Survivability Analysis of the Satellite Electrical Power Subsystem Architecture

Bryan E. Kaiser[1] and Svetlana V. Poroseva[2]
University of New Mexico, Albuquerque, New Mexico, 87131

Satellites are costly to operate and difficult to repair once in use. A failure of the satellite electric power subsystem (EPS) may result in the loss of a satellite. Analysis of the EPS ability to continue to deliver power to loads in the presence of multiple faults in its elements (or survivability) may assist in designing a more reliable EPS. The current paper analyses the EPS survivability which is due to its topology from the perspective of individual loads. The UoSAT-12 mini-satellite EPS is chosen as a testbed for conducting computational analysis of its survivability.

Nomenclature

VT	=	*link adjacent to a generator*
VB	=	*link adjacent to a load*
H	=	*link between two interconnections*
M	=	*number of total elements*
m	=	*number of faulted elements*
N_M	=	*total number of faults scenarios*
N_m	=	*total number of fault scenarios at a given m*
S	=	*number of "no response" outcomes*
R	=	*number of "reconfiguration" outcomes*
F	=	*number of "failure" outcomes*
$P(S)$	=	*probability of a"no response" outcome for m faulted elements*
$P(R)$	=	*probability of a "reconfiguration" outcome for m faulted elements*
$P(F)$	=	*probability of a "failure" outcome for m faulted elements*

I. Introduction

Satellites rely on self-contained electric power subsystems (EPS) for operation. EPS is usually composed of generators, loads, batteries, and connecting wires. Satellite generators include photovoltaic arrays, solar thermal devices, and nuclear reactors[1]. Common EPS loads are radar, communication equipment, motors, computers and other scientific instruments[2]. Satellite batteries alternate between the roles of a generator and a load depending on whether a battery is charging or discharging. Power buses and connecting wires deliver power from generators to loads.

There is a constant risk of EPS failure. Expected damage due to natural causes accumulates with time without repair and will eventually lead to EPS failure. Sudden damage may occur at any time due to hostility of the space environment. A combination of expected and sudden damage can result in earlier than expected EPS failure. Common types of EPS failure include mechanical failures, wiring failures/short circuits, solar cell failures, battery failures, computer failures, plasma discharge events, and impact events[3,4]. Any combination of such events is possible and defined hereafter as a fault scenario.

The traditional approach to risk assessment for EPS systems is to evaluate only worst-case fault scenarios that lead to EPS failure. In complex systems such as EPS, it is impossible to identify all possible worst-case scenarios without analyzing all fault scenarios possible in a given system. In the current research, all possible fault scenarios are generated and the impact of each scenario on the power availability to individual EPS loads is computationally analyzed.

[1]Undergraduate student, Mechanical Engineering, MSC01 1105, 1 UNM Albuquerque, NM 87131-0001, AIAA Student Member.
[2]Assistant professor, Mechanical Engineering, MSC01 1105, 1 UNM Albuquerque, NM 87131-0001, AIAA Senior Member.

A probabilistic framework for such analysis was proposed in Poroseva et al.[5] and Poroseva[6,7] for networks with multiple sources and sinks such as power systems, for example. The methodology is for evaluating the system's ability due to the system's topology to withstand multiple simultaneous faults (or *topological survivability*). The system's topology is defined as a number of system components, their type, and how they are connected to one another. In the current study, this approach is adopted for evaluating the survivability of the mini-satellite UoSAT-12 EPS[8]. This EPS was selected as a testbed because of its complexity and because the utilization of mini-satellites has increased in recent years. The satellite was launched to the low Earth orbit (LEO) in 1999 and retired in 2003.

Another objective of our research is the development of computational tools for conducting the analysis of the EPS topological survivability and the discernment of the survivability-enhancing design protocol.

II. The EPS Representation for the Survivability Analysis

Due to symmetry and complexity of the UoSAT-12 EPS topology, the current results are obtained for one-third of the system only (Fig. 1).

For the topological survivability analysis, only three types of elements are of importance: generators, loads, and links. In this study, it is assumed that the UoSAT-12 battery is discharging, that is, it acts as a generator, and all three solar arrays are generating power. Auxiliary power supplies are not used to charge loads and therefore, are not included in the current analysis. Figure 1 modified for the purposes of our study is shown in Fig. 2.

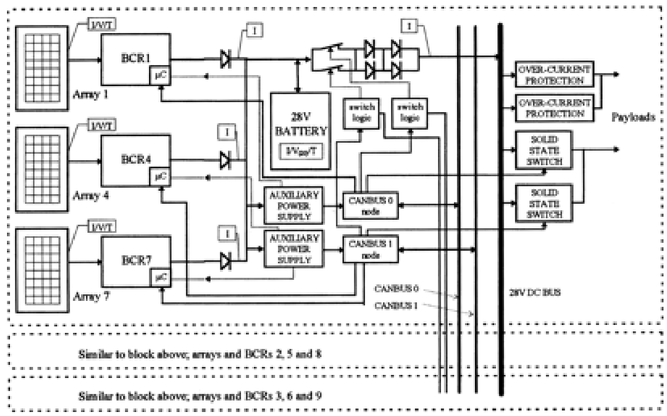


Figure 1. One-third of the UoSAT-12 mini-satellite EPS. [8]

In our previous works[6,7], it was found that for the topological survivability analysis of power systems, the most efficient way of representing a system is by links only. Indeed, if a generator or a load is connected to the system by a single link, the generator (load) and the link are connected in series. Then, a fault in the link makes the generator (load) unavailable to the system, and a fault in the generator (load) makes the link useless. Therefore, the generator (load) and the link can be represented by a single link.

If there are several links connecting a generator or a load to the system, faults in all of them isolate the generator (load) from the system, which is equivalent to a fault in the generator (load). Thus, there is no need to consider faults in generators and loads separately from faults in links, and they can be removed from the system. For the similar reasons, faults in interconnections can also be removed from consideration.

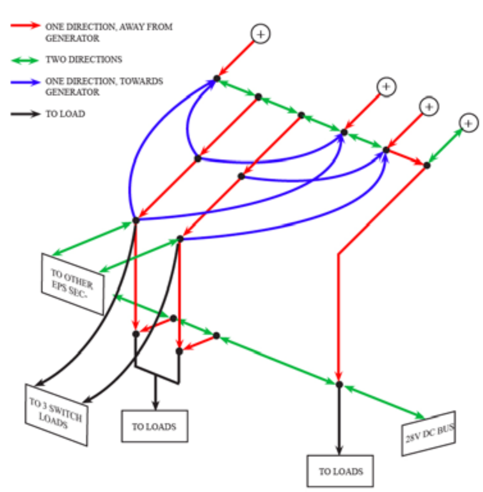


Figure 2. The simplified EPS diagram from Fig. 1 represented using only generators, loads, and links.

In the EPS representation by links, there are three different types of links: links adjacent to generators (vertical "VT" links), links adjacent to loads (vertical "VB links), and links between interconnections (horizontal "H" links). To recognize the three types of links mathematically, the VB- and VT-links are assigned weights.

A sign of the weight shows the flow direction through a link: the VT-links have positive weight and the VB-links have negative weight. No sign is assigned to the H-links, because the flow direction through such links may vary depending on the system's topology after faults.

A value of the weight assigned to a link can be based, for example, on its capacity or a maximum amount of power it can transport in relation to the total demand. Currently, such data are not available to the authors. Therefore, no specific weights are assigned to links. This is not a limitation of the approach though. Once available, such information can be easily incorporated into the analysis.

The EPS representation by links only is shown in Fig. 3. The VT-links are links 1-4 in Fig. 3, and the VB-links are links

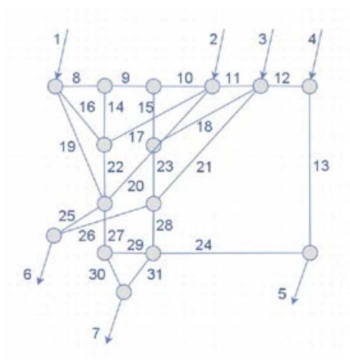
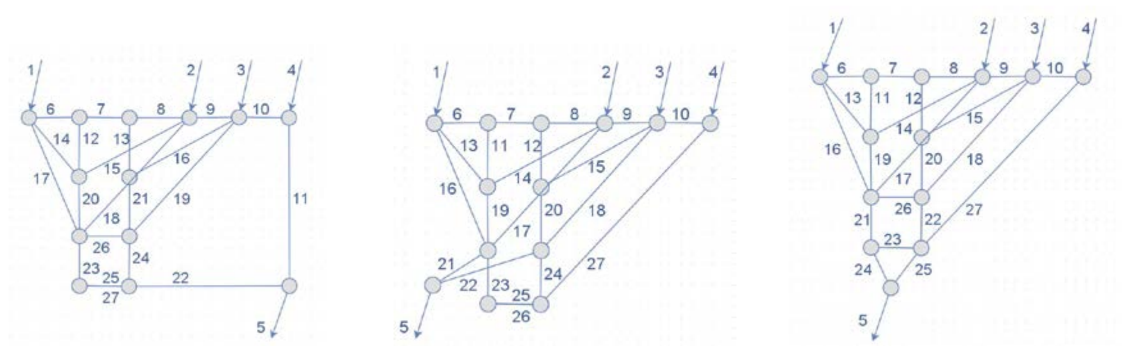


Figure 3. Figure 2 represented by the three types of links.

5,6, and 7. Links 8-31 are the H-links.

The EPS topology (Fig. 3) is then disintegrated into sub-topologies for each individual VB link[7]. As there are three VB-links in Fig. 3, there are three sub-topologies to analyze. The sub-topologies are shown in Fig. 4.

Power System Graph Converter[9] was used to generate Figures 3-4 and convert these diagrams in a form of an adjacency list suitable for the mathematical analysis. Note that labels of links change from one figure to another. This is due to automatic labeling of links by software. Software recognizes three types of links and generates ordered adjacency lists to reduce computational time of the topological survivability analysis[10].



(a) **(b)** **(c)**

Figure 4. *S*ub-topologies for VB-links 5-7 from Fig. 3: (a) for VB-link 5, (b) for VB-link 6 , (c) for VB-link 7. Notice that on this figure, the VB-links 5,6, and 7 from Fig. 3 are all labled as link 5.

III. Computational Analysis

A mathematical framework and a computational algorithm to conduct the topological survivability analysis for an individual load are described in detail in Refs. 6 and 11, respectively. Therefore, only main ideas are provided in this paper.

In a relation to the satellite EPS, we are concerned with availability of power to an individual load in a steady state of EPS. All faults are assumed to be failures that make faulty elements unavailable for EPS. Multiple faults are viewed as simultaneous events, and only one fault can occur in a given element. Origin of faults and their development in time are not a subject of the analysis. Instead, all possible fault scenarios are generated for a given EPS sub-topology (such as shown in Fig.4) and analyzed. An individual load may represent a stand-alone device or a group of devices.

For a given fault scenario, the general problem formulation is to establish how many power sources remain in operational conditions (survived), whether they are connected to a load and if they are connected, whether they can satisfy the load's demand for power.

In regards to demand, a fault scenario can be one of three types depending on the EPS response: "no response", reconfiguration, and complete failure. In a "no response" scenario, faults do not reduce power supply to the load. A fault scenario, in which the supply is reduced but not interrupted, requires reconfiguration. That is, if the load represents a group of devices, some of them must be intentionally disconnected to balance the demand and the power supply. Such a scenario is called a reconfiguration scenario. If faults completely isolate the load from power supply, the fault scenario is that of a complete EPS failure with respect to the load.

In the current study, it is assumed that a load requires supply from all available power sources to satisfy its demand in full. Once at least one power source becomes unavailable, a fault scenario is of the reconfiguration or complete failure type. It is also assumed that availability of at least one power source is sufficient to satisfy a load's demand partially. That is, if at least one power source is available for a load, a fault scenario is of the reconfiguration type. These criteria can be adjusted for each load to make them more realistic once information for a real system is available.

In a system with M elements, there are $N = 2^M$ possible fault scenarios. The total number N of all fault scenarios is the sum of S "no response" fault scenarios, R reconfiguration scenarios, and F scenarios of complete EPS failure: $N = S + R + F$ [6]. The EPS topology in Fig. 3 includes 31 elements. Thus, there are ~ 2.2 billion fault scenarios in EPS that can affect power supply to the three loads. For each individual load (sub-topologies in Fig. 4), a number of fault scenarios reduces to 2^{27} ~ 134 million.

The number of fault scenarios leading to a specific EPS response can be used to determine the response probability P of EPS to such scenarios: $P(S) = S/N$ (probability of "no response" scenarios), $P(R) = R/N$ (probability of reconfiguration scenarios), and $P(F) = F/N$ (probability of complete failure).

In a similar manner, one can define the EPS response probabilities at a given number of faults m:

$$P_m(S) = S(m)/N(m)\,,\ P_m(R) = R(m)/N(m)\,,\ P_m(F) = F(m)/N(m)\,,$$

where $\sum_{m=1,\ldots,M} N(m) = N$, $\sum_{m=1,\ldots,M} R(m) = R$, $\sum_{m=1,\ldots,M} S(m) = S$, $\sum_{m=1,\ldots,M} F(m) = F$.
The response probabilities sum to unity.

Such definition of the response probabilities is valid under the assumption that each fault scenario is equally likely. Since it is impossible to predict a fault scenario that will come to realization in EPS with time, this is a justified assumption. However, this is not a requirement of the analysis. If the information is available, the probability of each fault scenario can be incorporated into the analysis.

The three response probabilities completely characterize the topological survivability of EPS with respect to a given load. They can be used in multiple ways. For example, survivability of different loads can be compared with one another to identify those with the weakest connections or to ensure hierarchical power supply to loads. The survival probabilities for individual loads are required for evaluating survivability of EPS as a whole system[7]. The performance of alternative EPS designs can also be compared using these probabilities in regard to desirable design features, which include high $P(S)$, low $P(F)$, and a high ratio of $P(S)/P(R)$. The latter is important because a higher ratio indicates a higher ability of EPS to withstand damage without requiring reconfiguration.

Thus, the objective of the topological survivability analysis is to determine the EPS response probabilities. This requires knowledge of numbers S, R, and F or, equivalently, of numbers $S(m)$, $R(m)$, $F(m)$, and $N(m)$. The total number of fault scenario for a given number of faults can be calculated analytically: $N(m) = M!/m!(M-m)!$ Numbers $S(m)$, $R(m)$, and $F(m)$ should be computed.

IV. Results

Results of the topological survivability analysis are shown for all three sub-topologies in Fig. 5 and Table 1. The results were obtained with the deterministic computational algorithm described in Ref. 11. In the figures, m is the number of simultaneous faults in the system. Different colors correspond to different survival probabilities at a given m: blue is for $P_m(S)$, yellow is for $P_m(R)$, and red is for $P_m(F)$.

The topological survivability analysis of the UoSAT-12 EPS reveals that the response probabilities are quantitatively similar for all three loads. The similarity is remarkable because the shortest path from the VB-7 link to a VT link in the VB-7 sub-topology is a half of the distance of the same traverse as in the VB-5 and VB-6 sub-topologies.

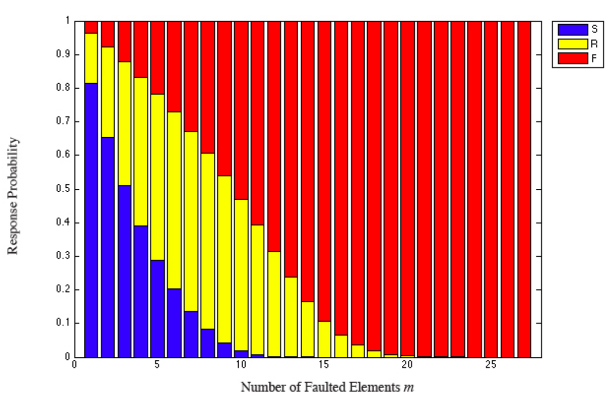


Figure 5. Response probabilities for the VB-5 sub-topology from Fig. 4.

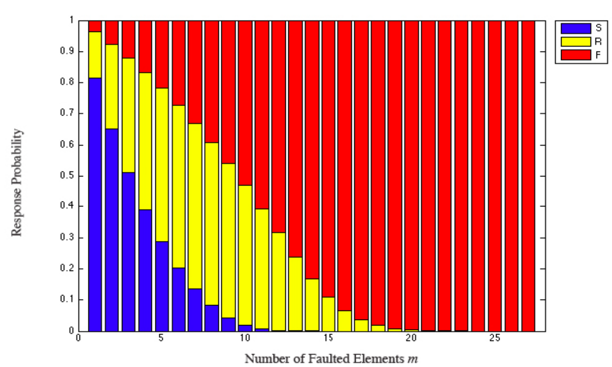


Figure 6. Response probabilities for the VB-6 *s*ub-topology.

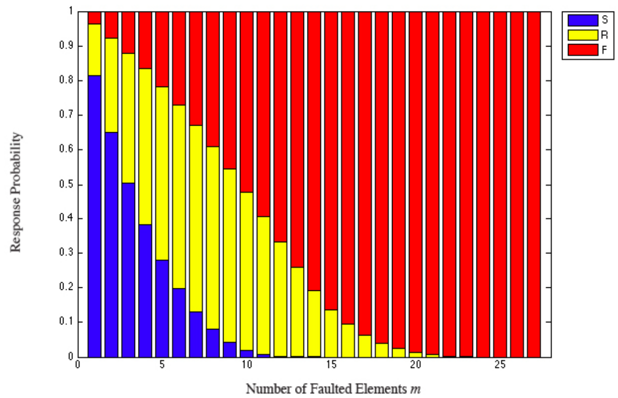


Figure 7. Response probabilities for the VB-7 sub-topology.

The analysis of the topological survivability of the UoSAT-12 EPS performed in the current study is simplified. It did not account for diodes and switches in EPS. The capacity limitation of wires was not considered either. Additionally, the analysis was performed at a steady state of EPS for the maximum power generation scenario in which all solar arrays and the battery generate power simultaneously. Certainly, the results of the analysis are affected by these simplifications. The algorithm, however, allows incorporating more realistic data into the analysis when such data are available. In our future work, we will use the results obtained for individual loads to evaluate the survivability of EPS as a whole system using the "selfish" algorithm described in Ref. 7, and we will analyze how the EPS survivability due to its topology varies during a day due to the limited availability of power from the solar arrays and the battery.

Acknowledgments

The first author would like to acknowledge the support of the New Mexico Space Grant Consortium.

References

[1] Larson, J.H. and Wertz, W.J., *Space Mission Analysis & Design*,3rd ed. Microcosm Inc& Lower Academic Publishers, The Netherlands, 1999, p. 393.

[2] Larson, J.H. and Wertz, W.J., *Space Mission Analysis & Design*,3rd ed. Microcosm Inc& Kluwer Academic Publishers, The Netherlands, 1999, pp. 403-405.

[3] Saleh, J.H. and Castet, J.F.,*Spacecraft Reliability and Multi-State Failures: A Statistical Approach,* John Wiley and Sons Ltd., West Sussex, U.K, 2011, p. 5.

[4] Landis, G.A., Bailey, S.G, and Tischler, R., "Causes of Power-Related Satellite Failures," *IEEE 4th World Conference on Photovoltaic Energy Conversion,* Vol. 2, IEEE, Waikaloa, HI, 2006, pp1943-1945.\

[5] S.V. Poroseva, S.L. Woodruff, M.Y. Hussaini, "Topology of the generator bus in a warship integrated power system", in: Proceedings of the IEEE Electric Ship Technologies Symposium, Philadelphia, PA, U.S.A, 2005, pp. 141-148.

[6] S.V. Poroseva, "Designing Power System Topologies of Enhanced Survivability", in: Proceedings of the 51st AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, Orlando, FL, USA, AIAA-2010-2572, 2010.

[7] S. V. Poroseva, ""Selfish" algorithm for reducing the computational cost of the network survivability analysis," Journal of Optimization and Engineering, 2012, doi:10.1007/s11081-012-9207-1 (On-line first).

[8] Van der Zel, V.M, Blewett, M.J., Clark, C.S, and Hamill, D.C. "Three Generations of DC Power Systems for Experimental Small Satellites," *Proceedings of the Eleventh Annual Applied Power Electronics Conference and Exposition,* Vol. 2, IEEE, San Jose, CA, 1996, pp. 664-670.

[9] Power System Graph Converter, http://www.unm.edu/~poroseva/software/

[10] D. Neumayr, S. V. Poroseva, "On Development of Computational Tools for Evaluating System Survivability Due to Its Topology," AIAA-2011-1818, Proc. of the 52st AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, 2011, April 4-11 (Denver, CO).

[11] S. V. Poroseva, N. Lay, M. Y. Hussaini, "Algorithm Development for Evaluating the IPS Survivability due to its Topology," Proceed. of IEEE Electric Ship Technologies Symposium (IEEE ESTS 2009), April 20-22, 2009 (Baltimore, MD), pp. 253-260.

Appendix

Table 1. Response Probabilities

	VB-5 sub-topology			VB-6 sub-topology			VB-7 sub-topology		
m	$P_m(S)$	$P_m(R)$	$P_m(F)$	$P_m(S)$	$P_m(R)$	$P_m(F)$	$P_m(S)$	$P_m(R)$	$P_m(F)$
1	0.8148	0.1481	0.037	0.8148	0.1481	0.037	0.8148	0.1481	0.037
2	0.6524	0.2707	0.0769	0.6524	0.2707	0.0769	0.6496	0.2735	0.0769
3	0.5121	0.3685	0.1193	0.5115	0.3685	0.12	0.5056	0.3744	0.12
4	0.3926	0.4434	0.164	0.3905	0.4428	0.1666	0.383	0.4505	0.1666
5	0.292	0.4972	0.2108	0.2884	0.4946	0.217	0.2806	0.5027	0.2168
6	0.2084	0.5317	0.2599	0.2037	0.5248	0.2715	0.1969	0.5323	0.2708
7	0.1402	0.5483	0.3115	0.1353	0.5345	0.3301	0.1303	0.5411	0.3286
8	0.0865	0.5475	0.366	0.0822	0.5248	0.393	0.0793	0.5305	0.3902
9	0.047	0.5286	0.4244	0.0437	0.4962	0.4601	0.0427	0.5018	0.4555
10	0.0212	0.491	0.4877	0.0191	0.4494	0.5315	0.0194	0.4563	0.5242
11	0.0077	0.4355	0.5568	0.0064	0.3867	0.6069	0.0072	0.3968	0.596
12	0.0023	0.3661	0.6316	0.0017	0.3134	0.685	0.0022	0.3284	0.6694
13	0.0006	0.2899	0.7096	0.0003	0.2372	0.7624	0.0006	0.258	0.7414
14	0.0001	0.2149	0.7849	0.0001	0.1664	0.8335	0.0001	0.1924	0.8075
15	0	0.1492	0.8508	0	0.108	0.892	0	0.1369	0.863
16	0	0.0969	0.9031	0	0.065	0.935	0	0.0938	0.9062
17	0	0.0588	0.9412	0	0.0362	0.9638	0	0.0621	0.9379
18	0	0.0332	0.9668	0	0.0185	0.9815	0	0.0398	0.9602
19	0	0.0171	0.9829	0	0.0086	0.9914	0	0.0246	0.9754
20	0	0.0079	0.9921	0	0.0036	0.9964	0	0.0144	0.9856
21	0	0.0031	0.9969	0	0.0013	0.9987	0	0.0078	0.9922
22	0	0.0009	0.9991	0	0.0003	0.9997	0	0.0014	0.9986
23	0	0.0002	0.9998	0	0.0001	0.9999	0	0.0003	0.9997
24	0	0	1	0	0	1	0	0	1
25	0	0	1	0	0	1	0	0	1
26	0	0	1	0	0	1	0	0	1
27	0	0	1	0	0	1	0	0	1