPOD_{PC1}$, $EPOD_{PC2}$,.., $EPOD_{PCn}$. Then the *EPOD* for the component *C*, $EPOD_C$, could be taken as the *EPOD* that has largest value among all the *EPOD* values computed for all points on component *C*. This is represented by (2.33).

$$EPOD_C = MAX\left(EPOD_{PC1}, EPOD_{PC2}, ..., EPOD_{PCn}\right) \tag{2.33}$$

2.2.2 Probabilistic Reconfiguration for Damage Reduction

Once the *EPOD* for all electrical components is obtained, this probabilistic information is used to determine the steps of reconfiguration for damage reduction. In the process of reconfiguration for an electrical system, one should know the status of all switches in the system. In addition to all the switches' status, information regarding the working status of all electrical components should also be known. If the *EPOD* of an electrical component, *C*, is 0.8, it means that the component *C* has 0.8 expected probability of getting damaged. In other words, it can be said that the component *C* has 0.8 probability that it will not be available to transfer electrical energy. If it were known that component C is damaged, then during the process of reconfiguration, steps would be determined such that the path of electrical energy flowing through component C is reconfigured. Since the damage information regarding component *C* is probabilistic, decisions regarding reconfiguration steps to reconfigure the path of electrical energy through component *C*, cannot be made with certainty. Hence an approach, which deals with decision making under uncertain conditions, needs to be developed for performing reconfiguration before a weapon hit.

Artificial intelligence (AI) is a fortuitous discipline to study reasoning during uncertain conditions. AI methods encourage one to view uncertainty as a problem to be solved by the application of heuristic knowledge [13]. To solve a problem, first goals are stated; then they are ordered, which represents the order in which they have to be achieved; and lastly the methods are determined to achieve the goals. Similar reasoning can be applied to the problem of Probabilistic Reconfiguration.

The goals of Probabilistic Reconfiguration for damage reduction are:

- To reduce interruption of electrical supply to vital loads.
- To reduce faults and cascading faults.

In the next sections, heuristic methods developed to achieve the above mentioned goals are discussed.

2.2.2.1 Reduction of Interruption of Electrical Supply to Vital Loads

The main objective of electrical network on the ship is to supply electrical energy to various loads. This electrical energy is supplied via various electrical components, which form a radial path from the electrical energy source to load. Some loads (vital loads) in the system have more than one possible radial path, i.e., the electrical energy to these loads can be provided through more than one path. But at any given time the load gets power supply via one path only. The damage assessment output provides the information about the probabilities of damage of electrical components in these radial paths.

A simplified electrical network of an SPS is shown in Fig. 2.6. This network consists of two generators (Gen1, Gen2), two switchboards (SB1, SB2), two load centers (LC1, LC2), five loads (L1,L2,..L5), thirteen circuit breakers (CB1,CB2,…CB13), fourteen cables (CL1,CL2,…,CL14) and one manual bus transfers (BT1). Normal path for the BTs are shown by continuous lines and alternate path is shown by dotted lines. In this figure two possible radial paths R1 and R2, for a load L2 is shown. Each radial path comprises of various electrical components. Also, assume that currently, load L2 is getting electrical supply via R2. Now path R1 and R2 comprises of electrical component as given below by (2.34) and (2.35).

$$R1: \{L2, CL4, BT1, CL3, CB4, LC1, CL1, CB1, SB1\} \tag{2.34}$$

$$R2: \{L2, CL4, BT1, CL10, CB8, LC2, CL7, CB6, SB2\} \tag{2.35}$$

Let us suppose $(EPOD)_C$ represents expected probability of damage for a component C. Now Availability Probability $(AP)_C$ for a component C is defined as the probability that the component C will be able to transfer electrical energy through it in case of the weapon hit.

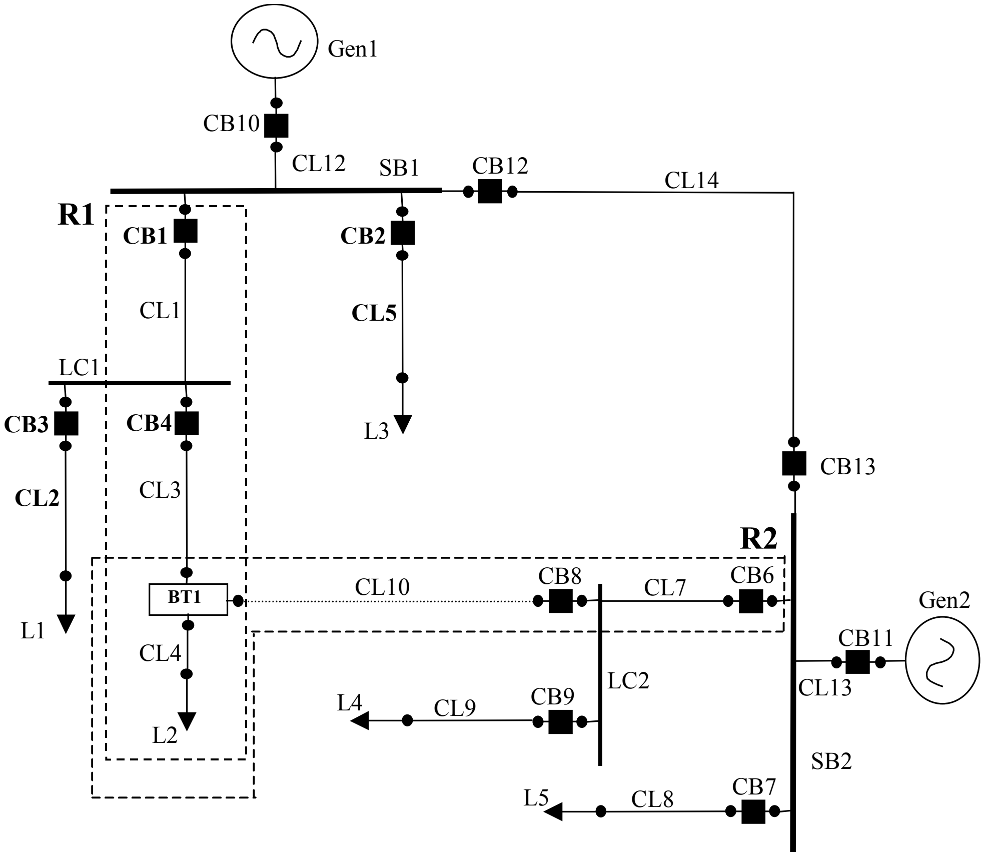

Fig. 2.6: Two Possible Paths for a Load L2

In a SPS electrical components can be divided into two categories, switch-controlled devices and not switch-controlled devices. A device, C_i, which is not a switch-controlled device, can transfer electrical energy if it is not damaged. Since $(EPOD)_{Ci}$ represents expected probability of damage for C_i, so the AP for C_i is given by (2.36).

$$(AP)_{Ci} = 1-(EPOD)_{Ci} \tag{2.36}$$

Next, consider a component C_j, which is a switch-controlled device, for e.g. a circuit breaker. In this case C_j will be able to transfer electrical energy through it if it is not damaged and is in closed position. If expected probability of damage for C_j is $(EPOD)_{Cj}$ and its status (close or open) is represented by S_{Cj} then AP for C_j is given by (2.37). If status of C_j is closed then $S_{Cj} = 1$, otherwise if C_j is in open position then $S_{Cj} = 0$.

$(AP)_{Cj} = [1-(EPOD)_{Cj}] * S_{Cj}$ (2.37)

Next, consider path R1, shown in Fig. 2.6. In path R1 if any one electrical component is damaged then path R1 will not be able to supply electrical energy to load L2. Also, if circuit breaker CB3 is damaged such that it leads to a short circuit fault at CB3, then because of coordination between protective devices, CB1 will open causing interruption of supply in path R1. In case if the damage on CB3 leads to an open fault condition at CB3, then it will not cause opening of CB1. This means that in order to supply power in path R1, none of the circuit breakers at load center level should be in short circuit fault condition. This means that all electrical components in path R1 and all circuit breakers at load centers, with a short circuit fault, are in series; as damage to anyone of these components will result in interruption of electrical supply to load L2.

It is extremely difficult to tell beforehand, that damage to a circuit breaker will lead to a short circuit fault or an open circuit fault. If we assume that the probability that damage caused by a weapon hit will lead to an open circuit fault on a circuit breaker is p1, then the probability that the circuit breaker will have a short circuit fault, in the event of a weapon hit, is (1-p1). Given that the weapon hit has occurred, the three possible states of a circuit breaker C, with expected probability of damage $EPOD_C$, are shown in Fig. 2.7. State 1 represents the situation if the weapon hit does not cause damage to circuit breaker. State 2 represents the situation if the circuit breaker is damaged and has an open circuit fault. State 3 represents the situation if the circuit breaker is damaged and has a short circuit fault.

The probability that the circuit breaker will not be damaged is given by (2.38).

$P_{C,\text{not damaged}} = 1-EPOD_C$ (2.38)

The probabilities of an open circuit or a short circuit fault on the circuit breaker, in the event of a weapon hit is given by (2.39) and (2.40).

$P_{C,\text{damaged, open circuit}} = p1*EPOD_C$ (2.39)

$P_{C,\text{not damaged, short circuit}} = (1-p1)*EPOD_C$ (2.40)

The probability that the circuit breaker C will not be in the state of short circuit after the weapon hit is given by (2.41).

$$P_{C,\text{ not short circuit}} = 1- P_{C,\text{not damaged, short circuit}} = 1- (1-p1)*EPOD_C \qquad (2.41)$$

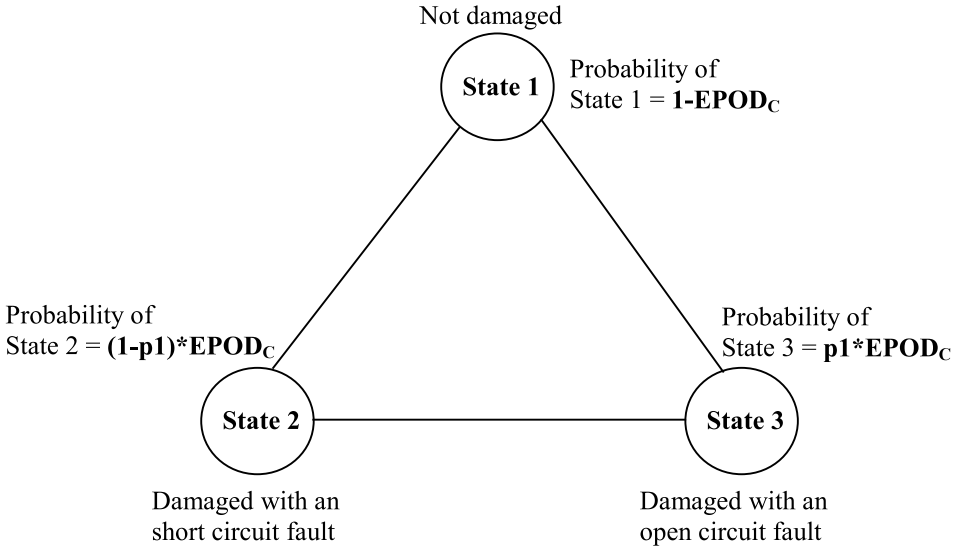

Fig. 2.7: Possible States of Circuit Breaker after the Weapon Hit

If we define Path Availability Probability (PAP) as the probability that a path can transfer electrical energy through it, after a weapon hit, then the PAP for path R1 is given by equation (2.42).

$$(PAP)_{R1} = (AP)_{L2}*(AP)_{CL4}*(AP)_{BT1}*(AP)_{CL3}*(AP)_{CB4}*(AP)_{CL1}*(AP)_{CB1}*(\text{probability that CB3 is not short circuited}) \qquad (2.42)$$

Substituting (2.41) in (2.42) gives (2.43).

$$(PAP)_{R1} = (AP)_{L2}*(AP)_{CL4}*(AP)_{BT1}*(AP)_{CL3}*(AP)_{CB4}*(AP)_{CL1}*(AP)_{CB1}*[1-(1-p1_{CB3})*EPOD_{CB3}] \qquad (2.43)$$

As stated earlier, it is very difficult to tell beforehand, that damage to a circuit breaker will lead to a short circuit fault or an open circuit fault. For the work reported in this dissertation, it is assumed that damage to a circuit breaker will always lead to an open circuit condition. Hence, in that case p1 = 1. Therefore, (2.43) reduces to (2.44).

$$(PAP)_{R1} = (AP)_{L2}*(AP)_{CL4}*(AP)_{BT1}*(AP)_{CL3}*(AP)_{CB4}*(AP)_{CL1}*(AP)_{CB1} \qquad (2.44)$$

In other words, if a path "R_k" has "n" components and their APs are represented by [$(AP)_{C1,}$ $(AP)_{C2,\ldots}$ $(AP)_{Cn}$], respectively, then Path Availability Probability for that path is given by equation (2.45).

$$(PAP)_{R_k} = \prod_{i=1}^{n} (AP)_{Ci} \qquad (2.45)$$

PAP for an electrical path basically gives a measure of success a path will have in delivering electrical energy to the load in that path. The higher the PAP for a path, the higher will be the success that path will have in providing electrical energy to a load. In other words, suppose a load L2 has two paths R1 and R2 (refer to Fig. 2.6). PAP for R1 and R2 is $(PAP)_{R1}$ and $(PAP)_{R2,}$ respectively. $(PAP)_{R1} > (PAP)_{R2}$ implies that path R1 has higher probability of delivering the electrical energy to load L2 when the weapon hit occurs. Therefore if the present (pre hit) supply path for load L2 is not R1 then the load L2 should be reconfigured so that it receives electrical energy via path R1; otherwise no reconfiguration steps are required. This procedure is shown in Fig. 2.8.

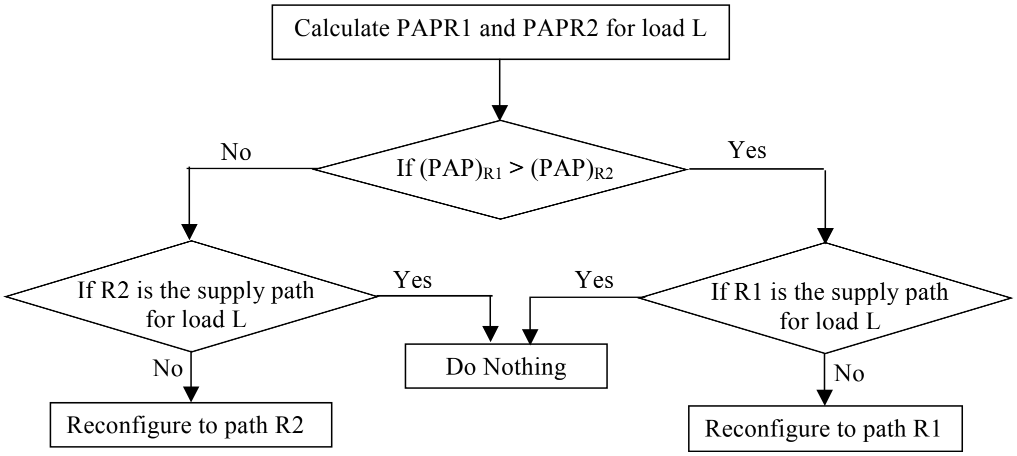

Fig. 2.8: Heuristic for Reduction of Interruption of Electrical Supply to Loads

The control actions determined by RRSI will always involve a change of electrical supply path of bus transfers. The bus transfer on a SPS can be of two types – automatic and manual. In order to change supply path of a manual bus transfer (MBT), a direct command can be given to it which would be “transfer BT”. But for an automatic bus transfer (ABT), no direct command can be given to it. Hence in order to change its supply path, the circuit breaker (CB) of the supply path from which the electrical supply is to be transferred (to the other path) is given a command to open. Hence for ABTs the control action would be to “Open CB” upstream.

Implementing a control action involves a certain cost. If the difference in the $(PAP)_{R1}$ and $(PAP)_{R2}$ is very little, then in that case it might be a good decision to disregard the suggested control action. Also it is possible that the difference in PAPs might be substantial, but the individual PAP values are small. In these cases, it might be a good decision to not implement the suggested control action. Hence as a probabilistic measure of the control action, the absolute value of the difference in PAP of both R1 and R2, and the PAP value of the selected path should be provided as an output. It is then up to the operator to decide whether the suggested action should be implemented.

The heuristic explained above is applied to loads that have more than one supply path. In a SPS, loads are categorized as vital or non-vital. Vital loads have two paths available to them. The method presented here is only applicable for vital loads. Since the objective of this method is to reconfigure vital loads such that the probability of supply interruption to those vital loads is reduced, the method is referred to as Reconfiguration for Reduction of Supply Interruption for vital loads.

2.2.2.2 Reduction of Faults and Cascading Faults

When a weapon hits a ship, it causes damage to electrical components of the ship leading to electrical faults and possibly cascading faults in the system. Suppose the components that will get damaged can be exactly determined, before the weapon hit takes place, and these components can be isolated then the electrical faults and cascading faults can be completely prevented. But since the weapon hit is a future event; it is impossible to exactly predict the components that will be damaged by a weapon hit. But the expected probability of damage for components determined by the Weapon hit Damage Assessment methodology, discussed earlier, can be used to identify components that have a very high probability of being damaged. Using a threshold value, components can be identified that have expected probability of damage, EPOD, higher than the threshold value, or in other words have a high probability of being damaged. If these identified components are isolated before a weapon hit takes place, then although it cannot be said that the electrical faults and cascading faults have been completely prevented, the chances of electrical faults and cascading faults occurring are reduced.

The EPOD value for a component represents the probability that component has of getting damaged, but it does not state for certainty that the component will get damaged. Thus a component that has an EPOD value higher than the threshold maybe isolated before the weapon hit, but after the weapon hit the component may not be actually damaged. In that case, it is possible that because of the isolation of that component, the electrical supply to some load downstream of that component might get interrupted. If the load is a vital load, then interruption of electrical supply to that load might reduce the ship’s chances of surviving the attack. Therefore it is better not to isolate component, upstream of a vital load, which have damage probability higher than the threshold. That is why the methodology to prevent electrical faults and cascading faults is included only for non-vital loads, i.e., only the components lying in the radial path of non-vital components are considered for isolation. Hence this method is referred to as Reconfiguration for Component Isolation for non-vital loads.

In order to illustrate the idea presented above, some cases are presented. These cases are based on a simplified electrical network of an SPS, as shown in Fig. 2.9. This network consists of two generators (Gen1, Gen2), two switchboards (SB1, SB2), two load centers (LC1, LC2), five loads (L1,L2,..L5), thirteen circuit breakers (CB1,CB2,…CB13), fourteen cables (CL1,CL2,…,CL14) and two manual bus transfers (BT1,BT2). Continuous lines show normal path for the BTs and alternate path are shown by dotted lines.

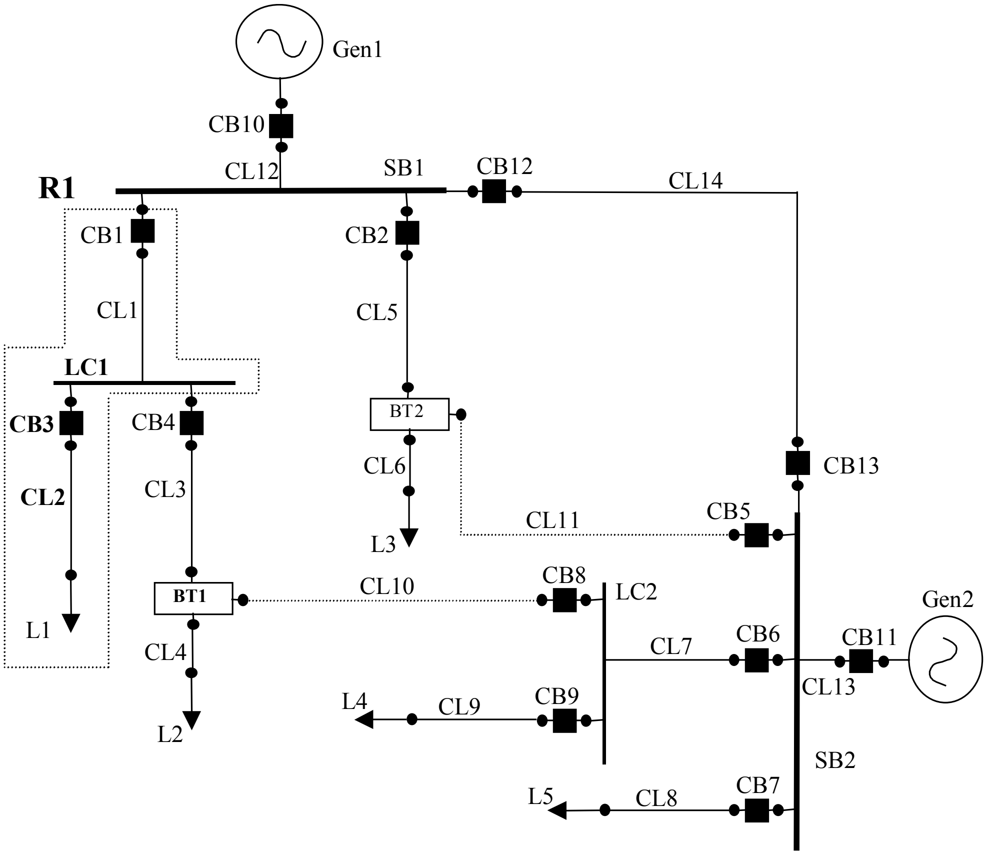

Fig. 2.9: Simplified Electrical Network for a SPS

The components having EPOD greater than the threshold and lying in the path supplying power to a non-vital load are referred to as non-critical components. It has been assumed that there was a situation in which a missile was detected. Therefore, in order to assess the damage that will be caused by the actual weapon hit, Weapon-hit Damage Assessment methodology, as explained in section 2.2.1, was executed. This computed EPOD for each component. For all the cases, a threshold expected probability of damage limit, $EPOD_{threshold}$, has also been assumed. As stated earlier that in this method only non-vital load are considered, so in all these cases only the non-vital loads L1 and L4 are considered. Different cases are presented below.

Case 1

Consider that among all the components in the electrical network, only cable CL2 had expected probability of damage, $EPOD_{CL2,}$ greater than the threshold. In other words $EPOD_{CL2} > EPOD_{threshold}$. Then to isolate CL2, before an actual hit, the circuit breaker upstream of CL2, CB3, needs to be opened. This action, if implemented, will cause de-energization of load L1. In the event of actual hit if cable CL2 is actually damaged, then load L1 will be de-energized anyway. If CL2 was isolated before the weapon hit takes place, then electrical faults or cascading faults, which can happen because of damage to CL2, have been prevented. In case CL2 did not get damaged by the weapon hit and was isolated before the weapon hit, then de-energization of L1 was not required and should be restored by a Restoration program. But since load L1 is a non-vital load, so it can be assumed that its temporary de-energization will not reduce the ship's chances of surviving the attack.

Case 2

In this case, only circuit breaker CB9 was determined as the non-critical component having EPOD greater than the threshold. Mathematically it can be written as, $EPOD_{CB9} > EPOD_{threshold}$. Since we have assumed that a circuit breaker is open circuited by the damaged caused to it due to a weapon hit, there are no isolating steps required to isolate circuit breaker CB9. If the circuit breaker CB3 is damaged by the weapon hit, then it will result in de-energization of load L4. In the event that CB9 is not damaged by the weapon hit, then load L4 will not be de-energized.

Case 3

In this case, only load center LC1 was determined as the component having EPOD greater than the threshold. Mathematically it can be written as, $EPOD_{LC1} > EPOD_{threshold}$. Then in order to isolate LC1, the circuit breaker upstream of LC1, CB1, needs to be opened. This action, if implemented, will result in de-energization of loads L1 and L2. In case that LC1 is not damaged by the weapon hit but was isolated before the weapon hit, then de-energization of L1 and L2 was not required and should be restored by a Restoration program.

Results of the three cases discussed above have been summarized in Table 2.1. For each case, it shows the non-vital load; non-critical component; actions to isolate the non-critical component; load(s) which will be de-energized if the non-critical component is isolated; and the last column shows the affect of not performing the component isolation, and after the weapon hit that non-critical component was actually damaged. Implementing a reconfiguration action involves a certain cost. In some situations, the operator may decide not implement a suggested component isolation action. The PAP for the radial path supplying power to a non-vital load and containing the non-critical component is a good measure to decide whether the suggested actions should be implemented. If the PAP value for that path is high, then it means that the path has a high probability of supplying electrical power to the non-vital load, after the weapon hit. So in that case, the operator may decide not to implement the suggested isolation action. Hence, the PAP value is also provided as an output along with the suggested component isolation actions, as a probabilistic measure of the suggested control action. This would aid the operator in deciding whether the suggested actions should be implemented.

Table 2.1

Results of Reconfiguration for Component Isolation for Load L1

Case No.	Non-vital load	Non-critical component with EPOD > $\mathrm{EPOD}_{\mathrm{threshold}}$	PAP of path for load	Component Isolation Actions	De-energized loads	Affect of not performing component isolation; and the component is damaged after the weapon hit
1	L1	CL2	PAP_{L1}	Open CB3	L1	L1 de-energized Possibility of electrical faults and cascading faults.
2	L4	CB9	-	-	-	L4 de-energized Possibility of cascading faults.
3	L1	LC1	PAP_{L1}	Open CB1	L1, L2	L1 & L2 de-energized Possibility of electrical faults and cascading faults.

In the cases discussed above, it was assumed that only one component had EPOD greater than the cut-off limit. If there is more than one component that has EPOD greater than the threshold, then based on the component's location there are two possible scenarios.

Scenario 1: Components are in different radial paths

In this case, since in a given radial path there is only one component that has EPOD greater than the threshold, the isolation actions for that component should be determined as explained earlier.

Scenario 2: Components are in the same radial path

In this scenario, consider that there are two electrical components, C1 and C2, in the same radial path with EPOD greater than threshold. Also, C1 is situated upstream of C2. Then it is possible that isolating C1 can also lead to isolation of C2. For e.g., consider path R1, which is supplying power to the non-vital load L1, as shown in Fig. 2.9. Let us assume that EPOD for cable CL2, load center LC1, and cable CL1 is greater than the cut-off limit. In that case, if cable CL1 is isolated by opening circuit breaker CB1 then this action will also isolate cable CL3 and load center LC1. Hence it is possible that isolating one upstream non-critical component can lead to isolation of some downstream non-critical components. Hence in the case when there is more than one non-critical component in a radial path, then only the farthest upstream non-critical component needs to be considered for isolation. The isolation procedure has already been discussed earlier.

2.2.2.3 Pre-hit Probabilistic Reconfiguration Methodology

In this section, the overall Pre-hit Probabilistic Reconfiguration methodology will be presented, which aims to reduce of supply interruption to vital loads and reduce electrical faults and cascading faults due to a weapon hit. This methodology uses the two heuristic methods developed in previous sections. It will be shown, that after the execution of the weapon-hit damage assessment method, the combination of Reconfiguration for Component Isolation (RCI) method and Reconfiguration for Reduction of Supply Interruption (RRSI) method for non-vital loads, will result in reconfiguring the system such that the goals of Pre-hit Probabilistic Reconfiguration are achieved. To be exact it will be shown that executing RCI, on the SPS, followed by the execution of RRSI will lead to achieving the goals of Pre-hit Probabilistic Reconfiguration.

Consider the electrical network shown earlier in Fig. 2.9. It is assumed that the weapon-hit damage assessment method was performed and its output is shown in Table 2.2. Only some of the components are shown in Table 2.2.

Table 2.2

Output of Weapon Damage Assessment

Component	Component Type	EPOD
CB1	Circuit Breaker	0.12
CL1	Cable	0.23
LC1	Load Center	0.69
CB3	Circuit Breaker	0.54
CL2	Cable	0.76
L1	Load	0.67
L5	Load	0.01
CL8	Cable	0.60

Using the EPOD values shown in Table 2.2, the RCI method was performed. It can be seen from Fig. 2.9, that there are three non-vital loads in the electrical network - L1, L4, and L5. In the RCI method, the radial path for each of these loads is formed and components with EPOD greater than a threshold are identified. The threshold for this case is assumed to be 0.5. Then isolation actions for components that have an EPOD value greater than the threshold and is farthest upstream in the radial path are determined. Table 2.3 shows the output of RCI for each non-vital load. This table shows that for load L1 and L5 the non-critical components were determined as LC1 and CL8, respectively. For load L4 there were no components found that have EPOD value greater than the threshold. The table also shows control actions for isolating components LC1 and CL8 and L5 and the PAP values associated with these actions. Implementation of these actions will result in de-energization of load L1.

Table 2.3
Output of RCI

Non-vital Load	Non Critical Component	Control Action	PAP
L1	LC1	Open CB1	0.007
L4	-	-	-
L5	CL8	Open CB7	0.121

After determination of control actions by RCI, RRSI was performed. Since RRSI is performed after RCI, the control actions suggested by the RCI and which the user/operator has selected for implementation should be considered implemented while determining control actions for reduction of supply interruption. Based on the control actions selected by the user/operator, RRSI can result in different sets of control actions. The user/operator can select any combination of control actions determined by the RCI method. The next step is then to determine the output of RRSI for possible combinations of control actions. Since the RRSI module only considers vital loads so not all the control actions, determined by RCI, will have an affect on the output of RRSI. For example, in the case presented here the control action to “Open CB7” will have no influence on the determination of control actions by RRSI. But the other action to “Open CB1” will influence the output of RRSI because the opening of CB1 will also result in interruption of electrical supply to the normal path of the vital load L2. In the case presented here the output of RRSI is required to be computed for two different cases. In one case, it is assumed that the control action “Open CB1” was implemented, and in the other case it was assumed that this control action was not implemented. Also it was assumed that all the vital loads were getting electrical supply through manual bus transfers via their normal paths. The output of RRSI for each of these two cases is shown in Table 2.4 and Table 2.5.

Table 2.4

Output of RRSI When “Open CB1” Control Action Is Implemented

Vital Load	PAP Normal	PAP Alternate	Control Action
L2	0.0	0.43	Transfer BT1
L3	0.79	0.91	Transfer BT2

Table 2.5

Output of RRSI When “Open CB1” Control Action Is Not Implemented

Vital Load	PAP Normal	PAP Alternate	Control Action
L2	0.48	0.43	-
L3	0.79	0.91	Transfer BT1

Table 2.4 shows control actions determined by the RRSI method after implementing the control action to open CB1 for vital loads L2 and L3. The PAP value for the normal radial path for load L2 was 0 as it contains the circuit breaker CB1, which is open and so has an AP value of 0. Table 2.5 shows control actions for vital loads when the control action to open CB1 is not implemented. In this case the PAP value of the normal radial path for load L2 was found to be greater than the PAP value of its alternate radial path. Hence no control actions were suggested for Load L2 in this case.

The final output of the Pre-hit Probabilistic Reconfiguration, for the case presented here, will be two different sets of control actions. These two sets are determined on the basis of two combinations of control actions determined by RCI method that can affect the RRSI method. These two sets of control actions are shown in Table 2.6 and Table 2.7. Each of these tables summarizes the results of RCI and RRSI and they also give the probabilistic information associated with each control action.

Table 2.6

Final Output of Pre-hit Probabilistic Reconfiguration Method When "Open CB1" Control Action Is Implemented

Determined Control Actions	**PAP of radial path for non vital load**	**$PAP_{best\ path}$ for vital load**	**PAP difference for vital load**
Open CB1	0.007	-	-
Open CB7	0.121	-	-
Transfer BT1	-	0.43	0.43
Transfer BT2	-	0.91	0.12

Table 2.7

Final Output of Pre-hit Probabilistic Reconfiguration Method When "Open CB1" Control Action Is Not Implemented

Determined Control Actions	**PAP of radial path for non vital load**	**$PAP_{best\ path}$ for vital load**	**PAP difference for vital load**
Open CB1	0.007	-	-
Open CB7	0.121	-	-
Transfer BT2	-	0.91	0.12

2.3 POST-HIT RECONFIGURATION FOR RESTORATION

After the Pre-hit Probabilistic Reconfiguration has been performed, a weapon hit takes place. The steps taken for Pre-hit Probabilistic Reconfiguration for damage reduction on the SPS, before the weapon hit, does not guarantee that none of the loads will be de-energized due to the eventual damage caused by the weapon hit. When the incoming weapon actually hits the ship, it will cause damage leading to fault(s) in SPS.

Because of these fault(s), protection equipment will operate and some of the loads may be de-energized. One or more of these loads might be loads that are vital for ship survivability. Researchers at PSAL have developed a Failure Assessment method that detects fault(s) and determines components in faulted sections of the SPS [14]. The output of this method is a list of faulted sections' damaged components and de-energized loads. Researchers at PSAL have also developed an expert system based reconfiguration for restoration methodology, XRest, to restore de-energized loads [2]. These methods can be combined to assess faults resulting from weapon damage and restore supply to the de-energized loads. In the XRest methodology, constraint check for generation capacity constraint violations, while performing restoration was not performed. In the event of generation capacity constraint violations, no load-shedding can be performed to disconnect non-vital loads to restore de-energized vital loads. Hence the methodology was modified such that the generation capacity constraint violations are checked and in the event of a violation, load-shedding is performed. In this section, the modified restoration methodology is presented. The reconfiguration for restoration methodology is discussed along with the load-shedding module.

2.3.1 Modified Reconfiguration for Restoration Methodology

The Reconfiguration for Restoration methodology consists of various systems such as Geographical Information System (GIS), Failure Assessment System (FAST) and Expert System Restoration (XRest). Fig 2.10 shows the block diagram representation of the Expert System Reconfiguration for Restoration scheme. The real time measurements data for a SPS are continuously updated in real time tables in a GIS database. The real time data consists of line currents, node voltages, generators frequency, circuit-breakers (CBs) status, LVRs/LVPs status, and BTs status measurements. The FAST uses historical data from the Historical database, frequency, voltage and current deviation limits from the Constraint database and real time data from the GIS database to detect and locate faults. Once a fault is detected and located, the output of FAST, the de-energized loads and faulted sections information, is provided as input to the XRest module. Various static, connectivity and real time information from the GIS database are also provided as input to XRest module. It also uses as input, the node voltage limits, cable current limits, and generation capacity limits as input from the Constraint database. The XRest module then determines which loads are restorable. Further it determines the control actions to restore each restorable load. The control actions represent the control commands for CBs, MBTs and LVPs. Various systems shown in Fig. 2.10 are discussed in the following sections.

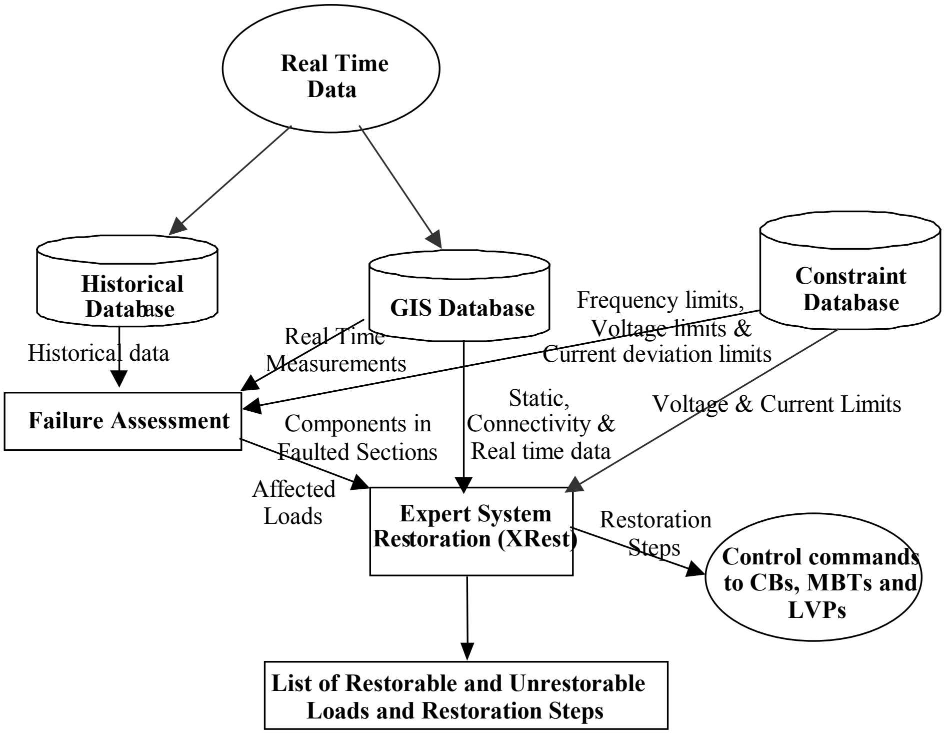

Fig. 2.10: Block Diagram of Expert System Reconfiguration for Restoration Method

2.3.1.1 Real Time Data Measurements

The real time data, shown in Fig. 2.10, are continuously measured and updated in the real time table in GIS database. Real time data consisted of:

A. Current measurements for Generators, Circuit Breakers, Loads, Power-Panels, Load Centers, Switchboards and Transformers.
B. Voltage measurements for Generators, Cables, Loads, Power-Panels, Load Centers, Switchboards and Transformers.
C. Circuit breakers' status.
D. LVPs' and LVRs' status.
E. Bus Transfers' position.
F. Generators' power and frequency

2.3.1.2 GIS Database

A Geographic Information System (GIS) is a computerized system designed to capture, store, process, analyze and manipulate characteristic and spatial data [15]. A GIS consists of two parts: digital map and database. Basically a GIS integrates digital diagrams such as computer-aided design and drafting (CADD) diagrams with information systems such as relational database management systems (RDBMS). The database of the GIS is used in the Reconfiguration for Restoration method as shown in Fig. 2.10. In this method, Microstation was used to model a Shipboard Power System based on the geographical 3-dimensional layout profile of a typical surface combatant ship.

A three-dimensional CADD map of the SPS was drawn based on the spatial position of the electrical elements of the ship. The elements in the CADD map were linked to a GIS database, which was developed using MS Access. The GIS database consists of tables that store data for the various electrical elements of SPS. Each type of element has a connectivity, a real time data, and a static table. The connectivity table contains information about the "from" and "to" nodes for each component, which basically is the connectivity scheme of the elements in the system. The real time measurement tables store the real time electrical values of the elements and the status of protective devices, for a given time. The static parameter tables store electrical parameters of cables, loads, transformers, generators, CBs, BTs and LVPs/LVRs. In addition to the GIS database, there are other databases such as Historical database and Constraint database, which store information used by the failure assessment and the restoration methods.

Automated queries were developed to extract the data from the databases and update in a local database used by the failure assessment and the reconfiguration for restoration methods.

2.3.1.3 Historical Database

The historical database, shown in Fig. 2.10, stores real time information for a period starting from a pre-fault time to some time after the fault had occurred and the system had attained steady state. Historical database consists of:

A. Circuit breakers' status.
B. Voltage of switch boards and load centers.
C. Current flowing through each circuit breaker.

This database is used to provide information to the failure assessment module.

2.3.1.4 Constraint Database

The constraint database, shown in Fig. 2.10, stores constraint information for cables, nodes and generator. Constraint database consists of:

a. Upper Current constraint for each cable.
b. Upper and Lower Voltage Constraint for all load nodes.
c. Generation Capacity Constraint for Generators.

2.3.1.5 Failure Assessment System (FAST)

The Failure Assessment System (FAST), shown in the block diagram in Fig. 2.10, assesses the damage due to a fault by performing two functions – fault detection and fault location. The fault detection function detects abnormal conditions in a SPS. If an abnormal condition is detected in a SPS, the fault location function locates the faulted section(s) and determines the loads that lost supply due to the fault. This method was developed using Rule Base methodology and was implemented using an expert system package called Exsys developed by Multilogic [16,17]. The real-time measurements of node voltages and line currents and connectivity data are extracted from the GIS database, and are used by FAST to detect abnormalities and identify faulted sections. In addition to the GIS database, data is also extracted from the constraint database and historical database.

The fault detection function utilizes the generator's frequency, voltage at the switchboards and load centers, and current measurements at the circuit breakers to determine the presence of a fault or an abnormality condition. It determines if current, voltage, and frequency measurements are within acceptable levels. If not, then an abnormality is detected. Several rules were developed to achieve this.

The fault location function utilizes the pre-fault and post-fault CBs' status, pre-fault, fault, and post-fault CBs' current measurements, and pre-fault, fault, post-fault voltage measurements at switchboards and load centers. These values are used by heuristics based rules to determine the faulted sections and de-energized loads. Further FAST uses historical data from the Historical database, frequency, voltage and current deviation limits from the Constraint database and real time data from the GIS database to detect abnormalities and identify faulted section(s). The output of FAST is a list of components in the faulted section(s) and de-energized loads, which serve as input to the Restoration method.

2.3.1.6 Expert System Based Restoration (XRest)

The Expert System Restoration (XRest) module, shown in Fig 2.10, consists of an Expert System, System Analysis module, Load Shedding module, Database Formation module, GIS database, Constraints database and Local database. This module first calls the Database Formation module. This module uses the output of the failure assessment module (de-energized loads and components in the faulted sections) and data from the GIS Database to construct a local database as shown in Fig. 2.11. In the modified version of XRest, it also considers the loads de-energized due to the control actions implemented during the pre-hit reconfiguration process. This information is also updated in the local database. The modified part is highlighted by bold dots in Fig. 2.11. The XRest module uses data contained in this local database for decision-making. Further, the local database contains connectivity information and static information for all electric components. It also contains post-fault CB's status and BT's position acquired from the GIS real-time tables and the information regarding de-energized loads. The XRest module uses data contained in this local database for decision-making.

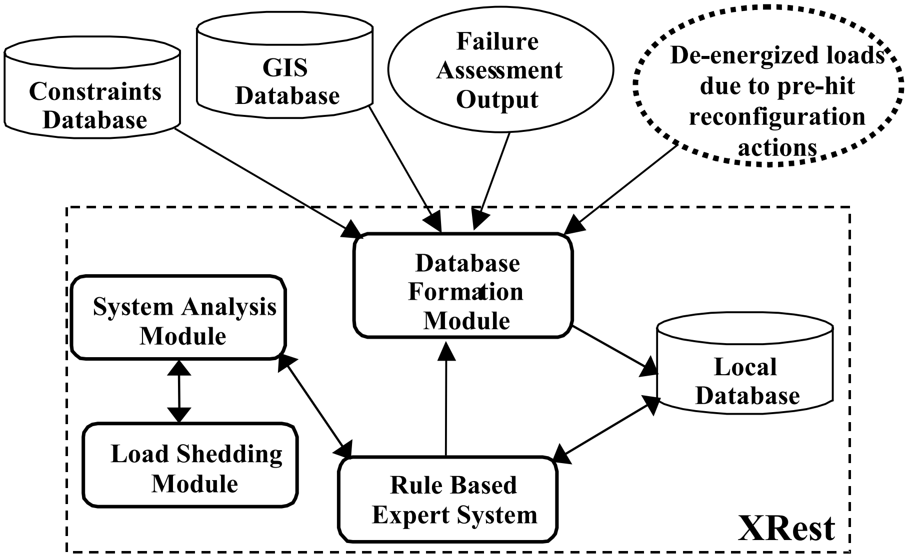

Fig. 2.11: Block Diagram of Databases Interaction for XRest

After the formulation of the local database, XRest calls the Rule Based Expert System (RBES) to reconfigure de-energized loads. A configuration of an electrical network at a given instant is defined by the status of switches in the network at that instant. In a SPS, the switches that define a configuration are CBs, BTs and LVPs/LVRs. The problem of reconfiguration for load restoration is to find an appropriate configuration in which the de-energized loads are reconfigured without causing any system violations.

First, the de-energized loads are re-arranged on the basis of their load priority (vital, non-vital), by the RBES. Loads having the same priority are further arranged on the basis of their location (switchboard or load center), with loads that are fed directly from a switchboard given a higher priority. Loads at the same location are further arranged on the basis of their rating, with loads of larger rating given a higher priority. Then the RBES picks a de-energized load, based on priority, and tries to determine the control actions required to reconfigure that load. For this, the RBES interacts with the Local database to obtain the system information consisting of various static, connectivity and real time data. Using this information and based on a set of rules, which are explained in the next section, RBES determines if the load is reconfigurable or not.

If the load is reconfigurable, then the RBES suggested an operation sequence to reconfigurable the load. The operation sequence consists of changing CB status, MBT positions and closing LVP switches. A new configuration was developed based on the suggested changes. Then RBES calls System Analysis module to check for any constraint violation. The System Analysis module performs load flow, on the new configuration. The connectivity scheme of the various electrical components are acquired from the local database and used to form the connectivity information input files for the Load Flow program. Then changes are made to these files to incorporate the changes suggested by the Expert System Restoration module. The Load Flow program determines the current flow in the cables and voltage at each node. The System Analysis module then checks for any current limit violations through cables and voltage limit violations at load nodes. If there are any violations, the load under consideration is said to be un-restorable. If there are no violations then the load is restorable and the new configuration is stored in the local database.

Then the next load is chosen from the priority list and the whole process is repeated, and for this load the initial configuration is taken as the post-fault configuration plus the control actions for the loads, which were previously determined as restorable. This process is performed for all de-energized loads, one by one.

Once all the de-energized loads have been considered then, in the modified restoration method, the System Analysis module will again be called to check whether the generation capacity constraints are satisfied. To check for the power constraints, total load in the system need to be calculated. The de-energized loads that have been restored should also be considered while calculating the total load of the system. Then if the total load in the system is greater than the total available generation then the generation capacity constraint is said to be violated. In case of such a violation, the System Analysis module calls the Load Shedding module, which determines the steps required for load shedding.

Finally, control actions for a new configuration consist of control actions determined during the load reconfiguration process and the steps determined by the load shedding module (in case of generation capacity constraint violation). In this configuration, as much de-energized loads as possible are restored.

2.3.1.7 Control Commands to CBs, BTs and LVPs

Once all the de-energized loads have been considered, then the output of the XRest is the control commands to CBs, MBTs and LVPs that are required to restore the load and to shed loads in case of generation capacity constraint violation. The control commands to CBs, MBTs and LVPs, as shown in the block diagram in Fig 2.10, consist of:

A. Changing circuit breaker status, i.e, to open or close a circuit breaker.

B. Changing MBT position, i.e., to switch MBT to alternate or normal path.

D. Closing LVP switch.

2.3.1.8 Load Shedding Module

The Load Shedding module should first shed non-vital loads. Once all non-vital loads have been considered, then the vital load should be considered for shedding. Vital loads should be shed in the order of increasing priority.

In order to determine the order of shedding, all the loads in the system should be arranged in the increasing order of their priorities. As stated earlier, SPSs consist of vital and non-vital loads. So vital load, which have higher priority should be arranged lower in the order of shedding. Also for the purpose of load shedding loads are assigned a category number. For a given priority, load with a higher category number is considered more important. Among the loads with same priority and category number the load that is receiving supply from the switchboard is given a higher priority than the load receiving supply from a load center. Also, load receiving supply from a load center is given a higher priority than the load receiving supply from a power distribution panel. If there are more than one load having same priority, category number and source of receiving supply, then loads having larger power rating should be higher in the order of shedding. The reasoning behind this approach is that, as less as possible number of loads should be shed for a given amount of load shedding requirement.

Once the order of shedding of loads is determined, then loads should be shed in that order until the generation capacity constraint is removed. Control actions for load-shedding should also be an output of restoration methodology.

A case is presented to illustrate the methodology of Reconfiguration for Load Restoration. A simplified electrical network for a SPS is shown in Fig. 2.12. Consider a scenario in which a weapon hits the ship. The weapon hit caused damage leading to fault(s) in the SPS. A Failure Assessment program, developed at PSAL, detects and locates the faults. Output of the Failure Assessment module is the list of faulted equipments and the list of loads that need to be restored. In this case it has been assumed that no load was de-energized due to control actions of pre-hit reconfiguration. This assumption will not affect the process of restoration. The problem then is to perform reconfiguration for load restoration. For this example, the output of the Failure Assessment module is shown in Table 2.8.

Table 2.8

Output of Failure Assessment Module

Components in Faulted Sections	Component type	De-energized loads
Xfmr11	Transformer	Elex1AB, Elex1BC, Elex1CA, Torpedo, LCP9AB, LCP9BC, LCP9CA, Elex2 and Sonar
C1109	Cable	
C1113	Cable	
C2117	Cable	
CB65	Circuit Breaker	

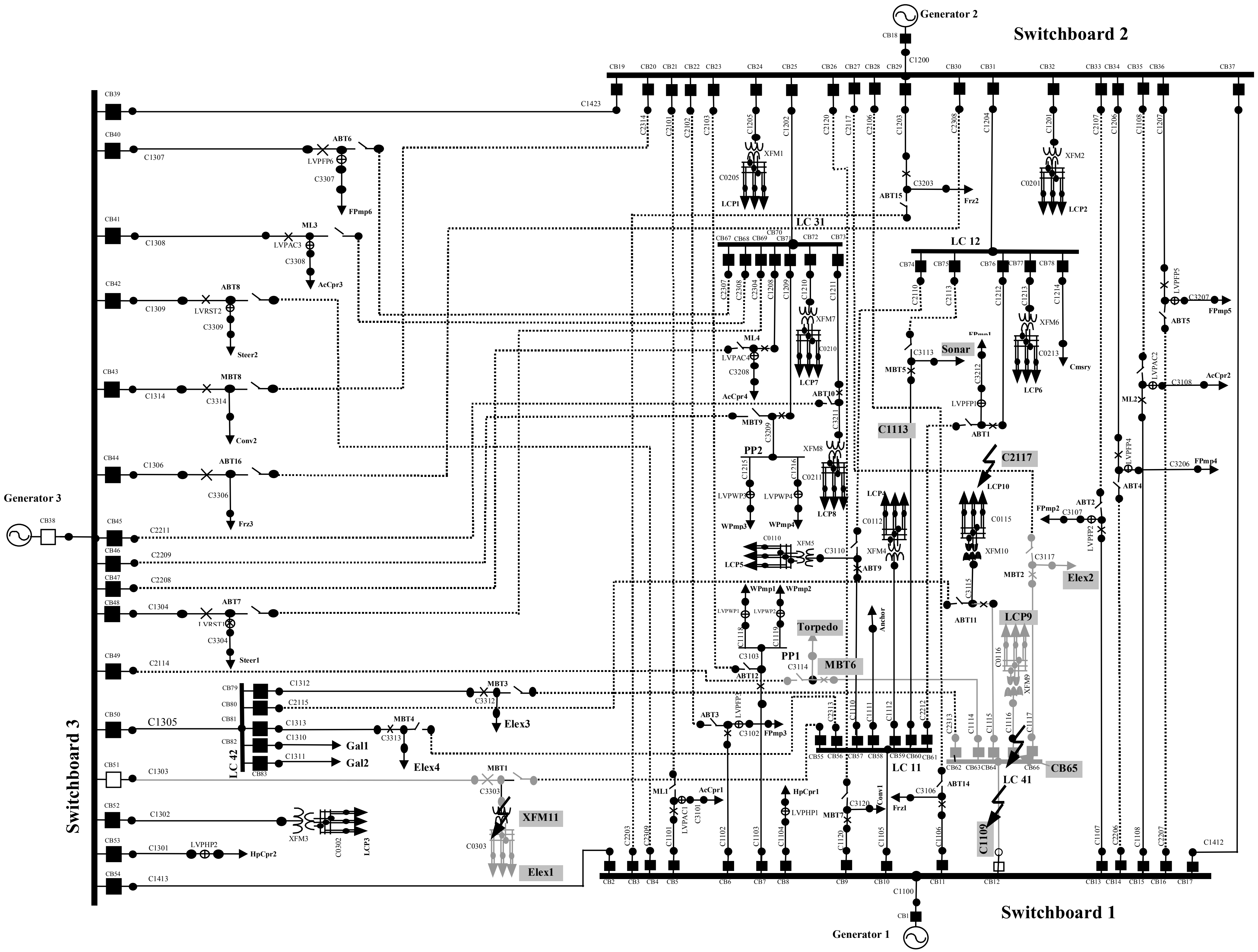

Fig. 2.12: A Simplified Electrical Network for a SPS

Based on the priority method discussed earlier, the loads are arranged in the priority order listed below:

Sonar, Torpedo, Elex2, Elex1AB, Elex1BC, Elex1CA, LCP9AB, LCP9BC, LCP9CA.

After the determination of priority order, the method determines if each load can be restored

Sonar

For load – Sonar, alternate path via MBT5 was available (Fig. 2.12). But when it was transferred to alternate side a current constraint was violated in the cable C1204. Hence the load Sonar was unrestorable, even though it had an alternate supply.

Torpedo

Alternate path via MBT6 was available for Torpedo (Fig. 2.12). Hence the control action suggested for Torpedo – Transfer MBT6

Elex2

Alternate supply via MBT2 was not available for Elex2 (Fig 2.12) as the alternate cable C2117 was damaged. Hence load Elex2 was unrestorable.

Elex1AB, Elex1BC & Elex1CA

Although these single-phase loads had alternate supply via BT - MBT1 (Fig 2.12), there was a fault downstream of the BT so these load were unrestorable.

LCP9AB, LCP9BC & LCP9CA

These single-phase loads could not be restored because these loads do not have the alternate path.

Finally, when reconfiguration actions for all the de-energized loads had been determined, then power constraints were checked. For the weapon hit scenario presented here there were no power constraint violations. The results for the Post-hit Reconfiguration for Load Restoration procedure are summarized in Table 2.9.

Table 2.9

Results of Post-hit Reconfiguration for Load Restoration

De-energized Load	**Restorable or Unrestorable**	**Control Actions for Restorable loads**	**Reason for being Unrestored**
Sonar	Unrestorable	-	Current constraint violation
Torpedo	Restorable	Transfer MBT6	-
Elex2	Unrestorable	-	No path found
Elex1AB	Unrestorable	-	No path found
Elex1BC	Unrestorable	-	No path found
Elex1CA	Unrestorable	-	No path found
LCP9AB	Unrestorable	-	No path found
LCP9BC	Unrestorable	-	No path found
LCP9CA	Unrestorable	-	No path found

2.4 BLACK BOX MODEL OF PREDICTIVE RECONFIGURATION METHODOLOGY

In this section a black box model of the Predictive Reconfiguration Methodology for a SPS has been presented as shown in Fig. 2.13. This model shows the inputs to the Predictive Reconfiguration and its outputs. As shown in the figure the Predictive Reconfiguration methodology takes several information as input. One input to the Predictive Reconfiguration method is the information regarding the detected weapon. This information consists of the predicted pdf (probability density function) of the weapon hit location and the Weapon Damage Function. Apart from these inputs the model also requires information that is intrinsic to ship. This information consists of static, connectivity, real-time, and geographic data related to electrical components of the SPS. The static information consists of electrical parameters and constraint information of various electrical components in the SPS. The connectivity information consists of the “to” and “from” node information of various electrical components of the ship. The real-time information consists of working status, statuses of various switches, current and voltage information of various electrical components of the SPS. Finally the geographical information consists of the geographic location and dimensions of various electrical components of the SPS.

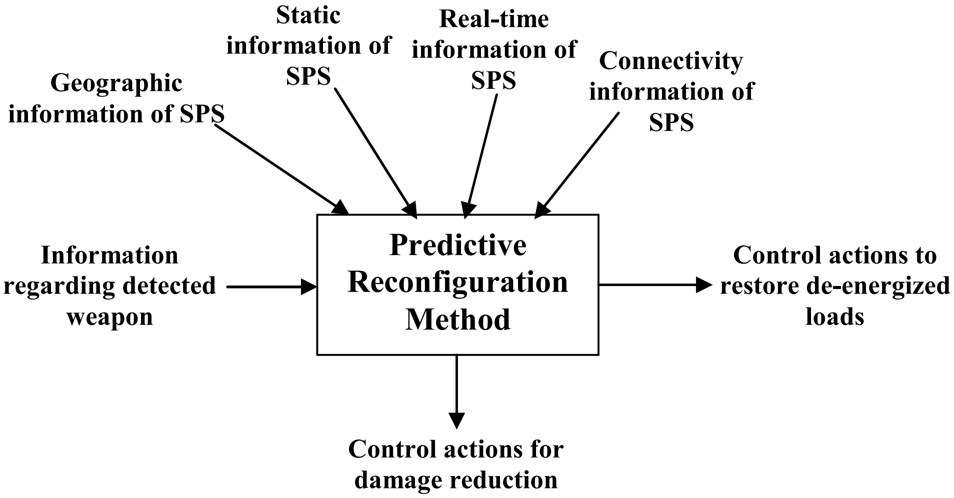

Fig. 2.13: Black Box Model of Predictive Reconfiguration Methodology

Using these inputs the model first determines and outputs the control actions, before the weapon hit, to reduce the damage that can be caused by the weapon hit. After the weapon hit the model also determines the control actions required to restore the loads, which are de-energized due to the faults caused by the weapon hit.

2.5 SUMMARY

In this chapter, first, the problem of Predictive Reconfiguration was formulated. Various factors, which affect the assessment of damage that will be caused by the hit of an incoming weapon, were also addressed. Assumptions were made, based on the information found in the literature, to develop a probabilistic method to assess the damage that will be caused by the weapon hit. Using these assumptions a method to compute the expected probability of damage for an electrical component was presented.

Then two modules, Reconfiguration for Component Isolation and Reconfiguration for Reduction in Supply Interruption, which performed pre-hit reconfiguration, were discussed. The first module determined control actions to isolate components having high expected probability of damage. This module only considered the components in the radial paths supplying power to the non vital loads. The second module determines control actions to reduce supply interruption to vital loads.

The Pre-hit Probabilistic Reconfiguration method, using these modules, was presented. The Pre-hit Probabilistic Reconfiguration determined control actions to reconfigure a SPS such that the damage that will be caused by a weapon hit is reduced. Probabilistic measures were also outputted along with each control action to assist the operator in deciding which control actions to implement. A modified Post-hit Restoration method was also presented which determines control actions to perform reconfiguration for restoration of SPS, after a weapon hit. Finally, a black box model of Predictive Reconfiguration methodology was presented to illustrate the inputs and outputs of the method.

CHAPTER III

IMPLEMENTATION

3.1 INTRODUCTION

A software agent is a software entity which functions continuously and autonomously in a particular environment, often inhabited by other agents and processes [18]. In a Multi-Agent system (MAS), agents act individually and/or in cooperation with other agents to fulfill goals set by the initiations of them and thereby maximize some expected utilities [19]. In this work a MAS, for pre-hit reconfiguration, has been developed. This MAS will perform reconfiguration for damage reduction, before a weapon hit, and reconfiguration for load restoration, after the weapon hit. It consists of agents that perform various tasks locally, and cooperate with each other to achieve a bigger goal. The two major agents, which use expert systems, were developed to determine the control actions required to perform reconfiguration for damage reduction and reconfiguration for load restoration.

3.2 MULTI-AGENT SYSTEM (MAS)

Wooldridge and Jennings (1995) have defined an agent, as “a computer system that is situated in some environment, and that is capable of autonomous action in this environment in order to meet its design objectives.” An abstract view of an agent is shown in Fig. 3.1. This figure shows the action output generated by the agent in order to affect its environment. An agent will not have complete control over its environment, in most domain of reasonable complexity. At best it will have partial control, in that it can influence its environment. This means that from an agent’s point of view the same actions performed twice in apparently identical circumstances might appear to have entirely different effects [20].

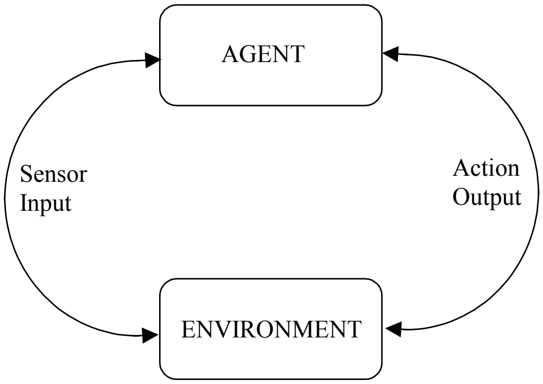

Fig. 3.1: An Agent in Its Environment

An intelligent agent is expected to have the following capabilities, as suggested by Wooldridge and Jennings [21].

Reactivity

Intelligent agents are not only able to perceive their environment but are also able to respond in a timely fashion to changes that occur in it in order to satisfy their design objectives.

Proactiveness

Intelligent agents are able to exhibit goal-directed behavior by taking the initiative in order to satisfy their design objectives.

Social ability

Intelligent agents are capable of interacting with other agents (and possibly human) in order to satisfy their design objectives.

MAS are typically distributed systems in which several distinct components, each of which is an independent problem solving agent, come together to form some coherent whole [22]. In [22], d'Inverno and Luck have written – "a MAS is any system that contains

1. Two or more agents
2. At least one autonomous agent; and

3. At least one relationship between two agents where one satisfies the goal of the other."

Fig. 3.2 illustrates the typical structure of a MAS [23]. The system consists of a number of agents that interact with one another through communication. The agents have ability to act in an environment and have different "spheres of influence". This means that they will have control over or will have ability to influence different parts of the environment. In some cases these "spheres of influence" may overlap or coincide. This gives rise to dependency relationships between the agents. Agents will also be linked with each other by other relationships [20].

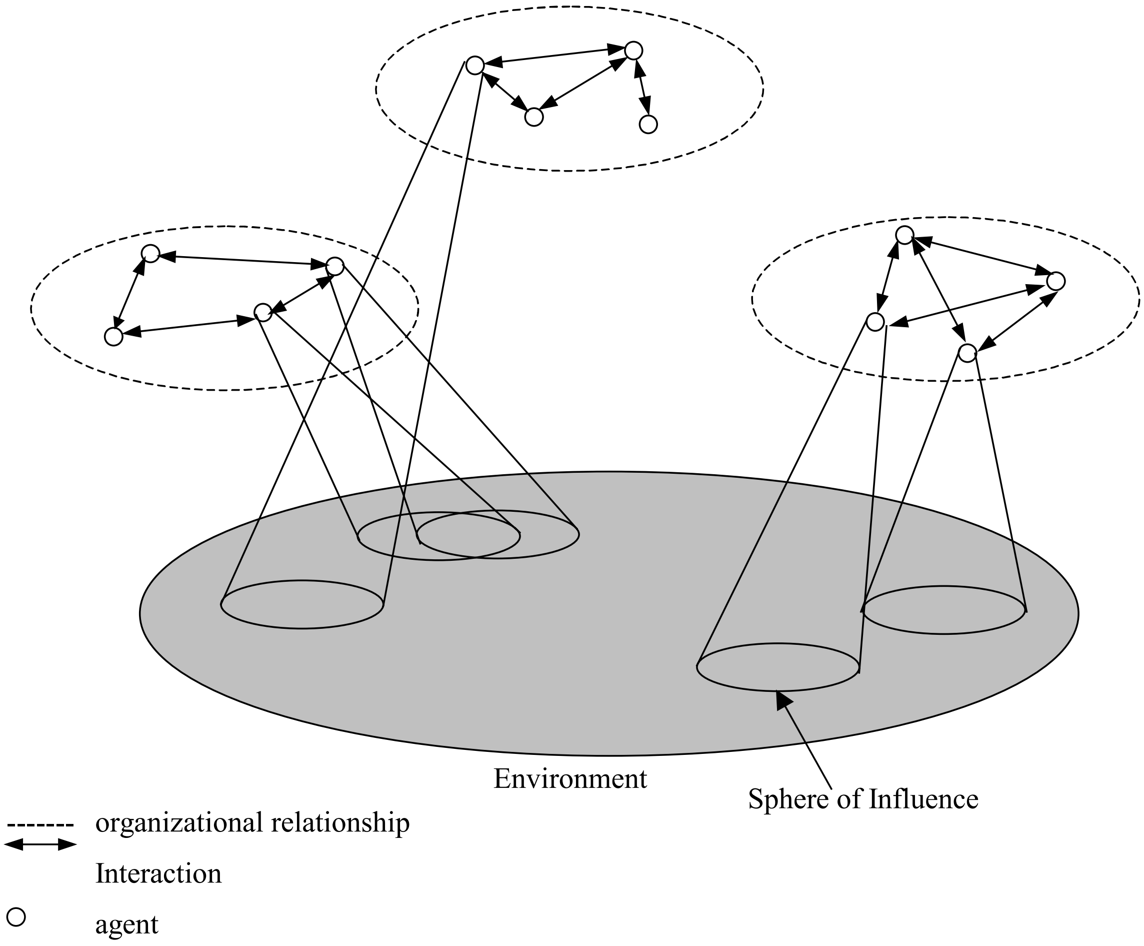

Fig. 3.2: Typical Structure of MAS [23]

Recently, some discussions on multi-agent technology application to utility power systems have been presented [24,25,26,27,28,29]. The problem of Predictive Reconfiguration consists of various complex sub-problems, such as weapon damage assessment, Pre-hit Probabilistic Reconfiguration, failure assessment after weapon hit, determination of de-energized loads, determination of restoration actions, system analysis, and load shedding. An MAS allows simultaneous complex tasks to be performed in real time [30]. The basic approach behind MAS is to decompose a complex problem into a number of (less complex) sub-problems. Each sub-problem falls under the responsibility of an agent. Since sub-problems are interrelated, a co-ordination mechanism is applied to ensure that local decisions lead to a globally desirable result [31]. This approach results in a modular and flexible software solution, which is well suited for the problem of Predictive Reconfiguration.

3.3 EXPERT SYSTEM

An expert system is a computer program that emulates the search behavior of human experts in solving a problem [32]. The most commonly used programming methodology is rule or knowledge based, in which rules are used to implement an expert's years of experience which creates the ability to distinguish one problem from another and to reach corresponding solutions. In general, the expert system approach is beneficial for problems that involve non-trivial logic reasoning and human knowledge. For such problems, the expert system technique provides a natural way to represent the knowledge and implement the inference procedure. The problem of reconfiguration in shipboard power systems is a problem in which finding a solution involves the analysis of a large number of alternatives or possible combinations or to be exact, possible switching combinations. It is important to reduce the number of alternatives to a manageable number. An expert system is a good tool to efficiently search through the possible combinations and then determine a feasible solution. Hence agents, based on expert systems, were developed to solve the problem of Predictive Reconfiguration.

3.4 MAS FOR PREDICTIVE RECONFIGURATION

Fig. 3.3 shows the block diagram of the MAS developed to perform Predictive Reconfiguration for shipboard power systems. In the MAS shown in Fig. 3.3, the Failure Assessment agent and the Post-hit Restoration agent to perform reconfiguration for restoration of a SPS have been developed, earlier, by researchers in the PSAL group at Texas A&M University.

The Query agent, shown in Fig. 3.3, interacts with other agents and extracts data, required by an agent, from the various databases. Coordination is central to a MAS for without it, any benefits of interaction vanish and the group of agents quickly degenerate into a collection of individuals with a chaotic behavior. The Pre-hit Coordination agent, shown in Fig. 3.3, is a coordinating agent that coordinates the activities of other agents. When an incoming weapon has been detected, the Pre-hit Coordination agent calls the Weapon Damage Assessment agent. This agent obtains information regarding characteristics of the incoming weapon, predicted location of weapon hit, the information regarding location of electrical components on the ship, dimensions of electrical components, and status and connectivity information of various electrical components, through the Query agent. This information is then used to determine the expected probability of getting damaged for each component, once the weapon hits the ship. After this, the Pre-hit Coordination agent then calls the Pre-hit Reconfiguration agent.

Pre-hit Reconfiguration agent takes as input the expected probability of damage for each electrical component, provided by the Pre-hit Reconfiguration agent, and then it determines the reconfiguration actions to reduce the possible damage. After determination of the reconfiguration actions, Pre-hit Reconfiguration agent calls System Analysis agent to check for any current or voltage constraint violations that may be caused due to the implementation of reconfiguration actions suggested by the Pre-hit Reconfiguration agent. In case, if the System Analysis agent finds a constraint violation for a reconfiguration action, then that reconfiguration action is discarded. Then the Pre-hit Reconfiguration agent stores the un-discarded reconfiguration actions in the

Reconfiguration database through Query database. Finally, after interacting with the Pre-hit Reconfiguration module, the Pre-hit Reconfiguration agent will give as output the reconfiguration actions for new configuration for damage reduction, and the list of loads that will go out of service in the new configuration.

Once the Pre-hit Coordination agent has determined the control actions for the new configuration, it passes controls to the Post-hit Coordination agent. This agent is also a coordinating agent. It then calls the Failure Assessment agent. The Failure Assessment agent then calls the Query agent, to obtain system information, consisting of current, voltage, generator frequency, CB status and BT status measurements. The Failure Assessment agent then performs a continuous check to identify an abnormal condition in the SPS. When an abnormal condition is detected, the Failure Assessment agent tries to assess the abnormal condition. If the Failure Assessment agent identifies the abnormal condition as fault(s), then it tries to detect and locate the fault(s). Once the fault(s) have been detected and located, the information regarding the de-energized load(s) and the component(s) in the faulted sections are given as output.

The Post-hit Coordination agent takes the output of the Failure Assessment agent and calls the Post-hit Restoration agent to determine reconfiguration steps for restoring the de-energized loads. This module takes as input the components in the faulted sections and de-energized loads, provided to it by the Pre-hit Reconfiguration agent, and then determines the control actions to restore as much load as possible. While determining the control actions, the Post-hit Restoration agent interacts with System Analysis agent to check for any current or voltage constraint violations that may be caused due to the implementation of control actions for a de-energized load. In case, if the System Analysis agent finds a constraint violation for control actions for a de-energized load, then those control actions are discarded and the load is determined as unrestorable. Once the control actions for all the de-energized loads have been determined, the Post-hit Restoration agent again calls the System Analysis agent to check for any generation capacity constraint violation. In case of a constraint violation, Load Shedding agent is called to perform load-shedding. The control actions for load shedding are stored in the

Restoration database through Query agent. Once the interaction of the Post-hit Coordination agent with the Post-hit Restoration module is complete, Post-hit Coordination agent then gives the list of restorable loads and control actions required to restore each load, as output. If load-shedding was performed then the loads which are to be shed and control actions to shed those loads are also given as output by the Post-hit Coordination agent.

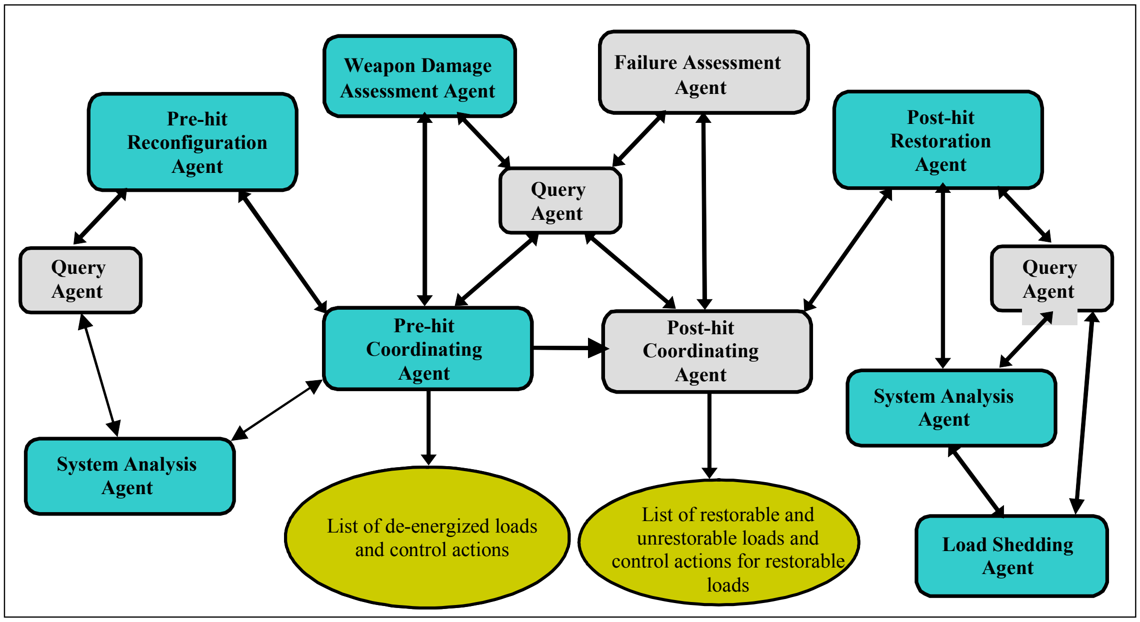

Fig. 3.3: Block Diagram of Multi-Agent System for Predictive Reconfiguration of Shipboard Power System

3.4.1 Query Agent

The function of the Query agent, shown in Fig. 3.3, is to extract appropriate information from various databases, as required by any contacting agent, and provide that information back to the contacting agent. The Query agent consists of a set of queries that extract information from the databases, as shown in Fig. 3.4. For e.g., if an Interacting Agent requires data {a,b,c,d}, it contacts the Query agent and conveys its requirements. The Query agent then contacts appropriate databases through appropriate queries, extracts the data, and returns the extracted data to Interacting agent. The Query agent extracts the required data from GIS, Historical, Constraint, Reconfiguration and Restoration databases. GIS, Historical and Constraint databases are global databases. Reconfiguration and Restoration databases are local databases created during the execution of Pre-hit Coordination and Post-hit Coordination agents respectively. The Query agent was implemented using Microsoft Visual C++. All the databases were developed using Microsoft Access.

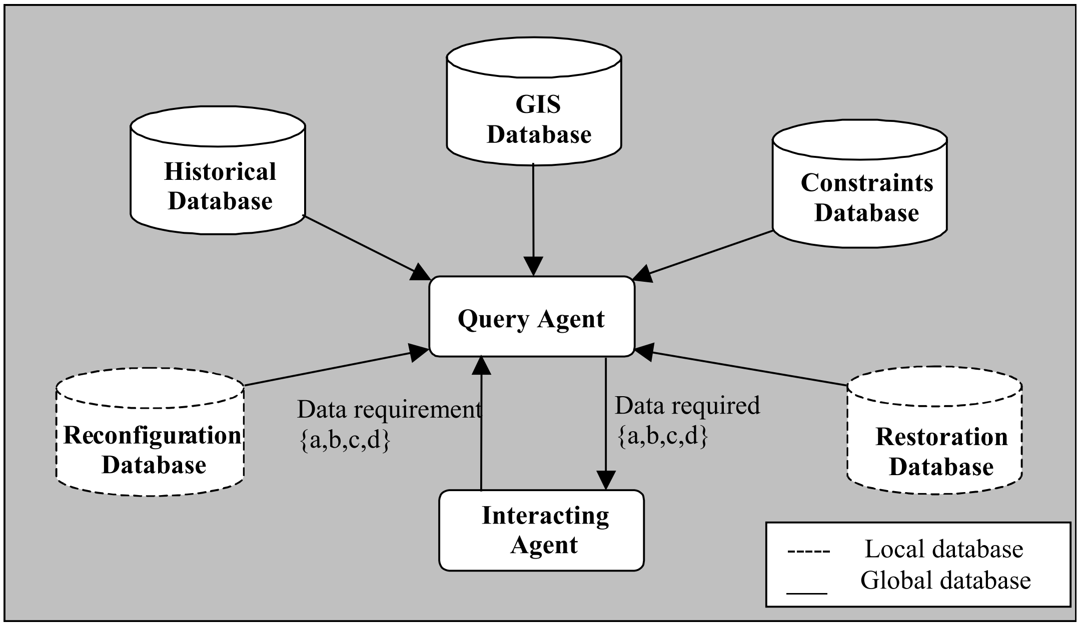

Fig. 3.4: Interaction of Query Agent with Other Databases

A Geographic Information System (GIS) is a computerized system designed to capture, store, process, analyze and manipulate characteristic and spatial data [16]. A GIS consists of two parts: digital map and database. A GIS integrates digital diagrams such as computer-aided design and drafting (CADD) diagrams with information systems such as relational database management systems (RDBMS). A CADD tool, MicroStation was used to develop a model of a Shipboard Power System based on the geographical 3-dimensional layout profile of a typical surface combatant ship.

The three-dimensional CADD map of the SPS was drawn based on the spatial position of the electrical elements of the ship. The elements in the CADD map were linked to a GIS database, which was developed using MS Access [33]. The GIS database, shown in Fig. 3.4, consists of tables that store data for the various electrical elements of SPS. Each type of element has a connectivity, a real time data, and a static table. The connectivity table contains information about the “from” and “to” nodes for each component, which is the connectivity scheme of the elements in the system. The real time tables store the real time electrical measurements at various locations in the system and the status of protective devices, for given time instant(s). The static parameter tables store static information such as rating, and resistance, inductance and capacitance of various components of SPS.

The historical database, shown in Fig. 3.4, stores real time information for a previous time period. For example, when used by the Fault Assessment agent it contains real time information, starting from a pre-fault time to some time after the fault had occurred and the system had attained steady state. The Historical database consists of circuit breakers status, voltage at switchboards and load centers nodes, and current flowing through each circuit breaker. The Failure Assessment agent uses this database.

In addition to the GIS database and Historical database there, is another global database, Constraint database. This database has information regarding the upper current ampacity for each cable and the upper and lower voltage limit for each load node. The Constraint database also has information regarding the generation capacity limits. This database is used when constraint checking is performed on the electrical network.

As explained earlier, Reconfiguration and Restoration databases are local databases, as they are used by pre-hit reconfiguration and post-hit reconfiguration for restoration programs, respectively. The main objective of these databases is to provide ease in implementation of the methodologies and to provide a buffer between permanent databases and the program implementing Predictive Reconfiguration methodology. This buffer was important as it protected GIS database from being corrupted. Details of these databases will be given in the sections discussing Pre-hit Coordination and Post-hit Coordination agents.

3.4.2 Pre-hit Coordination Agent

The Pre-hit Coordination agent is a coordinating agent and its function is to coordinate the activities of other agents and output a new configuration scheme that will reduce the damage that might be caused by the hit of an incoming weapon. The Pre-hit Coordination agent is called when an incoming weapon is detected. Then this agent calls various other agents in order to achieve its objective of suggesting a new configuration scheme. This agent is also responsible for giving as output the list of loads going out of service and the reconfiguration control actions for the new configuration. The Pre-hit reconfiguration agent has to provide this information before the actual hit. Then the suggested reconfiguration control actions along with the probabilistic values are outputted. The operator then selects some or all the control actions, from the outputted reconfiguration control actions, for implementation. When the Pre-hit Coordination agent has achieved its objective it passes the control to the Post-hit Coordination Agent. The Pre-hit Coordination agent was implemented using Microsoft Visual C++.

The block diagram of the Pre-hit Coordination agent is shown in Fig. 3.5. The Pre-hit Coordination agent consists of two modules – Database Creation Module and Agent Coordination Module. First, the Database Creation module creates a local database – Reconfiguration database. This database is created by the Query agent, using the GIS database. This database consists of connectivity and static information for all components. This database also consists of tables to store the intermediary results during the execution of the Pre-hit Probabilistic Reconfiguration. The Reconfiguration database is destroyed when the Pre-hit Coordination agent achieves its objective. After the formation of the Reconfiguration database, the Agent Coordination module is called. This module coordinates the activities of the other agents. It also decides which agent to call, at different stages of execution of the Pre-hit Probabilistic Reconfiguration.

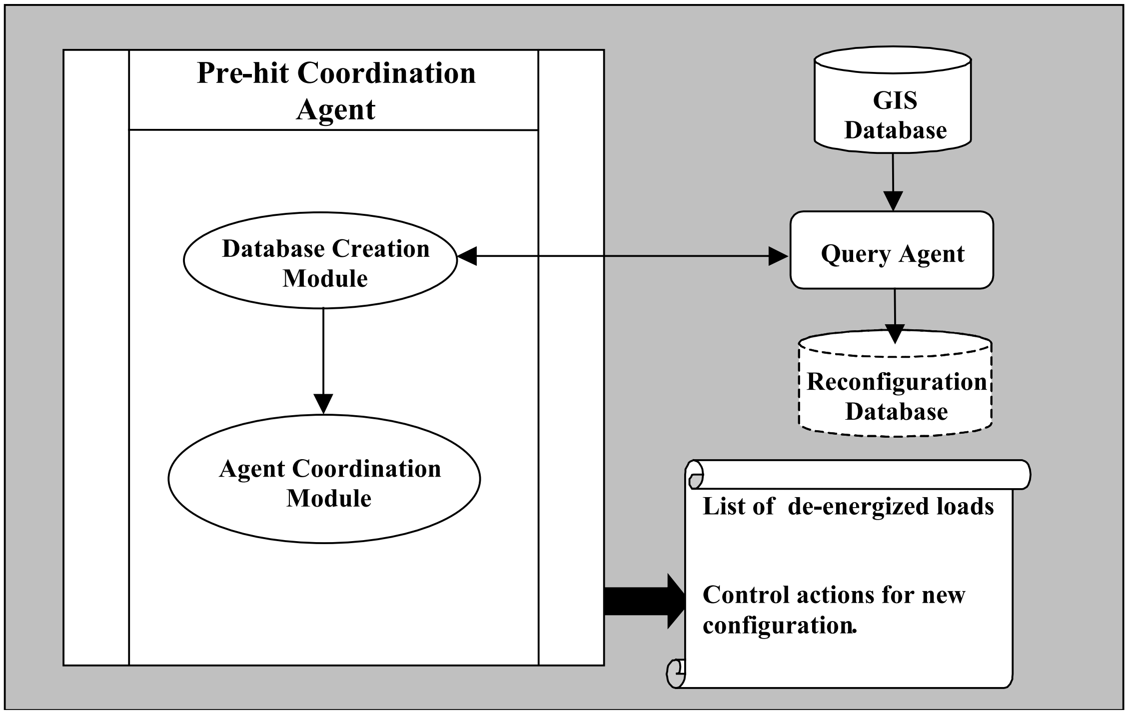

Fig. 3.5: Pre-hit Coordination Agent

3.4.3 Weapon Damage Assessment Agent

The function of the Weapon Damage Assessment agent, refer to section 2.2.1, is to assess the damage that might be caused to the electrical network of the SPS by an incoming weapon, and to output the expected probability of damage (EPOD) of each electrical component. The Weapon Damage Assessment agent is called by the Pre-hit Coordination agent, when an incoming weapon is detected. This agent then assesses the possible damage that might be caused when the weapon actually hits the ship and calculates the probability of damage for each electrical component of the SPS. Once the Weapon Damage Assessment agent has performed its function it notifies the Pre-hit Coordination agent. The Weapon Damage Assessment agent was implemented using Microsoft Visual C++.

The block diagram of the Weapon Damage Assessment Agent is shown in Fig. 3.6. It consists of two modules, EPOD of Point Calculation Module and EPOD of Component

Calculation Module. EPOD of Point Calculation Module takes as input, the predicted probability density function of weapon hit location, the function representing the weapon damage effectiveness, and the coordinates of locations of all electrical components. This module first transfers the ship's coordinate axes to the location represented by the means of the predicted probability density function and recalculates the location of all electrical components with respect to the transferred axes. It then calculates the EPOD for a point situated at some distance from the predicted hit location.

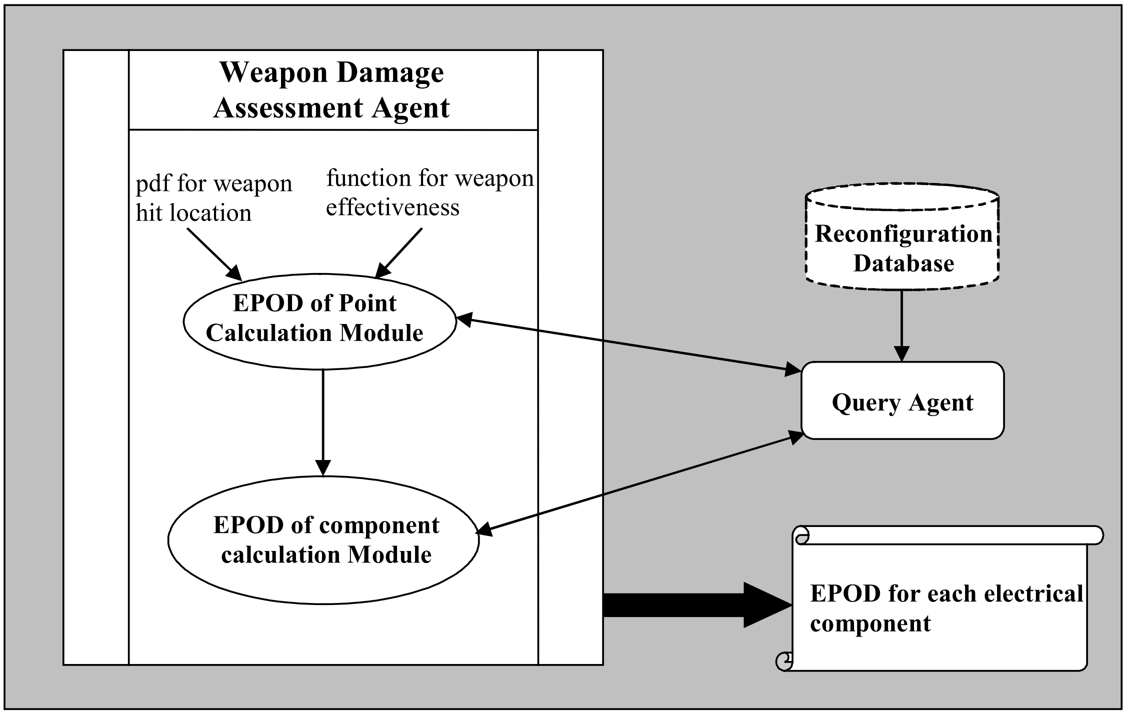

Fig. 3.6: Weapon Damage Assessment Agent

The EPOD of Component Calculation Module then uses the information provided by the EPOD of Point Calculation Module to compute the EPOD for each electrical component. In order to compute EPOD for each component, it uses the information about dimensions of all electrical components on ship, and information about location of electrical components, as input. The implementation of the method was based on the assumption that all electrical components had the shape of a cuboid. A cuboid is a rectangular solid. The EPOD value computed for each component is updated in the Reconfiguration database during execution of the agent.

3.4.4 Pre-hit Reconfiguration Agent

The function of the Pre-hit Reconfiguration agent is to suggest a new configuration in which the actual damage that will be caused, by the hit of an incoming weapon, is reduced. The Pre-hit Reconfiguration agent is called by the Pre-hit Coordination agent, after the Weapon Damage Assessment agent has performed its function. Then this agent tries to determine the reconfiguration actions for a new configuration in which the actual damage that will be caused, by the hit of an incoming weapon, is reduced. Once the Pre-hit Reconfiguration agent has performed its function it notifies the Pre-hit Coordination agent. The Weapon Damage Assessment agent was implemented using Microsoft Visual C++ and Multilogic Exsys Developer.

The block diagram of Pre-hit Reconfiguration agent is shown in Fig 3.7. It consists of two modules – Reconfiguration for Component Isolation module and Reconfiguration for Reduction of Supply Interruption module. First the Reconfiguration for Component Isolation module is called. This module takes as input the EPOD of electrical components, as input, from the Reconfiguration database through the Query agent. Then this module determines the components, which have an EPOD value higher than a user defined threshold value. Then reconfiguration for isolating these components is performed to reduce possible electrical faults and cascading faults. The reconfiguration actions for isolating these components are implemented on the pre-hit configuration to obtain a new configuration and this configuration is stored in the Reconfiguration database. Then the Reconfiguration for Reduction of Supply Interruption module is called. This module takes as input the new configuration stored in the Reconfiguration database. Then reconfiguration for reduction in supply interruption for vital loads is performed. This is done to ensure that vital loads will have a greater chance of continuance of supply after the weapon hit. Then the control actions for the new configuration are determined and stored in the Reconfiguration database. This information is passed to the Pre-hit Coordination agent by the Pre-hit Reconfiguration agent. Details of each of the modules of the Pre-hit Reconfiguration agent are discussed in the following subsections.

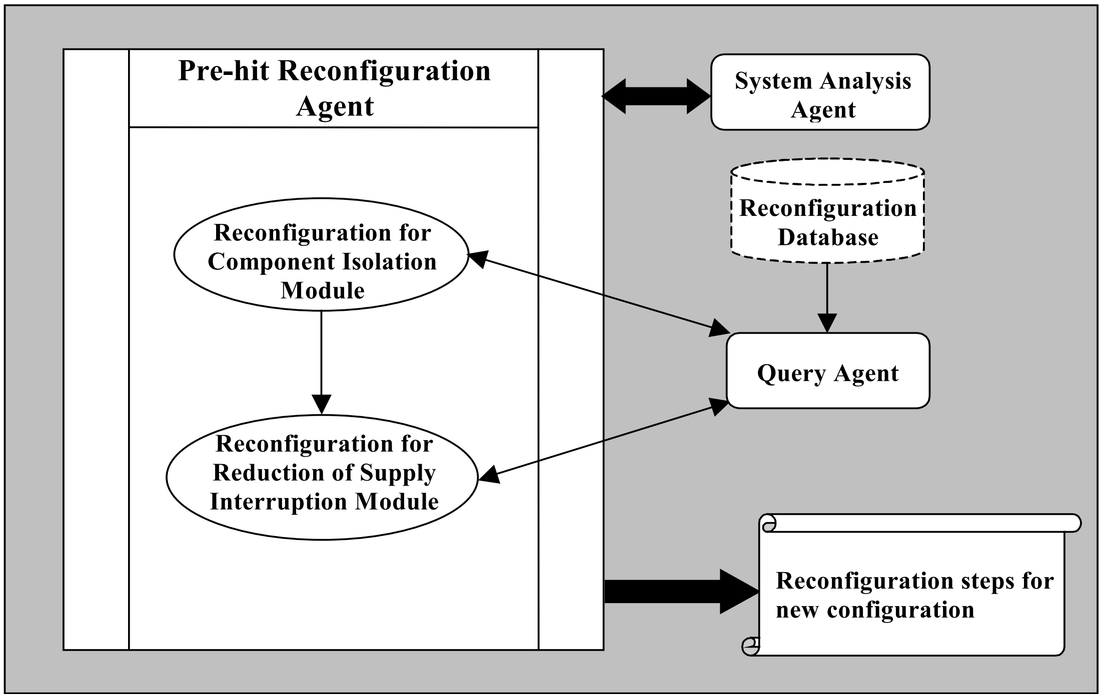

Fig. 3.7: Pre-hit Reconfiguration Agent

3.4.4.1 Reconfiguration for Component Isolation Module

The function of the Reconfiguration for Component Isolation Module, refer section 2.2.2.2, is to determine the control actions to isolate components that have a very high probability of getting damaged. First, a list of components that have EPOD values greater than a user-defined threshold value and lie in radial paths of non-vital loads, are determined. These components are referred as non-critical components. Then the control actions to isolate these non-critical components are determined. Depending on the extent of the damage due to weapon hit, the number of components in the non-critical components list can be large and the methodology to determine the isolation steps for each of them can be time consuming. Also it is possible that more than one non-critical component can lie on the same radial path. Hence it is possible that isolating one upstream non-critical component can lead to isolation of other downstream non-critical components.

For example, as shown in Fig. 3.8, load L1 is receiving electrical supply through a radial path R1. Suppose, there are three components in R1 that have EPOD values greater than user-defined threshold value. These components are cable CL2, circuit breaker CB3, and cable CL1. The non-critical component that is farthest upstream in R1 is cable CL1. If CL1 is isolated by opening circuit breaker CB1, then this action will result in isolation of CL2 and CB3 as well.

This module takes as input the connectivity information and switch status from Reconfiguration database, through Query agent. Then it identifies non-critical components and determines the control actions for isolating those components. The determined control actions are then stored in Reconfiguration database through Query agent. This module was implemented as an Expert System module using Multilogic Exsys Developer and Microsoft Visual C++.

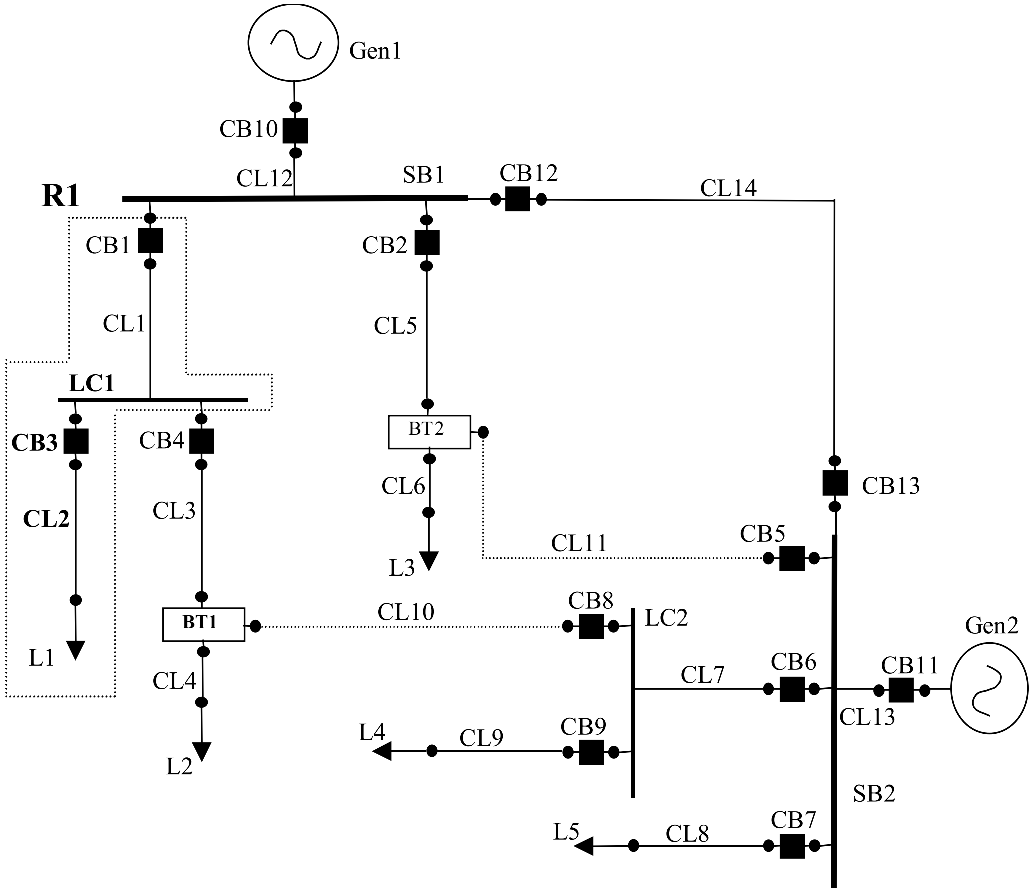

Fig. 3.8: Radial Supply Path, R1, for Load L1

3.4.4.2 Reconfiguration for Reduction of Supply Interruption Module

The function of Reconfiguration for Reduction of Supply Interruption Module, refer section 2.2.2, is to determine control actions to reduce the probability of supply interruption to the vital loads. In this methodology only the vital loads are considered for reconfiguration. For each vital load, all paths that can supply electrical power to it are determined. Then for each possible path, a Path Availability probability is calculated, based on the EPOD values of the electrical components in that path. Path Availability probability gives a measure of chance, for a path, to provide electrical energy to the load. After the calculation of the Path Availability probability, the path having the best Path

Availability probability is selected as path to supply electrical power to that load. If the path with the best Path Availability probability is the path supplying power to that load, before the weapon hit, then no reconfiguration steps are needed; otherwise the reconfiguration steps to energize the load through that path are determined. This procedure is repeated for each vital load. This module was implemented in Microsoft Visual C++.

3.4.5 Post-hit Coordination Agent

The Post-hit Coordination agent is another coordinating agent and its function is to coordinates the activities of other agents in order to perform reconfiguration for the restoration of SPS, after the incoming weapon has hit the ship. This agent is called when the Pre-hit Coordination Agent has achieved its objective. Then this agent starts the process of reconfiguration for the restoration of SPS, after the weapon has hit the ship. This agent then calls various other agents in order to achieve its objective of suggesting a new configuration scheme for load restoration. This agent is also responsible for giving as output the list of restorable and un-restorable loads and control actions for restorable loads. In the event if load shedding is performed by the Load Shedding agent, discussed later in section 3.4.9, then the Post-hit Coordination module also outputs the list of load to be shed and the control actions for load shedding. The suggested control actions for the new configuration are then given as output to the operator and then its up to the operator to implement the suggested control actions. The Post-hit Coordination agent was implemented using Microsoft Visual C++. The block diagram of the Post-hit Coordination agent is shown in Fig. 3.9.

Like the Pre-hit Coordination agent, the Post-hit Coordination agent also consists of two modules – Database Creation Module and Agent Coordination Module. The Database Creation module in this case creates a local database – Restoration database. This database is created by the Query agent using the GIS database and the Constraint database. This database consists of connectivity and static information for all components. It also contains the upper current limit information for all cables, upper and lower voltage information for all load nodes and generation capacity constraint information. This database also consists of tables that store results at the intermediary results during the execution of the Post-hit Reconfiguration for Restoration method. This database is destroyed when the Post-hit Coordination agent achieves its objective. After the formation of Restoration database, Agent Coordination module is called. This module coordinates the activities of the other agents. It also decides which agent to call, at different stages of execution of the Post-hit Restoration.

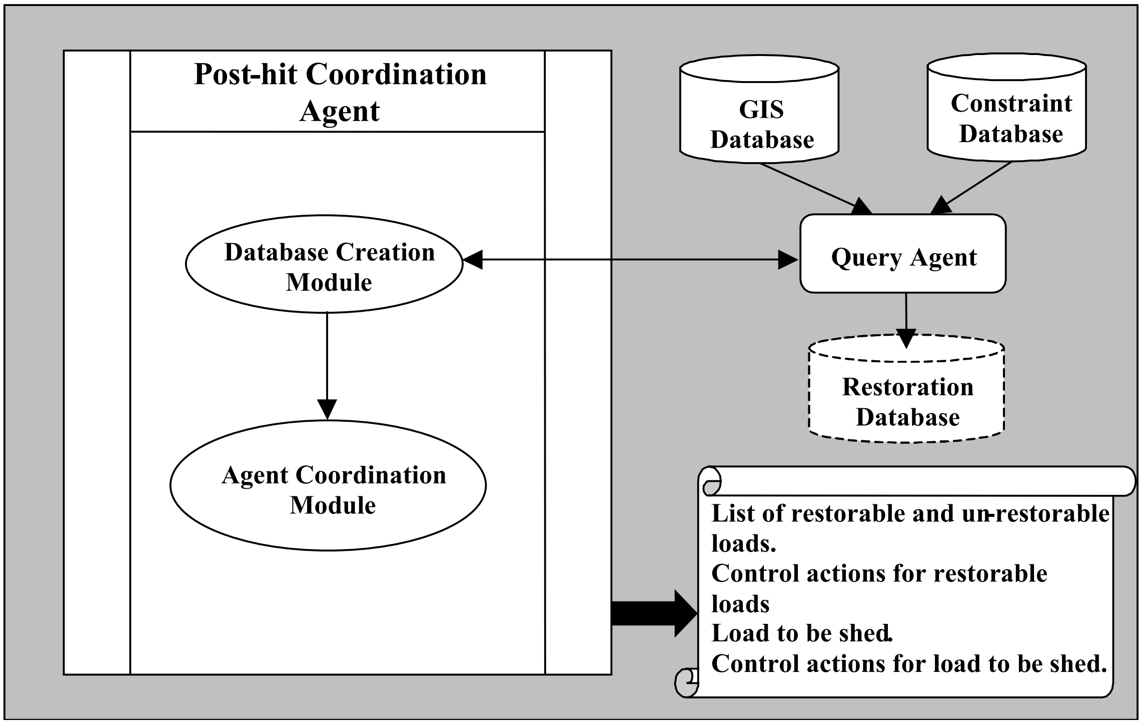

Fig. 3.9: Post-hit Coordination Agent

3.4.6 Failure Assessment Agent

The function of the failure assessment agent is to detect and locate fault(s) in the SPS. It also determines the component in the faulted section and de-energized loads. This agent was developed earlier by researchers in PSAL. The Failure Assessment agent is called by the Post-hit Coordination agent after the weapon has hit the ship. This agent then tries to detect any abnormal condition in the system. If an abnormal condition is detected, then it determines if the abnormal condition represents a fault. If the abnormal condition is detected as a fault, then the Failure Assessment agent determines the faulted sections in the SPS. Finally it determines the components in the faulted sections and de-energized loads and gives as output. This information is then stored in the Restoration database through the Query agent. The Failure Assessment agent was implemented using Multilogic Exsys Developer and Microsoft Visual C++.

The Failure Assessment agent, shown in Fig 3.10, consists of two modules, Fault Detection Module and Fault Location module. The Fault Detection Module utilizes the generator frequency, voltage levels at the switchboards and load centers, and current measurements at the circuit breakers to determine the presence of a fault or an abnormality condition. These values are extracted from GIS database through Query agent. The Fault Detection Module then checks whether present current, voltage, and frequency measurements are within acceptable levels. If not, then an abnormality is detected. If the detected abnormality is identified as the fault, then the Fault Location Module is executed.

The Fault Location Module method utilizes the pre-fault and post-fault CB status, pre-fault, fault, and post-fault current measurements, and pre-fault, fault, and post-fault voltage measurements at switchboards and load centers. These values are used by heuristics based rules to determine the faulted sections and de-energized loads. This module takes historical data from the Historical database, frequency, voltage and current deviation limits from the Constraint database, and real time data from the GIS database to detect abnormalities and identify faulted section(s). These values are obtained through the Query agent. Finally, the output of the Failure Assessment agent is a list of components in the faulted section and de-energized loads.

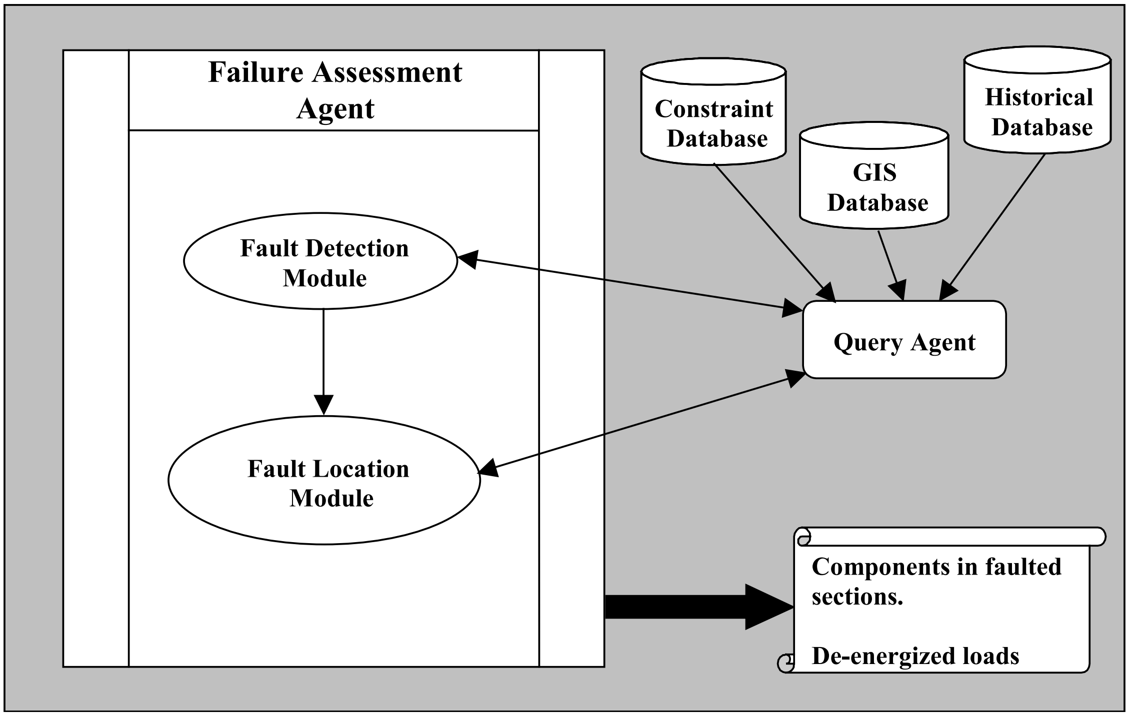

Fig. 3.10: Failure Assessment Agent

3.4.7 Post-hit Reconfiguration for Restoration Agent

The function of the Post-hit Reconfiguration for Restoration agent (refer to section 2.2.3) is to determine reconfiguration control actions for restoring de-energized loads, after a weapon has hit a ship. This agent was developed earlier by researchers in PSAL. This agent is called by the Post-hit Coordination agent, which provides the information regarding components in faulted sections and de-energized loads. The Post-hit Restoration agent was implemented using Microstation Exsys Developer and Microsoft Visual C++.

The Post-hit Reconfiguration for Restoration agent, shown in Fig 3.11, consists of two modules – Expert System Load Reconfiguration module and Data Flow Control module. This Expert System Load Reconfiguring module is an expert system based agent whose goal is to determine the control actions for reconfiguring a load. To determine the reconfiguration control actions, the Load Reconfiguring module will interact with the Query agent to obtain the system information consisting of various static, connectivity and real time data from Restoration database. The de-energized loads are ordered on the basis of their load priority (vital, non-vital), by the Load Reconfiguring module. Then loads having the same priority are further ordered on the basis of their location (switchboard or load center), with loads that are fed directly from a switchboard given a higher priority. Loads at the same location are further ordered on the basis of their rating, with loads of larger rating given a higher priority.

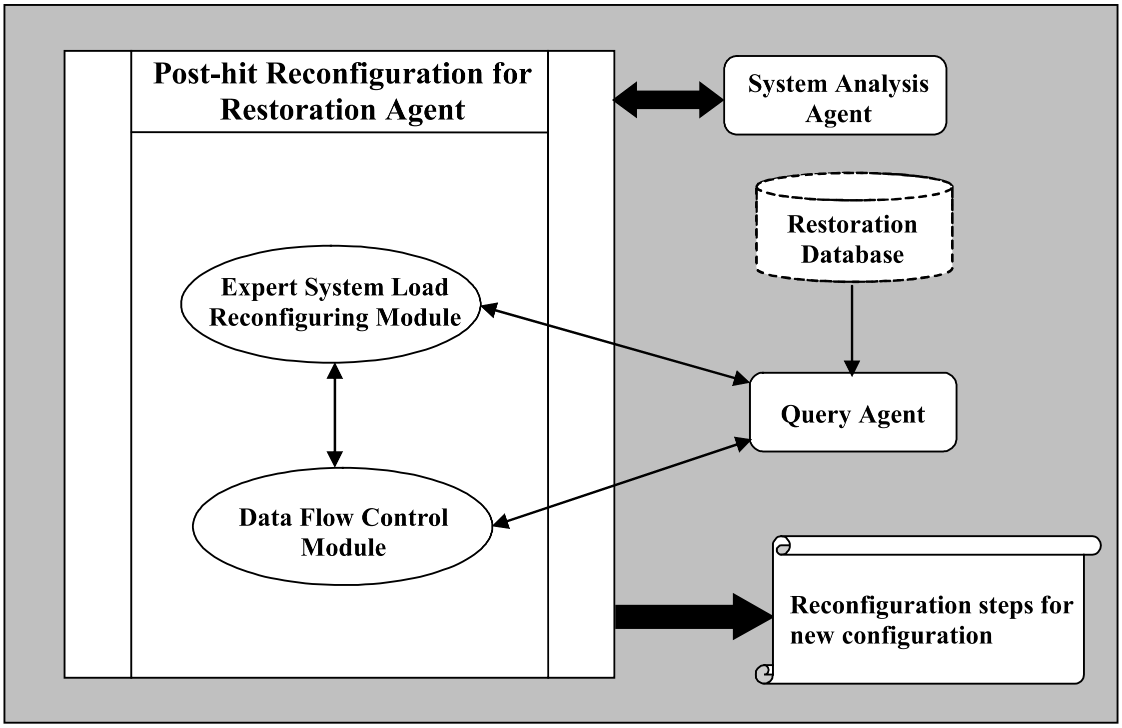

Fig. 3.11: Post-hit Reconfiguration for Restoration Agent

After ordering the loads, the first load from the priority order list is chosen and the Load Reconfiguring module then tries to determine the control actions for a new configuration in which that de-energized load is restorable. Once the control actions for a new configuration have been determined, the Post-hit Reconfiguration for Restoration agent calls the System Analysis agent to check for constraint violations in the new configuration. If there are no violations, then the information to implement the control actions for the new configuration is stored in the Restoration database through the Query agent. Then the next load from the priority order list is chosen. In case of a constraint violation, the load is determined as un-restorable and the next load from the priority order list is chosen. The same steps are repeated for the next load.

Once all the de-energized loads from the priority order list have been considered, then Post-hit Reconfiguration for Restoration agent calls the System Analysis agent to check for a generation capacity constraint violation. The control actions for load shedding and the load(s) to be shed are stored in the Restoration database. After the load shedding has been performed, then the System Analysis agent informs the Post-hit Reconfiguration for Restoration agent, which then passes the information about the restorable and un-restorable loads, control actions for restorable loads, loads to be shed (in case of generation capacity constraint violations) and load shedding steps; to the Post-hit Coordination agent. In case of a violation, the System Analysis agent calls the Load Shedding agent to perform load shedding. Finally, control actions for a new configuration will be obtained in which as much de-energized load as possible are restorable. The information regarding these control actions is then passed back to the Restoration agent. The Data Flow Control module is responsible for interacting with the System Analysis agent at different stages of the restoration process. This module decides whether the System Analysis agent is to be called to perform current and voltage constraint violation checks or to perform generation capacity constraint violation checks.

3.4.8 System Analysis Agent

The function of the System Analysis agent is to check for system constraint violations. This agent was developed earlier by researchers in PSAL. The System Analysis agent is called by the Post-hit Restoration agent. It consists of two modules – ATP Simulation module and Constraint Checking module, as shown in Fig. 3.12. First the ATP Simulation module is called. This module performs ATP simulation on the configuration of SPS, which is obtained from the Restoration database. Once the ATP simulation is performed, then the Constraint Checking module is called to check for a constraint violation. Then the System Analysis agent informs the Post-hit Restoration agent if there were constraint violations.

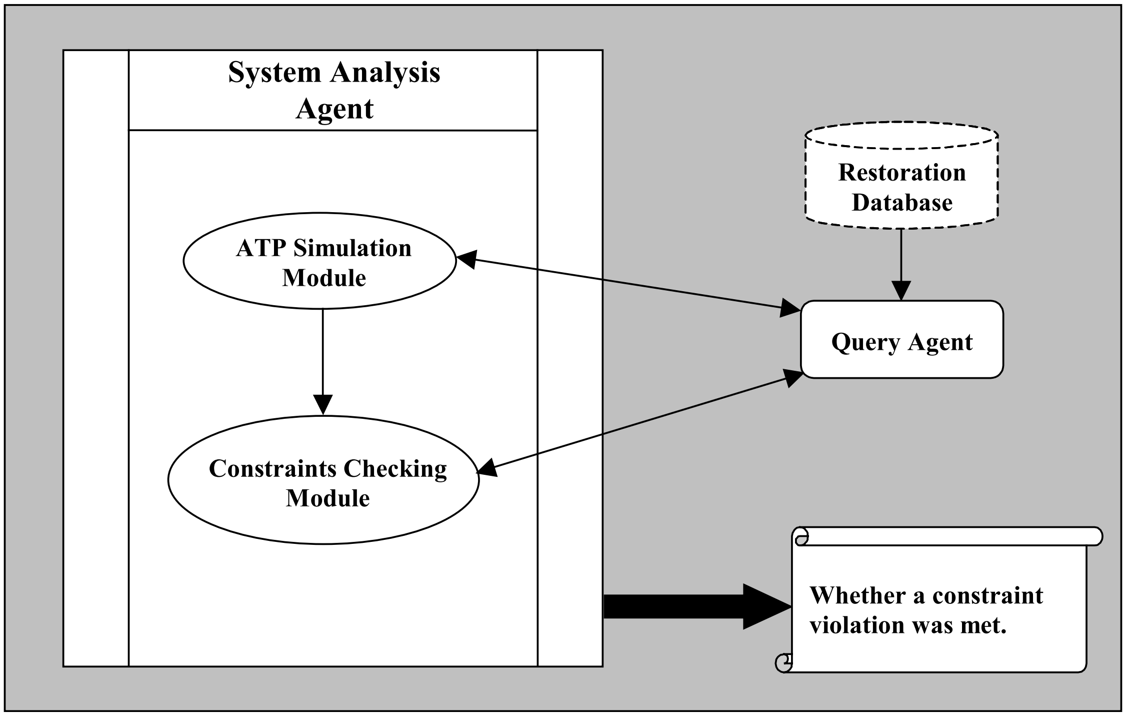

Fig. 3.12: System Analysis Agent

Details of the two modules of the System Analysis agent are presented in the following subsections.

3.4.8.1 ATP Simulation Module

This module uses the Alternate Transient Program (ATP) simulation program to obtain results similar to that of steady state circuit simulation. The results which are output from the ATP simulation, in a binary output file, are current flowing in each cable and voltage at each load node. To obtain these results, the ATP circuit simulation is performed until steady state has been reached. The ATP Simulation Module first obtains the present configuration from the Restoration database. A configuration is represented by the status of various switches in the electrical network. The information about the present configuration, i.e., the switch statuses, are then updated in the ATP simulation input files. Then this ATP Simulation is preformed using these input files. The simulation is performed until steady state has been reached. Then, from the binary output file, currents values in all the cables and voltage values at all the load nodes are extracted. This module was implemented using the Alternate Transients Program and Microsoft Visual C++.

3.4.8.2 Constraint Checking Module

The function of this module is to use the current and voltage information, obtained from the ATP Simulation module, to check for system constraint violations. This module was implemented in Microsoft Visual C++.

For every cable, an ampacity limit is defined. A cable carrying current greater than its ampacity limit can get overheated which can eventually cause damage to the cable and can lead to a fault. For the Constraint Checking Module, an upper current limit is defined for each cable which was equal to 110% of the ampacity limit for that cable. The constraint checks are made for each cable to see if the current flowing through any cable is greater than the upper current limit.

The allowable voltage limits for every load is defined. Voltage outside this range can lead to improper functioning or can cause damage to the load. In the Constraint Checking module, this voltage range is defined in terms of upper voltage limit and lower voltage limit. The upper voltage limit is chosen as 105% of the rated voltage and lower voltage is chosen as 95% of the rated voltage value. Constraint checks are made to see that if upper or lower voltage constraints are violated at any node.

A given power system has fixed generation capacity depending on the size of the generating units. If the load demand and power losses exceed the available generation capacity, then the system is unable to feed electrical energy to all loads. Hence the total amount of load fed by the system and power losses in the system is calculated and their sum is compared with the available generation capacity. If the sum is greater than the available generation capacity then the generation capacity constraint is said to be violated.

3.4.9 Load Shedding Agent

The function of the Load Shedding agent is to determine control actions to shed loads to meet a given amount of generation deficiency. The Load Shedding agent is called by the System Analysis agent, when a generation capacity constraint violation is determined. The load shedding agent then obtains status, connectivity and static information from the Restoration agent through the Query agent. Then it orders all loads in increasing order of priority. Next, it determines the control actions for shedding load for a given amount of generation deficiency. This agent was implemented in Multilogic Exsys Developer and Microsoft Visual C++. The block diagram of Load Shedding agent is shown in Fig 3.13.

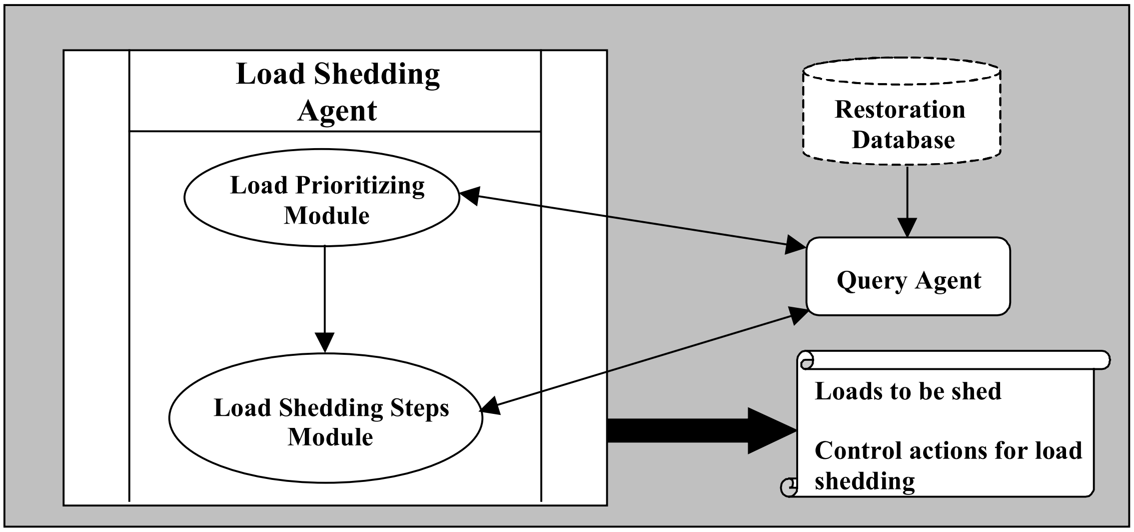

Fig. 3.13: Load Shedding Agent

The Load Shedding agent consists of two modules – Load Prioritizing module and

Load Shedding Steps Module. The Load prioritizing module considers all the loads available in the system and then orders them based on a pre-established priority order. The method of prioritizing was explained in section 2.3.1.8. After the loads are ordered, the Load Shedding Steps Module is executed. This module determines the control actions for shedding load(s) to meet the generation deficit. The loads are shed according to the priority order to remove the generation capacity constraint. Control actions for shedding the load(s) and the load(s) to be shed are then given as an output. This information is stored in the Restoration database through the Query agent.

3.5 SUMMARY

In this chapter, the implementation details for the Predictive Reconfiguration methodology were presented. This methodology was implemented using multi-agent technology. A Multi-Agent System (MAS) was developed to implement the Pre-hit Probabilistic Reconfiguration method for the SPSs. This MAS also implemented a Post-hit Restoration method, which was developed earlier at PSAL. Various agents were developed to perform specialized tasks. The structure of each of these agents were presented and discussed.

CHAPTER IV

ILLUSTRATION OF PREDICTIVE RECONFIGURATION METHODOLOGY

4.1 INTRODUCTION

A methodology for Predictive Reconfiguration was developed. The methodology was implemented using Multi-Agent technology. A Multi-Agent System for performing Predictive Reconfiguration was developed. The MAS was implemented using Microsoft Visual C++, Alternate Transient Program [34], Multilogic Exsys Developer [17,18], and Microsoft Access. The methodology was applied to a SPS model. This SPS was a reduced version of an SPS for a non-nuclear surface combatant ship.

In this chapter, test cases will be presented to illustrate the effectiveness of the methodology applied to a test SPS model. In section 4.2, the details of test SPS model is discussed and the database to store the electrical parameters of the test SPS is presented. In section 4.3, a complex case is presented to illustrate the MAS. Results of various agents will be presented. The effectiveness of the Pre-hit Reconfiguration method will be demonstrated. In section 4.4, another complex case is presented. In this case, load shedding was required to be performed during Restoration, after the weapon hit. In section 4.5 analysis of test results will be presented and conclusions will be drawn.

4.2 TEST SHIPBOARD POWER SYSTEM (SPS) MODEL

To investigate the behavior of the power system on a navy ship during fault scenarios caused by weapon hits, real field data measurements are required. Since such data is not publicly available, simulations have to be performed to generate data for various fault scenarios. Transients modeling and simulation for a SPS model was developed by researchers at PSAL to investigate the SPS behavior. A test SPS model, which represented an AC radial SPS on a non-nuclear surface combatant ship, was designed and modeled with the Alternate Transient Program (ATP). This test SPS was a reduced version of the actual electrical layout on a ship [14]. The methodology for Predictive Reconfiguration was applied to for test the SPS model. The electrical layout for this test SPS is shown in Fig. 4.1.

This layout consisted of three generators connected in a ring configuration. At any given time, only two of the generators were energized and the other served as an emergency generator. Each generator was connected to a generator switchboard. The circuits downstream of the main switchboards were distributed in a radial configuration. The other components of the SPS were load center switchboards, power distribution panels, bus transfer (BT) units, transformers, loads, Low Voltage Protection devices (LVPs), and Low Voltage Release devices (LVRs), circuit breakers, and interconnecting cable used for delivering power to various loads.

The test SPS model had 3 generator switchboards, 5 load centers switchboards, 2 power distribution panels, 28 bus transfer units, 11 transformers, 17 LVPs, 2 LVRs, 83 circuit breakers, 33 single phase loads, 42 three phase loads, 33 single phase cables, and 112 three phase cables.

The generators were ungrounded, delta-connected gas turbine synchronous machine, and were operated at 60 Hz and 450 V. The rated capacity of each generator was 2.5 MW with a rated power factor of 0.8 lagging. Load Centers LC11 and LC41 were downstream of SB1, LC12 and LC31 were downstream of SB2, and LC42 was downstream of SB3. There were nineteen dynamic induction motors and twenty-six constant impedance loads fed through main switchboards, load center switchboards or power panels. The total power consumption of this system was 3.8 MW. The eleven transformers with a ratio 450/120 V in the test SPS, served single phase loads operated at 115 V. There were two types of transformers, 3x25 kVA and 3x15 kVA. Each of the transformers was a three-phase transformer bank in a delta-delta connection. The three-phase and single-phase power cables connected various power elements mentioned above.

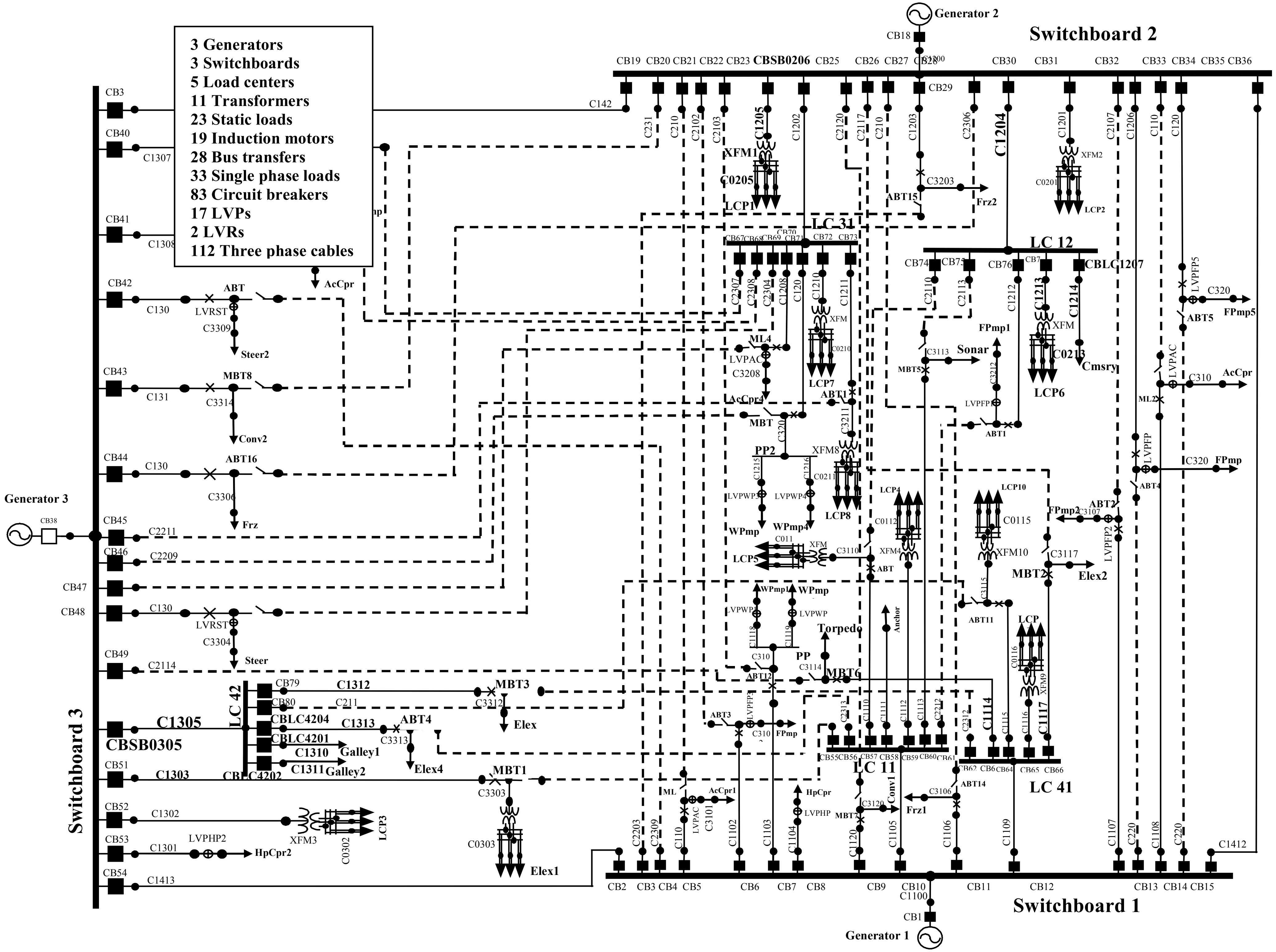

Fig. 4.1: Electrical Layout of Test SPS

The test SPS model also contained several types of protective devices applied on a naval ship. They were circuit breakers with inverse time over current relays, ABT, MBT, LVR and LVP. In Fig. 4.1, the symbols ─■─ and ─□─ denote a closed and open circuit breaker, respectively. The symbol ●×●⁄─● denotes a bus transfer unit, in which ●×● indicates a closed position, and ●⁄─● indicates an open position. An LVP and an LVR in the closed position is denoted by the symbol ●⊕●, and the open position is denoted by ●⊖●. These protective devices are shown in Fig. 4.1. The protective devices were designed for the protection of SPS in different situations. The circuit breakers for over-current and short-circuit fault protection, ABT and MBT to provide continuous power supply for vital loads, and LVP and LVR to provide low voltage protection for induction motors. Ratings and settings of these protective devices were chosen based on information from military documents [35,36] and notes from Dr. Butler-Purry, who participated in the ONR Scientist to Sea Program (April 28-May 2, 1997 aboard the USS Monterey).

The test SPS model, which was modeled and simulated in ATP, was also modeled with the Geographic Information System (GIS) modeling methodology developed by researchers at PSAL [33]. A three-dimensional (3D) layout of the example SPS was drawn as Microstation SE CADD diagrams [15]. Fig. 4.2 shows an isometric view of the SPS model on the ship. The structure of the ship and all components in the SPS model were drawn according to their physical sizes and geographic positions. Each element in the 3D drawing was linked to one or a set of tables in a database developed in Microsoft Access. This database is referred to as GIS database (refer to section 3.4.1).

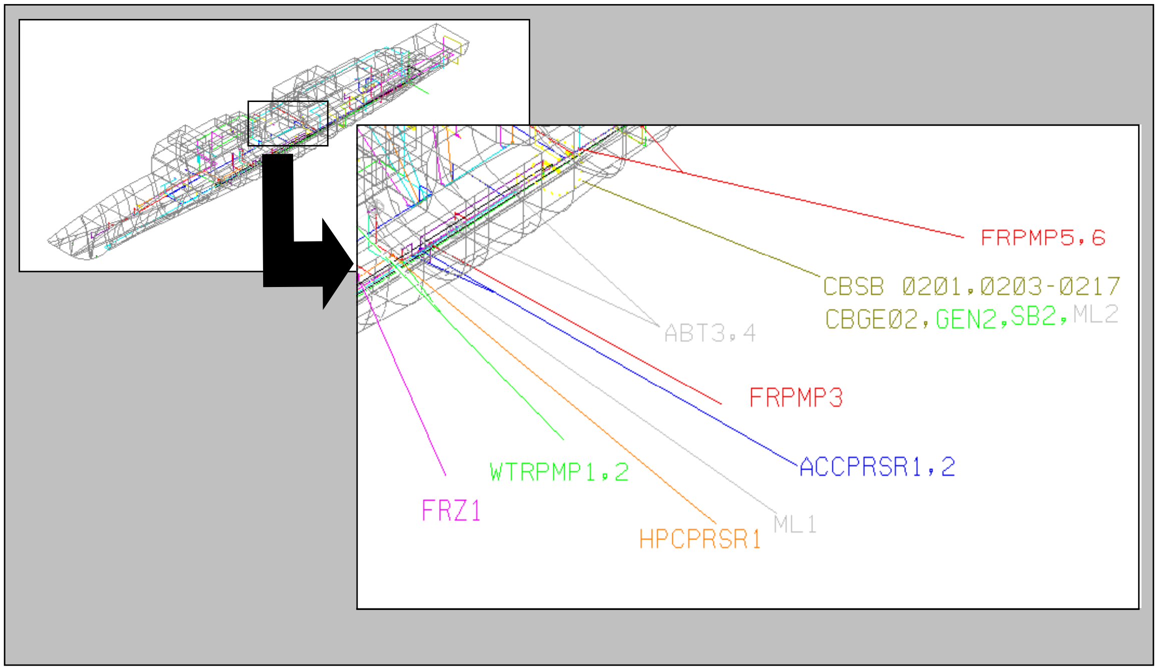

Fig. 4.2: 3D Diagram of the Test SPS on Ship

The GIS database contained one system table, which provided a list of all components in the test SPS model. In this system table, names of all components in the system, together with their types, geographic positions, and connection status, were stored. Connection status in the system table stated whether a component was available for system operation.

As stated earlier in section 3.4.1, in the GIS database, three tables were designed for each type of components. These tables were connection table, dynamic table and static table. In dynamic tables, real-time measurements for various components were stored. It also contained status information for switch type components (e.g. circuit-breakers). Also for bus transfers, the dynamic table contained information representing the data used by the bus transfer to supply power, via normal path or alternate path. A system operator could update data in connection tables and static tables, while data in dynamic tables were updated based on the measurements. At a given instant of time, configuration of the test SPS model could be determined from system connectivity information, the connection status, working status and switch status of various components in the test SPS model.

A Constraint database and a Historical database were also designed to store operation constraints and field measurement data, respectively. The GIS, Constraint and Historical databases were global databases. In addition to these global databases, two local databases were also developed. These databases were Reconfiguration and Restoration databases. The structures of global databases, GIS, Constraint, and Historical databases are given in Appendix A.

Since field measurements on naval ships are not publicly available, simulation generated measurements from time-domain ATP simulations results were used in test cases presented in this dissertation. The dynamic tables in the GIS database were updated with simulation generated measurements at specified time intervals. Measurements were also stored in the historical database, as appropriate.

4.3 ILLUSTRATIVE CASE

In this section, a scenario is presented to illustrate the Predictive Reconfiguration methodology. Results obtained after executing the Predictive Reconfiguration Methodology in this scenario, will be presented to show the effectiveness of the methodology.

In this scenario, it was assumed that an incoming missile was detected. The probability density function of the weapon hit location and its mean, for that missile, were assumed to be known. Thereafter, the Pre-hit Coordination agent was called to perform Pre-hit Probabilistic reconfiguration. Then the reconfiguration actions for pre-hit reconfiguration were determined. After the execution of Pre-hit Probabilistic reconfiguration, the Pre-hit Coordination agent passed a command to the Post-hit Coordination agent. It was assumed that Pre-hit reconfiguration actions were implemented on the test SPS, before the weapon-hit occurred. Also, it was assumed that the actual hit location was determined, after the missile hit the ship.

In the real weapon hit situation, protective devices will operate to isolate the faulted sections created due to the damage caused by the weapon hit. A failure assessment program will then use the status of the protective devices to detect and locate the fault(s) caused due to the weapon hit. In order to execute the Post-hit Restoration method real-time data are required. Since real time data are not available, simulation generated measurements were used to obtain post-fault configuration. In order to generate these measurements, first, the actual damaged components after the weapon hit were determined using the cookie-cutter approach. In using the cookie-cutter approach, a lethal radius must be assumed. All the electrical components lying inside the damage sphere, defined by the lethal radius around the actual hit location, were then assumed to be damaged. This is shown in Fig. 4.3 for a particular damage scenario. In this figure, a lethal radius of R was assumed. The damage sphere for that lethal radius is shown. The portions of the components C1214, C1213, C1105, C2312, and C2303 are inside of the damage sphere. So using cookie-cutter approach the damaged components can be identified. The damage to the electrical components, except circuit breakers, was then simulated as three-phase solid faults in the ATP simulation input files for the test SPS model. For circuit breakers, the damage was simulated as an open circuit situation (details are in section 2.2.2.1) in the ATP simulation input files.

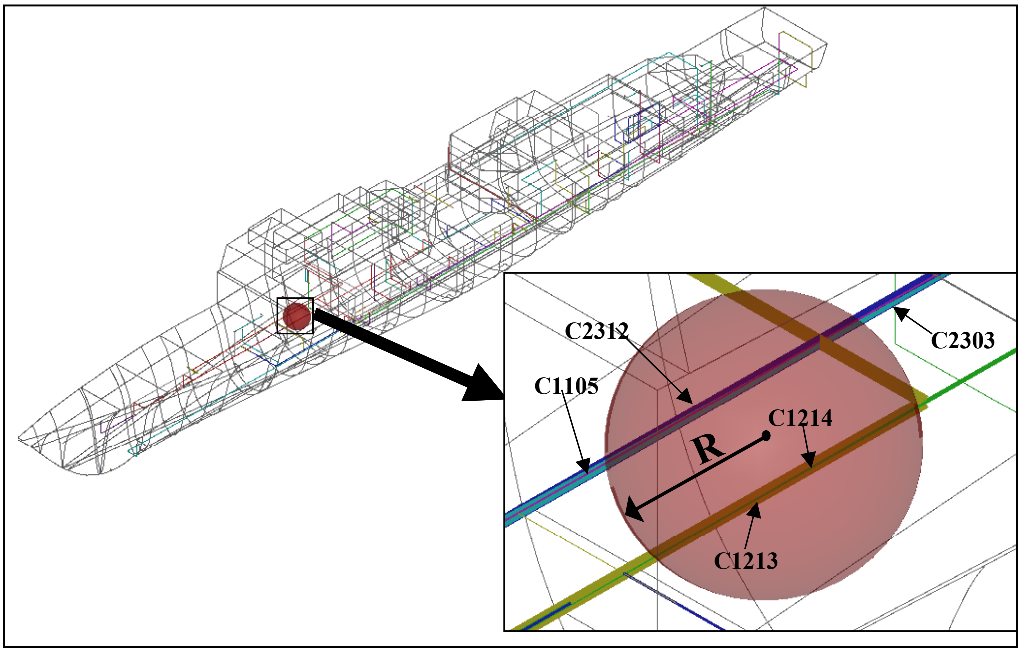

Fig. 4.3: Cookie Cutter Approach

The ATP simulation was then performed to generate the measurements. The results of the ATP simulation were used to update the GIS database and Historical database to provide the initial data required to perform the post-hit restoration. In actual operation of the Predictive Reconfiguration method, the GIS database and the Historical database would be updated with real time measurements from the ship. The Post-hit Coordination agent then performed the post-hit restoration and determined the restoration control actions. This completed the process of Predictive Reconfiguration methodology.

To test the effectiveness of the Predictive Reconfiguration methodology, for the test case mentioned above, restoration control actions were also determined assuming that pre-hit reconfiguration was not applied to the test SPS model. This process in which post-hit reconfiguration restoration was applied without determining the reconfiguration actions from Pre-hit Probabilistic Reconfiguration, will be simply referred to as Restoration process. Four random locations on the ship model were chosen as location of weapon hits. These locations were chosen by assuming a miss distance for a missile. For each of these scenarios, post-hit reconfiguration for restoration was performed twice. One scenario in which the assumption that pre-hit reconfiguration was applied and the other scenario in which the assumption that pre-hit reconfiguration was not performed. The results of each of these cases will be presented and compared to demonstrate the effectiveness of the Predictive Reconfiguration methodology.

4.3.1 Scenario

In the scenario, it was assumed that an incoming missile was detected by the weapon detection technology existing on a ship. As stated earlier in section 2.2.1.4, the probability density function of the weapon hit location is an input to Predictive Reconfiguration method. This probability density function, as defined in (2.6) in section 2.2.1.4, is given below as (4.1).

$$p(x,y,z)=\frac{1}{(2\pi)^{3/2}\sigma^{3}}e^{-\left[(x-\mu_x)^2+(y-\mu_y)^2+(z-\mu_z)^2\right]/2\sigma^2} \tag{4.1}$$

For this scenario, the means (μ_x,μ_y,μ_z), were given as (285,40,6), respectively.

Also the standard deviation σ was given as 5. Further as stated earlier in section 2.2.1.4, the function that describes the probability of kill for a point at a given distance from the location of the actual hit is given This function, as defined in (2.9) in section 2.2.1.4, is given below as (4.2).

$$F(x, y, z) = e^{-\left(x^2+y^2+z^2\right)/2\sigma_0^2} \tag{4.2}$$

For this scenario, the effectiveness factor, σ_0, was given as 15. Further this scenario investigates four cases with randomly chosen hit locations. These cases represented different miss distances for the missile. The four hit locations are given below.

Hit location 1

In this situation, the coordinates for hit location were chosen as (285,35,-4). The miss distance with respect to the predicted hit location in this case was 11.2 feet.

Hit location 2

In this situation the coordinates for hit location were chosen as (290,45,-3). The miss distance with respect to the predicted hit location in this case was 11.5 feet.

Hit location 3

In this situation the coordinates for hit location were chosen as (295,50,3). The miss distance with respect to the predicted hit location in this case was 14.5 feet.

Hit location 4

In this situation the coordinates for hit location were chosen as (273,35,-7). The miss distance with respect to the predicted hit location in this case was 18.4 feet.

4.3.2 Pre-hit Probabilistic Reconfiguration

Using the input data stated in the previous section, the Pre-hit Coordination agent is called to perform Pre-hit Probabilistic Reconfiguration and determine reconfiguration control actions. The Pre-hit Reconfiguration agent, first, called the Query agent and sent instructions leading to the formation of the Reconfiguration database. This database, as explained earlier in section 3.4.1, consists of tables created using the GIS database. After the formation of the Reconfiguration database, the Pre-hit Reconfiguration agent then called the Weapon Damage Assessment agent to compute the EPOD for each electrical component in the test SPS model.

The Weapon Damage Assessment agent computed the EPODs for all the electrical components in the test SPS model, for the given values of σ and σ_0. The information about the location of various components and their dimensions was obtained from the Reconfiguration database through the Query agent. The results of the Weapon damage Assessment agent are shown in Table 4.1. This table gives the computed EPODs for all the electrical components in the test SPS model. These results were stored in the Reconfiguration database by passing proper instructions to Query agent.

Table 4.1

Results of the Weapon Damage Assessment Agent

Name	Type	EPOD
ABT1	BT	0
ABT10	BT	0
ABT11	BT	0.490387
ABT12	BT	0.000149
ABT14	BT	0.000007
ABT15	BT	0.130425
ABT16	BT	0
ABT2	BT	0
ABT3	BT	0.052292
ABT4	BT	0.149745
ABT5	BT	0.00037
ABT6	BT	0.000001
ABT7	BT	0
ABT8	BT	0
ABT9	BT	0
MBT1	BT	0
MBT2	BT	0.024921
MBT3	BT	0.000174
MBT4	BT	0.000001
MBT5	BT	0
MBT6	BT	0
MBT7	BT	0.01972
MBT8	BT	0
MBT9	BT	0
ML1	BT	0.000027
ML2	BT	0.00002
ML3	BT	0
ML4	BT	0
C0110AB	CABLE	0
C0110BC	CABLE	0

Table 4.1 continued

Name	Type	EPOD
C0110CA	CABLE	0
C0112AB	CABLE	0
C0112BC	CABLE	0
C0112CA	CABLE	0
C0115AB	CABLE	0.621886
C0115BC	CABLE	0.693365
C0115CA	CABLE	0.652856
C0116AB	CABLE	0
C0116BC	CABLE	0
C0116CA	CABLE	0
C0201AB	CABLE	0.231896
C0201BC	CABLE	0.231896
C0201CA	CABLE	0.202482
C0205AB	CABLE	0.635424
C0205BC	CABLE	0.609508
C0205CA	CABLE	0.582316
C0210AB	CABLE	0
C0210BC	CABLE	0
C0210CA	CABLE	0
C0211AB	CABLE	0
C0211BC	CABLE	0
C0211CA	CABLE	0
C0213AB	CABLE	0.231896
C0213BC	CABLE	0.222439
C0213CA	CABLE	0.212515
C0302AB	CABLE	0
C0302BC	CABLE	0
C0302CA	CABLE	0
C0303AB	CABLE	0
C0303BC	CABLE	0
C0303CA	CABLE	0
C1100	CABLE	0
C1101	CABLE	0.000025
C1102	CABLE	0.062035
C1103	CABLE	0.000128
C1104	CABLE	0.000023
C1105	CABLE	0
C1106	CABLE	0.000008
C1107	CABLE	0
C1108	CABLE	0.000017
C1109	CABLE	0.015043
C1110	CABLE	0
C1111	CABLE	0
C1112	CABLE	0
C1113	CABLE	0
C1114	CABLE	0.848382
C1115	CABLE	0.746452
C1116	CABLE	0.014781
C1117	CABLE	0.848382
C1118	CABLE	0.000434
C1119	CABLE	0.000341
C1120	CABLE	0.023145
C1200	CABLE	0.062134
C1201	CABLE	0.179046
C1202	CABLE	0.062277
C1203	CABLE	0.120409
C1204	CABLE	0.111196
C1205	CABLE	0.731935
C1206	CABLE	0.183316
C1207	CABLE	0.012307

Table 4.1 continued

Name	Type	EPOD
C1208	CABLE	0
C1209	CABLE	0
C1210	CABLE	0
C1211	CABLE	0
C1212	CABLE	0
C1213	CABLE	0.275418
C1214	CABLE	0.500064
C1215	CABLE	0
C1216	CABLE	0
C1300	CABLE	0
C1301	CABLE	0
C1302	CABLE	0
C1303	CABLE	0.672443
C1304	CABLE	0
C1305	CABLE	0.579301
C1306	CABLE	0
C1307	CABLE	0.000005
C1308	CABLE	0
C1309	CABLE	0
C1310	CABLE	0.848382
C1311	CABLE	0.848382
C1312	CABLE	0.475958
C1313	CABLE	0.475959
C1314	CABLE	0
C1412	CABLE	0.09767
C1413	CABLE	0.09767
C1423	CABLE	0.043886
C2101	CABLE	0.160196
C2102	CABLE	0.142407
C2103	CABLE	0.126089
C2106	CABLE	0.179486
C2107	CABLE	0.074455
C2108	CABLE	0.064617
C2110	CABLE	0
C2113	CABLE	0
C2114	CABLE	0
C2115	CABLE	0.746452
C2117	CABLE	0.047579
C2120	CABLE	0.179486
C2203	CABLE	0.120409
C2203	CABLE	0.120409
C2206	CABLE	0.183316
C2207	CABLE	0.064617
C2208	CABLE	0
C2209	CABLE	0
C2211	CABLE	0
C2212	CABLE	0
C2303	CABLE	0
C2304	CABLE	0
C2306	CABLE	0.025098
C2307	CABLE	0.000004
C2308	CABLE	0
C2309	CABLE	0.111196
C2312	CABLE	0.014781
C2313	CABLE	0.000002
C2314	CABLE	0.0408
C3101	CABLE	0.000095
C3102	CABLE	0.063784
C3103	CABLE	0.000211
C3106	CABLE	0.00001

Table 4.1 continued

Name	Type	EPOD
C3107	CABLE	0
C3108	CABLE	0.00012
C3110	CABLE	0
C3113	CABLE	0
C3114	CABLE	0
C3115	CABLE	0.62934
C3117	CABLE	0.076259
C3120	CABLE	0.040275
C3203	CABLE	0.131851
C3206	CABLE	0.222627
C3207	CABLE	0.118965
C3208	CABLE	0
C3209	CABLE	0
C3211	CABLE	0
C3212	CABLE	0
C3303	CABLE	0
C3304	CABLE	0
C3306	CABLE	0
C3307	CABLE	0.00013
C3308	CABLE	0
C3309	CABLE	0
C3312	CABLE	0.000144
C3313	CABLE	0.000001
C3314	CABLE	0
CBGE01	CB	0
CBGE02	CB	0.07512
CBGE03	CB	0
CBLC1101	CB	0
CBLC1102	CB	0
CBLC1103	CB	0
CBLC1104	CB	0
CBLC1105	CB	0
CBLC1106	CB	0
CBLC1107	CB	0
CBLC1201	CB	0
CBLC1202	CB	0
CBLC1203	CB	0
CBLC1205	CB	0
CBLC1207	CB	0
CBLC3101	CB	0
CBLC3102	CB	0
CBLC3103	CB	0
CBLC3104	CB	0
CBLC3105	CB	0
CBLC3106	CB	0
CBLC3107	CB	0
CBLC4103	CB	0.013511
CBLC4104	CB	0.015234
CBLC4105	CB	0.012982
CBLC4106	CB	0.014462
CBLC4107	CB	0.014873
CBLC4201	CB	0.395255
CBLC4202	CB	0.411385
CBLC4203	CB	0.440333
CBLC4204	CB	0.452836
CBLC4205	CB	0.463836
CBSB0101	CB	0
CBSB0102	CB	0
CBSB0103	CB	0
CBSB0104	CB	0

Table 4.1 continued

Name	Type	EPOD
CBSB0105	CB	0
CBSB0106	CB	0
CBSB0107	CB	0
CBSB0108	CB	0
CBSB0109	CB	0
CBSB0110	CB	0
CBSB0112	CB	0
CBSB0113	CB	0
CBSB0114	CB	0
CBSB0115	CB	0
CBSB0116	CB	0
CBSB0117	CB	0
CBSB0201	CB	0.055009
CBSB0202	CB	0.083228
CBSB0203	CB	0.07441
CBSB0204	CB	0.06626
CBSB0205	CB	0.058768
CBSB0206	CB	0.022056
CBSB0207	CB	0.064173
CBSB0208	CB	0.040028
CBSB0209	CB	0.051914
CBSB0210	CB	0.019484
CBSB0211	CB	0.033435
CBSB0212	CB	0.034939
CBSB0213	CB	0.015023
CBSB0214	CB	0.030374
CBSB0215	CB	0.013113
CBSB0216	CB	0.026301
CBSB0217	CB	0.050194
CBSB0218	CB	0.09272
CBSB0219	CB	0.042674
CBSB0301	CB	0
CBSB0302	CB	0
CBSB0303	CB	0
CBSB0304	CB	0
CBSB0305	CB	0
CBSB0306	CB	0
CBSB0307	CB	0
CBSB0308	CB	0
CBSB0309	CB	0
CBSB0310	CB	0
CBSB0311	CB	0
CBSB0312	CB	0
CBSB0313	CB	0
CBSB0314	CB	0
CBSB0315	CB	0
CBSB0317	CB	0
GEN1	GEN	0
GEN2	GEN	0.111284
GEN3	GEN	0
LC11	LC	0
LC12	LC	0
LC31	LC	0
LC41	LC	0.015917
LC42	LC	0.458246
AcCprsr1	LOAD	0.0002
AcCprsr2	LOAD	0.000243
AcCprsr3	LOAD	0
AcCprsr4	LOAD	0
Anchor	LOAD	0

Table 4.1 continued

Name	**Type**	**EPOD**
Cmsry	LOAD	0.000067
Conv1	LOAD	0.071824
Conv2	LOAD	0
Elex1AB	LOAD	0
Elex1BC	LOAD	0
Elex1CA	LOAD	0
Elex2	LOAD	0.057519
Elex3	LOAD	0.000201
Elex4	LOAD	0.000001
Frpmp1	LOAD	0
Frpmp2	LOAD	0
Frpmp3	LOAD	0.000193
Frpmp4	LOAD	0.058584
Frpmp5	LOAD	0.029918
Frpmp6	LOAD	0.00004
Frz1	LOAD	0.000011
Frz2	LOAD	0.142169
Frz3	LOAD	0
Galley1	LOAD	0.706901
Galley2	LOAD	0.681223
HpCprsr1	LOAD	0.000024
HpCprsr2	LOAD	0
LCP10AB	LOAD	0.525316
LCP10BC	LOAD	0.569068
LCP10CA	LOAD	0.611552
LCP1AB	LOAD	0.527192
LCP1BC	LOAD	0.551458
LCP1CA	LOAD	0.572244
LCP2AB	LOAD	0.223311
LCP2BC	LOAD	0.231034
LCP2CA	LOAD	0.213485
LCP3AB	LOAD	0
LCP3BC	LOAD	0
LCP3CA	LOAD	0
LCP4AB	LOAD	0
LCP4BC	LOAD	0
LCP4CA	LOAD	0
LCP5AB	LOAD	0
LCP5BC	LOAD	0
LCP5CA	LOAD	0
LCP6AB	LOAD	0.147189
LCP6BC	LOAD	0.165624
LCP6CA	LOAD	0.184882
LCP7AB	LOAD	0
LCP7BC	LOAD	0
LCP7CA	LOAD	0
LCP8AB	LOAD	0
LCP8BC	LOAD	0
LCP8CA	LOAD	0
LCP9AB	LOAD	0
LCP9BC	LOAD	0
LCP9CA	LOAD	0
Sonar	LOAD	0
Steer1	LOAD	0
Steer2	LOAD	0
Torpedo	LOAD	0
Wtrpmp1	LOAD	0.000598
Wtrpmp2	LOAD	0.00044
Wtrpmp4	LOAD	0
LVPAcp1	LVPR	0.000035

Table 4.1 continued

Name	Type	EPOD
LVPAcp2	LVPR	0.000045
LVPAcp3	LVPR	0
LVPAcp4	LVPR	0
LVPAnchor	LVPR	0
LVPFpm1	LVPR	0
LVPFpm2	LVPR	0
LVPFpm3	LVPR	0.000152
LVPFpm4	LVPR	0.044349
LVPFpm5	LVPR	0.026209
LVPFpm6	LVPR	0.000021
LVPHpc1	LVPR	0.000037
LVPHpc2	LVPR	0
LVPWpm1	LVPR	0.000348
LVPWpm2	LVPR	0.000477
LVPWpm3	LVPR	0
LVPWpm4	LVPR	0
LVRStr1	LVPR	0
LVRStr2	LVPR	0
PP1	PP	0.000237
PP2	PP	0
SB1	SB	0
SB3	SB	0
Xfmr1	XFMR	0.6328
Xfmr10	XFMR	0.684452
Xfmr11	XFMR	0
Xfmr2	XFMR	0.179597
Xfmr3	XFMR	0
Xfmr4	XFMR	0
Xfmr5	XFMR	0
Xfmr6	XFMR	0.24413
Xfmr7	XFMR	0
Xfmr8	XFMR	0
Xfmr9	XFMR	0

After the computation of EPODs for all electrical components, the Pre-hit Reconfiguration agent called the Pre-hit Probabilistic Reconfiguration agent to determine the pre-hit reconfiguration control actions. The Pre-hit Probabilistic Reconfiguration agent first called the RCI module to determine the reconfiguration control actions for isolating the non-critical components, refer to section 2.2.2.2. For this test case, it was assumed that for the RCI module, the operator chose the threshold value for the expected probability of damage as 0.5. The RCI module then determined the components that have EPOD greater than the threshold value. These components are shown in bold letters in table 4.1.

The RCI module then obtained the information about the present configuration from the Reconfiguration database through the Query agent. The RCI module determined the control actions for isolating the non-critical components among the components highlighted in Table 4.1. These non-critical components are along the radial path of some non-vital loads. The control actions that will isolate the non-critical components along with the non-vital loads are shown in Table 4.2. The PAP values for the radial path supplying power to each non-vital load are given as a probability measure, along with the suggested control actions. These control actions were then updated in the Reconfiguration database by calling the Query agent to change the status and positions of various switches and BTs according to the determined control actions.

Table 4.2

Reconfiguration Actions Determined by RCI Module

Non vital load	**Non-critical component with EPOD > $\text{EPOD}_{\text{threshold}}$**	**Control actions for non-vital loads**	**PAP**
Galley1	C1305	Open CBSB0305	0.011136
Galley2	C1305	Open CBSB0305	0.011969
LCP1AB	C1205	Open CBSB0206	0.016593
LCP1BC	C1205	Open CBSB0206	0.016861
LCP1CA	C1205	Open CBSB0206	0.017199
Cmsry	C1214	Open CBLC1207	0.50064

After the determination of the control actions for isolating the components, the Pre-hit Probabilistic agent then called the RRSI module to determine the control actions for reducing the possibility of supply interruption to the vital loads, refer to section 2.2.2.3. As explained earlier, in section 2.2.2.3, the RRSI module can have different outputs depending upon which control actions, determined by RCI module, are selected for implementation. In this test case, the RCI module determined two different control actions as shown in Table 4.2. Out of these two control actions, the control action to open CBSB0305 can affect the output of RRSI module as it will cause interruption of electrical energy to vital loads Elex3 and Elex4. The control action to open CBSB0206 does not affect the electrical supply to any vital load and hence it does not have any influence on the determination of control actions by the RRSI module. In this test case, the RRSI module had two possible outputs depending upon whether the control action to open CBSB0305 was selected for implementation. Tables 4.3 and 4.4 shows the outputs of the RRSI module for these two cases, respectively. These tables show the reconfiguration control actions for some of the vital loads. These tables also show the PAP values of the best path and PAP difference, for each control action as a probability measure for that control action. These actions were then updated in the Reconfiguration database by calling the Query agent.

Table 4.3

Reconfiguration Actions Determined by RRSI Module When Control Action to "Open CBSB0305" Is Selected by the Operator

Vital loads	**Control actions for vital loads**	**$\text{PAP}_{\text{best path}}$**	**PAP difference**
Elex1AB	Transfer MBT1	1.0	0.672443
Elex1BC	Transfer MBT1	1.0	0.672443
Elex1CA	Transfer MBT1	1.0	0.672443
Elex3	Transfer MBT3	0.955119	0.955119
Torpedo	Transfer MBT6	1.0	0.852601
Elex2	Transfer MBT2	0.776158	0.651269
AcCprsr4	Transfer ML4	1.0	0.122453
Frpmp1	Open CBLC1203	1.0	0.128513
Frpmp4	Open CBSB0213	0.485639	0.007296
Frz2	Open CBSB0209	0.569618	0.029571
LCP8AB	Open CBLC3107	1.0	0.122453
LCP8BC	Open CBLC3107	1.0	0.122453
LCP8CA	Open CBLC3107	1.0	0.122453
Wtrpmp3	Transfer MBT9	1.0	0.122453
Wtrpmp4	Transfer MBT9	1.0	0.122453

Table 4.4

Reconfiguration Actions Determined by RRSI Module When Control Action to "Open CBSB0305" Is Not Selected by the Operator

Vital loads	**Control actions for vital loads**	**$\text{PAP}_{\text{best path}}$**	**PAP difference**
Elex1AB	Transfer MBT1	1.0	0.672443
Elex1BC	Transfer MBT1	1.0	0.672443
Elex1CA	Transfer MBT1	1.0	0.672443
Elex3	Transfer MBT3	0.955119	0.831797
Elex4	Open CBLC4204	0.999995	0.879366

Table 4.4 continued

Vital loads	**Control actions for vital loads**	**$\text{PAP}_{\text{best path}}$**	**PAP difference**
Torpedo	Transfer MBT6	1.0	0.852601
Elex2	Transfer MBT2	0.776158	0.651269
AcCprsr4	Transfer ML4	1.0	0.122453
Frpmp1	Open CBLC1203	1.0	0.128513
Frpmp4	Open CBSB0213	0.485639	0.007296
Frz2	Open CBSB0209	0.569618	0.029571
LCP8AB	Open CBLC3107	1.0	0.122453
LCP8BC	Open CBLC3107	1.0	0.122453
LCP8CA	Open CBLC3107	1.0	0.122453
Wtrpmp3	Transfer MBT9	1.0	0.122453
Wtrpmp4	Transfer MBT9	1.0	0.122453

Once the Pre-hit Probabilistic Reconfiguration agent completed its execution, then it informed Pre-hit Coordination agent. The Pre-hit Coordination agent then called the System Analysis agent to check for system constraint violations for each of the two cases. The System Analysis agent did not compute constraint violations for the reconfiguration control actions and notified Pre-hit Coordination agent. The Pre-hit Coordination agent then called the Query agent to obtain the results of the Pre-hit Probabilistic agent from the Reconfiguration database. Then the Pre-hit Coordination agent used these results, control actions determined by the RCI and RRSI modules, to suggest the control actions for pre-hit reconfiguration. The Pre-hit Coordination agent suggested two sets of outputs for the two cases in which the control actions were and were not implemented to open CBSB0305. These outputs are shown in Table 4.5 and Table 4.6, respectively. Since each control action was obtained with respect to either a vital or a non-vital load, the probabilistic information such as PAP and PAP difference, computed for a load can be outputted along with control action for that load, as shown in tables 4.5 and Table 4.6. These tables also give the loads that will be de-energized if the suggested control action was implemented.

Table 4.5

Reconfiguration Actions Determined by the Pre-hit Reconfiguration Agent When Control Action to “Open CBSB0305” Is Selected by the Operator

Control actions	**Probabilistic information attached with each control action**			**De-energized loads**
	PAP of radial path supplying power to the non vital load	**Vital load**		
		PAP$_{\textbf{best path}}$	**PAP difference**	
Open CBSB0305	0.011136	-	-	Galley1, Galley2
Open CBSB0206	0.016593	-	-	LCP1AB, LCP1BC, LCP1CA
Open CBLC1207	0.010672	-	-	Cmsry
Transfer MBT1	-	1.0	0.672443	-
Transfer MBT3	-	0.955119	0.831797	-
Transfer MBT6	-	1.0	0.852601	-
Transfer MBT2	-	0.776158	0.651269	-
Transfer ML4	-	1.0	0.122453	-
Open CBLC1203	-	1.0	0.128513	-
Open CBSB0213	-	0.485639	0.007296	-
Open CBSB0209	-	0.569618	0.029571	-
Open CBLC3107	-	1.0	0.122453	-
Transfer MBT9	-	1.0	0.122453	-

Table 4.6

Reconfiguration Actions Determined by the Pre-hit Reconfiguration Agent When Control Action to “Open CBSB0305” Is Not Selected by the Operator

Control actions	**Probabilistic information attached with each control action**			**De-energized loads**
	PAP of radial path supplying power to the non vital load	**Vital load**		
		PAP$_{\textbf{best path}}$	**PAP difference**	
Open CBSB0206	0.016593	-	-	LCP1AB, LCP1BC, LCP1CA
Open CBLC1207	0.010672	-	-	Cmsry
Transfer MBT1	-	1.0	0.672443	-
Transfer MBT3	-	0.955119	0.831797	-
Open CBLC4204	-	0.999995	0.879366	-
Transfer MBT6	-	1.0	0.852601	-
Transfer MBT2	-	0.776158	0.651269	-
Transfer ML4	-	1.0	0.122453	-
Open CBLC1203	-	1.0	0.128513	-
Open CBSB0213	-	0.485639	0.007296	-
Open CBSB0209	-	0.569618	0.029571	-

Table 4.6 continued

Control actions	**Probabilistic information attached with each control action**			**De-energized loads**
	PAP of radial path supplying power to the non vital load	**Vital load**		
		$PAP_{best\ path}$	**PAP difference**	
Open CBLC3107	-	1.0	0.122453	-
Transfer MBT9	-	1.0	0.122453	-

A low value of PAP, for a control action for a non-vital load, means that the radial path affected by that control action has a low probability of surviving the weapon hit. In this scenario, it has been assumed that for the non vital loads the reconfiguration actions that has PAP<0.2 were implemented. This means that the control action to open CBSB0305 was therefore selected for implementation. For a vital load, a high PAP difference along with a high $PAP_{best\ path}$ means that the load has high probability of surviving the attack if the control actions are implemented. In this scenario, it was assumed that for the vital loads the reconfiguration actions were implemented when $PAP_{best\ path}>0.6$ and PAP difference>0.5. The control actions that were implemented are shown in bold text in Table 4.5. The control actions were then updated in the Reconfiguration database.

4.3.3 Post-hit Reconfiguration for Restoration with Pre-hit Reconfiguration

Once a weapon hits the ship, it will destroy some sections of the ship. The power network in those sections will also be damaged, leading to faults in the SPS. It is assumed in the test case presented in this dissertation that after the implementation of the reconfiguration actions suggested by the Pre-hit Coordination agent, the test SPS model was hit by a weapon. The Pre-hit Coordination agent then passed the command to the Post-hit Reconfiguration for Restoration agent to start the process of reconfiguration for restoration.

The damaged components were identified using a cookie cutter approach. In this test case, a lethal radius of 15 feet was chosen. Then the simulation generated measurements were generated by performing the ATP simulation, and stored in the GIS and Historical databases. The Post-hit Coordination agent then called the Failure Assessment agent. This agent then interacted with the Query agent to obtain data from the GIS, Historical and Constraint databases, to detect the fault(s), locate the faulted sections, and determine de-energized loads in the test SPS model.

The Post-hit Coordination agent called the Query agent to create the Restoration database. The information, about the components in the faulted sections and the de-energized loads, were then stored in the Restoration database through the Query agent.

The Post-hit Coordination agent then called the Post-hit Reconfiguration for Restoration agent to determine reconfiguration control actions for the de-energized loads. The Post-hit Reconfiguration for Restoration agent interacted with the Query agent, to obtain data from the Restoration database, and determine the reconfiguration control actions for each de-energized load. Also, after the determination of the reconfiguration actions for a de-energized load, the Post-hit Reconfiguration for Restoration agent called the System Analysis module to check for voltage or current constraint violations. If there were no violations, then the load was considered restored; otherwise it was considered unrestorable. While checking for constraints, the System Analysis agent interacted with the Query agent to obtain constraint information for the cables and the load nodes from the Constraint database.

The Post-hit Reconfiguration for Restoration agent stored the information regarding the restorable and unrestorable loads in the Restoration database through the Query agent. Once all the de-energized loads in the list have been considered, the Post-hit Restoration agent called the System Analysis agent to check for power constraint violations. If a constraint violation was determined, then the Load Shedding agent was called to perform load shedding. The control actions for load shedding were stored in the Restoration database, by the Load Shedding agent, through the Query agent. Together reconfiguration control actions for each restorable load and control actions to perform load shedding form the total reconfiguration actions required for the reconfiguration for restoration of the test SPS model. The completion of reconfiguration for restoration process was conveyed to the Post-hit Coordination agent by the Post-hit Reconfiguration for Restoration agent. The Post-hit Coordination agent then gave as an output, the list of restorable and unrestorable loads along with the reconfiguration actions for restoring the restorable loads.

As stated earlier, this scenario investigates four cases with randomly chosen hit locations. For each of these cases, the Post-hit Coordination agent performed post-hit restoration. In each of these cases, the interaction between various agents during the reconfiguration for restoration process was the same, as explained earlier in this section. For each case, ATP simulation was performed for 1.2 seconds. For each damaged component, except circuit breakers, simultaneous three-phase solid faults on the system were staged at 0.6 sec, after the beginning of the simulation. The results from various agents for each case are presented below.

4.3.3.1 Hit at Randomly Selected Location 1

The missile hit location was randomly chosen as (285,35,-4). In this case, the damaged components obtained by the cookie-cutter method explained earlier are shown in Table 4.7.

Table 4.7

Damaged Components Obtained by the Cookie-Cutter Approach for Hit at (285,35,-4)

Damaged Components	**Component type**
C1205, C1303, C1305, C0205AB, C0205BC, C0205CA	Cable
LCP1AB, LCP1BC, LCP1CA, Galley1, Galley2	Load
Xfmr1	Transformer

The results of the Failure Assessment agent, in this case, are shown in the Table 4.8.

Table 4.8

Results of the Failure Assessment Agent for Hit at (285,35,-4)

Components in Faulted Sections	Component type	De-energized loads
C1303	Cable	-

In this case, cable C1303 was identified as components in the faulted section by the Failure Assessment agent. Due to the control actions, implemented by the Pre-hit Reconfiguration agent, many of the faults were prevented, which would have occurred if no pre-hit reconfiguration was performed. The reconfiguration control actions implemented during the pre-hit reconfiguration process isolated some sections of the electrical system, leading to de-energization of some loads. These loads are shown in Table 4.5. Since these loads have already been isolated before the Post-hit Coordination Agent is called so for the Post-hit Coordination agent these loads are not part of the present configuration. Therefore when the Failure Assessment agent was called, it did not identify these loads as de-energized loads, as they are not part of the present configuration. After the execution of the Failure Assessment agent, the Post-hit Coordination agent called the Post-hit Reconfiguration for Restoration agent. In this case, it tried to restore the load de-energized due to control actions in pre-hit reconfiguration process. The results of the Post hit Reconfiguration for Restoration agent and the System Analysis agent, for this case, are shown in Table 4.9. In this case, no system constraint violations were found by System Analysis agent.

Table 4.9

Results of Post-hit Reconfiguration for Restoration Agent and System Analysis Agent for Hit at (285,35,-4)

De-energized Load	Output of Post-hit Reconfiguration for Restoration agent		Output of System Analysis agent	
	Is Reconfigurable?	Reconfiguration actions	Constraint Violated?	Description of constraint violation
Galley1	No	-	-	-
Galley2	No	-	-	-
LCP1AB	No	-	-	-

Table 4.9 continued

De-energized Load	Output of Post-hit Reconfiguration for Restoration agent		Output of System Analysis agent	
	Is Reconfigurable?	**Reconfiguration actions**	**Constraint Violated?**	**Description of constraint violation**
LCP1BC	No	-	-	-
LCP1CA	No	-	-	-
Cmsry	Yes	Close CBLC1207	No	-

Finally, the results of the Post-hit Coordination agent are given in the Table 4.10.

Table 4.10

Results of Post-hit Coordination Agent for Actual Hit at (285,35,-4)

De-energized Load	Restorable or Unrestorable	Suggested reconfiguration actions for restorable loads	Reason for load being Unrestored
Galley1	Unrestorable	-	No reconfigurable path
Galley2	Unrestorable	-	No reconfigurable path
LCP1AB	Unrestorable	-	No reconfigurable path
LCP1BC	Unrestorable	-	No reconfigurable path
LCP1CA	Unrestorable	-	No reconfigurable path
Cmsry	Restorable	Close CBLC1207	-

4.3.3.2 Hit at Randomly Selected Location 2

The missile hit location was randomly chosen as (290,45,-3). In this case, the damaged components obtained by the cookie-cutter method explained earlier are shown in Table 4.11.

Table 4.11

Damaged Components Obtained by the Cookie-Cutter Approach for Hit at (290,45,-3)

Damaged Components	Component type
C1114, C1117, C1205, C1310, C1311, C0205AB, C0205BC, C0205CA, C1214	Cable
LCP1AB, LCP1BC, LCP1CA, Galley1, Galley2	Load
Xfmr1	Transformer

The results of the Failure Assessment agent, in this case, are shown in the Table 4.12.

Table 4.12

Results of the Failure Assessment Agent for Hit at (290,45,-3)

Components in Faulted Sections	Component type	De-energized loads
C1114, C1117	Cable	-

After the execution of the Failure Assessment agent, the Post-hit Coordination agent called the Post-hit Reconfiguration for Restoration agent. The results of the Post hit Reconfiguration for Restoration agent and the System Analysis agent, for this case, are shown in Table 4.13. In this case, the System Analysis agent was not called as no load was found to be reconfigurable.

Table 4.13

Results of Post-hit Reconfiguration for Restoration Agent and System Analysis Agent for Hit at (285,35,-4)

De-energized Load	Output of Post-hit Reconfiguration for Restoration agent		Output of System Analysis agent	
	Is Reconfigurable?	Reconfiguration actions	Constraint Violated?	Description of constraint violation
Galley1	No	-	-	-
Galley2	No	-	-	-
LCP1AB	No	-	-	-
LCP1BC	No	-	-	-
LCP1CA	No	-	-	-
Cmsry	No	-	-	-

Finally, the results of the Post-hit Coordination agent are given in the Table 4.14.

Table 4.14

Results of Post-hit Coordination Agent for Actual Hit at (285,35,-4)

De-energized Load	Restorable or Unrestorable	Suggested reconfiguration actions for restorable loads	Reason for load being Unrestored
Galley1	Unrestorable	-	No reconfigurable path
Galley2	Unrestorable	-	No reconfigurable path
LCP1AB	Unrestorable	-	No reconfigurable path
LCP1BC	Unrestorable	-	No reconfigurable path
LCP1CA	Unrestorable	-	No reconfigurable path
Cmsry	Unrestorable	-	No reconfigurable path

4.3.3.3 Hit at Randomly Selected Location 3

The missile hit location was randomly chosen as (295,50,3). In this case, the damaged components obtained by the cookie-cutter method explained earlier are shown in Table 4.15.

Table 4.15

Damaged Components Obtained by the Cookie-Cutter Approach for Hit at (295,50,3)

Damaged Components	**Component type**
C1114, C1117, C1310, C1311	Cable
Galley1, Galley2	Load

The results of the Failure Assessment agent, in this case, are shown in the Table 4.16.

Table 4.16

Results of the Failure Assessment Agent for Hit at (295,50,3)

Components in Faulted Sections	**Component type**	**De-energized loads**
C1114, C1117	Cable	-

After the execution of the Failure Assessment agent, the Post-hit Coordination agent called the Post-hit Reconfiguration for Restoration agent. The results of the Post hit Reconfiguration for Restoration agent and the System Analysis agent, for this case, are shown in Table 4.17. In this case, the System Analysis agent determined that there were no system constraint violations.

Table 4.17

Results of Post-hit Reconfiguration for Restoration Agent and System Analysis Agent for Hit at (295,50,,3)

De-energized Load	Output of Post-hit Reconfiguration for Restoration agent		Output of System Analysis agent	
	Is Reconfigurable?	**Reconfiguration actions**	**Constraint Violated?**	**Description of constraint violation**
Galley1	No	-	-	-
Galley2	No	-	-	-
LCP1AB	Yes	Close CBSB0206	No	-
LCP1BC	Yes	Close CBSB0206	No	-
LCP1CA	Yes	Close CBSB0206	No	-
Cmsry	Yes	Close CBLC1207	No	-

In this case, loads LCP1AB, LCP1BC, LCP1CA, and Cmsry were de-energized due to the control actions in the pre-hit reconfiguration process. In the post-hit restoration process these loads were restored. Finally, the results of the Post-hit Coordination agent are given in the Table 4.18.

Table 4.18

Results of Post-hit Coordination Agent for Actual Hit at (295,50,3)

De-energized Load	Restorable or Unrestorable	Suggested reconfiguration actions for restorable loads	Reason for load being Unrestored
Galley1	Unrestorable	-	No reconfigurable path
Galley2	Unrestorable	-	No reconfigurable path
LCP1AB	Restorable	Close CBSB0206	-
LCP1BC	Restorable	Close CBSB0206	-
LCP1CA	Restorable	Close CBSB0206	-
Cmsry	Restorable	Close CBLC1207	-

4.3.3.4 Hit at Randomly Selected Location 4

The missile hit location was randomly chosen as (273,35,-7). In this case, the damaged components obtained by the cookie-cutter method explained earlier are shown in Table 4.19.

Table 4.19

Damaged Components Obtained by the Cookie-Cutter Approach for Hit at (273,35,-7)

Damaged Components	**Component type**
C1205, C1213, C1303, C0205AB, C0205BC, C0205CA, C0213AB, C0213BC, C0213CA	Cable
LCP1AB, LCP1BC, LCP1CA, LCP6AB, LCP6BC, LCP6CA	Load
Xfmr1, Xfmr6	Transformer

The results of the Failure Assessment agent, in this case, are shown in the Table 4.20.

Table 4.20

Results of the Failure Assessment Agent for Hit at (273,35,-7)

Components in Faulted Sections	**Component type**	**De-energized loads**
C1213, C1303	Cable	LCP6AB, LCP6BC, LCP6CA

The de-energized loads in this case were identified as LCP6AB, LCP6BC, and LCP6CA. After the execution of the Failure Assessment agent, the Post-hit Coordination agent called the Post-hit Reconfiguration for Restoration agent. The results of the Post hit Reconfiguration for Restoration agent and the System Analysis agent, for this case, are shown in Table 4.21. In this case, the System Analysis agent determined that there were no system constraint violations.

Table 4.21

Results of Post-hit Reconfiguration for Restoration Agent and System Analysis Agent for Actual Hit at (273,35,-7)

De-energized Load	**Output of Post-hit Reconfiguration for Restoration agent**		**Output of System Analysis agent**	
	Is Reconfigurable?	**Reconfiguration actions**	**Constraint Violated?**	**Description of constraint violation**
LCP6AB	No	-	-	-
LCP6BC	No	-	-	-
LCP6CA	No	-	-	-
Galley1	Yes	Close CBLC4201	No	-
Galley2	Yes	Close CBLC4202	No	-
LCP1AB	No	-	-	-
LCP1BC	No	-	-	-
LCP1CA	No	-	-	-
Cmsry	Yes	Close CBLC1207	No	-

Finally, the results of the Post-hit Coordination agent are given in the Table 4.22.

Table 4.22

Results of Post-hit Coordination Agent for Actual Hit at (273,35,-7)

De-energized Load	**Restorable or Unrestorable**	**Suggested reconfiguration actions for restorable loads**	**Reason for being Unrestorable**
LCP6AB	Unrestorable	-	No reconfigurable path
LCP6BC	Unrestorable	-	No reconfigurable path
LCP6CA	Unrestorable	-	No reconfigurable path
Galley1	Restorable	Close CBLC4201	-
Galley2	Restorable	Close CBLC4202	-
LCP1AB	Unrestorable	-	No reconfigurable path
LCP1BC	Unrestorable	-	No reconfigurable path
LCP1CA	Unrestorable	-	No reconfigurable path
Cmsry	Restorable	Close CBLC1207	-

4.3.4 Post-hit Restoration without Pre-hit Reconfiguration

In order to determine the effectiveness of the Predictive Reconfiguration methodology, post-hit reconfiguration for restoration was also performed assuming that no pre-hit reconfiguration was performed. It was performed for all the cases discussed in sections 4.3.3.1, 4.3.3.2, 4.3.3.3, and 4.3.3.4. The results from various agents for each of those cases are given below.

4.3.4.1 Hit at Randomly Selected Location 1

The damaged components in this case due to the missile hit were the same as given in section 4.3.3.1. The results of the Failure Assessment agent, in this case, are shown in the Table 4.23.

Table 4.23

Results of the Failure Assessment Agent for Hit at (285,35,-4), Without Pre-hit Reconfiguration

Components in Faulted Sections	**Component type**	**De-energized loads**
C1205, C1303, C1305	Cable	Elex1AB, Elex1BC, Elex1CA, LCP1AB, LCP1BC, LCP1CA, Galley1, Galley2, Elex3, and Elex4

After the execution of the Failure Assessment agent, the Post-hit Coordination agent called the Post-hit Reconfiguration for Restoration agent. The results of the Post-hit Reconfiguration for Restoration agent and the System Analysis agent, for this case, are shown in Table 4.24. There were no system constraint violations in this case.

Table 4.24

Results of Post-hit Reconfiguration for Restoration Agent and System Analysis Agent for Hit at (285,35,-4), Without Pre-hit Reconfiguration

De-energized Load	Output of Post-hit Reconfiguration for Restoration agent		Output of System Analysis agent	
	Is Reconfigurable?	**Reconfiguration actions**	**Constraint Violated?**	**Description of constraint violation**
Galley1	No	-	-	-
Galley2	No	-	-	-
Elex3	Yes	Transfer MBT3	No	-
Elex1AB	Yes	Transfer MBT1	No	-
Elex1BC	Yes	Transfer MBT1	No	-
Elex1CA	Yes	Transfer MBT1	No	-
LCP1AB	No	-	-	-
LCP1BC	No	-	-	-
LCP1CA	No	-	-	-

Finally, the results of the Post-hit Coordination agent are given in the Table 4.25.

Table 4.25

Results of Post-hit Coordination Agent for Hit at (285,35,-4), Without Pre-hit Reconfiguration

De-energized Load	Restorable or Unrestorable	Suggested reconfiguration actions for restorable loads	Reason for being Unrestorable
Galley1	Unrestorable	-	No reconfigurable path
Galley2	Unrestorable	-	No reconfigurable path
Elex3	Restorable	Transfer MBT3	-
Elex1AB	Restorable	Transfer MBT1	-
Elex1BC	Restorable	Transfer MBT1	-
Elex1CA	Restorable	Transfer MBT1	-
LCP1AB	Unrestorable	-	No reconfigurable path
LCP1BC	Unrestorable	-	No reconfigurable path
LCP1CA	Unrestorable	-	No reconfigurable path

4.3.4.2 Hit at Randomly Selected Location 2

The damaged components in this case due to the missile hit were same as given in section 4.3.3.2. In this case the fault on cable C1214 resulted in a cascading fault condition, leading to fault on cable C1204. This will lead to de-energization of some loads downstream of load center LC12. The results of the Failure Assessment agent, in this case, are shown in the Table 4.26.

Table 4.26

Results of the Failure Assessment Agent for Hit at (290,45,-3), Without Pre-hit Reconfiguration

Components in Faulted Sections	**Component type**	**De-energized loads**
C1205, C1310, C1114, C1117, C1311,C1204	Cable	Elex1AB, Elex1BC, Elex1CA, LCP1AB, LCP1BC, LCP1CA, Galley1, Galley2, Elex2, LCP6AB, LCP6BC, LCP6CA, Cmsry and Torpedo

After the execution of the Failure Assessment agent, the Post-hit Coordination agent called the Post-hit Reconfiguration for Restoration agent. The results of the Post-hit Reconfiguration for Restoration agent and the System Analysis agent, for this case, are shown in Table 4.27. In this case the System Analysis agent determined that there were no system constraint violations.

Table 4.27

Results of Post-hit Reconfiguration for Restoration Agent and System Analysis Agent for Hit at (290,45,-3), Without Pre-hit Reconfiguration

De-energized Load	**Output of Post-hit Reconfiguration for Restoration agent**		**Output of System Analysis agent**	
	Is Reconfigurable?	**Reconfiguration actions**	**Constraint Violated?**	**Description of constraint violation**
Galley1	No	-	-	-
Galley2	No	-	-	-
Elex2	Yes	Transfer MBT2	No	-
Torpedo	Yes	Transfer MBT6	No	-
Elex1AB	Yes	Transfer MBT1	No	-
Elex1BC	Yes	Transfer MBT1	No	-
Elex1CA	Yes	Transfer MBT1	No	-
LCP1AB	No	-	-	-
LCP1BC	No	-	-	-
LCP1CA	No	-	-	-

Table 4.27 continued

De-energized Load	Output of Post-hit Reconfiguration for Restoration agent		Output of System Analysis agent	
	Is Reconfigurable?	**Reconfiguration actions**	**Constraint Violated?**	**Description of constraint violation**
Cmsry	No	-	-	-
LCP6AB	No	-	-	-
LCP6BC	No	-	-	-
LCP6CA	No	-	-	-

Finally, the results of the Post-hit Coordination agent are given in the Table 4.28.

Table 4.28

Results of Post-hit Coordination Agent for Hit at (30,12,54), Without Pre-hit Reconfiguration

De-energized Load	Restorable or Unrestorable	Suggested reconfiguration actions for restorable loads	Reason for being Unrestorable
Galley1	Unrestorable	-	No reconfigurable path
Galley2	Unrestorable	-	No reconfigurable path
Elex2	Restorable	Transfer MBT2	-
Torpedo	Restorable	Transfer MBT6	-
Elex1AB	Restorable	Transfer MBT1	-
Elex1BC	Restorable	Transfer MBT1	-
Elex1CA	Restorable	Transfer MBT1	-
LCP1AB	Unrestorable	-	No reconfigurable path
LCP1BC	Unrestorable	-	No reconfigurable path
LCP1CA	Unrestorable	-	No reconfigurable path
Cmsry	Unrestorable	-	No reconfigurable path
LCP6AB	Unrestorable	-	No reconfigurable path
LCP6BC	Unrestorable	-	No reconfigurable path
LCP6CA	Unrestorable	-	No reconfigurable path

4.3.4.3 Hit at Randomly Selected Location 3

The damaged components in this case due to the missile hit were same as given in section 4.3.3.3. The results of the Failure Assessment agent, in this case, are shown in the Table 4.29.

Table 4.29

Results of the Failure Assessment Agent for Hit at (295,50,3), Without Pre-hit Reconfiguration

Components in Faulted Sections	**Component type**	**De-energized loads**
C1114, C1117, C1310	Cable	Galley1, Galley2, Elex2, and Torpedo

After the execution of the Failure Assessment agent, the Post-hit Coordination agent called the Post-hit Reconfiguration for Restoration agent. The results of the Post-hit Reconfiguration for Restoration agent and the System Analysis agent, for this case, are shown in Table 4.30. In this case the System Analysis agent determined that there were no system constraint violations.

Table 4.30

Results of Post-hit Reconfiguration for Restoration Agent and System Analysis Agent for Hit at (295,50,3), Without Pre-hit Reconfiguration

De-energized Load	**Output of Post-hit Reconfiguration for Restoration agent**		**Output of System Analysis agent**	
	Is Reconfigurable?	**Reconfiguration actions**	**Constraint Violated?**	**Description of constraint violation**
Galley1	No	-	-	-
Galley2	No	-	-	-
Elex2	Yes	Transfer MBT2	No	-
Torpedo	Yes	Transfer MBT6	No	-

Finally, the results of the Post-hit Coordination agent are given in the Table 4.31.

Table 4.31

Results of Post-hit Coordination Agent for Hit at (295,50,3) Without Pre-hit Reconfiguration

De-energized Load	Restorable or Unrestorable	Suggested reconfiguration actions for restorable loads	Reason for being Unrestorable
Galley1	Unrestorable	-	No reconfigurable path
Galley2	Unrestorable	-	No reconfigurable path
Elex2	Restorable	Transfer MBT2	-
Torpedo	Restorable	Transfer MBT6	-

4.3.4.4 Hit at Randomly Selected Location 4

The damaged components in this case due to the missile hit were same as given in section 4.3.3.4. The results of the Failure Assessment agent, in this case, are shown in the Table 4.32.

Table 4.32

Results of the Failure Assessment Agent for Hit at (273,35,-7), Without Pre-hit Reconfiguration

Components in Faulted Sections	Component type	De-energized loads
C1205, C1213, C1303	Cable	Elex1AB, Elex1BC, Elex1CA, LCP1AB, LCP1BC, LCP1CA, LCP6AB, LCP6BC, and LCP6CA

After the execution of the Failure Assessment agent, the Post-hit Coordination agent called the Post-hit Reconfiguration for Restoration agent. The results of the Post-hit Reconfiguration for Restoration agent and the System Analysis agent, for this case, are shown in Table 4.33. In this case the System Analysis agent determined that there were no system constraint violations.

Table 4.33

Results of Post-hit Reconfiguration for Restoration Agent and System Analysis Agent for Hit at (273,35,-7), Without Pre-hit Reconfiguration

De-energized Load	**Output of Post-hit Restoration agent**		**Output of System Analysis agent**	
	Is Reconfigurable?	**Reconfiguration actions**	**Constraint Violated?**	**Description of constraint violation**
LCP6AB	No	-	-	-
LCP6BC	No	-	-	-
LCP6CA	No	-	-	-
Elex1AB	Yes	Transfer MBT1	No	-
Elex1BC	Yes	Transfer MBT1	No	-
Elex1CA	Yes	Transfer MBT1	No	-
LCP1AB	No	-	-	-
LCP1BC	No	-	-	-
LCP1CA	No	-	-	-

Finally, the results of the Post-hit Coordination agent are given in the Table 4.34.

Table 4.34

Results of Post-hit Coordination Agent for Hit at (273,35,-7), Without Pre-hit Reconfiguration

De-energized Load	**Restorable or Unrestorable**	**Suggested reconfiguration actions for restorable loads**	**Reason for being Unrestorable**
LCP6AB	Unrestorable	-	No reconfigurable path
LCP6BC	Unrestorable	-	No reconfigurable path
LCP6CA	Unrestorable	-	No reconfigurable path
Elex1AB	Restorable	Transfer MBT1	-
Elex1BC	Restorable	Transfer MBT1	-
Elex1CA	Restorable	Transfer MBT1	-
LCP1AB	Unrestorable	-	No reconfigurable path
LCP1BC	Unrestorable	-	No reconfigurable path
LCP1CA	Unrestorable	-	No reconfigurable path

4.3.5 Comparison of Results

In this section, a comparison of results obtained in sections 4.3.3 and 4.3.4 is presented. The results obtained in section 4.3.3 were results of performing reconfiguration for restoration using the reconfiguration actions determined by the Pre-hit Coordination agent or in other words they are the results of Predictive Reconfiguration. In section 4.3.4, the results were determined assuming no pre-hit reconfiguration was performed or in other words they are the results of Restoration process. In each situation, reconfiguration for restoration control actions for 4 different cases, based on four weapon-hit locations, were determined. The results for both situations in each case were compared and are presented below.

4.3.5.1 Comparison of Reconfiguration for Restoration Results When Weapon Hit Location Was Randomly Selected Location 1

For hit location (285,35,-4), a comparison of results between the cases when pre-hit reconfiguration was performed and when it was not performed is shown in Table 4.35. For each case, de-energized loads for which reconfiguration for restoration was performed, components in faulted sections, and loads which were unrestored have been compared. In the case where pre-hit reconfiguration was performed, the number of de-energized loads and the number of components identified in faulted sections were less. Thus pre-hit reconfiguration resulted in isolation of sections that would have caused faults in the electrical system.

Table 4.35

Comparison of Results for Hit Location (285,35-4)

De-energized Loads considered for reconfiguration for restoration		**Components in faulted sections**		**Unrestored loads**	
Predictive Reconfiguration	**Restoration process**	**Predictive Reconfiguration**	**Restoration process**	**Predictive Reconfiguration**	**Restoration process**
Galley1	Galley1	C1303	C1205, C1303, C1305	Galley1	Galley1
Galley2	Galley2			Galley2	Galley2
LCP1AB	LCP1AB			LCP1AB	LCP1AB
LCP1BC	LCP1BC			LCP1BC	LCP1BC

Table 4.35 continued

De-energized Loads considered for reconfiguration for restoration		**Components in faulted sections**		**Unrestored loads**	
Predictive Reconfiguration	**Restoration process**	**Predictive Reconfiguration**	**Restoration process**	**Predictive Reconfiguration**	**Restoration process**
LCP1CA	LCP1CA			LCP1CA	LCP1CA
Cmsry	Elex3				
	Elex1AB				
	Elex1BC				
	Elex1CA				

The reason for lesser number of de-energized loads is because the Pre-hit Probabilistic Reconfiguration method was able to predict the components, which would be damaged by the weapon hit and also reconfigure each vital load before the actual hit to a supply path that allows it to survive faults due to damage. In the situation where the Pre-hit Probabilistic Reconfiguration method was performed, loads Elex3, Elex1AB, Elex1BC, and Elex1CA were reconfigured before the actual weapon hit took place. For example, load Elex3 was reconfigured, before the weapon hit, by transferring MBT3 to an alternate path. Hence in general supply interruptions to vital loads were reduced. Whereas in the case where no Pre-hit Probabilistic Reconfiguration was performed, the vital loads mentioned earlier, were de-energized due to the damage caused by the weapon hit. Reduction of supply interruption to vital loads is one of the goals of Predictive Reconfiguration, which was achieved in this case. An interruption of electrical supply, even for a small time period, to some vital loads can reduce the chances of a ship's survivability. Also, since some components that were damaged due to the actual weapon hit were isolated before the hit, when Pre-hit Reconfiguration was performed, the chances of cascading faults were also reduced. This was also one of the goals of Predictive Reconfiguration. Hence the performance of the Predictive Reconfiguration methodology was superior to the performance of Restoration process.

4.3.5.2 Comparison of Reconfiguration for Restoration Results When Weapon Hit Location Was Randomly Selected Location 2

In this case also, there were lesser number of de-energized loads, and components in faulted sections in the case of Predictive Reconfiguration method as compared to Restoration process. This is shown in table 4.36. The reason for that is same as that explained in section 4.3.5.1. In case of Predictive Reconfiguration there was no interruption of electrical supply to any of the vital loads, whereas in the case of Restoration method, electrical supply to vital loads Elex1AB, Elex1BC, Elex1CA, Torpedo, and Elex2 was interrupted and was later on restored by reconfiguration for restoration method. Also, in this case, fault on cable C1204 resulted in a cascading fault condition in the case of Restoration process that eventually caused fault on cable C1204. This resulted in de-energization of non-vital loads Cmsry, LCP6AB, LCP6BC, and LCP6CA. These loads were unrestorable in the Restoration process. Whereas in Predictive Reconfiguration method cable C1204 was isolated due to control actions of Pre-hit Probabilistic Reconfiguration method, hence the cascading fault condition was averted. Hence the performance of the developed Predictive Reconfiguration methodology was superior to the performance of Restoration process performed without pre-hit reconfiguration.

Table 4.36

Comparison of Results for Hit Location (290,45,-3)

De-energized Loads considered for restoration		**Components in faulted sections**		**Unrestored loads**	
Predictive Reconfiguration	**Restoration process**	**Predictive Reconfiguration**	**Restoration process**	**Predictive Reconfiguration**	**Restoration process**
Galley1	Galley1	C1114, C1117	C1205, C1310, C1114, C1117, C1311	Galley1	Galley1
Galley2	Galley2			Galley2	Galley2
LCP1AB	Elex2			LCP1AB	LCP1AB
LCP1BC	Torpedo			LCP1BC	LCP1BC
LCP1CA	Elex1AB			LCP1CA	LCP1CA
Cmsry	Elex1BC			Cmsry	Cmsry
	Elex1CA				LCP6AB
	LCP1AB				LCP6BC

Table 4.36 continued

De-energized Loads considered for restoration		Components in faulted sections		Unrestored loads	
Predictive Reconfiguration	**Restoration process**	**Predictive Reconfiguration**	**Restoration process**	**Predictive Reconfiguration**	**Restoration process**
	LCP1BC				LCP6CA
	LCP1CA				
	Cmsry				
	LCP6AB				
	LCP6BC				
	LCP6CA				

4.3.5.3 Comparison of Reconfiguration for Restoration Results When Weapon Hit Location Was Randomly Selected Location 3

In this case nearly same numbers of loads were de-energized in the cases of Predictive Reconfiguration and Restoration process. But the numbers of components in faulted sections were less for Predictive Reconfiguration. Hence the chances of cascading faults were reduced. The comparison is shown in table 4.37. In this case also, there was no interruption of electrical supply any vital load in the case of Predictive Reconfiguration whereas in Restoration method, 2 vital loads were required to be restored. But it can be seen that, in this case the performance of Predictive Reconfiguration is not superior to Restoration process, as compared to cases in section 4.3.5.1 and 4.3.5.2. The reason for that is because in this case the miss distance of missile, with respect to the predicted hit location was large. It was 14.5 feet. This affected the accuracy of computing the EPOD values for the electrical components. So in this case LC1AB, LCP1BC, LCP1CA, and Cmsry were de-energized by the Pre-hit Probabilistic Reconfiguration module as it expected that the cable C1205 and C1214, upstream of those loads, have a very high probability of getting damaged. But when the actual hit occurred, cable C1205 and C1214 was not damaged. Hence the de-energization of these loads was unnecessary.

Table 4.37

Comparison of Results for Hit Location (295,50,3)

De-energized Loads considered for restoration		Components in faulted sections		Unrestored loads	
Predictive Reconfiguration	**Restoration process**	**Predictive Reconfiguration**	**Restoration process**	**Predictive Reconfiguration**	**Restoration process**
Galley1	Galley1	C1114, C1117	C1114, C1117, C1310, C1311	Galley1	**Galley1**
Galley2	Galley2			Galley2	**Galley2**
LCP1AB	Elex2				
LCP1BC	Torpedo				
LCP1CA					
Cmsry					

4.3.5.4 Comparison of Reconfiguration for Restoration Results When Weapon Hit Location Was Randomly Selected Location 4

In this case also, the performance of Predictive Reconfiguration was more or less same as that of Restoration process. The number of de-energized loads and unrestored loads in this case were nearly equal. This is shown in table 4.38. The reason for that is because in this case also the miss distance of missile was large. It was 18.4 feet. It should be mentioned, though, that in this case also, the de-energized loads in the case of Predictive Reconfiguration method were all non-vital loads where as in the case Restoration process, 3 vital loads, Elex1AB, Elex1BC, and Elex1CA were also de-energized but were later restored.

Table 4.38

Comparison of Results for Hit Location (273,35,-7)

De-energized Loads considered for restoration		Components in faulted sections		Unrestored loads	
Predictive Reconfiguration	**Restoration process**	**Predictive Reconfiguration**	**Restoration process**	**Predictive Reconfiguration**	**Restoration process**
LCP6AB	LCP6AB	C1213, C1303	C1205, C1213, C1303	LCP6AB	LCP6AB
LCP6BC	LCP6BC			LCP6BC	LCP6BC
LCP6CA	LCP6CA			LCP6CA	LCP6CA

Table 4.38 continued

De-energized Loads considered for restoration		**Components in faulted sections**		**Unrestored loads**	
Predictive Reconfiguration	**Restoration process**	**Predictive Reconfiguration**	**Restoration process**	**Predictive Reconfiguration**	**Restoration process**
Galley1	Elex1AB			LCP1AB	LCP1AB
Galley2	Elex1BC			LCP1BC	LCP1BC
LCP1AB	Elex1CA			LCP1CA	LCP1CA
LCP1BC	LCP1AB				
LCP1CA	LCP1BC				
Cmsry	LCP1CA				

4.4 SUMMARY

In this chapter a scenario based on a missile hit to the test ship model, was presented to illustrate the Predictive Reconfiguration method. Results of the various agents from four cases, based on four weapon hit locations, were also presented. In section 4.3.5, comparison of the Predictive Reconfiguration method and a reconfiguration for restoration method without pre-hit reconfiguration was presented. It was found that the Predictive Reconfiguration method was very effective for cases when the miss distance of actual missile hit was not large. In such cases, the Predictive Reconfiguration method was able to achieve its goal of reduction in supply interruption of vital loads and prevention of cascading faults. In other words, it was found that the effectiveness of Predictive Reconfiguration methodology is dependent on the accuracy of the prediction of the probability density function for the weapon-hit location. However, even in the case of inaccurate predictions for weapon hit location, the results of Predictive Reconfiguration method were either slightly better or at least the same as the results obtained by performing reconfiguration for restoration without pre-hit reconfiguration. Hence it can be concluded that the proposed Predictive Reconfiguration methodology is an effective methodology and its performance is superior to that of performing reconfiguration for restoration without pre-hit reconfiguration.

CHAPTER V

CONCLUSIONS AND FUTURE WORK

5.1 CONCLUSIONS

As a part of the research work conducted at the Power System Automation Laboratory (PSAL), a Predictive Reconfiguration methodology was developed and implemented for Shipboard Power Systems (SPS). This methodology was developed to determine control actions for reconfiguring a SPS, before a weapon hit, such that the damage that will be caused to the SPS is reduced.

The problem of Predictive Reconfiguration was formulated. The problem was to reduce the damage that will be caused by a weapon hit. In order to solve this problem, the interruption of supply to vital loads and the electrical faults and cascading faults that might be caused by the weapon hit should be reduced. In order to achieve these objectives, a method to assess the damage that will be caused by a weapon hit was developed. Various factors which affect the damage assessment of a weapon hit before the hit were addressed. It was concluded that a probabilistic approach was required to assess the weapon damage, before an actual hit. Using the information available from the attacker’s point of view, a method to compute the expected probability of damage for an electrical component was presented. In developing this method assumptions were made that the probability density function of the weapon hit location was known. It was also assumed that a function, which describes the probability of kill at a point, situated at a given distance from the actual hit location, was known.

Then a probabilistic approach to reconfigure the SPS, before a weapon hit, to reduce the damage that will be caused by the actual weapon hit was presented. This method used the expected probability of damage, computed for each electrical component. In this method two modules, which addressed two goals of Predictive Reconfiguration, were presented. The first module, referred to as Reconfiguration for Component Isolation, addressed the “reduction of electrical faults and cascading fault” goal of the Predictive Reconfiguration. This module determines control actions for non-vital loads only. The second module, referred to as Reconfiguration for Reduction in Supply Interruption, addressed the “reduction of supply interruption to vital load” goal of the Predictive Reconfiguration. This module determines control actions for vital loads, only. Test cases were presented to explain the both methodology.

The Pre-hit Probabilistic Reconfiguration method, which implemented both the modules, was then presented. It was shown that by executing the Reconfiguration for Component Isolation module, first, followed by the execution of Reconfiguration for Reduction in Supply Interruption module the goals of Predictive Reconfiguration could be achieved. Test cases were presented to illustrate this point. The execution of Pre-hit Probabilistic Reconfiguration determined control action to reconfigure the SPS such that the damage that will be caused by the weapon hit was reduced.

The methodology was implemented using Multi-Agent technology. A Multi-Agent System (MAS) was developed to implement the Pre-hit Probabilistic Reconfiguration method for the SPSs. This MAS also implemented a Post-hit Reconfiguration for Restoration method, which was developed earlier at PSAL. Various agents were developed to perform various tasks, which can be considered as specialized tasks. The structure of each of these agents were presented and discussed.

An illustration of the methodology was presented for a scenario, which considered a situation in which a ship was under attack and a missile was fired at the ship. This illustration was applied to a test SPS model. This test SPS model was based on the reduced electrical layout of a non-nuclear surface combatant ship. In this illustration, control actions for the Pre-hit Probabilistic Reconfiguration were obtained assuming the probability density function of the missile-hit location and a function that describes probability of kill at a point for that missile are given. Some of the determined control actions were then implemented. Four cases, assuming four hit locations, were presented. These hit locations were randomly chosen with different missile miss distances. Then for each of these cases, Post-hit Reconfiguration for Restoration was performed. Post-hit Reconfiguration for Restoration was also performed for each of these cases with the assumption that no pre-hit reconfiguration was performed earlier. Then the results obtained when pre-hit reconfiguration was performed were compared with results obtained when no pre-hit reconfiguration was performed.

Analysis of these comparisons showed that the effectiveness of the Pre-hit Probabilistic method is dependent on the accuracy of the prediction of probability density function for weapon-hit location. Of the 4 cases compared, Predictive Reconfiguration gave very good results, for two cases. In the other two cases, in which the miss distances were large, the results of Predictive Reconfiguration were comparable or slightly better than the cases in which no pre-hit reconfiguration was performed. It was concluded that the Predictive Reconfiguration methodology is an effective methodology and its performance is superior to that of performing reconfiguration for restoration without pre-hit reconfiguration.

5.2 FUTURE WORK

Work presented in this dissertation discussed a new Predictive Reconfiguration method developed to reduce the damage that will be caused by the hit of an incoming weapon. The future work in this area can address following aspects:

The weapon damage assessment methodology developed in this dissertation considers only a single weapon hit scenario. A comprehensive weapon damage assessment method can be investigated for multiple weapon-hit scenarios.

While calculating PAP for a radial path, it was assumed that damage to a circuit breaker will always cause an open circuit fault condition. The work in this dissertation can be extended by considering the effects of short circuit faults on circuit breakers.

The accuracy of the Pre-hit Probabilistic Reconfiguration methodology is dependent on the accuracy of the prediction of the weapon hit location. This methodology should be made more to provide high accuracy even for uncertain prediction.

The Predictive Reconfiguration methodology was not tested with real time information/data, as it was not available in the public literature. Hence the methodology should be tested with real information/data and more complex test cases using simulated data should be designed to test the effectiveness of the methodology.

The probabilistic information outputted with the control actions determined by the

Reconfiguration for Component Isolation (RCI) module is the Path Availability Probability (PAP) for the radial path of a the non-vital load, whereas the for the control actions determined by the Reconfiguration for Reduction in Supply Interruption (RRSI) module, PAP value of the better path and PAP difference are outputted. A uniform probabilistic measure should be computed for the control actions determined by either RCI module or RRSI module.

REFERENCES

[1] K. L. Butler, N. D. R. Sarma, and V. Prasad, "Network reconfiguration for service restoration in shipboard power distribution systems", *IEEE Trans. Power Systems*, vol. 16, no. 4, pp. 653-661, Nov. 2001.

[2] S. K. Srivastava, and K. L. Butler-Purry, "An expert system method for automatic reconfiguration for restoration of shipboard power systems", submitted to *IEEE Trans. Power Systems*.

[3] E. L. Zivi, "Integrated shipboard power and automation control challenge problem", in *Proc. 2002 IEEE Power Engineering Society Summer Meeting*, vol. 1, pp. 325-330, 21-25 Jul. 2002.

[4] K. L. Butler, N. D. R. Sarma, C. Whitcomb, H. Do Carmo, and H. Zhang, "Shipboard systems deploy automated protection", *IEEE Computer Applications in Power*, vol. 11, no. 2, pp. 31-36, Apr. 1998.

[5] R. M. Lloyd, *Conventional Warhead Systems Physics and Engineering Design*, American Institute of Aeronautics and Astronautics, Inc., 1998.

[6] G. Merrill, *Principles of Guided Missile Design*, D. Van Nostrad Company, Inc., 1960.

[7] P. Birtles, and P. Beaver, *Missile Systems*, Ian Allan, Shepperton, 1985.

[8] R. G. Lee, E. Archer, T. K. Garland-Collins, D. E. Johnson, G. M. Moss, A. W. Mowat, and C. Sparkes, *Guided Weapons*, Brassey's Defence Publishers Ltd., 1988.

[9] K. F. Gantz, *The United States Air Force Report on the Ballistic Missile: Its Technology, Logistics, and Strategy*, Doubleday Publications, 1958.

[10] D. Emerson, *TSARINA – User's Guide to a Computer Model for Damage Assessment of Complex Airbase Targets*, The RAND Corporation, July 1980.

[11] J. L. Kent, *Ship in Rough Water*, London Publishers, 1958.

[12] G. M. Clark, and D. Cooke, *A Basic Course in Statistics*, Arnold Publishers, 1998.

[13] P. R. Cohen, *Heuristic Reasoning about Uncertainty: An Artificial Intelligence Approach*, Pitman Publishing Limited, 1985.

[14] H. Xiao, “An Automated Knowledge-based Failure Assessment Methodology for Shipboard Electric Power Systems”, PhD dissertation, May 2004, Texas A&M University.

[15] “Bentley GeoEngineering Academic Suite,” Bentley Systems Incorporated, MicroStation Version 05.07.00.41 Windows x86, 1998.

[16] Multilogic, *Exsys Developer User Manual*, 1999.

[17] *Exsys Developer and Exsys Web Runtime Documentation Supplement*, Version 8.0, Multilogic, Inc. 1999.

[18] J. M. Bradshaw, *Software Agents*, American Association for Artificial Intelligence Press, 1997.

[19] J. Liu, and N. Zhong, *Intelligent Agent Technology – System, Methodologies and Tools*, World Scientific Publishing Co. Pte. Ltd., 1999.

[20] M. Wooldridge, *An Introduction to MultiAgent Systems*, John Wiley & Sons Ltd., 2002.

[21] M. Wooldridge and N. R. Jennings, “Intelligent Agents: Theory and Practice”, *The Knowledge Engineering Review*, vol. 10, no. 2, pp. 115-152, 1995.

[22] M. d’Inverno and M. Luck, *Undersatanding Agent Systems*, Springer Series on Agent Technology, 2001.

[23] R. Jennings, “On Agent-based Software Engineering”, *Artificial Intelligence*, vol. 117, no. 2, pp. 277-296, 2000.

[24] T. Nagata, and H. Sasaki, “A multi-agent system for power system restoration”, in *Proc.2001 IEEE Power Engineering Society Winter Meeting*, vol. 3, pp. 1359-1364, 2001.

[25] M. Amin, “Toward self-healing energy infrastructure systems”, *IEEE Computer Applications in Power*, vol. 11, pp. 31-36, Apr. 1998.

[26] T. Nagata, Y. Tao, H. Sasaki and H. Fujita, “A Multi-Agent approach to distribution system restoration”, in *Proc. 2003 IEEE Power Engineering Society General Meeting*, July 2003, (CD-ROM).

[27] J. Jung. and C.-C. Liu, “Multi-Agent System Technologies and an application for power system Vulnerability”, in *Proc. 2003 IEEE Power Engineering Society General Meeting*, July 2003, (CD-ROM).

[28] Z. Ming, R. Jianwen, L. Gengyin and X. Xianghai "A Multi-Agent based dispatching operation instructing system in electric power systems", in *Proc. 2003 IEEE Power Engineering Society General Meeting*, July 2003, (CD-ROM).

[29] S. K. Srivastava, H. Xiao, and K. L Butler-Purry, "Multi-Agent system for automated service restoration of shipboard power systems", in *Proc. 15th International Conference on Computer Applications in Industry and Engineering*, pp. 119-123, 7-9 Nov. 2002.

[30] E. Mangina, S. D. J. McArthur, and J. R. McDonald, "The use of a Multi-Agent paradigm in electrical plant condition monitoring", in *Proc. Large Engineering Systems Conference on Power Engineering*, pp. 31-36, 2001.

[31] P. M. Diep, J. Reaidy, and L. Y. Jiu, "Design and integration of intelligent agents to implement sustainable production systems", in *Proc. 2nd International Symposium on Environmentally Conscious Design and Inverse Manufacturing,* pp. 729 –734, 2001

[32] S. Fox, "AI and expert system myths, legends, and facts", *IEEE Magazine of Expert Intelligent Systems and Their Applications*, vol. 5, no. 1, pp. 8-20, Feb. 1990.

[33] U. P. Rajbhandari, "Development of a geographical information system based modeling of a shipboard power system", M.S. Thesis, May 2001, Texas A&M University.

[34] *Alternative Transients Program (ATP) Rule Book*, Canadian/American EMTP User Group, 1987-95.

[35] "Circuit Breakers, Low Voltage, Electric Power, Air, Open Frame, Removable Construction", Military Specification MIL-C-17587B(SH), Naval Sea Systems Command, April 1983.

[36] "Fault Current Calculations and Protective Device Coordinations for 60 and 4000 Hz Power Systems Supplied by Rotating Machinery", DDS 300-2, Nval Sea Systems Command, May 1995.

APPENDIX

The global databases consist of GIS, Historical and Constraint databases. The structures of each of these databases are given below.

GIS DATABASE

The GIS database has connectivity, dynamic and static information for each type of electrical component**.**

Component Type	Connectivity Information	Dynamic Information	Static Information
Bus Transfer	Type, node on normal side, node on alternate side, node on load side	Working Status, BT Position	-
Cable	Phase Type, from nodes, to nodes	Working Status, Current Magnitude, Current Phase, Voltage Magnitude, Voltage Phase	No. of parallel cables, Length, Rated Voltage, Ampacity, Size, Resistance, Self Inductance, Mutual Inductance, Self Capacitance, Mutual Capacitance, Type
Circuit Breaker	CB Location Type, from node, to node, Connected CB	Working Status, CB Status, Current Magnitude, Current Phase	Ampere Rating, Power Rating, kVar Rating, Time Setting for Instant Current, Time Setting for Instant Time, Time Setting for Short Current, Time Setting for Short Time, Time Setting for Long Current, Time Setting for Long Time, Type
Generator	from node, to node, Connected CB	Working Status, Current Magnitude, Current Phase, Voltage Magnitude, Voltage Phase, Power, Speed Frequency	Voltage Rating, Active Power Rating, Reactive Power Rating, Rated Frequency, Rated Speed, Rated Power factor, Type
Load Center	from node, to node, Connected CB, Connected SB	Current Magnitude, Current Phase, Voltage Magnitude, Voltage Phase	Voltage Rating
Load	Connected BT, Connected LVPR, Phase Type, from node, Connected CB normal side, Connected CB alternate side, Connected Unit normal side, Connected Unit alternate side,	Working Status, Current Magnitude, Current Phase, Voltage Magnitude, Voltage Phase	Voltage Rating, , Rated Frequency, Rated Power factor, Type, Rated Power, Full Load Current, Starting Current, Priority, Impedance Rating, Resistance, Reactance, Inductance

	Connected Transformer,		
LVP/LVR	Type, Phase Type, from node, to node	Working status, LVPR status, Current Magnitude, Current Phase, Voltage Magnitude, Voltage Phase	-
Power Panel	from node, to node, Connected CB, Connected LC or SB	Working status, Current Magnitude, Current Phase, Voltage Magnitude, Voltage Phase	-
Switchboard	from node, to node, Connected CB, Connected generator	Working status, Current Magnitude, Current Phase, Voltage Magnitude, Voltage Phase	Voltage Rating
Transformer	from node, to node	Working status, Current Magnitude, Current Phase, Voltage Magnitude, Voltage Phase	Voltage Rating, Tap Position, Power Rating, Turns Ratio

The GIS database also has a System table, which contains geographical information for each electrical component. Its structure is as given below.

Table Name	**Information stored**
Systemtable	Component Name, Component Type, Connection Status, Deck Frame, Alignment, X, Y, Z

HISTORICAL DATABASE

The Historical database stores real time information for a period starting from a pre-fault time to some time after the fault had occurred and the system had attained steady state. It consisted of tables for each circuit breaker, load center and switchboard in the system. The structure of these tables is given below.

Component Type	**Information stored**
Circuit Breaker	Time Step, CB Status, Currents in each phase
Load Center	Time Step, Voltage for each phase
Switchboard	Time Step, Voltage for each phase

CONSTRAINT DATABASE

The Constraint database consisted of tables that store constraint information for various components. There were five tables. The structure of each table is given below.

Table Name	**Information stored**
CableCurrent	Cable Name, Upper Current Limit
LoadVoltage	Load Name, Lower Voltage Limit, Upper Voltage Limit
Frequency	Generator Name, Lower Frequency Limit, Upper Frequency Limit
CBCurrent	CB Name, Lower Current Limit, Upper Current Limit
SBVoltage	Switchboard Name, Lower Voltage Limit, Upper Voltage Limit

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