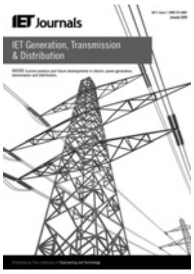
Published in IET Generation, Transmission & Distribution
Received on 1st August 2013
Revised on 9th February 2014
Accepted on 17th February 2014
doi: 10.1049/iet-gtd.2013.0530



ISSN 1751-8687

Reliability-centred maintenance for circuit breakers in transmission networks

Morteza Abbasghorbani[1], *Habib Rajabi Mashhadi*[1,2], *Yaser Damchi*[1]

[1]*Electrical Engineering Department, Ferdowsi University of Mashhad, Mashhad, Iran*
[2]*Center of Excellence on Soft Computing and Intelligent Information Processing, Ferdowsi University of Mashhad, Mashhad, Iran*
E-mail: h_mashhadi@um.ac.ir

Abstract: Reliability of power system can be influenced by the maintenance strategy adopted for the system's equipments. This study focuses on power circuit breakers maintenance planning based on the concept of reliability-centered maintenance (RCM) and applies the proposed approach on the 400 kV transmission network in Khorasan province in Iran. The RCM strategy takes into account the technical condition and importance of each circuit breaker from the network's perspective. The technical condition index of a specific circuit breaker is a numerical representation of the physical health of the breaker and can be evaluated by some criteria. To determine this index, the performance of the circuit breakers during interval 2007–2012 is considered. The importance of each circuit breaker is related to the consequence of its failure on the network. As the main drawback of the available researches in this area is the lack of a generic tool to determine the importance of the circuit breakers, this study proposes a three-stage procedure to accurately evaluate the importance of the circuit breakers. The main idea in the proposed approach is to analyse all failure modes of the circuit breakers and simulate the effect of each failure mode on the overall expected energy not served. The obtained results show the efficiency of the proposed approach.

1 Introduction

Owing 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 markets. To improve such aspects, power systems should be operated with the minimum abnormal conditions and those abnormal conditions, if occur, must be cleared as soon as possible. Therefore high-voltage (HV) circuit breakers, designed to interrupt faulted conditions, have played an important role in the power systems over the past 100 years, since the introduction of the first oil circuit-breakers [1].

The purpose of maintenance activity is to extend equipment's life time and/or reduce the probability of its failure [2, 3]. Maintenance strategies can be broadly classified into the corrective and preventive maintenances [4]. Preventive maintenance, owing to its impact on the reliability and life time of the circuit breakers, can effectively reduce the costs of failure and postpone the investment for replacement of the old circuit breakers. There are at least three basic approaches for the preventive maintenance, namely time-based maintenance, condition-based maintenance and reliability-centred maintenance (RCM).

Currently, the time-based maintenance is the most common approach for the maintenance planning. Although this approach has the favourable advantages such as simple scheduling and high availability, but it is not the most cost-effective strategy [5]. To enhance the cost effectiveness of the preventive maintenance, the condition-based maintenance approach utilises information about the equipment's actual condition when deciding on whether, when and the extent to which the maintenance should be carried out. In this selective way, the cost saving can be achieved without allowing increase in the risk of the unplanned outages [6]. Although condition-based maintenance is driven by the actual condition of the equipment, but it does not take into account how the system is impacted by the failure of an equipment. As the third preventive maintenance approach, the RCM not only considers the technical condition of the equipments, but also it takes the importance of the equipment to the whole system into account. Hence, the RCM is expected to be more cost effective than the traditional maintenance approaches [5].

It is a very challenging task for power system engineers to determine the optimal maintenance policy while keeping the maintenance costs at an acceptable level. This is among the most discussed issues in the asset management area, since the maintenance costs are considered as a large portion of the operation costs.

There are at least two viewpoints regarding the RCM in the literatures. In the first viewpoint, a trade-off is made between the maintenance cost imposed by and the gains achieved from the reliability improvement. Regarding this viewpoint, following two questions must be properly answered: (i) how can maintenance affect the components reliability? (ii) How can the effect of the components failure on the system reliability indices be quantified?

To address the first question, mathematical models are needed to quantify the impacts of the maintenance on the reliability [2, 7]. Probabilistic models have been widely used in this area. For instance, a model based on the historical data was proposed in [8] to represent the deterioration process and evaluate the maintenance strategies of a transformer. In [3], a Markovian state diagram was proposed for the circuit breakers which can quantitatively relate the inspection frequencies to the reliability and costs of the maintenance and failure. A modified state diagram, based on the one proposed in [3] has been presented in [9]. It is also assumed in [10] that increase in the preventive maintenance lowers the failure rate by half, whereas decrease in the preventive maintenance doubles the failure rate.

In the reviewed approaches, there are high uncertainties in the assumptions and procedures used for modelling the effect of the maintenance on the reliability of the equipments. This drawback makes the results to be unreliable. Recently, a procedure is proposed in [11, 12] to model the impact of the maintenance on the reliability of the circuit breakers more precisely. Based on this procedure, the reliability of a circuit breaker is related to its maintenance policy. Therefore, in order to investigate the effect of the alternative maintenance strategies on the reliability, the effect of the actual maintenance policy has to be clearly identified at first. In [11, 12], it is assumed that each failure of a circuit breaker is a result of a minor failure which has evolved into a major failure over time. Hence, a probabilistic model is proposed to simulate this process. However, this method needs large amount of data and is not useful when limited information is available.

Based on the second viewpoint in RCM, maintenance cannot be cost-effective unless the equipment is serviced according to its needs. In this way, unnecessary wasting of the maintenance resources, including both material and human resources, can be avoided [6]. On the basis of this idea, the components are prioritised based on their needs to preventive maintenance. In this method, the condition of the equipments as well as their importance to the system is considered to rank the components for the maintenance. Hence, for the components with the same technical condition, the maintenance tasks are conducted to those with higher importance to the network. For instance, this approach has been applied in [5, 13–15] in order to prioritise the circuit breakers based on their needs for the preventive maintenance. In these works, it is not required to model the impact of the maintenance on the reliability of the components. However, the main disadvantage of these researches is very simplifying assumption used to determine the importance index of each circuit breaker. For example, in [5] only one of the circuit breaker failure modes (stuck breaker) is considered, whereas to determine the importance of each circuit breaker the effect of all circuit breaker failure modes must be simulated in the network. In [13–15], it is been assumed that failure of a circuit breaker leads to the loss of power flowing through the breaker. However, because of the meshed configuration of the transmission networks, such an assumption is not justified. Moreover, calculation of the non-delivered energy must be performed by the reliability calculation.

To overcome the above-mentioned shortcomings, this paper focuses on developing a generic decision tool for the maintenance of the circuit breakers which takes into account the technical condition of circuit breakers as well as their importance in the network. Moreover, a three-stage approach is developed in this paper to determine the importance of each circuit breaker in the network. In the proposed approach, all failure modes of the circuit breakers are analysed and then the events occurred because of each failure mode is simulated.

This paper is organised as follows. Section 2 provides a detailed description of the procedure used to determine the condition index of the circuit breakers. In Section 3, the proposed method for calculation of the importance index of each circuit breaker in a transmission network is described. The procedure for accessing the circuit breakers priority for performing preventive maintenance is presented in Section 4. Section 5 presents the numerical results obtained from simulations on a real transmission network. Finally, a conclusion is drawn in Section 6.

2 Quantification of condition index

Knowledge of the circuit breakers condition is essential for making decisions on maintenance. Condition index of a circuit breaker is a numerical representation of the technical condition of the breaker. To determine this index, the main question is which source of information should be considered and how this information should be processed to extract useful knowledge out of it. Many equipment/network-specific data can be collected for evaluating the condition index. However, in practice they must be restricted to the major influencing variables. The evaluation of the condition index is based on a set of criteria which aim at providing insight into the actual condition of the breaker. These criteria can be generally termed as condition indicators (CIs).

In this paper, service age, manufacturer, type of circuit breaker including drive mechanism and extinguishing medium, history of circuit breaker performance including failure and success in performing its function are considered as the CIs [16]. Since the studied network is expanded on a large area, the substations are exposed to different meteorological condition. Hence, in this paper the meteorological conditions such as level of pollution (e.g. dust) and the coldness level are also considered as the CIs. The substations are categorised into several groups based on these CIs. Table 1 presents the CIs and their associated scores and weighting factors. In this table, each CI has been weighted to reflect its influence on the overall condition index.

Historical performance is the most important CI in Table 1. It is evident that the number of circuit breaker operations including success or failure is an extremely influential factor for calculation of the condition index. To consider this factor, all operations of each circuit breaker during interval 2007–2012 have been recorded in a database which was the most time consuming part of this research work. By help of this database, the number of operations (failure or success) of each circuit breaker per year can be found. The higher the number of failures, the higher need the circuit breaker has to the preventive maintenance. On the other hand, low number of success operations of a circuit breaker can confirm its proper functioning. Hence, with the assurance of the proper functioning of the breaker, the preventive maintenance can be postponed. However, the high number of success operations of a circuit breaker leads

Table 1 CIs scores and weighting factors for computation of condition index

CIs	Descriptions	Scores	Weights
historical performance	see Table 2		6
service age	≤20	1	5
	21–25	2	
	26–30	3	
	31–35	4	
	36–40	5	
	≥41	6	
mechanism drive	spring operated	1	4
	hydraulic	3	
	pneumatic	6	
extinguishing medium	vacuum	1	4
	SF6	2	
	minimum oil	6	
manufacturer know how	good	1	3
	⋮	⋮	
	poor	6	
pollution	low	1	3
	medium	2	
	high	4	
	extra high	6	
coldness	low	1	3
	medium	3	
	high	6	

to more stress on it. Hence, high success operations can increase the need for preventive maintenance. According to this idea, the scores of historical performance are presented in Table 2.

Based on the collected data about the circuit breaker operations, the success and failure operations of circuit breakers are divided into four and three groups, respectively, as presented in Table 2. For instance, the score of historical performance of the circuit breakers with high number of success and no failure is 3.

It should be noted that to make the scores of all CIs commensurable, all scores in Table 2 have been multiplied by 0.6. Moreover, if the number of operations (failure and success) of a circuit breaker is zero then the historical performance is neglected in calculation of the condition index of that breaker.

Based on Table 1, the condition index of the circuit breaker j can be calculated by (1)

$$C_j = \frac{\sum_{i=1}^{7} S_{i,j} W_i}{SW_j} \tag{1}$$

where $S_{i,j}$ and W_i are score and weighting factors of CI i for circuit breaker j, respectively. SW_j is also the summation of weighting factors for circuit breaker j. Therefore, for those circuit breakers that have no operations, SW_j equals 22 and for the others, equals 28.

Table 2 Scores relating to historical performance of circuit breakers

Types of operations		Successes			
	Number of operations	Zero	Low	Medium	High
failures	zero	—	1	2	3
	low	3	4	5	6
	high	7	8	9	10

Obviously, calculation of the condition index by means of an assessment matrix as in Table 1 extremely depends on the choice of the weighting factors. In fact, the weighting factors define how each CI can affect the condition index.

To assign the weighting factors to the CIs properly, the recommendations given in [5, 6, 17] and the opinions of the maintenance experts are taken into account.

3 Quantification of importance index

The importance of each circuit breaker is related to how its failure can affect the reliability indices of the network. The following two factors have the main impact on the importance of each circuit break: (i) circuit breaker position in the network structure and (ii) the substation layout which circuit breaker is installed on. In this paper, the importance index of each circuit breaker is obtained based on the following three stages.

3.1 *Circuit breakers failure modes analysis*

To determine the importance of each circuit breaker, its failure modes must be simulated. There are three modes of failure for a circuit breaker, including stuck breaker, active failure and passive failure [18]. Active and passive failure rates are usually defined as the percentage of total circuit breaker failure rate [19]. In this paper, the ratio of the circuit breaker active and passive failure rates to the circuit breaker total failure rate is derived from the data presented in the CIGRE report [20, 21]. Active and passive failure rates are calculated by

$$\begin{aligned} \lambda_a &= 0.9 \times \lambda_{cb} \\ \lambda_p &= 0.1 \times \lambda_{cb} \end{aligned} \tag{2}$$

where λ_a, λ_p and λ_{cb} are active, passive and total circuit breaker failure rates, respectively.

Regarding to circuit breaker position in the network, first it must be determined each failure mode of any circuit breaker leads to which outage event. For a better illustration, Fig. 1 shows a typical substation with one-and-a-half breaker scheme. The result of failure mode analysis for circuit breaker 2 is presented in Table 3. It is seen from Table 3 that active failure of the circuit breaker 2 results in the operation of circuit breakers 1 and 3. Accordingly, lines 1 and 2 are removed from the operation. Under this circumstance, in order to repair the circuit breaker 2, during

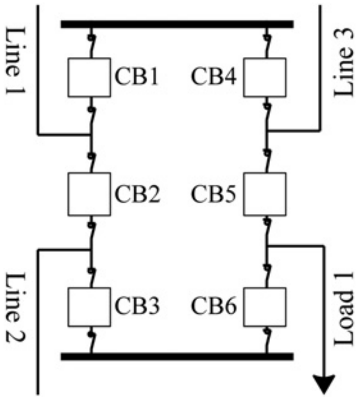


Fig. 1 *Typical substation with one-and-a-half breaker configuration*

Table 3 Circuit breaker 2 failure mode analysis

Circuit breaker indexes	Modes of failures	Probabilities	Out of service components
2	active	$\lambda_a . t_{sw}/8760$	line 1 and line 2
	passive	$\lambda_p . t_{cb}/8760$	—
	stuck	$(\lambda_{L1} + \lambda_{L2}) . P_{stuck} . t_{sw}/8760$	line 1 and line 2

switching time t_{sw} the failed circuit breaker is brought out of service by opening the two sectionalisers around it. Then, lines 1 and 2 can be brought back into the operation by closing the circuit breakers 1 and 3. As can be seen in Fig. 1, passive failure of the circuit breaker 2 does not have any impact on the network. Non-functioning (stuck) of the circuit breaker 2 while line 1 or 2 is failed results in the simultaneous outage of lines 1 and 2 for a switching time t_{sw}. During this switching time, circuit breaker 2 is removed from the service and the healthy line will be brought back into the operation. The occurrence probability of each described events are also presented in Table 3.

Owing to very low probability of occurrence, simultaneous failure of more than one circuit breaker is neglected in this paper.

In Table 3, P_{stuck}, λ_{L1} and λ_{L2} are stuck probability and failure rates of lines 1 and 2, respectively. In addition, t_{cb} is repair time of circuit breaker 2.

3.2 Contingency states simulation

Importance index of each circuit breaker depends on the risk imposed on the network because of the failure of the circuit breaker. In this paper, the imposed risk on the network is defined as the amount of the expected energy not served (ENS). Therefore, in the second stage, the outage events resulting from the failure modes of each circuit breaker must be simulated. Furthermore, since the transmission networks are usually reliable to the first-order contingencies and major portion of the expected ENS (EENS) belongs to the higher-order contingencies, the outage events up to the third-order contingencies are considered in this paper. In other words, the concurrence possibility of a circuit breaker failure and failure of one or two lines, generating units or transformers is taken into account.

For each of the outage events, the following linear programming optimal power flow is solved to reschedule the generating units, eliminate line overloading and avoid load shedding, if possible, or maximise the total load which can be met on each load bus

$$\begin{aligned}
&\max \sum_{i=1}^{NL} AP_i \\
&\text{s.t.} \\
&\boldsymbol{T} = \boldsymbol{A} \times (\boldsymbol{PG} - \boldsymbol{AP}) \qquad (3) \\
&\boldsymbol{PG}^{\mathbf{min}} \le \boldsymbol{PG} \le \boldsymbol{PG}^{\mathbf{max}} \\
&AP_i \le L_i \\
&|\boldsymbol{T}| \le \boldsymbol{T}^{\mathbf{max}}
\end{aligned}$$

where

$\boldsymbol{T}$: line flow vector.
$\boldsymbol{T}^{\mathbf{max}}$: rating vector for lines.
$\boldsymbol{A}$: matrix relating the line flows to the power injections at buses.
$\boldsymbol{PG}$: generation output.
$\boldsymbol{PG}^{\mathbf{max}}$: upper limit for generation output.
$\boldsymbol{PG}^{\mathbf{min}}$: lower limit for generation output.
AP_i: available power at load bus i.
L_i: peak load at bus i.
NL: number of load buses.

The ENS because of the outage event k, can be obtained by

$$\text{ENS}_k = 8760 \times \sum_{i=1}^{NL} L_i - AP_i \qquad (4)$$

3.3 Importance index formulation

The importance of a circuit breaker is defined as how much its failure can affect the EENS of the network. Based on this definition, the importance index of the circuit breaker j can be obtained using

$$I_j = \sum_{i \in \Omega_j} \text{ENS}_i \times \text{Prob}_i \qquad (5)$$

where Ω_j indicates a set of outage events, including one of the failure modes of the circuit breaker j. For non-functioning (stuck) of circuit breaker j and first contingency states such as active and passive failures, Prob_i in (5) is the same as those probabilities presented in Table 3.

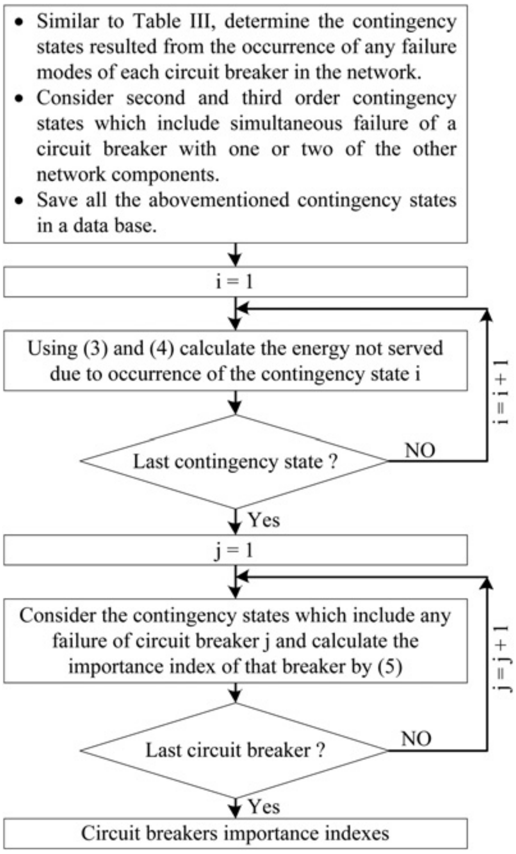


Fig. 2 *Flowchart of the procedure to determine the importance indexes*

As stated earlier, second- and third-order contingencies contain a circuit breaker failure and one or two failures of the other lines, generating units or transformers. For such outage events, the resulted ENS is shared among the failed components based on their failure probabilities. In other words, in second- or third-order contingencies the failed components with higher outage probabilities contribute to the larger portion of the resulted ENS [22].

As an example, for a second-order contingency when active failure of circuit breaker j is overlapped by a failure in line k, the Prob_i is calculated as follows

$$\text{Prob}_i = \frac{(\lambda_\text{a}.t_\text{sw})}{8760} \times \frac{(\lambda_k.t_k)}{8760} \times \frac{(\lambda_\text{a}.t_\text{sw})}{(\lambda_\text{a}.t_\text{sw}) + (\lambda_k.t_k)} \qquad (6)$$

where λ_k and t_k are failure rate and repair time of line k, respectively, and λ_a denotes the active failure rate of the circuit breaker j.

The flowchart of the procedure to determine the importance index of each circuit breaker is presented in Fig. 2.

4 Priority assessment of circuit breaker for maintenance planning

Once the importance and condition indices are obtained, each circuit breaker can be placed on a two-dimensional diagram as shown in Fig. 3. After evaluating the mean and standard deviation of the condition and importance indices, Fig. 3 can be divided into nine segments. For instance, the circuit breakers placed on segment 3 of Fig. 3 have the highest need for the preventive maintenance as these breakers are the most important circuit breakers in the network. Moreover, they have the worst condition index compared with the others.

In Fig. 3, μ_i, μ_c, σ_i and σ_c represent the mean and standard deviation values of the importance and condition indices. Clearly, all nine segments of Fig. 3 can be categorised into three areas. The first area, including segments 4, 7 and 8, contains the circuit breakers which have the lowest need for the preventive maintenance. Segments 1, 5 and 9 constitute the second area and contain the circuit breakers with the medium need for the preventive maintenance. Finally, the third area includes segments 2, 3 and 6 involving circuit breakers with the highest need for the preventive maintenance.

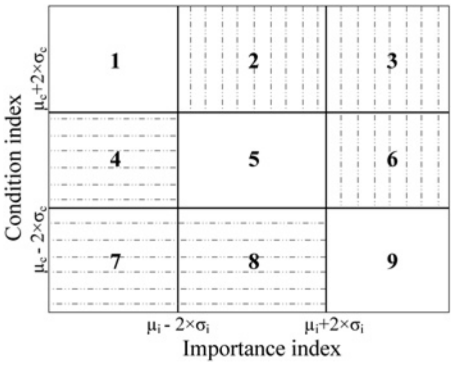


Fig. 3 *Decision making map for maintenance planning*

5 Case study

To provide more insight into the proposed procedure and method presented, the electric network of Khorasan province in Iran is considered. This network constitutes a large portion of Iranian power grid and consists of 63, 132 and 400 kV voltage levels. In this paper, the HV level of this network is considered. The single diagram of this network is shown in Fig. 4. As can be seen in Fig. 4, this network includes 28 buses, 25 generating units, 22 transmission lines, 22 transformers and 103 circuit breakers. The system peak load is 2867 MW and the total capacity of the generating units amounts to 3588 MW. The Khorasan network is connected to the rest of Iranian 400 kV transmission grid through four substations, including 25-Aliabad, 26-Shahvar, 27-Sefidabeh and 28-Golshan. The 24-Foulad is a private substation. Hence, the circuit breakers mounted in these substations are not considered in this paper.

Currently, time-based maintenance is the common strategy for maintenance planning in the Khorasan network. Based on this strategy, without any concern about the needs and requirements of the network components, the preventive maintenance is annually performed on all of the components. To revise this costly approach, the Khorasan utility tries to assess the priority of each component to perform the preventive maintenance. In the following, the priority assessment of the 400 kV circuit breakers has been considered.

5.1 *Technical condition assessment*

The condition index is an estimate of the circuit breakers' need for the preventive maintenance and as described in Section 2, it can be obtained by any useful information provided by the nameplates, circuit breakers historical performance and the meteorological condition of their location in the network. As stated in Section 2, the history of the circuit breaker performance in presence of contingency states occurred in its protection zone plays a key role in calculation of the breaker's condition index. To consider this factor, based on the circuit breakers operations over six recent years, a database is formed. Using this database, the number of circuit breaker operations (success or failure) per year can be obtained. Table 4 presents a grouping of the circuit breakers based on their operations per year.

For instance, as presented in Table 4, there are two circuit breakers with high number of failure and success in the network. As mentioned in Section 2, these circuit breakers are in more need of maintenance. Moreover, there are 21 circuit breakers without any operations over the past six years.

Based on the criteria presented in Table 1, the condition index of each circuit breaker can be determined. Fig. 5 shows the circuit breakers condition indices, evaluated by (1). As illustrated in Fig. 5, circuit breaker 79 has the highest condition index in the network. Hence, in terms of condition index and comparing with the other breakers, this circuit breaker has higher need for the preventive maintenance. The information related to each CI for circuit breaker 79 is presented in Table 5. It is seen that the high value of the condition index for this circuit breaker stems from various factors, including high level of pollution, hydraulic drive, low level of the manufacturer's proficiency and high failure per year.

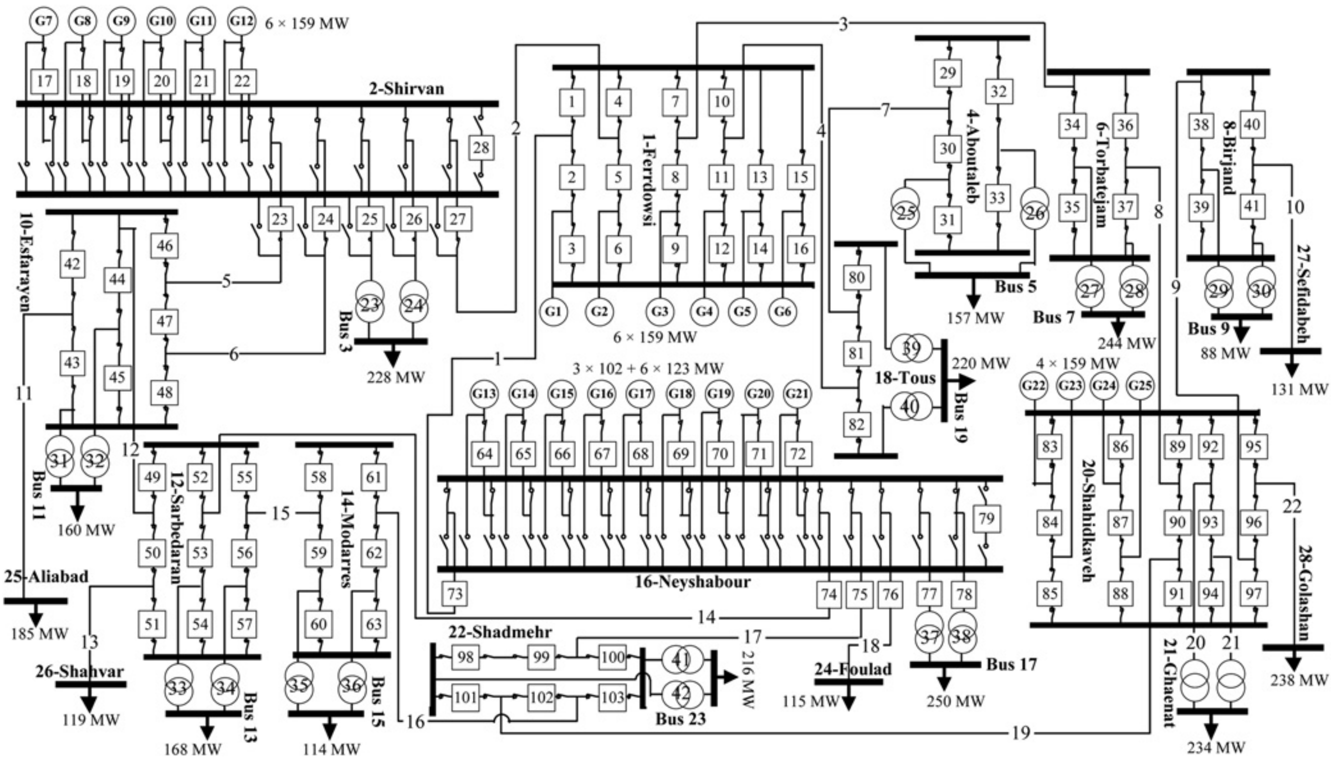


Fig. 4 *Single line diagram of the Khorasan 400 kV network*

5.2 Quantification of circuit breakers importance index

Table 6 presents the reliability data for transmission lines, generating units and transformers of the Khorasan network. To extract these data, the contingency events during interval 2007–2012 in the network were investigated. Owing to the lack of enough failure statistics for circuit breakers, the reliability data reported in [23] was utilised. The failure rate and repair time for the circuit breakers are 0.124 fail per year and 96.4 h respectively. Moreover, the stuck probability is assumed to be 0.01. Considering such a same reliability data for all the circuit breakers makes the importance index would be affected only by each circuit breaker position in the network.

Fig. 6 illustrates the importance index of each circuit breaker, obtained by the procedure described in Section 3.

As shown in Fig. 6, circuit breaker 76 is the most important circuit breaker in the network. To further investigate the reasons for high importance of circuit breaker 76, the failure modes of this breaker should be examined.

It is seen from Fig. 4 that because of the non-reliable scheme of substation 16-Neyshabour and radial configuration of substation 24-Foulad, passive failure of circuit breaker 76 leads to the disconnection of 115 MW for its repair time. Although, passive failure of circuit breaker 72, for example, results in disconnection of the generating unit 21 for a switching time, only. After the switching time, generating unit 21 can be brought back into the service by closing its bypass sectionaliser and circuit breaker 79.

Table 4 Number of circuit breaker placed in each groups based on the number of operations per year

Types of operations	Number of operations	Successes			
		Zero	Low	Medium	High
failure	zero	21	28	43	5
	low	0	0	0	0
	high	1	0	3	2

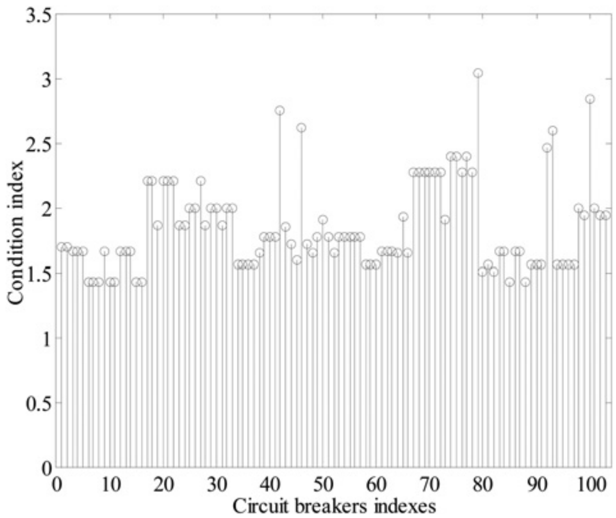


Fig. 5 *Condition index for the circuit breakers in the Khorasan network*

Table 5 Information related to the circuit breaker 79

CIs	Descriptions
service age	16
manufacturer know how	poor
mechanism drive	hydraulic
extinguishing medium	SF6
historical performance	zero success and high failure
pollution	high
coldness	medium

Table 6 Components reliability data

Components	Failure rates	Repair time, h
transmission line	0.0004923 f/yr km	21.65
generating unit	0.026 f/yr	46
power transformer	0.0875 f/yr	41.15

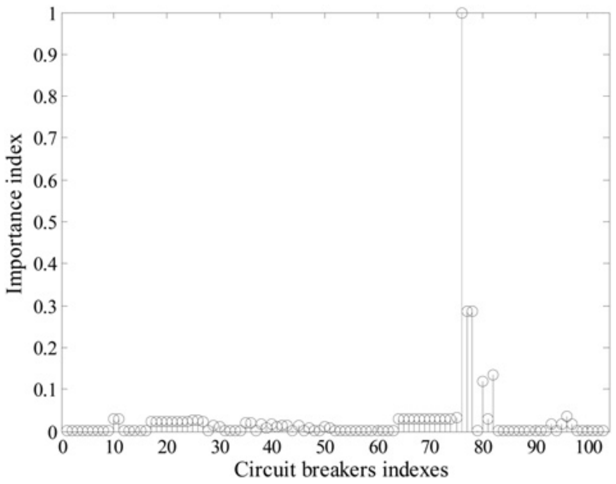


Fig. 6 *Importance index for each circuit breaker in the Khorasan network*

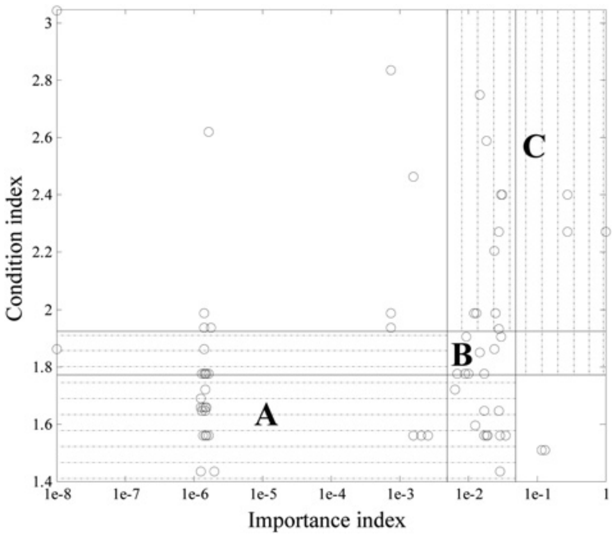


Fig. 7 *Priority of circuit breakers for maintenance planning*

Table 7 Number of circuit breaker in each area of Fig. 7

Areas	Number of circuit breakers
A	56
B	23
C	24

Moreover, in the case of active failure or non-functioning (stuck) of the circuit breaker 76, initially all the components connected to substation 16-Neyshabour will be disconnected for a switching time. During the switching time, circuit breaker 76 is isolated. In this situation, similar to the passive failure, 115 MW load of substation 24-Foulad will be lost for repair time of the circuit breaker 76.

5.3 *Priority assessment of circuit breakers in maintenance planning*

By use of the knowledge about the condition and importance of each circuit breaker, the position of all breakers is shown in Fig. 7. The mean values of condition and importance indices are 1.8490 and 0.0274, respectively, whereas the standard deviations of these two indices are 0.0386 and 0.0112. Fig. 7 is divided into three areas as described in Section 6. The circuit breakers placed in areas A, B and C have low, medium and high need for the preventive maintenance, respectively.

Table 7 presents the number of circuit breakers which are placed in each area.

6 Conclusion

This paper proposed a method for circuit breakers maintenance planning based on the concept of RCM. The RCM strategy takes into account the condition as well as importance of each circuit breaker in the network. The main feature of this paper was to propose a three-stage method for deciding on the importance of each circuit breaker. The efficacy of the proposed approach was successfully evaluated on a real transmission network. To evaluate the condition index of each breaker, the information provided by the breaker's nameplate, its performance during interval 2007–2012 and the meteorological condition was considered. Based on the knowledge about the condition and importance of each circuit breaker in network, the priority of circuit breakers for performing preventive maintenance was determined.

7 References

1 Choonhapran, P.: 'Application of high voltage circuit breakers and development of aging model'. PhD thesis, University of Darmstadt, Department of Electrical and Computer Engineering, Darmstadt, Germany, 2007

2 Endrenyi, J., Aboresheid, S., Allan, R.N., *et al.*: 'The present status of maintenance strategies and the impact of maintenance on reliability', *IEEE Trans. Power Syst.*, 2001, **16**, (4), pp. 638–646

3 Endrenyi, J., Anders, G.J., Leite da Silva, A.M.: 'Probabilistic evaluation of the effect of maintenance on reliability – an application', *IEEE Trans. Power Syst.*, 1998, **13**, (2), pp. 576–583

4 Billinton, R., Allan, R.N.: 'Reliability evaluation of engineering systems' (Plenum Press, 1992)

5 Chan, T., Chen-Ching, L., Jong-Woong, C.: 'Implementation of reliability-centered maintenance for circuit breakers'. Proc. IEEE Power Engineering Society General Meeting, San Francisco, CA, June 2005, pp. 684–690

6 Krontiris, T.: 'Fuzzy systems for condition assessment of equipment in electric power systems'. PhD thesis, University of Darmstadt, Department of Electrical and Computer Engineering, Darmstadt, Germany, 2012

7 Lindquist, T.M., Bertling, L., Eriksson, R.: 'Circuit breaker failure data and reliability', *IET, Gener. Transm. Distrib.*, 2008, **2**, (6), pp. 813–820

8 Jirutitijaroen, P., Singh, C.: 'The effect of transformer maintenance parameters on reliability and cost: a probabilistic model', *Electr. Power Syst. Res.*, 2004, **72**, pp. 213–224

9 Abeyguanawardane, S.K., Jirutitijaroen, P.: 'New state diagrams for probabilistic maintenance models', *IEEE Trans. Power Syst.*, 2011, **26**, (4), pp. 2207–2213

10 Hilber, P., Miranda, V., Matos, M.A., Bertling, L.: 'Multiobjective optimization applied to maintenance policy for electrical networks', *IEEE Trans. Power Syst.*, 2007, **22**, (4), pp. 1675–1682

11 Neumann, C., Rusek, B., Schorn, C., *et al.*: 'Modelling the effect of maintenance on failure occurrence and lifetime management of high-voltage circuit breakers' (CIGRE Session, Paris, 2010), pp. 1–8

12 Krontiris, T., Balzer, G.: ‘Assessing the effect of maintenance on high-voltage circuit breaker reliability’. Proc. IEEE Int. Conf. Probabilistic Methods Applied to Power Systems, Singapore, June 2010, pp. 761–766

13 Schlabbach, J., Berka, T.: ‘Reliability-centered maintenance of MV circuit-breakers’. Proc. IEEE Ninth Int. Power Technology Conf., Porto, September 2001, pp. 1–5

14 Balzer, G., Bakic, K., Haubrich, H.J., Neumann, C., Schorn, C.: ‘Selection of an optimal maintenance and replacement strategy of H. V. equipment by a risk assessment process’ (CIGRE Session, Paris, 2006), pp. 1–9

15 Orlowska, T., Balzer, G., Halfmann, M., Neumann, C., Strand, A.: ‘Life cycle management of circuit-breakers by application of reliability centered maintenance’ (CIGRE Session, Paris, 2000), pp. 1–8

16 Anders, G.J., Maciejewski, H., Jesus, B., Remtulla, F.: ‘A comprehensive study of outage rates of air blast breakers’, *IEEE Trans. Power Syst.*, 2006, **21**, (1), pp. 202–210

17 Janssen, A.L.J., Degen, W., Heising, C.R., *et al.*: ‘Life management of circuit-breakers’, *CIGRE Tech. Brochure*, 2000, **165**, (1), pp. 1–140

18 Billinton, R., Allan, R.N.: ‘Reliability evaluation of power systems’ (Plenum Press, 1984)

19 Dong, J., Koval, D.O., Zuo, M.J.: ‘Impact of circuit breaker failure modes on the reliability of the gold book standard network’, *IEEE Trans. Ind. Appl.*, 2010, **41**, (5), pp. 1323–1328

20 Janssen, A.L.J., Degen, W., Heising, C.R., *et al.*: ‘Final report of the second international enquiry on high voltage circuit breaker failures and defects in service’, *CIGRE Tech. Brochure*, 1994, **83**, (1), pp. 1–176

21 Yang, H.: ‘Incorporating station related maintenance and aging outages in in composite system reliability evaluation’. MSc thesis, University of Saskatchewan, Department of Electrical Engineering, Saskatoon, SK, Canada, 2005

22 Ghorani, R., Fotuhi-Firuzabad, M., Dehghanian, P.: ‘Transmission system critical components identification for reliability centered maintenance process in deregulated environment’. 21th Iranian Conf. Electrical Engineering, ICEE2013, Mashhad, Iran, May 2013, pp. 1–6

23 Billinton, R.: ‘Canadian experience in the collection of transmission and distribution component unavailability data’. Proc. IEEE Int. Conf. Probabilistic Methods Applied to Power Systems, Ames, IA, September 2010, pp. 268–273

doi: 10.1049/iet-gtd.2013.0530