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Priority Based Maintenance Management of Power Distribution Feeders using Critically Analysis and Condition Assessment

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Abstract

Components deterioration in all areas reduces the level of reliability and since these cases are part of the intrinsic nature of the components in all areas, the distribution of electrical energy is no exception and it results in aging and consequently, decreases the level of reliability. Distribution network feeders play a key role in improving the reliability of the distribution system. Feeders must be inspected and maintained to improve the reliability of the distribution system to the desired level. Inspection and maintenance of feeders is costly and the budget required to perform them is limited. On the other hand, some feeders in the network are more important than others in terms of different indices and their importance should be taken into account in planning.

This paper introduces a process based on inspection for quantification of MV overhead line condition and it was tried that all factors influencing the outage of distribution network integrated into one index that called Condition Index. Since the factors affecting outage can be fixed or variable over the time and also, because of preventive actions of these factor is different, so in this study, the criteria measure related to these factors are decoupled.

In order to purposefully distribution of capital and human resources in inspection of distribution networks, determination of the importance of each feeder is necessary. For this purpose, Importance Index has been introduced and calculated by using Fuzzy Analytical Hierarchy Process (FAHP) method based on criteria such as length, average load and outage rate of feeders. In order to determining inspection/service rate of each feeder, ranking of feeders has been done by combination of Importance and Condition Index on the basis of decision map. Based on report of regular inspection, assets manager make decision regarding to scheduling of mid & short term maintenance. Finally, this proposed framework has been applied on the 10 feeders of one sub-transmission substation in Mashhad Electric Energy Distribution Company (MEEDC) as a case study.

Keywords: distribution feeders, reliability, condition assessment, critically analysis.

1. Introduction

Today, the use of electricity has become one of the most fundamental foundations of modern society, and with the development of new electrical appliances, the need for high reliability feeding has increased dramatically. On the other hand, statistics show that more than 80% of power outages occur due to fault in the distribution network [1]. However, research has been done and papers published in this field are far less than generation and transmission fields [2].

The fixed rate and the outage rate of the customers will be reduced by proper maintenance, and operators will use different methods to maintenance of equipment [3], which will reduce the effects of equipment failure. In general, maintenance is divided into two categories: corrective maintenance and preventive maintenance [4]. Corrective maintenance is also referred to run to failure because no maintenance is performed on the equipment until the equipment is failed. This method is highly inefficient and due to the penalties for failure to service, it has a potential to impose such penalties on the system.

As the name of preventive maintenance indicates, the actions taken in this method are performed before the equipment is failed thereby improving its condition and also delaying the occurrence of subsequent failures. Preventive maintenance includes time-based, reliability centered and condition-based maintenance. Preventive maintenance based on risk is another advanced RCM method. Risk is defined as the multiplication of time-dependent probability of failure of the equipment and its consequences. Condition information is used to estimate the probability of equipment failure. In the long-term, selection and scheduling of maintenance actions is done concurrently with optimization algorithms because the amount of risk reduction depends on the time when a maintenance task is implemented.

Due to the radial structure as well as the variety of equipment used in power distribution networks, these networks have the highest risk and as a result have the greatest contribution to reducing the reliability of the power system. Therefore, improving the reliability level of power distribution networks is very important. Considering the importance of the risk associated with customers, electricity outages and their effect on the reliability of power systems, this paper presents a framework for evaluating, identifying, weighing, prioritizing and managing feeders that are most at risk and their failure cause to electricity outage.

2. Background

2.1 Asset Management in Distribution Networks

One of the most important goals for asset managers in the power system is a maximum usage of assets. For achieving the minimum cost goal within lifetime, maintenance optimization is essential, so one of the primary goals is to link system reliability and maintenance planning in an effective way. Research in this area has led to several maintenance methods such as reliability centered maintenance. Reliability centered maintenance has resulted in an optimal and functional balance between preventive maintenance and corrective maintenance to achieve the minimum total cost. From a system reliability view, the reason for maintenance is clear. System reliability can be improved through maintenance. This is associated with equipment quality improvement [3] .

Asset management means ensuring the return of capital and ensuring serviceability and compliance with defined security standards for the operation of a set of equipment throughout their technical life time [5] . Researchers and specialists in power system reliability divide power system activities into three main processes. These three processes are a set of decisions that are made to achieve the most optimal results. These activities are usually divided into the following three categories [6][7] :

1. Network development (long term)
2. Assets management (medium term)
3. System operation (short term)

As can be seen from this classification, asset management is the link between long-term development and short-term system operation. Below we will explain each term [8] :

Long Term Asset Management: The long term period consists of one year or more, which is working to upgrade and improve distribution and transmission line equipment.

Med-Term Asset Management: Medium term timeframe consists of a few months to one year and includes optimal scheduling for equipment maintenance and allocation of available funds. The main effort in this term is to extend the lifetime of the equipment with proper maintenance.

Short Term Asset Management: Short term asset management is categorized into operational asset management (daily and weekly) and real estate asset management (outages management).

2.2 Importance of inspection in distribution network maintenance

It is not always possible to view the physical condition of the network at any time. This is especially true for power distribution feeders that may have extended kilometers to the surface. However, it is possible to inspect a feeder and determine its condition prior to emergency maintenance or to check whether maintenance can be postponed or not [9]. Distribution networks can be inspected in a variety of ways, such as infrared photos, acoustic, and visual inspection. Listening can also be used to detect internal corrosion of wooden poles or loose joints. Damage to the equipment can be detected by hitting the pole and recording the reflected wave frequency and by detecting high frequency noise in loose connections [10].

But most of the inspections carried out in the distribution network are visual. Lines are usually inspected for tight connections. Oil filled equipment such as capacitors, regulators and transformers are also visited to find signs of oil leakage. Equipment bushings are usually visited to check for failure or contamination. Insulators are inspected for scratches, cracks, fracture contamination and other damages [9] .

In addition to the condition of the equipment, we will be able to inspect poorly repaired equipment. We will also be able to detect any abnormalities such as trees during inspection that affecting network reliability and service. Inspection is costly for some systems, so it is important to perform the best and least costly inspection schedule to keep the system at a high level of reliability [9] . It can be claimed that the inspection is similar to the eye and ear of RCM. RCM is a new definition of maintenance philosophy that focuses on maximizing equipment life. At RCM, we see a shift from repairment/replacement to inspection, and repairment/replacement takes place when its optimal service life has elapsed [11] .

There are two methods for monitoring of the condition: continuous and periodic. There are two limitations of continuous monitoring: (1) it is expensive, (2) it is noisy which can send the wrong message. Periodic monitoring is more commonly used because of its cost-effectiveness and for providing more accurate diagnostic using processed data. It is clear that the risk of periodic condition monitoring is the probability of failure occurring between the two periods [12].

2.3 Fuzzy Analytical Hierarchical Process

The hierarchical analysis process was first invented by Saaty in the 1980s [13] . The basis of this method of decision making is pairwise comparisons and begins by providing a hierarchical tree. The decision hierarchy tree is a multilevel tree that is at the first level, the goal, and at the next levels are the main criteria, sub criteria, and finally the options. This technique is widely used to select the optimal decision as well as to rank the factors. Advantages of this technique include the ability to incorporate qualitative criteria into the evaluation process, the criteria weighting algorithm and relative simplicity, and disadvantages include the limitations of using too many criteria, rank inversion, the difficulty of the pairwise comparison process, and the occurrence of inconsistencies between judgments. .

We will use fuzzy hierarchy analysis to obtain the importance index. [14] were among the pioneer researchers who applied the concept of fuzzy logic to the hierarchical analysis process. In fact, it is easier for a decision maker to express a judgment in a time interval rather than a fixed value. This stems from the fact that due to the fuzzy nature of pairwise comparisons, one is incapable of expressing her/his preference. In fuzzy problems, there is no complete information about the system and can be expressed for a particular criterion by using expressions such as more than one number, about one number or between two numbers. Triangular and trapezoidal fuzzy numbers (TFN) can represent these types of expressions. It is often easier to work with triangular fuzzy numbers because of its computational simplicity. Another reason is that triangular fuzzy numbers are suitable for displaying and processing information in a fuzzy environment. Fuzzy AHP formulation are based on [15].

3. Short/Mid-term Maintenance Decision-making framework

Periodic inspections and services of any equipment are the most common methods for monitoring the condition over the short to medium term. This paper presents a framework for prioritizing and deciding on short- and medium-term maintenance activities. This framework is based on the determination of the importance index and the condition index of all overhead distribution feeders, which is determined using the decision map of priorities for maintenance activities and periodic service. The general flowchart of the proposed framework is shown in Figure 1. It is noteworthy that this study did not address long-term planning.

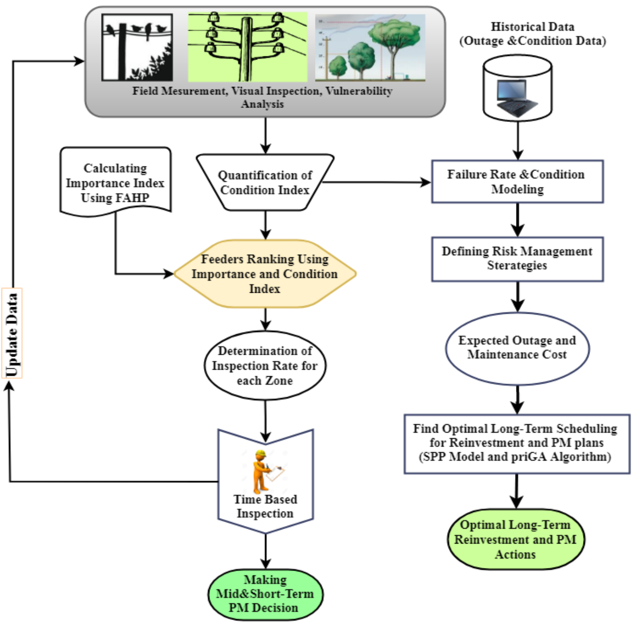

Fig.1 Short/Mid-term Maintenance Decision-making framework

The traditional method has been time-based scheduling so that all equipment is inspected and serviced at a fixed rate. This type of scheduling will distribute budget and funds equally across all equipment, although the condition and importance of the equipment may vary.

4. Decision Map

Different decision matrices or maps under different topics for prioritizing equipment and feeders have been reviewed in various papers. In [16], a decision map is defined with 9 sections that prioritize 103 power circuit breakers at three levels. In the [17], a risk space is defined with 4 boxes and three levels that prioritizes 6 categories of distribution feeders. Other papers have done this with titles such as the Health Index Matrix [18], Risk Matrix [19], and Hyper box [20].

In this paper, a framework is designed to allocate capital more efficiently considering the importance and condition of each feeder. As shown in Figure 2, a map can be designed based on the condition index and the importance index, and the equipment is ranked by zoning of the table. For example, if the equipment is of high importance and in very poor condition, it is located in zone 3 and considered as one of the critical equipment that needs a quick decision so that its condition being improved.

Likewise, when both feeder condition and significance indices are moderately high, they fall into zone 5, which means they have reached the warning boundary and need to be improved to prevent crisis. Similarly, equipment that is of low importance and in good condition is located in Zone 7 and will be considered as equipment under normal circumstances. Therefore, as long as it is in good condition, it does not need to spend money for its maintenance as much as it is in critical condition.

4.1 Way of zoning for the decision map

There are various methods for zoning and defining the boundaries of each zone. One way is to divide each axis into three equal parts. This method, of course, will not be the most accurate method, and a more precise method is needed. Since most equipment are usually of similar condition and importance, we assume that the distribution of this data will be normal. So the number of indexes is often spread around the mean. Next, the boundaries between the regions of decision map are obtained using the mean and standard deviation of the indices. Methods of calculation for the mean and standard deviation are shown in Equation (1) and (2) respectively.

$$\mu = \sqrt{\frac{1}{N}\sum_{i=1}^{N} x_i} \tag{1}$$

$$STD = \sqrt{\frac{1}{N}\sum_{i=1}^{N} (x_i - \mu)^2} \tag{2}$$

In the above equations, STD is the standard deviation, N is the number of data, x_i is the *ith* member of the set, and μ is the mean of the data. Therefore, by calculating the standard deviation and the mean, the boundaries of each region will be determined as follows:

$$Marginals = \mu \mp \sigma \quad (3)$$

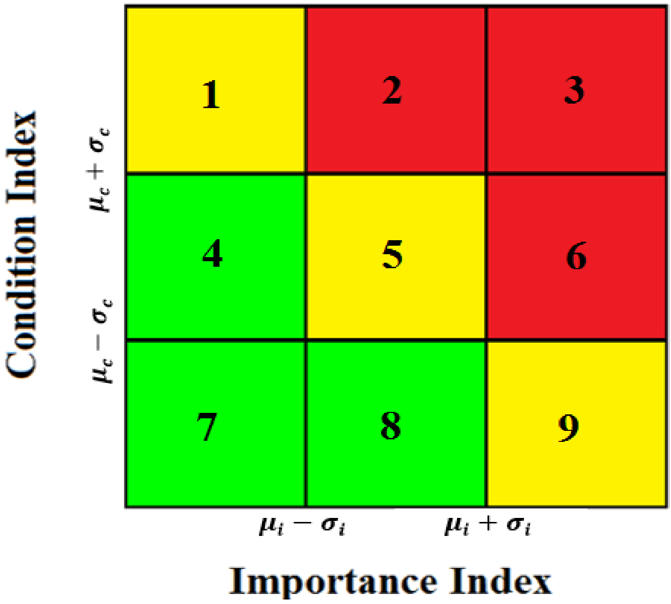

Fig.2 Decision Map for ranking of distribution feeders

4.2. Method of Determining Condition Index

In this research, the integration of physical condition indices of equipments and environmental condition indices of each equipments are called Condition Index. Overhead lines are structurally different from other equipments such as power transformers. The overhead lines are made up of a series of interconnected equipments that failure in each, may interrupt the distribution of energy for all customers connected to it.

To determine the feeder condition using the method of [21], it is necessary to see the overhead feeder as a single equipment despite all its equipment. Conductors, cross arms, insulators, cutout fuses, jumpers, connectors, sealing ends and poles are all equipment that form the distribution overhead lines. Deterioration or inferior of these equipment will cause them to failure and thus outage of the feeder.

In [22] to determine the condition index, the overhead line along with the tower and its accessories is considered as a single equipment and has calculated a condition index for all of them. In this research, the method introduced in [21] is developed and based on it the condition index is calculated.

The first step is to determine the feeder condition based on the factors affecting the feeder outage. For this purpose, we evaluate and calculate the condition indices of a feeder by dividing them into four categories which are major health index, minor health index, vulnerability Index and tree density index.

Table 1 presents the method of quantification the overhead line condition along with important and effective indices. These indices are based on statistical analysis of failures, expert experience and resource reviews. Another point in determining the factors affecting the overhead lines condition is to consider the vulnerability of the overhead lines to external factors that are among the factors affecting the rate of outage or failure of the lines. The inclusion of these indices was adopted after observing the extensive failures caused by these external factors in the statistical data.

As illustrated in Table 1, our criteria are broken down into four categories of vulnerability index, tree condition index, minor health index, and major health index. This distinction has been made due to the static and dynamics of some over time, as well as to better illustrate the impact of each of the risk management actions (in the long term) on equipment condition.

This quantification framework was originally designed to determine the condition of a pole and span afterwards. But due to the large number of poles, it was decided that this table is considered for one zone of a feeder. The basis of zone division is the existence of maneuver points and the distance between two switches or maneuver points.

A strategy to combining physical and environmental condition indices of overhead lines to assess their overall condition is presented in this research study. The approach is based on categorizing the apparatus into four groups: major and minor health indices, vulnerability index, and tree density index.The approach presented in this paper builds upon previous research, including the work of [23] on the condition assessment of power equipment and the approach introduced by [24] for the condition assessment of power transformers. Additionally, the paper draws on the work of [25] on developing a fault prediction model for overhead lines using machine learning techniques.

Table 1 Check list for inspection of one zone of overhead lines

Criteria		Item	Item Weight	Item Score	Criteria Weight
Vulnerability Index	1	Vulnerability of poles to cars accident	w_{11}	s_{11}	W_1
	2	Vulnerability of conductors and pole accessories to birds	w_{12}	s_{12}	
	3	Vulnerability of conductors and pole accessories to other external things	w_{13}	s_{13}	
	4	Vulnerability of zone to lightning,	w_{14}	s_{14}	
		Weighted Mean of Scores	$X_1 = \frac{\sum_{j=1}^{M_1} w_{1j} \times s_{1j}}{\sum_{j=1}^{M_1} w_{1j}}$		$X_V = W_1 \times X_1$
Tree Condition Index	1	Vulnerability of conductors and pole accessories to trees	w_{21}	s_{21}	W_2
		Weighted Mean of Scores	$X_2 = \frac{\sum_{j=1}^{M_2} w_{2j} \times s_{2j}}{\sum_{j=1}^{M_2} w_{2j}}$		$X_{tree} = W_2 \times X_2$
Minor Health Index	1	Condition of tie wires on insulators	w_{31}	s_{31}	W_3
	2	Condition of Connectors and Jumpers	w_{32}	s_{32}	
	3	Condition of conductors distance	w_{33}	s_{33}	
	4	Condition of span sag	w_{34}	s_{34}	
		Weighted Mean of Scores	$X_3 = \frac{\sum_{j=1}^{M_3} w_{3j} \times s_{3j}}{\sum_{j=1}^{M_3} w_{3j}}$		$X_{HI\_minor} = W_3 \times X_3$
Major Health Index	1	Condition of poles (aging, corrosion)	w_{41}	s_{41}	W_4
	2	Condition of insulators	w_{42}	s_{42}	
	3	Condition of cut-outs, arresters and cable terminations	w_{43}	s_{43}	
	4	Condition of cross-arms	w_{44}	s_{44}	
		Weighted Mean of Scores	$X_4 = \frac{\sum_{j=1}^{M_4} w_{4j} \times s_{4j}}{\sum_{j=1}^{M_4} w_{4j}}$		$X_{HI\_major} = W_4 \times X_4$
Overall Condition Index			$X_t = \frac{X_V + X_{tree} + X_{HI\_minor} + X_{HI\_major}}{\sum_{j=1}^{4} W_j}$		

4.3. Scoring method of Items

After determining the weight of each item, there is a need to set a method for scoring the items. Since Table 1 is designed for the inspector, it should be as easy as possible for the inspector to assign a score to minimize errors and preferences in scoring. Therefore, for each item in Table 1, we will provide a selective method for scoring. For example, the method of scoring of insulator condition is described in Table 2. The inspector must find the number of defective insulators per each zone. There are an average of 200 poles in each zone. So, based on knowledge of utility expert, we give the worst score (number 1) to a zone that has more than 10 defective insulators.

Table 2 Insulator inspection check list for each zone

Item	Defective Insulator (per zone)	Score (0 to 1)
Insulator Condition	$x = 1$	0.05
	$2 \le x \le 3$	0.2
	$3 < x \le 4$	0.4
	$4 < x \le 6$	0.7
	$6 < x \le 8$	0.8
	$8 < x \le 10$	0.9
	$x > 10$	1

4.4. Method of determining significance index:

The importance index indicates the sensitivity and criticality of a feeder. Different criteria can be used to measure the importance of a feeder. But in this study, we will only consider criteria that their effect on the condition index have not been examined.

- **Number of outages:** This criterion shows the number of feeder outages over the past years. This criterion is important because feeders with high failure are likely to have high failures in the future too.
- **Feeder length:** Although it is directly related to the number of outages per feeder, it is more susceptible to damage because it is widespread in the geographical environment.
- **Last repair time:** The more time passes since the last repair, the more wear and tear of equipment will increase and the need for inspection will increase.
- **Feeder with important consumer:** Feeders with important consumers such as hospitals, government departments, military industries and important business centers are more important than other consumers such as residential consumers.
- **Average feeder load:** The higher feeder load, the greater will be its detrimental

impact of the outage, so it needs more care and inspection.

- **Feeder with important equipment:** Feeders that have critical equipment such as reclosers, sectionalizers, automation switches, etc., require more inspection than other feeders.

Finally, by applying the above criteria and using the FAHP method, a numerical value will be obtained for each feeder importance index.

5. Practical Case Study

The case study consists of 10 feeders or 19 zones from Mashhad Electricity Distribution Network, among which are the types of feeders in terms of load type and geographical area. We define a set of consumers as a zone that are affected by failure in each part of the feeder. Therefore, a zone is considered between the two automation switches. There are some areas in different geographical areas such as agricultural, residential, industrial, urban and even rural. Some zones are of high importance and require regular inspection. The full specifications of the feeders, including length, load amount and load type, are proposed in appendix.

5.1. Calculation of importance and condition index

The index of the current condition of each zone is obtained using Table 1. We need to get the importance index for ranking. Then, using the FAHP method, the importance index of each zone is calculated. The significance index results are shown in Figure 3. After entering the data and answering the questionnaires filled in by the experts, the zones were ranked according to the importance index and criteria of section 3.4 by FAHP method and MATLAB software, the results of which can be seen in Figure 3 and Table 3.

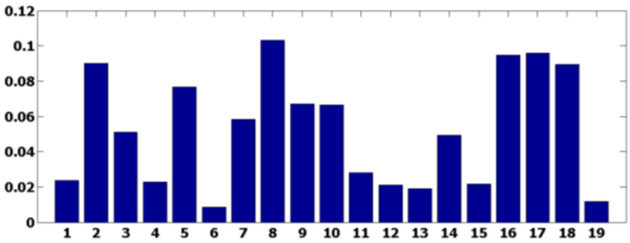

Fig.3 Importance Index of zone 1 to 19 calculated using FAHP

The results show that zone 8 is the most important zone due to its long length, high outrages, relative importance, with weight of 0.1032. Also zone 12 with the weight of 0.0212 is in the last rank. In terms of condition, zone 17 is worst and zone 6 is best. The exact weight of the other zones is given in Table 3.

Table 3 Condition and Importance Index

Zone Number	Importance Index	Condition Index
1	0.0236	0.61
2	0.0902	0.62
3	0.0511	0.52
4	0.0228	0.39
5	0.0469	0.55
6	0.0385	0.33
7	0.0585	0.47
8	0.1032	0.7
9	0.0672	0.49
10	0.0466	0.65
11	0.0281	0.56
12	0.0212	0.57
13	0.0392	0.53
14	0.0493	0.57
15	0.0217	0.63
16	0.0749	0.48
17	0.0959	0.705
18	0.067	0.63
19	0.0316	0.48
Mean	**0.05**	**0.541**
STD	**0.0258**	**0.105**

6. Discussion

After calculating the indices, the location of each zone in the decision map is determined in accordance with Figure 4. Zones that their importance and condition indices are located in box (4, 7, and 8) have priority 3; zones that their importance and condition indices are located in box (1, 5, and 9) have priority 2, and finally zones that their importance and condition indices are located in box (2, 3, and 6), will have priority 1. We now have to determine the inspection rate in consultation with the experts for feeders according to the prioritization results. According to Table 4, for priority 1 zones, twice per year, for priority 2 zones once per year and for priority 3 zones every two years inspection will be done.

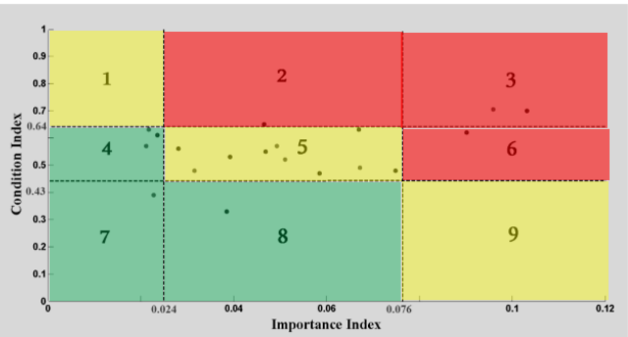

Fig.4 *Decision Map for prioritizing of distribution feeders (zones)*

By prioritizing and determining inspection rates for each zone, in addition to reducing inspection costs and focusing on worst condition and most important feeders, we will be able to conduct regular inspections to identify the condition of the affected zones and while updating data, we can decide and plan for short or mid-term maintenance.

Table 4 Inspection/PM rate based on Decision Map

Priority	Zone Number	Inspection/PM rate (per year)
1	2, 8, 10, 17	2
2	3, 5, 7, 9, 11, 13, 14, 16, 18, 19	1
3	1, 4, 6, 12, 15	0.5

Conclusion

This paper attempts to design and propose the most optimal and cost-effective measures to improve the condition of overhead distribution component by providing a comprehensive and accurate framework for managing of them. At first, it was attempted to design a detailed checklist so that the condition index could be quantified. The checklist will also change the system of inspection data recording, in addition to addressing the most important and effective components of the overhead line. So that there will be both quantitative data for the overhead lines components and quantitative data indicating the overall condition of the equipment. Then, by computing the importance index based on criteria independent of overhead lines condition, the importance and criticality of each zone were calculated. This index shows the sensitivity and criticality of one zone compared to other zones. For example, the feeder that supplies electricity for a hospital is much more sensitive than the lines that supply electricity for a residential building. Finally, using the calculated importance and condition indices, it was attempted to calculate the priority of 19 zones out of 10 feeders for inspection and service. By prioritizing these 19 zones, the capitals and time could be allocate to the most-needed feeder, and by spending that amount of capital, the risk of that feeder could be greatly reduced and reliability could be increased.

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Appendix

Feeder Number	Zone Number	Zone length (km)	Post failure load lost	Customer types connected ti each zone
F1	1	30	0.93	Industrial, Agriculture, Residential (Rural)
	2	45	2.015	Industrial, Agriculture, , Residential (Rural)
	3	45	0.62	, Residential (Rural)
F2	4	25	0.155	Agriculture, , Residential (Rural)
	5	30	2.17	Industrial, Agriculture
	6	10	0.93	Industrial, Agriculture, , Residential (Rural)
	7	45	1.55	Industrial, Agriculture, , Residential (Rural)
F3	8	49	1.55	Industrial, Agriculture, , Residential (Rural)
	9	20	2.17	Industrial, Agriculture, , Residential (Rural)
F4	10	25	1.116	Industrial, Agriculture
	11	14	0.713	Industrial, Agriculture
F5	12	15	1.083	Industrial, Agriculture
	13	15	1.085	Industrial, Agriculture
F6	14	20	0.465	Industrial, Agriculture, , Residential (Rural)
	15	14	0.775	Industrial, Agriculture, , Residential (Rural)
F7	16	10	0.155	Industrial
F8	17	18	4.185	Agriculture, Residential (Urban)
F9	18	25	3.85	Agriculture, Residential (Urban)
F10	19	10	0.465	Agriculture, Residential (Urban)
Sum		473	26	