A probabilistic reliability-centred maintenance approach for electrical distribution networks

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Abstract
Reliability improvement is a fundamental issue in electric distribution network (EDN) operation. In this regard, providing the most efficient maintenance policy can dramatically assist the electric utility companies in reducing the failure rate of EDN components. In the present study, a novel probabilistic reliability-centred maintenance (RCM) approach is proposed in which the reliability level of the EDN components are evaluated according to the three-state Markov model (MM). Using the MM, this study presents a trade-off between the corrective maintenance and the preventive maintenance (PM) actions and finally determines the precedence of EDN components in PM financial resource allocation. Through the method presented in this study, the financial resources of the PM are economically allocated with regards to economic parameters such as customer outage costs and budget constraints. The efficacy of the proposed RCM approach is evaluated through the implementation of the RCM approach on bus number four of the well-known Roy Billinton test system.

1 | INTRODUCTION

With the increasing dependency of residential, commercial, and industrial communities on electric power, enhancing the reliability level of the power system is an inevitable challenge for the electric utility companies. Indeed, the social welfare level is directly proportional to the reliability level of the power systems. Moreover, the reliability level of the electricity supplied to the customers is comparatively more affected by the performance of the electric distribution network (EDN) since the EDN is directly connected to the customers [1, 2]. Distribution network (DN) companies devote significant efforts to allocate their limited resources (e.g. budget and materials) to maintain the DN assets (e.g. lines, cables, and transformers) [3]. The EDN outages, which occur due to the failure of network components, can be reduced by implementing asset management policies in the EDNs [4]. The asset management strategies are categorised into three groups: Long-term, mid-term, and short-term asset management strategies. Herein, maintenance actions are attributed to substantial activities in the mid-term asset management strategies [5, 6].

Maintenance policies aim at reducing equipment failures through repairing equipment that is more probable to fail during their operation. The constraints burdened on the financial resources available for maintenance as well as the maintenance of budget evaluation complexity, necessitate researchers to conduct a number of fundamental researches. The reliability-centred maintenance (RCM) was employed in the power plant’s electrical network and then used in electric transmission and distribution networks after successful outcomes of conducting the RCM in the manufacturing industry [7]. In general, maintenance strategies can be classified into corrective maintenance (CM) and preventive maintenance (PM) The CM refers to the maintenance action(s) conducted after failure occurrence while the PM denotes the pre-fault maintenance actions that are executed before fault occurrence in EDNs’ components. The aim of DN maintenance-scheduling is to improve system reliability while reducing overall costs on multistage-planning horizon [8]. Determining the preferences of the components for the PM activities is the main challenge in executing PM actions in the EDNs [9–11]. Fragile points of the EDN, which are known as critical components, should be in higher precedence...
while assigning financial resources in the PM-scheduling problem. RCM contains critical component identification as its first and key step toward its fundamental target which is minimising the investment for preventive and corrective maintenance. Arya [9] has presented an algorithm for deciding preferences in maintenance activities for feeder sections of distribution systems. A component importance measure, known as diagnostic importance factor (DIF), has been used for this purpose. Bertling [10] presented a critical component identification using a simple sensitivity analysis. The authors in [14] proposed five key factors associated with the identification of critical components, that is, cost, functional dependency, complexity, maintainability, and safety impact. In [15], the relationship between reliability and maintenance has been established by relating the effect of PM to the causes of failures for the underground cables, which was shown to be critical for the reliability of the network. The authors in [16] provided a new scheme for comprehensive planning of RCM based on failure models to minimise the costs of repair and maintenance of cables in a 30-bus distribution network.

An Algerian electric company developed a maintenance program using the RCM method for reliability enhancement [17]. It prioritises the maintenance requirement of all failure modes and selects the effective maintenance activity for the critical failure modes. In [18], the key factors associated with the critical component identification in EDNs were introduced and afterwards, the most critical component types were identified in the light of the proposed criteria key factors.

In [19], an RCM methodology that is based on a quantitative statistical analysis of outage data is performed at the system/component level. In this study, the feeder with the highest failure rate was selected for a more critical analysis. A general and practical framework of RCM in EDN was presented in [20, 21]. In this framework, an approach was developed to identify the network critical components from the reliability point of view. The criticality factor based on the weighted combination of reliability indices, namely, the number of outages, duration of outages, and energy not supplied (ENS), was used in the RCM framework. Authors in [22] proposed an approach to minimise the maintenance cost in EDN, while the system reliability level is as close as the determined criterion in the electric utility. The maintenance plan for each EDN component is specified, according to the required performance standards while considering the budget limitations as a constraint. In [23], for the planning of PM budget based on network reliability, the indexes of the annual number of outages, annual outage duration, and annual ENS have been considered as the main criteria in the budget allocation process. In this study, the areas served by the EDN are prioritised relative to each other according to the mentioned criteria. The authors in [24] presented a practical model for maintenance-scheduling by considering the restricted PM budget and risk function with regards to value of lost load (VOLL). In [25], a failure rate model is proposed for overhead lines according to their failure types. Further, the optimal PM execution time is selected for a constant maintenance budget and in [26], the planning of maintenance task in EDN overhead lines was formulated as a mixed dynamic non-linear model with genetic algorithm (GA). In this way, the reliability and availability of indices were improved. In [27], the maintenance-scheduling for the overhead lines was conducted by employing a mixed-integer programming approach. Authors in [28] suggested a decoupled risk factor model according to a decision tree in which an appropriate model is derived and greatly reduces the complexity of the EDN maintenance-scheduling.

In [29], a method was proposed to allocate maintenance resources to various distribution assets. The criticality factor used in this study is a linear combination of reliability and cost-based indices. In [30], an approach was introduced to study the problem of balance between PM and CM as a multi-objective optimisation problem, with customer interruptions on one hand and the maintenance budget of the network operator on the other hand. In [31], the RCM method was presented with the aim of optimally allocating the total maintenance budget for EDN feeders. The maintenance budget for feeders was practically allocated to decrease the failure rate of the EDN feeders, and in [32], the feeders were prioritised with two different levels (first level without RCM planning and second level with RCM planning) to improve the reliability Index.

As it is obtained from the surveyed studies, the reliability model which is able to express the effect of PM actions on the reliability of the network is the first challenge in the RCM study. Also, RCM should provide asset managers with a powerful tool to prioritise component maintenance needs subject to economical parameters such as available PM budget and customers’ outage cost. The major contribution of this study is to introduce the three-state Markov model (MM) which is more adaptable with the lifecycle cost of EDN components, in the presence of PM actions, than the two-state model which has been used in most studies dedicated to PM-scheduling. Also, through this MM, we introduce the objective function to identify critical components of EDN with regards to utility budget constraint and customers’ interruption cost.

The rest of the study is organised as follows: The proposed maintenance policy and reliability model is described in Sections 2 and 3, respectively. The problem formulation is presented in Section 4, and the solution approach is explained in Section 5. The proposed RCM policymaking approach is implemented on a test system and the obtained results are reported and discussed in Section 6, and the conclusions are in Section 7.

2 PROPOSED MAINTENANCE POLICY

In this study, it is assumed that the distribution company is under the performance-based regulation (PBR) [33, 34]. The PBR is a regulatory approach that relies on financial incentives and disincentives to induce desired behaviour by a regulated electric company. The desired behaviours, or outcomes, are generally (1) lower costs, and (2) improved service quality. Service quality is measured in terms of reliability indices such as duration and frequency of outages. So, PBR penalises companies for providing poor reliability and rewards them for providing good reliability. In this study, it is assumed that the reward/penalty scheme is designed so that when an outage occurs the company
would be penalised as equal to customer outage cost. Under this reward/penalty scheme, RCM helps asset managers to determine the optimum level of service quality in which the overall cost, including the outage cost of the customer and the investment cost of preventive and corrective activities, is minimised. In comparison to the other maintenance policies such as time-based maintenance (TBM) and condition-based maintenance (CBM), in which the effect of the maintenance activities is almost studied at the component level, RCM provides us an organised framework for the improvement of system reliability and the reduction of maintenance costs by relying on cost/benefit studies and the reliability analysis of networks. Using RCM, we were able to prioritise component maintenance needs through a step-by-step study, and then allocate maintenance resources in the highest priority component.

3 | PROPOSED RELIABILITY MODEL

A possible way to evaluate the future conditions of an equipment is MM. It is a random approach where probabilities are identifiable based on the available conditions data. Using MM, the maintenance cost can be estimated for the asset managers in the planning of its future budget [35, 36]. As reported in different literatures, MMs have been utilised for investigating maintenance associated with periodic inspections. Based on MM, six maintenance models were introduced in [37, 38] to determine the best long-term PM for each failure mode. Theil [39] introduced a model in which inspection states were added to the Markov states. But in this study, no distinction was made between PM and CM. A major goal for asset managers of electric power networks is maximum asset performance. Maintenance optimisation and minimal lifecycle cost become crucial in reaching this goal while meeting demands from customers and regulators. This necessitates the determination of the optimal balance between PM and CM in order to obtain the lowest total cost. Therefore, this study focuses on maintenance-scheduling using PM and CM activities simultaneously.

The proposed approach optimally selects the critical components and their appropriate maintenance budget and execution time. Most of the previous researches only considered the healthy and failed states of each network component while calculating their reliability level as shown in Figure 1. However, the proposed approach uses a three-state MM in order to calculate the reliability level of each EDN component:

\[ P^H \cdot \lambda^{HF} = P^F \cdot \mu^{FH} \]  
\[ P^H + P^F = 1 \]

Equations of steady-state in this system are as formulated in Equations (1) and (2). Herein, \( P^H \) and \( P^F \) denote the probability of healthy and failed states of a component, respectively. This model is used to calculate the lifecycle cost of one component while it is not preventively maintained.

To model the lifecycle of the component in the presence of PM, we used the three-state MM shown in Figure 2. In this model, in addition to a healthy and failed state, the component has another state that is a minor failure state denoted by M in Figure 2. The state of the component is switched from healthy to minor by transition rate \( \lambda^{HM} \), \( \lambda^{MH} \) is the number of transition from \( i \) state to \( j \) state per total working time in \( i \) state, and \( \mu^{ij} \) is the number of transition from \( i \) state to \( j \) state per total repair time in \( i \) state (see the Appendix). The steady-state equations for the three-state system are shown in Equations (3) to (6), where \( \mu^M \) refers to the probability of the minor state:

\[ P^M + P^F + P^H = 1 \]
\[ P^H \cdot \lambda^{HM} = P^M \cdot \mu^{MH} + P^F \cdot \mu^{FH} \]
\[ P^M \cdot \mu^{MF} = P^F \cdot \mu^{FH} \]
\[ P^H \cdot \lambda^{HM} = (\lambda^{HM} + \mu^{MH}) \cdot P^M \]

Equipment outages can happen due to either random or ageing failures. Random failures are modelled through exponential probability distributions with constant failure rates, while ageing failures are modelled through Weibull or normal probability distributions [27], and maintenance activities cannot prevent random failures. However, failure rates that originated from ageing are time-varying and hence planned maintenance activities will bring about significant improvements over time.
4 | PROBLEM FORMULATION

4.1 | Fitness function

The fitness function is presented in Equation (7). Herein, $C^{CI}$ and $C^{ENS}$ refer to the total cost of customer interruption and the total cost of energy not sold due to the outage occurrence in the EDN, respectively. Moreover, $C^{PM}$ and $C^{CM}$ denote the total cost of PM and CM actions, respectively, implemented in the EDN. The first term of the objective function is formulated in Equations (8) and (9). In Equation (9), $CDF_{i}^{NS}$ and $CDF_{i}^{S}$ are customer damage functions that represent the customer’s interruption penalty that should be paid by the EDN due to non-scheduled (forced) and scheduled (maintenance) outages, respectively. $CDF_{i}^{NS}$ is a function of $r_{ij}$ that refers to service restoration time experienced by customers connected to $j$th load point, after forced outage of the $j$th component. $CDF_{i}^{S}$ is a function of $r'_{ij}$ that refers to service restoration time experienced by customers connected to $j$th load point, after maintenance outage of $j$th component. The binary variable ($m_{ij}$ is used to determine components that should be preventively maintained, which are known as critical components of the EDN. Moreover, $D_{ij}$ is the demanded power of customers connected to the $j$th load point.

Minimise $OF = C^{CI} + C^{PM} + C^{CM} + C^{ENS}$

Equation (9) consists of three terms. The first one refers to the cost of a non-scheduled outage when the component is not preventively maintained. The second and third ones refer to the cost of non-scheduled and scheduled outages, respectively, when the component is preventively maintained. The second and third terms of the objective function refer to the total material and labour costs that should be spent in the CM and PM actions and formulated in Equations (10) and (11) and Equations (12) and (13), respectively. Herein, $PM_{j}$ and $CM_{j}$ refer to the PM and CM actions costs of the $j$th component, respectively. Moreover, $Lbr_{ij}^{rep}$ and $Lbr_{ij}^{main}$ is the number of working hours required for repair/maintenance of $j$th equipment. In addition, $P_{ij}^{F}$ and $P_{ij}^{M}$, respectively, are the probability of the failed and minor states of the component:

$$C^{CI} = \sum_{i \in \Omega^{L}} \sum_{j \in \Omega^{L}} (CDF_{i}^{NS}(r_{ij}))$$

$$C^{CM} = \sum_{j \in \Omega^{F} \cup \Omega^{L}} CM_{j}$$

$$\forall j \in \{\Omega^{F} \cup \Omega^{L}\}$$

$$C^{PM} = \sum_{j \in \{\Omega^{F} \cup \Omega^{L}\}} PM_{j}$$

$$\forall j \in \{\Omega^{F} \cup \Omega^{L}\}$$

$$\forall i \in \Omega^{L}, j \in \Omega^{F}, \Omega^{L}$$

4.2 | Problem constraints

The introduced optimal PM-scheduling problem is subjected to a number of economic and technical restrictions, which are presented in the following sections.

4.2.1 | Available PM budget

The electric utility company has a restricted amount of financial resources, which can be spent on maintenance actions. These constraints should be considered in the proposed algorithm. Accordingly, the total PM cost is restricted in Equation (16), where $TAB^{PM}$ is the total available budget for PM actions:

$$C^{PM} \leq TAB^{PM}$$
4.2.2 | Operational constraints

In order to determine the interrupted load points, the load flow equations should be solved for each contingency. In fact, the number of load points that can be restored through the backup feeder should be determined according to its available capacity. These factors are considered in the load flow equations; therefore, the load flow equations should be enforced for all prospective contingencies as formulated in Equations (17) and (18). In this study, the forward-backward sweep method is used to solve the power balance equations:

\[
P_{ij}^{sub} - P_j + ENS = \sum_{k=1}^{NB} Y_{ik} V_{ij} V_{kj} \cos(\theta_{kj} - \theta_{ik})
\]

\[
\forall i \in \Omega^{LP}, j \in \{\Omega^u \cup \Omega^l\}
\]

\[
Q_{ij}^{sub} - Q_j = \sum_{k=1}^{NB} Y_{ik} V_{ij} V_{kj} \sin(\theta_{kj} - \theta_{ik})
\]

\[
\forall i \in \Omega^{LP}, j \in \{\Omega^u \cup \Omega^l\}
\]

The EDN feeder's thermal constraints should not be violated during the service restoration. This limitation is enforced in Equation (19). Moreover, the EDN load points should be supplied in an acceptable voltage range during the service restoration. These constraints are enforced in Equation (20):

\[
V\min \leq V_{ij} \leq V\max \quad \forall i \in \Omega^{LP}, j \in \{\Omega^u \cup \Omega^l\}
\]

\[
2P + 2Q = 2S \quad \forall i \in \Omega^l, j \in \{\Omega^u \cup \Omega^l\}
\]

5 | SOLUTION APPROACH

The proposed RCM-scheduling problem is a mixed-integer non-linear optimisation problem (MINLP) which is regarded as a knapsack problem. This kind of optimisation problem should be solved by employing evolutionary algorithms. In this regard, the well-known GA is selected as the optimisation algorithm for the proposed probabilistic RCM-scheduling problem since the accuracy and effectiveness of the GA algorithm has been demonstrated in various engineering fields. In this study, MATLAB software (ver.R2017b) is used for calculations. The procedure of the suggested approach is sketched in Figure 3. As shown in this figure (this figure is detailed in the Appendix), first, an initial GA population specifies the initial values (viz. 0 or 1) of PM actions for all EDN equipment. Second, the total PM and CM costs are calculated for all contingencies of EDN. Afterwards, the other terms of the objective function are evaluated for each contingency. Then, the fitness function is determined and the initial population of the GA is modified in order to reach an optimal solution.

This process is repeated until the termination criteria are satisfied. It should be noted that the maximum number of iterations and variance of the objective function criteria are regarded for terminating the GA algorithm. This simulation is then terminated based on the maximum number of iterations criteria. After termination, the last objective function is reported as the optimal fitness function.

6 | SIMULATION RESULTS

6.1 | Test system

The proposed probabilistic RCM-scheduling approach is implemented on a standard test system in order to evaluate the effectiveness of the proposed approach. The test system is the fourth bus of the well-known Roy Billington test system (RBTS-BUS4), which is sketched in Figure 4 [39, 40]. It is assumed that the remote controlled switches (RCS) are installed at 5D, 7 and 10 U of feeder 1; 15 and 17 U of feeder 2; 23 D, 26 and 28 U of feeder 3; 36 D, 39 and 41 U of feeder 4; 46 and 48 U of feeder 5; 52 and 54 U of feeder 6; 60 D, 63 and 65 U of feeder 7, in which “U” and “D” indicate “upstream” and “downstream” of a line section. The typical data of the components and loads characteristics—including fault occurrence rate, repair time, demanded electricity of customers, and customer types in the EDN—are derived from [40]. The maximum and minimum allowable voltage level at each load point is presumed to be equal to 1.05 pu and 0.95 pu, respectively. Moreover, the customer damage function (CDF) due to non-scheduled outages (CDFNS) is considered the same as the CDF presented in Figure 5 [40]. Furthermore, it is assumed that the EDN customers are not paid by the system operator due to scheduled outages, that is, CDFS = 0 [29]. The electricity price for various customer types is reported in Table 1 [22]. In addition, the data required for calculating the PM and CM costs, including needed labour hours, cost of labour, and cost of material required for repair actions are shown in Tables 2 and 3 [40]. Moreover, fault location time, switching time, repair time, and maintenance time are shown in Table 4. The value of repair time for line and transformers is from [31, 39] that is decomposed to minor parts in Table 4. The sectionalising switch model is used based on the model in [40].

6.2 | Scenarios

Scenario 1: Identifying the critical components subject to budget constraint equal to 2 k USD.

In order to demonstrate the effectiveness of the proposed probabilistic RCM-scheduling approach, two cases are defined. In the first case, it is assumed that PM actions are not conducted in the network, and in the second case, PM actions are accomplished in the RBTS-BUS4. The available financial resource for PM actions is assumed to be 2 k USD. The values of cost for each scenario are reported in Table 5. As shown in the table, the objective function for the second case is comparatively lower than that of the first case, which indicates the advantage of the proposed probabilistic RCM-scheduling approach. In addition,
the total customer interruption cost in “case II” is significantly lower than that of “case I”, since executing PM actions reduces the forced outage occurrence of the equipment, which in turn reduces the outage frequency and duration experienced by the customers. The interruption cost for each EDN load point is demonstrated in Figure 6. As shown in this figure, in all of the load points, the value of interruption cost in the second case is lower than that of the first case. These results imply that through the presented method, the PM budget is allocated in a way that the outage costs of important customers, namely, industrial (bus number 6–8 and 19–24) and commercial (bus number 5, 13, 18, and 29) customers, are reduced higher than other customers.

Table 6 shows the critical component selected for the PM action in case II. As shown in this table, all lines except L6 and L27 and transformers 9, 10, and 31 are selected for PM actions. Transformers 9, 31, and 10 supply industrial customers with an average load equal to 1.5, 1.5, and 1 MW, respectively. As shown in Figure 5, industrial customers have higher outage cost in comparison to the other customers, and so the results obtained in case II would be reasonable.
Scenario 2: Sensitivity study on the available PM budget

In order to evaluate the effect of the available PM budget, a sensitivity study is conducted in this section on this parameter. The values of the related costs are demonstrated in Table 7.

As shown in this table, the PM actions are economically justifiable with regard to PM budget variation. These results illustrate that with the increasing PM budget, the values of $C^{CI}$ and $C^{ENS}$ are reduced until the PM budget meets the value of 4.38 k USD. This implies that implementing PM action is not cost-effective for the PM budget higher than 4.38 k USD. A list of the critical components for each budget value is shown in Table 8. As shown in the table, in the budget value equal to 1 k USD, no transformers are selected for PM action. With the increasing value of the PM budget, transformers 9 and 31 are the first ones selected for PM measure. Following that, transformers 10, 16, 17, 24, 7, 25, 6, 37, and 38 are then selected. All of these transformers supply industrial and commercial customers whose outage costs are high. Additionally, the location of the RCS in the network is such that due to the outage of line L6 and L27, only load points 6 and 27 are disconnected, respectively, and other load points can be restored with switching. Therefore, as shown in Table 8, with the increasing value of the PM budget, all lines would be selected for the PM except lines L6 and L27.

### Table 4 Fault location time, switching time, repair time and maintain time

|                | Fault location time | Switching time | Repair time for transformers | Repair time for lines | PM implementation for transformers | PM implementation for lines |
|----------------|---------------------|----------------|-----------------------------|-----------------------|-----------------------------------|-----------------------------|
|                | 0.5 h               | 0.5 h          | 4 h                         | 2 h                   | 2 h                               | 0.5 h                       |

### Table 5 Obtained results for reliability-centred maintenance-scheduling cases

| Case | $C^{CI}$ (k USD) | $C^{PM}$ (k USD) | $C^{CM}$ (k USD) | $C^{ENS}$ (k USD) | OF (k USD) |
|------|-----------------|-----------------|-----------------|-----------------|------------|
| Case I | 215             | 0               | 12.4            | 3.79            | 231.19     |
| Case II | 58.8           | 1.99            | 9.89            | 1.61            | 72.29      |

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### Table 1 Energy price [22]

| Customer category | Residential | Commercial | Industrial |
|-------------------|-------------|------------|------------|
| Electricity price ($/kWh) | 0.05 | 0.12 | 0.12 |

### Table 2 The required labour hours, labour cost, and material cost for corrective maintenance (CM)

| Equipment      | $C_{rep}^{\text{CM}}$ (USD/h) | $L_{hr}^{rep}^{\text{CM}}$ (h) | $C_{mat,rep}^{\text{CM}}$ (USD) |
|----------------|-------------------------------|--------------------------------|--------------------------------|
| Lines          | 19.7218                       | 10                             | 138.37                         |
| Transformers   | 54.7745                       | 60                             | 230.065                        |

### Table 3 The required labour hours, labour cost, and material cost for preventive maintenance (PM) [40]

| Equipment      | $C_{main}^{\text{PM}}$ (USD/h) | $L_{hr}^{main}^{\text{PM}}$ (h) | $C_{mat,main}^{\text{PM}}$ (USD) |
|----------------|-------------------------------|--------------------------------|--------------------------------|
| Lines          | 8.07                          | 8                              | 65.7528                         |
| Transformers   | 54.7745                       | 60                             | 230.065                         |

As shown in this table, the PM actions are economically justifiable with regard to PM budget variation. These results illustrate that with the increasing PM budget, the values of $C^{CI}$ and $C^{ENS}$ are reduced until the PM budget meets the value of 4.38 k USD. This implies that implementing PM action is not cost-effective for the PM budget higher than 4.38 k USD. A list of the critical components for each budget value is shown in Table 8. As shown in the table, in the budget value equal to 1 k USD, no transformers are selected for PM action. With the increasing value of the PM budget, transformers 9 and 31 are the first ones selected for PM measure. Following that, transformers 10, 16, 17, 24, 7, 25, 6, 37, and 38 are then selected. All of these transformers supply industrial and commercial customers whose outage costs are high. Additionally, the location of the RCS in the network is such that due to the outage of line L6 and L27, only load points 6 and 27 are disconnected, respectively, and other load points can be restored with switching. Therefore, as shown in Table 8, with the increasing value of the PM budget, all lines would be selected for the PM except lines L6 and L27.
Scenario 3: Sensitivity study on the CDF due to scheduled outages ($CDF^{S}$)

In order to evaluate the effect of CDF due to scheduled outages ($CDF^{S}$), a sensitivity study is conducted in this section. The available budget for PM actions is assumed to be 4.38 k USD. The obtained results are demonstrated in Table 9.

As shown in the table, by increasing the value of $CDF^{S}$, the advantage of the PM actions is reduced, and so the number of selected components for the PM actions would consequently be reduced. When the value of $CDF^{S}$ is equal to $CDF^{NS}$, no transformers are selected for the PM actions. This is due to the fact that, as shown in Table 2 and 3, the labour and material cost for PM and CM actions are assumed to be equal for transformers. So, in the same value of $CDF^{S}$ and $CDF^{NS}$, there is no advantage in performing PM for transformers. The results of this table illustrate that the importance of EDN components for PM actions is decreased as the value of $CDF^{S}$ is increased.

7 | CONCLUSIONS

In this study, a probabilistic RCM-scheduling methodology is presented in which the PM and CM actions are simultaneously scheduled. The most significant advantage of the approach is that the critical components of EDN would be economically justifiable subject to the value of economic parameters such as CDF due to non-scheduled outages $CDF^{NS}$ and CDF due to scheduled outages $CDF^{S}$. The results show that the criticality degree of EDN components for PM actions is reduced as the value of $CDF^{S}$ is increased. Whatever the customers are equipped in terms of backup services such as diesel generators and uninterruptible power supply sources, the value of $CDF^{S}$ is lower and in turn the advantage of the PM actions would
be higher. Additionally, through the method presented in this study, the financial resources of the PM are economically allocated with regard to budget constraints. The proposed method presented in this study can be developed in future studies by using four or five-state MM which is more adaptable with the component’s lifecycle in the presence of PM actions. Also, this method will enable us to evaluate the effect of implementing an online condition monitoring system for promoting PM efficiency, which will be pursued in the future.

**NOMENCLATURE**

**Sets**

- $\Omega^{LP}$ set of network load points.
- $\Omega^{Ct}$ set of EDN contingencies.
- $\Omega^l$ set of network line sections.
- $\Omega^t$ set of network transformers.

**Constants**

- $D_j / Q_j$ active/reactive power demand of bus $i$ (kW/kVAr).
- $r_{ij}$ outage time should be tolerated by customers connected to load point $i$ due to occurrence of contingency in component $j$ (hour).
- $r'_{ij}$ outage time should be tolerated by customers connected to load point $i$ due to PM implementing in component $j$ (hour).
- $l_{ij}$ length of the line section $i$ (km).
- $\hat{p}_{ij}$ electricity price at load point $i$ ($$/kWh).
- $k_{ij}^{HF}$ failed state to healthy state rate for equipment $j$.
- $\lambda_{ij}^{HF}$ healthy state to failed state rate for equipment $j$.
- $P_{ij}^{HMF}$ probability of Healthy/Minor failure/failed states of equipment $j$.
- $\lambda_{ij}^{HM}$ healthy state to minor failure state rate for equipment $j$.

**Variables**

- $\mu_{ij}^{MF}$ minor failure state to healthy state rate for equipment $j$.
- $\theta_{ij}$ the angle of $Y_{ij}$.
- $L_{br_{ij}}$ number of working hours required for repair of $j$th equipment.
- $L_{br_{ij}}^{main}$ number of working hours required for maintenance of $j$th equipment.
- $\bar{V}_{ij}/V_{ij}$ maximum/minimum allowable voltage level of load point $i$.
- $T_{ij}$ maximum allowable current level of line $i$.
- $C_{ij}^{rep}$ per hour labour cost of doing Maintenance action on $j$th equipment (USD/h).
- $C_{ij}^{mat,rep}$ cost of material used in repair of $j$th equipment (USD).
- $C_{ij}^{mat,main}$ cost of material used in doing maintenance action on $j$th equipment (USD).
- $TAB_{PM}$ total PM available budget.

**Functions**

- $OF$ objective function.
- $C_{IC}$ customers’ interruption cost (USD).
- $C_{ENS}$ utility revenue lost due to energy not sold (USD).
- $CDF_{j}^{NS}$ customer damage function of customers connected to load point $i$ after a non-scheduled outage occurrence.
- $CDF_{j}^{S}$ customer damage function of customers connected to load point $i$ after a scheduled outage occurrence.
- $C_{PM}$ preventive maintenance cost (USD).
- $C_{CM}$ corrective maintenance cost (USD).

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APPENDIX A

%\% genetic algorithm (GA) parameters%\% MaxIt = 10,000; % maximum number of iterations nPop = 100; population size pc = 0.7; % crossover percentage nc = 2*round(pc*nPop/2); % number of off springs (also parents)
gamma = 0.4; % extra range factor for crossover  
\( p_{m} = 0.3; \) % mutation percentage  
\( n_{m} = \text{round}(p_{m} \times n_{\text{Pop}}) \) % number of mutants  
\( \mu_{u} = (1/174); \) % mutation rate  

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**Failure rate and repair rate for two-state Markov model (MM)**

[41]:  
Failure rate of \( i \)th component.  
\[ \lambda_{i} = \frac{\text{number of failures of component } i}{\text{total working time of component } i} \]  
Repair rate of \( i \)th component.  
\[ \mu_{i} = \frac{\text{number of repair of component } i}{\text{total repair time of component } i} \]

**Failure rate and repair rate [41] for three-state MM:**  
\[ \lambda_{MH}^{2} = \frac{\text{number of transition from minor state to healthy state}}{\text{total repair time in minor state}} \]  
\[ \mu_{FH}^{2} = \frac{\text{number of transition from failed state to healthy state}}{\text{total repair time in failed state}} \]  
\[ \lambda_{HM}^{2} = \frac{\text{number of transition from healthy state to minor state}}{\text{total working time in healthy state}} \]  
\[ \lambda_{MF}^{2} = \frac{\text{number of transition from minor state to failed state}}{\text{total working time in minor state}} \]