A Benchmark Case for the Grid Survivability Analysis

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***Abstract*—Among current priorities of the power system analysis is the development of metrics and computational tools for the resilience analysis during catastrophic events. New methods and tools are required for such an analysis and they have to be validated prior application to real systems. However, benchmark problems are not readily available due to the analysis novelty. The current paper presents a case based on the IEEE 14-bus system for this purpose. The grid is simplified to a graph with nodes representing generators, loads, and buses. Power inputs are imported from real-time simulations of the IEEE 14-bus system. Outcomes of all possible combinations of failed elements are presented in terms of probabilities for the grid to survive, partially survive, or fail. Only the power grid's ability to withstand adverse events (survivability) is analyzed. The grid's recoverability, the other part of the resilience analysis, is not considered.**

***Index Terms*—power system, resilience, survivability.**

I. INTRODUCTION

With the national power grid spreading over the continent and becoming integrated with wide-area control and communication electronics, the professional community started to recognize not only benefits of grid modernization, but also the increased likelihood and enormous cost of large-scale, long-duration blackouts caused by natural disasters, extreme weather and man-made physical and cyber activities [1]. Thus, the power grid resilience concept associated with such blackouts was born. Although the original source of this concept is currently difficult to name, several recent reviews on this subject provide a comprehensive insight into the concept [1-3]. Here, the resilience definition from [4] is used: "Resilience includes the ability to withstand and recover from deliberate attacks, accidents, or naturally occurring threats or incidents."

The resilient analysis compliments and overlaps with the reliability analysis when the power grid operates under normal conditions. There is a consensus in the professional community that power grids designed and operated based on standard reliability criteria will not be resilient [1-3]. New quantitative metrics of resilience and methods of their evaluation are required. Both, reliability and resilience metrics have to be used to ensure the grid operability under normal and adverse conditions.

Development of the resilience metrics and methods is on-going process rather that the established state of the art [1-3]. Success depends on availability of benchmark problems to verify and validate the proposed methods before making them available to the power grid designers and operators. The current paper contributes to the development of benchmark problems for the survivability analysis, which is an essential part of the resilience analysis as it concerns with the grid's ability to withstand massive sudden damage characteristic for catastrophic events. The analysis excludes the grid's ability to recover (recoverability) after a catastrophic event is over.

The system survivability is a well-known concept in the design of systems for combat operations [5,6]. It was first extended to the power system analysis in relation to the integrated power system of an all-electric warship [7-12]. Later, it was also applied to transmission systems and smart grids [13,14]. Probabilistic metrics used in the combat system analysis to describe the system's survivability were adjusted to the analysis of power grids in [7], with the method of their calculating also being proposed.

In particularly, the post-damage grid's ability to operate is quantified in terms of probabilities to survive (P_S), partially survive (P_R), and to fail (P_F), which are determined by comparing the power supply and demand for every possible combination of damaged grid elements in the given pre-damage grid topology (hereafter, *fault scenario*). The grid's topology is understood as a layout of connections between generators and loads. Once damaged, an element is considered irreparable and unavailable to the grid, which is typical for adverse events. A faults scenario is treated as a steady state. To ensure that no fault scenario is missing from the analysis, all fault scenarios are generated and analyzed. Whereas the analysis can be combined with full-scale power grid simulations, this is generally impractical, as in the grid comprised of M elements, there are 2^M fault scenarios to analyze. Such a problem is exponentially complex in time and

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thus, poses computational challenges. Various strategies were proposed in [15,16] to reduce the computational cost of the analysis, but the first step is to convert the grid into a graph that includes only critical elements.

Even the graph-based survivability analysis is expensive and for this reason, previous studies were limited to topologies with multiple generators, but a single load [7,13,16-20]. Survivability of a system with two generators and two loads was analyzed in [21]. Over-simplified power inputs were used In all cases.

In the current paper, a more realistic case based on the IEEE 14-bus system [22] is considered, with power inputs for generators and loads obtained from real-time grid simulations [23]. No limitations are imposed on transmission lines' capacity and efficiency.

II. GRID REPRESENTATION

The one-line diagram of the IEEE 14-bus system [24] used in the study is shown in Fig. 1a. Data describing the system steady state (without reactive component) are presented in Table I.

For the survivability analysis, the grid has to be converted to a graph and then, in a connectivity matrix [15,16]. For the grid with M elements, the matrix dimension is $M \times M$. With each grid element being either available or not (due to failure), there are $N = 2^M$ possible combinations of unavailable elements (fault scenarios), which is equivalent to the 2^M new matrices to consider. To make the analysis feasible, various computational strategies were proposed in [15,16] to reduce M without affecting results of the analysis. In this study, the following steps were applied to the diagram shown in Fig. 1a.

First, the grid was reduced to critical (vital) elements: generators, loads, and links between them. Other elements connected in series were absorbed into links connecting adjacent buses, because failure of any of the elements in series makes all elements in the chain unavailable for power flow.

Then, the simplified power grid diagram was converted into a graph (Fig. 1b). In the figure, nodes in blue, red, and black colors correspond to loads, generators, and buses, respectively. The synchronous condensers S3, S6, S8, and Bus 8 are removed from the graph, as they are not providing active power support to the loads. The transformers are absorbed into the links.

TABLE I. THE IEEE 14-BUS SYSTEM STEADY-STATE DATA

Bus	Generator (MW)	Load (MW)
1	219	0
2	40	21.7
3	0	94.2
4	0	47.8
5	0	7.6
6	0	11.2
9	0	29.5
10	0	9
11	0	3.5
12	0	6.1
13	0	13.5
14	0	14.9
Total	259	259

The next step is to identify groups of interconnected elements or *clusters* within a grid [24,25]. Candidates for clusters are distribution systems, smart grids, and various voltage levels within the power grid hierarchy. Each cluster is treated as a single cluster-load in the grid survivability analysis. Survivability of clusters can be analyzed separately from the grid. In Figs. 1a and 1b, the cluster is visually

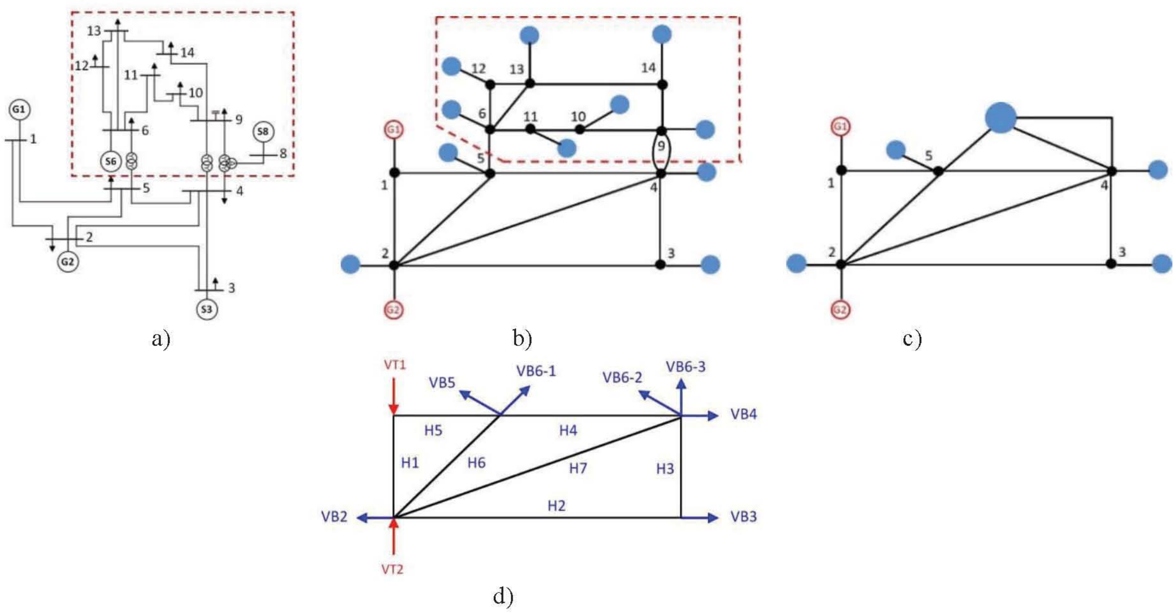

Figure 1. Transformation of the IEEE 14-Bus system diagram for the survivability analysis. Images: a) one-line diagram, b) traditional graph representation of the diagram from a) (blue circles are the loads and black circles are the buses), c) the graph from b) with the cluster load (large blue circle) representing the elements connected to Buses 6,9-14 inside the red box in b), d) the graph from c) represented by links only.

recognized as a group of interconnected loads with combined power demand of 87.7MW from buses 9-14 and 6, separated from the rest of the grid by transformers at both ends (where this group is connected to the grid) and with no active power generation within the group. The group is within the red dashed box in Figs. 1a,b. In Fig. 1c, this group is represented by the large blue circle connected to the grid by three links: one from Bus 5 and two from Bus 9. In the current study, it is assumed that the total power demand from the cluster-load can be fully satisfied through any of the three links.

A number of elements in the graph can further be reduced if to switch from a traditional graph representation of a power grid to its representation by links only [15]. In such a representation, a node and an edge adjacent to the node are substituted by a single link. When there are several edges adjacent to the same node, several links are used to substitute for the node and its adjacent edges. Failure of a node is equivalent to failures of all links that absorbed the node.

Three types of links are used in this approach reflecting a hierarchical structure of power grids: links adjacent to generators (vertical top "VT" links), links adjacent to loads (vertical bottom "VB" links), and links connecting buses (horizontal "H" links). Vertical links are directed and horizontal links are undirected to reflect that power flow direction through H-links may vary.

Figure 1d shows transformation of the graph from Fig. 1c into a graph represented by links only. In the figure, links VB6-1, VB6-2, and VB6-3 connect the cluster-load (VB6 cluster) to the grid. Number "6" is due to Bus 6, the bus with the smallest label in the group, but any other bus number from this group would serve the purpose. Since the group is connected to the grid by three links (one at Bus 5 and two at Bus 9), these links are labeled as VB6-*i*, i = 1,2,3 to distinguish between them.

The total number of elements in the graph represented by links is $M = \sum VT_i + \sum VB_j + \sum H_k$, where i, j, and k are the numbers of *VT*, *VB*, and *H* links, respectively. For the graph in Fig. 1d, $M = 16, i = 2,\ j = 7,$ and $= 7$, and thus, there are $N = 2^{16} = 65536$ scenarios to consider. To compare, $M = 28$ (12 nodes and 16 links) and $N = 2^{28}$ in the traditional graph representing the grid (Fig. 1c).

The next step is to convert the grid represented by links to a connectivity (adjacency) matrix [15,16]. Existing connections between two links are indicated by ones in the matrix, while the rest of the entries are zero. The matrix can be modified to incorporate various properties of the grid elements such as power generated and demanded, cost, likelihood of damage etc. In the current paper, only power generated and demanded is assigned to VT and VB links, respectively (Table 2). Shunt capacitance of links are not included in consideration. It is assumed that a link can tolerate any amount of power as opposed to an actual transmission line. All links are assumed to be equally vulnerable to damage.

The survivability analysis can be applied to the entire grid (multi-load analysis), but also to evaluate and to compare survivability of isolated loads (single-load analysis). In the single-load analysis, the initial topology of a grid is modified for every load by excluding all VB links unrelated to a load for which the analysis is conducted. As a result, some of the H-links may become connected in series in such topologies and thus, can be combined together [15].

Figure 2 illustrates this process for the VB4 link in Fig. 1d. Once all VB-links but VB4 are removed, links H2 and H3 are connected in series and can be represented by a single link. As a result, the total number of links in the modified topology for the VB4 link is reduced to 9. The number of fault scenarios in this new topology is reduced to $2^9 = 512$. In a similar fashion, modified topologies for VB2, VB3, and VB5 links and for the cluster-load were obtained (Fig. 3).

TABLE II. DATA FOR VT AND VB LINKS IN FIG. 1D.

Bus in Figs. 1,2	Link	Assigned Power (MW)
1	VT1	+219
2	VT2	+40
2	VB2	-21.7
3	VB3	-94.2
4	VB4	-47.8
5	VB5	-7.6
6, 9-14	VB6-1,2,3	-87.7
Total power:		0

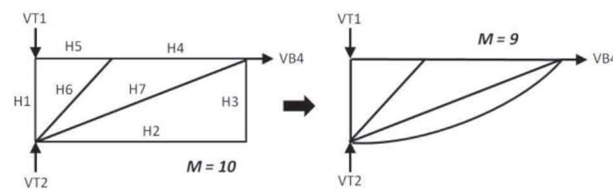

Figure 2. The modified grid topology for the VB4-link analysis.

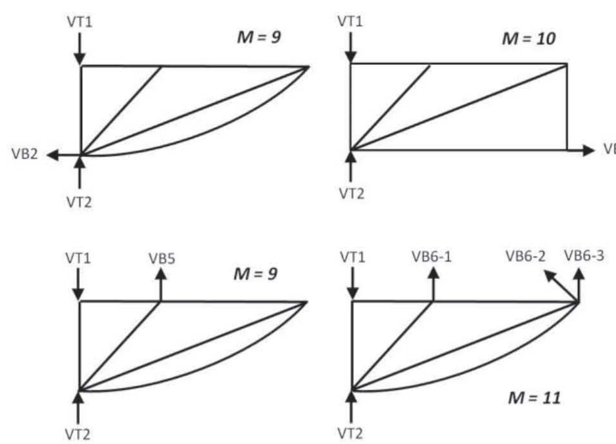

Figure 3. Modified grid topologies for othre four loads.

III. SURVIVABILITY METRICS

In the survivability analysis of power grids, the goal is to determine probabilities for the grid to survive, partially survive, or fail at any number m of damaged links: $P_S(m)$, $P_R(m)$, and $P_F(m)$, respectively, with $P_S(m) + P_R(m) + P_F(m) = 1, m = 1,..,M$ [7].

These probabilities are calculated as:

$$P_S(m) = \frac{S(m)}{N(m)}, P_R(m) = \frac{R(m)}{N(m)}, P_F(m) = \frac{F(m)}{N(m)},$$

where $N(m) = M!/m!(M-m)!$ and $N = \sum_{m=0}^{M} N(m) = 2^M$. The numbers *S(m)*, *R(m)*, and *F(m)* are the numbers of fault scenarios when the grid survived, partially survived or failed, respectively. At a given *m*, $N(m) = S(m) + R(m) + F(m)$.

Thus, the analysis objectives are:

- to identify which of the three categories every fault scenario belongs to,
- to determine numbers of scenarios within each of the three categories at every *m*, and
- to calculate the probabilities to survive, partially survive, and to fail.

The procedure of generating fault scenarios and the analysis of the links availability and connectivity are described in detail in [15,16]. Here, we will just notice that a link can only be in two states: failed (equivalently, unavailable to the power flow) or undamaged. If an undamaged link remains connected to the grid after an adverse event is over, it is considered available to the power flow. Each fault scenario, which is a combination of unavailable links, corresponds to a unique combination of available links. A combination of available links in a post-damage grid reflects a new grid topology described by a new graph and a new connectivity matrix. All fault scenarios are generated in this analysis. The link availability and the total amount of power available to the loads is determined and compared to power demand in every scenario with the purpose of evaluating whether the demand is satisfied fully, partially, or does not meet a criterion of the minimum necessary critical supply. If power demand is fully satisfied in a post-damage grid, a fault scenario is categorized as a survival scenario. If power demand cannot be satisfied fully or partially (above minimum acceptable level), a post-damage scenario is of failure. If power demand is partially satisfied, such a scenario is called a scenario of partial survival (or reconfiguration [7]).

IV. Application to the Test Case

The graph in Fig. 1d represents a pre-damage IEEE 14-bus system topology or "no-fault scenario" ($m = 0$) included in the total number 2^M of possible fault scenarios for the entire grid, with *M* = 16. Each of the $(2^{16} - 1)$ fault scenarios was generated and analyzed manually in the study. The following criteria were applied to categorize fault scenarios in the grid:

- a fault scenario is of survival if the power demand is satisfied for all loads (259 MW);
- a fault scenario is of partial survival if available power is equal or more than 3.5 MW, which corresponds to the demand of the smallest load in the cluster-load;
- all other scenarios are of the grid failure.

Survival and failure probabilities for the grid with the imposed criteria are provided in Table 3. Figure 4 visualizes data from the table.

TABLE III. Survival probabilities for the Graph in Fig. 1d.

m	*P(S)*	*P(R)*	*P(F)*
0	1	0	0
1	0.438	0.563	0
2	0.358	0.633	0.008
3	0.182	0.791	0.027
4	0	0.943	0.057
5	0	0.903	0.097
6	0	0.846	0.154
7	0	***	***
8	0	***	***
9	0	***	***
10	0	***	***
11	0	***	***
12	0	0.091	0.909
13	0	0.036	0.964
14	0	0.008	0.992
15	0	0	1
16	0	0	1

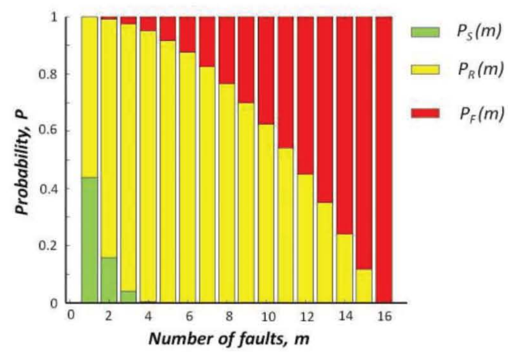

Figure 4. Vizulatization of data from Table III.

The figure demonstrates that this power grid has little chances to survive without shedding loads. Since a process of load shedding relies on availability of resources such as power, communication, and control, which are likely to be reduced during and after an adverse event, one should seek to minimize the grid reliance on this protection strategy. This can be accomplished, for example, by partitioning and re-positioning links in the grid's topology without changing the number of generators and loads and power demand [7,16,17]. Efficiency of wide-area protection schemes may also be improved in such a manner [29] that is beneficial for the grid's survivability.

When assessing survivability of isolated loads (VB2-VB5 links in Figs. 1d, 2, and 3), the following criteria were applied to categorize fault scenarios: a fault scenario is of survival if the load demand is fully satisfied and of failure otherwise. There are no reconfiguration scenarios for these loads. The cluster-load survives if it receives 87.7 MW to satisfy demand of all its loads and fails if available power < 3.5 MW. Other scenarios are of partial survival.

Results for all loads are presented in Table 4. Figure 5 illustrates the results for the isolated and cluster loads. (All values in the tables are rounded to the third digit after the decimal point.) At m = 11, all scenarios are of failure for any load. The data shows that chances of isolated loads to survive vary from one load to another and that they are not the same as for the grid.

TABLE IV. SURVIVAL PROBABILITIES FOR THE LOADS.

m	0	1	2	3	4	5	6	7	8	9	10
VB2											
P(S)	1	0.889	0.750	0.583	0.397	0.214	0.095	0.028	0	0	
P(F)	0	0.111	0.250	0.417	0.603	0.786	0.905	0.972	1	1	
VB3											
P(S)	1	0.800	0.578	0.350	0.148	0.044	0.005	0	0	0	0
P(F)	0	0.200	0.422	0.650	0.852	0.956	0.995	1	1	1	1
VB4											
P(S)	1	0.778	0.556	0.345	0.143	0.024	0	0	0	0	
P(F)	0	0.222	0.444	0.655	0.857	0.976	1	1	1	1	
VB5											
P(S)	1	0.889	0.750	0.571	0.349	0.127	0.024	0	0	0	
P(F)	0	0.111	0.250	0.429	0.651	0.873	0.976	1	1	1	
VB6											
P(S)	1	0.909	0.818	0.673	0.524	0.344	0.165	0.039	0.006	0	0
P(R)	0	0.091	0.164	0.261	0.315	0.333	0.271	0.124	0.030	0	0
P(F)	0	0	0.018	0.067	0.161	0.323	0.565	0.836	0.964	1	1

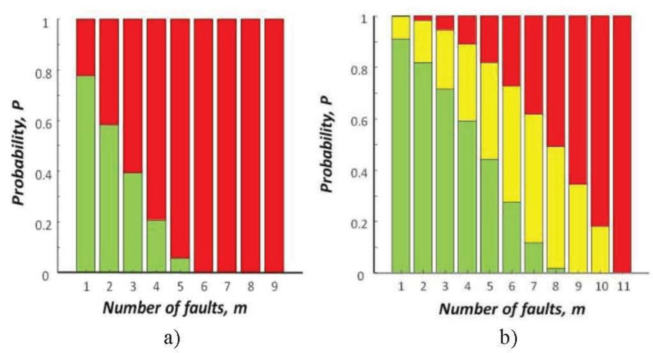

Figure 5. Vizulatization of data from Table V for a) isolated load at VB4 and b) cluster-load at VB6. Notations are the same as in Fig. 4

V. CONCLUSION

The paper presents a benchmark case for the survivability analysis of power grids, which is an essential part of the resilience analysis. The case is based on the IEEE 14-Bus system simplified to a graph. Probabilities to survive, fail, and partially survive (where applicable) are determined for the entire grid and for the isolated loads at any number and in all possible combinations of failed grid's elements. It is shown that probabilities to survive and to fail are different for different loads and for the entire grid. That is, the analysis has to be conducted separately for every load and for the grid to assess risks correctly and to mitigate post-damage grid recovery expenses more efficiently. Such an analysis is of importance for the grid stakeholders, operators, and consumers as they may have different views on the matter and can contribute in various ways to meet their goals.

The study opens a path towards the larger grid analysis, refinement of definitions, rules and algorithms for the practical grid application through which the relation between the concepts of survivability, reliability, and resiliency of power grids can be better understood.

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