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Original article

# Reliability assessment to determine the optimal forced outage rate of components

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A B S T R A C T

Determining the optimal forced outage rate (FOR) of components can lead to reducing the operational and maintenance costs in electric power systems. FOR is closely associated with two factors: number of outages and duration of outages. Therefore, it is possible to decrease the FOR through decreasing the number of outages or reducing the duration of outages. Decreasing number of outages is usually carried out through reinforcement of the network and reducing the duration of outages is mainly performed through increasing the repair and maintenance groups. Both of the proposed methods to decrease the FOR possess the costs. Therefore, it is very suitable to find the optimal rate of FOR and avoiding unnecessary costs. This paper presents a new methodology to find the optimal rate of FOR. in order to determining the optimal FOR of components, the system reliability is assessed and evaluated from view of FOR and the optimal rate of FOR is denoted for all components. EENS index is used to evaluate the system reliability. The simulation results show that the proposed method is an effective and suitable methodology to denote the optimal FOR of components and through this method, the unnecessary investment in the system can be eliminated. In this paper, the FOR of all lines are assessed to denoted the optimal rate of FOR. In additions, the superiority of the lines from view of reliability is denoted and important lines are introduced. A typical test system is considered and LOLE index is calculated for different FORs of all lines. Then, the optimal FOR of lines are determined as well as the impact of lines on the system reliability is investigated.

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**1. Introduction**

Reliability describes the ability of a system or component to function under stated conditions for a specified period of time. Reliability is theoretically defined as the probability of failure, the frequency of failures, or in terms of availability, a probability derived from reliability and maintainability. Maintainability and maintenance may be defined as a part of reliability engineering. Reliability plays a key role in cost-effectiveness of systems. In electric power systems, the reliability is an important issue and plays a major role in cost-effectiveness of the power systems. Reliability has been widely investigated from different views and aspects (Ashok Bakkiyaraj and Kumarappan, 2013, Paliwal et al., 2014).

A linear power flow model based on an approximated version of AC power flow formulation has been reported by (Safdarian et al., 2014). This model is then used to develop an efficient reliability assessment approach, which is capable of taking both active and reactive powers into account. The analysis technique is based on the linear programming format, which leads to an optimal solution within a short computation time. Voltage and reactive power violations as well as transmission system overloads are alleviated by generation rescheduling or load shedding as the last resort. Numerical tests show the acceptable accuracy of the results along with a significant reduction in the computational effort. A methodology to assess the reliability of power system in the presence of wind farms is presented by (Lin et al., 2014). This paper discusses that wind energy is an important substitution of fossil-based energy for future society. However, large-scale integration of wind power will introduce great risks to both power system planning and operation due to its stochastic nature. By adopting power system reliability theory, the risks can be quantitatively estimated. The features of existing reliability models of wind power, reliability assessment algorithms and its applications in wind power related decision making problems has also been reported by (Lin et al., 2014). The paper also reveals significant differences existed in reliability models and algorithms between planning and operational phase of power systems, which are neglected in existing review articles. A reliability evaluation in distribution systems has been reported by (Yssaad et al., 2014). This paper argues that the electricity distribution systems currently operate in a liberalized market. These systems should therefore be able to provide electricity to customers with a high degree of reliability and be cost-effective for suppliers. RCM (Reliability Centered Maintenance) was invented by the aircraft industry in the 1960s, to organize the increasing need for maintenance for reducing costs without reducing b safety. Today RCM-methods are seen as very complex and are not fully accepted by the Algerian power industry. The extensive need of human and capital resources in the introduction phase is also a negative factor that could be one of the reasons of why RCM methods are not used in our branch. a discussion of the two primary objectives of RCM: to ensure safety through preventive maintenance actions, and, when safety is not a concern, preserve functionality in the most economical manner has been reported by (Yssaad et al., 2014). For the power distribution systems facilities, the mission should be considered at the same level as safety. The effects of renewable sources on power system reliability has been reported by (Koh et al., 2013). This paper serves to establish power system reliability of hierarchical level 1 (HL1) using analytical techniques. The IEEE Reliability Test System (IEEE-RTS) generation model and load model are applied to convolute a system risk model. Incorporating photovoltaic (PV) improves system reliability but the variability of PV power output compromises on PV capacity credit. Energy storage (ES) is included into system risk model to enhance system reliability performance. System adequacy indices are investigated to show the system reliability performance. Impact on system generation cost, via variation of PV and ES capacities are presented. Actual Singapore PV irradiance data and Energy Market Company price information are incorporated in this study. This analytical technique can help Independent Service Operators (ISO) to evaluate the potential of PV to benefit system reliability and find ways to improve its potentials. Fostering demand response (DR) through incentive-based and priced-based programs has always great impact on improvement of efficiency and reliability of the power systems (Nikzad and Mozafari, 2014). The use of DR lowers undesirable effects of failures that usually impose financial costs and inconveniences to the customers. Hence, quantifying the impact of demand response programs (DRPs) on reliability improvement of the restructured power systems is an important challenge for the independent system operators and the regional transmission organizations. In this paper, the DR model which treats consistently the main characteristics of the demand curve is developed for modeling. In proposed model, some penalties for customers in case of no responding to load reduction and incentives for customers who respond to reducing their loads are considered. In this paper, in order to make analytical evaluation of the reliability, a mixed integer DC optimal power flow is proposed by which load curtailments and generation re-dispatches for each contingency state are determined. Both transmission and generation failures are considered in contingency enumeration. The proposed technique is modeled in the GAMS software and solved using CPLEX as a powerful mixed integer linear programming (MILP) solver. Both supply-side reliability for generation companies and demand-side reliability for customers are calculated using this technique.

In this paper, the FOR of all lines are assessed to denoted the optimal rate of FOR. In additions, the superiority of the lines from view of reliability is denoted and important lines are introduced. A typical test system is considered and LOLE index is calculated for different FORs of all lines. Then, the optimal FOR of lines are determined as well as the impact of lines on the system reliability is investigated.

## 2. Materials and methods

### 2.1. Forces outage rate

Forces Outage Rate (FOR) is mathematically defined as below:

$$FOR = \frac{\sum_{i=1}^{n} O_i \times T_i}{TP} \quad (1)$$

Where, Oi shows the ith outage, Ti indicates the duration of ith outage, TP shows the total period of time and n shows the number of outages during TP. According to the proposed relationship, FOR is associated with two factors: number of outages (Oi) and duration of outages (Ti). Therefore, reducing the FOR is possible through reducing number of outages or duration of outages.

### 2.2. Reliability assessment

Reliability assessment is mainly carried out in electric power systems through several indexes such as expected energy not supplied (EENS), loss of load expectation (LOLE), and loss of load probability (LOLP). These indexes can be calculated as follows:

$$LOLP = \sum_{i=1}^{np} P_i \quad (2)$$

Where, np shows the number of outages in which the load is curtailed due to insufficient generation sources and Pi shows the probability of each outage in which the load is curtailed.

$$LOLE = \sum_{i=1}^{np} P_i \times T_i \quad (3)$$

Where, Ti shows the duration of each outage in which the load is curtailed.

$$LOLE = \sum_{i=1}^{np} P_i \times T_i \times L_i \quad (4)$$

Where, Li shows the curtail load of each outage in which the load is curtailed.

### 2.3. Illustrative test system

Figure 1 shows a standard six-bus test system. The system data are given by (Rider et al., 2007). The other data are provided in Tables 1 and 2.

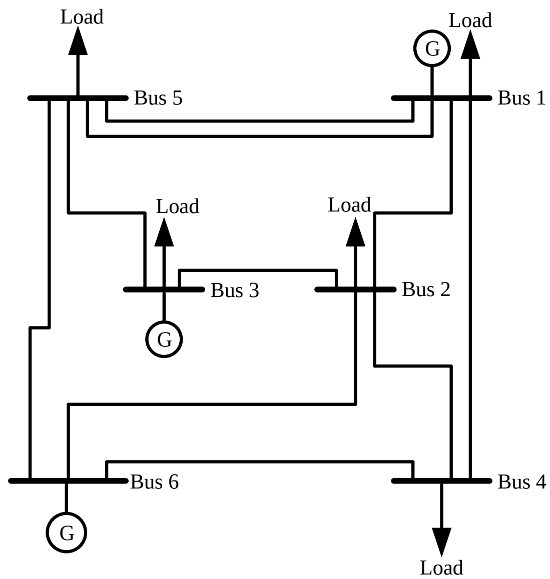


**Fig. 1.** standard six-bus test system.

**Table 1**
The generator data for six-bus test system.

| Bus | Type | PD | QD(MVar) | $P_G^{max}$ | $P_G^{min}$ | $Q_G^{max}$ | $Q_G^{min}$ |
|---|---|---|---|---|---|---|---|
| 1 | VΘ | 80 | 16 | 150 | 0 | 48 | -10 |
| 2 | PQ | 240 | 48 | - | - | - | - |
| 3 | PV | 40 | 8 | 360 | 0 | 101 | -10 |
| 4 | PQ | 160 | 32 | - | - | - | - |
| 5 | PQ | 240 | 48 | - | - | - | - |
| 6 | PV | 0 | 0 | 600 | 0 | 183 | -10 |

**Table 2**
The branch data for six-bus test system.

| Bus From | Bus To | rij[p.u.] | xij[p.u.] | $b_{ij}^{sh}$ [p.u.] | $s_{ij}^{max}$ [MVA] |
|---|---|---|---|---|---|
| 1 | 2 | 0.040 | 0.400 | 0.00 | 120 |
| 1 | 3 | 0.038 | 0.380 | 0.00 | 120 |
| 1 | 4 | 0.060 | 0.600 | 0.00 | 100 |
| 1 | 5 | 0.020 | 0.200 | 0.00 | 120 |
| 1 | 6 | 0.068 | 0.680 | 0.00 | 90 |
| 2 | 3 | 0.020 | 0.200 | 0.00 | 120 |
| 2 | 4 | 0.040 | 0.400 | 0.00 | 120 |
| 2 | 5 | 0.031 | 0.310 | 0.00 | 120 |
| 2 | 6 | 0.030 | 0.300 | 0.00 | 120 |
| 3 | 4 | 0.059 | 0.590 | 0.00 | 120 |
| 3 | 5 | 0.020 | 0.200 | 0.00 | 120 |
| 3 | 6 | 0.048 | 0.480 | 0.00 | 120 |
| 4 | 5 | 0.063 | 0.630 | 0.00 | 95 |
| 4 | 6 | 0.030 | 0.300 | 0.00 | 120 |
| 5 | 6 | 0.061 | 0.610 | 0.00 | 98 |

**3. Results**

In the proposed test system, the FOR of all lines is considered as 0.02 and then the reliability indexes are calculated as follows:

LOLE= 196.4034 (hour/year)

EENS=111020 (MWh/year)

In order to show the effects of FOR, the FOR of all lines are increased by 50% and in this case, the reliability indexes are obtained as follows:

LOLE= 263.1737 (hour/year)

EENS=148760 (MWh/year)

It is seen that FOR has a great effect on the results and by changing the FOR, the reliability of system is significantly changed. It is obvious that with decreasing FOR, the reliability is improved, but decreasing FOR needs to reinforcement of the network through investment. Nevertheless, it may not be necessary to improve the reliability more than a specified level. In such cases, the planner has to make a tradeoff between reliability and cost. In this paper, the optimal point for investment is found through denoting the optimal FOR of components. The EENS and LOLE versus FOR are depicted in Figures 2 and 3. It is seen that by increasing FOR, the reliability is decreased and indexes are increased.

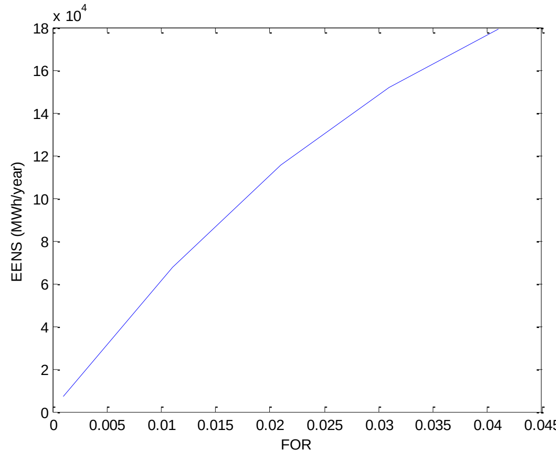


**Fig. 2.** EENS versus FOR.

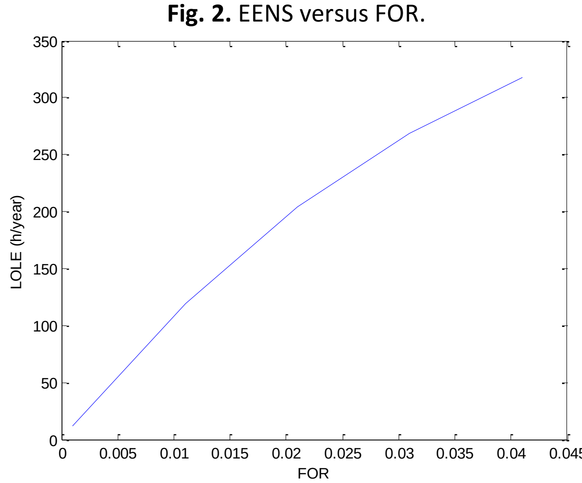


**Fig. 3.** LOLE versus FOR.

In this section, the optimal FOR of lines is determined. The desired level of reliability is assumed as LOLE less than 24 hours per year. In this regard, the FOR is changed from 0.001 to 0.05 and LOLE is calculated for all FORs. The results are depicted in Figure 4. It is seen that by choosing the FOR equal to 0.002, the LOLE will be obtained less than 24 (h/year). The proposed network has 12 lines; these lines are defined as Table 3. The discussed approach is used to evaluate all lines and the superiority of all lines from view of reliability is shown in Table 4.

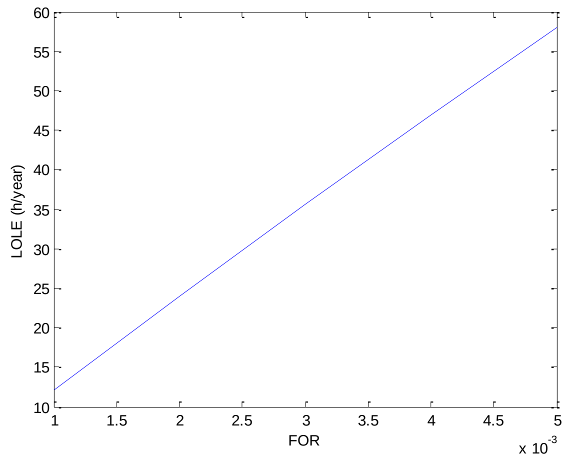


**Fig. 4.** LOLE versus FOR changing from 0.001 to 0.05.

**Table 3**
the network lines.

| To bus | From bus | Line No |
|---|---|---|
| 4 | 1 | 1 |
| 2 | 1 | 2 |
| 1 | 5 | 3 |
| 4 | 2 | 4 |
| 2 | 3 | 5 |
| 6 | 4 | 6 |
| 6 | 5 | 7 |
| 6 | 4 | 8 |
| 3 | 5 | 9 |
| 6 | 2 | 10 |
| 6 | 2 | 11 |
| 1 | 5 | 12 |

**Table 4**
The superiority of the lines from view of reliability.

| **The most important lines** | **Line 9** |
|---|---|
| The medium important lines | Lines 3-5-6-7-8-10-11-12 |
| Not important lines | Lines 1-2-4 |

## 4. Discussion

As stated above, the FOR of components has a great effect on the system reliability and EENS. It is seen that some components have more effects on the system reliability and lead to more EENS and some others have less effects. Therefore, providing a priority list for component outage may be suitable for power system operator and planner. In this paper, the proposed list has been prepared and studied. The simulation results showed that line 9 has the most effect on the reliability and then, lines 3-5-6-7-8-10-11-12 are place at the next priority (Abdul Rahman et al., 2013, Green Ii et al., 2013, Qin et al., 2013).

## 5. Conclusion

This paper addressed a new methodology to denote the optimal FOR of all components in electric power systems. The FOR of all lines were assessed to denoted the optimal FOR. A typical test system was considered and

LOLE index calculated for different FORs of all lines. Then, the optimal FOR of lines were determined and impact of lines on the system reliability was shown.

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