Service restoration in naval shipboard power systems

K.L. Butler-Purry, N.D.R. Sarma and I.V. Hicks

Abstract: Service restoration is an important problem in naval shipboard power systems. When faults occur as a result of battle damage or equipment failure and are isolated by protective devices, some critical loads are left without supply. Fast restoration of supply to these vital loads is necessary for system survivability. Loads have different priorities that must be considered during restoration in the shipboard power systems (SPS). These loads are categorised as vital or non-vital. Vital loads have two paths through which they can be supplied. Under some circumstances, it may be preferred to supply a vital load through one of the two paths. Butler *et al* have developed a method to restore maximum loads in SPS based on the fixed-charge network flow method. An enhancement to their method is proposed to handle priority for loads and paths while restoring service in SPS. The proposed method is illustrated with some case studies on a simplified SPS.

List of symbols

$A = E_{\mathrm{NFL}} \cup E_{\mathrm{o}}$	set of edges which are available for the restoration of power to all load points given in D
B	a constant which is very large compared to the voltages.
C_{a_j}	capacity in phase j of edge a. $j = a$, b and c phases.
$D = \{D_1, D_2, \ldots, D_M\}$	set of load nodes in the network.
E	set of edges in the network.
E_{c}	set of edges in closed position in the network.
$E_{\mathrm{o}} = (E - E_{\mathrm{c}})$	set of open edges in the network.
E_{NFL}	set of edges that are not faulted
F_i	set of edges at node i, for which current flows into the node.
f_{i_j}	0–1 variable for a fixed type of load in phase j at node i. $j = a$, b and c phases.
H_a	status for an edge a and is defined as follows: $H_a = \begin{cases} 1, \text{ if edge a is closed} \\ 0, \text{ otherwise.} \end{cases}$
H_{ai}	status for the low-priority path switch at then ith ABT/MBT.
H_{ni}	status for the higher-priority path switch at the ith ABT/MBT.
I_{a_j}	current flows (in amps) in phase j in edge a. $j = a$, b and c phases.
j	a, b and c phases.
l_{i}	maximum possible value (current) for load at node i.
L_i	load variables corresponding to a load at node i.
l_{i_j}	maximum possible load in phase j at node i.$j = a$, b and c phases.
L_{i_j}	Load variables corresponding to phase j, at node i.
M	total number of loads in the system.
N	set of nodes in the network.
$\{N,E\}$	Network under consideration.
O_i	set of edges at node 'i' for which current flows out of the node.
(r,i)	directed edge from node r to node i
$S1_{i\_j}$, $S2_{i\_j}$	slack variables used in the voltage equations in phase j for node i. $j = a$, b and c phases.
T_i	total contribution of the load L_i in the objective function (in amps)
V_{i_j}	voltages in phase j at node i. $j = a$, b and c phases (in volts).
W	maximum value of the largest low-priority load in the system.
W_{i_j}'	weighted-factor term corresponding to the load L_{i_j}. $j = a$, b and c phases.
z_{a_j}	impedance (in ohms) in phase j of edge a. $j = a$, b and c phases.

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1 Introduction

A typical AC radial shipboard power system (SPS) consists of three-phase generators that are delta connected in a ring configuration using generator switchboards [1]. Bus tie circuit breakers interconnect the generator switchboards that allow for the transfer of power from one switchboard to another. The generator switchboards along with bus-tie circuit breakers and bus-tie cables form a ring (loop) configuration. Load centres and some loads are supplied from generator switchboards. Further, load centres supply power to some loads directly and supply power to power-panels to which some loads are connected. Feeders supplying power to load centres, power panels and loads are radial in nature. Loads are categorised as either vital or non-vital and are either three-phase 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 normal path is the preferred path. The ABTs are normal path seeking and the alternate path is used only when the normal path is not available. There are also transformers that step down the voltage from 450 to 120 volts to supply the single-phase loads at the 120-volt level.

When faults occur as a result of battle damage or equipment failure and are isolated by protective devices such as circuit breakers and fuses, some critical loads are left without supply. Fast restoration of supply to these vital loads is necessary for system survivability. During this restoration, the capacities of the generators and cables should not be violated and voltage magnitudes at each node should be within tolerable limits. Loads have different priorities that must be considered during restoration in the navy SPS. Further, under some circumstances, it may be preferred to supply a vital load through one of the two paths. Presently, there is some automation utilised on SPS during restoration. Vital loads that have ABTs, switch over to the alternate path automatically when there is an interruption of supply on the normal path. But loads that have MBTs need manual switching to their alternate path. Also other forms of manual reconfiguration are performed. With the reduced manning requirements for future SPS [2], it is necessary to increase the automated restoration actions.

Shipboard power systems are very similar to isolated finite inertia utility systems in that the available generators are the only source of supply for the system loads. There are, however, several differences between utility and shipboard power systems; for example, ships have large dynamic loads relative to generator size, a larger portion of non-linear loads relative to power generation capacity, and transmission lines are not nearly as significant as for utilities because of their short lengths [1].

In the literature there are several papers [3] discussing the restoration problem for utility systems. Most of the methods are based on heuristic search techniques [4–7]. Some of the methods are based on graph theory [8–10]. Aoki *et al.* [11] and Lee and Grainger [12] attempt to use the network flow approach to solve the problem of service restoration for utility systems. As pointed out by Lee and Grainger [12], the method of Aoki *et al.* [11] handles multiple faults as a series of subproblems and has some limitations. In the method suggested by Lee and Grainger [12], the optimal solution obtained by solving the maximal flow problem is disturbed to meet the radial condition and finally they conclude that straightforward application of the network flow approach is not suitable for solving the problem for utility systems.

In a previous paper by the authors [13], a method was presented in which the problem was formulated as a variation of the fixed charge network flow problem, but did not include the handling of load priorities and priority to paths for vital loads. This paper discusses modifications to the method presented in [13], to handle priorities of the loads and priorities of the paths through which some vital loads are supplied. The method generates control actions necessary to perform the reconfiguration. The control actions can be used to automatically reconfigure the network through a microprocessor-based control system. The method was applied to a simplified shipboard power system model developed in the laboratory and various case studies are presented to illustrate the effectiveness of the proposed formulation.

2 Mathematical problem formulation for service restoration

Consider a simplified shipboard power system (SPS) model as shown in Fig. 1. This system consists of three delta connected generators connected in a ring configuration. Two generators are energised while the third generator is an emergency generator and not energised. Some loads are connected to load centres or generator switchboards directly and some via ABT/MBTs. The loads connected via ABT/MBTs have normal and alternate paths. Since supply should be from only one source (in radial systems), only one of these paths is energised at any given time. Further, there are circuit breakers (CBs) which are operated to isolate faults and restore supply to the de-energised loads.

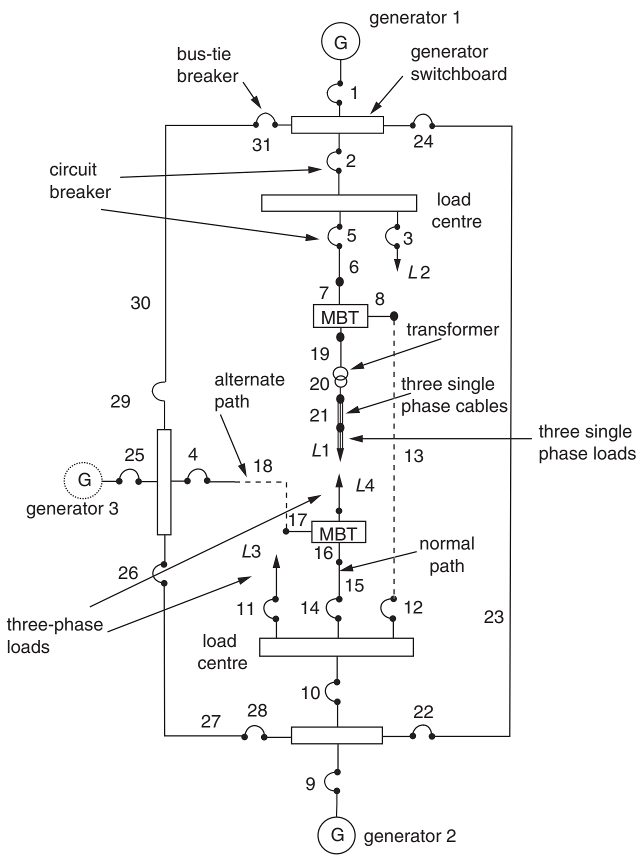

Fig. 1 *Example system*

In formulating the problem, the system shown in Fig. 1 is represented in a graphical form as shown in Fig. 2. In Fig. 2, each component is modelled as an edge in the graph. A node is denoted by a number in a box and an edge is denoted by a number. In the graphical representation of the system, each ABT/MBT is represented with two switches as shown in Fig. 3. To maintain the radiality in the system, only one of these switches is in a closed position at any given time. A transformer is modelled as shown in Fig. 4,

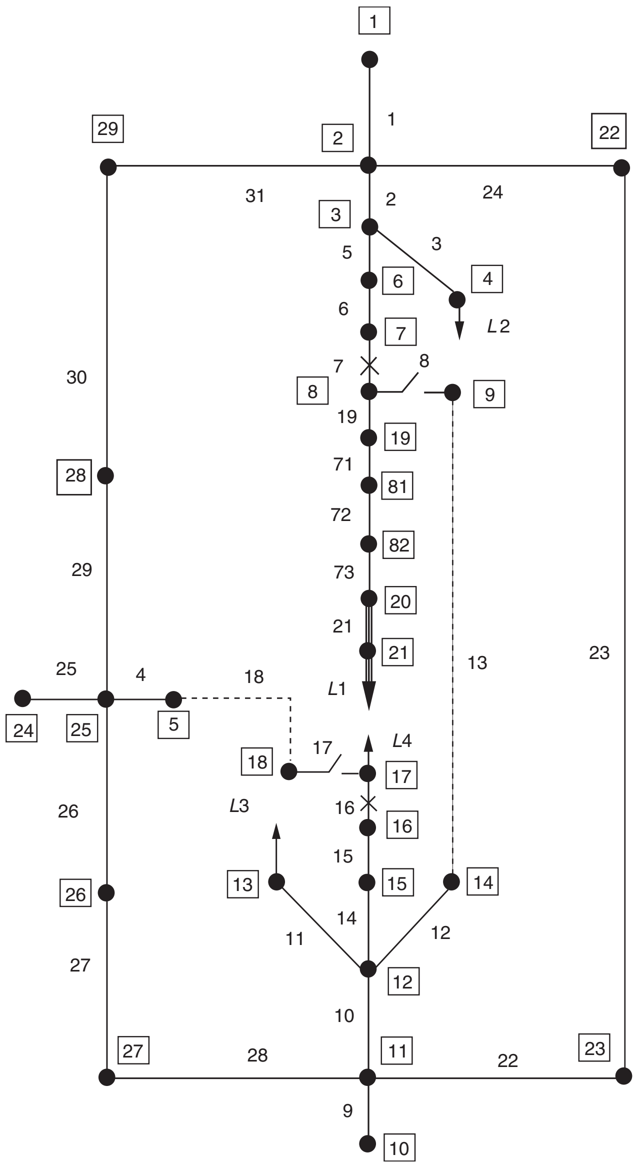

Fig. 2 *Graphical representation of the example system*

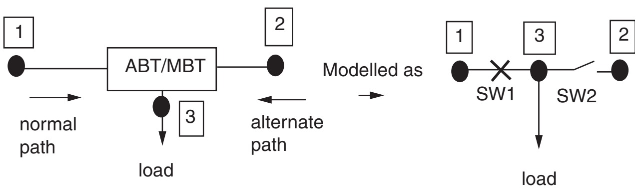

Fig. 3 *Graphical representation of ABT/MBT*

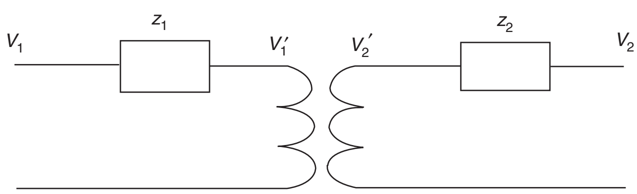

Fig. 4 *Modelling of a transformer*

where z_1 and z_2 represent the primary and secondary side impedances and the transformer windings are represented as an ideal transformer without any losses. In this model the core losses, which are very small, are neglected. In the graphical representation of the system, the transformer (component number 20) in Fig. 1 is represented by the edges numbered 71, 72 and 73 in Fig. 2. Edges 71 and 73 represent the primary-side and secondary-side impedances of the transformer and 72 represents the ideal transformer. Also in the graphical representation, the edges in thick lines indicate normal paths and the edges in dotted lines indicate alternate paths.

There are two possible graphical representations of the system that have been developed based on the location of a fault. Below the generator switchboards, radial distribution is used and faults on any components downstream of the generator switchboards may interrupt power supply to some loads. On the other hand, if the fault is on a component in the ring, then it is likely that the ring will be split and generators will no longer operate in parallel. Therefore, based on the fault location, there are two possible graphical representations of the system as explained below.

- If there is no fault in the ring: The graph is modified by merging the generator switchboards, bus-tie breakers, and cables connecting these switchboards. This reduced network has one generator representing all the generators connected in the ring. This network is used to formulate the problem as will be explained later.
- If there is a fault in the ring: The graph is modified by isolating the faulted component in the ring and the remaining network is used to reconfigure the network to restore the service. If after isolating the faulted component in the ring, there are any components (bus-tie components) connecting any two generators, then these components are merged as explained above.

The mathematical formulation of this reconfiguration for restoration problem is described in this section. The problem is formulated as a variation of the fixed charge network flow problem [12, 13] and solved as an optimisation problem.

2.1 Model of priority to the loads

Loads are categorised as vital and non-vital loads. Vital loads are those electrical loads required to support important systems such as combat systems, mobility systems, fire systems, etc. Non-vital loads are those that can be shed during an electrical casualty. Therefore, the loads are to be configured in the following order of priority:

- high-priority loads–vital loads
- low-priority loads–non-vital loads

While reconfiguring the loads it is important to consider their priority. Accordingly, it is required that high-priority loads be considered for reconfiguration before reconfiguring the low-priority loads. Therefore it is required that in the objective function the contribution of the high-priority loads is always greater than the contribution of the low-priority loads. Also it is required that the contribution of the loads be in proportion to the rated current values. In order to achieve this, a coefficient (or weighted-factor), W'_i, which is defined below in (1) and (2), is prefixed to each of the load terms in the objective function.

For a high-priority load:

$$W_i' = \left(\frac{W}{l_i}\right) + 1 \qquad (1)$$

For a low-priority load:

$$W_i' = 1 \qquad (2)$$

As will be discussed in a later section, by using this weighted factor, the maximum contribution (T_x) of each high-priority load (L_x) in the objective function is given by:

$$T_x = l_x W'_x = l_x \left[\left(\frac{W}{l_x} \right) + 1 \right] = W + l_x \tag{3}$$

The maximum contribution (T_y) of each low-priority load (L_y) in the objective function is given by:

$$T_y = l_y W'_y = l_y \times 1 = l_y \tag{4}$$

It can be seen that by choosing the weighted factor W'_i as explained above, the total contribution of the high-prority loads L_i in the objective function is elevated by W. As this W is the maximum value of the largest low-prority load, it can be seen that the contribution of each high-priority load will be greater than the contribution of each low-priority load. Therefore, since the objective function is a maximisation function, all high-prority loads will be attempted to be restored before the low-prority loads. Further it can be seen from (3) and (4) that the contribution in the objective function of any load is in proportion to its magnitude.

2.2 Model of priority to the paths

As mentioned earlier, vital loads have two paths (normal and alternate) through which power can be supplied. Under normal circumstances power is supplied through the normal path. When there is a loss of power upstream of the normal path due to faults, power is restored to the vital loads by switching to the alternate path using ABT/MBTs. In the case of ABTs, the switchover happens automatically. But in the case of MBTs, switching has to happen manually or through remote operation. For vital loads, one path will have a higher-priority than the other. Whenever reconfiguration is performed, it is required to use the higher-priority path first. To handle this, a variable H_{nj} representing the status of the switch corresponding to the higher-priority path for each ABT/MBT is added in the objective function. Since the objective function is to be maximised, it will try to set the value of H_{nj} (higher-priority paths switch status) to 1 whenever possible, thus giving the priority to the higher-priority paths.

2.3 Problem formulation

Based on the discussion above and as discussed in [13], the problem formulation for reconfiguration for service restoration in SPS can now be stated as follows:

Objective function:

$$\text{Maximize} \sum_{i=1}^{M} (W'_{i\_a} L_{i\_a} + W'_{i\_b} L_{i\_b} + W'_{i\_c} L_{i\_c}) + \sum_{j=1}^{TT} H_{nj} \tag{5}$$

Constraints:

(a) Source capacity constraint: At all source nodes

$$\sum_{a \in Oi} I_{a\_j} \le C_{i\_j} \tag{6}$$

where j = phase a, b and c

(b) Node constraints: At each load node D_i,

$$\sum_{a \in Oi} I_{a\_j} = \sum_{a \in Oi} I_{a\_j} + L_i \tag{7}$$

At each other intermediate node i

$$\sum_{a \in Oi} I_{a\_j} = \sum_{a \in Oi} I_{a\_j} \tag{8}$$

(c) Load constraints: Two types of loads have been modelled: variable and fixed type. For a variable-type load, the load can be restored up to its maximum current rating ($L_i^{\max}$). Such loads represent a lump load in a panel consisting of several groups of loads that can be independently controlled by opening/closing their respective switches. This is similar to circuit breaker panels used in our houses. But for fixed type of loads, it can be restored either at its maximum current rating or cannot be restored at all. Such loads, when connected, will be equal to its rated current value. Accordingly load constraints are formulated as follows:

At a load node when D_i is variable type

$$L_{i\_j} - L_{i\_j}^{\max} \le 0 \tag{9}$$

At a load node when D_i is fixed type

$$L_{i\_j} - f_{i\_j} l_{i\_j}^{\max} = 0 \tag{10}$$

(d) Flow constraints: In each edge i

$$X_{i\_j} \le H_i C_{i\_j} \quad \text{for } i \in A \tag{11}$$

(e) Radiality constraint: At each node i

$$\sum_{a \in F_i} H_a \le 1 \tag{12}$$

(f) Voltage value constraints: For a simple node connectivity as shown in Fig. 5a, at node k

$$V_{k\_j} = V_{i\_j} - z_{a\_j} I_{a\_j} \tag{13}$$

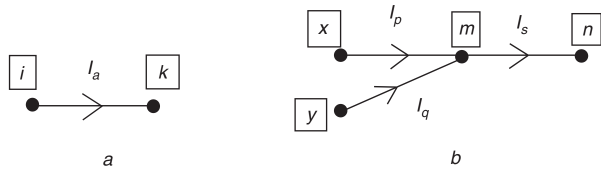

Fig. 5 *Connectivity of nodes*
a Simple node connectivity
b Node connectivity at triplet (x, y, m)

Since some loads have a normal and an alternate supply path, a node may have more than one edge connected to it. However, only one of the edges is energised at a given time. For example, as shown in Fig. 5b, consider a node m connected to nodes x and y through edges $p = (x, m)$ and $q = (y, m)$ whose impedance are z_p and z_q, respectively, and current flows in these edges are I_p and I_q, respectively. The set of nodes (x, y, m) is referred to as the triplet (x, y, m). Suppose that node n is connected from node m through edge $s = (m, n)$ whose impedance is z_s. I_s is the current flow in the edge s.

At node m of the triplet (x, y, m), V_{m_j} is given as (14) and (15). It may be noted that, due to the radiality constraint, either I_{p_j} or I_{q_j} will be zero.

$$V_{m\_j} = V_{x\_j} - z_{p\_j} I_{p\_j} + B(1 - H_p) - S1_{m\_j} \tag{14}$$

$$V_{m\_j} = V_{y\_j} - z_{q\_j} I_{q\_j} + B(1 - H_q) - S2_{m\_j} \tag{15}$$

As explained in [13], this formulation makes the problem a linear optimisation problem. This approach to solving the problem is efficient because an optimal solution of the linear system is determined. As the main objective is to determine an optimal configuration that maximises the total load satisfying all the constraints, the variables of interest in the optimal solution are the optimal values of L and H. The values of some of the voltages in the optimal solution are not as per the actual current flows in the network because of (14) and (15). To get the actual voltages, a transformation of the optimal solution as shown in [13] can be performed.

(g) Voltage limit constraints: At all nodes i

$$V_{i\_j}^{\min} \leq V_{i\_j} \leq V_{i\_j}^{\max} \tag{16}$$

These constraints will ensure that while optimising the loads (which affect the flows in the edges), the voltage constraints are also satisfied.

(h) Simulation of faults: A fault on any component (edge) i is simulated in the model by equating the respective current flow variable, I_i and status variable Y_i to zero. This is done because when there is a fault in a component, this component is not available and there cannot be any flow in it. For example, if a fault is on an edge f, the additional constraints given in (17) will be added to the problem:

$$I_{f\_j} = 0; \; H_f = 0 \tag{17}$$

When this problem [presented in (5)–(17)] is solved, the results are the control actions (switching actions) to reconfigure the network so that power is supplied to maximum loads, satisfying the capacity and voltage constraints, and maintaining the radial condition. It also gives priority to the loads and priority to the preferred paths at vital loads. The suggested control actions can be implemented through a microprocessor-based control system to remotely control the switches to automatically reconfigure the network.

3 Illustration

To illustrate the restoration method, a simplified SPS model as shown in Fig. 1 was used. The details of the system are given in Table 1. In this work, DC models of data and electrical behaviour have been used. Even though the DC results yield approximate results, the optimisation algorithm will still tend to determine the optimal configurations among various candidate configurations based on voltage drop and other costs [14]. The voltage limits were assumed to be 438 (min) and 450 (max) volts at all the nodes on the high-voltage side and 113 (min) and 120 (max) at all nodes on the low-voltage side of the network. It was assumed that generators 1 and 2 were in operation and generator 3 reserved as the emergency generator.

Table 1: Details of the test system

Name of the component	Details
Generators	Rating: 136.4 kW, 450 V
Transformer	Voltage Ratio (V_p/V_s):450 V/120 V;
	Primary winding resistance, $Z_p = 0.432$ ohms;
	Secondary winding resistance, $Z_s = 0.282$ ohms
Cables	Impedance $Z = 0.01$ ohms
	Current ampacity = 300 amps

In the example system shown in Fig. 1, each load L_i was modelled in three phases whose values are L_{i_a}, L_{i_b}, and L_{i_c}. The load size is defined for each case separately. For the case studies, the CPLEX program [15] was used to solve each resulting optimisation problem. This commercial tool developed by ILOG [15] solves linear optimisation problems. These case studies are presented in this paper to illustrate the effectiveness of the proposed method. For the specific scenarios presented for each case, the system will be reconfigured to supply maximum loads, satisfying the current and voltage constraints. While doing so, it will consider the priority to loads and paths.

3.1 Case 1.1: Case without fault

To illustrate the basic problem formulation, case 1.1 considers the system without faults. The graphical representation of Fig. 1 was developed as shown in Fig. 2. Since there were no faults on the components connected in the ring, Fig. 2 was modified as shown in Fig. 6 by merging the nodes corresponding to the generator switchboards connected in a ring. In Fig. 6, node 30 represents the new node generated by merging the generator switchboards and bus-tie-breakers (nodes 2, 22, 23, 11, 27, 26, 25, 28, 29). Node 31 represents the new source node whose capacity is equal to the sum of the capacities of generators supplying power at nodes 1, 10 and 24. Accordingly, the capacity of edge 32 is equal to the capacity of source node 31.

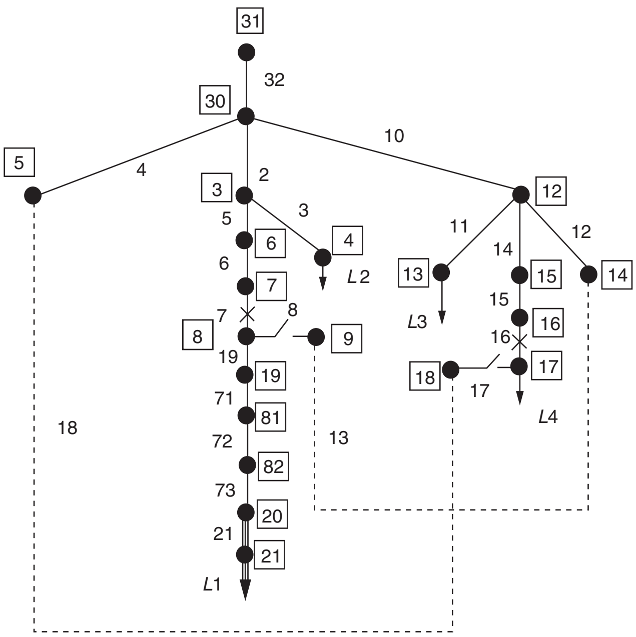

Fig. 6 *Graphical representation of the example system after merging components in the ring configuration*

For this case, load L_1 represented three single-phase unbalanced loads supplied through a transformer. L_1 was a variable load with 15, 20 and 25 amps in phase a, phase b and phase c, respectively. Loads L_2 and L_3 were three-phase balanced variable loads with 70 and 100 amps (in each phase), respectively. Load L_4 was a balanced fixed load of 80 amps (in each phase). Also loads L_1 and L_3 were vital loads and L_2 and L_4 were non-vital loads.

Based on these values of the loads, the weighted factors were calculated for all loads using (1) and (2). For the two MBTs, the switches numbered 7 and 16 were assumed to correspond to the high-priority paths of the two MBTs. Accordingly, H_7 and H_{16} were included in the objective function. The objective function for this example is given in (18). The solution obtained from the CPLEX package for this case is shown in Tables 2a–c. It can be seen that all loads were supplied. Further it can be seen that $H_7 = 1$, $H_{16} = 1$, $H_8 = 0$, and $H_{17} = 0$ indicating that the loads L_1 and L_4, which have two paths, are supplied through their high-priority paths.

$$\begin{aligned} \text{Maximize}\{&7.67L_{1\_a} + L_{2\_a} + 2.25L_{3\_a} + L_{4\_a} \\ &+ 6L_{1\_b} + L_{2\_b} + 2.25L_{3\_b} + L_{4\_b} \\ &+ 5L_{1\_c} + L_{2\_c} + 2.25L_{3\_c} \\ &+ L_{4\_c} + H_7 + H_{16}\} \end{aligned} \tag{18}$$

3.2 Case 2: Restoration

Two cases are presented in this section to illustrate the capability of the method to restore maximum load satisfying the constraints and considering the priority of loads and paths.

3.2.1 Case 2.1: Restoration – illustration of handling priority of loads:

This case illustrates that the method restores high-priority loads first. To illustrate this, for this example, loads L_1, L_2, L_3 and L_4 were balanced fixed-type loads with 25 amps in each phase. Consider loads L_1 and L_4. To illustrate that, among L_1 and L_4, only high-priority load can be restored, initially, load L_1 was set to be a vital load and others were set to be as non-vital loads. Also the total available generation capacity was set to 25 amps (so that both L_1 and L_4 cannot be restored). A fault was considered on the cable (edge 15) connecting load L_4 (at node 17). After it was isolated, there would be no power to the load L_4 at node 17 (as can be seen in Fig. 1).

The graphical representation of the system shown in Fig. 1 was developed as shown in Fig. 2. Since there were no faults on the components connected in the ring, Fig. 2 was modified to the system shown in Fig. 6 by merging the nodes corresponding to the generator switchboards connected in a ring.

The weighted-factors were calculated for each load. For the two MBTs, the switches numbered 7 and 16 were assumed to correspond to the high-priority paths. Accordingly, H_7 and H_{16} were included in the objective function. The objective function for this example is given in (19). Since the fault was on component 15, a set of new constraints, as shown in (20), was added to the data for case 1.1. This indicates that these components are not available. Also the affected load (load that has lost supply due to this fault) was L_4. Formulating the problem as explained with these modifications, CPLEX generated the results for loads as shown in the Table 3. This solution indicates that only L_1

Table 2:

(a) Optimal solution for loads computed for case 1.1

Name of the Load	L_{i_a} (amps)	L_{i_b} (amps)	L_{i_c} (amps)
L_1	15	20	25
L_2	70	70	70
L_3	80	80	80
L_4	100	100	100

(b) Optimal solution for switch/CB/MBT/ABT status (1 = ON, 0 = OFF) computed for case 1.1

Switch	Status	Switch	Status	Switch	Status	Switch	Status
H_2	1	H_8	0	H_{15}	1	H_{32}	1
H_3	1	H_{10}	1	H_{16}	1	H_{71}	1
H_4	1	H_{11}	1	H_{17}	1	H_{72}	1
H_5	1	H_{12}	1	H_{18}	0	H_{73}	1
H_6	1	H_{13}	1	H_{19}	1		
H_7	1	H_{14}	1	H_{21}	1		

(c) Optimal solution for flows in all the components computed for case 1.1

Flow variable (I_i)	I_{i_a} (amps)	I_{i_b} (amps)	I_{i_c} (amps)	Flow variable (I_i)	I_{i_a} (amps)	I_{i_b} (amps)	I_{i_c} (amps)
I_2	73.83	75.11	76.39	I_{14}	100.0	100.0	100.0
I_3	70	70	70	I_{15}	100.0	100.0	100.0
I_4	0	0	0	I_{16}	100.0	100.0	100.0
I_5	3.83	5.11	6.39	I_{17}	0	0	0
I_6	3.83	5.11	6.39	I_{18}	0	0	0
I_7	3.83	5.11	6.39	I_{19}	3.83	5.11	6.39
I_8	0	0	0	I_{21}	15	20	25
I_{10}	180.0	180.0	180.0	I_{32}	253.83	255.11	256.39
I_{11}	80.0	80.0	80.0	I_{71}	3.83	5.11	6.39
I_{12}	0	0	0	I_{72}	3.83	5.11	6.39
I_{13}	0	0	0	I_{73}	3.83	5.11	6.39

Table 3: Optimal solution for loads computed for case 2.1 when load L_1 was set as a high-priority load

Name of the load	L_{i_a} (amps)	L_{i_b} (amps)	L_{i_c} (amps)
L_1	25	25	25
L_2	0	0	0
L_3	0	0	0
L_4	0	0	0

was restored while the other loads were not restored.

$$\begin{aligned}\text{Maximise}\{&2L_{1\_a} + L_{2\_a} + L_{3\_a} + L_{4\_a} + 2L_{1\_b} \\ &+ L_{2\_b} + L_{3\_b} + L_{4\_b} + 2L_{1\_c} \\ &+ L_{2\_c} + L_{3\_c} + L_{4\_c} + H_7 + H_{16}\}\end{aligned} \quad (19)$$

$$I_{15\_a} = 0;\ I_{15\_b} = 0;\ I_{15\_c} = 0;\ H_{15} = 0 \quad (20)$$

For the next case, load L_4 was set as a high-priority load and load L_1 was set as a low-priority load. The other conditions remained the same. The objective function for this condition is given in (21). CPLEX generated the results for loads as shown in Table 4. This solution indicates that L_4 (modelled as a high-priority load) was restored while the other loads were not restored. Many similar cases were simulated and the results indicated that while restoring loads, high-priority loads were given the highest priority.

$$\begin{aligned}\text{Maximise}\{&L_{1\_a} + L_{2\_a} + L_{3\_a} + 2L_{4\_a} \\ &+ L_{1\_b} + L_{2\_b} + L_{3\_b} + 2L_{4\_b} \\ &+ L_{1\_c} + L_{2\_c} + L_{3\_c} + 2L_{4\_c} + H_7 + H_{16}\}\end{aligned} \quad (21)$$

Table 4: Optimal solution for loads computed for case 2.1 when load L_4 was set as a high-priority load

Name of the load	L_{i_a} (amps)	L_{i_b} (amps)	L_{i_c} (Amps)
L_1	0	0	0
L_2	0	0	0
L_3	0	0	0
L_4	25	25	25

3.2.2 Case 2.2: Restoration – illustration of handling priority of paths

This case illustrates that a path that is given a high priority will be considered before a path with low priority to restore a load. To illustrate this, loads L_1 and L_4 were set as high-priority loads. Initially the path through switch 16 was designated as the high-priority path at load L_4. For load L_1, the path through switch 7 was designated as the high-priority path. A fault was simulated on the CB (edge 11) connecting to load L_3 (at node 13). The total available generation was set to 150 amps in each phase so that all loads can be supplied. The objective function for this example is given in (22). Since the fault was on component 11, a set of new constraints, as shown in (23), was added. This indicates that these components are not available. Also the affected load due to this fault was L_3. Formulating the problem as explained, CPLEX generated the solution for loads as shown in Table 5. The solution for MBTs was $H_{16} = 1$, $H_7 = 1$, $H_{17} = 0$ and $H_8 = 0$. This solution indicates that L_4 was restored through switch 16 that was modelled as a high-priority path. Load L_3 was not restored as it had no alternate path.

Table 5: Optimal solution for loads computed for case 2.3 when path through switch 16 was given high-priority

Name of the load	L_{i_a} (amps)	L_{i_b} (amps)	L_{i_c} (amps)
L_1	25	25	25
L_2	25	25	25
L_3	0	0	0
L_4	25	25	25

$$\begin{aligned}\text{Maximise}\{&2L_{1\_a} + L_{2\_a} + L_{3\_a} + 2L_{4\_a} \\ &+ 2L_{1\_b} + L_{2\_b} + L_{3\_b} + 2L_{4\_b} \\ &+ 2L_{1\_c} + L_{2\_c} + L_{3\_c} + 2L_{4\_c} \\ &+ H_7 + H_{16}\}\end{aligned} \quad (22)$$

$$I_{11\_a} = 0;\ I_{11\_b} = 0;\ I_{11\_c} = 0;\ H_{11} = 0 \quad (23)$$

In the next case, the path through switch 17 was designated as the high-priority path to load L_4 and all other conditions remained the same as above. The objective function for this condition is given in (24). It can be seen that the objective function (24) now has the term H_{17} (instead of H_{16} in (22)), since the path through switch 17 was now designated as a high-priority path. For this formulation, CPLEX generated the solution for loads as shown in Table 6. The solution for MBTs was $H_{17} = 1$, $H_7 = 1$, $H_{16} = 0$ and $H_8 = 0$. This solution indicates that L_4 was restored through switch 17 that was modelled as a high-priority path. Load L_3 was not restored, as it had no alternate path. This indicates that a load will be restored through the path that was modelled as high-priority path, if available. The reconfigured network for this case is shown in Fig. 7, which shows that load L_4 was supplied through the path through switch 17 which was modelled as a high-priority path.

$$\begin{aligned}\text{Maximise}\{&2L_{1\_a} + L_{2\_a} + L_{3\_a} + 2L_{4\_a} \\ &+ 2L_{1\_b} + L_{2\_b} + L_{3\_b} + 2L_{4\_b} \\ &+ 2L_{1\_c} + L_{2\_c} + L_{3\_c} + 2L_{4\_c} + H_7 + H_{17}\}\end{aligned} \quad (24)$$

Table 6: Optimal solution for loads computed for case 2.3 when path through switch 17 was given high priority

Name of the load	L_{i_a} (amps)	L_{i_b} (amps)	L_{i_c} (amps)
L_1	25	25	25
L_2	25	25	25
L_3	0	0	0
L_4	25	25	25

Several case studies were performed on a typical naval shipboard power system model based on a surface combatant ship. The results obtained were as expected and proved the effectiveness of the method.

4 Conclusions

A new and simple method of reconfiguration for service restoration in shipboard power systems was presented. The

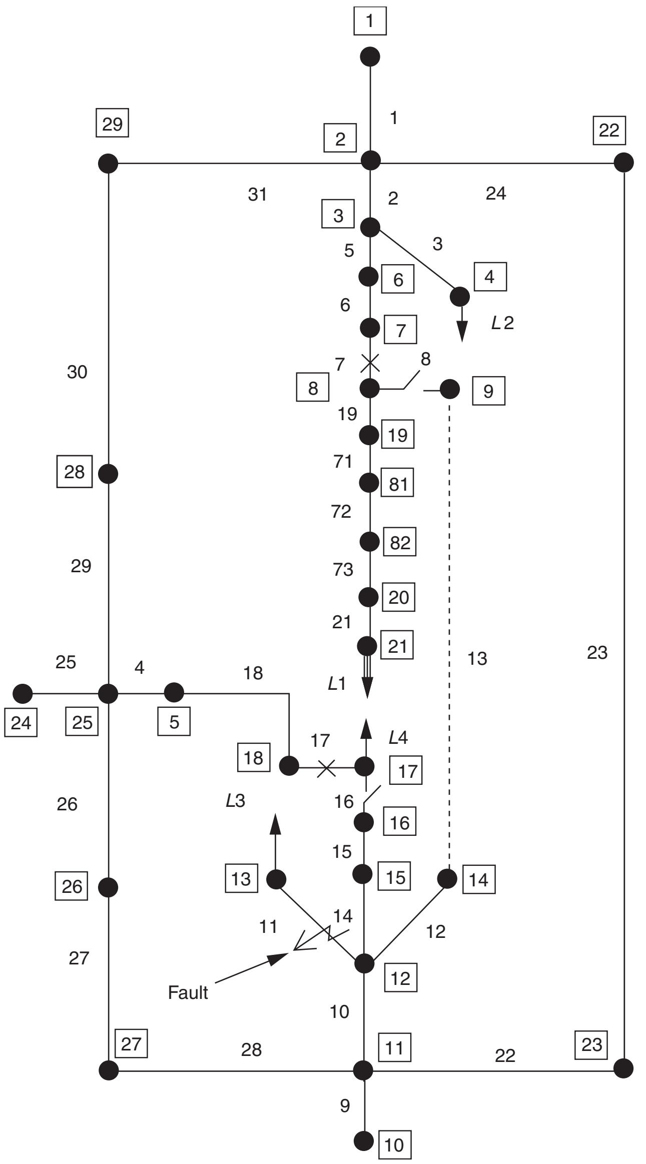

Fig. 7 *Reconfigured network for case 2.2*

service restoration problem was formulated as a variation of the fixed charge network flow problem. Since it is in a mixed integer linear form, an optimal result is ensured. The proposed method does not need load-flow/power-flow analysis to verify the current capacity and voltage constraints. The method generates control actions necessary to perform the reconfiguration. The control actions can automatically reconfigure the network through a microprocessor-based control system to restore maximum load satisfying the constraints and also ensuring the radial condition. While doing so, it considers the priority of the loads and also considers the preferred path of a vital load to have a higher priority than its alternate path during reconfiguration.

The method was applied to a simplified shipboard power system model. Various case studies were presented to illustrate the effectiveness of the proposed formulation. The cases demonstrated the ability of the restoration method to reconfigure the system within the constraints when there is no fault, and to reconfigure the system in the presence of a fault. The results obtained matched the expected results exactly. The authors have also tested the method for a large SPS model that was based on an actual surface combatant ship. All cases demonstrated that the method provides the optimal solution for service restoration in shipboard distribution systems.

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