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On Development of Computational Tools for Evaluating System Survivability Due to Its Topology

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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. Our study is relevant to systems with sources (elements generating a quality of interest) and sinks (elements consuming this quantity). A key factor for such a system to survive is its topology, that is, the number of sources and sinks and their connections with one another. Previously, we developed a methodology for conducting the analysis of the system survivability due to its topology. However, the application of the analysis to real-life systems such as, for example, power systems, is a computational challenge. System topologies usually contain thousands of elements. The problem can be solved in principle by decomposing a topology with multiple sinks and multiple sources into a few sub-topologies with multiple sources and a single sink. An efficient computational procedure for the survivability analysis of a single-sink topology has already been developed in our previous studies. Two other steps that have yet to be developed are i) automatical transformation of a system diagram into a form suitable for the computational analysis and ii) automatical decomposition of a system with multiple sources and sinks into simpler sub-systems. The current paper reports on software development for converting a standard power system diagram into a structured adjacency matrix or list.

I. Introduction

THE ability to withstand multiple unrecoverable faults caused by natural (hurricanes, earthquakes, floods, wild fires) or hostile (physical destructions or electronic intrusions) disruptions is a desirable feature of any system. The focus of our study is on systems with multiple sources and multiple sinks, where a “source” is understood as an element generating a quality or service of interest and a “sink” is an element consuming this quality or service. Interruption of the quality/service supply to a sink leads to complete or partial disabling the sink.

An example of systems with sources and sinks are power systems, with sources and sinks being generators and loads, respectively. Regardless the system size, the requirement of survivability is usually vital for power systems. Indeed, if one considers the US electric power system, one of the Nation’s eight critical infrastructures[1], the operability of the other seven critical infrastructures – telecommunications, natural gas and oil, banking and finance, transportation, water supply systems, government services, and emergency services – depends on the availability of electric power. Thus, power interruption can have dramatic consequences for lives and economy.

On the opposite scale end are microgrids such as existing or NextGen all-electric vehicles (ships, aircrafts, spacecrafts) and distribution systems. Some of microgrids are intend to perform in highly hostile and/or unpredictable environment, with the success of their mission critically depending on their ability to survive. And all

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microgrids have to deal with a spatial limitation on the elements redundancy and positioning that significantly contributes in microgrid's vulnerability and makes survivability a key issue in grid's design.

Multiple studies exist on survivability of military or exploration-type vehicles, but only a few for utility transmission and distribution systems. At the same time, various reviews[2-4] showed that the modern electric power infrastructure is not prepared to withstand many forms of large-scale damages. Incorporation of distributed renewable energy resources (DRERs) and energy storage devices (DESDs) into NextGen smart grids is a popular idea and intuitively seems to be beneficial. However, it may have an ambiguous effect on the system performance due to the nature of renewables. Taking into account that 80% of customer reliability problems in existing distribution systems are due to disruptions that occur within the distribution system[5], studies on the impact of DRERs and DESDs on the system's reliability and survivability are required, but currently missing.

Existing survivability studies rarely deal with the system survivability due to its topology (*topological survivability*[6]). Here, the system topology is defined as the number of generators and loads and their connection with one another. However, a system topology is a key factor to consider in the analysis of the micro- and macro system survivability along with reliability, redundancy, and reconfiguration strategies[6-8].

Traditional reliability/availability analysis[9-11] does not apply to this problem, because it concerns with the system performance in the presence of operational faults (manufacturing faults, fatigue cracking, and maloperation) that are random, predictable, with predictable repair time. Faults caused by adverse events are sudden and not random. The damage they cause is typically of several orders of magnitude larger in scale than damage due to operational faults and with limited possibility for repair in a short term. New analytical and computational tools are required to conduct the analysis of the system survivability.

Previously, we suggested[6] a basic mathematical framework for quantifying the topological survivability of a system with multiple generators and a single load and developed[12] an efficient computational procedure for conducting the analysis of its topological survivability. This approach is applicable when the load represents either an isolated industrial load, or multiple commercial and residential loads interconnected into a single distribution system, or a lower voltage level network. In complex utility grids and microgids such as, for example, a notional medium voltage DC shipboard power system[13], all loads cannot be represented by a single load. A computationally efficient approach for the analysis of topologies with multiple generators and multiple loads was suggested in Ref. 14. The approach disintegrates the complex system topology into a set of few simple sub-topologies, with every sub-topology including all system generators and a single load.

Our current goal is to develop a computational tool that automatically disintegrates the complex system topology into a set of sub-topologies (one for every system load) and then, simultaneously conducts the analysis of topological survivability of all sub-topologies. Based on the results of the analysis, the state of the entire system is evaluated for any combination of faults.

To achieve this goal, two other algorithmic steps have yet to be developed. That is, i) automatical transformation of a system diagram into a form suitable for the computational analysis and ii) automatical decomposition of a system with multiple sources and sinks into sub-systems with simpler topologies. Here, we report on software development for automatically converting a standard power system diagram into a structured adjacency matrix[12] (or list) suitable for the computational analysis.

II. System Representation for Computational Analysis

System analysis starts from representing a system diagram in a mathematical form, usually, in a form of an adjacency matrix or an adjacency list. An adjacency matrix is the $M \times M$ symmetric matrix $\mathbf{X}$ that describes the connectivity of M system elements. If two elements i and j are connected with one another, we say that $X_{i,j} = 1$ and the two elements (nodes) are adjacent. If elements i and j are not directly connected with one another, then, $X_{i,j} = 0$. Each row (column) of $\mathbf{X}$ is a complete description of all adjacent and non-adjacent elements. The adjacency list organizes adjacent elements into lists or sets. That is, for each system element, there exists the corresponding list that contains only elements adjacent to the element. This reduces computational cost of search algorithms[12], because each set only accounts for adjacent elements. The use of the adjacency list is particularly beneficial for representing sparse systems such as, for example, power systems, since each set is relatively small.

In the analysis of the topological survivability of a system, links are as important as generators and loads. Indeed, by removing links, one can isolate a perfectly functioning otherwise generator or a load from the system and make it unavailable. Therefore, for the purposes of the survivability analysis, links are included as individual elements into the adjacency matrix (list) representing a system. Notice that this is a different approach from the traditional reliability analysis and from the main stream of the network analysis. There, links are excluded from the matrix elements. Although the approach adopted in our study results in the increased size of the adjacency matrix (list), it allows one more straightforward description of fault scenarios, their counting, and assigning the likelihood of their occurring. Overall, we found it more beneficial for the survivability analysis than the traditional approach.

Intersections (physical connection) of links are not included in the matrix (list) elements, because a fault in an intersection can be represented by faults in links that connect at the intersection.

The *structured* adjacency matrix (list) differs from the adjacency matrix (list) in a way that it contains additional information on whether a system element generates, consumes, or simply transfers power from one element to another. Specifically, initial positions $i, j = 1, ..., g$ in the structured adjacency matrix (list) are assigned to the system generators (g is the number of generators). The following positions, $i, j = g+1, ..., g+v$, are reserved for loads (v is the number of loads). The remaining elements are links that simply transfer power. Using the structured adjacency matrix (list) further reduces computational time required by search algorithms[12].

A power system diagram can be represented in various ways depending on the topic of research. In addition to the standard representation with generators, loads, and links, another representation was suggested in Ref. 14 for survivability and reliability analyses. Specifically, a system can be represented by only links of thee different types: links that supply power to a system (they contain generators), links that consume power (they contain loads), and links that deliver power between links of those two types. Again, intersections are not considered as elements of the adjacency matrix (list).

Manual generation of the adjacency matrix from a standard system diagram for complex and large-scale topologies is extremely time-consuming and error-prone process. Regardless how attentive is a person performing the task, errors (typos) are unavoidable. The process of verifying the final matrix requires several multi-hours (or even multi-days) iterations from more than one person, and there is no guarantee that the outcome is correct. If errors introduced at this step of the system analysis remain present in the final matrix (list), the analysis will lead to wrong conclusions and ultimately to costly mistakes in the system design and operation.

Conversion of a system diagram into the adjacency list is even more challenging procedure. The adjacency list is a more abstract form of a system than the matrix, with less obvious visual connection to the original system diagram. Although it is a more efficient tool in computational analysis[12], verification of the correspondence of an adjacency list to a system diagram is much more difficult than in a case of an adjacency matrix.

Thus, automatization of the procedure of converting a standard system diagram into the structured adjacency matrix or list is mandatory for making the analysis of the topological survivability of a system a reliable design tool.

III. Software Description

In order to conveniently convert a system diagram into a structured adjacency matrix or list, a user-friendly Java application was developed. The software allows representing a system topology by the means of an undirected graph. The java program utilizes the powerful open-source graph library JGraph[15]. Java was mainly chosen because of its platform independency, since a java virtual machine is available for a vast variety of operating systems.

The application can be opened by simply clicking on the executable file: power_sys_drawing_RC_1.0.jar. All utilized libraries and developed classes were compiled into one single executable jar-file.

Prior converting, an original system diagram should be simplified to a diagram including only generators, loads, links, and intersections (junctions) of links. It is recommended that any elements connected in series in the original power system diagram be represented as a single link. This will significantly reduce computational time required for the analysis. However, the software can handle multiple links in series too.

After being simplified, a system diagram can be reproduced in the software environment by drawing. Drawing means pointing a cursor where an element should be placed and by clicking the right mouse button and choose the type of element to be inserted there. Lines are drawn by clicking first the left mouse button on a starting point and, while holding it down, moving the cursor to the end point. The software tool with drawn system topology and popped up context menu is shown in Figure 1.

When an element is selected, it has a green boundary around it. Selected element or a group of elements can be moved around. Each element, except junctions, has a label indicating its order in the matrix (list). The element order is automatically calculated and recalculated during the system drawing to ensure that the output of the drawing is a structured matrix (list). In this regard, a system drawing can be started from any system element including an intersection.

When an element is selected, its label is shown by a yellow square and it can be moved around to improve the display. To move the label, the cursor should point on the yellow square. Then, the left mouse button has to be pressed. Without releasing it, the label should be dragged to the desired location.

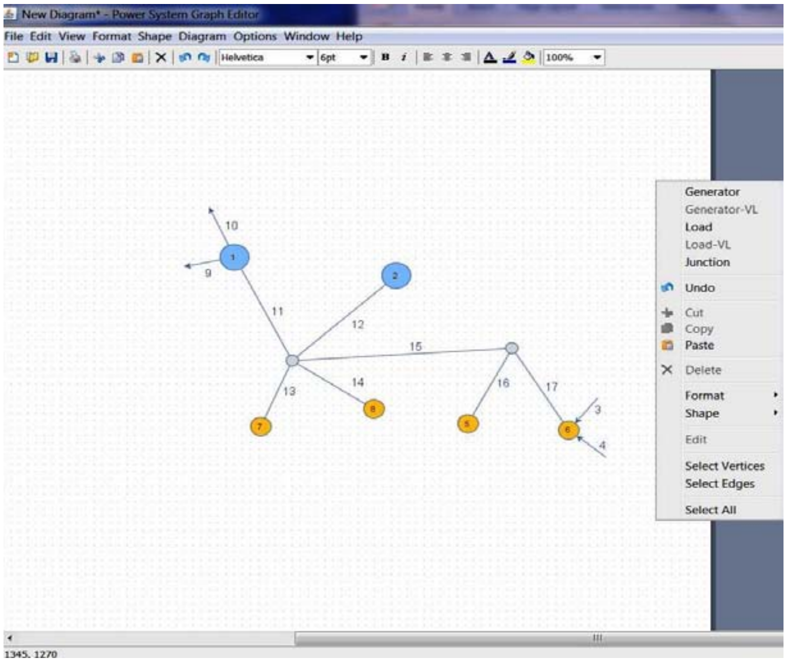


Figure 1. Power System drawing tool with popped up context menu.

As discussed in Section II, a system can be represented by only links of three different types. The software is also capable of drawing these representations. A link with a generator is represented by Generator_VL; a link with a load by Load_VL.

If this system representation is utilized, it is recommended to first draw junctions and lines connecting them and then, add Generator_VL and Load_VL links to the corresponding junctions. To do so, a junction of interest should be selected by pointing the cursor on the junction and then, by clicking the right mouse button. In the popped up context menu, the user can choose between the insertion-commands Generator_VL and Load_VL. Depending on which element the user clicks, only applicable menu entries are enabled.

Various combinations of the two system representations described above are also possible. Exceptions are the following. Generator_VL link cannot be connected to a Generator element and Load_VL link cannot be connected to a Load element. Also, Generator-VL and Load_VL links cannot be directly connected to links, only to junctions.

For larger topologies, the subgroup feature of the program can be applied. Selected elements of the drawn graph can be collapsed into a subsystem. This feature allows one to draw large systems while maintaining a structured and clear display of the graph. However, this functionality does not affect the adjacency matrix (list) in any way.

The software also provides basic editing functionality such as redo-undo, font and element color specifications etc. The Menu options are shown in Fig. 2.

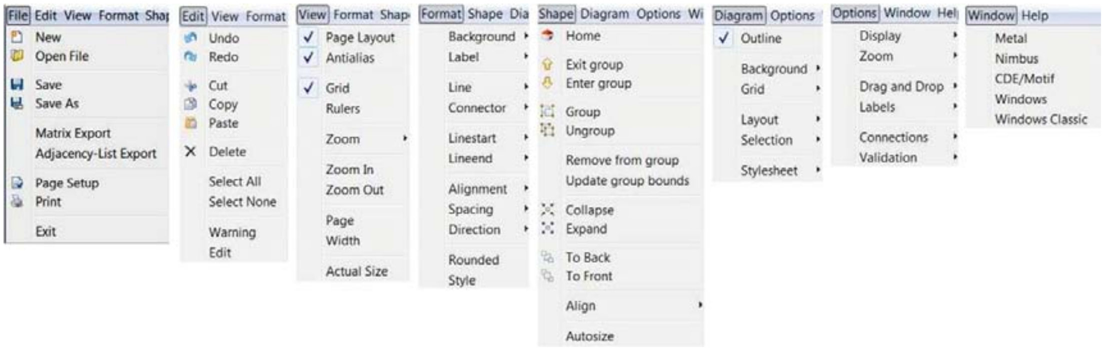


Figure 2. Menu options.

The finished system drawing can be saved for future editing from the menu (command Save and Save As). Furthermore, the user can save the drawing as a graphic (bmp, jpg).

The commands Matrix Export and Adjacency-List Export are used to convert the drawing into an adjacency matrix or an adjacency list. This feature creates a structured adjacency matrix (list) and writes it to disk as a .csv-file (comma-seperated values). For post processing, this file can be opened in any text editor and/or imported by another program. For the users convenience the export path can be specified.

IV. Software Installation

To install software, it is sufficient to download a single executable file: power_sys_drawing_RC_1.0.jar. Request should be send to the authors. The software is compatible with any computer platform that supports Java applications. So far, it has been successfully tested on Windows 7, Windows Vista, Red Hat Enterprise Linux and Ubunut Linux platforms.

V. Application

As an example, Figure 3 shows the topology of a notional medium voltage DC shipboard power system[13].

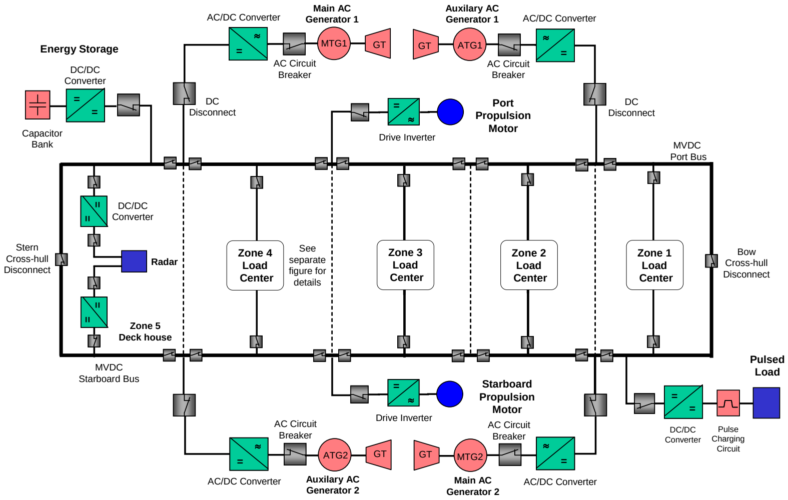


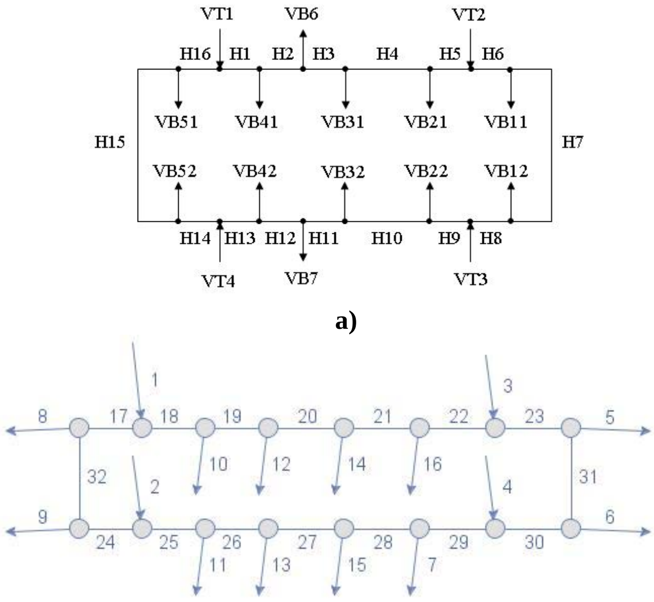
Figure 3. Architecture of a notional MVDC shipboard power system.

Simplification of this topology with the purpose of conducting the topological survivability analysis results in a topology shown in Fig. 4a. In Figure 4a, a storage in *Zone* 5 and a pulsed load in *Zone* 1 with the corresponding cables and devices are excluded for the sake of simplicity only. Links that include a generator are labeled by “VT”, and links that include a load are labeled by “VB”. Both types are shown in the figure by arrow-headed links. The direction of arrows shows the direction of power flow. Links that simply transfer power from one point to another are labeled by “H”. There are four generators that supply power to the system through four VT links (VT1-VT4) and seven loads that are connected to the system by twelve VB links. Vertical links VB11 and VB12 connect Zone 1 Load Center to the system. Similarly, links VB21 and VB22, VB31 and VB32, VB41 and VB42, and VB51 and VB52 connect Zone 2-5 loads, respectively, to the system.

The topology in Fig. 4a drawn in the software environment is shown in Fig. 4b. Figure 5 presents the result of converting the drawing from Fig. 4b into a structured adjacency matrix. As the matrix is symmetric, only the half of it is given. The orange and blue backgrounds highlight links with generators and loads, respectively.

One can see that constructing and verifying an adjacency matrix manually even for a microgrid with small number of elements such as a shipboard power system would be an effort requiring time. One can also notice that the matrix in Fig. 5 is sparse, and therefore, the adjacency list is a preferable representation for this topology.

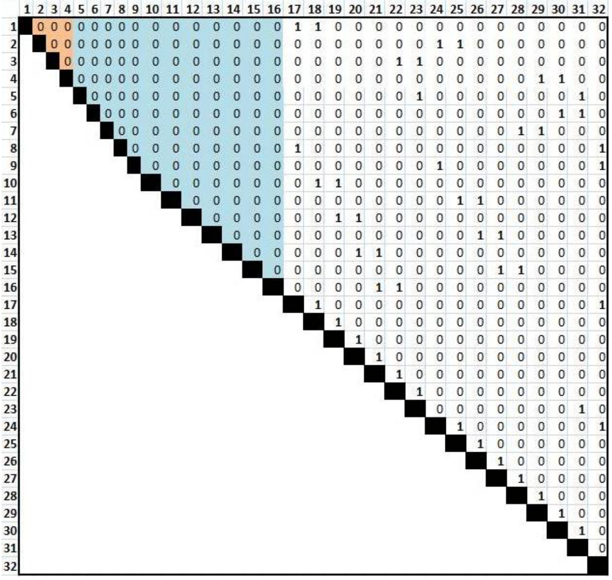
The developed software has a broad application. Practically any network-related study or graph analysis starts from the matrix/list representation of a network (graph). Thus, the software can be used for any analysis where the network/graph connectivity is of interest whether a network has sources and sinks or includes only one type of elements.



a)

b)

Figure 4. Simplified topology from Fig. 3 (a) drawn in the software environment (b)



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32
1	■	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2		■	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0
3			■	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0
4				■	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0
5					■	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0
6						■	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0
7							■	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0
8								■	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
9									■	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1
10										■	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0
11											■	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0
12												■	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0
13													■	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0
14														■	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0
15															■	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0
16																■	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0
17																	■	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1
18																		■	1	0	0	0	0	0	0	0	0	0	0	0	0	0
19																			■	1	0	0	0	0	0	0	0	0	0	0	0	0
20																				■	1	0	0	0	0	0	0	0	0	0	0	0
21																					■	1	0	0	0	0	0	0	0	0	0	0
22																						■	1	0	0	0	0	0	0	0	0	0
23																							■	0	0	0	0	0	0	0	1	0
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28																												■	1	0	0	0
29																													■	1	0	0
30																														■	1	0
31																															■	0
32																																■

Figure 5. Structured adjacency matrix corresponding to the topology shown in Fig. 4.

Acknowledgments

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