



Prioritization of Transmission Network Components Based on their Failure Impact on Reliability of Composite Power Systems

M. Abbasghorbani*

Electrical Engineering Department, Shomal University, Amol, Iran

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ABSTRACT

This paper proposes an efficient method to identify the importance of transmission network components from the network's reliability perspective. The proposed method is able to reveal the weak points of the network and can be employed as useful tool by power system planners to identify where investments should be made to increase the overall system reliability. The proposed approach has two main stages, including evaluation of the network contingency states and a sensitivity analysis which shows the link between reliability of each component and overall system reliability. Unlike the similar methods in this area and with the help of two reasonable simplifications, the proposed method can be employed to real transmission networks with acceptable computational burden. The proposed method is implemented on two test systems including the IEEE Reliability Test System (IEEE RTS) and the Roy Billinton Test System (RBTS). The obtained results demonstrate the efficiency of the proposed approach.

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NOMENCLATURE

T	Line flow vector	L_i	Load at bus i
T^{max}	Rating vector for lines	$IEAR_i$	Interrupted energy assessment rate at bus i (\$/kWh)
A	Matrix relating the line flows to the power injections at buses	NL	Number of load buses
PG	Generation output	NLS	Number of load segments of the LDC
PG^{max}	Upper limit for generation output	T_j	Time duration of each load segment of the LDC
PG^{min}	Lower limit for generation output	$P(e_k)$	Available probability of set e_k
AP_i	Available power at load bus i	$Q(\bar{e}_k)$	Unavailable probability of set \bar{e}_k
ENS	Energy Not Served	$EENS$	Expected Energy Not Served

1. INTRODUCTION

Due to the deregulation of the power systems and emergence of the electricity markets, it is desirable to further improve reliability and availability of the power systems in order to increase the competitiveness of the electricity markets. In this regards, reliability and risk assessments are of great concern for the utilities and considerable researches have been conducted in this area in the past decades [1-5].

New deregulated environment also forces utilities to reduce overall costs. Maintenance costs are considered as a large part of the operation costs. However, reducing

maintenance activities can lead to higher damages caused by an increased number of forced outages due to poor maintenance [6, 7]. Therefore, it would be a good solution to rank the network components based on their needs for maintenance and conduct the maintenance budget to those components that are critical for network.

In maintenance planning, network components can be ranked by condition and importance indices [8-10]. The condition index reflects the physical health of each component and can be determined by condition indicators such as type, age and operating history. On the other hand, importance index is associated with the risk imposed on the system due to the outage of each

*Corresponding Author Institutional Email: ghorbani@shomal.ac.ir
(M. Abbasghorbani)

component. This paper is focused on identifying the importance index of the transmission components which is related to their position in the network.

Although the determination of network critical component plays a very important role in the asset management methods, a limited number of researches have addressed this issue in the transmission network. Due to the mesh structure, complex configuration and great number of components in the transmission network, a method is needed capable of prioritizing the equipment within an acceptable time frame and with logical computations volume.

For instance, the components of common substations have been prioritized in literature [11] without considering the effect of transmission lines or generating units. Also, Hilber and Bertling [12] and Hilber et al. [13] proposed a number of indexes to rank the components of power distribution networks according to their outage costs. These approaches are suitable for distribution networks which have radial configurations and could not be applied to transmission networks.

Implementing the methods proposed by Dehghanian et al. [14] and Gharakheili et al. [15] require access to the experts with deep information about the system. Given that the transmission network is located in a large geographical area with a great number of components, it is challenging to find specialists who have accurate information about all the components and thus limits the possibility of using these methods. The effect of substations' components failure on the prioritization process of network equipment has been considered in a number of studies [10, 16-18]. However, in practice, implementing these methods for real networks with a large number of substations having different layouts will be a very complicated and time consuming task. Moreover, by literature review [10, 16-19], the enumeration method has been used to investigate the possible network contingencies which in real networks can dramatically prolong the computation time and limit the application of these methods. For instance, Setreus et al. [17] investigated all first- and second-order contingencies. However, transmission networks are usually reliable to the outage of one or two components and major portion of expected energy not served belongs to the higher order contingencies. Moreover, using enumeration method to evaluate all of the higher order contingencies can be very time consuming in large transmission networks.

To cover the above challenges, this paper provides an effective way to determine the importance of transmission network components over a reasonable period of time. To reduce the computational burden, two assumptions have been considered in this paper. First of all, failure of substation components can be taken into account by increasing the unavailability of the lines or generating units, connected to the substation. Since, the

substation components failure can lead to the loss of transmission lines or generating units. Hence, in general and according to consultation with the network repair and maintenance specialists, it can be deduced that those substation components located on more important transmission lines and generating units of the network, are of high prominence in the network. Therefore, only by determining the priority of the lines and generating units, one can perceive the importance of substation components with an acceptable approximation and it is not necessary to model all network substations with all the corresponding details. In the next step, the Monte-Carlo simulation method has been employed to investigate the probable network contingencies. In this method, the probable network contingencies are selected based on the failure probability in each network component. So, unlike the enumeration method, there is no need to check all possible events up to a specific order (for example, 3, 4 or more). Based on these two simplifications and in order to reveal the weak points of the network, the proposed approach could be applied in large networks.

The rest of the paper is organized as follows. The Monte-Carlo based method for evaluation of the reliability of the composite power system is briefly presented in section 2. Section 3 provides a detailed description of the proposed approach to determine the importance of network components. The numerical results obtained from simulations on two test systems IEEE RTS and RBTS and the discussions are presented in section 4. Finally, a conclusion is drawn in section 5.

2. COMPOSITE POWER SYSTEM RELIABILITY EVALUATION APPROACH

In the electric power systems, Monte-Carlo simulations are employed to estimate the reliability indices by simulating the actual process and random behavior of the system. The procedure and details of the composite system risk evaluation can be found in literature [1]. In this paper, in order to evaluate the risk of the composite power system, a computer routine has been developed in MATLAB based on a Monte Carlo-based approach. The developed approach is summarized in three steps, as expressed below.

2.1. State Sampling In order to determine the state (failure or normal) of the network components, random numbers, uniformly distributed in [1], are generated and assigned to each component. Then, comparing the random number to the component's unavailability, the component is considered to be failed if the random number is less than the component's unavailability; otherwise it is assumed in normal state. This step is repeated for all components of the transmission network.

If there is any failed component, step 2 must be approached otherwise step 1 must be repeated.

2. 2. Contingency State Analysis Once system state is obtained, as can be seen in Equation (1) a linear programming optimal power flow is solved to reschedule the generating units, eliminate line overloading and avoid load shedding if possible or maximize the total load which can be met on each load bus.

In Equation (1), the priority for supplying loads in each contingency state is considered by their IEAR. Furthermore, loads are modelled using multi-step annual Load Duration Curves (LDC) [1].

$$\begin{aligned} & \max \sum_{i=1}^{NL} AP_i \times IEAR \\ & s.t. \\ & \mathbf{T} = \mathbf{A} \times (\mathbf{PG} - \mathbf{AP}) \\ & \mathbf{PG}^{\min} \leq \mathbf{PG} \leq \mathbf{PG}^{\max} \\ & AP_i \leq L_i \\ & |\mathbf{T}| \leq \mathbf{T}^{\max} \end{aligned} \quad (1)$$

The annual energy not served due to the contingency state k, can be obtained by Equation (2).

$$ENS_k = \sum_{i=1}^{NL} \sum_{j=1}^{NLS_j} (L_{ij} - AP_{ij}) \times T_j \quad (2)$$

where, i and j represent the index of load bus and load segment in the corresponding LDC, respectively.

2. 3. Quantification of EENS Assuming that the outages of the transmission components are independent, the occurrence probability of the contingency state k can be calculated using Equation (3) [20, 21].

$$Prob_k = P(e_k) \times Q(\bar{e}_k) \quad (3)$$

where, e_k and \bar{e}_k are sets of elements of contingency state k which are in service and on outage, respectively.

The EENS due to the occurrence of the kth contingency state is expressed by

$$EENS_k = Prob_k \times ENS_k \quad (4)$$

The total EENS for the composite power system can be obtained by aggregation of the EENS values of all contingency states.

3. IMPORTANCE INDEX OF NETWORK COMPONENTS

The importance of each network component is related to its position in the network structure. In order to determine the importance of each component, the following two stages were considered. Moreover, the flowchart of the proposed approach is illustrated in Figure 1.

3. 1. Contingency States Analysis In the first stage, the Monte-Carlo approach (based on the procedure described in section 2) is employed to select and analyze the contingency states of the network. The procedure is described by the following steps.

Step 1. Choose a state for the network by determining the state (normal or failure) of all components, according to the state sampling procedure presented in section 2.

Step 2. Regarding to the selected state, run the optimal power flow presented in Equation (1), and calculate the ENS for the selected contingency state using Equation (2).

Step 3. If the ENS for the selected state is not zero, save the state and go back step 1. Steps 1-3 are repeated for a predefined number of iterations.

3. 2. Sensitivity Analysis for Ranking the Network Components

After performing the aforementioned three steps in section 3.1, a database is formed that contains the contingency states which result in load curtailment. In order to determine the importance index of the network components, the following basic idea is applied:

A component is of higher important if a specific increase in its failure rate results in higher increase in the overall expected energy not served, compared to another component. Based on this idea, the rank of each network component can be obtained based on the following steps.

Step 1. For each contingency state in the formed database, calculate the occurrence probability and EENS by Equations (3) and (4), respectively. Then, aggregate the EENS of the contingency states to obtain the overall EENS of the transmission network ($EENS_{Base}$).

Step 2. Increase the failure rate of the ith component by a small value, e.g. ξ . Update the occurrence probability of the contingency states and recalculate the new EENS ($EENS_{New}$) of the composite power system similar to step 1.

Step 3. Calculate the importance index for the ith component by subtracting the new EENS ($EENS_{New}$) of the transmission network from the $EENS_{Base}$ and dividing the result by ξ . Do steps 2 and 3 for all components of the network.

4. SIMULATION RESULTS AND DISCUSSION

In order to provide more insight into the presented approach and assessment of its performance, two test systems, namely RBTS and IEEE RTS were considered to perform simulations.

4. 1. Roy Billinton Test System (RBTS) The single line diagram of the RBTS is shown in Figure 2. It includes 9 lines and 11 generating units. The system peak load is 185 MW and the total capacity of the generating

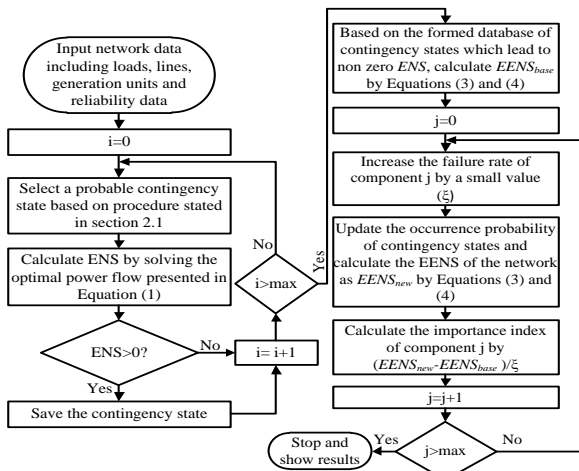


Figure 1. Flowchart of the proposed approach to determine the importance index of network components

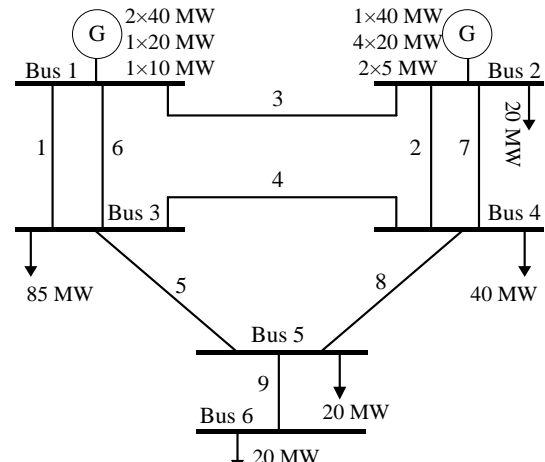


Figure 2. Single line diagram of the RBTS

units is 240 MW. The other network data such as failure and repair rate of each component as well as the generation units and transmission lines data are provided by Billinton et al. [22].

Contingency state analysis: Based on the presented approach in section 3, a contingency states analysis is performed in the RBTS. In this analysis the Monte-Carlo approach is repeated for 4000,000 iterations [23] to select and evaluate highly probable contingency states of the system and save those resulting in the load shedding.

It is worth noting that in both test systems, the priority order of the load buses for load curtailment was determined by the *IEAR*, which can be found in literature [23]. The loads on the load buses were modelled by nine-step LDC. The steps of the LDC and their time durations are presented in Table 1.

Using the state sampling method presented in section 2, 1103 distinct states were selected after 4000,000 iterations, among them there were 617 contingency states which led to the load curtailment. The overall EENS of the network was 148.8 MWh/year. The program was executed on a machine with Core i7 3.5 GHz CPU and 8 GB of RAM. The computation time was 2.748 mins.

Table 2 summarizes the contingency states which led to the load curtailment based on the number of failed components in each state. The contribution of each group of contingencies to the EENS of the system is also presented in Table 2. As can be seen in Table 2, there is a first-order contingency in the RBTS which has resulted in load shedding contributed to 70.54 percent of the EENS of the RBTS. The first-order contingency corresponds to the outage of line 9. Based on the presented results in Table 2, higher order contingency states have lower contribution to the EENS of the RBTS owing to their low occurrence probabilities.

TABLE 1. LDC data

LDC steps	Time duration (in hour of year)
1	19
0.95	96
0.9	314
0.85	656
0.8	1445
0.7	2027
0.6	1883
0.5	1977
0.4	319

The contingency states, leading to load shedding, have been also listed in Table 3 based on the type of the failed components. For instance, there are 17 contingency states which solely include failed transmission lines, constituting the major portion (72.35%) of the EENS in the RBTS. Hence it can be inferred that the major problem of the RBTS is related to the transmission lines.

TABLE 2. Contingency states grouping based on the number of failed components

No. of failed component	No. of contingency states	Contribution to the EENS of the system
1	1	70.54%
2	53	21.79%
3	367	7.14%
4	184	0.52%
5	12	0.002%

TABLE 3. Contingency grouping states based on the failed components

The failed components	No. of contingency states	Contribution to the EENS of the system
Line	17	72.35%
Generating unit	244	11.50%
Generating unit + Line	356	16.14%

The effect of each contingency state on the EENS is shown in Figure 3. As an example, 70.54 percent of the EENS is associated with the outage of line 9. As depicted in Figure 2, due to the radial configuration of the network, the outage of line 9 directly leads to the disconnection of the load bus 6. In the RBTS, outage of line 9 is much more important than the other contingency states. Therefore, for better illustration Figure 3 has two vertical axes. The left one belongs to outage of line 9 and the other contingency states is shown on the right vertical axis.

Ranking of the network components: The rank of the lines and generating units was determined based on the sensitivity analysis approach described in section 3. The importance index of the RBTS components is illustrated in Figure 4.

As shown in Figure 4, line 9 is the most important component in the RBTS. Similar to Figure 3, for better clarification, the importance index of line 9 is shown on a separate vertical axis (right one) and the importance index of the other components are shown on the left vertical axis. Followed by line 9, it can be seen in Figure 4 that generating units 11, 3 and 4 are more important than the other components. It must be noted that these units are the largest units in network, having the capacity of 40 MW. Generating units 3 and 4 are placed on bus 1 and generating unit 11 is mounted on bus 2.

4. 2. IEEE Reliability Test System (IEEE RTS)

The single line diagram of the IEEE RTS is illustrated in Figure 5. This test system is composed of 24 buses, 38 transmission lines and 32 generating units. The peak load in the system reaches 2850 MW while the total installed generating capacity amounts to 3405 MW. Detailed network data including reliability data for each component and the generation and transmission data can be obtained from literature [24].

Contingency state analysis: In this case study, the Monte-Carlo approach was repeated for 1,000,000 iterations [23] and highly probable contingency states of the system were selected and evaluated and those resulting in load shedding were saved. Utilizing the state sampling method described in section 2, after 1,000,000 iterations 37,697 distinct states were selected and among these states there were 16,683 contingency states which caused load curtailment. The overall EENS of the IEEE RTS was obtained as 2318.22 MWh/year. The computation time for this case study was 16.61 min.

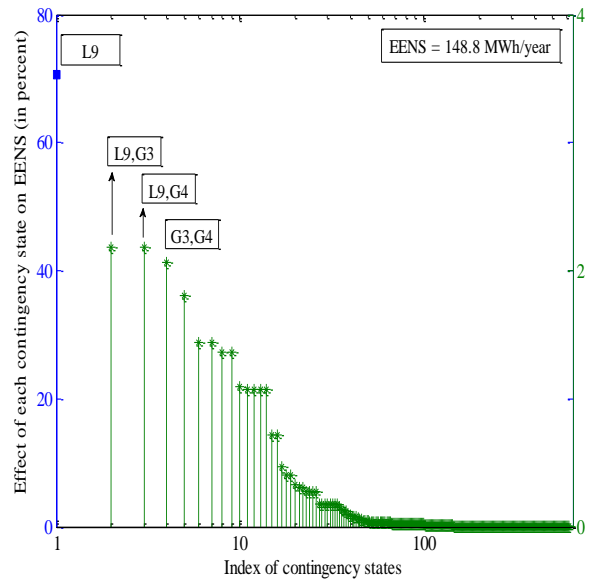


Figure 3. Impact of each contingency state on the EENS (in percent)

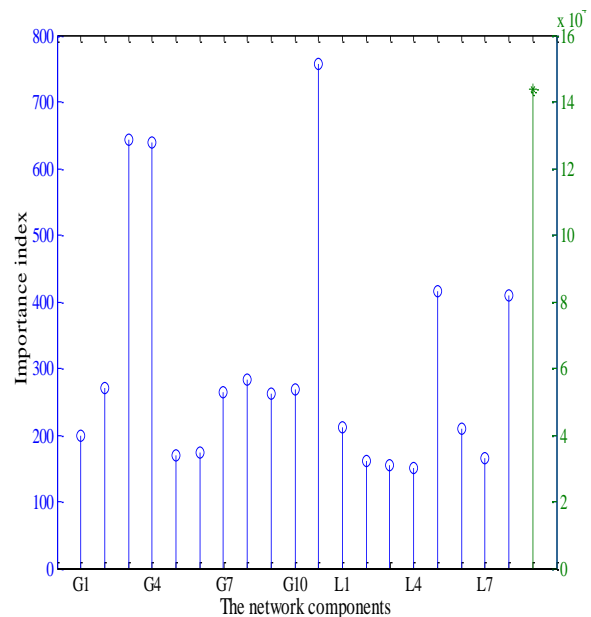


Figure 4. Importance index of lines and generating units in the RBTS

Table 4 summarizes the contingency states with the same number of failed components. The contribution of each group of the contingencies to the EENS of the system is also presented in this table. Based on the information given by Table 4, there is no first-order contingency which results in the load shedding. In other words, the RTS is reliable to the outage of one line or one generating unit. Moreover, the contribution of the second-order contingencies to the EENS is not considerable (6.18 percent). Therefore, as shown in Table 4, the major part

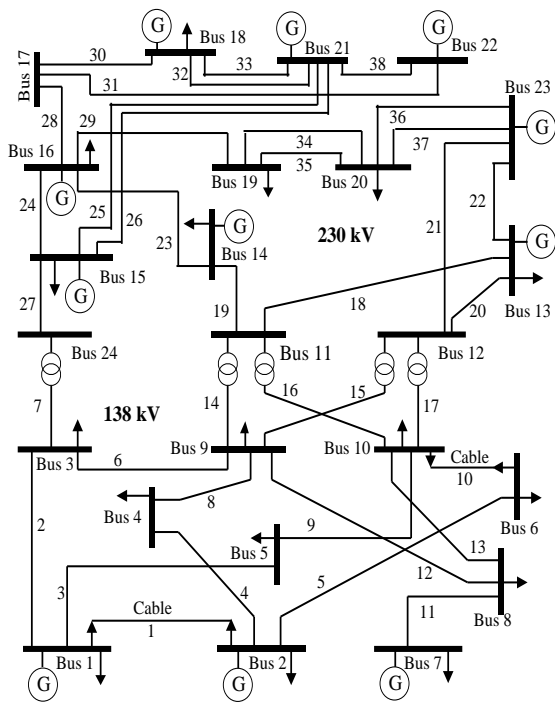


Figure 5. Single line diagram of the RTS

TABLE 4. Contingency states grouping based on the number of failed components

No. of failed component	No. of contingency states	Contribution to the EENS of the system
1	0	0%
2	13	6.18%
3	836	30.42%
4	6620	44.29%
5	6756	18.03%
6	2037	1.05%
7	361	0.03%
8	60	0.00%

of the EENS in the IEEE RTS is associated with the third- and fourth-order contingencies.

In order to provide more insight into efficiency of the proposed method, it's worth estimating the simulation time if the enumeration method was considered to evaluate the contingency states. As mentioned, in proposed method, it takes 16.61 min to simulate 37697 distinct states. While considering enumeration technique as alternative method leads to 974120 states (including one to four components in failure mode) which must be evaluated. Obviously, this will take a very long time. Moreover, this problem can be much more acute in real transmission networks with hundreds of lines and generating units.

The contingency states which resulted in load shedding are summarized in Table 5 based on the type of the failed component. For instance, there are 14,916 contingency states which solely include failed generating units, majorly contributing to the EENS of the IEEE RTS (99.68%). Furthermore, lines outages have negligible impact on the EENS of the network. Therefore, it can be concluded that the major problem of the IEEE RTS is associated to the generating units and the IEEE RTS is very reliable against transmission lines outages.

The information regarding impact of each contingency state on the EENS is depicted in Figure 6. For instance, more than seven percent of the EENS has been imposed due to simultaneous outages of the generating units 22, 23 and 32. Generating units 22, 23 and 32, located on buses 18, 21 and 23, respectively are the largest units in network, having the capacities of 400, 400 and 350 MW, respectively.

Ranking of the lines and generating units: The sensitivity analysis technique described in section 3 is used to rank the transmission lines and generating units. Based on the obtained results, importance indices of the IEEE RTS components are illustrated in Figure 7.

In the IEEE RTS, generating units are more important than transmission lines. Hence, for better illustration, in Figure 7 the importance indices of lines and generating units are shown on right and left vertical axis respectively. Based on this figure, generating units 22, 23

TABLE 5. Contingency states grouping based on the failed components

The failed components	No. of contingency states	Contribution to the EENS of the system
Line	2	0.00%
Generating unit	14916	99.68%
Generating unit + Line	1765	0.32%

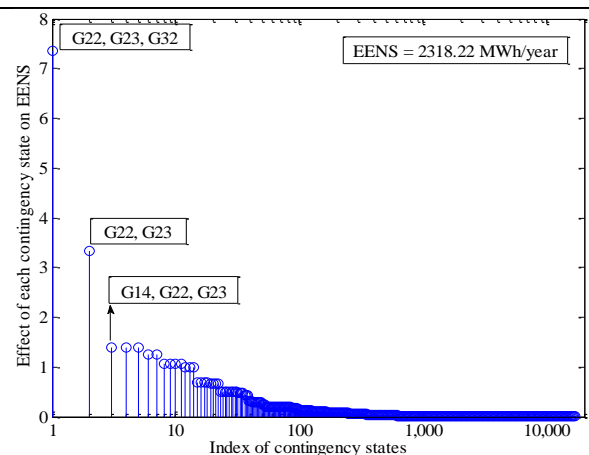


Figure 6. Impact of each contingency state on the EENS (in percent)

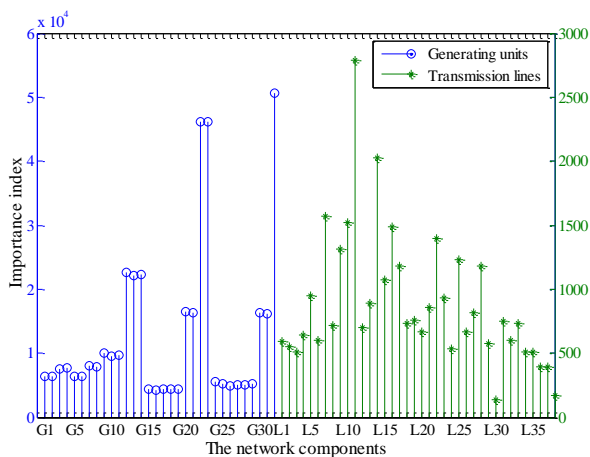


Figure 7. Importance index of lines and generating units in the RTS

and 32 are of higher importance from network perspective, comparing to the other components. As mentioned earlier, these units possess largest capacities within the network. Moreover, line 11 is the most important transmission line in the network. As can be seen in Figure 5, outage of line 11 results in isolation of bus 7. Hence, all the 300 MW generation capacity of bus 7 will be lost.

5. CONCLUSION

This paper proposed a probabilistic approach for ranking network components, based on their importance from the network perspective. The proposed approach is established based on the Monte-Carlo based techniques which are commonly employed for evaluating the reliability of the composite power systems. Hence, the proposed approach can be easily applied to the real transmission networks in a straightforward manner to identify the critical components within the system. The application of the proposed methodology was demonstrated through two case studies on IEEE RTS and the RBTS. Based on the findings in both case studies, the proposed approach can find the most influential components in the context of power system reliability. Moreover, the proposed method is able to reveal the weak points of the network and serve as a useful tool for the power system planners to identify where investments should be made to increase the overall system reliability.

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Persian Abstract

چکیده

این مقاله یک روش کارآمد برای تعیین اهمیت هر یک از تجهیزات شبکه انتقال ارائه می‌کند. روش پیشنهادی قادر به شناسایی نقاط ضعف شبکه قدرت می‌باشد و می‌تواند به عنوان ابزاری مفید در بخش برنامه‌ریزی شبکه مورد استفاده قرار گیرد. در واقع به کمک روش پیشنهادی این مقاله شرکت‌های برق منطقه‌ای قادر خواهند بود برای رسیدن به بهترین قابلیت اطمینان ممکن، منابع مالی محدود خود را به سمت تجهیزاتی سوق دهند که از اهمیت بیشتری برای شبکه برخوردار است. روش پیشنهادی از دو بخش اصلی تشکیل شده است. بخش اول شامل ارزیابی حوادث احتمالی شبکه است و در بخش دوم از آنالیز حساسیت برای تعیین ارتباط بین قابلیت اطمینان هر تجهیز با قابلیت اطمینان کل شبکه استفاده شده است. بر اساس دو ساده‌سازی صورت گرفته، روش پیشنهادی مقاله قادر به پیاده‌سازی در شبکه‌های واقعی است. عملکرد روش پیشنهادی بر روی دو شبکه انتقال نمونه RTS و RBTS مورد بررسی قرار گرفته است. نتایج بدست آمده کارایی روش پیشنهادی را تایید می‌کند.
