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Designing Power System Topologies of Enhanced Survivability

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Survivability, or the ability to deliver service in spite of multiple simultaneous faults caused by natural or hostile disruptions, is a desirable feature of any complex system. For some systems such as the integrated power system in an all-electric ship, the ability to withstand massive sudden damage is of vital importance. Although many factors contribute to power system survivability, a key factor is its topology – the number of generators and the connections between generators, between loads, and generators with loads. Previously, we developed a basic mathematical framework and computational tools for analyzing the topological survivability of power systems with multiple generators and a single load. This paper considers a case of multiple generators and multiple loads with application to the topology of a notional medium voltage DC shipboard power system. Possible improvements are suggested.

Nomenclature

m	=	number of faulty elements
M	=	total number of system elements
N	=	total number of fault scenarios
$N(m)$	=	number of fault scenarios with a given m
$k!$	=	factorial
S, R, F	=	numbers of "no-response", reconfiguration, and complete failure scenarios
P	=	probability of the fault scenarios of a given type (S, R, or F)

I. Introduction

THE ability to withstand multiple simultaneous faults caused by natural and hostile disruptions is a desirable feature of any power system. Such disruptions are sudden, massive in scale, often without the possibility of being repaired in a short term. For some complicated modern systems, such as the integrated power system (IPS) of an all-electric ship, the requirement of survivability is vital. Power interruption on a battlefield can have drastic consequences for a ship, its crew, and the mission. Traditional reliability/availability analysis does not apply to unpredictable recoverable faults. Therefore, new analytical and computational tools are required to conduct the analysis of the IPS survivability.

Many factors[1,2] contribute to the IPS survivability. Ideally, all of them should be recognized and mathematically described as well as their interaction with one another[3]. This is a difficult task to accomplish. Our research focuses on the impact of the IPS topology on its ability to withstand massive sudden damage. The IPS topology – the number of power sources (hereafter, generators) included in the system, how they are connected with one another and with loads, and how the loads are connected between themselves – is a key factor to consider in the analysis of the IPS survivability along with reliability, redundancy, and reconfiguration strategies[2,4]. Notice though, that reliability of the system elements is no guarantee against massive sudden damage. Reconfiguration strategies[2,5-7] depend on the system topology. A number of possible links connecting a component with the rest of the system is fixed. Once these links are gone, the component is lost, and there can be nothing left to reconfigure. Redundancy, particularly generator redundancy, is the most accepted[8] strategy for enhancing the IPS post-hit performance. However, this option is limited by various constraints such as, for example, cost, weight, and the requirement of the

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spatial separation of generators. Thus, maximum resistance to multiple faults should be directly built into the IPS topology.

To demonstrate the effect of the IPS topology on its survivability, we introduced in Ref. 9 the concept of the "topological survivability" – the capacity inherent in the system topology to maintain operations after receiving damage – and suggested a basic mathematical framework for quantifying the topological survivability of a system with multiple generators, but a single load. This approach is applicable when loads in a system are interconnected into a single distribution system. This is not a case in a notional medium voltage DC shipboard power system[10]. The current paper discusses how the analysis of the topological survivability can be applied to the IPS with multiple distributed loads. Computational issues associated with conducting survivability analysis of large-scale systems is also addressed.

II. IPS Topology

The topology of a notional MVDC IPS[10] is shown in Fig. 1. The system consists of two 36 MW main generators (MTG), and two 4 MW auxiliary generators (ATG), each connected through diode rectifiers to port and starboard longitudinal DC busses operating at 1 kV. The primary loads on the system are two 36.5 MW propulsion systems interfaced to the system through bi-directional Pulse Width Modulation motor drives. Other loads represented on the MVDC system include a pulse power load and a number of zonal distribution systems serving ship service loads (shown by squares *Zone X Load* Center, where X = 1,…,4), all coupled to the MVDC busses through power electronic converters.

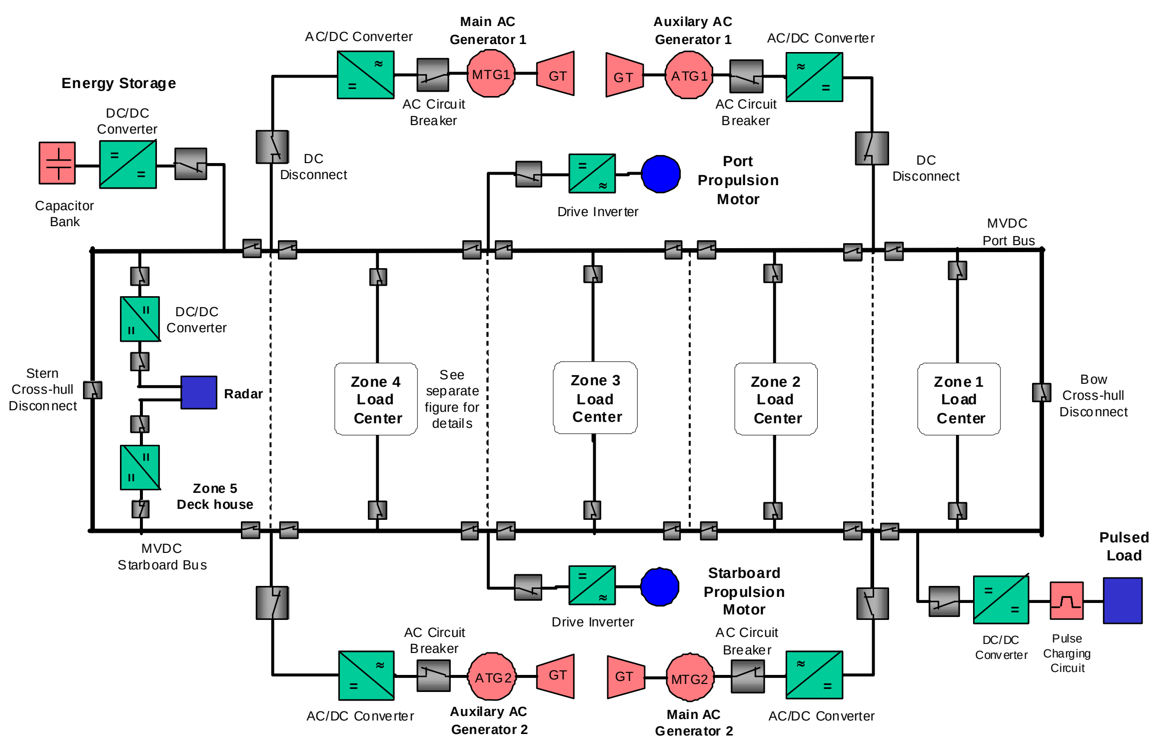


Figure 1. Architecture of a notional MVDC shipboard power system.

Figure 1 contains redundant information that is not necessary for the analysis of the topological survivability. Therefore, the IPS diagram can be simplified. Specifically, all elements that are connected in series can be represented by a single element (hereafter, link), as a fault in any of them results is interruption of power flow through all of them. Figure 2 is a simplified representation of Fig. 1. Storage in *Zone* 5 and a pulsed load in *Zone* 1 with the corresponding cables and devices are excluded from further consideration for the sake of simplicity only. In the figure, *VT*1-*VT*4 are links from the generators to the generator bus. Their connection to the bus is shown by red circles. The generator bus has the ring topology formed by links *H*1-*H*16. Links *VB*7-*VB*11 are from the loads to the generator bus. Their connection to the bus is shown by blue circles. Links *VT*1-*VT*4 and *VB*7-*VB*11 are called vertical links to emphasize the direction of power flow from generators to the generator bus to loads. Links *H*1-*H*16

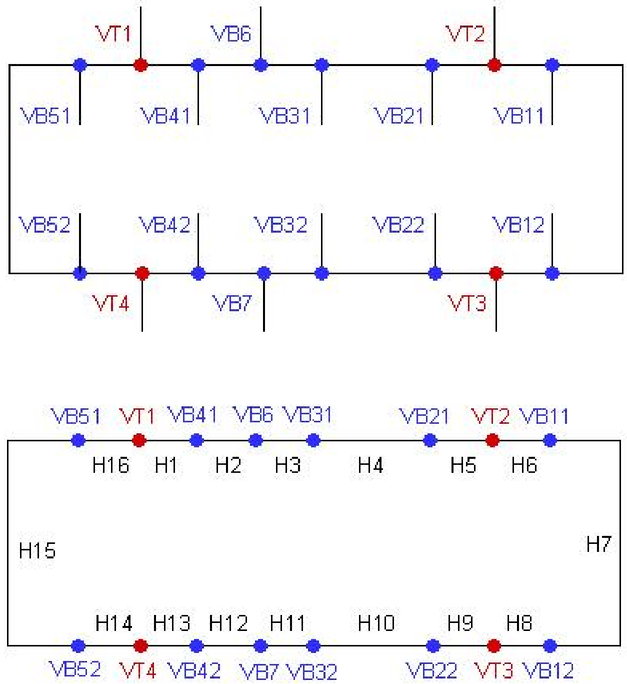


Figure 2. Simplified IPS topology

are called horizontal links as they transfer power flow within the generator bus (hereafter, loop). Vertical links VB11 and VB12 connect *Zone* 1 *Load* Center to the loop. The capacity of each link is such that power demand from the load is totally satisfied if only one link is available. Similarly, links VB21 and VB22, VB31 and VB32, VB41 and VB42, and VB51 and VB52 connect *Zone* 2-5 loads, respectively, to the loop. Notice that if the analysis is conducted for damage of a predictable scale, system elements that fall within the damage range can again be combined into a single element. That is, the diagram in Fig. 2 can further be simplified in such a case.

III. General Framework

In power systems, survivability is associated with the continuation of the generation and distribution of power from power sources to loads. In this regard, the main focus of survivability analysis in application to power systems is the damage outcome or the final steady state of a system after all faults (including cascadian and secondary) have occurred and before any repair has been accomplished. Faults in system elements are failures that cannot be recovered in a short term. Multiple faults are viewed as simultaneous events; only one fault can occur in a given element. Faults in interconnections are not considered as they are equivalent to faults in adjacent elements. Since, one cannot predict what elements and how many of them will be damaged, the outcome of all possible combinations of faults (fault scenarios) should be analyzed. The purpose of the analysis is i) to determine availability and connectivity of system elements and ii) to calculate power flow available to the loads after a given number of faults occurred in the system.

The total number of fault scenarios N at a given number of faults m is the binomial coefficient,

$$N(m) = \binom{M}{m} = \frac{M!}{m!(M-m)!},$$

where M is the total number of elements and $0 \le m \le M$. This number and the total number of fault scenarios $N = \sum_m N(m) = 2^M$ are independent of the system topology and can be easily computed. Each fault scenario results in one of three types of responses from IPS: no response, reconfiguration, and complete failure. No response from IPS is required if faults do not interrupt power flow to loads. We denote the number of "no-response" scenarios by

S. If power flow is reduced, the system survives, but reconfiguration or load shedding is required. The total number of reconfiguration scenarios is denoted by *R*. Scenarios in which power supply to loads is completely interrupted are called scenarios of complete failure. Their number is denoted by *F*. At any *m*, $N = S + R + F$. The number of fault scenarios leading to each IPS response depends on the system topology. These numbers can be used to define probabilities *P*(*S*), *P*(*R*), and *P*(*F*) of each IPS response at a given *m*:

$$P(S) = S / N \ , \ P(R) = R / N \ , \ P(F) = F / N \ .$$

The probabilities of the three responses sum to unity: $P(S) + P(R) + P(F) = 1$. These three probabilities can be used to compare the performance of different topologies and the effectiveness of different design strategies. The current analysis treats all fault scenarios being equally likely taking into account that faults under consideration are unpredictable. This assumption is not a requirement though. If the probabilities of different fault scenarios can be assessed on some reasonable grounds, these probabilities can be incorporated into the analysis.

For very small and simple topologies, *S*, *R*, and *F* as well as the response probabilities can be calculated analytically[9]. As the number of system elements and the complexity of the system topology increase, computations become the only choice to generate fault scenarios, analyze the connectivity of system elements, determine a type of the system response, and compute the response probabilities. A computationally efficient graph-based algorithm suitable for survivability analysis of a system with multiple generators and a single load was developed and tested in Ref.11. Various topologies and design strategies were analyzed in Refs. 12-14.

For more complex topologies with multiple generators and multiple loads, further development in the procedure is required. We suggest reducing the problem complexity by disintegrating the main system topology into sub-topologies with multiple generators and a single load. Indeed, faults in vertical links connecting other loads to the generator bus cannot interrupt power flow to the load under consideration. Therefore, only those fault scenarios that directly affect power flow to a given load have to be analyzed. Faults that isolate other loads may increase the amount of power available to the load under consideration and thus, increase its chances to survive. This factor can be taken into account by analyzing all loads simultaneously. Survivability can be evaluated for each load and for the whole system.

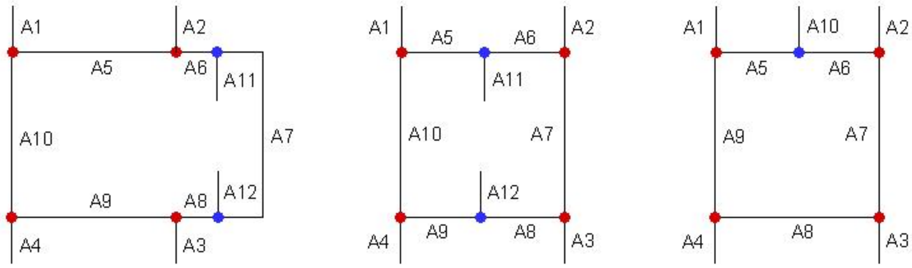
Depending on how many loads are available and how many generators they are connected to, one can determine the state of the whole system for a given set of faults. There are three possible system states: the whole system can be down (no power to any load or available power is insufficient to satisfy the demand of a single load, complete failure); available power is less than the total demand, but sufficient to satisfy the demand of one or more loads (reconfiguration, load shedding is required); power is sufficient to satisfy the total power demand (no response from the system is required). Mathematically, these criteria can be expressed as follows. Let $W_L = \sum_{j=1,..,7} W_{L_j}$ be power demand from all loads in the system, and $W = \sum_{i=1,..,4} W_{G_i}$ be power available to the loads. If $W \geq W_L$, this is a "no response" state, if $\min[W_{L_i}] \leq W < W_L$, this is, a reconfiguration (load-shedding) state, if $W < \min[W_{L_i}]$, this is a complete failure state. Respectfully, a fault scenario is of the same type as a state of the system it results in: complete failure, no response, and reconfiguration scenarios.

The number of sub-topologies to analyze is determined by the number of distributed loads and other factors discussed in the next section.

IV. Application to the Notional MVDC IPS Topology

As there are seven loads in Fig. 2, there are seven sub-topologies to consider. In addition, one can also utilize the symmetry of loads in *Zones* 1 and 5, also in *Zones* 2-4, and motors (VB6, VB7). Then, one has to consider only three sub-topologies shown in Fig. 3.

The topologies in Figs. 3a and 3b can further be simplified to the topology in Fig. 3c. For each of loads in *Zones* 1-5, fault scenarios in the topology in Fig. 3c will be analyzed twice, separately for each of the two VB links attached to a load. That is, each of loads in *Zones* 1-5 will have two sets of A-links (Table 1). Faults in those links of the topology in Fig. 2 that are placed in the same cell in Table 1 have an identical impact on the availability of power flow through a corresponding *A*-link of the topology in Fig. 3c. That is, the A-link is unavailable, if any of these links is damaged. We call such links identical. For example, for the load in *Zone* 1, links H1-H5 (A9-link) are identical and so are links H9-H13 (A7-link) and links H14-H16 (A8-link). Multiple faults in identical links can be



a) b) c)

Figure 3. Sub-topologies: a) for loads in *Zones* 1,5, b) for loads in *Zones* 2-4, c) for motors

reduced to one fault. For example, for the same load in *Zone* 1, the fault scenario VT1-H1-H2-H5-H7 in the topology in Fig. 2 is equivalent to the fault scenario VT1- H1-H7.

The total number of elements in the initial IPS topology (Fig. 2) is M = 32, that is, there are 2^{32} scenarios to analyze. To compare, the topology in Fig. 3c has only 10 elements and 1024 scenarios to analyze. The complexity of the problem is reduced drastically. The generation of all fault scenarios for the topology in Fig. 3c and the analysis

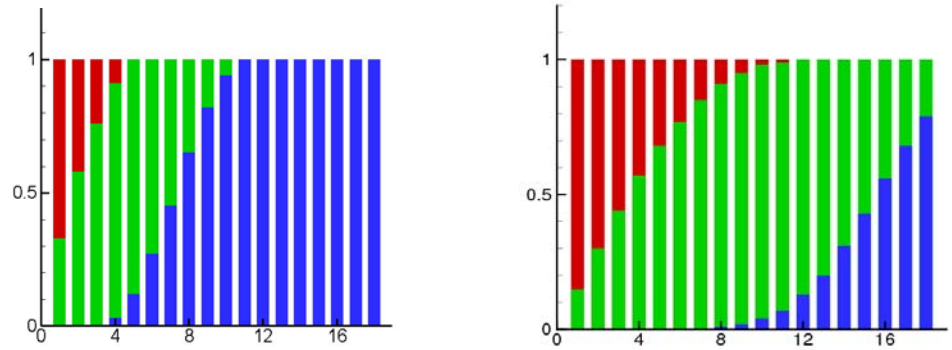
Loads	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10
***Zone* 1**										
Set 1	VT2	VT3	VT4	VT1	H6	H7,H8	H9-H13	H14-H16	H1-H5	VB11
Set 2	VT2	VT3	VT4	VT1	H6,H7	H8	H9-H13	H14-H16	H1-H5	VB12
***Zone* 2**										
Set 1	VT1	VT2	VT3	VT4	H1-H4	H5	H6-H8	H9-H13	H14-H16	VB21
Set 2	VT4	VT3	VT2	VT1	H10-H13	H9	H6-H8	H1-H5	H14-H16	VB22
***Zone* 3**										
Set 1	VT1	VT2	VT3	VT4	H1-H3	H5	H6-H8	H9-H13	H14-H16	VB31
Set 2	VT4	VT3	VT2	VT1	H11-H13	H9,H10	H6-H8	H1-H5	H14-H16	VB32
***Zone* 4**										
Set 1	VT1	VT2	VT3	VT4	H1	H2-H5	H6-H8	H9-H13	H14-H16	VB41
Set 2	VT4	VT3	VT2	VT1	H13	H9-H12	H6-H8	H1-H5	H14-H16	VB42
***Zone* 5**										
Set 1	VT4	VT1	VT2	VT3	H14,H15	H16	H1-H5	H6-H8	H9-H13	VB51
Set 2	VT4	VT1	VT2	VT3	H14	H15,H16	H1-H5	H6-H8	H9-H13	VB52
Motor VB6	VT1	VT2	VT3	VT4	H1,H2	H3-H5	H6-H8	H9-H13	H14-H16	VB6
Motor VB7	VT4	VT3	VT2	VT1	H12,H13	H9-H11	H6-H8	H1-H5	H14-H16	VB7

Table 1. Correspondence of links in Fig. 2 and Fig. 3c for individual loads

of their outcome can be conducted prior generating the fault scenarios for the topology in Fig. 2. The results of the analysis can be saved in computer memory. Then, after a fault scenario for the topology Fig. 2 is generated, it is identified as one of the existing fault scenarios in the database for a given load. It illuminates a need for conducting a time-consuming graph-search analysis to establish the elements connectivity and power flow availability for all of 2^{32} fault scenarios possible in the topology shown in Fig. 2.

V. Comparison of Different IPS Topologies

Once the analysis of a system with multiple generators and loads is reduced to the problem of a system with multiple generators and a single load, the computational algorithm described in Ref. 11 can be used as a core of a computational procedure. Alternative system designs with the same numbers of generators and loads, but different topologies connecting them can be compared based on survivability of the sub-topologies that they can be disintegrated into. Computational analysis of some simplified IPS topologies with four generators and a single load



a) **b)**

Figure 4. Response probabilities vs. number of simultaneous faults: *P(S)*, *P(R)*, *P(F)* for 4-generator (a) Ring and (b) Dual Bus.

was conducted in Refs. 13,14. Figure 4 shows the results of such analysis for ring and dual bus topologies[15]. The figure demonstrates the superior performance of the later topology that has redundant links from generators to the generator bus and places these links in strategically better positions.

However, instead of generating all fault scenarios for the sub-topologies, one can also analyze all possible paths connecting a load with each generator in a given topology. In a path, all elements are connected in series. In this way, we will again exploit the idea that if a single element in the chain of elements connected in series goes down, the whole chain becomes unavailable. Thus, the need to check whether all elements in the chain are connected is eliminated. For complex topologies, there are graph algorithms developed for identifying all paths existing between given nodes. The topology in Fig. 3c, however, is very simple, and no computational algorithm is required. Table 2 shows all paths between the load and generators for this topology ("1" indicates that an element is included in the path).

N	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10
1	1				1					1
2	1					1	1	1	1	1
3		1				1				1
4		1			1		1	1	1	1
5			1			1	1			0
6			1		1			1	1	1
7				1	1				1	1
8				1		1	1	1		1

Table 2. Paths between generators and the load in Fig. 3c.

For each load in *Zones* 1-5, there are 16 paths, because these loads are connected to the loop by two links. There are eight paths for each of the motor loads.

Different topologies with the same numbers of generators and loads can be compared by the number of paths existing for power delivery from generators to a load. For example, the superiority of the dual bus topology[15] can be demonstrated with this approach also. One of the possible layouts for the dual bus topology is shown in Fig. 5a. The numbers of generators and loads are the same as in the topology in Fig. 2. The dual bus topology can be disintegrated into two sub-topologies (Figs. 5b,c). There are 32 paths available for the load in *Zone* 1, 30 for the loads in *Zones* 2-5, and 16 for each of the motor loads (VB6 and VB7). Clearly, each load has more chances to survive than in the notional IPS topology shown in Fig. 2. Moreover, repositioning the VT-links from their current locations in Fig. 5a will reduce the number of the sub-topologies to one (Fig. 5b) and will increase the number of paths delivering power to loads in *Zones* 2-5 from 30 to 32. That is, the approach suggested in the paper can indicate how a simple change in the system design will improve its chances to survive. Additional consideration is the

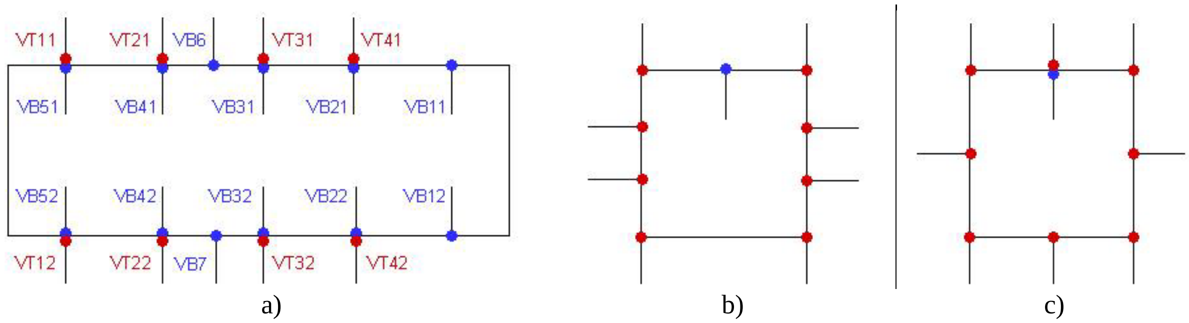


Figure 5. Dual Bus topology a) and its sub-topology b).

amount of power produced by each generator that can be represented by different weights assigned to different paths.

VI. Conclusions

A new methodology for quantifying the ability of a power system topology with multiple generators and multiple loads to withstand massive sudden damage is suggested and discussed in application to a notional medium voltage DC shipboard power system. The methodology is based on analyzing system responses to each possible combination of faults in system elements. Clearly, such analysis can be unfeasible for large-scale complex topologies. In Ref. 11, an efficient computational algorithm was suggested for survivability analysis of systems with multiple generators and a single load. In the present paper, we show that a problem of a complex topology with multiple generators and multiple loads can computationally be reduced to a case of a simple topology with multiple generators and a single load. Thus, computational expenses can be reduced drastically. We also suggest a new measure to compare survivability of different topologies with the same numbers of generators and loads. The comparison is made based on the number of paths connecting a load with generators. This number is much less than the number of fault scenarios possible in a given topology, and the analysis of their availability for power flow does not require a graph-search procedure. In this way, computational burden can further be reduced.

Acknowledgments

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References

[1]F. E. Oliveto, "System Efficiency/Merit," *Proc. IEEE 1998 NAECON*, July, Dayton, OH, 1998, pp. 51-59.

[2]J. Hill, "Survivable Architectures for Vital Systems," *Proc. ASNE Reconfiguration & Survivability Symposium*, February, Jacksonville, FL, 2005.

[3]K.-S. Tam, K. Russel, and R. Broadwater, "A Framework for Mission-based Interdisciplinary Reconfiguration for Navy Ships," *Proc. ASNE Reconfiguration & Survivability Symposium*, February, Jacksonville, FL, 2005.

[4]J. Hill, R. Steinberg, "Design Features for Survivability of High Speed Ships," *Proc. ASNE Reconfiguration & Survivability Symposium*, February 2005 (Jacksonville, FL).

[5]K. L. Butler-Purry, N. D. R. Sarma, "Self-healing Reconfiguration for Restoration of Naval Shipboard Power Systems," *IEEE Trans. Power on Systems*, vol. 19 (2), 2004, pp. 754-762.

[6]K. R. Davey, R. E. Hebner, "Reconfiguration: A Tool for Designing New Ships," *Proc. IEEE Electric Ship Technologies Symposium*, July, Philadelphia, PA, 2005, pp. 81-85.

[7]S. K. Srivastava, K. L. Buttler-Purry, "A Pre-hit Probabilistic Reconfiguration Methodology for Shipboard Power Systems," *Proc. IEEE Electric Ship Technologies Symposium*, July, Philadelphia, PA, 2005, pp. 99-104.

[8]J. W. K. Sajdak, D. Klinkhamer, "Four Levels of Ship Survivability," *Proc. ASNE Day 2006*, June, Arlington, VA, 2006.

[9]S. V. Poroseva, S. L. Woodruff, and M. Y. Hussaini, "Topology of the Generator Bus in a Warship Integrated Power System," *Proc. IEEE ESTS*, July 25-27, Philadelphia, PA, 2005, pp.141-148.

[10] IEEE , "Recommended Practice for 1 to 35kV Medium Voltage DC Power Systems on Ships," IEEE P1709/ Draft D0.8.2, New York, NY, Jan. 2010.

[11]S. V. Poroseva, N. Lay, and M. Y. Hussaini, "Algorithm Development for Evaluating the IPS Survivability due to its Topology," *Proc. of IEEE Electric Ship Technologies Symposium*, Baltimore, 2009.

[12]S. V. Poroseva, Y. P. Li, M. J. Willis, S. L. Woodruff, and M. Y. Hussaini, "Enhancing Survivability of All-Electric Warships through Implementation of Effective Topologies into the Integrated Power System," *Proc. the ASNE Day 2006*, Arlington, 2006.

[13]S. V. Poroseva, S. L. Woodruff, and M. Y. Hussaini, "Modeling Topological Survivability of Power Systems,," *Proc. Ships & Ship Systems Technology Symposium*, West Bethesda, 2006.

[14]S. V. Poroseva, S. L. Woodruff, and M. Y. Hussaini, "Application of Web-Topology to Enhance Survivability of the Integrated Power System in an All-Electric Warship," *Proc. Grand Challenges in Modeling and Simulation Conference*, Edinburg, UK, 2008.

[15]Doerry, N. 2006. "Zonal Ship Design," *Naval Engineers Journal*, Vol. 118, No. 1, pp. 39-53.