Contingency ranking for timely power system security assessment using a new voltage-angle index and based on the PMU data

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Given the importance of the power system security and the role of the operator in enhancing this feature, improving the operator's actions and information in the power system management is critical. The proper tools and available information for the operator can continuously improve the power system security. During power system operation, the operator needs to identify probable hazardous contingencies to assess power network security online. Thus, contingency ranking based on their importance has always been of interest to researchers. In present study, a new method is proposed for appropriate contingency ranking and online power network security assessment based on the Phasor Measurement unit (PMU) data. In the proposed method, unlike the previous methods, two voltage and angle indices were used. Since the variables of load-flow studies are used to calculate the proposed index, this index can provide a comprehensive assessment of the network security. The proposed index is implemented on three IEEE 14-, 30- and 57-bus test systems to evaluate its performance. First, using this index, contingency analysis is carried out in 2000 operational points and the obtained results are compared with a randomly selected operating point. The results indicated the performance and response time of the proposed index.

keywords: *Power systems, Security assessment, Contingency rating, Phasor measurement units, Voltage-angle index.*

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1. INTRODUCTION

The security of power systems is important in various technical, economic, social and even political aspects. Therefore, operating engineers have always tried to improve and upgrade the security and stability of power systems. On the other hand, with the relaxation of competition in the electricity industry, the possibility of high and unprofitable investment in power systems has been eliminated, and consequently, the margin of security in network utilization has decreased [1]. In such a situation, the power network operator will encounter a lot of stress to maintain network security [2]. The operator of power systems must assess network security over a period of less than 15 minutes [3]. In most power systems if the elimination of any of the contingencies does not cause any interruption in network performance, it is concluded that the desired operating state is secured. Single-contingency analysis is carried out to assess the security. In such a study, the contingencies are eliminated from the simulated network separately and one after the other; in the contingency analysis, all transient and permanent effects should be considered in the occurrence of the contingency. Obviously, it is not feasible to perform such a study for today's multi-thousand-bus test systems, even with ultra-fast processors, in less than 15 minutes, and it must be thought how to solve this problem. To solve this problem, important and probable contingencies are made offline, and online security assessments are only performed on them. This is called "contingency screen". To do this, the indices are usually defined. In offline contingency analysis, any contingency with a higher index value will be more important and will have priority over other contingencies in online contingency studies. Depending on the operator's experience and the offline contingency studies, a number of contingencies, which are on the top of priority list, are selected and will be examined in online contingency studies by the operator. To screen important contingencies, various methods and indices have been proposed, and most of these indices are defined based on the deviations of the voltage of the buss, the production power of the power plants or the transmission power of the lines from the nominal values. The task of these indices is to prioritize the contingencies correctly. Therefore, these indices should be in a way that can correctly determine the importance of each contingency. In

[4], the deviations of the buss' voltage, the apparent power of the elements and loads connected to the buss from the nominal values are summed up and a combination of them is considered as the index and criterion. In [5], the deviations of the voltage and current apparent power in the lines from the nominal values are summed up. Then a combination of them is normalized and considered as an index, in which the transient security assessment was defined in response to this question: Do the fluctuations of the system, which occurred after the occurrence of error, interrupt the synchronism of the system's generators? For this purpose, an index known as "Transient Security Index" was defined. In [6], the sum of squares of load of lines-to-their nominal values ratio was defined as the overload index and the sum of squares of the deviations of the buss' voltage from the nominal values was defined as the overvoltage index. In [7], the authors have ranked probable contingencies based on the FVSI index of the line. In [8], probable contingency ranking using the P-V curve sensitivity was presented. The probable contingency ranking method based on the branch parameter and specific right hand-side vector is given in [9]. In [10] the Performance Index (PI) is defined in terms of both bus voltage violations and line overloads, which is used for security level classification and to rank contingencies in order of their severity following a given list of contingencies. [11] describes a ranking approach that accounts for both the severity and likelihood of the underlying system contingencies. A risk-based contingency ranking (RCR) metric is developed, which incorporates limit violations associated with bus voltages and transmission line thermal limits along with their failure rates. In [12] a recursive method is proposed for contingency ranking based on the bi-level optimization model. In addition, [13] presents a mathematical formulation for selecting, ranking, and grouping the most critical N-1 network contingencies, based on the calculation of a Power Constraint Index (PCI) obtained from the Outage Transfer Distribution Factors (OTDF). With the advent of artificial intelligence, the probable contingencies ranking based on neural networks and fuzzy logic were carried out in [14] and [15], respectively. Considering the importance of contingency ranking in the online power system security assessment, it seems necessary to have an index that can determine the importance of each contingency correctly and accurately. Hence, in present study, first, the voltage-angle index was introduced by introducing the two voltage and angle indices of the phase of buss. Since the voltage deviation does not identically increase the risk of operation in all buses of a power system and the buses of a network are not equally important, this was considered in the calculation of the voltage index. Simulation results show the proper performance of the proposed index in prioritizing the network power contingencies. The structure of present study is as follows: in part 2, security in the operation of power system is examined, in part 3, the proposed index is presented and described, in part 4, the studied problem is described, in part 5, the simulation and its results are analyzed and finally, in part 6, the conclusion is presented.

2. SECURITY IN THE OPERATION OF POWER SYSTEM

Dynamic Security Assessment (DSA) of system includes analyses determining whether a power system can satisfy all the static and transient security constraints and reliability against important contingencies in the steady and transient states or not. In the field of operation, a secure system is a system that provides pre- and post-contingency operation measures well. This definition indicates that analyses used to assess system security should include all aspects of security, including thermal load of elements, fluctuations of voltage and frequency, and all types of stability. The computations required to evaluate the power system security are technically difficult and sensitive; hence, security assessment has been assigned to offline simulation environments. In these environments, the steady and transient states of the system is simulated in a predicted operating point using tools such as load-flow. For more complex assessments, such as considering stability issues, it is necessary to calculate the operation limits and constraints before the error occurs. To this end, all contingencies must be studied even if their likelihood of occurrence is very small. Today, due to the competitive atmosphere of power systems and the uncertainty about the future status of the system, the system security assessment requires a new method called Online Dynamic Security Assessment. In this method, network stability is calculated at the operating point as soon as the contingency occurs. After a contingency that could be dangerous for network security, computation of stability should be made much faster than initiation of automatic control or intervention of operator. Although it is not yet known whether this method can prevent or fail from the global outages similar to those that occurred in the United States in 2003, but it can certainly notifies the operator before it occurs and provides him with the opportunity to take corrective measures. Although full simulation provides the most accurate security assessment for the operator, today, the problem of response time in the analysis of large networks is a huge challenge. Since the system security assessment should specifies the security situation of the network in the case of important contingencies, as well as it is impossible to assess the impact of all contingencies, one of the most important elements in an online DSA is contingency screen, which is the selection of those contingencies which should be considered in the security assessment. There are many ways to do this, but in short, this is a compromise between speed and accuracy. Screening methods used for thermal overload or voltage drop are simpler than those used for stability issues, because in the stability issues, complex dynamics and nonlinear characteristics of the network may invalidate simple screening methods. Indices and methods appropriate for contingency screen can help the operator to better assess the power system security.

3. INTRODUCTION OF THE PROPOSED INDEX

In reference [16] the bus voltage variations to define the voltage index for the rating of the contingencies, which shows the buses voltage deviation well and is a relatively good index. However, some of the contingencies have a greater effect on the transmission power of the lines. In order to overcome this defect in the voltage index, since the transmission power through the lines is dependent on the phase angle of the buses, the authors combine the voltage and angle indicators and arrived at an index called Voltage-Angle Index. This index with few input information, provides an appropriate assessment of system security that is the innovation of this article. Generally, the ranking of contingencies for online security assessment is a conciliation between speed and accuracy, which means that the indicators used, in addition to the proper accuracy, should also have acceptable performance speeds. In load-flow studies, the amount and phase angle of bus voltage are defined as state variables; which means that by knowing them, other quantities of the network can be easily found according to the simple network equations. On the other hand, at the time of conducting a contingency analysis, elimination of each element from the network creates fluctuations in network quantities. Certainly, these fluctuations will be more visible in the state variable than any other variable. Therefore, the use of these two quantities can provide the operator with an accurate network security assessment. In the following parts, first, the voltage index is introduced considering the effect of power flow and then, the phase angle index of the buss is defined. Then, the voltage-angle index is described. It should be noted that observing of the network for ranking of contingencies using the proposed index is mandatory. The power system is visible when all its state variables can be calculated based on the number, type, and location of the measurements. In references [17] and [18], methods are proposed for optimal placement of phasor measuring units with the aim of fully observing the power system. The results obtained from the simulation and comparison with other indexes show the accuracy and validity of the proposed index.

A. Voltage index

One of the quantities that has always been considered for network security assessment is the bus voltage. When an effective contingency occurs in the network, the voltage of some buss exceeds the permissible values. The greater this voltage deviation, the more important this contingency and it will have the higher priority in the contingency list. When the contingency occurs, the voltage of buss varies. The amount of these deviations can be calculated according to Eq. 1 [16].

$$\mathrm{VD_i} = \begin{cases} \left(\frac{(|\mathrm{v_i}|-1.05)}{1.05}\right) \times 100 & ;\ \text{if}\ :\ |\mathrm{v_i}| > 1.05 \\ \left(\frac{0.95-|\mathrm{v_i}|}{0.95}\right) \times 100 & ;\ \text{if}\ :\ |\mathrm{v_i}| < 0.95 \\ 0 & ;\ \text{other wise} \end{cases} \quad (1)$$

Where VD_i is the voltage deviation of the i^{th} bus. Using this formula, the voltage deviations of all buss are measured. Since voltage deviations of all buss are not equally important, then, in defining the voltage index, unlike [16], the P_i coefficient is used to determine the importance of each bus. This coefficient indicates the power transmission of each branch. So, the voltage index is equal to the sum of voltage deviations of all buses multiplied by P_i.

$$\text{VoltageIndex} = \sum_{i=1}^{N} (\text{VoltageDeviation}_i \times P_i) \quad (2)$$

Where N is the number of buss of the studied network. Thus, when a contingency analysis is performed, first, the voltage deviation of each bus is calculated using Eq. 1, and then, sum of them is obtained using Eq. 2, which is the voltage index.

B. Angle index

One of the quantities in the network that has a significant relationship with the power of the network is the phase angle of the buss. This relationship is important so that in some studies, the load flow injected to a bus is defined only as a function of the phase angle of the buss. This relationship between power and phase angle has led to the use of phase angles of the buss' voltages, instead of current powers in the lines, as a criterion in the static network security assessment. The use of PMUs facilitates access to the phase angles of the voltages. To define this index, similar to the definition made for the voltage index, first, the deviation of phase angles at the time of occurrence of the contingency is defined according to Eq.3 [16].

$$\mathrm{AD_i} = \begin{cases} \frac{\delta_\mathrm{i}-(\pi/18)}{(\pi/18)} \times 100 & ;\ \text{if}:\quad \delta_\mathrm{i} > (\pi/18) \\ \left|\frac{(-\pi/18)-\delta_\mathrm{i}}{(\pi/18)}\right| \times 100 & ;\ \text{if}:\quad \delta_\mathrm{i} < (-\pi/18) \\ 0 & ;\ \text{Othe rwise} \end{cases} \quad (3)$$

Where AD_i is the angle deviation of the i^{th} bus. When a contingency analysis is performed, first, the phase angle deviation of each bus is calculated and then the angle deviations of all buss are summed. The resulting number is defined and called as the phase angle index corresponding to that contingency:

$$\text{AngleIndex} = \sum_{i=1}^{N} \text{AngleDeviation}_i \quad (4)$$

Where N is the number of buss of the network.

C. Voltage-Angle index

In the contingency ranking method based on the voltage index, the voltage index uses the voltage deviation of the buss during the occurrence of the contingency in its definition. Since this index includes the nominal voltage deviation well, in terms of definition, it is a very good criterion for network security assessment, but since the effects of some contingencies appear in current power of the lines instead of the voltage, this definition cannot provide accurate system security assessment. In order to overcome this weakness in the voltage index, considering the relationship between current power in lines and the phase angle of buss, the angle index is used in the proposed method, in addition to the voltage index, to properly rank the contingencies and assess the network security. In order to define the proposed index, an equation is proposed that is a weigh function of the voltage index and the angle index. This weight function is expressed in Eq. 5. According to the simulation results and for the proper effects of the voltage and angle indices, the weight coefficients were considered 0.85 and 0.15, respectively. As the load demand increases or any network element is eliminated, a large voltage difference can be observed in some buss, which will result in voltage collapse and insecurity in the network. To consider this phenomenon, the parameter α is defined in the proposed index. This factor increases the sensitivity of the mentioned index.

$\alpha = 1 - (max(V_a - V_b))$

Given above equation, the parameter α depends on the maximum voltage difference between the two buses a and b. Therefore, the voltage-angle index is defined as follows:

$$\mathrm{VAI_i} = \frac{(0.85 \times \text{VoltageIndex} + 0.15 \times \text{AngleIndex})}{\alpha} \quad (5)$$

4. DESCRIPTION OF THE STUDIED PROBLEM

The present study aims to properly rank the contingencies for the online security assessment of the studied power network based on PMU data. One of the tasks of the security assessment indices is to correctly prioritize the contingencies. Therefore, these indices should be in a way that can correctly determine the importance of each contingency. The more important a contingency, the different quantities of the network will change more as that contingency occurs. In other words, when an important and dangerous contingency occurs in the network and that element is eliminated from the circuit, some quantities, such as the voltage of some buss and the current power of some lines, may exceed their nominal values. Therefore, one of the contingency screen methods is to study the network in offline mode and for different operational points, and in each of these operational points, contingency analysis is performed for each contingency. Those contingencies, which were able to totally have larger values in the index are considered as the contingencies with higher priority. For this purpose and for each contingency, the proposed index has been examined on the sample network and in a large number of operational points, and according to the results, the contingencies have been screened. The process of implementing the problem is that when a contingency occurs at an operational point in the network, the voltage and angles of the buss change. The deviations of the voltage and the angle of the *ith* bus are estimated using the Eqs. 1 and 3, respectively. Using the Eqs. 2 and 4, sum of these deviations is calculated in N buses, and finally, using Eq. 5, the voltage-angle index is estimated. The stronger, the contingency, the larger the voltage-angle index, resulting in a more dangerous and more important contingency and it will have a higher priority in the list of contingencies. In this project, sample 14-, 30- and 57- bus networks have been examined in 2000 randomly generated operational points. In each of these operational points, each line was eliminated from the circuit in turn, and the voltage-angle index corresponding to each contingency was obtained at each of these operational points. Finally, all the indices of each contingency were averaged and the obtained value was considered as the final index of that contingency. In Fig. 1, the flowchart of the problem can be seen. Since in present study, the contingency means the elimination of lines from the circuit, and in the 14-bus network, there were 20 transmission lines, so 20 contingencies were considered for this network. Similarly, the 30- and 57-bus networks had 41 and 80 contingencies.

5. SIMULATION AND ANALYSIS OF RESULTS

In this part, the proposed index is tested on three IEEE 14-, 30- and 57-bus networks based on the flowchart shown in Fig. 1, and the results are described and compared with other existing indices. To understand whether the research method is a good method to measure the importance of the contingencies, the results obtained using 2,000 randomly selected operational points, with the title of “learned”, were compared with a randomly selected operational point, with the title of “test”. The results related to the sample 14-, 30- and 57-bus networks are shown in Figs. 2-4, respectively. The horizontal axis shows the No. of the contingencies, the numbers of which for the sample networks used are 20, 41, and 80, respectively, and the vertical axis indicates the priority of the contingency. It is evident from the comparison of the two graphs shown in Fig. 2, that the general form of the two graphs are nearly the same. If the contingencies with the priority of 1 to 10 are identified as the final list of contingencies to be made available to the operator for online study, we will have 14 buss for the network in each of the two learned and test modes:

1. Important contingencies in the learned study: 1, 8, 10, 12, 15, 16, 17, 18, 19, and 20
2. Important contingencies in the test study: 1, 8, 10, 12, 15, 16, 17, 18, 19 and 20

Therefore, the predicted important contingencies are the same with 100% accuracy, i.e., the success rate of the ranking of contingencies and security assessment using the proposed index is 100%. So, the research method and the proposed index are appropriate for measuring the importance of the contingencies. According to the results of the 30-bus network shown in Fig. 3, the contingencies with the priority of 1 to 20 in each of the two learned and test modes are as follows:

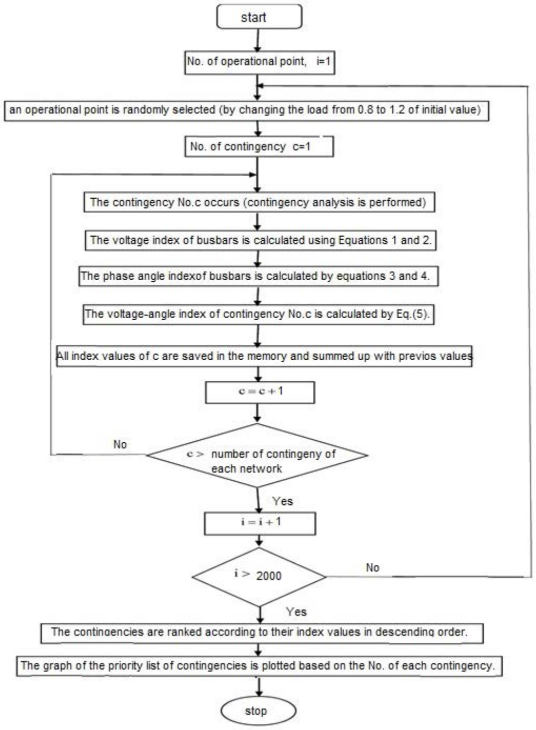

Fig. 1. Flowchart of the examination of voltage-angle index

1. Important contingencies in the learned study: 1, 2, 4, 5, 7, 8, 9, 10, 15, 17, 18, 19, 21, 22, 25, 27, 30, 36, 37 and 38.
2. Important contingencies in the test study: 1, 2, 4, 5, 7, 8, 9, 10, 15, 17, 18, 19, 21, 22, 25, 27, 36, 30, 37 and 38.

For the 30-bus network, all the contingencies were properly detected and screened, and no mistakes was made in each of these 20 contingencies. This indicates 100% accuracy and success in detecting the contingencies with higher priority. If the important contingencies with a priority of 1 to 40 are identified as the final list of contingencies that should be made available to the operator for online study, following data will be obtained from the study of the 57-bus network, the results of which are given in Fig. 4:

1. Important contingencies in the learned study: 6, 9, 10, 12, 15, 18, 22, 28, 29, 33, 35, 37, 38, 39, 40, 41, 42, 43, 46, 47, 48, 49, 50, 53, 54, 55, 56, 57, 58, 59, 60, 64, 65, 66, 67, 70, 71, 72, 74 and 80
2. Important contingencies in the test study: 6, 7, 9, 10, 15, 17, 18, 22, 25, 29, 33, 37, 38, 39, 40, 41, 42, 43, 46, 47, 48, 49, 50, 53, 54, 55, 56, 57, 58, 59, 60, 64, 65, 66, 67, 70, 71, 72, 74 and 80

As seen, the difference between the contingencies of the learned and test studies for this 57-bus network is two. According to the number of selected contingencies, a difference of 5% or 95%

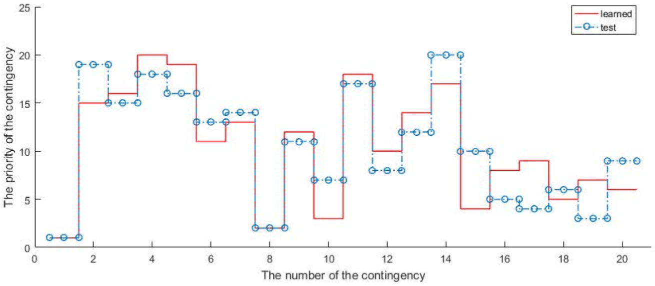

Fig. 2. The result of the contingency analysis for the voltage-angle index in the sample 14-bus network.

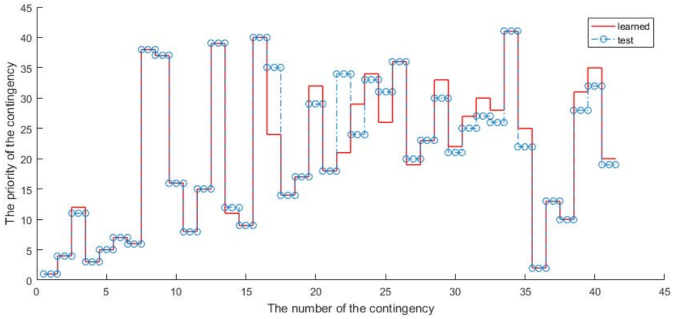

Fig. 3. The result of the contingency analysis for the voltage-angle index in the sample 30-bus network.

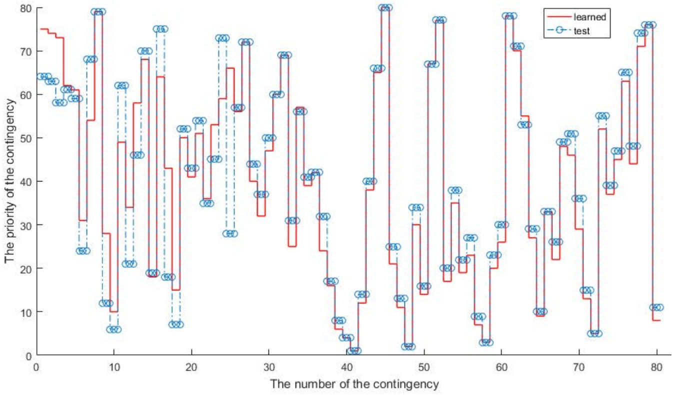

Fig. 4. The result of the contingency analysis for the voltage-angle index in the sample 57-bus network.

accuracy is represented. This difference between the learned and test studies is quite acceptable. In real networks, which have more number of buss, and considering the operator's experience in selecting the important contingencies, this difference will be less.

By examining the results of proposed index and the results of indices studied in reference [16], it is observed that the accuracy of each of these indices is almost acceptable. It is not easy to decide which of these indices can better assess network security. But, certainly, two issues affect this decision: first, the repeatability of the results of this assessment in different cases and, secondly, logicality of the definition presented for the index. The simulations made for the proposed index and the voltage, power deviation, relative power, indices and angle index [16] show the repeatability of all of them. For three sample networks, using 2,000 randomly selected operational points, important contingencies were determined according to these indices and then, the indices were tested on another randomly selected operational point. The percentage of similarity between the results of these two studies (learned and test) for the voltage-angle index and other indices are listed in Table 2. But, another issue is important here. It is that how much each of these indices is an appropriate measure to prioritize and screen the contingencies. In order to investigate the difference between the indices, the priority lists of the contingencies obtained using these indices were compared and percentage of the difference between the indices for the sample 14- , 30- and 57-bus networks, are shown in Tables 2-4, respectively. According to these results, the important contingencies presented by the voltage-angle index are largely different from those presented by some of the indices proposed in [16]. The differences between this index and all other indices are completely predictable, because different indices and quantities are used in their definitions. In the meantime, the voltage-power index, which is derived from the combination of two voltage and power deviation, has a more proximity to the voltage-angle index in terms of type and kind, and it is expected that there are more similarities between the results of these two indices. But, because of two reasons, it is impossible to see the similarities between them in present study. Firstly, the definition of the power deviation index has weaknesses, such as considering the nominal power identical for all lines. Secondly, the networks studied in this study are not secured at all, even in the case of without contingency. Specifically, a sample 30-bus network has 3 lines that in the case of cut of each of them, some buss will be unloaded. The percentages of differences between the results obtained from different indices clearly indicates that the sufficient and necessary accuracy should be made in choosing the security assessment indices. By choosing the wrong one, a contingency, which is not important causes waste of time during an online assessment, or an important contingency, which was not identified, can cause problems and outages in the network. It seems that the Voltage-Angle Index, due to the use of network state variables in its definition, can provide an accurate network security assessment. As aforementioned, due to the problems in the indices of power and given the availability of network phasor using the PMU, it seems that the voltage-angle index could play an important role in power system security assessment in future.

6. CONCLUSION AND FUTURE TRENDS

In the present study, the voltage-angle index was proposed to rank probable contingencies and assess the power system security based on PMU data. The results of simulation in three 14-, 30- and 57- bus networks were compared with those of previous indices. The comparison results showed the better accuracy of the proposed index. In the definition of the proposed method, the amount and phase angle of the buss' voltages were used together. Since these two quantities are introduced as state variables in load flow studies, using them can provide a correct network security assessment for the operator. The results of present study show the accuracy of the proposed index and correctness of the issue studied. Moreover, due to the availability of network phasors using the PMU, the proposed index will have a proper speed in online assessing the power system security. Investigating algorithms of the occurrence probability of contingencies and involving these probabilities in determining the importance of the contingencies and using new load flow

Table 1. Percentage of the success of different indices in the contingency ranking

	Index	Voltage	Power deviation	Relative power	Voltage-power	Phase angle	Voltage-angle
Sample Network	14-bus	90	90	90	80	100	100
	30-bus	85	95	95	95	100	100
	57-bus	92.5	90	92.5	92.5	92.5	95

Table 2. Percentage of the difference between different indices in the contingency ranking and the security assessment of 14-bus network

	Voltage	Power deviation	Relative power	Voltage-power	Phase angle
Power deviation	60				
Relative power	60	50			
Voltage-power	30	40	70		
Phase angle	80	60	40	50	
Voltage-angle	20	50	60	30	50

Table 3. Percentage of the difference between different indices in the contingency ranking and the security assessment of 30-bus network

	Voltage	Power deviation	Relative power	Voltage-power	Phase angle
Power deviation	40	-	-	-	-
Relative power	60	40	-	-	-
Voltage-power	20	20	60	-	-
Phase angle	60	35	30	50	-
Voltage-angle	40	30	40	20	35

Table 4. Percentage of the difference between different indices in the contingency ranking and the security assessment of 57-bus network

	Voltage	Power deviation	Relative power	Voltage-power	Phase angle
Power deviation	47.5	-	-	-	-
Relative power	37.5	42.5	-	-	-
Voltage-power	2.5	47.5	37.5	-	-
Phase angle	32.5	45	32.5	32.5	
Voltage-angle	2.5	42.5	35	2.5	32.5

methods to accelerate the security assessment can be considered in future studies.

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