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Optimized restoration of combined ac/dc shipboard power systems including distributed generation and islanding techniques

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Abstract

Reconfiguration involves changing the status (OFF/ON) of switches, and reconfiguration for restoration involves changing the switch status to maximize the supply to loads that are left unsupplied after fault removal. Shipboard Power Systems (SPS) need automated reconfiguration for restoration schemes to restore vital loads quickly and efficiently in order to improve fight-through and survivability capabilities. The restoration in this paper is achieved using optimization with multiple objectives—maximizing the restored load and giving priority to vital loads. A restoration scheme for SPS with an integrated power system (IPS) and distributed generation (DG) involving islanding has been developed. This formulation includes a hybrid power system that has both ac and dc parts. The restoration formulation in this paper also considers the unbalanced nature of SPS operation with mutual coupling.

Keywords: Restoration; Distributed generation; Islanding; Shipboard power systems

1. Introduction

Reconfiguration for restoration involves restoring power to outaged portions of the feeder, which improves service to loads by reducing outage time. The manual process of restoration for a shipboard power system (SPS) leave many loads without supply, especially if they were downstream of the fault on a radial system. Thus, a need exists for automated restoration. The integrated power system (IPS) of the SPS presents a better survivability solution in a battle situation since multiple generators can be scattered in various locations throughout the ship. Taking advantage of this survivability requires reconfiguring the power system to minimize the amount of service interruption when a portion of the system is suddenly taken out of service due to battle damage or other faults.

Restoration is a combinatorial problem where the state space to search for the solution is huge and a complete listing of all possible states is very difficult. The problems with integer variables are non-deterministic polynomial-time (NP) hard, meaning no known algorithm exists to solve these problems in polynomial time. The basic objective of the restoration in this paper is to maximize the number of loads supplied, giving priority to vital loads.

Designers are considering the inclusion of both centralized power sources as well as localized DG for SPS. Energy storage devices like flywheels and batteries are already on ships. DG creates a new set of constraints for shipboard system analysis relating to restoration optimization. When a DG or several DGs energize a portion of the system that has been separated from the main generation system, it is called islanding. Islanding can be either intentional or unintentional. Intentional islanding increases reliability and helps to maintain the continuity of supply to the important loads. If the DG cannot carry the entire load of the island, then part of the load needs to be shed. The load to be shed should be decided in an optimum manner, considering all the priorities.

Restoration for balanced terrestrial distribution systems has been approached using heuristics [1–3], mathematical programming [4,5], meta-heuristics [6,7] and expert systems [8,9]. Additionally, some combination approaches [10,11] have been formulated. However, most of the approaches use a resistive model of loads and lines and simplify the distribution system.

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Most of the methods require running a complete power flow after each switching step to determine if the constraints are satisfied. Reference [12] provides a solution to unbalanced ac distribution systems using optimization. Butler et al. [13] use a novel fixed charge network flow method for restoration of SPS, which is essentially linear optimization, performed using the software CPLEX. However, they consider distribution system loads as constant current and cables as three phase with no mutual couplings so that the three phases could be decomposed. After decomposition, three separate independent equations are formulated for each phase, which simplifies the optimization process. Only the magnitude of current is considered for calculations, and bi-directional flow of current was not allowed during restoration. However, with several fault scenarios and the introduction of DG, this assumption is not valid. Also, with the IPS, the SPS has ac as well as dc components, and a need for strategic change clearly arises.

2. Shipboard Power Systems

SPS have radial distribution architecture, but currently researchers are contrasting the radial distribution architecture with a zonal approach. The zonal approach employs a starboard bus and a port bus and partitions the ship into a number of electrical zones. The zonal architecture minimizes switchboard feeder cables length and hence the weight of ship. In the ac distribution system, the distributed three-phase ac must be rectified, converted to 400 Hz with an inverter, shifted to an appropriate voltage level with a transformer, and then once again rectified to provide the required dc power. The dc zonal electric distribution system (ZEDS) does not need to have an intermediate 60 Hz step. The power is converted to dc at the output of the generator, and is reconverted to the form required at the point of use, so fewer distribution transformers and ac switchgears are required, and thus it beneficially reduces the weight and size of the ship.

The ZEDS, as shown in Fig. 1, is a zonal architecture where the ship is divided into electrical zones; it shows the interconnectivity and location of generators, switchboards and bus tiebreakers. The power is radially distributed from the generator switchboards to load. Each zone has two load centers; one fed from the port bus and the other from the starboard bus. The loads are classified as non-vital, semi-vital and vital loads. Vital and semi-vital loads are those loads required for combat systems, fire systems, etc. Non-vital loads provided from the nearest load center can be shed for survivability. Both load centers provide power through automatic bus transfers (ABT) for vital and semi-vital loads in the zone. SPS have a tightly coupled structure, due to the low impedance of the cables. The power flow analysis of a SPS shows that the voltages at the nodes are approximately equal with similar voltage angles. Because of this nature, the fault currents are very high, thus necessitating a fast and efficient restoration scheme.

For the unbalanced SPS, the problem remains the same: maximizing the supply to out-of-service loads giving priority to vital loads. The power flow equations of balanced SPS when applied to unbalanced SPS fail to converge. Unbalanced SPS have mutually coupled cables and different loadings in all three phases, leading to unbalanced voltages and currents, unlike the balanced SPS, thus requiring a different forms of analysis.

3. Introduction to LINGO

The LINGO commercial optimization software package from LINDO Systems Inc. solves the constrained optimization problem [15]. LINGO is a tool for solving both linear and non-linear optimization problems. Branch-and-bound type techniques cannot be directly applied unless the problems are convex. LINGO has a direct solver, a linear solver, a non-linear solver and a branch-and-bound manager. LINGO uses the revised simplex method for its linear solver, and successive linear programming, as well as a generalized reduced gradient for its non-linear solver. LINGO can solve problems with unlimited constraints and variables but cannot handle complex numbers. The formulation is input in the format desired by the software. The direct solver first computes the values for as many unknown variables as possible, and if, at that stage all unknown variables are calculated, then the solution report is displayed. If unknown variables still exist, then LINGO calls other solvers based on the model equations. If the model is continuous and linear, LINGO calls the linear solver. If the problem involves non-linear constraints, LINGO calls the non-linear solver. In the case of integers, LINGO uses the branch-and-bound manager. LINGO's solver status window gives a count of the linear and non-linear variables and constraints in a model. If there

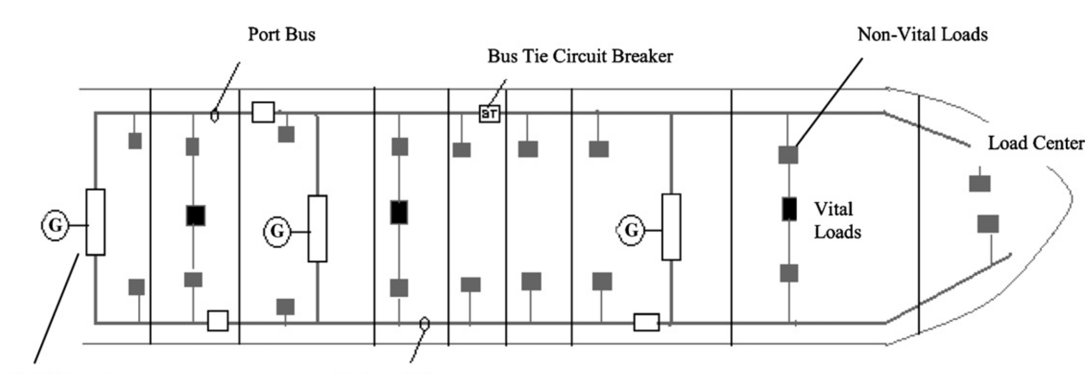

Fig. 1. Shipboard power system (from [14]).