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A Robust Reliability-Based Maintenance Planning for Power Systems

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Abstract

Power company operators have emphasized and used equipment maintenance planning concerning the increased number of worn-out equipment in power networks and limited resources to reduce the possibility and the risk of failure as one of the asset management tools. Reliability–based maintenance defines a comprehensive and optimal program for managing repair resources, determining dominant failure modes with failure mode and effect analysis, and selecting the time and strategy for each failure mode's repair. This paper proposes a suitable method based on a weighted reliability index for prioritizing the distribution network components to determine a robust reliability-based maintenance strategy at two levels. The first level introduces the robust reliability-based prioritization for power distribution station feeders and the robust reliability-based maintenance strategy prioritization for sample feeder components at the second level. Furthermore, this article presents a new method for optimal maintenance of distribution network components to improve the distribution network reliability by considering the cost. Moreover, this method presents a lifetime efficiency index model and an optimal bat algorithm method to achieve optimal maintenance for power transformers. The power transformer failure rate is simulated by a Weibull distribution function with a suitable approximation and the lifetime of the power transformer by carrying out maintenance, using the Taylor series in the Weibull distribution function in the MATLAB tool. The obtained results in terms of cost and response time compared to other methods show that the proposed method can obtain higher quality solutions than other studied methods for the problem of optimal maintenance.

Keywords: Maintenance, Bat Algorithm, Reliability, Sectioner, Transformer

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1- Introduction

Power company operators have emphasized and used equipment maintenance planning concerning the increased number of worn-out equipment in power networks and limited resources to reduce the possibility and the risk of failure as one of the asset management tools. Reliability-based maintenance defines a comprehensive and optimal program for managing repair resources, determining the dominant failure modes with failure mode and effect analysis, and the time and repair strategy of each failure mode. Maintenance studies are classified into two categories, equipment-based and system-based. Equipment-based maintenance determines the equipment's optimal maintenance policy for increasing the equipment's reliability in the operation period without taking into account the operation constraints. However, the system-based studies optimize the equipment maintenance system planning through the probability distribution function of equipment failure, to minimize the annual maintenance cost taking into account the operation constraints. These studies were conducted in two distribution and transmission networks. The consequences and duration of an equipment interruption due to damage and repair and maintenance in two distribution and transmission networks are different. In general, the maintenance methods at the equipment level are categorized into three general categories: no maintenance, time-based, and condition-based. In the no-maintenance method, no maintenance is done on the equipment until it is damaged. In the time-based maintenance method, every piece of equipment is maintained at specific time intervals regardless of its state of damage. [1]

Regional electricity companies strive to reduce their current costs for more profit and to maintain competitiveness in electricity markets. Therefore, the maintenance cost reduction, which constitutes a significant part of the operating costs of the transmission network, is of double importance. On the other hand, electrical network equipment including transformers, transmission lines, and power switches that have been in use for the past few decades have naturally worn out with the increase in lifespan. As a result, currently, regional electricity companies are facing a big challenge of worn-out equipment that requires comprehensive maintenance planning to preserve the system reliability at an acceptable level and avoid heavy costs related to blackouts. Also, the new competitive environment requires the regional power companies to prefer maintenance of the current equipment instead of replacing worn-out equipment with very high costs. Accordingly, the preventive maintenance program is a challenging issue for regional electricity companies making them look for the highest level of reliability achieved by limited human and financial resources in preventive maintenance planning. The power network should be operated with minimal adverse conditions to maintain the reliability and availability of network equipment at an acceptable level. This article presents a reliability-based maintenance planning method in power systems.

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2- Maintenance backgrounds

Maintenance offers increased productivity and efficiency in various ways, so it is considered an important issue in every industry. Effective and in-time maintenance increases safety and saves money by predicting the failure time reducing the repairs cost and minimizing devices operation failure time intervals. All human artifacts and devices have a limited life span with the possibility of device failure or even the entire system at any moment. We know that each device has a reliability and optimal performance requiring a lot of costs to increase to a higher level. In turn, the increased cost reduces the profitability of the product. However, there are good solutions to enhance the productivity of the existing facilities with detailed and continuous planning so that the devices work with maximum efficiency and accessibility. In most cases, preventive maintenance is not effective in the functioning of the system, and in many cases, preventive maintenance causes the deterioration of the functional condition of objects because it provides more opportunities for imposed failures on the system. [11] Reliability-based maintenance is known by most experts as the most cost-effective method for creating and developing maintenance strategies at the global level. The proper use of this method is associated with the rapid achievement of stable recovery in various fields. Increasing the equipment availability and reliability improving the product's quality, and reducing accidents with safety and environmental consequences include the main achievements of using reliability-based maintenance. Recently, the majority of repair strategies have shifted from a time-based strategy, in which inspection, replacement of parts, or repairs are carried out only based on the operating time of the equipment or calendar time, to reliability-based and condition-based strategies, where the equipment conditions are determined with the help of analyzes including the sound, temperature, oil, vibration, etc. analysis to take the necessary measures. These strategies are more focused on operating conditions and seek higher resource efficiency with a more effective maintenance category. In fact, by reliability-based maintenance, we strive to obtain the maximum reliability of the system, not individual subcategories, and since all the system subcategories enjoy the same importance and priority, therefore, we must focus on the critical components of a system with a direct impact. Reliability-based maintenance determines the relationship between system components' behavior and system reliability by evaluating the system failure causes. Electricity distribution networks are considered one of the vital arteries of societies with their sensitivity to providing energy for human societies' activities in today's world. The successful performance of these networks is the constant and reliable supply of electricity to customers, which can only be obtained by predicting faults and preventing accidents. Reliability-based maintenance programs play important roles in reducing the direct and indirect costs of the organization and improving network reliability. In the meantime, the entire network's reliability is determined by defining the network’s components' reliability. Thermography and corona methods include methods for identifying defects before accidents and blackouts occur. In the following, we briefly provide the readers with various types of maintenance methods and the advantages and disadvantages of each.

2-1 Maintenance types

- Corrective maintenance: In this approach, maintenance tasks are performed only after failure detection with no intervention is done until the time of failure. There are two types of corrective maintenance: planned or break-down maintenance and unplanned or emergency maintenance. Break-down maintenance is the process of performing maintenance on a failed equipment with little effects and without risk that are controllable and economical. In the breakdown maintenance, there is a prior preparation regarding the defect, cause, corrective measures, repair instructions, tools, parts and other necessary requirements, and the relevant information for any maintenance process with no prior incidence is documented so that to refere yo in case of necessarily; therefore, break-down maintenance processes should be planned in a preventive or predictive manner and according to the frequency of repetition and the importance of the equipment.
- Emergency maintenance: Emergency maintenance deals with sudden breakdowns or a potential equipment failures. Usually, there is no prior preparation about the type of problems and how to face them. The reason is that actions and experiences are not recorded and analyzed in these organizations (the absence of knowledge management).
- Preventive maintenance: The purpose of preventive maintenance is to protect equipment before failure, which includes two types of Time-Based Maintenance (TBM) and Condition-Based Maintenance (CBM) maintenance.
  - Time-Based Maintenance (TBM): Time-based maintenance divides maintenance activities into two categories of routine activities and different levels of major repairs based on calendar time or operating hours. This maintenance type method has a good performance, but it may cause excessive activities or even failure before planned major repairs. In fact, this method is usually incomplete and cannot return the system to its initial state and inevitably reduces the system reliability.
  - Condition-Based Maintenance (CBM): This maintenance type is based on the principle that various engineering technologies knowledge be adopted to tests the equipment parts prior to parts replacement or renewing to evaluated their technical conditions in terms of the possibility of continued correct operation or the possibility of failure.
- Total productive maintenance (TPM): It was defined in 1971 by Japanese Institute of Plant Maintenance. TPM is a holistic approach to equipment maintenancei ncluding the active engaging employees at all organizational levels to improve the efficiency and safety of production and expand the effectiveness of equipment through the elimination of six major breackdowns, including equipment failure due to emergency failures, machines' set up and adjustment, short-term idling and stopage, reduced speed, reduced yeild, and process

defects (rework). This maintenance method is a practical method for effective maintenance and improvement of equipment and overall integrity of production operations. Its productivity means a spontaneous and proactive approach to the conditions and operation of the equipment, the purpose of which is to continuously improve the productivity and overall performance of the institution, and its totality means the principle and philosophy of inclusiveness that deals with all aspects of equipment used in all areas of an operating company and the people who set up, adjust and maintain this equipment.

- Reliability-based maintenance (RCM): this method is a process to optimize the maintenance of a system or equipment to ensure its reliability and performance so that each equipment can perform their main tasks in the best way. In other words, this method determines the appropriate amount and type of maintenance methods to reach the maximum ability and inherent reliability of the equipment based on the relevant working conditions. To achieve this goal, reliability-based maintenance analyzes each failure mode and determines the most suitable method according to reliability indicators , cost, etc. Figure 1 shows the maintenance types and methods adopted by the reliability-based maintenance system.

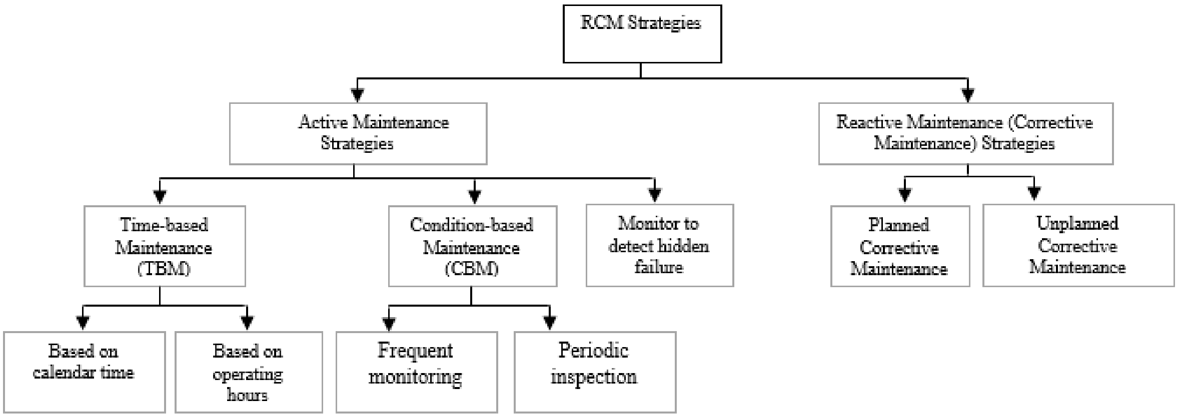

Fig. 1 Reliability-based maintenance system strategies [12]

2-2 Maintenance types advantages and disadvantages

Table 1 shows some of the advantages and disadvantages of using different maintenance methods in organizations. Examining the advantages and disadvantages of different maintenance types shows that the reliability-based maintenance is more advantegous than disadvantagous with its disadvantages are controllable. Also, since this method adopts a combination of different maintenance approaches and determines the appropriate strategy according to the degree of sensitivity of the equipment and the risk of failure, it bears the

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advantages of all methods and moderates their disadvantages. Therefore, it seems logical to use it in the organization to increase the system reliability and optimize the costs.

Table 1. Maintenance types and their advantages and disadvantages

Maintenance types	Advantages	Disadvantages
Corrective Maintenance	Less use of spare parts, lower initial costs	The need for a strong and ready maintenance team, Low quality of repairs due to urgency, Wasting semi-finished products and materials for the increased the maintenance time (compared to the standard) due to the observation of minor problems and breakdowns, The impossibility of accurate production planning
Time-based Maintenance (TBM)	Increase equipment availability time, Minimize parts inventory, Improve safety and pollution control Reduce defective products, Reduce the finished price of products, Reduce the atmosphere of tension and anxiety in the maintenance sector, Reduce overtime payments	High initial costs, Need to visit and inspect the equipment, Possibility of damage due to early failure, Consumption of more spare parts, Group replacement of parts that have not yet reached the end of their life span, Imposition of unwanted costs.
Condition-based Maintenance (CBM)	Reduce unexpected breakdowns, Order parts at the time of need, Increase the equipment life, Reduce stoppages and breakdowns.	Additional skills required (employee training) High investment cost, Potential savings are not easily understood by managers, High cost of reviewing each component, Unavailability of some components and parts.
Total productive Maintenance (TPM)	Involvement and promotion of employees, Maintenance and efficiency of existing equipment, Discovere and fixing defects and	Expensive and time-consuming to hold theoretical and practical training courses for all personnel, Change the organizational culture for the participation

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Maintenance types	Advantages	Disadvantages
	operational issues, Monitor and improve the effectiveness of the process, create and maintain a tidy, neat and orderly workplace, discover and fix inherent defects	of all employees in the maintenance affairs, High initial investment net
Reliability-based Maintenance (RCM)	Increase the accessibility and efficiency, Safety and health of the environment, Eliminate the stopping of machinery, More effective maintenance costs, Reduce the volume of routine activities by 40-70%. More useful life span of expensive items, Obtaina comprehensive data base, Motivating more people and better teamwork	100 % reliability, Extremely costly, Difficult to achieve and not the answer is not necessarily correct. Difficult to start using this method and it slowly shifts a time-based maintenance to a condition-based maintenance.

2-3 Reliability- based maintenance litreature

At first, we take into account a number of reliability-based maintenance papers in manufacturing and industrial factories and companies. Ahmadi and Mokhtarzadeh (2019) examined indicators including the total operation without failure, predicted and actual repair time, the number of times the repairman repaired the equipment, the time of stopping in production and cost to prioritize the level of sensitivity of equipments for repairs and preventive maintenance.[24] In their studies, Pak-Aeen et al. (2017) classified related indicators into two categories: process indicators and results indicators , with process control indicators including planning and scheduling control and work request execution control, while the results control indicators include the number of stops, breakdown rate, average time between breakdowns and average repair time. [25] Sediqi Shiri (2018) analyzed the maintenance performance indicators including failure rate, reliability, average time between failures, average repair time, average waiting time for repair and average time out of service. [26] In his research, Farzin (2019) measured failure rate indicators , average time between failures, average repair time, reliability, overall effectiveness of equipment, production efficiency, equipment efficiency, production rate, wasted production and opportunity cost. [28] Behari et al. (2016) examined indicators such as failure rate, average time between failures, average repair time, accessibility and maintainability and maintenance cost to adopt the reliability-based maintenance in electricity distribution systems. [30] Oliveira et al. (2016) measured the rate of use of indicators including

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failure time, accessibility, economic issues, average repair time, average time between failures, the overall effectiveness of equipment from the relevant industry using a descriptive questionnaire; their results show that the amount of maintenance performance evaluation indicators adoption depends on the number of equipment, the number of maintenance staff, the total productivity of maintenance adoption and the maintenance management computer system adoption. [31] Extensive studies have been conducted regarding reliability-based maintenance system deployment in industrial and manufacturing plants. Abed (2010) adopted the failure analysis technique and its effects to identify potential failures and their effects. Then, he selected 10 potential failures with the highest risk priority number to carry out corrective projects to reduce their risk. After that, to increase the ability to identify the probability of failure, he used a condition-based maintenance (predictive maintenance) using tools such as a laser thermometer, clamp ammeter, etc. to analyze the temperature and the electric motor current, and finally he presented the index of the average time between failures and the average repair time before and after the implementation of reliability-based maintenance in a diagram format.[32] In their research, Sepri and Kiapi (2011) presented a strategy for maintaining the distribution network of Neka city - Mazandaran province - with reliability indicators and used Hierarchical Analytical Method to prioritize equipment for reliability based maintenance. In this research, first the feeders were prioritized and then the feeders were assigned into geographical areas using the software information system and finally the areas were prioritized, accordingly. Reliability indicators in their research included the definite number of unplanned cutouts, feeder blackout time and undistributed energy. [33] Alipour et al. (2011) examining two indicators , the average time to failure and the average repair time for equipment, concluded that the average time to failure in a ten-year trend is decreasing, and the average repair time is decreasing, contrary to expectations. Therefore, they showed the inefficiency of traditional (and time-based) maintenance strategies and the need to shift to new strategies such as reliability-based maintenance.[34] In their research, Pouraqababa et al. (2011) first investigated the reliability of Shahid Montazeri Isfahan power plant using the Markov model, and then using the results, they presented a preventive maintenance program for each unit to attain the highest reliability and accessibility. Accordingly, they used the Weibull distribution function and the results of the presented repair program showed that the highest possibile accessibility is attained through lowering the failure rate and increasing reliability. [35] In a research, Zhu et al. (2017) integrated the sequential incomplete maintenance policy with condition-based maintenance. The researchers developed a sequential maintenance model based on two improvement factors to predict the evolution of the failure rate function in different maintenance cycles. When the system reliability reached the threshold R, an incomplete preventive program was implemented on the system. But after that, they made an optimal preventive program including reliability threshold limit, number of preventive maintenance cycles and preventive program time intervals by minimizing the cumulative cost

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rate in the life cycle of the system based on Monte Carlo simulation.[38] Afifi (2018) addressed the reliability-based maintenance application on the steam production workshop. With the help of the root cause analysis techniques of the system failure, he identified the failure mode and its effect, potential errors and their causes and effects, and through critical analysis, he checked the criticality of each failure and then carried out various maintenance tasks based on findings and finally presented plans for the maintenance staff. He concluded a 25% reduced the manpower cost, 80% saved the equipment failure cost, with increased the system reliability. [39] Sarchiz et al. (2017) in their research entitled " reliability-based maintenance on the of electricity distribution systems Optimization" developed a mathematical model with accessibility and economy as its constraints. They acknowledged that preventive maintenance based on fixed or variable time intervals cannot be accepted without scientific planning based on technical and economic perspectives, therefore preventive maintenance strategies should be developed with the help of mathematical models based on interpretations. The real situation possibility should be considered and finally the mathematical models output should lead to determining the target requirements, priority and amount of preventive maintenance and reduce the life cycle costs of electrical equipment [40]. Bogaj (2020) in his research on the aviation industry, after explaining the steps required to implement reliability-based maintenance, found that available tasks can be determined in cases with minor importance of safety issues in the discussion of maintenance and acceptability and minimal cost suffice. However, in an industry like airplanes, failure and its severity analysis is important [41]. In a research, Dehghanian et al. (2016) presented a comprehensive plan for establishing reliability-based maintenance in electricity distribution systems. Therefore, at first, the necessary prerequisites for the implementation of reliability-based maintenance were reviewed, then in the second part, with the analysis, the key components were identified, potential basic errors were investigated and their possible causes, and followed by ranked and selected the possible maintenance strategies advantages using the cost analysis method [42]. In their research, shanmugantan et al. (2018) showed that the survival of aviation industries depends on their ability to optimize operating costs, and costs can be reduced by optimizing operating costs related to the operational equipment maintaining cost. The researchers first showed the significant difference between the machines with the help of variance analysis, then estimated the reliability with the help of Weibull distribution, and finally with the help of the control chart, they controlled the average index of time between failures. According to the results of the continuous monitoring of the average time between breakdowns, it is possible to identify the machines that are prone to breakdowns and allocate the necessary resources for maintenance. [44] In a research, Sinha Makhupadiia (2016) investigated the reliability-based maintenance adoption on a cone stone crusher machine. For this purpose, they used two different tools of potential failure states and their causes and effects and the total analysis time chart for reliability analysis. Their results showed that the dust sealing components, lubrication pipe, cover and cup are the main parts of

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the equipment and therefore they should be prioritized in the maintenance olanning. Also, the maintenance of the cone crusher is satisfactory, which means that preventive maintenance reduce repair costs and predict errors [45]. In a research, Batedi & kiakha (2019) integrated reliability-based maintenance with statistical techniques of forecasting and cost engineering for the equipment of the automatic part of the foundry to improve the maintenance programs and manage costs. At first, they found the criticality degree of machines using critical analysis, and then they calculated the error risk value adopting analyzing potential failures technique and their causes and effects. After that, they estimated the life time of the machines usingmachine vibration data and using non-linear regression. Later on, they used the non-linear regression analysis method to monitor the vibration and predict the vibration that causes failure using the equipment vibration data based on the ISO standard. Then they estimated the reliability parameters by drawing the probability diagram, and finally they adopted functions to calculate the machines planned and unplanned costs. Their results show that this model can better classify the system subsets based on criticality and costs [46]. Dejibala et al. (2017) conducted a research to optimize the maintenance policy in the largest chemical fertilizer producer in Algeria. At first, they evaluated the current maintenance policies using the Lavina questionnaire and suggested that it is better to use the reliability-based maintenance approach as an effective tool to optimize the dependence of production equipment. As an example, they applied this approach to the steam turbine generator as a vital equipment in the production process. Finally, they presented a new maintenance program based on reliability analysis using Weibull distribution and the method of analyzing potential critical errors and their causes [47]. Tu et al. (2015) conducted a comprehensive study on the reliability analysis method for the aircraft electronic system by using the dynamic fault tree approach based on the Marco chain. Reliability models were built using fuzzy dynamic fault tree modeling method, based on deep analysis of failure modes, their causes and effects. In their research, modular design was used to subdivide the dynamic fault tree into static and dynamic subsets. The static tree was solved with Wick's zero decision diagram and the dynamic tree was solved with the Marco chain method. Their findings showed that the proposed method is more flexible and consistent than the usual fault tree for fault detection and reliability estimation. [48]

3- The proposed algorithm

A distribution network includes different levels, each requiring a reliability analysis study. We first need the studied feeders data, including the length of each feeder, the failure rate and the duration of their repair to calculate the reliability indicators for the feeders of a distribution post (first level); Also, we need the amounts of unsupplied energy and the number of subscribers who have experienced interruptions per load point. The unsupplied energy per load point is obtained from the product of the unsupplied load in a certain period of time, which is shown in equation 1.

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$$C_{s_i} = \lambda_i.(f_i.P_i + c_i.P_i.r_i) \tag{1}$$

Where, C_{s_i} is the definitive cost of the ith load point [riyals/year]. f_i fixed interruption cost per kilowatt at the ith load point [riyals/ number of interruptions per kilowatt], c_i the cost of unsupplied energy at the ith load point [riyals/kWh] and p_i average power at the ith load point [kilowatts]. In the feeders of a distribution post of this paper, the values of the unsupplied energy is a known data of the problem, and for the loads of a distribution feeder, the values of the unsupplied load and definitive duration are reported as the known data of the problem. Now, for the feeders of a distribution post, having the failure rate and repair time for each feeder, the unavailability of electrical energy can be calculated by equation 2 at each load point.

$$U_i = \frac{\lambda_i}{\lambda_i + \mu_i} = \lambda_i.r_i \tag{2}$$

Where, U_i is the unavailability of component ith [number of failures ×hours/year], λ_i failure rate of component ith[number of failures/year], μ_i repair rate of component ith [number of repairs/year] and r_i duration of repair of component ith [hours]. As a result, the reliability indicators were calculated, including System Average Interruption Frequency Index (SAIFI), System Average Interruption Duration Index (SAIDI), Average Service Availability Index (ASAI), Average Energy Not Supplied (AENS) per feeder according to relations (3)-(7).

$$\text{SAIFI} = \frac{\sum_{i=1}^{n} \lambda_i \times N_i}{\sum_{i=1}^{n} N_i} \tag{3}$$

In Equation 3, N_i is the number of subscribers of the ith component and n is the total number of system load points. This index is usually expressed in terms of the number of common annual interruptions.

$$\text{SAIDI} = \frac{\sum_{i=1}^{n} U_i \times N_i}{\sum_{i=1}^{n} N_i} \tag{4}$$

$$\text{ASAI} = \frac{\sum_{i=1}^{n} N_i \times T_t - \sum_{i=1}^{n} U_i \times N_i}{\sum_{i=1}^{n} N_i.T_t} \tag{5}$$

In Equation 5, T_t is the total hours of the studied time period and it is equal to 8760 hours for one year. Equation 6 shows the total number of hours studied for all components for the time period of one year.

$$\sum_{i=1}^{n} N_i.T_t = N_t \times 8760 \tag{6}$$

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Where, N_t is the total number of components.

$$\text{AENS} = \frac{\sum_{i=1}^{n} L_{ci}.d_i}{\sum_{i=1}^{n} N_i} = \frac{ENS}{\sum_{i=1}^{n} N_i} \tag{7}$$

In Equation 7, L_{ci} is the unsupplied load of the ith load point [kilowatts], d_i is the critical duration of the ith load point [hours] and ENS is the unsupplied energy [kilowatt hours]. In the following, the reliability index values calculated for each feeder are normalized. The normalization process was done for all reliability indicators values of all the feeders to compare all the reliability indicators values of these feeders. Also, having the P, c, f, λ , and r values, the cost of common power cut per feeder can be calculated by Equation 8.

$$\begin{aligned} R(t) &= P(TTF > t) \\ &= \int_t^{\infty} f(u)du \\ &= 1 - \int_0^t f(u)du = 1 - F(t) = e^{-\frac{t}{\eta}}.\sum_{i=0}^{\beta-1} \frac{\left(\frac{t}{\eta}\right)^i}{i!} = e^{-\left(\frac{t}{\eta}\right)^{\beta}} \end{aligned} \tag{8}$$

In the above Equation, R(t) is the reliability function. Then, the value of the common power interruption cost is normalized per feeder. Therefore, the weight coefficients of the WI index can be calculated by dividing the normalized cost per normalized reliability index. The WI reliability index is calculated per feeder, since the WI index values per feeder comparison should be done by the same weighting coefficients. Finally, the feeders are prioritized for maintenance based on reliability indicators . The relations 9 and 10 were used to calculate the failure rate and energy unavailability for a radial feeder loads (second level), respectively, and then the repair time was calculated by Equation 11.

$$\lambda_s = \sum_{i=1}^{N} \lambda_i \tag{9}$$

$$U_s = \sum_{i=1}^{N} \lambda_i \times r_i \tag{10}$$

$$r_s = \frac{U_s}{\lambda_s} \tag{11}$$

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Having these Equations values, we can evaluate the main indicators of reliability of the distribution network. Figure 2. Shows the proposed method for reliability-based prioritization in the first and second levels flowchart.

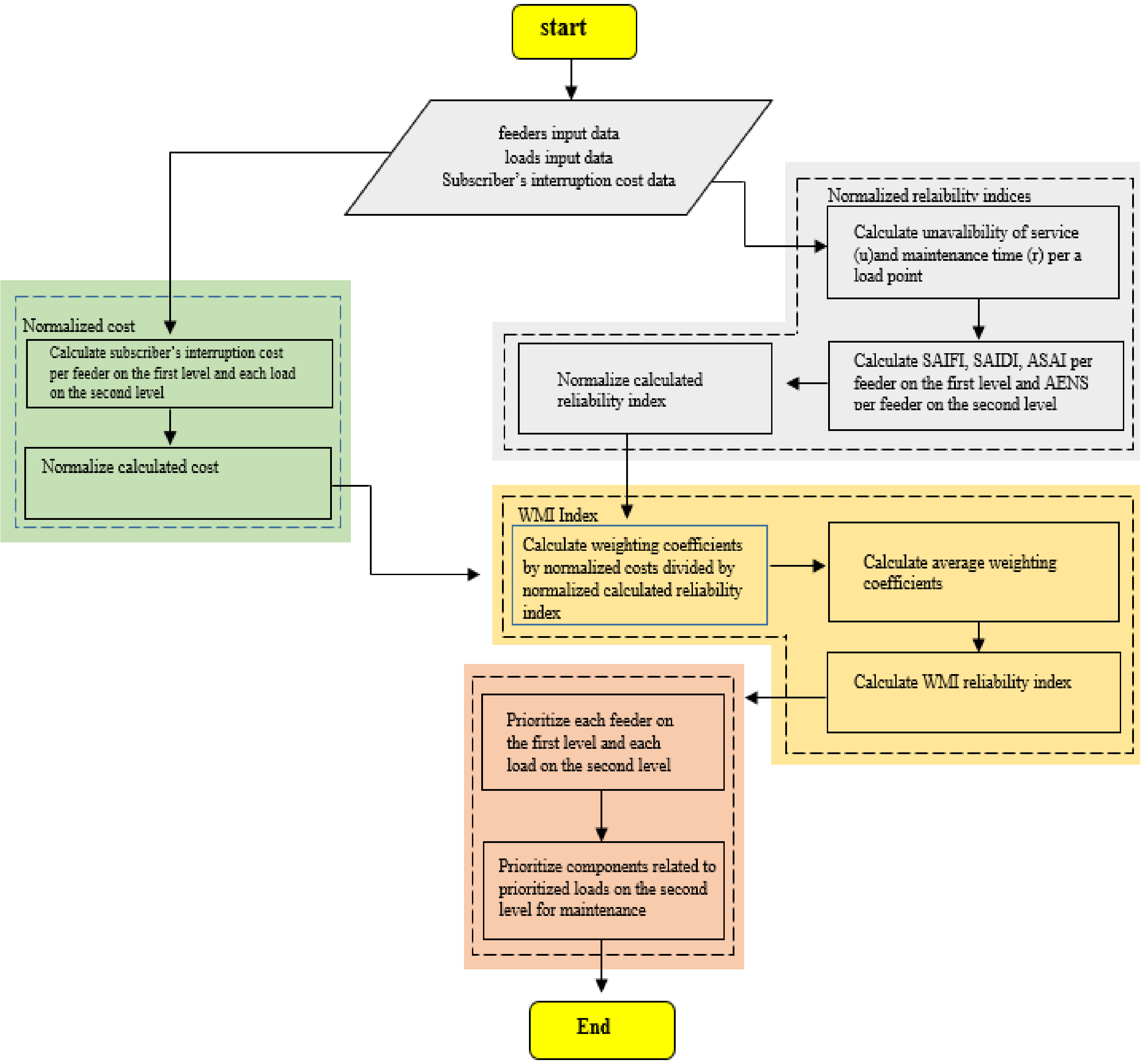

Figure 2. Flowchart of the proposed method for reliability-based prioritization in the first and second levels flowchart

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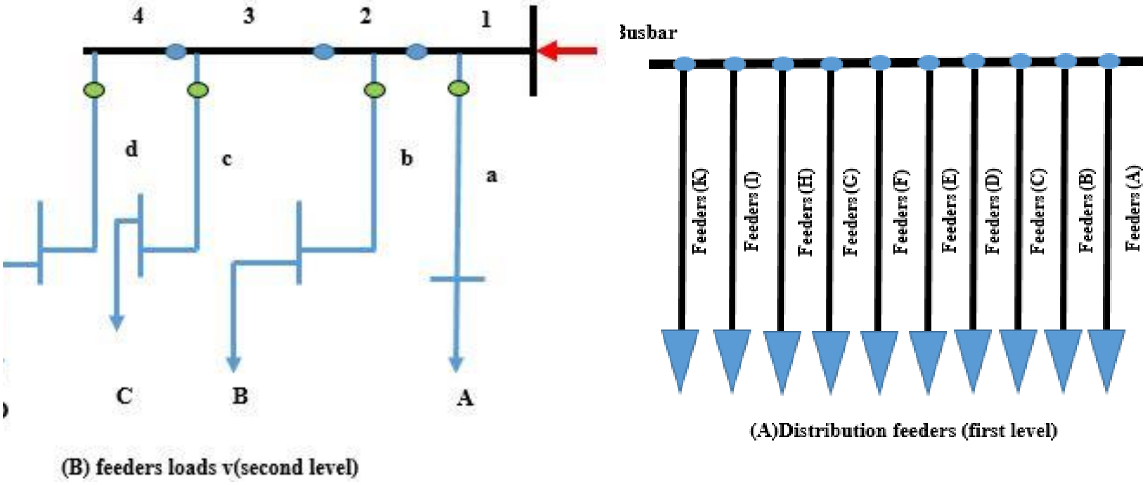
4- Discussion and results

This section addresses the results for the distribution network components prioritization problem to perform reliability-based maintenance and the simulation results for the optimization problem of reliability-based maintenance for power transformers. The proposed method has been developed using MATLAB software to solve the optimization problem of power transformer maintenance, and the results of this method have been compared with a number of other optimization methods.

4-1 Reliability maintenance planning by prioritizing power system components

This section addresses the process of prioritizing components to carry out maintenance strategy at two levels. Feeders and loads are ranked based on reliability in the first and second level, respectively. Also, each feeder feeds the allocated load independently from other feeders. Figure 3 presents a 10-feeder system. Also, Table 2 shows reliability parameters, including failure rate, repair time and energy unavailability for the loads per feeders of a calculated distribution post. The independence of feeders means that the time calculated for the repairs of each feeder is only for the loads on that feeder. According to the Table 2 outputs and the "unavailability" parameter, I is considered the most critical feeder in terms of repairs. Table 3 shows the normalized values of reliability indices. Among all the feeders in the network, the feeder will be more critical where the values of AENS, SAIFI and SAIDI have the highest values and ASAI has the lowest values. Accordingly, feeder I is identified as the most critical feeder.



(A)Distribution feeders (first level)

(B) feeders loads v(second level)

Figure 3. Sample network under study

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Table 2. Calculations of reliability indicators for different feeders in the system under study

Load feeder E			Load feeder D			Load feeder C			Load feeder B			Load feeder A			feeder
u	r	λ	u	r	λ	u	r	λ	u	r	λ	u	r	λ	
												5.4	20	0.27	A
									19.2	20	0.96				B
						13	20	0.65							C
			12.2	20	0.61										D
8.6	20	0.43													E

Load feeder K			Load feeder I			Load feeder H			Load feeder G			Load feeder F			feeder
u	r	λ	u	r	λ	u	r	λ	u	r	λ	u	r	λ	
												15.8	20	0.79	F
									6.2	20	0.31				G
						9.8	20	0.49							H
			20	20	1										I
19.4	20	0.97													K

Table 3. Calculations of reliability indicators and normalized values for different feeders in the system under study

AENS^{norm}	ASAI^{norm}	SAIDI^{norm}	SAIFI^{norm}	AENS	ASAI	SAIDI	SAIFI	feeder
0.060700	0.049965	0.27	0.0135	1.2140	0.9993	5.4	0.27	**A**
0.021440	0.049890	0.96	0.0480	0.4288	0.9978	19.2	0.96	**B**
0.018045	0.049925	0.65	0.0325	0.3609	0.9985	13	0.65	**C**
0.052775	0.049930	0.61	0.0305	1.0555	0.9986	12.2	0.61	**D**
0.034940	0.049950	0.43	0.0215	0.6988	0.9990	8.6	0.43	**E**
0.046160	0.049910	0.79	0.0395	0.9232	0.9982	15.8	0.79	**F**
0.057300	0.049965	0.31	0.0155	1.1460	0.9993	6.2	0.31	**G**
0.046950	0.049945	0.49	0.0245	0.9390	0.9989	9.8	0.49	**H**
0.051650	0.049885	1	0.0500	1.0330	0.9977	20	1	**I**
0.034015	0.49890	0.97	0.0485	0.6803	0.9978	19.4	0.97	**K**

Table 4 presents the weight coefficients and the average weight coefficients of WI index calculations. It should be noted that the comparison of WI index values for each feeder should be done by the same weight coefficients; Therefore, the average of the weighted coefficients has been calculated. In effect, the weighting coefficients belong to the reliability indicators and not to the cost of common power interruptions, and the weighting coefficients are weighted according to the effect of each of the indicators on the presented WI index. Another important point is that the costs of common power interruptions are not part of the data of the problem and the weight coefficients do not include them and should not be normalized along with the reliability indicators . Also, because the WI index is defined to compare the criticality of the components and its scale is not very important, the costs are normalized separately but on the same scale as the normalized reliability indicators (between zero and one).

Table 4. Cost calculations and weighting coefficients at the first level

k_4	k_3	k_2	k_1	Cost ^{norm}	Cost (Rials)	feeder
1/592883	0/0966	0/358104	7/162074	0/096688	4160748364	**A**
20/859515	0/4462	0/465863	9/317250	0/447228	19245492860	**B**
55/417013	0/9985	1/538462	30/769231	1	43035838170	**C**
9/328432	0/4916	0/807062	16/141246	0/492308	21185409410	**D**
7/142788	0/2493	0/580393	11/607860	0/249569	10739678500	**E**
14/439233	0/6653	0/843690	16/873797	0/666515	28682045370	**F**
1/983997	0/1136	0/366719	7/334387	0/113683	28682081396	**G**
9/122407	0/4278	0/874076	17/481510	0/428297	18430820530	**H**
11/571346	0/5963	0/597660	11/953200	0/597660	25719009722	**I**
18/758724	0/6367	0/657812	13/156247	0/638078	27458293930	**K**
15/021634	0/4722	0/676755	14/179680	**Average**		

Figure 4 shows the WI index comparison of the calculated weight coefficients average values at the first level; according to the figure, the weight coefficients k 4 and then k1, which belong to AENS and SAIFI, respectively, have the greatest influence on the presented WI index. Accordingly, at the first level, the higher the ratio of ENS to the total number of subscribers for a feeder, AENS value will be higher and as a result WI index value will be higher. The higher the value of the WI index for a component, the more critical and important that component is. Similarly, at the first level, after the value of the ratio of ENS to the total number of subscribers for a feeder, the higher the value of interruptions or the failure rate of the feeder, the higher the value of SAIFI, and as a result, the value of the WI index will be higher and will have a greater impact on the importance and criticality of that feeder. According to the cost/benefit studies, it is better to perform optimal maintenance on components of higher importance.

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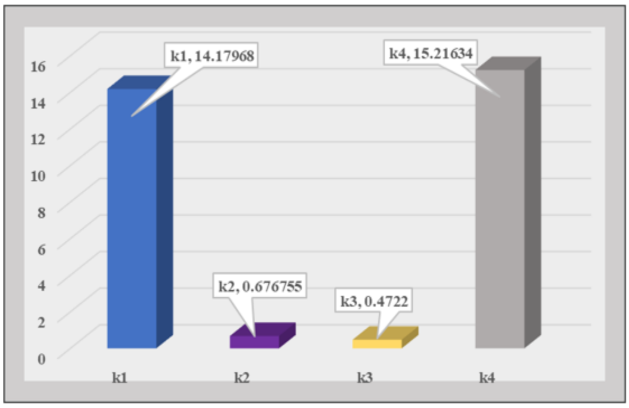

Figure 4. Average weighted coefficients of the WI index at the first level

Table 5 shows the WI index calculations by weight coefficients and normalized reliability indicators. According to the mentioned table, the value of WI index for feeder I is greater than other feeders; Therefore, Feeder I is more critical than other feeders, and optimal maintenance should be done on this feeder first.

Table 5. WI index calculation at the first level by the average weighted coefficients and normalized reliability indicators

WI	**Feeder**		WI	**Feeder**
36/2357	F		26/1918	A
26/2789	G		33/5207	B
28/1583	H		23/9088	C
43/7054	I		33/2342	D
37/5758	K		22/8871	E

Maintenance based Prioritization is done on each of the reliability indicators for ten sample distribution feeders with the results are presented in Table 6. The WI index is more important than other studied indicators because it considers all the important studied indicators by weight coefficients and also the cost. According to Table 6, if SAIFI or SAIDI or ASAI or WI is more important for the system, feeder I should be the first priority for maintenance; however, if the AENS index is more important for the system, feeder A should be the first priority for maintenance. Based on WI index, feeder I should be the first priority for maintenance because the value of WI index for feeder I is higher than other feeders. At the first level, because the loads of the feeders are independent from each other, feeder I has the first priority in terms of SAIFI because its failure rate is higher than other feeders; Feeder I has the first priority in terms of SAIDI because its unavailability is higher than other feeders. According to ASAI, feeder I has the first priority because its unavailability is more than other feeders. Feeder A has the first

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priority in terms of AENS index because the ratio of ENS to the total number of its subscribers is higher than other feeders. In general, feeder I has a higher priority for maintenance than other feeders, because according to the WI index, its interruption has a greater impact on the cost than the interruption of other feeders.

Table 6. Prioritization of maintenance based on each of the reliability indicators for the feeders of a distribution post

WI	AENS	ASAI	SAIDI	SAIFI	**feeder**
8	1	8	10	10	**A**
4	9	2	3	3	**B**
9	10	4	5	5	**C**
5	3	5	6	6	**D**
10	7	7	8	8	**E**
3	6	3	4	4	**F**
7	2	8	9	9	**G**
6	5	6	7	7	**H**
1	4	1	1	1	**I**
2	8	2	2	2	**K**

The second level focuses on a four loads sample radial feeder components. The reliability studies were carried out on the feeder loads to prioritize the components of this radial feeder maintenance, such as the main and secondary lines, and finally, the loads components with the greatest impact on the feeder reliability have been prioritized in the order of importance. At this level, the sample feeder components are interdependent. At the second level, an example radial feeder is analyzed as shown in Figure 3-b. The total number of the main and secondary lines of this feeder sections is equal to eight sections, the main sections are marked with the numbers 1, 2, 3 and 4 and the secondary sections are marked with the letters a, b, c, and d. therefore, the loads connected to this feeder are shown with letters A, B, C and D. Reliability indicators have been evaluated for these eight sections. In the second level, the reliability parameters such as failure rate, repair duration and energy unavailability for the loads of a sample distribution radial feeder are calculated in Table 7. According to the results, different parts of this radial feeder can be dependent on each other, and interruptions in one part may cause interruptions of other parts from this feeder, and as a result, the interruptions of one part may cause the subscribers of this feeder to face interrupted electricity for several times. The main and lines repair time are 4 and 2 hours, respectively. The repairing time for the main lines with no interruption on the intended load is assumed to be 0/5 hours. For example, according to Table 7, for the failure rate of load A, 0/75 [number of failures per year] has been obtained,

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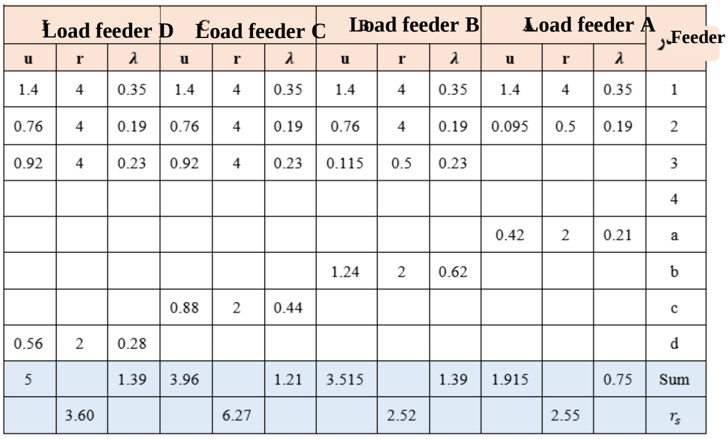
which is the total failure rate of different parts of this radial feeder. Also, for the amount of unavailability of load A, [1/915] the number of failures hours/years was obtained, which is the sum of the unavailability of different parts of this radial feeder. Finally, for the repairing time of load A, the value of 2/55 has been obtained, which is the result of dividing the unavailability of load A by the failure rate of load A.

Table 7. Reliability parameters analysis for loads of a distribution feeder



Load feeder D			Load feeder C			Load feeder B			Load feeder A			Feeder
u	r	λ	u	r	λ	u	r	λ	u	r	λ	
1.4	4	0.35	1.4	4	0.35	1.4	4	0.35	1.4	4	0.35	1
0.76	4	0.19	0.76	4	0.19	0.76	4	0.19	0.095	0.5	0.19	2
0.92	4	0.23	0.92	4	0.23	0.115	0.5	0.23				3
												4
									0.42	2	0.21	a
						1.24	2	0.62				b
			0.88	2	0.44							c
0.56	2	0.28										d
5		1.39	3.96		1.21	3.515		1.39	1.915		0.75	Sum
	3.60			6.27			2.52			2.55		r_s

Table 7 presents distribution feeder reliability calculations, with the results in Table 8. To improve the reliability indicators of this feeder, the reliability of each load of this feeder must be evaluated and the components with the bigger maintenance effect on increasing the reliability of the feeder loads and thus increasing the reliability of the entire distribution feeder are identified with the maintenance strategy should be done accordingly.

Table 8. Calculation of reliability indicators for a feeder

SAIFI	SAIDI	ASAI	AENS	feeder
1/149	3/420	0/9996	9/677	Feeder Figure 3-4

Table 9 presents the normalized values of reliability indicators for feeder loads. The SAIFI value for loads B and D is equal and higher than other loads of this feeder because the loads B and D failure rate is equal and higher than the failure rate of loads A and C. Also, the ASAI and SAIDI values for load D are larger than other loads for the unavailability of load D. The AENS index value for load D is higher than other loads because the ENS ratio to the total number of subscribers is higher than other feeders. All studied reliability indicators are normalized to the same scale for all loads.

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Table 9 Calculation of reliability indicators for the loads of a feeder

AENS norm	ASAI norm	SAIDI norm	SAIFI norm	AENS	ASAI	SAIDI	SAIFI	feeder
0/859189	0/079531	0/152347	0/059666	10/8	0/9997	1/915	0/75	**A**
0/715990	0/079523	0/279634	0/110581	9	0/9996	3/515	1/39	**B**
0/424025	0/079515	0/315036	0/096261	5/33	0/9995	3/960	1/21	**C**
1	0/079507	0/397772	0/110581	12/57	0/9994	5	1/39	**D**

Common power interruption costs, costs normalized values and weight coefficients were calculated per feeder loads, and then the weight coefficients average values were calculated. Table 10 presents all calculated values.

Table 10 Calculation of cost and weighting coefficients in the second level

K_4	K_3	K_2	k_1	Cost ^{norm}	Cost (Rials)	feeder
0/202122	0/013811	1/139904	2/910552	0/173661	1339384475	**A**
0/944786	0/053793	2/419080	6/117299	0/676457	5217258041	**B**
0/316158	0/078092	3/117450	10/202564	0/982109	7574634071	**C**
1	0/079507	2/514003	9/043145	1	7712620346	**D**
1/115767	0/056300	2/297609	7/068390	**Average**		

Figure 5 shows that the weight coefficients k_1 and then k_2, which belong to SAIFI and SAIDI, respectively, have the greatest effect on the presented WI index; Therefore, in the second level, the higher the value of the failure rate for the load, the greater the value of SAIFI, and as a result, the value of the WI index will be greater. The higher the value of the WI index for a load, the more critical and important the load is; also, in the first level, following the value of the failure rate for a load, the duration of the load is longer, that is the SAIDI value will be higher, and as a result, the WI index value will be higher, and it will have a greater effect on the importance and criticality of that load. From the perspective of cost/benefit studies, it is better to perform optimal maintenance on components associated with more critical loads. The WI index is normalized and calculated by the average of weighted coefficients and reliability indicators per feeder loads and is listed in Table 10.

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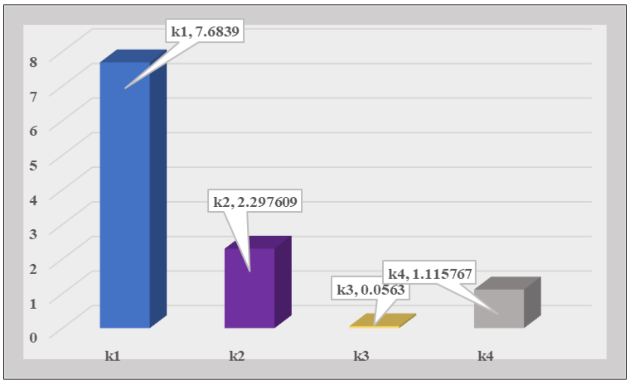

Figure 5. Average weighted coefficients of the WI index at the second level

Table 11 shows that the WI index value for load D is higher than other loads of this feeder, and this means that load D is more critical than other loads, and optimal maintenance should be performed first on this load components.

Table 11. Calculation of the WI index at the second level by the average weighted coefficients and normalized reliability indices

WI	**Load feeder**
21/8078	A
27/9994	B
23/6546	C
35/3946	D

Table 12 presents distribution feeder loads prioritizing according to the reliability indicators to carry out maintenance on the these loads components. According to the mentioned table, if SAIFI is more important for the system, the components related to loads B and D, i.e. main lines 2 and 3, sub-line b, main line 4 and sub-line d should be the first priority for maintenance. Also, if SAIDI or ASAI or AENS or WI are important for the system, the load D components, i.e. main line 4 and sub-line d, should be considered as the first priority for maintenance. In general, given that the load D components interruption has a greater impact on the cost than the interruption of other components; they are the priority to carry out the maintenance process. In the second level, loads B and D are considered the first priority according to SAIFI because their failure rate is the same and higher than other loads; in addition, because the unavailability value for this load is higher than other loads, load D has the first priority according to SAIDI. Load D has the first priority according to ASAI because the value of unavailability for this load is higher than other loads. Load A has the first priority in terms of AENS index because the ratio of ENS to the total number of subscribers is higher than other loads. In general, load D

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has a higher priority for maintenance compared to other feeders, because according to the WI index, the interruption of this load has a greater impact on the cost than the interruption of other loads.

Table 12. Prioritization of maintenance based on each of the reliability indicators for the loads of a feeder

WI	SAIFI	SAIDI	ASAI	AENS	Load
4	3	4	4	2	A
2	1	3	3	3	B
3	2	2	2	4	C
1	1	1	1	1	D

4-2- Evaluating the proposed method efficiency on the transformer optimal maintenance

The distribution network components do not enjoy the same importance. Transformer is one of the most important components of the distribution network. the results of the proposed method have been compared with other methods to show the effectiveness of the proposed method to obtain optimal maintenance of a power transformer. Table 13 presents Weibull distribution function parameters for power transformer failure rate modeling. Also, the shape and scale parameters should be selected appropriately to achieve the maximum useful life of 40 years for the power transformer under the minimum required reliability of 0.9. The Rayleigh distribution function (where $\beta = 2$) is a special and common case of the Weibull distribution function. According to the relationship, for $\beta = 2$ to achieve the maximum useful life of 40 years under the minimum required reliability of 0/9, the scale parameter (η) should be set to the value of 55/42. It should be noted that although the Rayleigh distribution function reduces the complexity of the proposed model, there is no requirement to use the Rayleigh distribution function in lifetime modeling (βcan be any number), but η must be chosen in proportion to β. Table 14 presents the maintenance problem modeling parameters. Also, Table 15 presents the constraints values. In this research, PM efficiency is assumed constant and its value is 80%.

Table 13. Parameters of failure rate distribution function

Weibull Distribution Parameters	(β)	(η)
Failure rate	2	55/42

Table 14. Parameters to model power transformer maintenance

Value	Parameter
40	The maximum lifetime (L)
28052800	Corrective maintenance cost (replacing a new transformer) (C_{cm}) [Riyal]
7013200	Preventive maintenance cost (x) [Riyal]
84145400	Preventive maintenance cost (y) [Riyal]

Table 15. Maintenance modeling constraints

Value	Constraint
0/ ≤ 9	Required reliability
200%≤	Life-time equired productivity index

4-3 Optimization of power transformer maintenance with bat algorithm (proposed method)

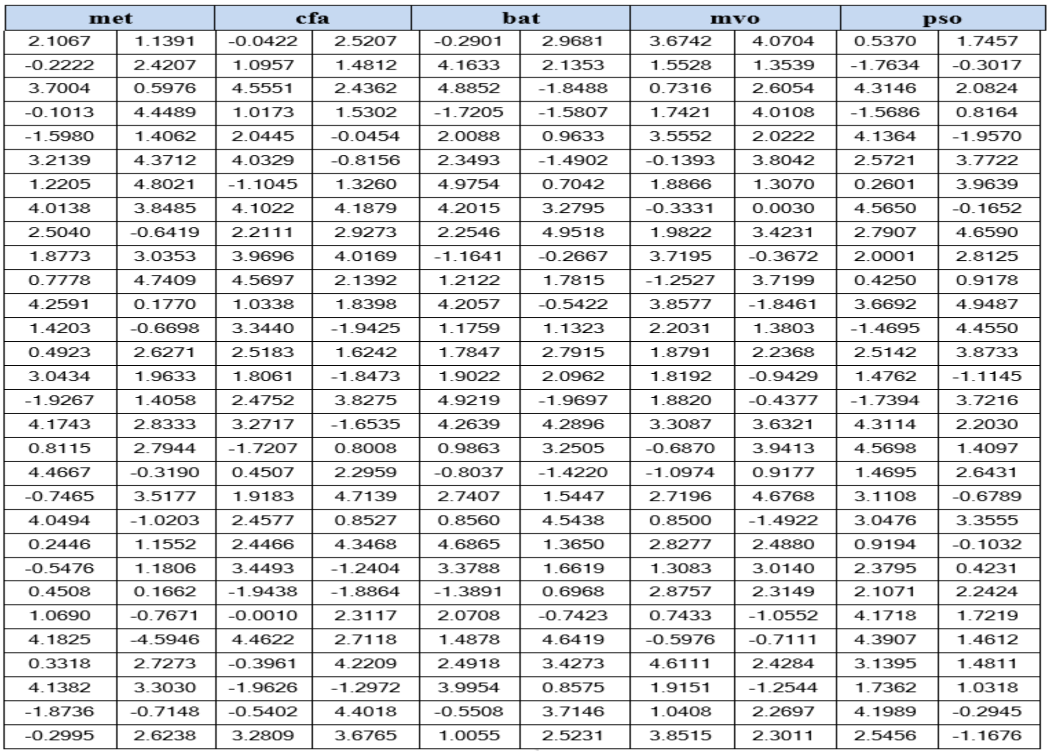
the objective function is developed and compared by PSO, MVO, BAT, CFA and Met methods (proposed method) to find the optimal maintenance for power transformer. Results of the bat algorithm presented in the previous section implementation to evaluate the algorithm performance are as follows. In this section, we first explain how the data used in the test are produced and how the test environment is tested, and then we present the results of the tests in different static and dynamic scenarios situations. Then, we compare the results with other similar methods while maintaining the same conditions, that coveres w=h=30 in a 30*30 circular coverage environment with an approximate radius (u(3.6). The reason for using γ = 0/3 is that after running a large number of tests and various values of γ, we found that if we use a higher value for γ, the range of circular coverage for a large number of transformers is reduced and it is out of coverage. While if we use a smaller value of γ for the range of circular coverage in an environment, it can accommodate the transformer well, so we chose values for γ that have the highest coverage and the lowest error. Also, by the test and error, we found that the best volume is φ=0/3 has the highest efficiency. Also, the maximum velocity (vMax) is set to 0/1. Table 16 shows the simulation parameters.

Table 16 Simulation parameters

Size	parameter	Row
10	The number of iterations between two points Response Time	1
30	The number of bats that determine their position	2
1 as a percentage	The maximum distance that the bat can move	3
0.3	γ parameter that controls the power between maintenance and repair	4
0.1	Maximum speed limit in the environment (vMax)	5
100	Total loudness (φ)	6
30,50,100	The number of repetitions	7

PSO, BAT, MVO, and CFA techniques along with the proposed approach (met) have been evaluated and investigated here, and the results obtained from 30 repetitions of the four mentioned methods are shown below. Tables 17, 18 and 19 present three different implementations values with four different algorithms to obtain the BestFitness values. Next, the output of the best solution is shown. In this section, each technique is evaluated according to the two important parameters of cost and response time. This is calculated in the bat algorithm using the loudness and echo of each bat. Table 17 shows the output of the best solution or alternative with the number of 30 iterations.

Table 17. Values of the best solution for response cost with 30 iterations



met		cfa		bat		mvo		pso	
2.1067	1.1391	-0.0422	2.5207	-0.2901	2.9681	3.6742	4.0704	0.5370	1.7457
-0.2222	2.4207	1.0957	1.4812	4.1633	2.1353	1.5528	1.3539	-1.7634	-0.3017
3.7004	0.5976	4.5551	2.4362	4.8852	-1.8488	0.7316	2.6054	4.3146	2.0824
-0.1013	4.4489	1.0173	1.5302	-1.7205	-1.5807	1.7421	4.0108	-1.5686	0.8164
-1.5980	1.4062	2.0445	-0.0454	2.0088	0.9633	3.5552	2.0222	4.1364	-1.9570
3.2139	4.3712	4.0329	-0.8156	2.3493	-1.4902	-0.1393	3.8042	2.5721	3.7722
1.2205	4.8021	-1.1045	1.3260	4.9754	0.7042	1.8866	1.3070	0.2601	3.9639
4.0138	3.8485	4.1022	4.1879	4.2015	3.2795	-0.3331	0.0030	4.5650	-0.1652
2.5040	-0.6419	2.2111	2.9273	2.2546	4.9518	1.9822	3.4231	2.7907	4.6590
1.8773	3.0353	3.9696	4.0169	-1.1641	-0.2667	3.7195	-0.3672	2.0001	2.8125
0.7778	4.7409	4.5697	2.1392	1.2122	1.7815	-1.2527	3.7199	0.4250	0.9178
4.2591	0.1770	1.0338	1.8398	4.2057	-0.5422	3.8577	-1.8461	3.6692	4.9487
1.4203	-0.6698	3.3440	-1.9425	1.1759	1.1323	2.2031	1.3803	-1.4695	4.4550
0.4923	2.6271	2.5183	1.6242	1.7847	2.7915	1.8791	2.2368	2.5142	3.8733
3.0434	1.9633	1.8061	-1.8473	1.9022	2.0962	1.8192	-0.9429	1.4762	-1.1145
-1.9267	1.4058	2.4752	3.8275	4.9219	-1.9697	1.8820	-0.4377	-1.7394	3.7216
4.1743	2.8333	3.2717	-1.6535	4.2639	4.2896	3.3087	3.6321	4.3114	2.2030
0.8115	2.7944	-1.7207	0.8008	0.9863	3.2505	-0.6870	3.9413	4.5698	1.4097
4.4667	-0.3190	0.4507	2.2959	-0.8037	-1.4220	-1.0974	0.9177	1.4695	2.6431
-0.7465	3.5177	1.9183	4.7139	2.7407	1.5447	2.7196	4.6768	3.1108	-0.6789
4.0494	-1.0203	2.4577	0.8527	0.8560	4.5438	0.8500	-1.4922	3.0476	3.3555
0.2446	1.1552	2.4466	4.3468	4.6865	1.3650	2.8277	2.4880	0.9194	-0.1032
-0.5476	1.1806	3.4493	-1.2404	3.3788	1.6619	1.3083	3.0140	2.3795	0.4231
0.4508	0.1662	-1.9438	-1.8864	-1.3891	0.6968	2.8757	2.3149	2.1071	2.2424
1.0690	-0.7671	-0.0010	2.3117	2.0708	-0.7423	0.7433	-1.0552	4.1718	1.7219
4.1825	-4.5946	4.4622	2.7118	1.4878	4.6419	-0.5976	-0.7111	4.3907	1.4612
0.3318	2.7273	-0.3961	4.2209	2.4918	3.4273	4.6111	2.4284	3.1395	1.4811
4.1382	3.3030	-1.9626	-1.2972	3.9954	0.8575	1.9151	-1.2544	1.7362	1.0318
-1.8736	-0.7148	-0.5402	4.4018	-0.5508	3.7146	1.0408	2.2697	4.1989	-0.2945
-0.2995	2.6238	3.2809	3.6765	1.0055	2.5231	3.8515	2.3011	2.5456	-1.1676

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Table 18. Values of the best solution for response cost with 50 iterations

met		cfa		bat		mvo		pso	
-0.5020	-2.8622	1.4363	1.9499	-2.0596	3.2443	2.4976	0.6487	1.3956	-1.0690
-2.5057	1.6759	3.1575	-2.2515	1.6849	-1.5953	2.8779	-0.1772	-1.4341	1.5562
-1.9251	0.0562	-1.0072	0.3672	2.4380	4.8069	-1.7105	-1.6662	0.6567	2.4777
1.4584	2.5871	-0.5262	2.8702	-2.4539	3.5121	-2.3592	-2.7098	1.8141	-2.7785
-1.0698	-0.5243	4.7389	-1.2630	-2.4042	1.1294	4.6001	1.5186	1.2981	-1.3863
1.6941	3.4720	3.9901	0.7473	0.4736	-1.7101	-0.8452	1.5578	0.3537	3.3406
1.9297	-2.4545	3.0926	-0.0877	-0.9126	-2.2301	1.4467	0.2933	1.3001	4.3561
2.5351	-0.5355	0.5749	-0.8031	3.0606	-0.2433	4.6095	3.0622	-0.4161	4.3019
0.0013	-0.3906	-1.2185	2.5096	2.8619	4.0511	-0.2687	2.1267	-0.2959	1.4199
3.0683	-0.2740	-2.5491	2.8282	3.9330	-2.4219	2.2758	1.4989	2.5587	-1.8963
2.8344	4.9052	-0.6868	3.7302	2.9194	0.7939	1.8178	-1.8550	-1.3731	-0.5918
-0.2590	3.4136	4.5248	4.3449	2.8388	4.4070	2.0628	4.8940	3.9677	-2.9679
1.0615	1.1681	0.4427	3.5235	2.5035	3.6883	2.0884	0.9147	3.4921	-2.4186
-0.2367	-1.9389	2.6086	4.1241	-2.0295	1.2099	3.8873	-0.5792	4.0597	2.4604
3.2816	-2.1056	0.5930	-2.6848	-0.6661	4.6488	3.5026	-2.8600	3.1850	4.5030
2.0292	4.9667	0.0143	1.5624	2.6935	-0.1880	2.5252	2.9934	-1.1601	-0.8731
0.9352	-2.0143	3.6655	-1.4677	1.5668	2.9622	-0.0968	0.3818	4.8968	2.0951
2.9979	0.5949	4.0878	3.8760	4.6938	-1.0371	0.7864	0.3591	1.6725	0.5034
-1.7907	-0.1282	3.5232	1.3591	1.2255	-1.5436	4.2771	-2.9774	3.7938	2.8702
-0.4107	1.2952	-2.0196	-0.4428	-2.8695	4.4054	0.0505	-1.5617	3.6804	-2.8190
4.1342	0.3052	2.6719	-2.0877	1.0257	0.0954	2.1608	2.0261	-0.3778	3.2516
2.1286	1.4296	-1.0707	3.2349	3.1168	1.5350	-0.3649	-1.7129	4.4182	-2.1267
3.0718	-2.5858	3.8610	1.4189	-0.2417	0.2568	-2.9177	-2.9038	2.3010	1.5578
-0.5482	-1.1484	4.9833	4.2884	-1.5275	1.7881	0.0344	1.8081	-0.7789	2.8162
-0.5572	2.0661	3.5221	1.8759	4.9661	-1.3032	2.5576	0.1031	0.4925	3.8791
4.4516	4.6436	1.8916	0.7121	1.5271	0.3691	-2.5635	-0.9267	-1.3880	0.6398
-1.8367	2.1125	0.9661	-1.4235	-2.1882	-2.8515	4.0945	-2.3625	-1.0663	-0.6446
-2.9480	-1.4443	-0.4591	-1.4448	1.8706	1.3633	-1.8200	3.1474	4.2446	1.0662
3.5127	3.6100	0.4706	3.0308	-2.2488	3.2639	2.0174	3.0556	0.0365	-2.1797
0.4395	-2.5212	1.7453	3.8900	2.6525	-2.2643	4.7382	-2.4915	2.5090	4.8830

Table 19. The values of the best solution for replacing the virtual machine with 100 iterations

met		cfa		bat		mvo		pso	
-0.3414	1.9525	4.6937	3.0411	-0.0314	4.5407	4.8940	1.9955	4.3310	-2.7299
1.0132	3.1989	-1.8160	0.0540	1.3300	3.9213	-1.4530	1.2340	-0.0826	-0.2165
1.2291	-0.5418	1.0437	0.6785	0.8892	1.5304	1.7737	-0.4432	4.6517	4.7249
0.2132	2.3796	-0.6510	4.0862	-1.3829	4.2934	-1.2543	4.7298	-2.9804	-2.9763
2.6934	-1.3969	3.7793	4.2914	0.3665	2.3977	-1.6780	1.3538	1.7225	2.7938
3.3754	2.9520	-1.4350	4.5109	-0.3737	4.3705	0.5020	1.9044	-1.5795	-1.5636
0.0000	4.7584	2.1876	-0.3964	4.2471	4.0002	4.8215	0.3442	-2.9010	0.8609
4.3928	-1.5898	-0.7238	2.1843	-0.7708	4.9315	-0.4873	0.9862	0.8047	-0.7493
-1.3837	2.7201	-0.5935	3.7445	-2.3465	-1.6228	2.7116	0.3245	3.8621	-1.5671
2.1731	-2.0501	0.7424	-2.0441	4.9147	2.1536	1.8464	-0.1509	-1.6804	1.5148
1.6439	3.9039	4.0972	-2.6624	0.6864	3.8907	3.4530	4.3660	-0.0045	4.0939
-1.3145	-1.0493	-2.6983	4.2675	-0.9019	0.2311	2.1134	-2.1935	4.7609	-2.3202
-0.6882	2.9380	1.5844	-1.1679	1.7286	1.9489	-0.0351	-1.1231	4.7091	-0.0843
2.4764	-2.6397	0.0531	0.2183	1.1723	2.6144	3.8634	-0.6911	3.4933	4.5314
-0.4606	-1.8711	-1.8260	2.8086	2.4218	-2.9302	-1.2986	2.1464	1.4742	3.0054
1.1200	0.1126	1.2894	3.9831	1.4703	0.8907	1.2611	3.4154	3.4133	1.5321
-3.7690	-1.3906	1.2484	4.3306	-0.0214	2.1465	2.1915	2.7026	3.1689	3.3115
1.4815	-1.6081	1.5482	4.7189	0.1691	-2.5898	-2.7656	2.1675	3.6417	3.9429
2.0844	2.8860	2.4614	1.1586	-0.9656	1.1651	-2.6216	2.7026	0.2027	-1.6934
4.6793	1.7593	-2.5948	1.2918	-2.3627	1.7904	1.0368	-1.5187	-1.0833	-2.2075
-0.9707	-0.8298	-2.0271	2.8322	-0.3710	1.5341	3.2460	0.1876	-0.3176	-0.2928
-1.3998	-1.4811	0.6314	4.5186	1.9336	3.6064	-1.8982	-0.5008	4.0039	-1.4929
0.0000	0.8596	3.7961	2.2876	1.8192	2.6878	-1.0056	-1.2633	2.0822	0.2293
3.1612	-2.6052	4.2040	-1.5216	-2.1195	-2.3005	1.1951	3.4546	-0.5802	1.9781
1.4037	-2.3832	-0.8371	3.0623	1.2716	3.1240	4.1465	2.4008	-1.6003	2.5734
0.1006	4.7245	-0.9622	0.8836	1.5163	2.7007	-2.7289	0.0461	-2.7985	4.4475
-1.8283	4.8248	3.8233	-0.4693	0.8729	0.8071	-0.5850	1.7373	3.8300	4.4719
-2.6447	-0.0320	4.4270	2.3878	4.7850	-1.1725	-0.0829	1.1764	-2.8147	-1.1586
-0.5602	0.2069	-0.5138	1.6627	1.7844	-0.3316	-1.1323	1.6490	-2.3060	-0.1466
0.8890	0.1666	1.3631	-0.6036	1.6091	-2.9004	-0.8926	-1.1402	1.5716	-1.1508

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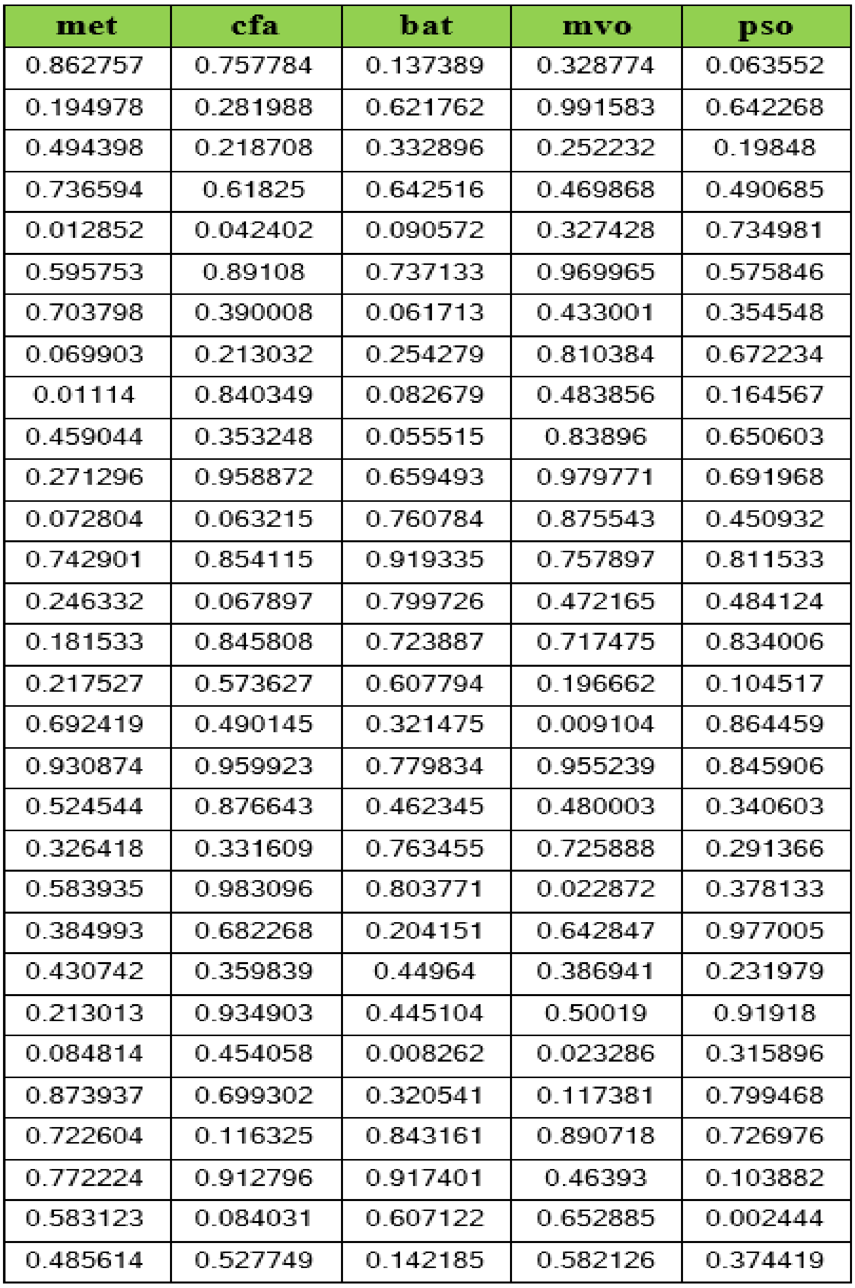
In the following, the elapsed time for three experiments performed with different number of iterations is shown. Table 20 shows the response time and elapsed time for maintenance with 30iterations.

Table 20. Response time and elapsed time for maintenance with 30 iterations



met	cfa	bat	mvo	pso
0.862757	0.757784	0.137389	0.328774	0.063552
0.194978	0.281988	0.621762	0.991583	0.642268
0.494398	0.218708	0.332896	0.252232	0.19848
0.736594	0.61825	0.642516	0.469868	0.490685
0.012852	0.042402	0.090572	0.327428	0.734981
0.595753	0.89108	0.737133	0.969965	0.575846
0.703798	0.390008	0.061713	0.433001	0.354548
0.069903	0.213032	0.254279	0.810384	0.672234
0.01114	0.840349	0.082679	0.483856	0.164567
0.459044	0.353248	0.055515	0.83896	0.650603
0.271296	0.958872	0.659493	0.979771	0.691968
0.072804	0.063215	0.760784	0.875543	0.450932
0.742901	0.854115	0.919335	0.757897	0.811533
0.246332	0.067897	0.799726	0.472165	0.484124
0.181533	0.845808	0.723887	0.717475	0.834006
0.217527	0.573627	0.607794	0.196662	0.104517
0.692419	0.490145	0.321475	0.009104	0.864459
0.930874	0.959923	0.779834	0.955239	0.845906
0.524544	0.876643	0.462345	0.480003	0.340603
0.326418	0.331609	0.763455	0.725888	0.291366
0.583935	0.983096	0.803771	0.022872	0.378133
0.384993	0.682268	0.204151	0.642847	0.977005
0.430742	0.359839	0.44964	0.386941	0.231979
0.213013	0.934903	0.445104	0.50019	0.91918
0.084814	0.454058	0.008262	0.023286	0.315896
0.873937	0.699302	0.320541	0.117381	0.799468
0.722604	0.116325	0.843161	0.890718	0.726976
0.772224	0.912796	0.917401	0.46393	0.103882
0.583123	0.084031	0.607122	0.652885	0.002444
0.485614	0.527749	0.142185	0.582126	0.374419

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Table 21 shows the response time with 50 iterations.

Table 21. Response time and elapsed time for maintenance with 50 iterations

met	cfa	bat	mvo	pso
0.163117	0.590385	0.153809	0.429486	0.272936
0.984233	0.904752	0.322102	0.401292	0.331502
0.370256	0.433356	0.858949	0.251964	0.760916
0.029354	0.187543	0.238679	0.460162	0.059993
0.718557	0.198074	0.979664	0.224765	0.57125
0.170166	0.601244	0.165455	0.108982	0.498699
0.002108	0.846165	0.405549	0.293097	0.188313
0.208522	0.616227	0.8823	0.457144	0.285951
0.992668	0.989624	0.008125	0.571628	0.124729
0.328757	0.596182	0.001726	0.165538	0.096321
0.928013	0.526492	0.385708	0.713093	0.906539
0.57354	0.067512	0.793772	0.883095	0.194185
0.168787	0.464006	0.837895	0.457805	0.046533
0.950055	0.329083	0.573851	0.023204	0.361322
0.943789	0.934821	0.92597	0.860025	0.799592
0.597429	0.452071	0.369133	0.843393	0.981248
0.399221	0.329093	0.757006	0.755605	0.091423
0.131627	0.533551	0.167417	0.118465	0.971725
0.245761	0.937967	0.04187	0.64102	0.352654
0.29028	0.869831	0.147642	0.113794	0.669858
0.534494	0.653182	0.973629	0.088149	0.33291
0.505681	0.735233	0.190608	0.390194	0.396525
0.360698	0.635882	0.788855	0.965433	0.408493
0.692733	0.861529	0.050233	0.352956	0.067426
0.096697	0.489407	0.4519	0.631183	0.379605
0.386379	0.825351	0.746342	0.697106	0.786509
0.824793	0.898938	0.873746	0.957228	0.860671
0.542789	0.356147	0.588034	0.188871	0.84409
0.179534	0.840624	0.714759	0.107846	0.619674
0.186455	0.486946	0.966658	0.680735	0.828329

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Table 22 shows the response time for maintenance with 100 iterations.

Table 22. Response time and elapsed time for maintenance with100 iterations

met	cfa	bat	mvo	pso
0.154879	0.566677	0.8336005	0.330159	0.821732
0.422517	0.005856	0.8984331	0.569572	0.591302
0.227322	0.532018	0.9743682	0.656752	0.186365
0.456435	0.500866	0.0397603	0.467564	0.372577
0.25316	0.838587	0.7175826	0.052575	0.379018
0.341811	0.548813	0.440638	0.026851	0.750705
0.085124	0.456425	0.5946741	0.16738	0.59756
0.149206	0.463396	0.1907502	0.487051	0.660669
0.700919	0.81887	0.1296514	0.155304	0.226551
0.556398	0.51003	0.5814852	0.561299	0.227242
0.718824	0.183533	0.9083867	0.674647	0.706637
0.38063	0.855765	0.307391	0.88534	0.681085
0.133839	0.422477	0.8439636	0.701381	0.311395
0.577097	0.978032	0.8925932	0.655109	0.79386
0.416326	0.819371	0.9696718	0.022063	0.729616
0.200807	0.871321	0.2891548	0.368426	0.106835
0.629212	0.262408	0.9184549	0.162261	0.840103
0.637601	0.652158	0.7175021	0.697282	0.584703
0.722596	0.827718	0.3399009	0.902562	0.361207
0.688144	0.246755	0.8210092	0.642587	0.08801
0.85631	0.997505	0.7785571	0.652778	0.337567
0.921385	0.397549	0.2403735	0.751277	0.433086
0.085619	0.147164	0.8670114	0.396898	0.636084
0.307613	0.23269	0.3873513	0.82402	0.895043
0.565177	0.997536	0.8460902	0.320997	0.452619
0.615675	0.926416	0.9080954	0.389287	0.97672
0.466156	0.238586	0.7634685	0.654232	0.794941
0.749451	0.96223	0.2126416	0.814088	0.175189
0.78661	0.408086	0.5557866	0.690681	0.231569
0.861321	0.383879	0.0670768	0.145058	0.888802

Figure 6 shows a bar comparison of the four tested algorithms based on maintenance cost.

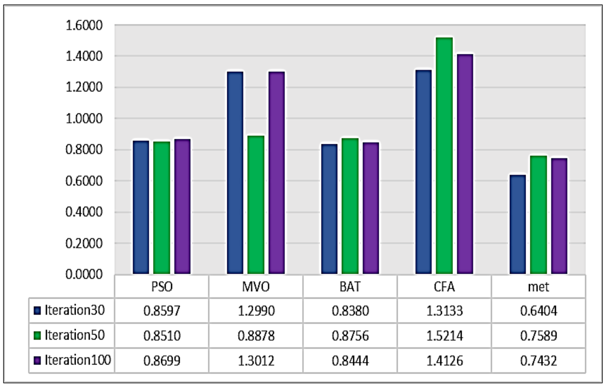

Figure 6. Average fitness function, maintenance cost (Best Fitness)

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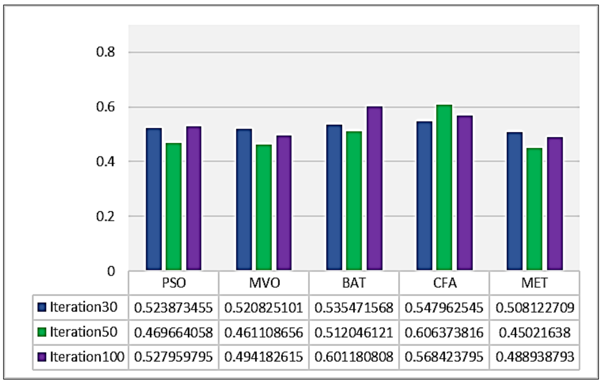
Figure 7 shows the comparative graph of average response time of the four investigated algorithms.



	PSO	MVO	BAT	CFA	MET
🟦 Iteration30	0.523873455	0.520825101	0.535471568	0.547962545	0.508122709
🟩 Iteration50	0.469664058	0.461108656	0.512046121	0.606373816	0.45021638
🟪 Iteration100	0.527959795	0.494182615	0.601180808	0.568423795	0.488938793

Figure 7. The proposed method average response time of the four investigated techniques

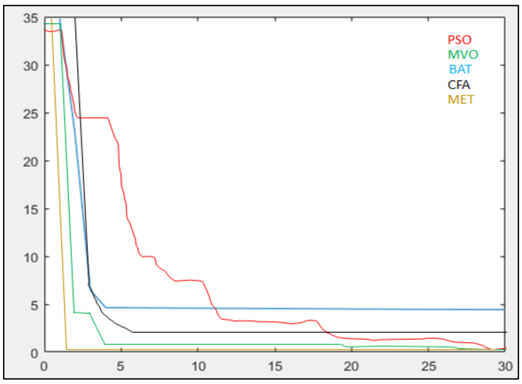


Figure 8. The cost convergence diagram of the four investigated techniques of the proposed method with 30 iterations

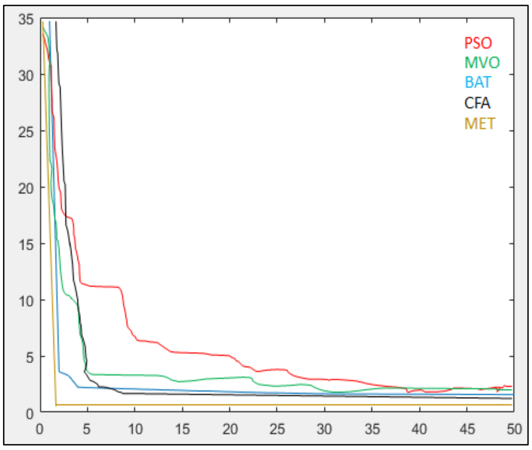


Figure 9. The cost convergence diagram of the four investigated techniques of the proposed method with 50 iterations

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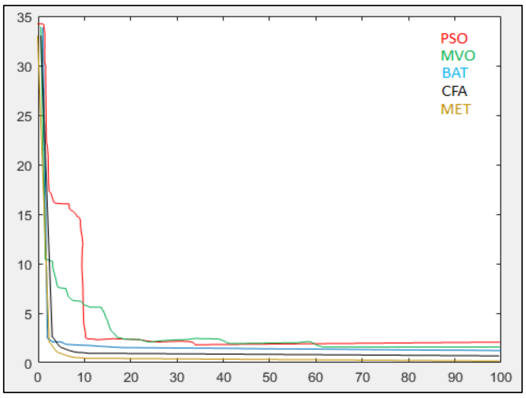

Figure 10. The cost convergence diagram of the four investigated techniques of the proposed method with 100 iterations

Figure 11 shows that the failure rate has an increasing nature, and the failure rate after performing PM (preventive maintenance) cannot be lower than the initial equipment failure rate or the previous PM failure rate. According to Figure (4-12), a power transformer that can last up to 40 years under the required reliability level (0.9 to 1), without maintenance will last about 18 years (17.9889 years) can operate for about 38 years under the required reliability level, with optimum maintenance. As mentioned before, PM efficiency is assumed to be 80%. For example, the power transformer reliability after the first operation of PM, whose efficiency is 80%, is obtained as $R_{PM1} = 0.9725 + (1 - 0.9725) \times 0.8 = 0.9945$, where 0.9725 corresponds to the reliability of the power transformer by performing the PM operation at the time of 2.258959 [years] before the first PM operation (at this time there are two solutions for reliability, the lower limit of which is considered) and 1 corresponds to the maximum possible reliability with 0.8 s related to PM efficiency.

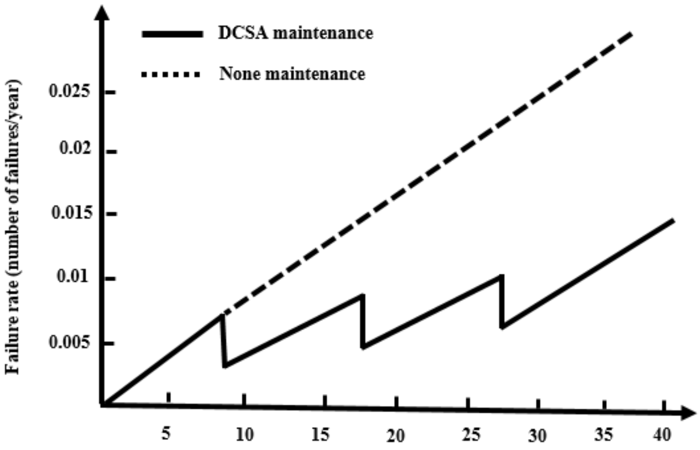

Figure 11. Failure rate of a power transformer with and without maintenance

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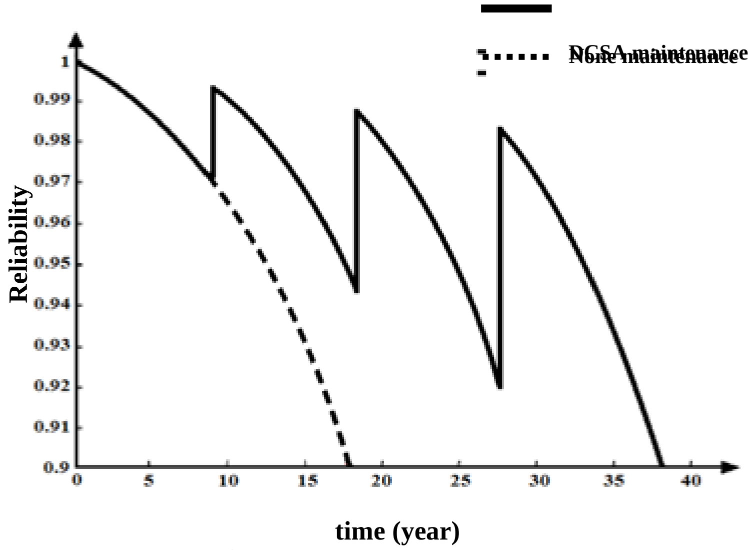

Figure 12. Power transformer reliability with and without maintenance

Table 23 presents the expected cumulative number of power transformer failures with optimal maintenance obtained from the proposed method and without maintenance.

Table 32-4 Expected cumulative number of power transformer failures

No.	Time [year]	Expected cumulative number failures (number of failures)	
		With optimal maintenance	Without maintenance
1	9/258959	0/027912	0/027912
2	18/517918	0/083736	0/111648
3	27/776877	0/139560	0/251208
4	40/000000	0/269731	0/520939

According to Table 23, the expected cumulative number of failures with optimal maintenance is less than without maintenance case. Thus, the expected cumulative number of failures is equal to 0/0520939, even without performing maintenance at the end of the study period (at the end of the useful life period of the equipment), which is less than 1. This article is interpreted in the way that under normal working conditions, when there is no sudden error in the system, this transformer does not burn in the study period, and corrective maintenance or replacement is not performed during the study period, because corrective maintenance or replacement is performed when the equipment breaks down; but the failure rate and the expected number of failures increase as time passes, and the equipment wears out followed by its useful life ends (the reliability of the equipment becomes less than the expected reliability).

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The expected number of failures for an equipment can be greater than 1; for example, if the expected number of failures for the equipment in the study period is equal to 2, it means that in the study period, the equipment will break down and corrective replacement will take place (corrective maintenance cannot return the reliability of the equipment to the initial state of the factory settings). And again, the new equipment that replaced the damaged equipment is also damaged during the study period. On the other hand, by performing optimal maintenance, the expected number of breakdowns at the end of the study period is reduced and equals 0/269731. CM depends on the expected number of breakdowns, and whenever the equipment breaks down, CM operations are performed. For the studied transformer, although the equipment does not burn in the studied period, the cost of CM is considered in the studied period. The expected number of failures depends on the PM operation times, the PM level, and the number of PM operations. As the expected number of failures increases, the cost of CM also increases. In this research, the minimization process has been done for both PM cost and CM cost.

5- Conclusion

One of the main challenges of power systems management is planning in line with the highest efficiency and the lowest possible maintenance costs for equipment affecting the network such as power transformers. Transformers are used in transmission and distribution networks to increase or decrease voltage. The reliability of the transmission network depends on the availability and efficiency of power transformers. Power transformers are gradually worn out and damaged by operation and the passage of time; therefore, there is a need for preventive measures to increase the useful life of the power transformer. In general, the maintenance strategy for distribution network components includes PM and CM. PM operations for a power transformer can include monitoring, cleaning, lubrication, adjustment, or replacement. Through PM operations, the cost incurred due to the occurrence of errors is reduced, but it leads to the imposition of PM operation costs. When a fault occurs in the system, CM operations, which include minimal corrective repairs and replacements, are performed to return the system to operational status. One of the most influential external factors in reducing the reliability of distribution substation equipment is the corrosion due to atmospheric factors, which is usually seen in the form of gradual rusting and rotting of parts; also, pollution in urban and industrial areas can deposit on different parts of the equipment under normal conditions and cause changes or combinations that ultimately lead to a decrease in the quality of the technical specifications of that equipment.

The internal factors affecting the reduction of the lifespan and reliability of the equipment include sudden changes and continuous shocks to the system; among these factors, we can mention sudden changes in temperature and pressure, increase in electric current due to severe short circuits, sudden and repeated electrical overloads, application of electrical loads

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exceeding the permissible limit, sudden expansion and contractions, etc. The effect of these factors can be seen in the form of a drop in electrical and mechanical characteristics, loosening of bonds, etc.; Many other factors such as incorrect and inappropriate use of equipment and mistakes in design reduce the useful life of facilities. In other words, these factors cause their early wear. For example, the useful life of an equipment that should last for about 30 years may be reduced by half due to the aforementioned factors. In such circumstances, to continue using this equipment for more than 15 years, we will face a decrease in the reliability of this equipment. Thus, the use of such a system without proper maintenance strategy will be associated with many problems and defects. Optimum maintenance strategy is an important issue to increase equipment productivity. it is necessary to carry out proper maintenance during their lifetime to maintain the expected performance of the power transformer. Maintenance can improve reliability, but this may lead to unnecessary maintenance costs. Therefore, reliability and maintenance costs must be balanced. A large number of studies have focused on maintenance optimization and obtained optimal maintenance by mathematical or heuristic optimization methods. In addition, increasing the failure rate of equipment reduces their lifespan to less than their expected lifespan. On the other hand, the maintenance strategy can increase the useful life of the power transformer. In this research, a lifetime efficiency index model for the power transformer has been presented to show to what extent a maintenance strategy is effective in increasing the useful life of the power transformer.

This paper proposes a suitable approach to prioritize reliability-based maintenance strategies at two different levels. At the first level, reliability-based maintenance have been prioritized for the feeders of one of the distribution stations. At the second level, reliability-based maintenance strategy prioritization has been done for the components of a sample feeder. Also, this research has presented a lifetime efficiency index model for power transformers and a creative method to achieve optimal maintenance for power transformers. By the lifetime efficiency index, the lifetime of the power transformer can be analyzed under conditions with and without maintenance. This study proves that the proposed method can obtain higher quality solutions for optimal maintenance than MVO, PSO, BAT and CFA methods. Optimum maintenance is a balance between PM and CM under conditions of required lifetime productivity index and required reliability. The probability of failure of power transformer is modeled by a suitable Weibull distribution function, which expresses the course of failure and interruptions of power transformer. The optimal maintenance strategy can be the expected number of transformer failures In other words, optimal maintenance can improve reliability and minimize the total cost of maintenance when the constraints of operation and economic cost are met. Among the important results in the plan to provide a suitable method for complex planning of repairs and location of network sectionalizers, we can count the following:

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- Reliability-based maintenance planning in power systems with optimal cost and time;
- Improving network reliability and using multi-objective optimization methods;
- Minimization of investment and project implementation costs;
- Increasing the lifespan of network equipment;
- Combination of distribution network repair problem using the sectioner location problem.

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