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Component criticality importance measures for the power industry

Jose F. Espiritu, David W. Coit*, Upyukt Prakash

Rutgers University, Department of Industrial & Systems Engineering, 96 Frelinghuysen Road, Piscataway, NJ 08854, USA

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Abstract

New reliability importance measures have been developed for the power industry to be applied for Electricity Transmission Systems (ETS). Reliability criticality measures are useful metrics to rank components regarding their impact on system performance. Criticality measures serve as useful tools to prioritize reliability improvement activities, identify weak-links in the system and many other uses. These proposed measures pertain to the outage rate of the system and component instead of the probability of failure or survival for a defined mission time. Outage rate is the best suited and appropriate output variable to evaluate the importance of the components in the electricity distribution system. The ETS is the component of the bulk transmission system to provide electricity to large municipalities, large industrial customers and the retail distribution system. The ETS is composed mainly of components such as lines, transformers, breakers and buses. All these components are interconnected with the aim of transporting electrical energy from the bulk transmission system to various load points. The new criticality measures are demonstrated on some commonly used electrical configurations, such as, breaker-and-a-half, breaker-and-a-third and the Dual Element Spot Network (DESN) for ETS.

Keywords: System reliability; Reliability importance measures; Electricity transmission systems

1. Introduction

New component reliability importance measures have been developed to be used within the power industry. These can be used by designers and managers working in the Electricity Transmission Systems (ETS) area to identify and rank the most important components within the system, and specifically, to identify where investments should be made to increase the overall system availability. Several existing popular reliability criticality measures cannot be directly applied to these power systems, because they have been developed mainly for components with specified finite mission times. Alternatively, for ETS, the different components within the system exhibit outage rates and repair rates instead of probability of failure for a specified time interval.

ETS provide a power supply to the customers as economically and reliably as possible. Increasing the investment in the planning or operating phase can increase system availability but it can also lead to increased operational costs. Consequently, the economic considerations may become prohibitive. On the other hand, under-investment can lead to other problems, including excessive maintenance cost and loss of power to the consumer. Thus, the economic and reliability constraints become competitive, and it is critical to have timely and accurate indicators and metrics to characterize the reliability of the system. Therefore, there is a need for a formal methodology to calculate the importance of each component of the system and to rank them. In that way, managers and administrators can prioritize where investments should be made to upgrade old and aging equipment and to guarantee the maximum increase of reliability considering the whole distribution system.

Reliability analysts have proposed different analytical and empirical Critical Importance measures which rank the components regarding their importance in the system. Several importance measures (e.g., Birnbaum [1], Fussell-Vesely [2], Reliability Achievement Worth, Reliability Reduction Worth [3–5]), have been proposed in past. None of these measures can be directly applied to ETS because these methodologies were developed on the assumption that there is a definite time period (or mission time) for the system. In contrast to this,

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Abbreviations: CI, Criticality Importance; ETS, Electricity Transmission Systems; FV, Fussell-Vesely; RAW, Reliability Achievement Worth; RRW, Reliabilty Reduction Worth; DESN, Dual Element Spot Network

* Corresponding author. Tel.: +1 732 445 2033; fax: +1 732 445 5467.
E-mail address: coit@rutgers.edu (D.W. Coit).

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ETS have no definite life time period and are expected to work endlessly without any service interruptions. In addition, for ETS, component and system reliability are expressed in terms of outage rates rather than probability of failure.

In this paper, importance measures such as Birnbaum, Criticality Importance, Reliability Achievement Worth (RAW), Reliability Reduction Worth (RRW) and Fussell-Vesely have been extended to make them compatible with ETS. The new proposed metrics are applied to some commonly used electrical configurations, including breaker-and-a-half, breaker-and-a-third and the Dual Element Spot Network (DESN) for ETS.

System reliability is generally defined as the probability that the system provides the service for which was intended for a specified mission time, under the condition that the components of the system can be in two possible states, either failed or perfect functioning. However, some systems, like in the distribution systems area, have more complex behavior and the components and system exhibit failures as a stochastic process in terms of outage rates. The total system unavailability can be expressed in terms of total system downtime. Oversimplification of the functioning of the ETS could lead to erroneous conclusions about the system reliability and incorrect conjectures regarding reliability improvement efforts.

In the power systems area, Hamoud et al. [11] presented a method that relates the reliability of the ETS at a specific load point to the reliability of each individual component. The assessment of component criticality was performed by using a computer program and it was performed for each component in the system. Hilber and Bertling [12] proposed an importance index method for defining the importance of individual components in an electrical network with respect to total interruption cost. In their approach, they considered several load points simultaneously and they ranked the components in terms of total system interruption cost. Hamoud et al. [14] presented a method for quantifying the risk associated with the failure of the Supervisory Control and Data Acquisition (SCADA) systems used in power systems. The calculated risk is used to identify the importance of stations and to establish the reliability requirements for the SCADA system that has the lowest capital cost.

Due to economic constraints, investments to upgrade aging systems need to be made appropriately. Therefore, a company or utility needs to know the reliability importance or importance ranking of the components within the system. Thus, there is a need for new quantitative criticality measures that can be directly applied to the ETS area, such that managers and other decision makers have useful metrics to evaluate where investments could be made in order to improve the functioning and reliability of the overall system.

Assumptions:

(1) Component failures are statistically independent. Failure at one component does not impact the outage rate of the other components.
(2) Time between component outages and repair durations are distributed in accordance with known exponential distributions.

2. Background: overview of criticality measures

Importance measures are widely used in systems engineering to identify components within the system that more significantly influence the system behavior with respect to reliability, risk and/or safety. The information gathered by the use of importance measures provides management with useful insights for the safe and efficient operation of the system.

Importance measures (or reliability importance indices) are valuable in establishing direction and prioritization of actions related to an upgrading effort (reliability improvement) in system design, or suggesting the most effective way to operate and maintain system status. In general, importance measures are used to quantify the contribution of individual elements of a system to the overall system performance (e.g., reliability, risk, availability) [6–9].

Birnbaum [1] first introduced the concept of importance in 1969 and it is one of the most widely used reliability importance measures. Analytically, it is defined by:

$$I_i^{\mathrm{B}}(t) = \frac{\partial R_{\mathrm{s}}(t)}{\partial R_i(t)} = R_{\mathrm{s}}(t; R_i(t) = 1) - R_{\mathrm{s}}(t; R_i(t) = 0) \tag{1}$$

where $I_i^{\mathrm{B}}(t)$ is the Birnbaum importance of component i; $R_{\mathrm{s}}(t)$ the system reliability at time t; $R_i(t)$ the reliability of component i at time t; $R_{\mathrm{s}}(t; R_i(t)=0)$ the system reliability at time t given component i is failed and $R_{\mathrm{s}}(t; R_i(t) = 1)$ is the system reliability at time t given component i is perfectly working.

The Birnbaum importance ranking represents the maximum loss in system reliability when component i switches from the condition of perfect functioning ($R_i(t)=1$) to the condition of certain failure ($R_i(t)=0$). A weakness of Birnbaum importance measure is that $I_i^{\mathrm{B}}(t)$ does not depend on the component reliability, $R_i(t)$, or unreliability, $F_i(t)$. Therefore, two components may have a similar metric $I_i^{\mathrm{B}}(t)$ value, although these current levels of reliability could differ substantially. In practice, the less reliable component is generally a greater concern, i.e., more critical.

The Criticality Importance (CI) measure is another popular existing metric. The CI metric is a natural extension of the Birnbaum metric. The CI metric includes the component unreliability, $F_i(t)$, whereas the Birnbaum measure does not. In this way, a less reliable component is given more attention, i.e., is more critical. The CI ranking is mathematically expressed as:

$$\begin{aligned} I_i^{\mathrm{CR}}(t) &= I_i^{\mathrm{B}}(t)\frac{F_i(t)}{F_{\mathrm{s}}(t)} \\ &= [R_{\mathrm{s}}(t; R_i(t) = 1) - R_{\mathrm{s}}(t; R_i(t) = 0)]\frac{F_i(t)}{F_{\mathrm{s}}(t)} \end{aligned} \tag{2}$$

where $F_{\mathrm{s}}(t)$ is the system unreliability at time t and $F_i(t)$ is the unreliability of component i at time t.

Two other types of measures that are commonly used to rank the importance of components in a system [13] are the Reliability Reduction Worth (RRW) and the Reliability Achievement Worth (RAW). It is important to note that these are defined in terms of reliability, and not risk. The RRW considers the impact of a loss of reliability, and alternatively, RAW considers the impact of an increase in reliability.

The Reliability Achievement Worth (RAW) is the ratio of the actual system reliability obtained when element i is always in perfect functioning ($R_i(t) = 1$) to the actual value of the system reliability. This measure quantifies the maximum possible percentage increase in system reliability generated by a particular component. It is defined as:

$$\mathrm{RAW}_i = \frac{R_s(t; R_i(t) = 1)}{R_s(t)} \tag{3}$$

The Reliability Reduction Worth importance measure, as defined by Levitin et al. [5], is the ratio of the actual system reliability to the value of the system reliability when element i is considered always failed ($R_i(t) = 0$). This measure is an index measuring the potential damage caused to the system by a particular component. The expression for RRW is given as:

$$\mathrm{RAW}_i = \frac{R_s(t)}{R_s(t; R_i(t) = 0)} \tag{4}$$

Fussell and Vesely [2] proposed an alternative measure. According to this measure, the importance of a component in the system, depends on the number and on the order of the cutsets in which it appears. It quantifies the maximum decrement in system reliability caused by a particular component. There are different forms of the Fussell-Vesely metric [8,10]. The version of the FV expression is defined by:

$$I_i^{\mathrm{FV}}(t) = \frac{R_s(t) - R_s(t; R_i(t) = 0)}{R_s(t)} \tag{5}$$

where I_i^{FV} is the Fussell-Vesely importance of component i.

The previously introduced criticality importance measures (Birnbaum, Criticality Importance, RRW, RAW and Fussell-Vesely) are functionally different. They measure subtly different properties of the system behavior, and thus, one can infer different information from each one of them. There is no general consensus that one measure is the "best" and none of them can be directly applied to ETS without the selection of some mission time, t, which would be somewhat arbitrary given the indefinite need for electricity.

3. Reliability of Electricity Transmission Systems

The ETS is a component of the bulk electricity system, which delivers power from the bulk transmission system to large municipalities, large industrial customers and the retail distribution system. The main components are lines, buses, circuit breakers and transformers. This system can be a simple radial configuration or a more complex configuration. For a simple radial system, a single incoming power service is received and it distributes power to the facility. There is no duplication of equipment and little spare capacity is typically included, as in Fig. 1. Alternatively, the ETS can be designed with redundancy, as in Fig. 2.

Different types of outages can be considered when analyzing the reliability of the ETS systems (e.g., overlapping component sustained outages, sustained outages overlapping component maintenance outages, transient outages overlapping component sustained outages and transient outages overlapping component maintenance outages). In the remaining, we consider the first case when we have component sustained outages overlapping other component sustained outages. However, the new criticality metrics can also be extended to consider each category of outages.

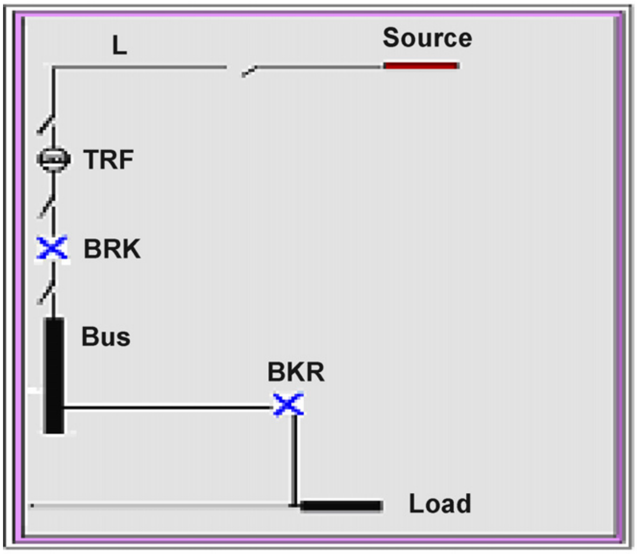

Fig. 1. Radial configuration.

Billinton and Allan [15,19], Billinton and Li [16] and Billinton and Zhang [20] discuss the reliability evaluation of electric systems. They presented direct approximation equations for the reliability analysis of series and two and three components parallel systems configurations. Moreover, they note that for complex systems, a series-parallel transformation based on the system minimal cut sets can provide a good approximation to the actual system reliability metric.

For a parallel configuration, the equations used to determine the total system outage rate, average repair time and the combined system sustained outage rate follows the rationale presented by Billinton and Allan [19]: "a two component parallel system fails if the first component has a sustained outage occurring at rate (λ_1) and during the repair time (r_1) of component 1, the second component has a sustained outage occurring at

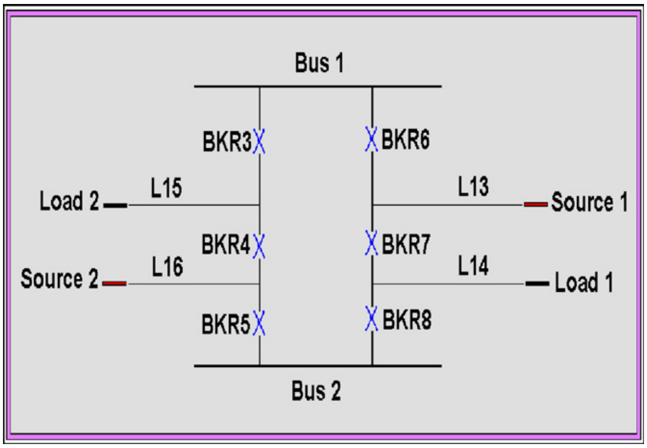

Fig. 2. Breaker-and-a-half configuration—two diameters.

rate (λ_2), or if the second component has a sustained outage (λ_2) and during its repair time (r_2) the first component has a sustained outage (λ_1) if the first system component fails." Thus, for a two component parallel system the outage rat and average repair duration and expected downtime can be estimated as follows [15–20]

$$\lambda_p = \lambda_1\lambda_2(r_1 + r_2) \tag{6}$$

$$r_p = \frac{r_1 r_2}{r_1 + r_2} \tag{7}$$

$$U_p = \lambda_p r_p \tag{8}$$

where λ_p is the outage rate for a two component parallel system; r_p the average outage duration for a two component parallel system and U_p is the unavailability for a two component parallel system.

Recursive equations to analyze general parallel configurations (minimal cut sets) to obtain the outage rate λ_p and average repair time r_p have been developed [17,18]. By combining these equations with those proposed by Billinton and Allan [15,19] and Billinton and Li [16], we have analyzed the reliability of some common ETS configurations such as DESN, breaker-and-a-half and breaker-and-a-third. By using these accurate approximations, we can perform sensitivity analysis using the new proposed criticality measures which are discussed in the next section.

The equations for a series–parallel configuration to determine the total system outage rate, average repair time and the system outage time are given as follows:

$$\lambda_{s-p} = \sum_{i=1}^{n} \lambda_i \tag{9}$$

$$r_{s-p} = \frac{\sum_{i=1}^{n} \lambda_i r_i}{\lambda_{s-p}} \tag{10}$$

$$U_{s-p} = \lambda_s r_s = \sum_{i=1}^{n} \lambda_i r_i \tag{11}$$

where λ_i is the outage rate of parallel subsystem i (from Eq. (6)); r_i the average repair time for subsystem i (from Eq. (7)); λ_{s-p} the total outage rate for a series–parallel system; r_{s-p} the average outage duration for a series-parallel system and U_{s-p} is the outage time for a series–parallel system.

ETS are complex networks. There are several methods to estimate the reliability in a complex configuration; one of them is based on the idea of cut-sets. Cut sets are a set of components which collectively interrupt all of the connections between the input and the output nodes, when removed from the system. The reliability estimates in the present work are based on minimal cut-sets. Thus, the original ETS network is transformed into an equivalent series–parallel system with the minimal cut-sets connected in series, and each cut-set consists of a number of components connected in parallel.

As an example of the reliability modeling of ETS, consider Fig. 2, which represents a functional diagram of a breaker-and-a-half configuration. In this diagram, components 13 and 16 represent the supply lines; components 14 and 15 are the load line; the circuit breakers are defined by components 3–8; and finally, the buses are represented with components 1 and 2. Table 1 shows the minimal cut-sets (up to fourth order) obtained for overlapping component sustained outages for the breaker-and-a-half configuration, as in Fig. 2. Fourth order (or higher) cut sets are not considered because their relative frequency or probability is rare (requiring four or more simultaneous failures).

Fig. 3 shows an equivalent series–parallel model. These minimal cut sets are used as an approximation to estimate the system reliability. Since the approximation is based on minimal cut sets, it provides a lower bound approximation to the true reliability of the system.

4. Custom criticality measures

Traditional importance measures were reviewed in a previous section. None can be applied directly to ETS because they are not properly characterized by probability of failure or success for specified mission times. ETS have more specific measures such as outage rates, repair time and system downtime. In this section, the previously discussed measures have been transformed and applied to ETS.

The newly developed metrics for the evaluation of the importance of components for the ETS were developed, based on the original criticality measures, by using the individual component

Table 1
Minimal cut sets for breaker-and-a-half for failure at load 1

{LINE 14}
{BKR 7, BKR 8}
{BKR 7, BKR 5}
{BKR 7, BUS 2}
{LINE 13, LINE 16}
{LINE 16, BKR 6, BKR 7}
{LINE 16, BUS 1, BKR 7}
{LINE 13, BKR 4, BKR 5}
{LINE 13, BKR 4, BUS 2}
{LINE 13, BKR 4, BKR 8}
{LINE 13, BKR 3, BKR 5}
{LINE 13, BKR 3, BUS 2}
{LINE 16, BKR 3, BKR 7}
{LINE 16, BKR 4, BKR 7}
{LINE 13, BKR 3, BKR 8}
{LINE 13, BUS 1, BKR 5}
{LINE 13, BUS 1, BUS 2}
{LINE 13, BUS 1, BKR 8}
{LINE 13, BKR 5, BKR 6}
{LINE 13, BUS 2, BKR 6}
{LINE 13, BKR 8, BKR 6}

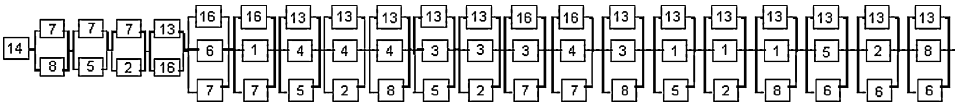

Fig. 3. Breaker-and-a-half transformation for failure at load 1.

sustained outage rates (λ_s^i) instead of probability of failure at a specific time, $F_i(t)$. The new metrics are related to an increase or decrease of the total system unavailability (U_s) rather than system reliability at an specified time.

All of the developed equations require a lower limit ($\lambda_s^i = l_s^i$) and an upper limit ($\lambda_s^i = u_s^i$) outage rate specification for each individual component in the system. Selection of these values depends on each specific component. The principal idea is to select a maximum outage rate which makes the component fully unavailable and the minimum outage rate can be selected to make the component always functioning. There is the possibility for selecting ∞ and 0; however, these two extremes may not be realistic. In all of our examples, we have selected as maximum outage rate of 100 outages/year, and as minimum outage rate, 0 outages/year. In practice, lower and upper limits should be based on the highest and lowest conceivable outage rates for a particular application. Past experience or data may be useful to make this selection.

The newly developed criticality importance measures are presented in the remainder of this section. Examples of applications of the developed measures for some common electric configurations are shown in Section 5.

Transformed Birnbaum importance measure:

$$I_i^{\mathrm{ETS-B}} = U_s(\lambda_s, r_s|\lambda_s^i = u_s^i) - U_s(\lambda_s, r_s|\lambda_s^i = l_s^i) \qquad (12)$$

where $U(\lambda_s, r_s)$ is the system unavailability; l_s^i the lower limit for sustained outage rate of component i (outages/year); u_s^i the upper limit for sustained outage rate of component i (outages/year); $U_s(\lambda_s, r_s|\lambda_s^i = l_s^i)$ the system unavailability when the sustained outage rate of component i is l_s^i and $U_s(\lambda_s, r_s|\lambda_s^i = u_s^i)$ is the system unavailability when the sustained outage rate component i is u_s^i.

The transformed Birnbaum importance measure represents the maximum change in system unavailability when component i switches from the condition of highest possible availability, $U_s(\lambda_s, r_s|\lambda_s^i = l_s^i)$ to the condition of lowest possible availability, $U_s(\lambda_s, r_s|\lambda_s^i = u_s^i)$. In order to explicitly consider the actual component outage rate, we have also proposed the following transformed Criticality Importance measure.

Transformed criticality importance measure:

$$\begin{aligned} I_i^{\mathrm{ETS-CR}} &= [U_s(\lambda_s, r_s|\lambda_s^i = u_s^i) \\ &\quad - U_s(\lambda_s, r_s|\lambda_s^i = l_s^i)] \left(\frac{\lambda_s^i}{U(\lambda_s, r_s)}\right) \end{aligned} \qquad (13)$$

where λ_s^i is the sustained outage rate of component i.

Two other commonly used criticality importance measures have been extended to be directly applied in the ETS area. The Transformed Reliability Reduction Worth measure and the Transformed Reliability Achievement Worth measure are given by:

Transformed Reliability Reduction Worth:

$$I_i^{\mathrm{ETS-RRW}} = \frac{U_s(\lambda_s, r_s|\lambda_s^i = u_s^i)}{U_s(\lambda_s, r_s)} \qquad (14)$$

Transformed Reliability Achievement Worth:

$$I_i^{\mathrm{ETS-RAW}} = \frac{U_s(\lambda_s, r_s)}{U_s(\lambda_s, r_s|\lambda_s^i = l_s^i)} \qquad (15)$$

Finally, the Transformed Fussell-Vessely importance measure is defined as follows:

Transformed Fussell-Vessely:

$$I_i^{\mathrm{ETS-FV}} = \frac{U_s(\lambda_s, r_s|\lambda_s^i = u_s^i) - U_s(\lambda_s, r_s)}{U_s(\lambda_s, r_s)} \qquad (16)$$

5. Numerical examples

The different importance measures were applied to several commonly used ETS. The configurations are the breaker-and-a-half, breaker-and-a-third and DESN.

5.1. Example 1

The DESN configuration is a common type of configuration used in the power industry. It has two different load points (8 and 9) as shown in Fig. 4. The components labeled 12 and 13 represent two lines; components 1 and 2 represent the transformers, and circuit breakers are represented by components 3–5, 10, 11 and 20. Finally, components 6 and 7 represent the buses. Table 2 shows the component data used for each component in the DESN configuration. Typical outages are repair rates are given. In the examples, they are varied for similar components so the effect of different outage rates can be observed in the transformed criticality measures. For each component, the maximum sustained outage rate (u_s^i) was set to 100 outages/year and the minimum was set to 0. In practice, these values should be selected based on a particular problem, and the highest and lowest conceivable outage rates for that application.

All minimal cut-sets (up to fourth order) were obtained for failures at load 8, load 9 and simultaneous failures at both loads. For failures at load 8, load 9, and loads 8 and 9, there are 17, 17 and 19 minimal cut sets, respectively that lead to system fail-

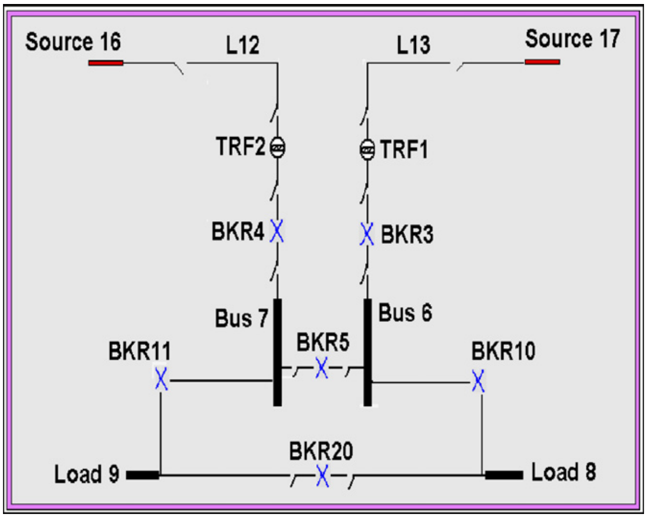

Fig. 4. DESN configuration.

Table 2
Outage rates and repair times for components—DESN

Component	Sustained outage rate, λ_i (outages/year)	Repair duration, r_i (h/outage)
Line 12	0.758	12
Line 13	0.657	14
TRF 1	0.165	116
TRF 2	0.178	145
Bus 6	0.100	2.9
Bus7	0.120	3.5
BKR 3	0.060	157
BKR 4	0.062	134
BKR 5	0.070	176
BKR 10	0.090	160
BKR 11	0.060	168

ure. The minimal cut sets are shown in Appendix A. Reliability importance measures were computed for each component and for each new criticality measures. The components were ranked according to their importance based on their respective metric values as given in Tables 3–5.

In Table 3, we can see that for failures at load 9, in all the different metrics, the most important component is the breaker 11, the second ranked component is bus 7 and the least important component is breaker 10, which has no impact at all for failure at load 9.

Table 4 shows the component rankings for the different components in the DESN configuration for failures at load 8. In all the different metrics the component ranked highest is breaker 10, and the component ranked the lowest is breaker 11. This is as expected, because the breaker 11 has no influence in failures at load 8.

In the analysis for simultaneous failures at both loads, the components that are the most important are the breaker 3 for the Birnbaum, RRW and FV, and the transformer 2 is ranked highest in criticality importance for RAW and Criticality Importance.

5.2. Example 2

Fig. 5 represents a functional diagram of a breaker-and-a-half configuration with two diameters. In this diagram, components 13 and 16 represent the supply lines, components 14 and 15 are the load lines, the circuit breakers are defined by components 3–8, and finally, the buses are represented with components 1 and 2. The minimal cut sets (up to fourth order) for this configuration are shown in Appendix A.

The individual component sustained outage rates and repair times used in this example are shown in Table 6. The sensitivity analysis is performed considering the total unavailability of the system at the different load points of the breaker-and-a-half configuration. Table 6 shows the component data used for each

Table 3
Component rankings and metric values for failure at load L9

Component	Birnbaum		CI		RAW		RRW		FV	
	Rank	Value	Rank	Value	Rank	Value	Rank	Value	Rank	Value
Line 12	9	6.89973	6	0.48658	6	1.00489	9	1.63706	9	0.63706
Line 13	8	6.90635	9	0.42215	9	1.004239	8	1.63832	8	0.63832
TRF 1	7	57.224	4	0.878447	4	1.008862	7	6.31514	7	5.31514
TRF 2	4	83.3717	3	1.380676	3	1.014	4	8.7428	4	7.7428
Bus 6	10	1.4306	10	0.01331	10	1.000133	10	1.13296	10	0.13296
Bus7	2	350	2	3.907533	2	1.040664	2	33.5237	2	32.5237
BKR 3	5	77.4497	8	0.432339	8	1.004342	5	8.20133	5	7.20133
BKR 4	6	77.0469	7	0.444427	7	1.004464	6	8.16373	6	7.16373
BKR 5	3	86.8226	5	0.565437	5	1.005687	3	9.07202	3	8.07202
BKR 10	11	0	11	0	11	1	11	1	11	0
BKR 11	1	16800	1	93.78078	1	16.0792	1	1563.08	1	1562.08

Table 4
Component rankings and metric values for failure at load L8

Component	Birnbaum		CI		RAW		RRW		FV	
	Rank	Value	Rank	Value	Rank	Value	Rank	Value	Rank	Value
Line 12	9	5.17233	8	0.26258	8	1.00263	9	1.34379	9	0.34379
Line 13	8	8.94242	6	0.39348	6	1.00395	8	1.59497	8	0.59497
TRF 1	5	74.0943	3	0.81879	3	1.00826	5	5.9542	5	4.9542
TRF 2	6	62.499	4	0.74507	4	1.00751	6	5.17835	6	4.17835
Bus 6	2	290	2	1.94224	2	1.01981	2	20.403	2	19.403
Bus 7	10	1.5086	10	0.01212	10	1.00012	10	1.10092	10	0.10092
BKR 3	3	100.283	5	0.40298	5	1.00405	3	7.71231	3	6.71231
BKR 4	7	57.7577	9	0.23983	9	1.0024	7	4.86586	7	3.86586
BKR 5	4	75.8608	7	0.35565	7	1.00357	4	6.07714	4	5.07714
BKR 10	1	16000	1	96.4425	1	28.1096	1	1071.62	1	1070.62
BKR 11	11	0	11	0	11	1	11	1	11	0

Table 5
Component rankings and metric values for failure at loads 8 and 9

Component	Birnbaum		CI		RAW		RRW		FV	
	Rank	Value	Rank	Value	Rank	Value	Rank	Value	Rank	Value
Line 12	8	5.21205	5	19.07528	5	1.23572	8	25.9745	8	24.97452
Line 13	7	6.97347	4	22.12112	4	1.28405	7	34.4487	7	33.44868
TRF 1	4	57.7802	2	46.03155	2	1.85293	4	279.519	4	278.5187
TRF 2	2	62.979	1	54.12631	1	2.1799	2	304.539	2	303.5391
Bus 6	10	1.7782	10	0.858567	10	1.00866	10	9.57708	10	8.577082
Bus7	9	2.09553	9	1.214135	9	1.01229	9	11.1056	9	10.10565
BKR 3	1	78.2025	3	22.65502	3	1.29291	1	378.357	1	377.3572
BKR 4	3	58.2013	6	17.42276	6	1.21099	3	281.838	3	280.838
BKR 5	11	0	11	0	11	1	11	1	11	0
BKR 10	6	19.1781	7	8.333748	7	1.09091	6	93.5139	6	92.51387
BKR 11	5	28.1726	8	8.161518	8	1.08887	5	136.944	5	135.9437

Table 6
Outage rates and repair times for components—breaker-and-a-half

Component	Sustained outage rate, λ_i (outages/year)	Repair duration, r_i (h/outage)
Line 13	0.930	15
Line 14	0.860	12
Line 15	0.780	18
Line 16	0.880	10
Bus1	0.200	2.7
Bus 2	0.180	3.2
BKR 3	0.090	150
BKR 4	0.076	167
BKR 5	0.023	159
BKR 6	0.070	176
BKR 7	0.034	168
BKR 8	0.056	146

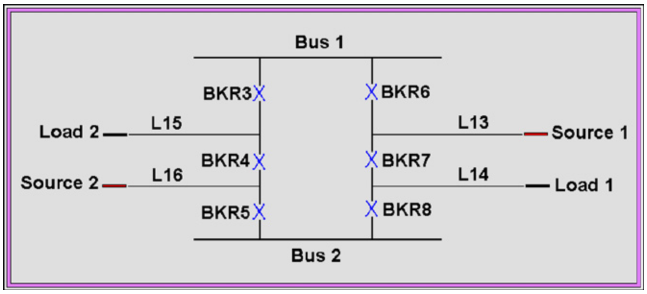

Fig. 5. Breaker-and-a-half configuration—two diameters.

component in the breaker-and-a-half configuration. Similar to the previous example, the lines have the maximum sustained outage rates, while the breakers have the minimum outage rates in the system.

In this electric configuration, there are 21 minimal cut sets (up to fourth order) that lead to system failure at load point 1, 21 minimal cuts for failure at load 2, and for simultaneous failure at both loads, there are a total of 41 minimal cut sets. Based on these minimal cuts and by using the recursive equations [19] to obtain the total system downtime, the five new criticality measures were applied to determine the importance of each component within the system. Tables 7–9 show the metric values and ranking of the different components in the breaker-and-a-half configuration for failures at load 1, load 2 and failures at loads 1 and 2, respectively.

In Table 7 we can see that for all metrics, the most important component is line 14, because affecting the outage rate of this component definitely impacts the unavailability at load 1. The second ranked component in importance is the breaker 7 by using transformed Birnbaum, RRW and FV, while by using the transformed CI and RAW, it is line 13. The least important com-

Table 7
Component rankings and metric values for failures at load L1

Component	Birnbaum		CI		RAW		RRW		FV	
	Rank	Value	Rank	Value	Rank	Value	Rank	Value	Rank	Value
Line 13	6	1.51632	2	0.13635	2	1.0013654	6	1.145251	6	1.145251
Line 14	1	1200	1	99.78516	1	465.47318	1	116.0314	1	116.0314
Line 15	12	0	12	0.00000	12	1	12	1	12	0
Line 16	5	1.59537	3	0.13575	3	1.0013593	5	1.152901	5	1.152901
Bus1	11	0.00079	11	0.00002	11	1.0000002	11	1.000076	11	7.58E−05
Bus 2	7	0.21093	7	0.00367	7	1.0000367	7	1.020358	7	0.020358
BKR 3	10	0.04366	8	0.00038	8	1.0000038	10	1.004218	10	0.004218
BKR 4	9	0.04861	9	0.00036	9	1.0000036	9	1.004697	9	0.004697
BKR 5	3	10.4805	6	0.02331	6	1.0002331	3	2.013142	3	1.013142
BKR 6	8	0.05123	4	0.00035	4	1.0000035	8	1.00495	8	0.00495
BKR 7	2	23.8733	10	0.07848	10	1.0007855	2	3.307551	2	2.307551
BKR 8	4	9.62365	5	0.05211	5	1.0005214	4	1.93	4	0.93

Table 8
Component rankings and metric values for failures at load L2

Component	Birnbaum		CI		RAW		RRW		FV	
	Rank	Value	Rank	Value	Rank	Value	Rank	Value	Rank	Value
Line 13	6	1.511345	6	0.099739	6	1.0009984	6	1.106249	6	0.106249
Line 14	12	0	12	0	12	1	12	1	12	0
Line 15	1	1800	1	99.62886	1	269.43998	1	127.733	1	126.733
Line 16	5	1.598690	5	0.099831	5	1.0009993	5	1.112446	5	0.112446
Bus 1	7	0.391752	7	0.00556	7	1.0000556	7	1.027743	7	0.027743
Bus 2	11	0.001705	11	2.18E−05	11	1.0000002	11	1705112.1	11	0.000121
BKR 3	4	21.76404	3	0.138995	3	1.0013919	4	2.543003	4	1.543003
BKR 4	2	50.30752	2	0.271309	2	1.0027205	2	4.567145	2	3.567145
BKR 5	9	0.084749	10	0.000138	10	1.0000014	9	1.006012	9	0.006012
BKR 6	3	25.53648	4	0.126846	4	1.0012701	3	2.810819	3	1.810819
BKR 7	8	0.089546	9	0.000216	9	1.0000022	8	1.006352	8	0.006352
BKR 8	10	0.077819	8	0.000309	8	1.0000031	10	1.005519	10	0.005519

Table 9
Component rankings and metric values for failures at loads L1 and L2

Component	Birnbaum		CI		RAW		RRW		FV	
	Rank	Value	Rank	Value	Rank	Value	Rank	Value	Rank	Value
Line 13	4	1.509938	3	45.80344	3	1.845136	4	49.79298	4	48.79298
Line 14	2	1.928525	1	54.09781	1	2.178546	2	63.36346	2	62.36346
Line 15	1	2.122223	2	53.99351	2	2.173607	1	69.68253	1	68.68252
Line 16	3	1.594433	4	45.76622	4	1.843869	3	52.54941	3	51.54940
Bus 1	12	0.00064	12	0.004172	12	1.000042	12	1.020818	12	0.020818
Bus 2	11	0.001078	11	0.006331	11	1.000063	11	1.035112	11	0.035111
BKR 3	10	0.035529	6	0.1043	6	1.001044	10	2.157846	10	1.157845
BKR 4	5	0.09692	5	0.240261	5	1.002408	5	4.158927	5	3.158926
BKR 5	7	0.053526	10	0.040155	10	1.000402	7	2.745505	7	1.745504
BKR 6	9	0.041688	8	0.095183	8	1.000953	9	2.358811	9	1.358810
BKR 7	6	0.08903	7	0.098735	7	1.000988	6	3.90299	6	2.902989
BKR 8	8	0.04915	9	0.089776	9	1.000899	8	2.602262	8	1.602261

ponent in the system is line 15, as would be expected because it is a load and not a source point. Furthermore, we can consider bus 1 as the second least important component for failures at load 1.

Table 8 shows all of the metric values for the developed criticality importance measures, for failure at load 2. Line 15 is the most important component and breaker 4 is the second most important component in the system when considering failures at load 2. The least important components in the electric configuration are the line 14 and the bus number 2.

In the analysis for failures at both load points, we see from the results shown in Table 9, that the lines are the four most important components for all different metrics, while the buses

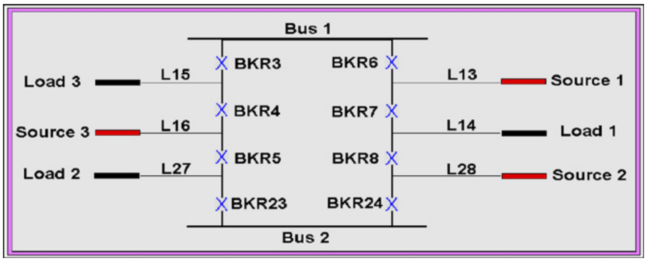

Fig. 6. Breaker-and-a-third configuration.

Table 10
Outage rates and repair times for components—breaker-and-a-third

Component	Sustained outage rate, λ_i (outages/year)	Repair duration, r_i (h/outage)
Line 13	0.98	20
Line 14	0.76	28
Line 15	0.50	12
Line 16	0.88	21
Line 27	0.69	16
Line 28	0.56	19
Bus1	0.30	4.5
Bus 2	0.20	3.8
BKR 3	0.10	187
BKR 4	0.23	176
BKR 5	0.09	190
BKR 6	0.20	154
BKR 7	0.12	125
BKR 8	0.09	178
BKR 23	0.20	186
BKR 24	0.40	169

Table 11
Component rankings and metric values for failures at load L1

Component	Birnbaum		CI		RAW		RRW		FV	
	Rank	Value	Rank	Value	Rank	Value	Rank	Value	Rank	Value
Line 13	8	0.04372	4	0.002011	4	1.0000201	8	1.002032	8	0.002032
Line 14	1	2800	1	99.86805	1	757.87857	1	131.4067	1	130.4067
Line 15	15	0	15	0	15	1	15	1	15	0
Line 16	12	0.005873	11	0.000243	11	1.0000024	12	1.000273	12	0.000273
Line 27	16	0	16	0	16	1	16	1	16	0
Line 28	7	0.055216	5	0.001451	5	1.0000145	7	1.002577	7	0.002577
Bus1	13	0.00186	13	2.62E−05	13	1.0000003	13	1.000087	13	8.7E−05
Bus 2	14	0.000804	14	7.55E−06	14	1.0000001	14	1.000038	14	3.77E−05
BKR 3	4	0.07731	10	0.000363	10	1.0000036	4	1.003625	4	0.003625
BKR 4	5	0.072762	6	0.000785	6	1.0000079	5	1.003407	5	0.003407
BKR 5	9	0.040219	12	0.00017	12	1.0000017	9	1.001886	9	0.001886
BKR 6	6	0.063667	8	0.000598	8	1.000006	6	1.002982	6	0.002982
BKR 7	3	23.07251	3	0.129936	3	1.0013011	3	2.081505	3	1.081505
BKR 8	2	30.89585	2	0.130496	2	1.0013067	2	2.448652	2	1.448652
BKR 23	10	0.039372	9	0.00037	9	1.0000037	10	1.001844	10	0.001844
BKR 24	11	0.035774	7	0.000672	7	1.0000067	11	1.001672	11	0.001672

are the least important components for all the different criticality importance measures.

5.3. Example 3

The breaker-and-a-third design is another common ETS configuration. It can be analyzed for failures at three different load points and any possible combinations, e.g., failure at loads 1 and 2, failure at loads 1–3, etc. The simplified diagram illustrated in Fig. 6 is composed of six lines which are labeled 13 through 16, 27 and 28; components 3–8, 23 and 24 represent eight circuit breakers, and components 1 and 2 represent the buses. This configuration has 35 different minimal cut sets of components that guarantee system failure at load 1, 37 sets of components for system failure at load 2, 37 sets of components for failure at load 3, and 98 minimal cut sets that guarantee system failure at loads 1–3 simultaneously. All the of the minimal cut sets (up to fifth order) for this configuration are shown in Appendix A. Table 10 shows the component data used for each component in the breaker-and-a-third configuration. The components were ranked according to their importance with respect to system downtime for overlapping component sustained outages at loads 1–3 and failure at all loads. The results are shown in Tables 11–14, respectively.

As indicated by the criticality metrics, the most important component for failures at load 1 is line 14, since changes in the outage rate of this component have a direct impact in the unavailability of load point 1. In this case, the components ranked second and third are breakers 8 and 7, which are the breakers closest to the line 14. The least important for all of the metrics are the lines 15 and 27 as shown in Table 11.

Table 12 shows the ranking for the different components for failure at load 2. In this case, the most important component is line 27 and the second most important component is

Table 12
Component rankings and metric values for failures at load L2

Component	Birnbaum		CI		RAW		RRW		FV	
	Rank	Value	Rank	Value	Rank	Value	Rank	Value	Rank	Value
Line 13	14	0.005353	11	0.000466	11	1.0000047	14	1.000471	14	0.000471
Line 14	15	0	15	0	15	1	15	1	15	0
Line 15	16	0	16	0	16	1	16	1	16	0
Line 16	9	0.269831	5	0.02111	5	1.0002111	9	1.023777	9	0.023777
Line 27	1	1600	1	98.14635	1	53.947748	1	142.2596	1	141.2596
Line 28	12	0.022336	10	0.001112	10	1.0000111	12	1.001975	12	0.001975
Bus1	13	0.011446	14	0.000305	14	1.0000031	13	1.001014	13	0.001014
Bus 2	5	0.750145	6	0.013338	6	1.0001334	5	1.066555	5	0.066555
BKR 3	6	0.475654	9	0.004229	9	1.0000423	6	1.042244	6	0.042244
BKR 4	7	0.447663	7	0.009153	7	1.0000915	7	1.039706	7	0.039706
BKR 5	2	229.0366	2	1.832536	2	1.0186674	2	21.34318	2	20.34318
BKR 6	8	0.391705	8	0.006965	8	1.0000697	8	1.034753	8	0.034753
BKR 7	11	0.030682	13	0.000327	13	1.0000033	11	1.002724	11	0.002724
BKR 8	10	0.043691	12	0.00035	12	1.0000035	10	1.003881	10	0.003881
BKR 23	3	36.71762	4	0.652844	4	1.0065713	3	4.257693	3	3.257693
BKR 24	4	33.36171	3	1.186352	3	1.0120059	4	3.954015	4	2.954015

Table 13
Component rankings and metric values for failures at load L3

Component	Birnbaum		CI		RAW		RRW		FV	
	Rank	Value	Rank	Value	Rank	Value	Rank	Value	Rank	Value
Line 13	12	0.038218	10	0.006004	10	1.00006	12	1.006067	12	0.006067
Line 14	15	0	15	0	15	1	15	1	15	0
Line 15	1	1200	1	96.18878	1	26.238335	1	192.4157	1	191.4157
Line 16	9	0.276505	6	0.039008	6	1.0003902	9	1.043938	9	0.043938
Line 27	16	0	16	0	16	1	16	1	16	0
Line 28	14	0.009326	13	0.000837	13	1.0000084	14	1.001487	14	0.001487
Bus1	5	2.086782	5	0.100363	5	1.0010046	5	1.333538	5	0.333538
Bus 2	13	0.010727	14	0.000344	14	1.0000034	13	1.001716	13	0.001716
BKR 3	3	86.96534	4	1.394182	4	1.0141389	3	14.92787	3	13.92787
BKR 4	2	102.3045	2	3.772209	2	1.0392008	2	17.36319	2	16.36319
BKR 5	6	0.536358	9	0.007739	9	1.0000774	6	1.085909	6	0.085909
BKR 6	4	71.61851	3	2.296299	3	1.0235027	4	12.45853	4	11.45853
BKR 7	11	0.130252	12	0.002506	12	1.0000251	11	1.020856	11	0.020856
BKR 8	10	0.18548	11	0.002676	11	1.0000268	10	1.029708	10	0.029708
BKR 23	7	0.525066	8	0.016835	8	1.0001684	7	1.084007	7	0.084007
BKR 24	8	0.431535	7	0.027673	7	1.0002768	8	1.068905	8	0.068905

Table 14
Component rankings and metric values for failures at loads 1–3

Component	Birnbaum		CI		RAW		RRW		FV	
	Rank	Value	Rank	Value	Rank	Value	Rank	Value	Rank	Value
Line 13	3	0.00526	2	69.27615	2	3.2548	3	70.9972	3	69.9971
Line 14	5	0.00297	4	30.35908	4	1.435937	5	40.6426	5	39.6425
Line 15	4	0.00375	6	25.21382	6	1.337145	4	51.1755	4	50.1755
Line 16	2	0.00619	1	73.23427	1	3.736121	2	83.4884	2	82.4884
Line 27	6	0.0028	5	25.97107	5	1.350823	6	38.3795	6	37.3795
Line 28	1	0.00905	3	68.10235	3	3.135027	1	121.93	1	120.930
Bus1	15	3.6E−05	15	0.146356	15	1.001466	15	1.48639	15	0.4863
Bus 2	16	1.6E−05	16	0.042741	16	1.000428	16	1.21328	16	0.21327
BKR 3	7	0.00151	10	2.028313	10	1.020703	7	21.2628	7	20.2628
BKR 4	13	0.00051	11	1.561591	11	1.015864	13	7.77391	13	6.77391
BKR 5	12	0.00066	13	0.802383	13	1.008089	12	9.90735	12	8.90734
BKR 6	9	0.00124	8	3.340763	8	1.034562	9	17.6704	9	16.6704
BKR 7	14	0.00023	14	0.368883	14	1.003702	14	4.07034	14	3.07033
BKR 8	8	0.00127	12	1.541488	12	1.015656	8	18.1122	8	17.1122
BKR 23	10	0.00078	9	2.093283	9	1.02138	10	11.4455	10	10.4454
BKR 24	11	0.00071	7	3.801619	7	1.039519	11	10.466	11	9.46603

breaker 5. When considering failures at load 3, the most important component is line 15. Breaker 4 is the second most important and the least important components in this case are lines 15 and 27.

Table 14 shows the metric values for simultaneous failures at loads 1–3. We can see that the most important components are the lines, which range from first to sixth in importance, followed by the breakers and the least important components are the buses.

6. Discussion

In all previous examples, it was observed that, among the five new transformed importance measures, two different clusters of solutions were obtained. Each cluster gave the same ranking of components. The measures contained in the first cluster are: Birnbaum, Fussell-Vesely and RRW. In the second cluster, the measures which gave the same rankings for the different components in the system are: RAW and Criticality Importance. Therefore, we are just obtaining two different sets of rankings, and thus, we recommend that only two importance measures need to be further considered. The two criticality importance measures recommended are the RAW and the RRW, because these two measures require less computation to be calculated and are conceptually easier to understand.

The two metrics can be applied for any number of studies or analyses that require an objective quantitative ranking of the components. RAW is based on the upper limit on component sustained outage rate. This metric describes the potential for improvement and would be useful for studies to determine which components should be upgraded to a newer and more reliable replacement. Alternatively, RRW is based on the lower limit for component sustained outage rate. This is a more appropriate metric if no upgrades or improvements are under consideration, but it may be important to understand where further deterioration is more critical, and perhaps, inspections are to be determined and prioritized.

7. Conclusions

Reliability importance measures are valuable in establishing direction and prioritization of actions in relation with upgrading in the functioning of the system, or suggesting the most efficient way to operate and maintain system status. In the present work, based on popular importance measures, new criticality importance metrics, Birnbaum, Fussell-Vesely, reliability achievement worth (RAW), reliability reduction worth (RRW) and Criticality Importance (CI), have been developed for the power industry to be directly applied in the ETS. These new metrics pertain to outage rates and system unavailability instead of a specific probability of failure. They have been applied to several common electric configurations such as the breaker-and-a-half, breaker-and-a-third and DESN. The ranking of components provided by the applications of the formulas can provide insightful meaning in where investments to increase the availability of the system should be made.

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Appendix A. Minimal cut sets for breaker-and-a-half, breaker-and-a-third and DESN

A.1. Breaker-and-a-half configuration (minimal cut-sets up to fourth order)

Table A1.1 Minimal cut sets for breaker-and-a-half for failure at load 1

{LINE 14}
{BKR 7, BKR 8}
{BKR 7, BKR 5}
{BKR 7, BUS 2}
{LINE 13, LINE 16}
{LINE 16, BKR 6, BKR 7}
{LINE 16, BUS 1, BKR 7}
{LINE 13, BKR 4, BKR 5}
{LINE 13, BKR 4, BUS 2}
{LINE 13, BKR 4, BKR 8}
{LINE 13, BKR 3, BKR 5}
{LINE 13, BKR 3, BUS 2}
{LINE 16, BKR 3, BKR 7}
{LINE 16, BKR 4, BKR 7}
{LINE 13, BKR 3, BKR 8}
{LINE 13, BUS 1, BKR 5}
{LINE 13, BUS 1, BUS 2}
{LINE 13, BUS 1, BKR 8}
{LINE 13, BKR 5, BKR 6}
{LINE 13, BUS 2, BKR 6}
{LINE 13, BKR 8, BKR 6}

Table A1.2 Minimal cut sets for breaker-and-a-half for failure at load 2

{LINE 15}
{BKR 4, BKR 6}
{BKR 4, BKR 3}
{BKR 4, BUS 1}
{LINE 13, LINE 16}
{LINE 13, BKR 4, BKR 5}
{LINE 13, BKR 4, BUS 2}
{LINE 16, BKR 6, BKR 7}
{LINE 16, BUS 1, BKR 7}
{LINE 16, BKR 3, BKR 7}
{LINE 16, BKR 6, BKR 8}
{LINE 16, BUS 1, BKR 8}
{LINE 16, BKR 3, BKR 8}
{LINE 13, BKR 4, BKR 8}
{LINE 16, BKR 6, BUS 2}
{LINE 16, BUS 1, BUS 2}
{LINE 16, BKR 3, BUS 2}
{LINE 16, BKR 6, BKR 5}
{LINE 16, BUS 1, BKR 5}
{LINE 16, BKR 3, BKR 5}
{LINE 13, BKR 4, BKR 7}

Table A1.3 Minimal cut sets for breaker-and-a-half for failure at loads 1 and 2

{LINE 14, LINE 15}
{LINE 13, LINE 16}
{BKR 4, BKR 5, LINE 13}
{BKR 4, BUS 2, LINE 13}
{BKR 4, BKR 8, LINE 13}
{BKR 7, BKR 6, LINE 16}
{BKR 7, BUS 1, LINE 16}
{BKR 7, BKR 3, LINE 16}
{BKR 7, BKR 8, LINE 15}
{BKR 7, BUS 2, LINE 15}
{BKR 7, BKR 5, LINE 15}
{LINE 14, LINE 16, BKR 6, BUS 2}
{LINE 14, LINE 16, BUS 1, BUS 2}
{LINE 14, LINE 16, BKR 3, BUS 2}
{BKR 3, BKR 4, LINE 14}
{BUS 1, BKR 4, LINE 14}
{BKR 6, BKR 4, LINE 14}
{BKR 7, BKR 8, BKR 4, BKR 6}
{BKR 7, BKR 8, BKR 4, BKR 3}
{BKR 7, BKR 8, BKR 4, BUS 1}
{BKR 7, BKR 5, BKR 4, BKR 6}
{BKR 7, BKR 5, BKR 4, BKR 3}
{BKR 7, BKR 5, BKR 4, BUS 1}
{BKR 7, BUS 2, BKR 4, BKR 6}
{BKR 7, BUS 2, BKR 4, BKR 3}
{BKR 7, BUS 2, BKR 4, BUS 1}
{LINE 14, LINE 16, BKR 6, BKR 5}
{LINE 14, LINE 16, BUS 1, BKR 5}
{LINE 13, LINE 15, BKR 3, BKR 5}
{LINE 13, LINE 15, BKR 3, BUS 2}
{LINE 13, LINE 15, BKR 3, BKR 8}
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{LINE 13, LINE 15, BUS 2, BUS 1}
{LINE 13, LINE 15, BKR 8, BUS 1}
{LINE 13, LINE 15, BKR 6, BKR 5}
{LINE 13, LINE 15, BKR 6, BUS 2}
{LINE 13, LINE 15, BKR 6, BKR 8}
{LINE 14, LINE 16, BKR 6, BKR 8}
{LINE 14, LINE 16, BUS 1, BKR 8}
{LINE 14, LINE 16, BKR 3, BKR 8}
{LINE 14, LINE 16, BKR 3, BKR 5}

A.2. Breaker-and-a-third system (minimal cut-sets up to fifth order)

Table A2.1 Minimal cut sets for breaker-and-a-third for failure at load 1

{LINE 14}	{BKR 7, BKR 8}	{LINE 13, LINE 16, LINE 28}
{LINE 28, BKR 7, BUS 2}	{LINE 28, BKR 7, BKR 24}	{LINE 28, BKR 7, BKR 23}
{LINE 28, BKR 7, BKR 5}	{LINE 13, BKR 8, BKR 6}	{LINE 13, BKR 8, BKR 3}
{LINE 13, BKR 8, BUS 1}	{LINE 13, BKR 8, BKR 4}	{LINE 13, BKR 8, LINE 16, BKR 23}
{LINE 13, BKR 8, LINE 16, BKR 5}	{LINE 13, BKR 8, LINE 16, BUS 2}	{LINE 13, BKR 8, LINE 16, BKR 24}
{LINE 13, LINE 28, BKR 6, BKR 24}	{LINE 13, LINE 28, BUS 1, BKR 24}	{LINE 13, LINE 28, BKR 4, BKR 24}
{LINE 13, LINE 28, BKR 3, BKR 24}	{LINE 13, LINE 28, BUS 1, BUS 2}	{LINE 13, LINE 28, BKR 6, BUS 2}
{LINE 13, LINE 28, BKR 4, BUS 2}	{LINE 13, LINE 28, BKR 3, BUS 2}	{LINE 13, LINE 28, BUS 1, BKR 23}
{LINE 13, LINE 28, BKR 6, BKR 23}	{LINE 13, LINE 28, BKR 3, BKR 23}	{LINE 13, LINE 28, BKR 4, BKR 23}
{LINE 13, LINE 28, BKR 6, BKR 5}	{LINE 13, LINE 28, BUS 1, BKR 5}	{LINE 13, LINE 28, BKR 3, BKR 5}
{LINE 13, LINE 28, BKR 4, BKR 5}	{LINE 28, LINE 16, BKR 7, BKR 4}	{LINE 28, LINE 16, BKR 7, BKR 3}
{LINE 28, LINE 16, BKR 7, BUS 1}	{LINE 28, LINE 16, BKR7, BKR 6}	

Table A2.2 Minimal cut sets for breaker-and-a-third for failure at load 2

{LINE 27}	{BKR 5, BKR 23}	{BKR 5, BUS 2}
{BKR 5, BKR 24}		
{LINE 28, BKR 5, BKR 8}	{LINE 28, BKR 5, BKR 7}	{LINE 16, BKR 24, BKR 6}
{LINE 16, BKR 23, BKR 4}	{LINE 16, BKR 23, BKR 3}	{LINE 16, BKR 23, BUS 1}
{LINE 16, BKR 23, BKR 6}	{LINE 16, BUS 2, BKR 3}	{LINE 16, BUS 2, BUS 1}
{LINE 16, BUS 2, BKR 4}	{LINE 16, BUS 2, BKR 6}	{LINE 13, LINE 16, LINE 28}
{LINE 16, BKR 24, BKR 4}	{LINE 16, BKR 24, BKR 3}	{LINE 16, BKR 24, BUS 1}
{LINE 13, BKR 6, LINE 28, BKR 5}	{LINE 28, BKR 5, LINE 13, BUS 1}	{LINE 13, BKR 3, LINE 28, BKR 5}
{LINE 13, LINE 28, BKR 4, BKR 5}	{LINE 13, LINE 16, BKR 7, BKR 24}	{LINE 13, LINE 16, BKR 8, BKR 24}
{LINE 13, LINE 16, BKR 23, BKR 8}	{LINE 13, BKR 23, LINE 16, BKR 7}	{LINE 28, LINE 16, BKR 4, BKR 8}
{LINE 16, BUS 2, BKR 7, BKR 3}	{LINE 16, BUS 2, BKR 8, BKR 3}	{LINE 28, LINE 16, BKR 6, BKR 7}
{LINE 28, LINE 16, BUS 1, BKR 7}	{LINE 28, LINE 16, BKR 3, BKR 7}	{LINE 28, LINE 16, BKR 4, BKR 7}
{LINE 28, LINE 16, BKR 6, BKR 8}	{LINE 28, LINE 16, BUS 1, BKR 8}	{LINE 28, LINE 16, BKR 3, BKR 8}

Table A2.3 Minimal cut sets for breaker-and-a-third for failure at load 3

{LINE 15}	{BKR 3, BKR 4}	{BKR 4, BUS 1}
{BKR 6, BKR 4}	{LINE 13, LINE 16, LINE 28}	{LINE 13, BKR 8, BKR 4}
{LINE 16, BKR 3, BKR 24}	{LINE 16, BKR 24, BKR 6}	{LINE 13, BKR 7, BKR 4}
{LINE 16, BKR 3, BKR 23}	{LINE 16, BUS 2, BKR 6}	{LINE 13, LINE 16, BKR 7, BKR 24}
{LINE 16, BKR 3, BKR 5}	{LINE 16, BKR 23, BKR 6}	{LINE 13, LINE 16, BKR 7, BKR 23}
{LINE 16, BKR 3, BUS 2}	{LINE 16, BKR 5, BKR 6}	{LINE 13, LINE 16, BKR 7, BKR 5}
{LINE 16, BKR 24, BUS 1}	{LINE 13, LINE 16, BKR 8, BKR 24}	{LINE 13, LINE 16, BKR 7, BUS 2}
{LINE 16, BKR 24, BUS 2}	{LINE 13, LINE 16, BKR 8, BKR 23}	{LINE 13, LINE 28, BKR 4, BKR 5}
{LINE 16, BKR 24, BKR 23}	{LINE 13, LINE 16, BKR 8, BKR 5}	{LINE 13, LINE 28, BKR 4, BKR 23}
{LINE 16, BKR 24, BKR 5}	{LINE 13, LINE 16, BKR 8, BUS 2}	{LINE 13, LINE 28, BKR 4, BKR 24}
{LINE 16, LINE 28, BKR 7, BKR 6}	{LINE 16, LINE 28, BKR 8, BKR 6}	{LINE 13, LINE 28, BKR 4, BUS 2}
{LINE 16, LINE 28, BKR 7, BUS 1}	{LINE 16, LINE 28, BKR 8, BKR 3}	
{LINE 16, LINE 28, BKR 7, BKR 3}	{LINE 16, LINE 28, BKR 8, BUS 1}	

Table A2.7 Minimal cut sets for breaker-and-a-third for failure at loads 1–3

{LINE 13, LINE 16, LINE 28}
{LINE 14, LINE 15, BKR 5, BKR 23}
{LINE 14, LINE 15, BKR 5, BKR 24}
{LINE 14, LINE 15, BKR 5, BUS 2}
{LINE 14, LINE 27, BKR 3, BKR 4}
{LINE 14, LINE 27, BKR 6, BKR 4}
{LINE 14, LINE 27, BUS 1, BKR 4}
{LINE 14, LINE 16, BKR 23, BUS 1}
{LINE 14, LINE 16, BKR 3, BUS 2}
{LINE 14, LINE 15, LINE 27}
{LINE 15, LINE 27, BKR 7, BKR 8}
{LINE 14, LINE 16, BKR 6, BKR 24}
{LINE 14, LINE 16, BKR 3, BKR 24}
{LINE 14, LINE 16, BUS 1, BKR 24}
{LINE 14, LINE 16, BUS 1, BUS 2}
{LINE 14, LINE 16, BKR 6, BUS 2}
{LINE 14, LINE 16, BKR 6, BKR 23}
{LINE 14, LINE 16, BKR 3, BKR 23}
{LINE 16, LINE 28, BKR 7, BKR 6}
{LINE 16, LINE 28, BKR 7, BKR 3}
{LINE 16, LINE 28, BKR 7, BUS 1}
{LINE 13, LINE 28, BKR 4, BKR 5}
{LINE 28, LINE 15, BKR 5, BKR 7}
{LINE 13, LINE 27, BKR 4, BKR 8}
{LINE 13, LINE 16, BKR 8, BKR 24}
{LINE 13, LINE 16, BKR 8, BUS 2}
{LINE 13, LINE 16, BKR 8, BKR 23}

{LINE 14, LINE 27, LINE 13, BKR 8, BKR 4}
{LINE 14, LINE 27, LINE 13, BKR 7, BKR 4}
{LINE 14, LINE 27, LINE 16, BKR 3, BKR 24}
{LINE 14, LINE 27, LINE 16, BKR 3, BKR 23}
{LINE 14, LINE 27, LINE 16, BKR 3, BKR 5}
{LINE 14, LINE 27, LINE 16, BKR 3, BUS 2}
{LINE 14, LINE 27, LINE 16, BUS 1, BKR 24}
{LINE 14, LINE 27, LINE 16, BKR 24, BKR 6}
{LINE 14, LINE 27, LINE 16, BUS 2, BKR 6}
{LINE 14, LINE 27, LINE 16, BKR 23, BKR 6}
{LINE 14, LINE 27, LINE 16, BKR 5, BKR 6}
{LINE 14, LINE 15, LINE 28, BKR 5, BKR 8}
{LINE 14, LINE 15, LINE 28, BKR 5, BKR 7}
{LINE 14, LINE 15, LINE 16, BKR 23, BKR 4}
{LINE 14, LINE 15, LINE 16, BKR 23, BKR 3}
{LINE 14, LINE 15, LINE 16, BKR 23, BUS 1}
{LINE 14, LINE 15, LINE 16, BKR 23, BKR 6}
{LINE 14, LINE 15, LINE 16, BUS 2, BKR 4}
{LINE 14, LINE 15, LINE 16, BKR 24, BKR 4}
{LINE 14, LINE 15, LINE 16, BKR 24, BKR 6}
{LINE 14, LINE 15, LINE 16, BKR 24, BUS 1}
{LINE 14, LINE 15, LINE 16, BKR 24, BKR 3}
{LINE 14, LINE 15, LINE 16, BUS 2, BKR 6}
{LINE 14, LINE 15, LINE 16, BUS 2, BUS 1}
{LINE 14, LINE 15, LINE 16, BUS 2, BKR 23}
{LINE 14, LINE 15, LINE 13, LINE 28, LINE 16}
{LINE 14, LINE 13, LINE 16, BKR 23, BKR 8}
{LINE 27, LINE 16, LINE 28, BKR 7, BKR 6}
{LINE 27, LINE 16, LINE 28, BKR 7, BUS 1}
{LINE 27, LINE 16, LINE 28, BKR 7, BKR 3}
{LINE 27, LINE 13, LINE 28, BKR 4, BKR 5}
{LINE 27, LINE 13, LINE 28, BKR 4, BKR 23}
{LINE 27, LINE 13, LINE 28, BKR 4, BUS 2}
{LINE 27, LINE 13, LINE 28, BKR 4, BKR 24}
{LINE 15, LINE 13, LINE 16, BKR 8, BKR 24}
{LINE 15, LINE 13, LINE 16, BKR 8, BKR 23}
{LINE 15, LINE 27, LINE 28, BKR 5, BKR 7}
{LINE 15, LINE 27, LINE 28, BKR 23, BKR 7}
{LINE 15, LINE 27, LINE 28, BUS 2, BKR 7}
{LINE 15, LINE 27, LINE 28, BKR 24, BKR 7}
{LINE 15, LINE 27, LINE 13, BKR 8, BKR 4}
{LINE 15, LINE 27, LINE 13, BKR 8, BKR 3}
{LINE 15, LINE 27, LINE 13, BKR 8, BUS 1}
{LINE 15, LINE 27, LINE 13, BKR 8, BKR 6}
{BKR 7, BKR 8, BKR 5, BKR 23, LINE 15}
{BKR 7, BKR 8, BKR 5, BUS 2, LINE 15}
{BKR 7, BKR 8, BKR 5, BKR 24, LINE 15}
{BKR 5, BKR 23, BKR 3, BKR 4, LINE 14}
{BKR 5, BUS 2, BKR 3, BKR 4, LINE 14}
{BKR 5, BKR 24, BKR 3, BKR 4, LINE 14}
{BKR 5, BKR 23, BUS 1, BKR 4, LINE 14}
{BKR 5, BUS 2, BUS 1, BKR 4, LINE 14}
{BKR 5, BKR 24, BUS 1, BKR 4, LINE 14}
{BKR 5, BKR 23, BKR 6, BKR 4, LINE 14}
{BKR 5, BUS 2, BKR 6, BKR 4, LINE 14}
{BKR 5, BKR 24, BKR 6, BKR 4, LINE 14}
{BKR 7, BKR 8, BKR 3, BKR 4, LINE 27}
{BKR 7, BKR 8, BUS 1, BKR 4, LINE 27}
{BKR 7, BKR 8, BKR 6, BKR 4, LINE 27}
{LINE 14, LINE 28, LINE 16, BKR 6, BKR 8}
{LINE 14, LINE 28, LINE 16, BUS 1, BKR 8}
{LINE 14, LINE 28, LINE 16, BKR 3, BKR 8}
{LINE 14, LINE 13, LINE 16, BKR 23, BKR 7}
{LINE 15, LINE 13, LINE 28, BKR 4, BKR 5}
{LINE 15, LINE 13, LINE 28, BKR 3, BKR 5}
{LINE 15, LINE 13, LINE 28, BUS 1, BKR 5}
{LINE 15, LINE 13, LINE 28, BKR 6, BKR 5}
{LINE 15, LINE 16, LINE 28, BKR 7, BKR 6}
{LINE 15, LINE 16, LINE 28, BKR 7, BUS 1}
{LINE 15, LINE 16, LINE 28, BKR 7, BKR 3}
{LINE 15, LINE 16, LINE 28, BKR 7, BKR 4}

A.3. DESN configuration

Table A3.1 DESN minimal cut sets for load 9

{BUS 7}
{LINE 13, BKR 4}
{LINE 13, TRF 2}
{LINE 13, LINE 12}
{BKR 4, BUS 6}
{TRF 2, BUS 6}
{BKR 11}
{TRF 1, BKR 4}
{TRF 1, TRF 2}
{TRF 1, LINE 12}
{LINE 12, BKR 3}
{LINE 12, BUS 6}
{BKR 4, BKR 5}
{TRF 2, BKR 5}
{LINE 12, BKR 5}
{BKR 4, BKR 3}
{TRF 2, BKR 3}

Table A3.2 DESN minimal cut sets for load 8

{LINE 12, LINE 13}
{LINE 13, TRF 2}
{LINE 13, BKR 5}
{TRF 1, TRF 2}
{TRF 1, BKR 5}
{BKR 3, BUS 7}
{BUS 6}
{LINE 13, BKR 4}
{LINE 12, TRF 1}
{TRF 1, BKR 4}
{BKR 3, TRF 2}
{BKR 3, BKR 5}
{BKR 10}
{LINE 13, BUS 7}
{LINE 12, BKR 3}
{TRF 1, BUS 7}
{BKR 3, BKR 4}

Table A3.3 DESN minimal cut sets for loads 8 and 9

{BUS 7, BUS 6}
{BUS 7, BKR 10}
{BKR 11, BUS 6}
{BKR 11, BKR 10}
{BKR 4, BKR 3}
{BKR 4, TRF 1}
{BKR 4, LINE 13}
{TRF 2, BKR 3}
{TRF 2, TRF 1}
{TRF 2, LINE 13}
{LINE 12, BKR 3}
{LINE 12, TRF 1}
{LINE 12, LINE 13}
{BUS 6, BKR 4}
{BUS 6, TRF 2}
{BUS 6, LINE 12}
{BUS 7, BKR 3}
{BUS 7, TRF 1}
{BUS 7, LINE 13}

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