J Electr Eng Technol.2015; 10(4): 1422-1431
http://dx.doi.org/10.5370/JEET.2015.10.4.1422

ISSN(Print) 1975-0102
ISSN(Online) 2093-7423

Reliability Evaluation of Power System Operations Considering Time-Varying Features of Components

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Abstract – The reliability of power system components can be affected by a numbers of factors such as the health level of components, external environment and operation environment of power systems. These factors also affect the electrical parameters of power system components for example the thermal capacity of a transmission element. The relationship of component reliability and power system is, therefore, a complex nonlinear function related to the above-mentioned factors. Traditional approaches for reliability assessment of power systems do not take the influence of these factors into account. The assessment results could not, therefore, reflect the short-term trend of the system reliability performance considering the influence of the key factors and provide the system dispatchers with enough information to make decent operational decisions. This paper discusses some of these important operational issues from the perspective of power system reliability. The discussions include operational reliability of power systems, reliability influence models for main performance parameters of components, time-varying reliability models of components, and a reliability assessment algorithm for power system operations considering the time-varying characteristic of various parameters. The significance of these discussions and applications of the proposed techniques are illustrated by case study results using the IEEE-RTS.

Keywords: Power system operations, Reliability evaluation, Reliability influence factors of components, Time-varying reliability model

1. Introduction

The fundamental task of power systems is to supply the power to the customers as economically and reliably as possible. The modern power system is developing towards high voltage, long distance and large capacity. Therefore, power system outages due to the unreliable components could result in huge economic losses and societal costs. According to a survey conducted by the President's Council of Economic Advisers and the U.S. Department of Energy's Office of Electricity Delivery and Energy Reliability, the losses caused by power system outages in U.S. is up to $44-82.5 billion every year [1]. Since 2003, the U.S. and Canada 8·14, London 8·28, India 7·30 and other power system outages have confirmed the conclusions above. The reliability of power systems is the basis for the sustainable economic and social development of a country as well as an important aspect of the national security. Therefore, it is necessary and important to examine the measures for improving the reliability of power systems, enhancing the reliability performance of components and reducing the outage losses.

Since the 1930s, when W. J. Lyman, P. E. Benner and S. M. Dean studied the component maintenance and optimal reserve capacity using probability and statistical theory [2-4], the research in power system reliability has advanced in a series of areas such as term definition, index system, evaluation models and algorithms, software and engineering applications [5-11]. These research outcomes have been successfully applied to the processes of design, planning and operation analysis of generation systems, composite generation and transmission systems, distribution systems, power plant and substations. In recent years, fruitful achievements have also been made in the reliability and risk analysis of power system containing renewable energies [9].

Despite the encouraging advancements in the research of power system reliability assessment, its applications in the industry are also facing many challenges, for example in the following areas: 1) it is difficult to reach a common understanding on concepts of failure and system reliability index as well as the system failure criterion; 2) it is difficult to develop an effective model considering the failure modes of components (such as generating units, transformers and circuit breakers) recovery processes, load characteristics, weather conditions, and scheduled maintenance; 3) the reliability evaluation of an actual power system requires a large number of data, such as

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Received: October 24, 2013; Accepted: February 23, 2015

component independent outages, relevant outages, common mode outages and outages under different weather conditions; 4) the reliability evaluation of a power system, especially a composite generation and transmission system, usually involves complex and extensive computations and the evaluation time grows exponentially with the increase of the number of components [11].

Most of the component reliability models proposed in various references may not fully incorporate the following factors:

1) The current status of components, such as component age and component inspection results;
2) The external environmental factors, such as temperature, humidity and wind speed;
3) The influence of adverse weather, such as ice disaster, snowstorm and flood;
4) The impact of system operation status on the component reliability performance.

Based on some of the publicly available research results on power system reliability, this paper discusses the main influencing factors of component reliability performance, proposes a descriptive definition and time-varying reliability model of power system operations, and also proposes a reliability assessment algorithm of power system operations considering time-varying characteristics of key parameters.

2. Definition of the Reliability of Power System Operations

Extending the traditional definition of power system reliability, the operational reliability of power system is defined in this paper as: the ability of a power system to provide the customers with electricity at a reasonable cost and with an acceptable level of continuity and quality considering the component health level, external weather conditions and operating behavior and conditions.

This definition indicates that:

1) The component health level should be taken into account, such as the results of oil chromatographic analysis and component age;
2) Except for the traditional power system variables, such as voltage, current and power, other operation variables, such as ramping of generating units, probability of generating unit start-up, duration of generating unit start-up and load shedding strategy, should be taken into account;
3) The operation behaviors of power system will affect the reliability parameters of components. For example, the failure rates of transformers slightly change with the amount of transmission power [12];
4) The external environment will also affect the operational behaviors of power systems and the reliability parameters of components [13-17]. For example, the temperature, humidity and wind speed will affect the capacity limit of the transmission components, the component reliability performance and the accuracy of load forecasting.

The operational reliability techniques can be used to evaluate and forecast the reliability of power systems incorporating the key influencing factors.

3. Time-Varying Reliability, Electrical and Operation Parameters of Components

3.1 Factors affecting failure rate of components and time-varying failure rate model

The component failure rate is the number of times the component failed to continuously perform its required function per unit exposure time [8]. Failure rate is commonly denoted by λ:

$$\lambda = \frac{\text{Number of failures}}{\text{Exposure time}} \tag{1}$$

Failure rate can be computed for a single component or a class of components based on classification of the components, such as unit line length, the same poles line, or the same corridor line. According to reliability theory, if reliability function of a component meets an exponential distribution, the actual variation of component failure rate usually follows a shape of the bathtub curve, as shown in Fig. 1. Failure rate of a component is normally assumed to be constant during the useful life of the component in traditional power system reliability assessment.

In a practical power system, many factors may affect the failure rates of system components. From the definition of operational reliability of power systems, this paper divides these factors [12-22] into three categories: the health level of component, external environment, and operation conditions of power systems.

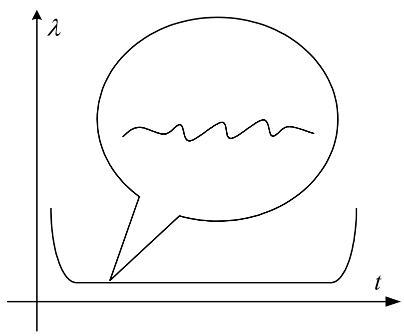

Fig. 1. Bathtub curve of component failure rate

3.1.1 Component failure rate considering health level

The reliability performance of a component, in particular, the failure rate, is closely related to its current health level. Take the transformer as an example. Its failure rate is related to its age, results of oil chromatographic analysis, core conditions, winding conditions, bushing conditions and cooling system status. In order to consider the influence of these factors in a component reliability model, the transformer inspection performance can be scored firstly by a weighted model [18]:

$$S = \frac{\sum_{i=1}^{n} w_i r_i}{\sum_{i=1}^{n} w_i} \tag{2}$$

where S is the score of the component performance; r_i is the score of factor i; w_i is the importance coefficient of factor i, which can be obtained from design and operation experience of the component.

According to the score of the component performance, the failure rate λ considering the health level can be expressed as:

$$\lambda = Ae^{B \times S} + C \tag{3}$$

$$A = \frac{[\lambda(0.5) - \lambda(0)]^2}{\lambda(1) - 2\lambda(0.5) + \lambda(0)} \tag{4}$$

$$B = 2\ln\left(\frac{\lambda(0.5) + A - \lambda(0)}{A}\right) \tag{5}$$

$$C = \lambda(0) - A \tag{6}$$

where A, B and C are intermediate coefficients; $\lambda(0)$, $\lambda(0.5)$, and $\lambda(1)$ are component failure rates in the best, average, and worst states, respectively.

3.1.2 Component failure rate considering external environment

Operation experience of power systems and component failure analysis show that the failure of transmission components is closely related to the corresponding external environment, including weather, vegetation, animal invasion, and human activities. Among them, weather is of the largest influence. The major weather conditions include temperature, wind speed, icing, lightning stroke and humidity [13-17], etc.

There are many theoretical and experience models for quantitatively analyzing the changes of component failure rate with environmental parameters including temperature and wind speed [13-17], etc.

References [13] present a model for transformer failure rate changing with external temperature:

$$\lambda = \frac{1}{E_{NIL}} \exp\left(\frac{B}{\Theta_{Herf} + 273} - \frac{B}{\Theta_H(\Theta_A, I) + 273}\right) \tag{7}$$

where E_{NIL} is the rated component life expectancy; B is a constant; Θ_H is the temperature at the hottest spot of the winding (℃); Θ_{Href} is the reference temperature value at the hot spot (℃); Θ_A is the environment temperature (℃); I is the transformer current.

3.1.3 Component failure rate considering the operation conditions of power systems

As the operation conditions of power systems, such as bus voltage or branch current, change, the failure rate of components will also change. For example, Equation (7) above takes the impact of the current change on the failure rate of transformers into account.

The discussion above shows that the component failure rate λ is a constant when the component is in the same operation condition and external environment. However, the actual component failure rate has an apparent time-varying characteristic. In other words, the failure rate is closely related to its own health level, the external environment conditions and operation conditions of power systems. Therefore, the following equation can be presented:

$$\lambda(t) = \lambda(R_t, W_t, O_t) \tag{8}$$

where $\lambda(t)$ is the component failure rate at time t; R_t, W_t and O_t are the component health level, external environmental conditions, and operation conditions of component at time t, respectively.

3.2 Time-varying repair time model of component

Repair time refers to the actual corrective maintenance time for repairing the components, including fault location time, fault correction time and check-out time, which is the time interval from the outage caused by the component failure to the electricity recovery after repairing or replacing the failed components [5-7]. The reciprocal of repair time is the repair rate, and usually denoted by μ. The repair rate of a component is also assumed constant during the useful life of the component in traditional power system reliability assessment.

Similar to the discussion in Section 3.1, the component repair time obviously differs with bad weather conditions, quality of repair personnel, and other factors. For example, if a component fails due to ice disaster, snowstorms, or floods, the time required by the repair personnel to arrive at the fault site, and in turn, the correction and repair time would be extended. In the worst case, it is even impossible to repair the failed component when a disastrous weather occurs. Here, the repair rate is modeled as:

$$\mu(t) = \mu(R_t, W_t, Z_t, ...) \tag{9}$$

where $\mu(t)$ is the component repair rate at time t; Z_t is a factor related to the quality of repair personnel at time *t*.

It is difficult to build an accurate analytical expression considering various factors because the component repair process is related to the quality of personnel and other human factors. Therefore, the model is usually represented by statistics data. In order to reflect the impact of various factors on the component repair time, the bad weather and the quality of personnel are rated comprehensively based on expertise. The rating method is similar to the one in Equation (2). The scores can be divided into several levels based on the expertise. Assume that within a level, the component repair time does not change.

Using the model described above, combining the weather forecasting results and the quality of the maintenance personnel, the time required to repair the failed component in a future period can be predicted. In turn, the repair rate can be also predicted.

3.3 Time-varying electrical and operational parameters of components

The electrical parameters, such as transmission line impedance and thermal stability limit of transmission line, of power system components will vary with the external environment changes. However, because for transmission lines, the change of impedance with the external temperature is so little comparing with thermal stability limit, these parameters are usually considered as constants in an actual calculation. The thermal stability limit of transmission lines has an important effect on the operational reliability of power systems, which is one of important factors affecting the load curtailments in reliability evaluation. The thermal stability limit of overhead transmission line depends on wind speed and direction, environmental temperature, altitude, location, and quality of conductor itself [23-24]. Reference [23] indicates that wind speed is the key factor affecting the thermal stability limit of transmission lines.

4. Time-Varying Reliability Model of Components

As described in [5-7], the availability of a component at time t is defined as:

$$A(t) = \frac{\mu(t)}{\lambda(t) + \mu(t)} \tag{10}$$

The fundamental difference between the operational reliability model and the traditional model of components is that the operational reliability model is a time-varying model with an availability function, while the traditional reliability model is a constant model with a numerical value of availability.

When a component has more than two states, it is necessary to build a multi-state multi-phase Markov model, whose calculation process is more complex than the traditional reliability model. When taking account of the planned outage and outages caused by partial failure mode, multiple failures, and aging failures, it becomes more complex to build the Markov model and solve the availability function for operational reliability of component.

5. Reliability Assessment Algorithm of Power System Operations Considering Time-Varying Characteristic of Various Parameters

The analysis and state classification of events are the key processes for reliability evaluation of power system operations. These processes include estimate or forecast load of the power systems, determine the own reliability performance of components, acquire or predict the environment conditions, and determine the operation conditions of the power systems, such as transformer tap position, reactive power compensation capacity, and operating states of switching devices. Based on reliability assessment principle of power systems, after the reliability model of each component considering the operating behavior of power systems is built, the system reliability can be evaluated using analytical methods or Monte Carlo methods.

However, it is difficult to obtain the analytical model of the reliability indices, which vary with time. Furthermore, for time-varying operation parameters, such as changes of load, temperature, wind speed, and other reliability parameters, it is more difficult to directly express them as continuous functions of time *t*. Thus, by learning from integral theory, the total period of time *T* can be divided into several short or small intervals. For each small interval, the operational reliability indices can be evaluated by assuming that the parameters of electricity, reliability, and weather are constants. If in a certain period, there are dramatic changes in the weather, we can reduce the length of time interval to improve the calculation accuracy in the actual calculation process.

The operational reliability indices can be evaluated using the following steps:

Step 1 Divide the total period of time *T* into several small intervals;

Step 2 Perform the following steps for each interval:

a) Analyze the inspection results of components and determine the reliability performance of components considering health level;

b) Predict the weather-related parameters and calculate the component reliability parameters related to the weather, such as failure rate and repair time; determine the operational electrical parameters of components related to weather, such as the operating capacity limit of transmission line;

c) Forecast load and determine dispatching strategies for generating units;
d) Calculate power flow and component failure rates considering influence of the transmission power and bus voltage;
e) Build component reliability model and calculate occurrence probability of component in different states;
f) Calculate system reliability indices for given time interval using analytical methods or simulation methods [6-7];

Step 3 Accumulate reliability indices of each minor interval to form the bus and system indices of power system;
Step 4 Analyze the distribution characteristics of reliability indices.

6. Case Studies

The IEEE-RTS [25] is used to test and validate the proposed models and algorithms. The single line diagram of the IEEE-RTS is shown in Fig. 2. This system consists of 32 generating units, 33 transmission lines and 5 transformers with a total rated generating capacity of 3450 MW and a peak load of 2850 MW. The electrical and reliability parameters of the system are shown in Reference [25].

The power system reliability research center at Chongqing University developed a Bulk Power System Reliability Assessment (BPSRA) software product coded by VC++, which has been embedded two common reliability assessment methods, i.e. contingency enumeration approach and Monte Carlo method. It has many calculation functions, including evaluating the reliability of power systems and recognizing the weak parts of power systems, which has been tested by many provincial and regional power grids in China.

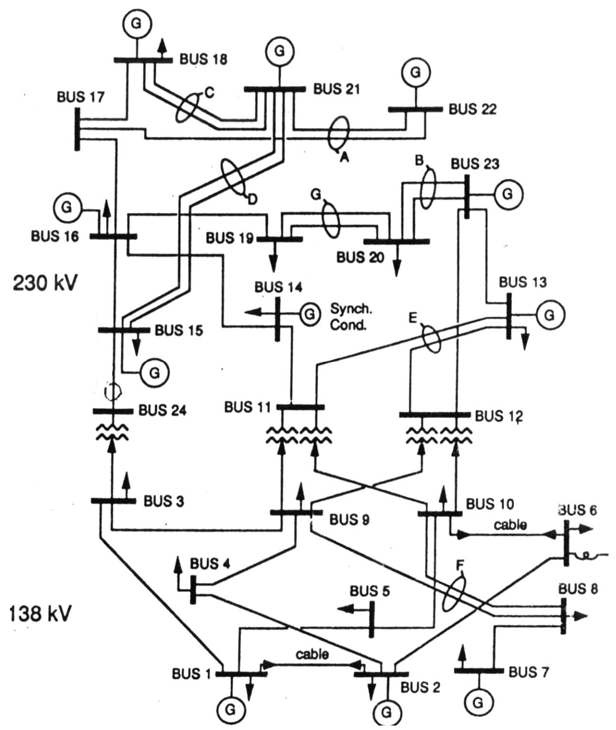

Fig. 2. Single line diagram of the IEEE-RTS

Table 1. Annualized system indices for the IEEE-RTS

	LOLP	LOLF (Occ./Yr)	EENS (MWh/Yr)
BPSRA	0.0839	57.2370	124080
Reference [6]	0.0800	54.7534	122045.88

Table 2. Annualized bus indices for the IEEE-RTS

Bus No.	BPSRA			Reference [6]		
	LOLP	LOLF (Occ./Yr)	EENS (MWh/Yr)	LOLP	LOLF (Occ./Yr)	EENS (MWh/Yr)
1	0.0021	1.5281	368.02	0.0020	1.4618	361.99
2	0.0023	1.6449	352.24	0.0022	1.5735	346.47
3	0.0025	1.9725	723.85	0.0024	1.8870	711.98
4	0.0029	2.1345	353.76	0.0028	2.0419	347.96
5	0.0041	2.7866	382.44	0.0039	2.6657	376.17
6	0.0056	3.9265	1045.01	0.0053	3.7561	1027.88
7	0.0056	3.9265	177.64	0.0053	3.7561	174.73
8	0.0089	6.0774	2105.30	0.0085	5.8137	2070.79
9	0.0120	8.3485	3015.31	0.0114	7.9863	2965.88
10	0.0136	9.6661	4249.85	0.0130	9.2467	4180.18
13	0.0208	14.5450	7568.57	0.0198	13.9139	7444.49
14	0.0314	21.0427	8607.89	0.0299	20.1297	8466.77

In this section, a non-sequential Monte Carlo method (state sampling method) with the sampling size 10000 was used to evaluate the reliability of power system. A DC flow-based optimal load shedding approach [6-7] is used to evaluate the load curtailments in reliability evaluation.

Table 1 and Table 2 show the annualized system indices and bus indices for the IEEE-RTS. It can be seen from Tables 1 and 2 that the calculation results of BPSRA are basically consistent with the Reference [6], which can be used to verify the correctness and validity of the BPSRA.

6.1 Effect of component health level on the system reliability

As mentioned in Section 3, health levels of power equipments affect the reliability of components and the system. Many factors can reflect the health level of the components, and they should be assessed by the comprehensive scoring method (Equation (2)-(6)). In order to simplify the calculation, Fig. 3 - Fig. 5 give the trend of the LOLP, LOLF and EENS indices of IEEE-RTS changing with the score of equipment health level directly. The score of component health level is within [0, 1]. 0 means the best component reliability performance with the minimum failure rate, whereas 1 means the worst component reliability with the maximum rate. And 0.5 means the mean of failure rate [18]. To highlight the comparison of system reliability of two different models, the conventional reliability indices (TLOLP, TLOLF and TEEENS) with constant failure rate, i.e. the mean of failure rate, are also shown in Fig. 3 - Fig. 5.

It can be seen from Fig. 3 - Fig. 5 that LOLP, LOLF and EENS indices increase with the increase of the score of equipment health level. In other words, the system reliability performance decrease with the decrease of component health level. When the health score changes in the interval of 0.5±(0.5×5%), the changes of LOLP, LOLF and EENS indices are more than 10%.

As well known, constant failure rates of components are used in conventional reliability evaluation process, which results in constant system reliability indices. In other words, conventional reliability evaluation assumed that the reliability performance of a component or a system is changeless in one year. However, the health level of the component may vary with time, which has not been considered in conventional reliability evaluation. Therefore, component health level should be taken into account in the reliability assessment of power systems.

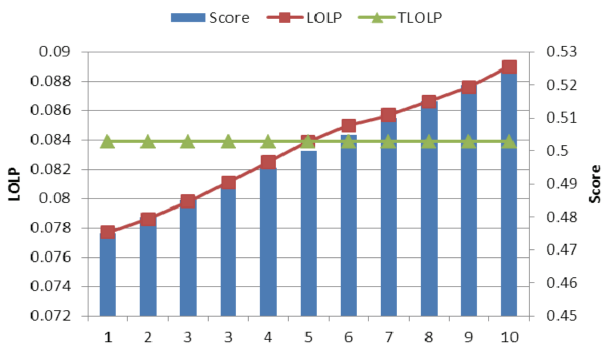

Fig. 3. Effect of component health levels on LOLP

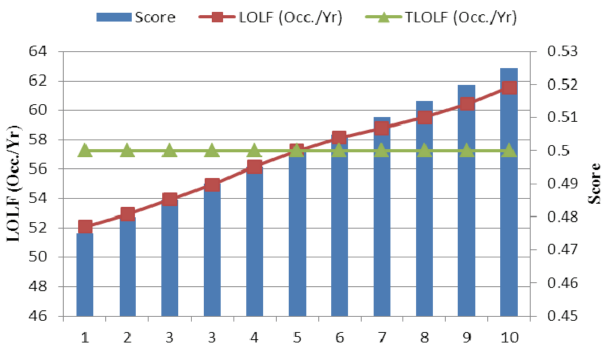

Fig. 4. Effect of component health level on LOLF

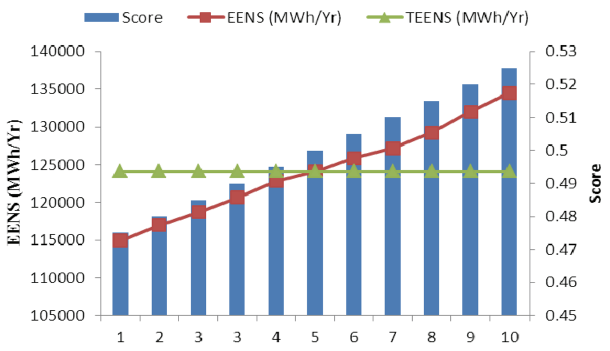

Fig. 5. Effect of component health level on EENS

6.2 Effect of external weather conditions on the system reliability

It was pointed out in Section 3 that the reliability of power components are closely related to its external weather conditions. This section will briefly introduce the effects of external weather conditions on the reliability of the power system, taking temperature as an example. Assuming the standard environmental temperature of all equipment of IEEE-RTS is 25 ℃, Fig. 6 - Fig. 8 give the main system reliability indices changing with the environmental temperature. To highlight the comparison of system reliability of two different models, the conventional reliability evaluation results with constant environment temperature (25℃) are also shown in Fig. 6 - Fig. 8.

It can be seen from Fig. 6 - Fig. 8, LOLP, LOLF and EENS indices increased with the increase of temperature, which means that system reliability reduced with increasing ambient temperature. When the temperature changes in the range of 25 ± 5℃, the changing rates of LOLP, LOLF and EENS indices are more than 15%. Therefore, the effect of environmental temperature variation should also be taken into account in the reliability assessment of power systems.

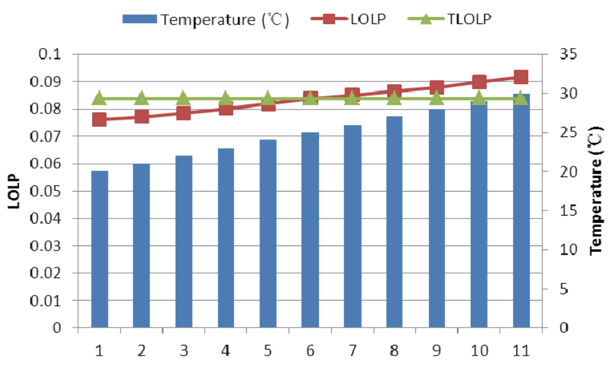

Fig. 6. Impacts of the environment temperature on LOLP

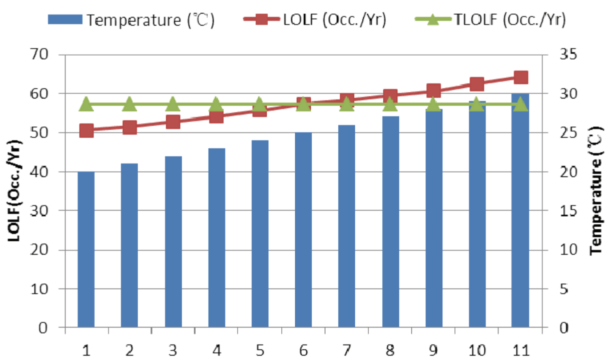

Fig. 7. Impacts of the environment temperature on LOLF

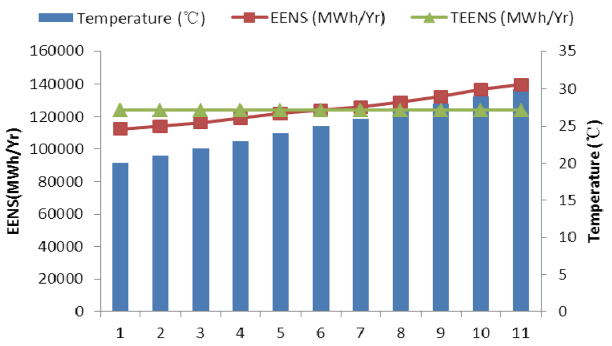

Fig. 8. Impacts of the environment temperature on EENS

6.3 Effect of operating conditions on the system reliability

It was pointed out in Section 3 that electric component failure rate would vary with the change of branch current, power flow, etc. By changing system load, this section can get different system operation conditions to quantify the influence of operation conditions on system reliability.

The trends of LOLP, LOLF and EENS indices of IEEE-RTS changing with the peak load are presented in Fig. 9 - Fig. 11. Taking the influence of operating conditions on equipment failure rate into consideration, Fig. 9 - Fig. 11 also show the variation tendency of system reliability indices under different peak loads.

It can be seen from Fig. 9 - Fig. 11 that when the peak load fluctuated within 2850±(2850×5%) MW, LOLP, LOLF and EENS indices changed significantly, illustrating that system reliability is greatly influenced by the load change. The impact is greater than that of equipment health level and weather conditions. When impacts of the operation condition on component failure rate are considered, reliability indices increase slightly.

In addition, the influence of operating conditions on the system reliability indices varies under different load levels. The influence on LOLF is bigger than that of LOLP and EENS, but the variation is no more than 6%.

It can be concluded from all of the above analysis that the reliability of power system is, indeed, affected by the health level of components, external environment and operation environment of power systems. Generally, above three factors may vary with time, which will cause the change of system reliability. However, constant reliability parameters used in the conventional reliability assessment process cannot reflect the impact of these three factors. The assessment result could not, therefore, reflect the short-term trend of the system reliability performance considering the influence of these three factors or provide the system dispatchers with enough information to make decent operational decisions. Therefore, all of these three factors should be considered in reliability evaluation process.

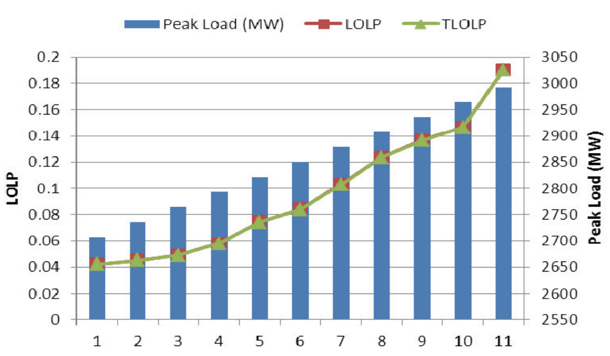

Fig. 9. Impacts of the operation condition on LOLP

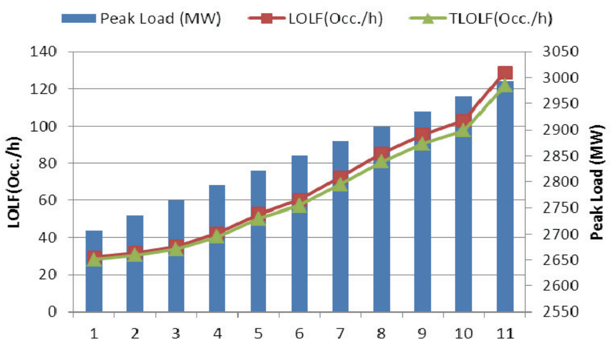

Fig. 10. Impacts of the operation condition on LOLF

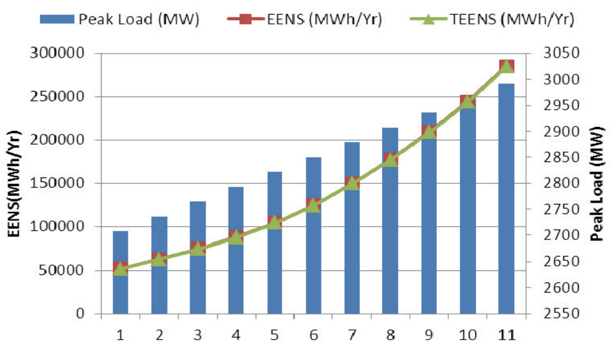

Fig. 11. Impacts of the operation condition on EENS

6.4 Reliability evaluation of power system operations considering time-varying features of components

Assume that the period for the operational reliability evaluation is 13:00 to 24:00 on Tuesday of Week 51. Table 3 shows the load level, environment temperature and equipment health score during these 12 hours. (12 hours is relatively short compared with the whole life cycle of electrical equipment. So the equipment health levels in Table 3 only have small changes over time.)

According to the calculation method in section 3, the equipment failure rates in 12 hours can be obtained. Together with the electrical parameters of IEEE-RTS, network topology and so on, system reliability indices can be calculated using Monte Carlo method. Results are shown in Fig. 12 - Fig. 14. To distinguish the effect of load change, health level, external conditions and operating conditions on system reliability, two kinds of calculation

Table 3. Load levels, temperatures and equipment health scores in 12 hours

Hour	Peak Load (MW)	Temperature (℃)	Score
13:00	2707.5	28	0.502
14:00	2707.5	28	0.502
15:00	2650.5	28	0.502
16:00	2679.0	27	0.503
17:00	2821.5	26	0.503
18:00	2850.0	26	0.503
19:00	2850.0	25	0.504
20:00	2736.0	24	0.504
21:00	2593.5	24	0.505
22:00	2365.6	23	0.505
23:00	2080.5	23	0.505
24:00	1795.5	20	0.505

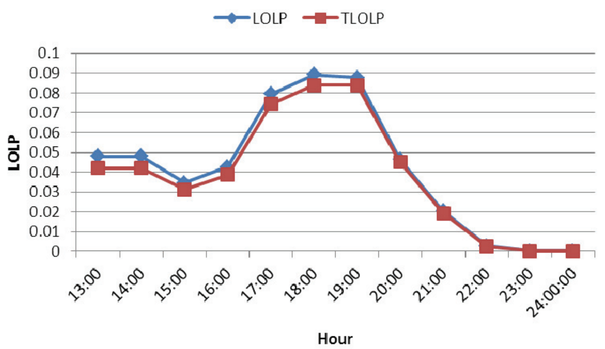

Fig. 12. Comparison of the LOLP between traditional reliability and operational reliability of the IEEE-RTS in 12 hours

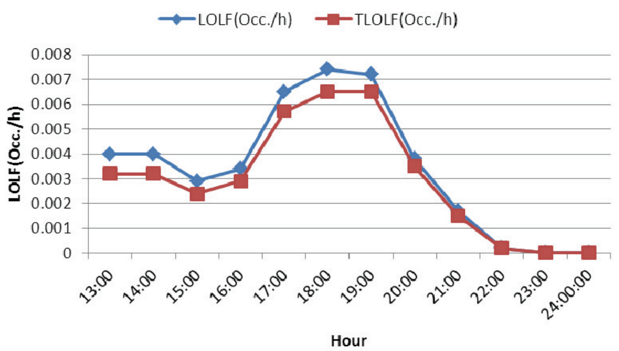

Fig. 13. Comparison of the LOLF between traditional reliability and operational reliability of the IEEE-RTS in 12 hours

results are given in Fig. 12 - Fig. 14: (1) reliability indices in 12 hours as the load changes (Traditional reliability indices, i.e. TLOLP, TLOLF and TEENS); (2) reliability indices in 12 hours as the load, component health level, external environment and operating conditions change simultaneously (Operational reliability indices, i.e., LOLP, LOLF and EENS).

Seen from Fig. 12 - Fig. 14:

1) The health level of components, external environment and operation environment of power systems may change over time, and the reliability of power systems is not a constant value. Based on the method proposed in this paper, we can obtain the short-term trend of system reliability indices.
2) After taking the influence of component health levels, external weather conditions and operating conditions into account, the calculation results of LOLP, LOLF and EENS indices have a small increase.
3) The evaluated mean and variance of LOLP index in these 12 hours are 0.0416 and 0.001, respectively. Based on the 2σ principle in statistics, the system can ensure that the LOLP index is less than 0.1048 at a probability of 95.4% in these 12 hours, providing dispatching personnel with a quantitative decision-making basis to develop prevention measures for system risks, which cannot be obtained by conventional reliability assessment.

7. Conclusions

This paper presents a definition of operational reliability, investigates the factors affecting component reliability performance, the time-varying model of component failure rate and repair time, and the solution algorithm. The IEEE-RTS is used to test and verify correctness of the proposed definition and model as well as feasibility of the method.

The results of case study indicate that the model for the reliability evaluation of power system operations should consider the following influence factors, such as the own reliability performance of components, external environment, and system operation conditions.

It should be noted that the researches on the operational reliability theory are in process of continuous improvement. This paper just provides an initiation for the researchers to facilitate the development of the operational reliability research.

Acknowledgements

This work was supported in part by the National Natural Science Foundation of China (51307185), Natural Science Foundation Project of CQ CSTC (No. cstc2012jjA90004) and the Fundamental Research Funds for the Central Universities (Project No. CDJPY12150002).

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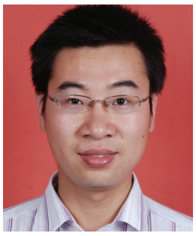

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