Designing Power System Topologies of Enhanced Survivability

Svetlana V. Poroseva[1]
Florida State University, Tallahassee, FL, 32310

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. 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 each other[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; there will be only so many possible links between a component and the rest of the system and once these links are gone, the component is lost. 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 spatial separation of generators. Thus, maximum resistance to multiple faults should be directly built into the IPS topology.

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[1] Assistant Scholar Scientist, Center for Advanced Power Systems, 2000 Levy Ave. Suite 140, Tallahassee, FL, 32310, AIAA Senior Member.

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. An issue with the computational 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.

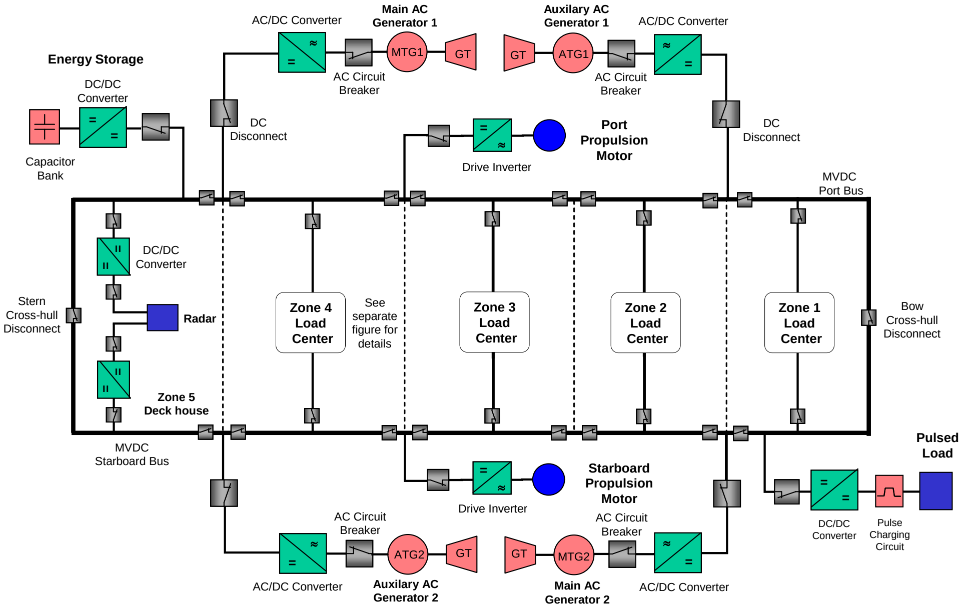


Figure 1. Architecture of a notional MVDC shipboard power system.

For the purposes of the analysis of the topological survivability, Fig. 1 contains redundant information and 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 shows 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, *V*T1-*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 *V*T1-*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 are called horizontal links as they transfer power flow within the generator bus (or the loop). Vertical links VB11 and VB12 connect *Zone* 1 *Load* Center to the loop. One of the two links is sufficient to supply power to the load. 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, all elements in Fig. 2 that fall within the damage range can again be combined into a single element.

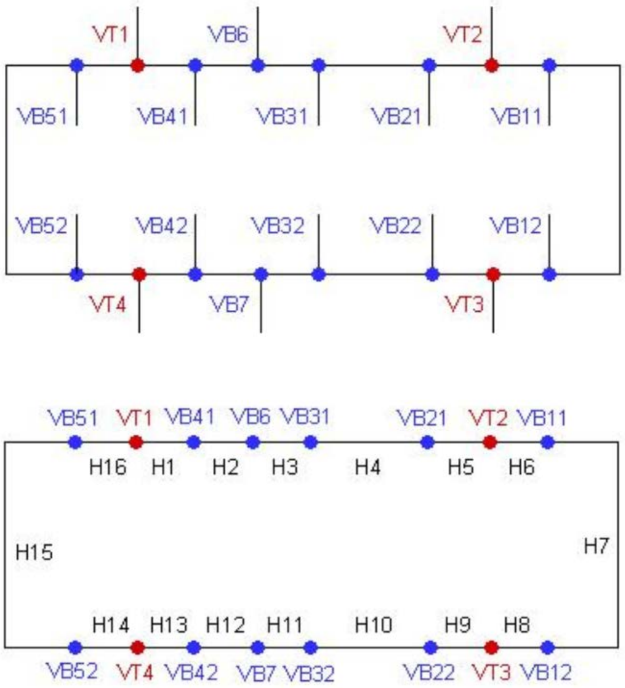


Figure 2. Simplified IPS topology

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. In this regard, faults in system elements are viewed as 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 such faults 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 the system elements after a given number of faults occurred in the system and ii) to calculate power flow available to the loads.

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

$$N(m)=\binom{M}{m}=\frac{M!}{m!(M-m)!}, \tag{1}$$

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.

The numbers *S*, *R*, *F*, and *N* can be used to define probabilities *P*(*S*), *P*(*R*), and *P*(*F*) of each IPS response at a given *m*:

$$P(S) = S / N\ ,\ P(R) = R / N\ ,\ P(F) = F / N\ . \quad (2)$$

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 them to determine the connectivity of the system elements, determine the type of the response scenario, and compute the response probabilities. A computationally efficient graph-based algorithm suitable to the 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 for this case in Refs. 12-14.

For more complex topologies with multiple generators and multiple loads, more efficient 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 do not directly influence power flow to the load under consideration. Only those fault scenarios that directly affect power flow to a given load have to be analyzed. Faults related to other loads do influence, however, the amount of power available to the load under consideration. That is, if faults isolate other loads, there is no power demand from isolated loads and, therefore, the load under consideration has more chances to survive. This factor should be taken into account by analyzing all loads simultaneously.

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 the power demanded by all loads in the system, and $W = \sum_{i=1,..,4} W_{G_i}$ be the 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.

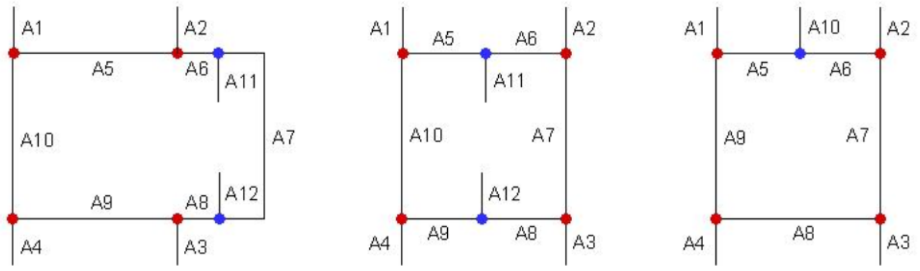
The number of sub-topologies to analyze is determined by the number of distributed loads and other factors discussed in the next section.

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 vertical 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 the links from Fig. 2 shown in the same cell in Table 1 have an identical impact on the availability of a corresponding *A*-link for power flow. 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). Moreover, multiple faults in identical links in the same A-link will be 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 of the outcome of each fault scenario can be conducted prior generating the fault scenarios for the topology in Fig. 2.



a) b) c)

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

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.

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

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 the 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. However, instead of generating fault scenarios for the sub-topologies, one can analyze possible paths from the load to each generator existing 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 is very simple, and no computational algorithm is required.

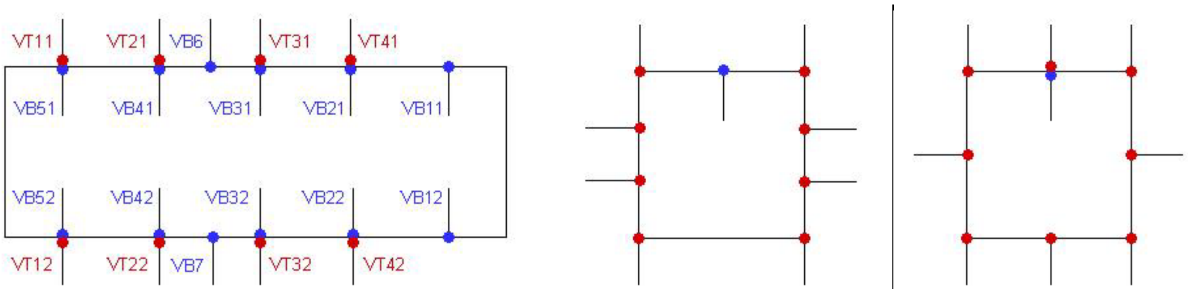
Table 2 shows all paths between the load and generators for this topology ("1" indicates that an element is included in the path).

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 motors.

Different topologies can be compared by the number of paths existing for power delivery from generators to a load. For example, one of the alternative topologies for an IPS system is the dual bus topology[15]. One of the possible layouts for this topology is shown in Fig. 4a. This topology can be disintegrated into two sub-topologies (Figs. 4b,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 motors (VB6 and VB7). Clearly, repositioning the VT-links from generators to the loop will increase the number of paths delivering power to loads in *Zones* 2-5 and thus, will improve their chances to survive.



a) b) c)

Figure 4. Dual Bus topology a) and its sub-topology b).

Acknowledgments

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