

Techniques of Network Reconfiguration for Service Restoration in Shipboard Power System: A Review

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Abstract: The shipboard power system supplies energy to sophisticated systems for weapons, communications, navigation, and operation. After a fault is encountered, reconfiguration of a shipboard power system becomes a critical activity that is required to either restore service to a lost load or to meet some operational requirements of the ship. Reconfiguration refers to changing the topology of the power system in order to isolate system damage and/or optimize certain characteristics of the system related to power efficiency. When finding the optimal state, it is important to have a method that finds the desired state within a short amount of time, in order to allow fast response for the system. Since the reconfiguration problem is highly nonlinear over a domain of discrete variables, various techniques have been proposed by the researchers. The main tasks of this paper include reviewing the shipboard power system characteristics, studying and reviewing shipboard power system integrated protection, shipboard power distribution systems and typical loads of shipboard power system. A variety of techniques used in previous works have been explained in methodologies review. Many criteria and concepts are used as the basis for consideration in order to achieve the desired objectives.

Key words: Reconfiguration, Fault Location, Service restoration, Distribution Power System

INTRODUCTION

The Navy ship electric power system supplies energy to the weapons, communication systems, navigation systems, and operation systems. The reliability and survivability of a Shipboard Power Systems (SPS) are critical to the mission of a ship, especially under battle conditions. SPS are geographically spread all along the ship.

They consist of various components such as generators, cables, switchboards, load centres, circuit breakers, bus transfer switches, fuse and load.

The generators in SPS are connected in ring configuration through generator switchboards. (Sarma *et al.*, 1994). Bus tie circuit breakers interconnect the generator switchboards which allow for the transfer of power from one switchboard to another. Load centers and some loads are supplied from generator switchboards. Load centers in turn supply power to power panels to which different loads are connected. Feeders then supply power to load centers and power panels. The distribution of loads is radial in nature. For vital loads, two sources of power (normal and alternate) are provided from separate sources via automatic bus transfers (ABTs) or manual bus transfers (MBTs). Further, vital loads are isolated from non-vital loads to accommodate load shedding during an electrical system causality.

Circuit breakers (CBs) and fuses are provided at different locations in order to remove faulted loads, generators or distribution systems from unfaulted portions of the system. These faults could be due to material causalities of individual loads or cables or due to widespread system fault due to battle damage. Because of the faults and after isolating the fault, there are unfaulted sections which are left without supply. It is required to quickly restore supply to these unfaulted sections of the SPS. This is accomplished by changing the configuration of the system by opening and/or closing some switches (CBs/MBTs/ABTs) to restore supply to maximum load in the unfaulted section of SPS to continue the present mission (Butler *et al.*, 1999).

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Shipboard Power System Characteristics:

Today's SPS generally use three-phase power generated and distributed in an ungrounded configuration. The ungrounded systems can keep equipment in continued operations in the event of the single-phase ground fault. Ungrounded systems mean all cabling are insulated from the ship hull. Thus, it optimizes continuity of power (increase equipment reliability).

SPS have different characteristics from typical utility power systems in overall configuration and load characteristics. Some of the unique characteristics of the SPSs are as follows: (L. Sun *et al.*, 2004)

- There is very little rotational inertia relative to load in SPS.
- SPS is an isolated system with no power supply from outside power system.
- SPS has a wider frequency range compared to the terrestrial power system.
- Shipboard prime movers typically have shorter time constant than prime movers in terrestrial power systems.
- Due to the limited space on shipboard, SPS does not have a transmission system.
- The electric power in SPS is transmitted through short cables. It leads to less power loss and voltage drop as compared to terrestrial power systems.
- There is a large portion of nonlinear loads relative to the power generation capability.
- In SPS, a large number of electric components are tightly coupled in a small space. A fault happens in one part of the SPS may affect other parts of the SPS.
- A large number of electronic loads, such as combat, control and communication sensors, radiators, and computers are sensitive to power interruptions and power quality.
- Some electrical components, which affect the reconfiguration process, are unique to SPS such as Automatic Bus Transfers (ABT), Manual Bus Transfers (MBT), Low Voltage Protection devices (LVPs), and Low Voltage Release devices (LVRs).

Due to these unique characteristics of the SPS, some of the mathematical expediences used in terrestrial power system analysis may not be applicable to SPS accordingly. For example, infinite buses and slack buses do not have manifestations in SPSs. Constant voltage, constant frequency, and constant power simplifications are usually invalid in SPS. Also, the SPSs are tightly coupled both electrically and mechanically, requiring integrated modelling of both systems (Xiuxia Yang *et al.*, 2005). A brief overview of the loads in the SPS is explained in the following section.

Loads in the SPS:

The loads in the SPS provide various services to the ship. According to the importance of the services being provided, the loads in the SPS can be classified into non-vital, semi-vital, and vital-loads in increasing priority order as follows:

Non-vital (Non-essential):

-Readily sheddable loads that can be immediately secured without adversely affecting ship operations, survivability, or life. Examples are hotel loads such as heating and galley; ship, avionics, and ground support equipment shops; aircraft fuelling systems; refrigeration systems; and other loads that can be shut down for a short time until full electric power capability is restored.

Semi-vital (Semi-essential):

- Loads important to the ship but that can be shut down or switched to the alternate plant in order to prevent total loss of ship's electrical power. Examples include aircraft and cargo elevators, assault systems, some radar, communications, and seawater service pumps.

Vital (Essential):

- Non-sheddable loads that affects the survivability of ship or life. Power to these loads is not intentionally interrupted as part of a load shedding scheme. Examples of vital loads are generators, boilers, and their auxiliaries; close-in weapon systems; electronic countermeasures; tactical data system equipments with volatile memories; medical and dental operating rooms; and primary air search radar.

The vital loads are required to be connected to two independent power sources in the SPS. If a load is classified as vital load at any major mission of the ship, such as propulsion system, it has to be connected to the SPS through Automatic Bus Transfer (ABT). ABT is a device that can sense the loss of power from

normal power source. When normal power is absent, ABT can automatically disconnect the load from the normal power and switch the load's power flow from an alternate power source. ABTs are designed to transfer loads very quickly. If a load is classified as a vital load in some missions and a non-vital load in other missions, such as the lighting system, the load is connected to its SPS through a Manual Bus Transfer (MBT). MBT is a device, like an ABT, that can connect loads either to a normal power source or to an alternate power source. But unlike the ABT, the MBT must be shifted manually by an operator when the operator notices that the load's primary source of power becomes unavailable. Loads that are classified as non-vital loads in any missions are connected to only one power source in the SPS. The electric loads are hard wired to their source(s) at the time of ship construction. How "vital" they are is determined at that time and does not change unless the power system hardware is modified (A. Feliachi *et al.*, 2006). One of the important aspects in considering loads in SPS is Protection and integrated power system is one type of protection in SPS.

Integrated Power System (IPS):

The IPS design is applied because it is simpler and cheaper, and better to centrally produce a commodity such as electricity, than to locally produce it with the user of commodity. In the IPS, the ship service and the propulsion loads are provided by a common set of generators. The integrated power systems are currently used for a wide range of ship applications. The primary advantage of using integrated power systems is the flexibility to shift power between the propulsion and mission-critical loads as needed. The integrated power system can also improve the survivability and reliability of the SPS. It has been identified as the next generation technology for SPS platform and an important step to achieve the all-electric ship initiative (Xiuxia Yang *et al.*, 2005). In SPSs, different faults may occur because of equipment insulation failures, over voltages caused by switching surges, or battle damage. Shipboard power protection systems are required to detect faults and undesirable conditions and quickly remove the faults from the power system.

Shipboard power protection systems are also required to maintain power balance for the remaining part of the power system automatically and quickly. Therefore, an integrated power protection system is necessary for SPSs to maximize service continuity and minimize loss-of-load caused by accidental system abnormal behaviour or hostile damage.

The main objective of Shipboard power distribution systems are designed to minimize the size and weight, save money, and improve the survivability of the vessel. Additionally, shipboard power distribution systems are desired to possess the ability to continually transfer power to vital systems during and after fault conditions. There are two possible types of shipboard power distribution architecture radial and zonal.

Radial electric Power Distribution:

Distribution lines are usually radial and operate at low-level voltages in a radial shipboard power system. Current shipboard radial electric power distribution systems have multiple generators (typically three or four), which are connected to switchboards. The generators could be steam turbine, gas turbines, or diesel engines. The generators are operated either in a split plant or a parallel configuration. The 450V, 60Hz three phase ac power is then distributed to load centers. Each load is classified as being nonessential, semi-essential, or essential. If there is any generation capacity loss, a load shedding algorithm will be initiated based on load priority. In a current navy ship power system, three-phase step-down power transformers are normally used. Both the transformer primary and secondary windings are connected in a delta, resulting in no reliable current path from the power lines to the ship's hull. Therefore, the system has a high impedance ground and will not be affected by single phase grounded fault.

Zonal Electric Power Distribution:

The zonal power distribution system consists of two main power distribution buses running longitudinally along the port and starboard side of the ship. One main bus would be positioned well above the waterline while the other would be located below the waterline, which maximizes the distance between buses and improves the survivability (B. R. Gautam *et al.*, 2007). The effects of damage to the distributed system and other equipment should not disturb generators. The zonal architecture is flexible and saves the cost for short switchboard feeder cables and elimination of distribution transformers. A zonal distribution system also allows for equipment installation and testing prior to zone assembly (E.J. William, 2003).

Need for Reconfiguration:

Faults in a shipboard power system may occur due to material casualties of individual loads or widespread fault due to battle damage. In addition to load faults, casualties can happen to cables, power generating

equipment, or power distribution buses. If the fault is severe, such as a generator fault, it may cause a power deficiency to the remaining power system, system load generation unbalance, and even an entire system collapse. After the fault has occurred, protective devices operate to isolate the faulted section. But, this may lead to unfaulted sections that are not getting supplied. Therefore, it is required to restore supply automatically and quickly to these un-faulted sections of the shipboard power system to improve the system survivability. This can be achieved by changing the configuration of the system by opening and/or closing switches to restore supply to maximum load in the un-faulted sections of the shipboard power system. Reconfiguration can be aimed at supplying power to high priority loads and/or supplying power to maximum amount of loads depending upon the situation. The need reconfiguration is also proposed to maintain power balance of the remaining power system parts after fault detection and isolation. Fast reconfiguration is necessary for a shipboard power system considering the unique shipboard power system characteristics.

Methodologies Reviews:

In recent years, several reconfiguration methodologies have been proposed for power systems. With the advancement in the power system, the topology of power systems has become more complicated. However, in previous reconfiguration methodologies, no generic methodology was proposed for the reconfiguration of a power system with a complicated topology. Most of the previous reconfiguration methodologies are topology dependent. New reconfiguration methodologies need to be researched and developed for power systems with large scale and complicated topologies (Xiuxia Yang *et al.*, 2005). There are slight differences between reconfiguration of terrestrial power system and shipboard power system.

Reconfiguration of Terrestrial and Shipboard Power System:

The reconfiguration approach for power system can be implemented in centralized manner or in decentralized manner. In centralized approach, various methods are applied to the reconfiguration approach, such as evolutionary programming, heuristic method, artificial intelligent method, etc.

Many of the proposed automatic reconfiguration methodologies are developed for distribution system reconfiguration. The distribution system is usually reconfigured for restoring the loads in the distribution system, decreasing the power loss in the distribution system, stabilizing the distribution system, etc. Compared to the terrestrial power systems, the SPS has its unique characteristics. Some of the significant literatures of the terrestrial and SPS reconfiguration process are reviewed below. The reconfiguration techniques can be divided into three techniques which are Optimization Technique, Heuristic Technique and Intelligent Technique.

Optimization Techniques:

Schmidt *et al.*,(2005) put forward a fast integer programming based reconfiguration methodology to minimize the power loss in a distribution system. The power loss in the distribution system is the electric power that is consumed by transmission equipments, such as transformers, cables, wires, etc. This methodology is only applicable to radial power systems.

Tzeng *et al.*,(2006) proposed a feeder reconfiguration methodology for the distribution system. In that particular research, dynamic programming is used to find the optimal switching actions for load balancing in a distribution system. In a power system, the loads get electric power supply from load feeders. The load feeders that supplies more loads need more current injections than those load feeder supplying lesser loads. This will cause the imbalanced current distribution in the power system. With the same loads supplied in the power system, the imbalanced current distribution in the power system leads to more power loss than balanced current distribution in the power system. The imbalanced current in the power system also leads to the over current problem and stability problem. The load feeders in the power system need to be balanced by switching the circuit breakers and other switching devices so that the current distribution in the power system can be balanced.

Jiang and Baldick, (1996) proposed a comprehensive reconfiguration algorithm for distribution system reconfiguration. They employed simulated annealing to optimize the switch configuration of a distribution system. The objective of the reconfiguration is to decrease the power loss in the distribution system. Matos and Melo, (1999) put forward a simulated annealing based multi objective reconfiguration for power system for loss reduction and service restoration. A reconfiguration for enhancing the reliability of the power system was proposed by Brown *et al.*, (2004). A predictive reliability model is used to compute reliability indices for the distribution system and a simulated annealing algorithm is used to find a reconfiguration solution.

Wang and Zhang *et al.*,(2006) proposed a particle swarm optimization algorithm based reconfiguration methodology for distribution system. A modified particle swarm algorithm has been presented to solve the

complex optimization problem. The objective of the methodology was to minimize the power loss in the power system. Jin *et al.*,(2004) introduced a binary particle swarm optimization based reconfiguration methodology for distribution system. The objective of the reconfiguration was load balancing. The reconfiguration methodology proposed in that work can only be applied in the power system with radial configuration.

Butler *et al.*,(1999) put forward an optimization method that can be applied to the reconfiguration of SPS. The objective for reconfiguration is to maximize the load restored in the SPS. A commercial software package is used for solving the optimization problem in the reconfiguration process. Butler *et al.*, (2001) improve the reconfiguration methodology proposed in Butler *et al.*, (1999). The reconfiguration methodology is similar to the reconfiguration methodology proposed in Butler *et al.*,(2001). However, in this work, more constraints, such as voltage constraints for buses in the SPS, are applied to the reconfiguration compared to the work in this research. In Butler *et al.*,(2002), the reconfiguration methodology is implemented by using a commercial optimization software, which cannot provide a real time performance.

Heuristic Methods:

Gomes *et al.*,(2006) proposed a heuristic reconfiguration methodology to reduce the power loss in a distribution system. In this work, the optimal power flow and sensitivity analysis are used to find the reconfiguration solution. This reconfiguration methodology is only applicable to radial power systems. Hsu *et al.*,(2006) proposed a reconfiguration methodology for transformer and feeder load balancing in a distribution system. When the number of loads that are supplied through a load feeder increases, the current injection to the load feeder increases. The current that flows through the transformer is connected to the load feeder increases, too. It may lead to the risk of over current on the transformers and the transmission lines in the system. The proposed reconfiguration methodology is based on heuristic search.

Another heuristic search based reconfiguration algorithm was proposed by Wu *et al.*,(1999). In the research, the reconfiguration methodology was applied to the radial power system for service restoration, load balancing, and maintenance of the power system. Zhou, *et al.*,(1993) put forward a heuristic reconfiguration methodology for distribution system to reduce the operating cost in a real time operation environment. The operation cost in the power system is the power loss in the distribution system. The operation cost reduction is based on the long term operation of the power system. The knowledge based systems, such as expert systems, have also been applied to the reconfiguration of power systems for a long time. Knowledge based system is a computer system that is programmed to imitate human problem-solving by means of artificial intelligence and reference to a database of knowledge on a particular subject. Jung *et al.*,(1995) proposed an artificial intelligent based reconfiguration methodology for load balancing in a distribution system. An expert system was applied to the heuristic search in order to reduce the search space and reduce the computational time for the reconfiguration.

Intelligent Methods:

Salazar *et al.*,(2006) proposed a feeder reconfiguration methodology for distribution system to minimize the power loss. A reconfiguration algorithm was proposed based on the artificial neural network theory. Clustering techniques to determine the best training set for a single neural network with generalization ability are also presented in that research. k. Hsu and Huang, (1995) put forward another artificial neural network based reconfiguration for a distribution system. The reconfiguration can achieve service restoration by using artificial neural network and pattern recognition method.

Heo and Lee *et al.*,(2006) proposed MAS based intelligent identification system for power plant control and fault diagnosis. The proposed methodology can achieve the online adaptive identification for control in real time power plant operation and offline identification for fault diagnosis. Enacheanu *et al.*,(2002) proposed a distribution system architecture that can make the reconfiguration in the power easy to achieve. The reconfiguration in that work is to locate and isolate the faults in the power system. A remote agent is used in that work as a central controller for the reconfiguration of power systems. Liu *et al.*,(2005) put forward another restoration method for the power system. However, this method is also centralized because the restoration decision is made with the help of coordinating agents that have global information in the MAS. Wang *et al.*,(1996) proposed a fuzzy logic and evolutionary programming based reconfiguration methodology for distribution systems. In this research, a fuzzy mutation controller is implemented to adaptively update the mutation rate during the evolutionary process. The objective of the reconfiguration is to reduce the power loss in the distribution system. Zhou *et al.*,(1997) put forward another fuzzy logic based reconfiguration methodology for distribution system. A fuzzy logic based reconfiguration was developed for the purpose of restoration and load balancing in a real-time operation environment. Kuo and Hsu, (1993) proposed a service

restoration methodology using fuzzy logic approach. In this research, the fuzzy logic based approach was estimated the loads in a distribution system and devised a proper service restoration plan following a fault.

Srivastava and Butler *et al.*,(2006) proposed an automatic rule based expert system for the reconfiguration process of an SPS. The objective of the reconfiguration process is to supply the de-energized loads after battle damage or cascading faults. In the event of battle damage or cascading faults, a failure assessment (FAST) system detects faults, identifies faulted components in damaged sections, and determines de-energized loads. The reconfiguration method uses the output of a FAST system, real time data, topology information and electrical parameters of various components to perform reconfiguration for load restoration of an SPS.

Again the same author, Butler *et al.*,(2005) proposed automated self-healing strategy for reconfiguration for service restoration in Naval SPS. A model of the 3-D layout of the electrical network of shipboard power system using a geographical information system was explained. A self-healing system is a system that when subjected to a contingency (or threat) is able to access the impact of the contingency, contain it and then automatically perform corrective action to restore the system to the best possible (normal) state to perform its basic functionality. In recent years, Multi Agent System (MAS) technologies have been applied to the reconfiguration process in SPS. Srivastava *et al.*,(2002) proposed MAS based reconfiguration methodology for automatic service restoration in the SPS. In this research, the overall function of the MAS is to detect and locate the fault(s), determine faulted equipments, determine de-energized loads, and perform an automated service restoration on the SPS to restore de-energized loads. The MAS also gives an output list of restorable loads and switching actions required to restore each load. The restoration methodology proposed in this research work is not completely decentralized.

Solanki *et al.*,(2005) proposed Genetic Algorithm (GA) reconfiguration methodology for SPS. In this research, the reconfiguration process can isolate the fault and restore the power supply quickly and autonomously. Also, this reconfiguration methodology can be applied only to radial SPS. Solanki *et al.*,(2006) demonstrated the GA for the reconfiguration of the SPS. In the simulation of the reconfiguration process in this research, the GA and SPS are implemented on the same PC. The communication bandwidth of the GA cannot be researched by using this simulation platform. E.J. William, (2004) proposed an Artificial Neural Network Algorithm (ANN) to determine fault locations on shipboard Electrical Distribution System (EDS). It traces the location of the fault on SPS. The EDS is protected when faults are located and isolated as quickly as possible. The goal is to increase the availability of shipboard EDS by locating and isolating faults by using Power system CAD (PSCAD) and ANN analysis. However the only problem with this is that the fault path accuracy is unpredictable and require sensitive current measurement device.

Discussion:

Various methods have been applied to the reconfiguration process of the terrestrial and shipboard power system. However, most of the reconfiguration methodologies are centralized. A central controller is a requirement to gather data from the power system, make reconfiguration decisions after calculation and analysis. The literature review has revealed some important points which most of the reconfiguration methodologies for terrestrial power system and SPS are centralized solutions. Also, the simulation scenarios in these researches are not in real time and cannot provide the bandwidth requirement latency performance of the system. From the analysis, the number of the researcher for terrestrial power system is greater than shipboard power system (SPS). There are only a few numbers of researchers who explore in the area of shipboard power system. Most of the cases are studied by the same researchers like Sarma, Buttler and Sarasvarti. The number of researches which focus on reconfiguration on fault location for shipboard power system is very few as compared to the terrestrial power system.

From the literature, several approaches and methods have been proposed in the reconfiguration process for SPS. They vary in term of functions and applications. Many techniques have been employed for the solution of the reconfiguration problem such as genetic algorithms (GA) (Xiuxia Yang, 2005), simulated annealing (Matos *et al.*, 1999), particle swarm optimization (PSO) (J.Vesterstrom *et al.*, 2004), tabu search (TA) (M.A.Abido, 2002), multi agent system (MAS) (J. S. Heo, 2006) and etc. Generally, most of the techniques apply sensitivity analysis and gradient based optimization algorithms by linearizing the objective function and the system constraints around an operating point (Abou El Ela, *et al.*, 2009). The results reported in the literature were promising and encouraging for further research in this direction.

More recently, a new evolutionary computation technique, called Differential Evolutionary (DE) algorithm has been proposed and introduced R.Storn, K. Price, (1995). The algorithm is inspired by biological and sociological motivations and can take care of optimality on rough, discontinuous and multi-modal surfaces. The DE has three main advantages: it can find near optimal solution regardless the initial parameter values, its

convergence is fast and it uses few number of control parameter. In addition, DE is simple in coding, easy to use and it can handle integer and discrete optimization. The performance of DE algorithm was compared to that of different heuristic techniques. It is found that the convergence speed of DE is significantly better than GA (D.Karaboga, S.Okdem, 2004). Meanwhile in Matos, M.A (1999), the performance of DE was compared to PSO. The comparison was performed on suite of 34 widely used benchmark problems. It was found that, DE is the best performing algorithm as it finds the lowest fitness value for most of the problems considered in that study. Also, DE is robust: it is able to reproduce the same results consistently over many trials, whereas the performance of PSO is far more dependent on the randomized initialization of the individuals Matos, M.A, (1999). In addition, the DE algorithm has been used to solve high dimensional function optimization (up to 1000 dimensions) .It is found that, it has superior performance on a set of widely used benchmark functions.

Conclusion:

From the observation of the previous works, most of the reconfiguration objectives in methodology are almost similar even the methods utilized are different. Among the most familiar objectives are minimizing the fuel cost, maximize the load restored, improving the voltage profile and enhancing power system voltage stability in both normal and contingency conditions. The results are compared to those reported in the literature. Among the methods proposed, DE algorithm seems to be promising approach for engineering problem due to the great characteristics and its advantages. A novel DE-based approach is proposed to solve the reconfiguration for service restoration problem in shipboard power system in recent year. However, GA algorithm and MAS algorithm are still applicable in the system.

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