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Research Article

Reliability-Centered Maintenance for Overhead Transmission Lines in Composite Power System

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Reliable overhead transmission lines have a vital role in maintaining the reliability of power systems at a desirable level and ensuring the continuity of electrical energy. In this regard, a proper preventive maintenance program can ensure the reliable functioning of transmission lines. Based on the concept of reliability-centered maintenance, this paper proposes a preventive maintenance strategy that can be implemented in real power systems due to the limited data requirements. The priority of each line for preventive maintenance was obtained by two indices revealing the technical condition and importance of each line in the network. The proposed method was applied to a real transmission network in Khorasan province of Iran. In order to extract the condition index of lines, failure statistics during six recent years as well as technical data of lines were investigated. Moreover, this paper presents a two-stage method to determine the importance index of each line by evaluating the consequences of line failures on the network. The presented results show the efficiency of the proposed approach.

1. Introduction

With the advent of electricity market, it is sensible to increase reliability and availability of the network components so as to maintain competitiveness in this market. In this regard, the importance of proper functioning of network transmission lines as a link between the generation units and demand centers is crucial. Therefore, reliability of the lines should increase as much as possible by considering financial and technical constraints. In this context, preventive maintenance has a vital role because of its helpful impact on reducing the failure rates.

Maintenance activities can be categorized into two main groups named corrective and preventive ones. Due to the beneficial impact of preventive maintenance on the reduction of failure rates, it can effectively lower the cost related to transmission line outages. Preventive maintenance can be scheduled based on different approaches such as time-based maintenance (TBM), condition-based maintenance (CBM), and reliability-centered maintenance (RCM) strategies [1, 2]. RCM method, as the most efficient and cost-effective approach among the other preventive maintenance strategies, considers the equipment's importance for the system as well as their physical condition [3–6].

Given the need to reduce costs in the electricity market and due to the fact that maintenance expenses constitute a large part of network operation costs, this paper addresses the issue of planning RCM-based preventive maintenance for overhead transmission lines in a real network. The number of studies conducted in this field is limited. Some of the related research studies, however, have been reviewed in the following.

In [7], RCM-based maintenance is proposed for transmission line system. In this study, several attributes such as line age, length of segment, radial versus loop feed, line voltage and type of construction, number of extended outages, number of top customers, and environments are used to evaluate and rank each individual line segment. While performing RCM-based preventive maintenance, it is necessary to calculate the importance of each transmission line in terms of its failure impact on the reliability indices of the network by evaluating the probable network contingencies.

In [8], a bilevel approach is proposed for yearly maintenance scheduling of transmission lines within a market environment. The proposed approach considers the maximization of the average transmission capacity margin as well as the minimization of the market-clearing impact. As a result, it determines the time of preventive maintenance for each line in 52 weeks of the year. However, the issue has not been looked at for a longer period of time to find out the transmission line needs in performing preventive maintenance.

In [9], based on duality theory, a short-term scheduling for transmission line maintenance by considering transmission and voltage constraints is proposed. Initially, over a period of one year, the transmission lines were designated for the week to be repaired. Then, in a short period of time, the exact time of performing the preventive maintenance in hour was determined by considering the voltage and transmission constraints. However, similar to [8], the issue has not been looked at for a longer period of time to determine whether all lines need to be repaired annually.

An RCM strategy was applied for maintenance planning of the Turkish national power transmission system considering transformers, circuit breakers, and lines as the three main subsystems [10]. The proposed method is based on the analysis of failure statistics recorded in the network. So, probable failures were not simulated to quantify the importance of each component from the network point of view.

In [11], an index was introduced to prioritize transmission lines for preventive maintenance. In the proposed method, the wear process of each transmission line was modeled by a Markov chain. Yet, the information required by this model is not available for all lines in real networks. Moreover, in order to evaluate the importance of lines for the network, two indicators of increasing line flows as a result of increasing network loads and increasing the generation cost due to line outage were used. Nevertheless, to quantify the impact of line outages on the network reliability index, it is necessary to examine the possible network contingencies with the help of optimal power flow and calculate the cost of energy not served.

Ardabili et al. [12–15] address the problem of determining the optimal time for performing preventive maintenance. For this, it is necessary to model the impact of preventive maintenance on each equipment reliability index. In this regard, semi-Markov chain is applied in [12–14] and in [15], it is assumed that preventive maintenance can decline the equipment failure rate to a certain extent. Furthermore, in [16], an exponential function is applied to model the effect of preventive maintenance on the failure rate of each network transmission line. Due to the fact that there are high uncertainties in the assumptions and procedures used for modelling the effect of maintenance on the reliability of the equipment, the results can be unreliable. Moreover, these kinds of modelling need large amount of data and are not useful when limited information is available.

As mentioned before, many studies conducted in the field of preventive maintenance planning are based on simplifying assumptions to model the effect of repairs on the reliability indices of the equipment [17–19]. These assumptions introduce great uncertainty into the planning process. Unlike these methods, this article seeks to determine the priority of transmission line preventive maintenance without using these simplifying assumptions with the help of two indices of physical condition and importance, which are calculated independently. In order to quantify the condition index of each line, eleven attributes such as line service age, insulator type, tower type, failure, and theft rate are considered. For this purpose and as one of the most challenging parts of this research work, failure statistics of a real transmission network in the last 6 years were reviewed and evaluated. Moreover, a two-stage approach was developed in this paper to determine the importance index of each transmission line. The proposed importance index can reveal how a line outage can affect the network reliability indices. Finally, knowing the condition and importance indices, the priority of each line in preventive maintenance scheduling was determined. In summary, the contributions are as follows:

(i) Introducing a preventive maintenance strategy that can be implemented in real power systems due to the use of limited data available in networks
(ii) Introducing the condition index of transmission lines indicating to which extent preventive maintenance is needed based on the physical health of lines
(iii) Introducing a method independent of network operating point to determine the importance index of transmission lines based on reliability calculation and simulation of probable contingency states
(iv) Determining the preventive maintenance priority of transmission lines based on two independent indicators of physical condition and importance

The rest of the paper is organized as follows: in Section 2, the quantification of line condition index is explained. The determination of importance index of each transmission line is presented in Section 3. In Section 4, the procedure of maintenance priority assessment for transmission lines is stated. Obtained results from applying the proposed method on a real transmission system and discussions are presented in Section 5. Finally, Section 6 provides conclusions.

2. Line Condition Index Quantification

Knowledge of the transmission lines' condition is vital for making decisions on maintenance planning. The condition index of a transmission line represents the technical condition of that line numerically. To determine this index, the main question is, which source of information should be considered and how this information should be processed to extract beneficial knowledge out of it. Lots of data can be collected for assessing this index. Yet, the most influencing factors, which can be generally named as condition indicators (CIs) must be considered.

According to the advice of maintenance experts and available data, this paper focused on eleven CIs to obtain condition indices of transmission lines. It is worth noting that, to determine the indicators and their weighting factors in the process of calculating the conditions index, a questionnaire was prepared and has been provided to experts who are members of the preventive maintenance teams of Khorasan province with several years of experience in the field of preventive maintenance of transmission lines. Then, according to the weighted average of the scores assigned by the experts, the weighting factor and scores of each condition indicator have been determined.

As shown in Table 1,service age, insulator type, bundle type, and tower type are some of the condition indicators. Furthermore, as the studied network is expanded over a vast region, the transmission lines face various metrological and geographical conditions. Thus, level of snow, wind speed, dust pollution, weather type, and geographical condition are also considered as condition indicators. Finally, the theft rate of transmission line components and the average number of failures per year are taken into consideration to obtain the condition index.

Table 1 indicates the CIs' scores and weighting factors. The weighting factors reveal the impact of each CI on the overall condition index. For instance, the average number of failures per year is the most important CI in the table. To consider this factor and as the most challenging part of this research work, all failures occurred in transmission lines during 6 recent years have been recorded in a database. Different events such as line tearing, jumper melting, jumper opening, insulator failure, tower failure, and contact of tree branches to the lines were some of the reasons of line failures. With the help of this database, the number of failures of each transmission line per year can be found. Moreover, various scores dedicated to the descriptions of each CI reflect the transmission lines' need for preventive maintenance based on their condition in a specific CI's point of view. As an example, the scores assigned to dust pollution show that the line exposed to high degree of pollution requires three times more preventive maintenance than those located in a low polluted area.

Given that each line may encounter an extremely different geographical situation, the need for preventive maintenance differs dramatically along this kind of line. Hence, based on the expert's opinions, in this study, each line is divided into a maximum of three zones. Then, the condition index is calculated for each zone individually. Information about lines passing through a route is extracted from geographic information systems (GIS) software.

According to Table 1, condition index of transmission line's zone j can be determined by

$$C_j = \frac{\sum_{i=1}^{11} S_{i,j} \times W_i}{\sum_{i=1}^{11} W_i}, \quad (1)$$

where W_i and $S_{i,j}$ are weighting factor and score related to i^{th} CI for j^{th} transmission line zone, respectively.

3. Line Importance Index Quantification

The importance of each transmission line depends on how its outage can influence the reliability indices of the network. In fact, this index is largely affected by the lines' position in the network. In this paper, the following two steps are considered to obtain this index.

3.1. Failure States Evaluation. The importance index of each transmission line relates to the risk imposed on the power system owing to the outage of the transmission line. In this paper, the expected energy not served (EENS) is taken into account to evaluate the imposed risk on the system. Hence, in the first step, contingency states of the network resulting from transmission line failures need to be simulated. Moreover, due to the fact that most networks are reliable against the outage of one component, the contingency states up to the order of three, including simultaneous outage of one to three lines along with one or two generating units are examined in this paper.

The subsequent optimal power flow is solved for each of the failure events to remove the possible line overloading and avoid load curtailment by means of rescheduling the generating units, if possible, or maximize the total load which can be supplied on load buses [20]:

$$\begin{aligned} &\max \sum_{i=1}^{NL} AP_i,\\ &s.\,t.\,,\\ &\mathbf{T} = \mathbf{A} \times (\mathbf{PG} - \mathbf{AP}),\\ &\mathbf{PG}^{\mathbf{min}} \leq \mathbf{PG} \leq \mathbf{PG}^{\mathbf{max}},\\ &AP_i \leq L_i,\\ &|\mathbf{T}| \leq \mathbf{T}^{\mathbf{max}}, \end{aligned} \quad (2)$$

where T is the line flow vector, T^{max} is the rating vector for lines, A is the matrix relating the line flows to the power injections at buses, PG is the generation output, PG^{max} is the upper limit for generation output, PG^{min} is the lower limit for generation output, APi is the available power at load bus i, Li is the peak load at bus i, and NL is the number of load buses.

The annual energy not served (ENS) due to the contingency state k can be obtained by [20]:

$$\mathrm{ENS}_k = 8760 \times \sum_{i=1}^{NL} (L_i - AP_i). \quad (3)$$

3.2. Importance Index Formulation. The importance of a transmission line is defined as to what extent its outage can alter the EENS of the system. Concerning this idea, the importance index of the transmission line j can be determined by

$$I_j = \sum_{i\in\Omega_j} \mathrm{ENS}_i \times P_{j,i}, \quad (4)$$

Table 1: Scores and weighting factors of condition indicators for determining the line condition index.

Condition indicators	Descriptions	Scores	Weights
Service age	≤10	3	1
	10–20	4	
	≥20	6	
Insulator type	Porcelain type 1	2	3
	Silicon	2	
	Porcelain type 2	4	
	Glass	6	
Bundle type	No	4	1
	Yes	6	
Tower type	Monopole	3	2
	Lattice or H	6	
Location	Plain	4	1
	Mountain	6	
Weather	Dry	2	1
	Mild	4	
	Humid	6	
Wind	Low	2	2
	Medium	4	
	High	6	
Snow	Low	2	2
	Medium	4	
	High	6	
Dust pollution	Low	2	3
	Medium	4	
	High	6	
Theft rate	Low	1	4
	Medium	2	
	High	4	
	Extra high	6	
Average number of failures per year (AFR)	Low	1	5
	Medium	2	
	High	4	
	Extra high	6	

where Ω_j is a set of contingency states, including the failure of the transmission line j. Moreover, $P_{j,i}$ represents the share of failure in transmission line j on the energy not served resulted from contingency state i. $P_{j,i}$ is determined as follows:

$$P_{j,i} = \frac{\mathrm{FOR}_j}{\sum_{e=1}^{N_i} \mathrm{FOR}_e}, \tag{5}$$

where FOR_j and N_i are force outage rate of line j and number of failed components in contingency event i, respectively. Based on (5), the resulted ENS for each event is shared among the failed components based on their failure probabilities.

Figure 1 illustrates the procedure to determine the importance index of each transmission line.

As shown in Equation (2), one of the main constraints in the process of calculating network reliability indices and determining the importance index of transmission lines is the line loading limits. To determine the safe loading limit of lines, weather conditions are normally considered conservatively, such as low wind speed and high ambient temperature. This method, which is known as static thermal rating (STR), underestimates the thermal rating of lines. On the contrary, dynamic thermal rating (DTR) as an alternative approach to estimate the thermal limit of transmission lines utilizes the actual weather information [21, 22]. As a result, it is proven that DTR can increase the capacity of transmission lines by 30–50% [23]. As mentioned earlier, the proposed method is implemented on a real transmission network. Yet, due to the lack of accurate weather data history for different points of the network, the effect of DTR on determining the importance index of transmission lines is neglected. However, in the case of data availability, the proposed method has the possibility to consider the issue.

4. Maintenance Priority of Transmission Lines

Knowing the importance and condition indices, the position of each overhead transmission line on a two-dimensional diagram such as Figure 2 could be determined. Based on statistical analyses and consultation with maintenance experts, importance and condition indices can be divided into

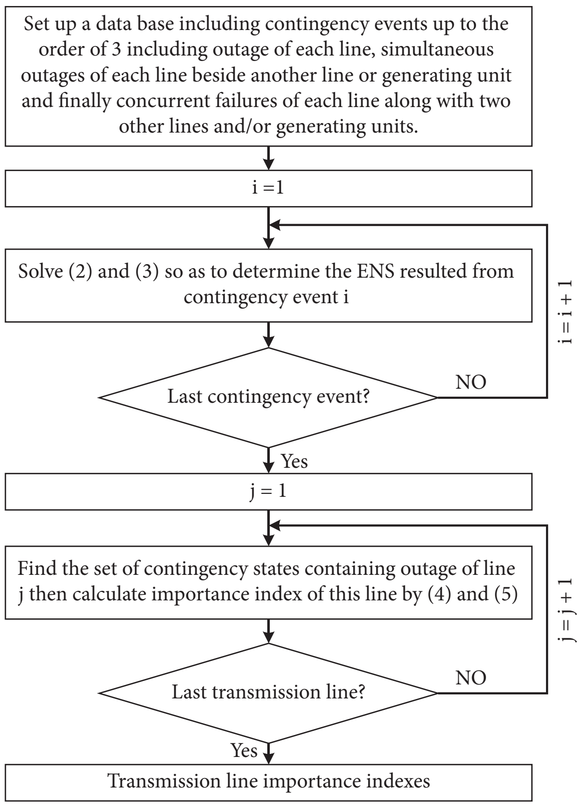

Figure 1: The flowchart of determining importance index.

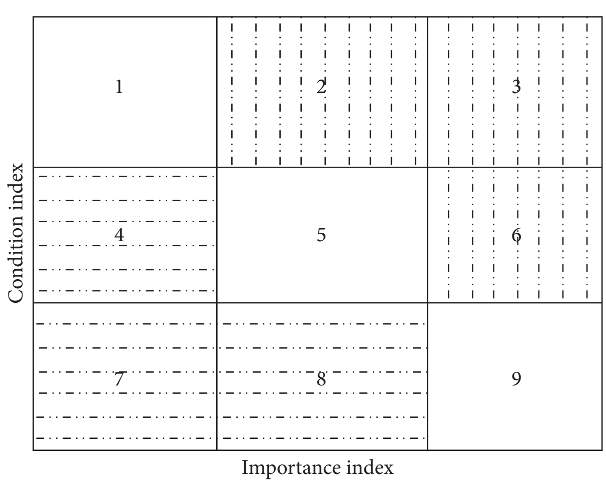

Figure 2: Decision making map for preventive maintenance scheduling of transmission lines.

three ranges including low, medium, and high value. Consequently, based on these circumstances, 9 segments will be created on Figure 2.

Regarding Figure 2, the transmission lines located in segment 3 have the highest need for preventive maintenance because they have the worst condition index as well as being the most important lines in the network. Moreover, the transmission lines placed on the segment 7 have the lowest need for preventive maintenance since these lines have the best condition index and the lowest importance in the network.

As follows, in this study, all the segments of Figure 2 are categorized into three areas. Segments 4, 7, and 8 form the first area which contains the transmission lines with the lowest need for preventive maintenance. The second area includes segments 1, 5, and 9 including the transmission lines with the medium need for the preventive maintenance. Finally, segments 2, 3, and 6 constitute the third area which includes the transmission lines with the highest need for the preventive maintenance.

5. Simulation Results

The proposed method was implemented on the regional electricity network of Khorasan province in Iran. This network accounts for a large portion of Iran's electricity network and includes voltage levels of 63, 132, and 400 kV. The single line diagram of this network is depicted in Figure 3. This network includes 182 buses, 47 conventional dispatchable generating units, and 300 lines (including power transformers, cable, and overhead transmission lines). The peak load of the network is estimated as 3474.4 MW, while its total generation capacity is 5076.77 MW. It is worth noting that although the Khorasan network is selected as the test system in this study, it can be replaced with other kinds of power networks in actual scenarios. In other words, the proposed model is applicable in any real network, provided that network data and contingency statistics are available to quantify the importance and technical condition indices.

At present, time-based preventive maintenance activities are performed for all equipment of Khorasan province electricity network. According to this strategy, preventive maintenance activities are carried out for all equipment once a year, regardless of the needs of the equipment or their importance for the network. To change this costly approach, the Khorasan Regional Electricity Company attempts to determine the priority of the network equipment for preventive maintenance purposes. Accordingly, the preventive maintenance priority of 219 overhead transmission lines in this network has been determined.

5.1. Technical Condition Assessment. As mentioned in Table 1, the condition index can be estimated based on the information such as weather conditions, geographical location, history of failures occurred on the line, and other identification data. As illustrated in Table 1, the number of annual failures on the transmission line plays a very significant role in determining the condition index of the lines. To consider this feature, Khorasan transmission network failures during the past 6 years were investigated. Figure 4 shows the average number of annual failures in each transmission line of the network.

As would be observed in Figure 4, the highest number of failures is related to line 273. In a way that, 7.5 failures have occurred on this line per year. In contrast, line 276 has not met any outage in the last 6 years.

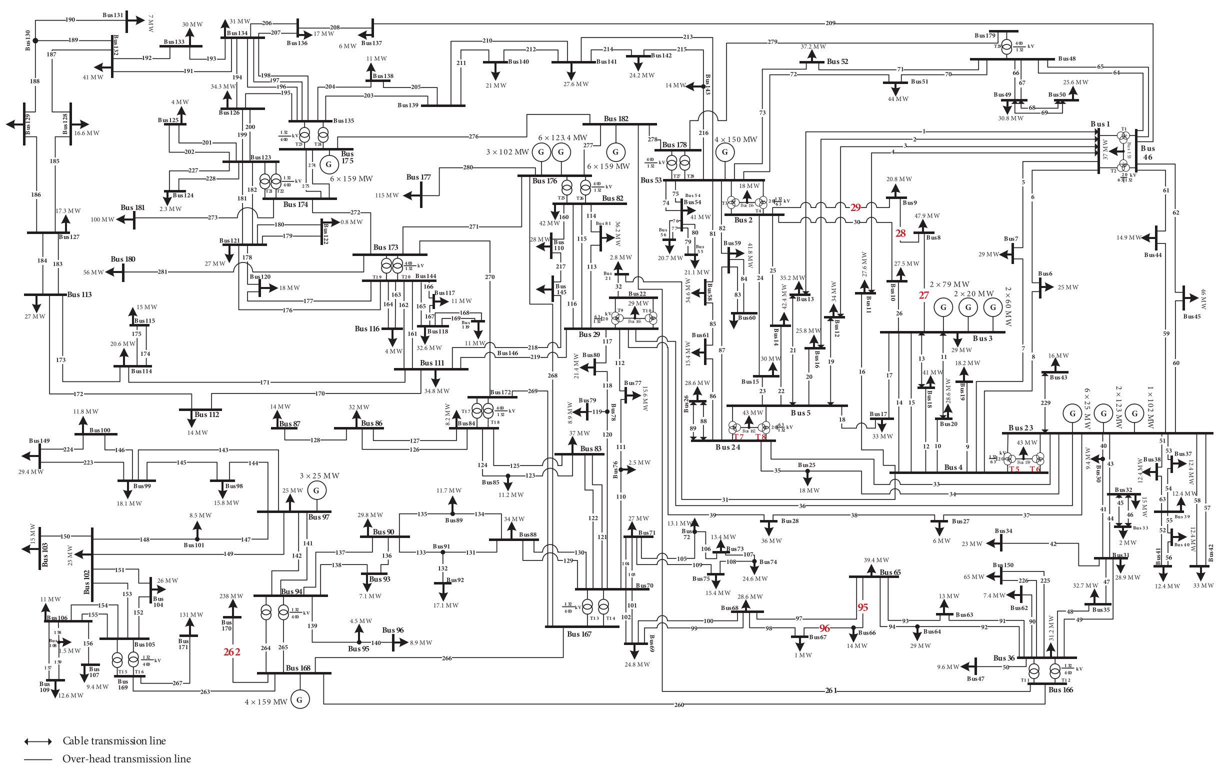

Figure 3: Single line diagram of the Khorasan network.

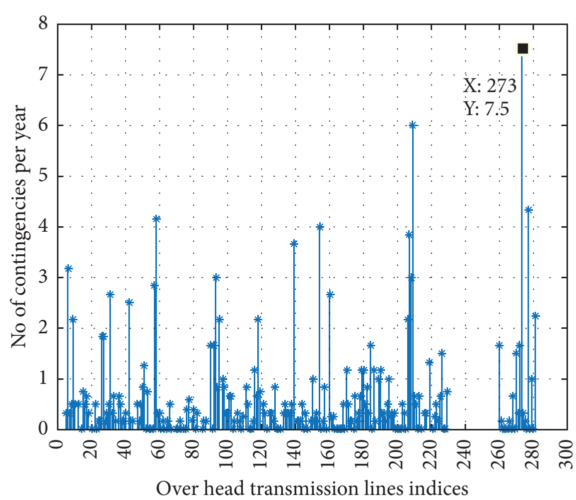

Figure 4: Mean failures per year for each line of the Khorasan network.

According to the consultation with the maintenance experts and as shown in Table 2, transmission lines are divided into 4 categories based on the number of failures. For example, according to the information presented in the table, the number of failure statistics in 14 transmission lines is very high.

As stated earlier, each transmission line of the network was divided into a maximum of three different zones, according to the maintenance experts' opinions. For example, line 118, with a length of 147 km, was divided into three zones with lengths of 78, 35, and 34 km, respectively.

Table 2: Grouping the transmission lines based on the number of annual failures.

No. of failures per year	No. of lines in each group
Low ($n < 0.5$)	132
Medium ($0.5 \leq n < 1.5$)	59
High ($1.5 \leq n < 2.5$)	14
Extra high ($n \geq 2.5$)	14

According to the weighting coefficients introduced in Table 1 and using (1), the condition index of the areas corresponding to 219 overhead transmission lines is calculated and shown in Figure 5. According to the figure, the transmission line 6 with a length of 21 km has the largest amount of condition index in the network; thus, only based on this index, it has the greatest need for preventive maintenance.

To investigate the cause of this, the properties of this line are listed in Table 3. As can be seen in the table, the high number of annual failures, high theft rate, and high rate of dust pollution are the most important factors in increasing the condition index of that line.

5.2. Quantification of the Transmission Lines Importance Index. The reliability information of the transmission lines, generating units, and power transformers of the Khorasan regional power network is presented in Table 4. In order to extract this information, the network contingency events during the last 6 years were examined. Since the number of failures in each network line is considered one of the

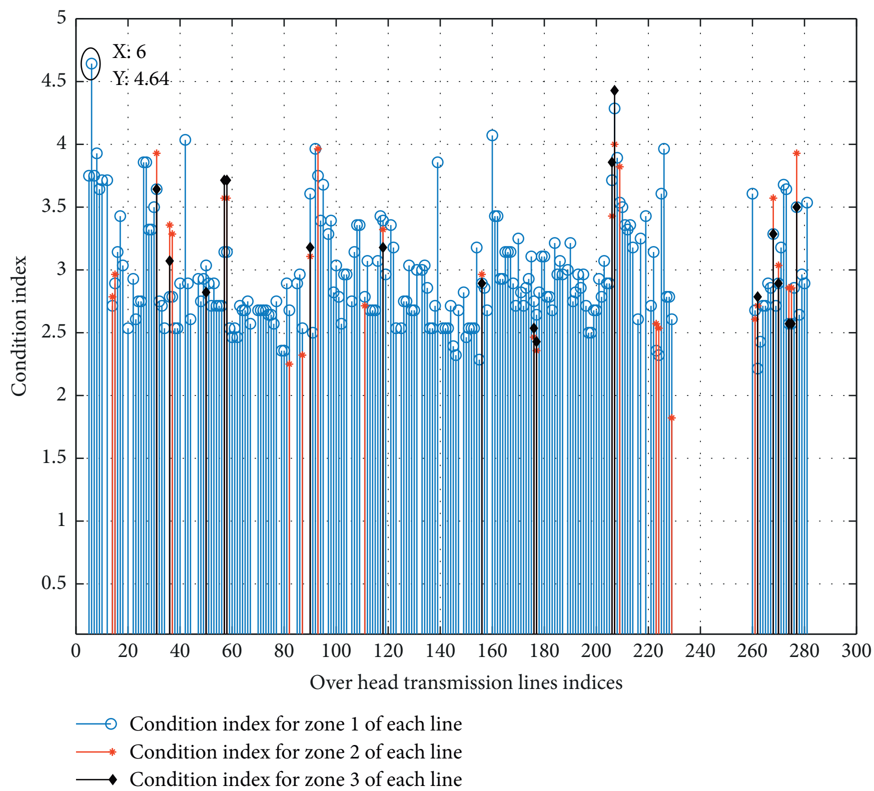

Figure 5: Condition index for the overhead transmission lines in Khorasan network.

Table 3: Information related to the line 6.

Condition indicators	Descriptions	Scores	Weights
Service age	27	6	1
Insulator	Internal porcelain	4	3
Bundle	No	4	1
Dust pollution	High	6	3
Stealing rate	Extra high	6	4
Location	Plain	4	1
Weather	Mild	4	1
Wind	Medium	4	2
Snow	Medium	4	2
Tower	Lattice	6	2
Failure number	Extra high	6	5

Table 4: Components reliability data.

Components	Failure rate (fail/year)	Repair time (hour)
Transmission line	0.6166	7.58
Generating unit	0.026	46
Power transformer	0.137	43.45

determinant factors in specifying the condition index, according to Table 1, the failure rate and repair time were considered to be the same for all network lines. As a result, the importance index of transmission lines can be calculated independently of their failure statistics. In this way, it can be ensured that the estimated important index for the transmission lines is only affected by the location of these lines in the network.

To calculate the importance index of the network lines, contingency events up to the order of three were evaluated. Consequently, the total number of studied events was 4758348, of which 1626626 ones led to the load shedding in the network. Based on this and according to the steps of Section 3, the importance indices associated with transmission lines and power transformers are calculated and shown in Figure 6 as well.

To further examine the calculated importance indices, as shown in Figure 6, the components are divided into two categories of radial and nonradial. Radial components are those whose failures cause parts of the network load to be lost immediately, so these lines are of high importance. For example, line number 262 is the most important transmission line of the network, and as can be seen in Figure 3, the load amount of 238 MW will be lost in the case of its failure. Lines 95 and 96 also have a radial arrangement. For further investigation, the location of these two lines in the network is depicted in Figure 7. As illustrated by the figure, in the case of a short-circuit in any of the lines 95 or 96, the circuit breakers located at buses 65 and 67 will simultaneously dismiss both lines out of the circuit, thus a load amount of 14 MW on bus 66 will be removed.

Figure 6 shows that, among the nonradial lines, lines 27 and 29 are of high importance for the network. To clarify the reasons of this fact, the location of these lines in the network is depicted in Figure 8. As would be observed from the figure, in the case of failure on line 27 (29), it is necessary to supply the total load on buses 8 and 9

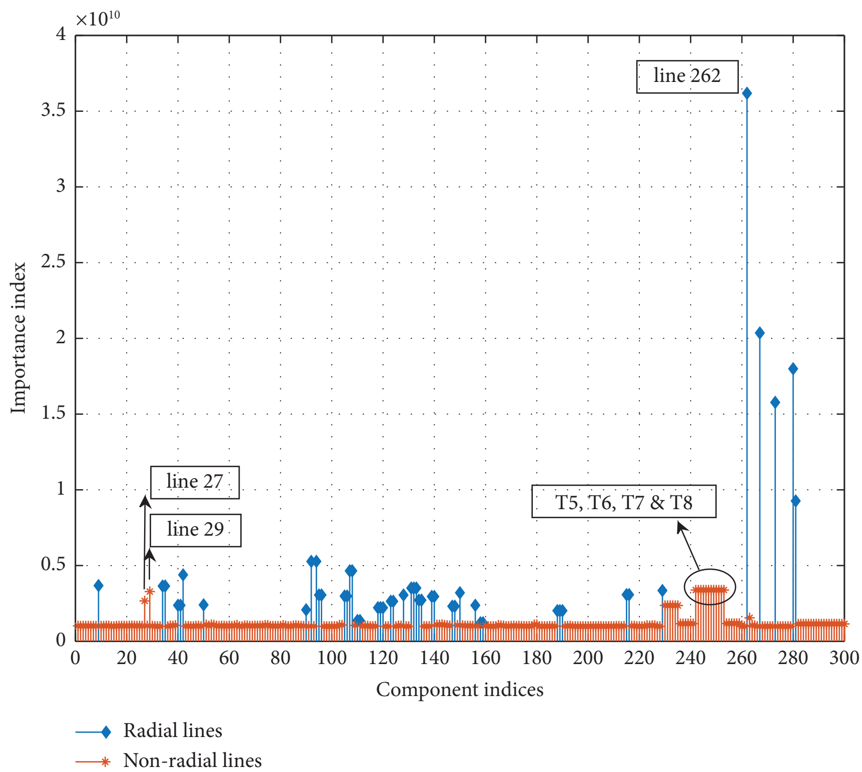

Figure 6: Importance index for the lines in Khorasan network.

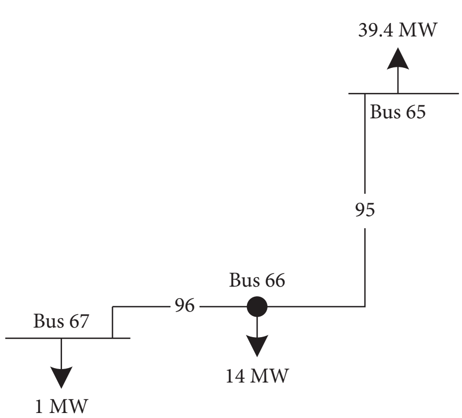

Figure 7: The position of lines 95 and 96 in the network.

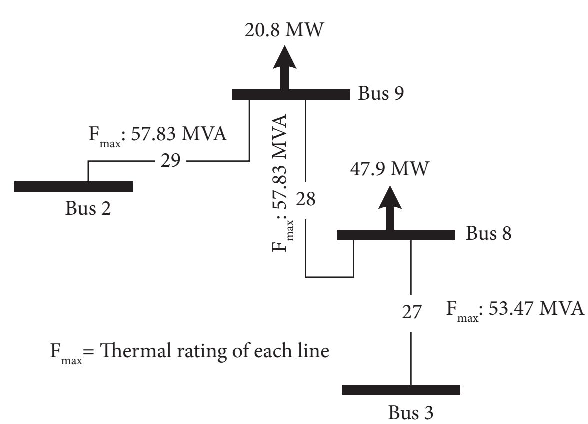

Figure 8: The position of lines 27 and 29 in the network.

(68.7 MW) through the transmission line 29 (27). Due to the fact that the maximum transmissible powers through lines 27 and 29 are 53.47 and 57.83 MVA, respectively, it is not possible to transfer the total load of buses 8 and 9 via each of these lines alone, and load shedding is inevitable. The other important components in the network are transformers T5–T8, which are located at buses 23 and 24. Since each of the three winding transformers is modeled with the help of three lines, these transformers are equivalent to lines 242–253 in Figure 3. These transformers are responsible for transferring power from the level of 132 kV to that of 63 kV, and the simulation results indicate that load removal in the network is inevitable if failures occur in these transformers.

5.3. Priority Assessment of the Transmission Lines in Maintenance Planning. The importance index histogram of 219 overhead transmission lines of Khorasan electricity network is shown in Figure 9. Using this diagram and based on the consultations with the maintenance experts, network lines are divided into three categories of low, medium, and high importance. As shown in Figure 9, these categories include 84, 99, and 36 transmission lines, respectively.

As mentioned earlier, some transmission lines have been divided into a maximum of three zones. Accordingly, 267 zones were considered for 219 overhead transmission lines of the network. Figure 10 plots the histogram curve of the condition index for these zones. Based on the figure and consultation with the maintenance specialists, lines

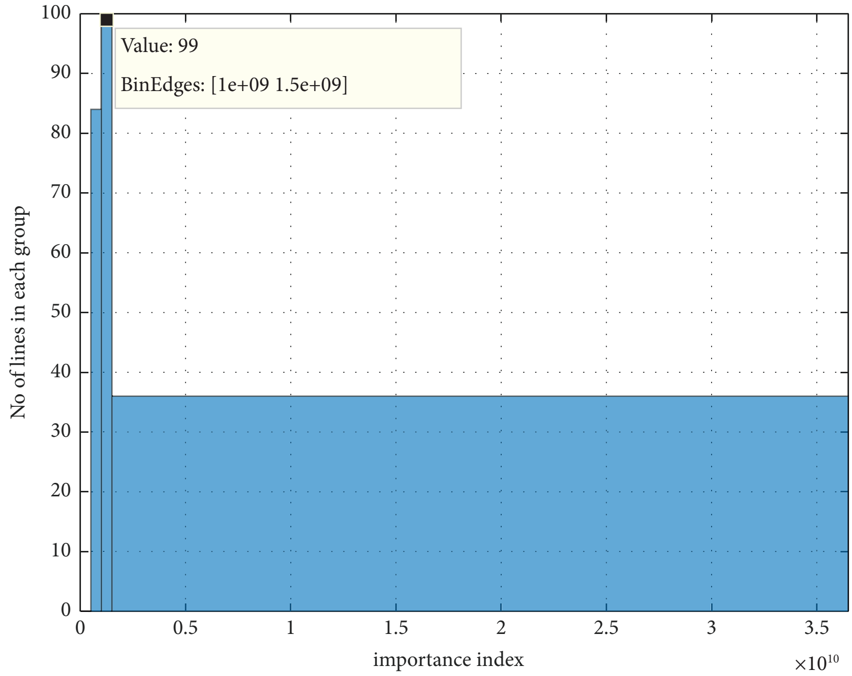

Figure 9: Histogram curve of lines importance index.

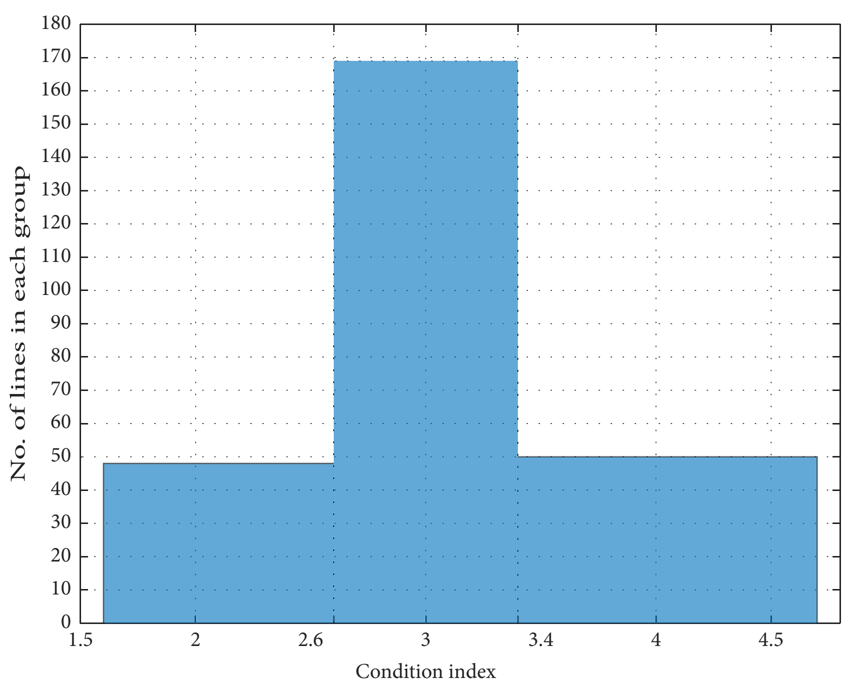

Figure 10: Histogram curve of lines condition index.

are divided into three categories of low-, medium-, and high-demand ones based on the need for preventive maintenance, in which 48, 169, and 50 transmission line zones are located.

Knowing the condition and importance indices of 267 zones considered for the overhead transmission lines, the position of each is shown in Figure 11. Based on the boundary values considered in the histogram curves associated with the condition and importance indicators, Figure 11 is divided into three zones of A, B, and C with low, medium, and high need for preventive maintenance activities. Among the 267 zones intended for the overhead transmission lines, those located in each of the category's A, B, and C are listed in Table 5. As it is clear, 58 zones of the transmission line areas meet the highest need for preventive maintenance.

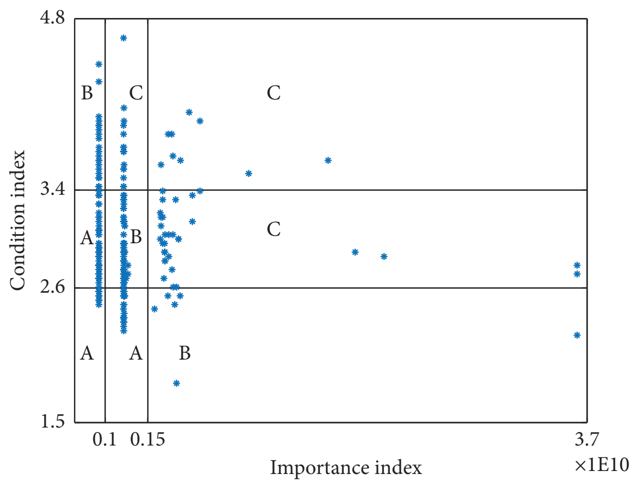

Figure 11: Priority of transmission line for maintenance planning.

Table 5: No. of transmission lines zones in each area of Figure 11.

Areas	No. of transmission lines zones
A	112
B	97
C	58

6. Conclusion

The current paper presents a way to plan reliability-centered maintenance (RCM) for overhead transmission lines in a composite power system. In addition to the technical condition, proposed strategy also takes the importance of each line for the network into consideration. The proposed method's performance has been successfully evaluated on a very large transmission network. In order to determine the condition index of the overhead transmission lines, in addition to the geographical location, technical data, and climatic characteristics of the line crossing route, the network failure statistics during the last 6 years have been examined. Also, the importance index of the network lines has been obtained based on a two-stage approach which evaluates the network failure events up to a maximum of three (including one to three outages of lines with generation units). Knowing the importance and condition indicators, transmission line priorities have been determined for the preventive maintenance activities. In the future works, the proposed method can be developed on other network equipment such as protection systems and generating units, in order to achieve a comprehensive plan of preventive maintenance for the network.

Data Availability

The programming codes used to support the findings of this study are available from the corresponding author upon request. Moreover, regarding the fact that the studied network is a real one, the data of network can be provided subject to obtaining permission from the Khorasan regional electricity company.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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