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Reliability Enhancement of Power System by Condition Monitoring Transformer Using Fuzzy AHP

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ABSTRACT: This paper proposed reliability enhancement of power system using condition monitoring transformer. Even though reliability of the power system depends on the generation, transmission and distribution components, distribution has a larger effect on system reliability defined in terms of customer interruptions and satisfactions. There is uncertainty associated with the transformer operation, limited availability of historical data and the abnormal failure rates; because of different manufacturers, utility, circuits, loading, line fault, maintainers. Hence, the impact of transformer condition on distribution system reliability is evaluated. The available historical data shows that the failure rates of the distribution transformer are differing for each circle and every year. Therefore, it is not possible to use an average failure rate of transformer to evaluate system reliability using a statistical analysis. Therefore, condition monitoring data of transformer is used to evaluate the system reliability. Our first objective was to assess the condition of the transformer. For this the conditions of different criteria's were investigated and then used to assign the scores on relative basis. Based on the importance of a particular type of criteria for the healthy operation of the transformer a weight is assigned to each criterion. The assignment of weight to each parameter is a very important step in the transformer condition assessment method. Fuzzy analytical hierarchy process (FAHP) has been used for deciding and selecting the weights of transformer condition criteria. The distribution system reliability is then calculated by this condition dependent failure rate of transformer and for this calculation other components of the transformer are assigned their average failure rate. The different conditions of transformer were then used to study the effect on the RBTS 4 bus distribution system reliability indices: SAIFI, SAIDI, CAIDI, ASAI, and ENS studied.

Keyword: Distribution system, reliability evaluation, Fuzzy AHP.

I. INTRODUCTION

Over the past few years the restructuring and deregulation of the power utility industry is resulting in significant competitive, technological and regulatory changes. Power system restructuring and deregulation provides comprehensive coverage of the technological advances, which have helped redesign the ways in which utility companies manage their business [8]. The market environment, how to realize optimal system planning and reliable operation at acceptable electricity prices with qualified service and how to transit to the market environment smoothly at lowest costs and lowest risks should be considered thoroughly [15]. In order to reduce cost some of the observed practices among utilities are to postpone preventive maintenance, spend less resource on training its staff and wait until equipment fail before replacement [20]. Power delivery companies are under increasing pressure to provide higher levels of reliability at lower cost. The best way to pursue these goals is to plan, engineer, and operate power delivery systems based on quantitative models that are able to predict expected levels of reliability for potential capital and operational strategies. Doing so requires both system reliability models and component reliability models [14]. The developments are followed rapidly by electrical power industry, which is now under extreme pressure to ensure reliable power supply, which is expected to supply energy on demand without local failure or large scale blackout. This event considerably increases pressure to objectively assess reliability and overall probabilistic risk [3, 5].

Reliability evaluation technique can assess in the objective of assessment of these probabilistic risk and help to account, not only severity, but also for likelihood. [5]. Earlier power distribution system has received significantly less attention related to reliability evaluation as compared to that of generation and transmission. But now-a-days with the development of competitive power system market we need not to overlook any part of the power system [6].

Analysis of the customer failure statistics of most utilities shows that the distribution system makes the greatest individual contribution to the unavailability of supply to the customer. This is reinforcing the need to be concerned with the reliability evaluation of distribution system. A number of alternatives are available to achieve acceptable customer reliability, including alternative reinforcement schemes, allocation of spares, and improvement in maintenance policy. In this work it is proposed to ensure that the limited capital resources are used to achieve the greatest possible incremental reliability and enhancement in the system by condition based maintenance policy [1, 19].

Roy Billinton *et al* [6] have described the basic technique needed to evaluate reliability of distribution system. The reliability indices that are evaluated are affected greatly by relevant operational characteristics and policy. IEEE Standard 1366–2003 [12] gives the guidelines for power distribution system reliability analysis. This standard generalizes the terms to support a consistent reporting practice among the utilities. Unfortunately due to geographical location, loading level (urban – greater than 93 customers/km, suburban – between 31 and 93 customers/km and rural – less than 31 customers/km), system design, and definition of sustained interruption used, reliability analysis differs among distribution companies. Although there are some reliability indices defined in IEEE 1366-2003, System Average Interruption Duration Index (SAIDI) and System Average Interruption Frequency Index (SAIFI) are commonly used by the utilities. Power system reliability models typically use average equipment failure rates and have calibrated model based on historical reliability indices, all-like components within a calibrated region remain homogeneous as expressed by R. E. Brown *et.al* (2004) [14]. They demonstrate a method of customizing failure rates using equipment inspection data which allows available inspection information to be reflected in the system models, and allows for calibration based on interruption distributions rather than mean values. They also present a method to map equipment inspection data to a normalized condition score, and suggest a formula to convert this score into failure probability which shows that the incorporation of condition data leads to richer reliability models. J.J. Burke and associates (2000) illustrated that a profound consequence of deregulation is the emergence of performance based rates (PBR's). PBR's are contracts that penalize and reward a utility based on system performance. Utilities are exposed to financial risk due to the uncertainty of system reliability. A method of assessing the uncertainty of system reliability and discuss how to use this information to manage PBR risk has also been proposed by them. They show that method can be used to negotiate a fair PBR, to compute the expected financial impact of a PBR, and to make design decisions that maximize profits while minimizing risk. McCalley *et.al.* (2006) proposed that Cost-effective equipment maintenance for electric power transmission systems requires ongoing integration of information from multiple, distributed, and heterogeneous data sources storing various information about equipment. They described a federated, query-centric data integration and knowledge acquisition framework for condition monitoring and failure rate prediction of power transformers. A monitoring and analytics system for critical decision-making regarding maintenance, refurbishing, or replacement of electric power transformers was proposed by Zhengkai Wu and associates (2011) [22]. The proposed system uses key feature classification to design warning logic and danger detection mechanisms that enable evaluation of the transformer condition and maintenance decision-making. System classification and similarity comparison are accomplished based on key features. Reliability, awareness, and maintenance cost are integrated in the system using feature classification – connecting both maintenance needs and electricity service quality. A reliability-based method for transmission maintenance planning has been presented by Li Wenyuan *et.al* (2004) [13]. A quantified impact assessment of the planned outage on operation reliability of the whole transmission system is a main feature of the proposed method. This reliability centered maintenance (RCM) approach for transmission systems provides not only the lowest risk maintenance schedule but also the most reliable operation mode for the planned outage. Another feature of the method is ease of incorporation into the existing traditional transmission maintenance procedure. Clearly, despite the good reliability of transformers, in view of the serious consequences of failures, it is important that effective condition assessment systems are employed so that faults can be detected at an early stage so as to improve the prospects for repairs and minimize the impact of any failures. In order to enhance system reliability and electricity supply to customers.

The objective of this paper is to develop the effective condition assessment systems so that faults can be detected at an early stage so as to improve the prospects for repairs and minimize the impact of any failures. This paper has focused on following different issues; condition assessment of transformer, condition and impacts of the maintenances of transformer on system reliability. Fuzzy analytic hierarchy process **(**AHP) technique will be applied in transformer to analyze criteria for condition weight. Study the impact of transformer hazard rate models on aging mechanism and investigate the best suited reliability model for a statistical approach.

II. TRANSFORMER CONDITION MEASURE

Many utilities around the world have distribution systems with a large percentage of very old transformers.

The amount of very old transformers is increasing, and age-related deterioration is, in many cases, beginning to have a detrimental impact on distribution system reliability. In the future, issues surrounding aging infrastructure will increasingly become more critical for distribution systems in terms of cost and reliability. Therefore, it is very important to monitor the condition of transformer.

Transformer condition criteria are broadly categorized into four types as follows

(i) General condition: includes Age of transformer, Experience with transformer type, Noise level, Transformer loading condition and Core and winding losses.

(ii) Winding condition: Winding turn ratio, Condition of winding, Condition of solid insulation and Partial discharge (PD) test.

(iii) Oil condition: Gas in oil, Water in oil, Acid in oil and Oil power factor.

(iv) Physical condition: Condition of tank, Condition of cooling system, Condition of tap changer and Condition of bushing.

Score is assign for each criterion for various ranges of condition data of field. Weight is for these criteria on the bases field exports opinion and finally applies fuzzy AHP to calculate final weight for each criterion. Table 5 shows the weight and score sheet for condition criteria.

Table 1: Scoring criteria for transformer age.

Age of transformer	Score
<1	0.00
1-10	0.05
11-20	0.10
21-25	0.25
26-29	0.40
30-31	0.50
32-35	0.60
36-40	0.80
Greater then 40	1

The world has distribution systems with a large percentage of very old equipments. The amount of very old equipment is increasing, and age-related deterioration is, in many cases, beginning to have a detrimental impact on distribution system condition and reliability. In the future, issues surrounding aging infrastructure will increasingly become more critical for distribution systems in terms of cost and reliability [21]. The guideline for scoring for these criteria is presented in Table 1.

In practice there are varieties of transformers of different types of rating, made by different manufactures. The utility engineers need to review the history of the failure of transformer on the system then conclusion need to be drawn regarding the reliable operation of the transformer as per their types, ratings and manufacturers this will score for developing the scoring guideline for these criteria. A score of 0 indicates satisfactory performance with the particular transformer type. For all of these conditions of transformer criteria need to be developed by the maintenance personnel based on test result. The condition score is given in percentage in range from 0 to 1. Condition sore “0” indicate the fine condition and as the score towards 1, it indicates reduced condition.

III. WEIGHT ASSIGNMENT FOR CONDITION CRITERIA

The assignment of weight to each parameter is a very important step in the transformer condition assessment method. Weight assignment method is more system specific and also need inputs from the maintenance expert and transformer manufacturers. The weight selection measure for each criterion should be selected in such a way that it will highlight the criticality of particular parameter in the overall transformer condition assessment. Fuzzy analytical hierarchy process (FAHP) used for deciding and selecting the weights. Analytical Hierarchy Process (AHP) is a process that helps us pick up one of the options of a list of choices. Each choice has a few parameters attached to it and we can set the weights of each parameter. AHP allows decision makers to model a complex problem in a hierarchical structure but a questionnaire and interview based approach has been adopted for present methodology to identify the aesthetic attributes of transformer condition criteria and their relative importance but it is found that data collected through questionnaire and interviews are some time very much vague and insufficient to interpret the results. The present methodology deals with the application of FAHP to evolve the prioritized aesthetic attributes of transformer condition criteria. This section presents an integrative design approach to obtain the prioritized aesthetic attributes of transformer condition criteria. The proposed method has been illustrated using transformer expert survey data.

A. Fuzzy AHP Approach

In conventional AHP, the pair wise comparisons for each level with respect to aesthetic criteria are conducted using a nine-point scale. Each pair wise comparison indicates an estimate of the priorities of the compared aesthetic criteria. The pair wise comparison ratios are in crisp real numbers. Even though the discrete scale of 1-9 has the advantages of simplicity and easiness for use but it does not take into account its inability to adequately handle the inherent uncertainty and impression associated with the mapping of the decision-makers perception to exact numbers. Importance of different aesthetic of transformer condition criteria always contains uncertainty and multiplicity of the meaning. These descriptions are usually linguistic and vague. It may also be recognized that human assessment on qualitative attributes is always subjective and thus imprecise. Chan *et al* [18] has reported that most decision-makers tend to give assessments based on their knowledge, past experience and subjective judgment. Therefore conventional AHP seems to be inadequate for this work to generate importance weights for the aesthetic criteria of transformer condition. In order to model this kind of uncertainty in human preference, fuzzy sets can be incorporated with the pair wise comparison as an extension of AHP [17]. Kahraman *et al.* [10] used fuzzy AHP to select the best supplier firm providing the most satisfaction for the attribute determined. The use of fuzzy methodology allows the decision maker to incorporate both qualitative and quantitative data into the decision model. For this reason, decision makers usually feel more confident to give interval judgment rather than fixed value judgments. The fuzzy theory also allows use of mathematical operators and computer in the fuzzy domains. In this study, triangular fuzzy numbers, $\tilde{1}$ to $\tilde{9}$ have been used to represent subjective pair wise comparisons of aesthetic criteria of transformer condition. A tilde "~" is placed above a symbol if the symbol represents a fuzzy set.

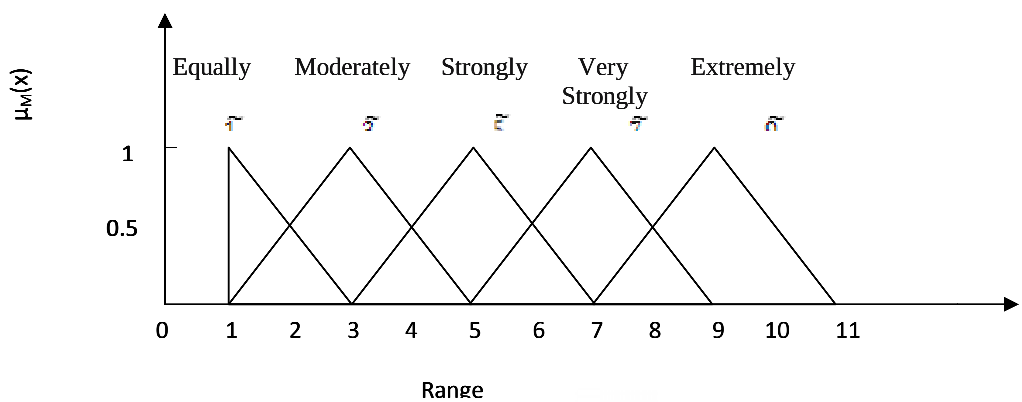

Fig. 1. The Membership functions of triangular fuzzy numbers $\tilde{1}$ $\tilde{3}$ $\tilde{5}$ $\tilde{7}$ and $\tilde{9}$

In order to take the imprecision of human qualitative assessments into consideration; the five triangular fuzzy numbers are defined with the corresponding membership function as shown in Figure 1. The α – cut values and index of optimism μ incorporated into fuzzy AHP matrix take care of the accuracy of the measurement. α − cut is known to incorporate the experts or decision makers confidence over his/her preference or the judgments. It will yield an interval set of values from a fuzzy number. Some main operations for positive fuzzy numbers are described by the interval of confidence as given below:

$\forall \mathbf{m_L}, \mathbf{m_R}, \mathbf{n_L} \mathbf{n_R} \in \mathbf{R}^+, \widetilde{\mathbf{M}}_\alpha = [\mathbf{m}_L^\alpha, \mathbf{m}_R^\alpha],$

$\widetilde{\mathbf{N}}_\alpha = [\mathbf{n}_L^\alpha, \mathbf{n}_R^\alpha], \boldsymbol{\alpha} \in [\mathbf{0}, \mathbf{1}]$

$\widetilde{\mathbf{M}} \oplus \widetilde{\mathbf{N}} = [\mathbf{m}_L^\alpha + \mathbf{n}_L^\alpha, \mathbf{m}_R^\alpha + \mathbf{n}_R^\alpha]$

$\widetilde{\mathbf{M}} \ominus \widetilde{\mathbf{N}} = [\boldsymbol{m}_L^\alpha - \boldsymbol{n}_L^\alpha, \boldsymbol{m}_R^\alpha - \boldsymbol{n}_R^\alpha]$

$\widetilde{\mathbf{M}} \otimes \widetilde{\mathbf{N}} = [\boldsymbol{m}_L^\alpha \boldsymbol{n}_L^\alpha, \boldsymbol{m}_R^\alpha \boldsymbol{n}_R^\alpha]$

$$\frac{\widetilde{\mathbf{M}}}{\widetilde{\mathbf{M}}} = \left[\frac{\mathbf{m}_L^\alpha}{\mathbf{n}_R^\alpha}, \frac{\mathbf{m}_R^\alpha}{\mathbf{n}_L^\alpha}\right] \quad (1)$$

where $\widetilde{\mathrm{M}}$ and $\widetilde{\mathrm{N}}$ are crisp values of interval of confidence. According to classical AHP [2] hierarchical analysis, a decision-maker can obtain the ratios a_{ij} (i, j =1,… , n) by pair-wise comparison of factors $A_1,\ldots,A_m$ under some specific criteria. However, the a_{ij} is an estimator and depends on the decision-makers' subjective perception or experience of the relative significance of factors A_i and A_j. Therefore, it exits vagueness from Saaty's original method between scales 1 to 9 on decision-makers judgment. In the AHP analytic process, the triangular fuzzy numbers replaced the crisp ratios to present the weights, and to distinguish the relative significance of eight aesthetic criteria.

The fuzzy judgment matrices for seven aesthetic criteria can be obtained from quantified decision-makers' cognition by linguistic variables and it's the corresponding triangular fuzzy numbers. After individual paired comparison ratio judgments have been gathered, it is necessary to calculate the geometric mean. Finally, the weight of five aesthetic criteria is obtained by using the eigenvector method, and by utilizing eigen-value to test the consistency of the decision process. The procedure of this the approach is as follows:

Step 1: Constructing the fuzzy comparison matrix

Step 2: Estimating the degree of optimism for Degree of satisfaction for the judgment matrix is estimated by the index of optimism. The larger value of the μ indicates the higher degree of optimism.

Step 3: Solving fuzzy eigen value

Step 4: Determining the weights of attributes, the consistency ratio is used to estimate directly the consistency of pair wise comparisons. The comparisons are acceptable if CR< 0.1. If the consistency test is not passed, the original values in the pair wise comparison matrix must be revised by the decision maker.

Final weight score are calculated with the help of relative importance weight of main criteria and relative important weight of sub criteria. Further, a survey was carried out to find out the importance of the sub criteria. The final weight score is defined as:

$$FS_k = (A_{dk} \otimes A_k)\, SM_k \qquad (2)$$

Where

FS_k = Final score of sub criteria k

A_{dk} = Relative importance weight of criteria d of sub criteria k

A_k = Relative importance weight of sub criteria k

B. Weight of Aesthetic Attribute

A fuzzy AHP technique is used to evaluate the aesthetic attributes of transformer condition criteria. It has been presented in this paper. About twenty-five professionals working at responsible positions in the field of product design were interviewed to evaluate the aesthetic attributes of the transformer condition criteria in the hierarchy model. The aim of interaction was to understand their opinions on three aspects:

(a) Weight judgments of aesthetic attributes of the transformer condition criteria.

(b) Their attitude toward the FAHP approach used by this study and

(c) Their suggestions in general.

All aesthetic attributes of transformer condition criteria have been listed and after that the decision-makers were requested to express the preference, $\tilde{1}$ *to* $\tilde{9}$, by pair-wise comparison of the relative importance of each aesthetic attribute using triangular fuzzy numbers by separate questionnaire to estimate their relative importance in relation to the element at the immediate proceeding level. After finalizing the assessment of relative importance of aesthetic attributes of transformer condition criteria, the fuzzy comparison matrixes for the aesthetic attributes are prepared as shown in Table 2

Table 2: Fuzzy comparison matrix of aesthetic attributes of transformer.
condition criteria

Transformer	General condition	Winding condition	Oil Condition	Physical condition
General condition	1	$\tilde{5}$	$\tilde{9}$	$\tilde{3}$
Winding condition	$\tilde{5}^{-1}$	1	$\tilde{7}$	$\tilde{1}^{-1}$
Oil Condition	$\tilde{9}^{-1}$	$\tilde{7}^{-1}$	1	$\tilde{5}^{-1}$
Physical condition	$\tilde{3}^{-1}$	$\tilde{1}$	$\tilde{5}$	1

After finalizing the assessment of relative importance by these experts for the aesthetic attributes of car profile, the triangular membership function and α-cuts were used to convert the subjective judgments of experts to become fuzzy judgments. After that, a degree of optimism for the experts was estimated by the index of optimism μ. All initial individual fuzzy comparison matrices based on triangular membership function and α-cut were formulated. The lower limit and upper limit of the fuzzy numbers with respect to α-cut level are defined.

The α-cut values and index of optimism μ incorporated into fuzzy AHP matrix take care of accuracy of the service quality measurement. The fuzzy comparison matrix is obtained for the aesthetic attributes. Fuzzy comparison matrix (FCM) for the determinants of aesthetic attributes.

C. Estimating the Degree of Optimization

Degree of satisfaction for the judgment matrices is estimated by the index of optimism μ. The larger value of the index μ indicates the higher degree of optimism.

The following crisp judgment matrix can be obtained after setting the index of optimism μ, in order to estimate the degree of satisfaction. After normalization, the importance weights of the aesthetic attributes can be determined. Verify the consistency ratio is less than 0.1, and then comparison is acceptable, otherwise not.

If the consistency test is not passed, the original values in the pair wise comparison matrix must be revised by the decision maker. Here CR of the matrix can be calculated as the value of CR is 0.026043. For matrix A as, CR<0.1 so this comparison is acceptable.

Table 3: Weight of aesthetic attributes of transformer condition.

Aesthetic attributes for transformer condition	Weight
General condition	0.57588
Winding condition	0.183059
Oil Condition	0.043555
Physical condition	0.197506

In similar manner Aesthetic attributes for sub criteria also calculated of General condition, Winding condition, Oil Condition and Physical condition. The Fuzzy comparison matrix of aesthetic attributes of transformer condition sub criteria and corresponding Weight result of aesthetic attributes of transformer condition for sub criteria are calculated. A structured questionnaire was framed to collect the responses of expert engineer's of power System Company. Final weight for each criteria is calculated as procedure defined above. Final weight score of each criteria are shown in Table 5.

IV. CONDITION RANKING

After a transformer has been inspected, it is desirable to score conditions according to their relative criteria as in Table 4. Each inspection item result is assigned a weight based on its relative importance to overall transformer condition. The summation of weight and condition score of respective criteria provided the condition ranking as given by equation 3.

$$\boldsymbol{Transformer\ condition\ rank}\ (\boldsymbol{TCR}) = \sum \boldsymbol{W_i} \times \boldsymbol{SC_i} \qquad (3)$$

Consider a transformer with inspection item results. Further, suppose that each inspection item result is normalized so that values correspond to the following: best inspection outcome; and worst inspection outcome.

Each inspection item result is assigned a weight based on its relative importance to overall transformer condition. By taking the weighted average of inspection item results, the final condition of a transformer is obtained. By definition, a weighted average of 0 corresponds to the best possible condition obtain, and a weighted average of 1 corresponds to the worst possible condition obtain. After each transformer is assigned a condition score between 0 and 1, transformer using the same inspection item weights can be ranked and prioritized for maintenance (typically considering cost and criticality as well as condition).

$$\boldsymbol{condition\ obtain} = \frac{\boldsymbol{TCR(x) - TCR(1)}}{\boldsymbol{TCR(0) - TCR(1)}} \qquad (4)$$

This approach using inspection items have guidelines that suggest scores for various inspection outcomes. The final condition of transformer is obtained by equation 4.

Table 4: Definitions of condition classifications [9].

Condition	Definition
Normal	No obvious problems, No remedial action justified. No evidence of degradation
Aged? Normal in service?	Acceptable, but does not imply defect-free
Defective	No significant impact on short-term reliability, but asset life may be adversely affected in long term unless remedial action is carried out.
Faulty	Can remain in service, but short-term reliability likely to be reduced. May or may not be possible to improve condition by remedial action
Failed	Cannot remain in service. Remedial action required before equipment can be returned to service (may not be cost effective, necessitating replacement).

A. Condition Classification

It is not usually practicable to quantify withstand strengths and operational stresses. Hence, a more qualitative evaluation of the health of the equipment is carried out, often referred to as its condition, and this is used to assess the expected reliability. The following classification in terms of required action is useful:

B. Assessment of Reliability Indices

A distribution system is the segment of an overall power system which links the bulk system to the individual customers. The basic distribution system reliability indices are statistical aggregations of reliability data for a well defined set of loads, components, or customers. Every customer is connected to a feeder. A feeder is the connection from a sub-station to a customer through wires, transformers etc. It is fairly common practice in the electric utility industry to use the standard IEEE reliability indices like CAIDI, SAIFI, SAIDI, ASAI and ASUI along to track and benchmark reliability performance. These standard IEEE reliability indices with three basic load point indices are assessed for a typical radial distribution system and IEEE reliability test system for educational purposes-basic distribution system data and results [4].

V. RESULT

Due to limited availability of component data and transformer condition data, numerical analysis is done using assumed value for transformer. All aesthetic attributes of transformer condition criteria were listed and after that the decision-makers were requested to express the preference, $\tilde{1}, \tilde{3}, \tilde{5}, \tilde{7}$& $\tilde{9}$ by pair-wise comparison of the relative importance of each aesthetic attribute using triangular fuzzy numbers by separate questionnaire to estimate their relative importance in relation to the element at the immediate proceeding level.

Table 5: Transformer condition scores.

Criteria	A_d	Sub criteria	A_k	Weight (W_i=A_d*A_k)	Criteria Condition Score (SC)	Criteria Condition rank (CCR=W_i*SC)
General	0.198	CWL	0.493	0.097614		
		CL	0.107	0.021186		
		Ex. T	0.102	0.020196		
		Age	0.249	0.049302		
		Noise	0.049	0.009702		
Winding condition	0.576	CW	0.106	0.061056		
		CSI	0.596	0.343296		
		PD	0.247	0.142272		
		WT	0.051	0.029376		
Oil Condition	0.183	Oil p.f.	0.094	0.017202		
		Water	0.548	0.100284		
		Acid	0.197	0.036051		
		Gas	0.161	0.029463		
Physical Condition	0.044	Bushing	0.241	0.010604		
		Cooling	0.046	0.002024		
		Tank	0.128	0.005632		
		Tap C.	0.585	0.02574		
					Transformer condition rank (TCR)	

After finalizing the assessment of relative importance of aesthetic attributes of transformer condition criteria. Each inspection item result is assigned a weight based on its relative importance to overall transformer condition. These weights are typically determined by the combined opinion of equipment designers and field service personnel, and are sometimes modified based on the particular experience of each utility. The final condition of a transformer is then calculated by taking the weighted average of inspection item results.

The product of relative weight of the each criteria and scores of respective criteria gives the condition score of individual criteria and summation of this gives transformer condition rank. The proposed method to calculate the condition rank of transformer is shown in table 5. Transformer condition rank (TCR) obtained by equation (3).By definition, a weighted average of 0 corresponds to the best possible condition and a weighted average of 1 corresponds to the worst possible condition. transformer condition rank in equation (3). After each piece of equipment is assigned a condition score between 0 and 1, equipment using the same inspection item weights can be ranked and prioritized for maintenance (typically considering cost and criticality as well as condition). This approach has been used to develop several utilities inspection forms and weights for most major pieces of power delivery equipment. In addition, inspection items have guidelines that suggest scores for various inspection outcomes. An inspection form for power transformers is illustrated in Table 5. The best and worst condition of TCR is used to normalize each transformer condition rank by using equation (4). The reliability of transformer is estimated on the basis of condition rank of transformer.

Table 6: Criteria score, rank, TCR and condition obtain of transformer for following cases Normal, Infant mortality, and Defective and Critical condition.

Criteria	Weight	Normal		Infant mortality		Defective		Critical	
		Score	Rank	Score	Rank	Score	Rank	Score	Rank
Age	0.0493	0.05	0.002465	0.05	0.002465	0.5	0.02465	0.8	0.039442
Ex. T	0.0202	0.1	0.00202	0.8	0.016157	0.2	0.00404	0.1	0.00202
Noise	0.0097	0	0	0.5	0.004851	0	0	0	0
CWL	0.09761	0.2	0.019523	0.2	0.019523	0.6	0.05857	0.8	0.078091
CL	0.02119	0	0	0.5	0.010593	0.5	0.01059	0.75	0.01589
WT	0.02938	0	0	0	0	0.5	0.01469	0.75	0.022032
CW	0.06106	0	0	0.5	0.030528	0.5	0.03053	0.5	0.030528
CSI	0.3433	0.25	0.085824	0.25	0.085824	0.5	0.17165	0.75	0.257472
PD	0.14227	0	0	0.5	0.071136	0.5	0.07114	0.8	0.113818
Gas	0.02946	0.25	0.007366	0.5	0.014732	0.75	0.0221	0.75	0.022097
Water	0.10028	0	0	0	0	0.5	0.05014	0.5	0.050142
Acid	0.03605	0	0	0.5	0.018026	0.5	0.01803	0.75	0.027038
Oil p.f.	0.0172	0	0	0.25	0.004301	0.25	0.0043	0.5	0.008601
Tank	0.00563	0.1	0.000563	0.1	0.000563	0.5	0.00282	0.8	0.004506
Cooling	0.00202	0.1	0.000202	0.1	0.000202	0.3	0.00061	0.4	0.00081
Tap C.	0.02574	0.2	0.005148	0.1	0.002574	0.3	0.00772	0.5	0.01287
Bushing	0.0106	0.1	0.00106	0.1	0.00106	0.3	0.00318	0.5	0.005302
TCR			**0.12417125**		**0.2825342**		**0.494743**		**0.6906572**
Condition Obtain			**0.01575412**		**0.26035866**		**0.588133**		**0.89073805**

A. Calculation of Condition Obtained

Once, the transformer has been inspected; it is desirable to score condition their relative criteria as in Table 5. The summation of product of weighted and condition score of respective criteria is calculated as given by equation (3). The result of transformer condition criteria shows that Best TCR value is 0.11397165 and worst TCR value is 0.761396. These inspection item results is normalized each inspection by using equation (4).

Depending on various criteria score of transformer they are categorized into the following cases: Normal, Infant mortality, Defective and Critical condition.

It is not always feasible to transfer load that is lost in a distribution system onto another feeder through a normally open point. This restriction may exist because the failure occurs during the high load period and the feeder to which the load is being transferred or the supply point feeding the second system has limited capacity due to detracted condition of connected component (like transformer). In this case the outage time associated with a failure event is equal to the isolation time if the load can be transferred, or equal to the repair time if the load cannot be transferred. The average of these values can be evaluated using the concept of expiration is shown in equation (5)

$$\begin{aligned} \textbf{outage time} = & \left(\textbf{outage time} \middle| \textbf{transfer}\right) \\ & \times \boldsymbol{P}(\textbf{of transfer}) \\ & + \left(\textbf{outage time} \middle| \textbf{notransfer}\right) \\ & \times \boldsymbol{P}(\textbf{no transfer}) \qquad (5) \end{aligned}$$

The probability of transfer is dependent on the condition of transformer. For normal condition there is no restriction to transfer. For defective and critical condition there is restriction to transfer load. The probability of restriction can be calculated by the condition obtained of the transformer as the probability of transfer by equation (6).

$$\begin{aligned} & \boldsymbol{P}(\textbf{probability of transfer}) = \\ & \mathbf{1} - \textbf{condition obtain} \qquad (6) \end{aligned}$$

B. Reliability Performance Measure

The reliability performance of the distribution system is evaluated by considering the ability of the network fed from bulk supply points. This considers the distribution functional zone only. The analytical approach is used to all functional zones of a distribution system to measure reliability performance.

C. Reliability Evaluation

IEEE Reliability test for electrical distribution system BUS 4 with some modification is used to evaluate the Reliability performance of bus 4 system for different condition classifications and respective failure rate. The feeder are operated as radial feeders but connected as a mesh through normally open sectionalising points. Following a fault on a feeder, the ring main units permit the sectionalising points to be moved and customer to be supplied from alternative supply points.

Customer and loading data are refer from [1] for each load point, several of which are considered the same. The defined average load assumes that this will be the average value seen by the load point duo to diversity between customers and normal load variations throughout the day and through the year. This shows the load and number of customers on each feeder and on the main RBTS bus-bar together with the values for each 33/11kV supply point in BUS 4.

The transformer condition classifications Normal, Infant mortality, Defective, Critical depends on various criteria score and condition obtained. The condition obtained is used as condition based failure rate of transformer. Reliability system data for the component is used for transformers having condition classifications Normal, Infant mortality, Defective, Critical with failure rate on the basis of condition obtained is 0.015 f/yr, 0.260 f/yr, 0.588 f/yr and 0.890 f/yr respectively, and power transformer and lines having a failure rate of 0.65 f/yr. If all components failure is short circuits then each failure will cause the main breaker to operate. The fuses in the lateral distribution operate whenever a failure occurs on the section they were supposed to protect. Here it is suppose that the fuse-gear operates with a profanity of 0.9 and all failure can be isolated within 0.5 hours.

D. System Studies

A range of reliability indices ware calculated for a number of studies. The different conditions of transformer were used to study the effect on the distribution system reliability. Theses indices includes System indices: These are SAIFI, SAIDI, CAIDI, ASAI, ENS these can be determine for each feeder and whole system.

Case-I: The test system considered is used with all the three supply point (SP1 to SP3) and load point transformer condition as normal, and their respective failure rate on the basis of condition obtained as 0.015f/yr. The distribution system have open points in a meshed configuration so that the system effectively operates as a radial system but, in the event of a system failure, the open points can be moved in order to recover load that has been disconnected. This operational procedure can have marked effect on the reliability indices of a load point because loads that would otherwise have been left disconnected until repair had been completed can now are transferred on to another part of the system. Here it is also assumed that all the component of system are healthy therefore there is no restriction on the quantity of load that can be transferred through the back fed. Results indicate that system average interruption frequency index and system average interruption duration index is highest at feeder F1. In addition to it the customer average interruption duration index and total energy not supply by the system is highest at feeder F7.

Case-II: In this case, the test system considered with transformer at supply point SP2 as Defective and SP3 as Critical, SP1 and load point transformer condition is normal. Their respective failure rate on the basis of condition obtain for Transformer at SP2 is 0.588 f/yr, for Transformer at SP3 is 0.890 f/yr, for Transformer at SP1 and load point is 0.015 f/yr. The distribution system have open points in a meshed configuration so that system is effectively operate as a radial system but, in the event of a system failure, the open points can be moved in order to recover load that has been disconnected. This operational procedure is dependent on the condition of transformers which can have striking effect on the reliability indices of a load point. The reliability indices of feeder F1 can be calculated as open mesh with no transfer, F2 & F3 can transfer load on to another part of the system until repair had been completed. Feeder F4, F5, F6 and F7 can be calculated with no restrictions to transfer load to another part of the system. The outage time can be calculated by using equation (5.1). For feeder F2 the probability of transfer to feeder F4 is 0.11 and for feeder F3 the probability of transfer to feeder F5 is 0.412.

Results indicate that system average interruption frequency index and system average interruption duration index is highest at feeder F7. Next the customer average interruption duration index and total energy not supply by the system is more considerable at feeder F4, F5 and F6 than feeder F1, F2 and F3. The customer average interruption duration index is maximum at feeder F6 and energy not supply index is highest at feeder F7.

E. Comparative result of case-I and II

The three cases are compared to illustrate the effects of condition parameters on the unreliability indices. Figure 5.2 shows the comparison between the failure rates of the three cases at the load points. Results indicate that the failure rate at each load points in case-II show considerable increase as compared to those of case-I. This indicates that the systems operated with deteriorated transformer conditions are more unreliable. Fig. 2 graphically represents the SAIFI of each feeder for the three cases. This clearly shows that SAIFI is almost constant for each feeder in case-I but in case-II it increases as the transformer conditions deteriorate. Fig. 3 then illustrates the SAIDI of the feeders. Similarly SAIDI is almost constant for each feeder in case-I but in case-II it increases as the transformer conditions get worse.

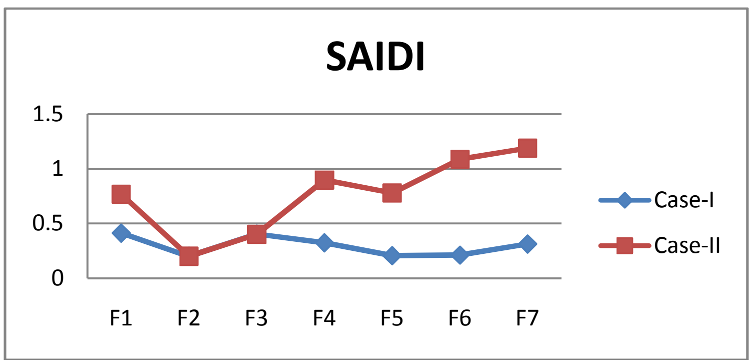

Fig. 2. Feeder SAIFI (interruption / customer yr) for case-I and II.

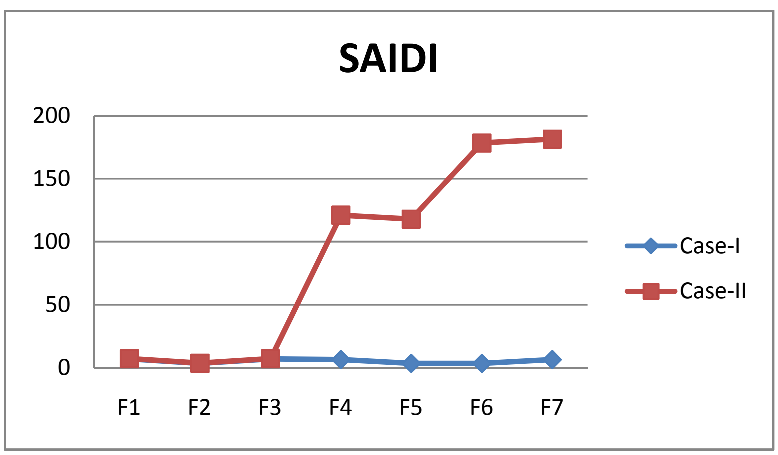

Fig. 3. Feeder SAIDI (hours/ customer yr) for case-I and II.

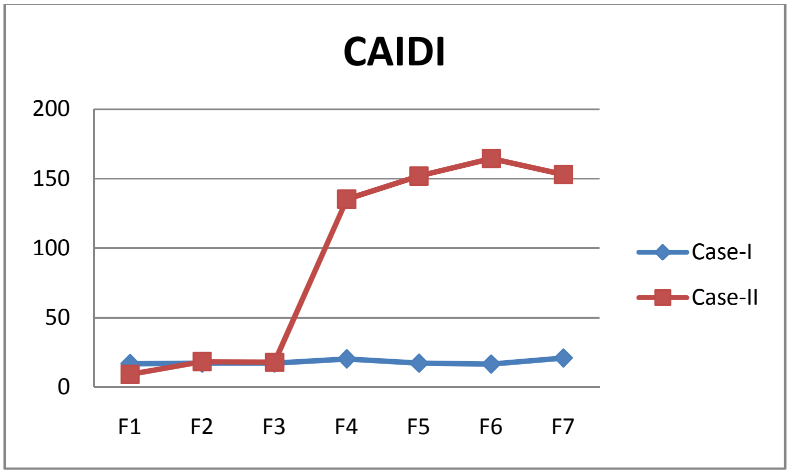

Fig. 4. Feeder CAIDI (hours/ customer interruption) for case-I and II.

Next, the different ASAI of the feeders for the three cases are represented in Fig. 5.

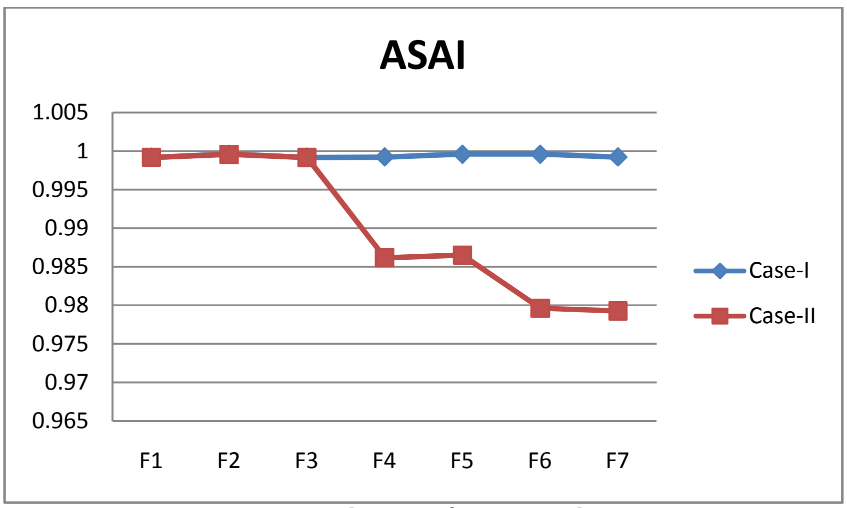

Fig. 5. Feeder ASAI for case-I and II.

Subsequently, the ENS of the feeders is illustrated by Fig. 6.

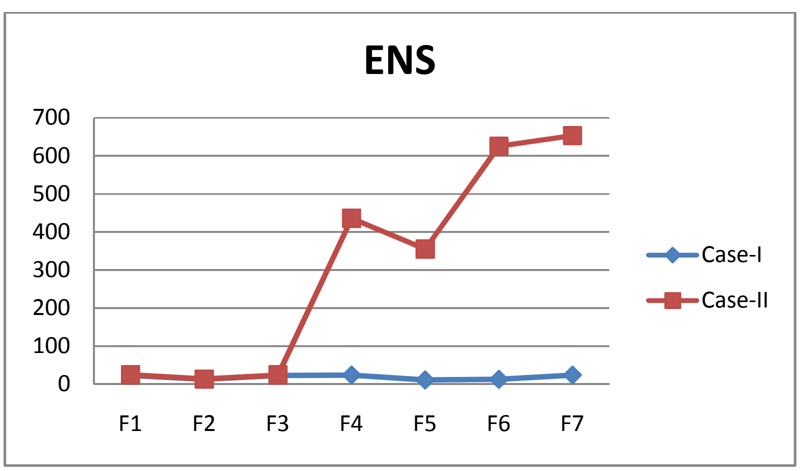

Fig. 6. Feeder ENS (MWh/yr) interruption) for case-I and II.

Table 7 represents the summed up reliability indices for the mentioned cases and are represented graphically in Fig. 7.

These system indices point out that the system with degraded transformer condition will have poor reliability performance.

Table 7: System Reliability indices for case-I and II.

Cases	SAIFI	SAIDI	CAIDI	ASAI	ENS
Case-I	0.357404	6.767172	18.93426	0.999227	130.8643
Case-II	0.832163	85.44333	102.6762	0.990246	2178.174

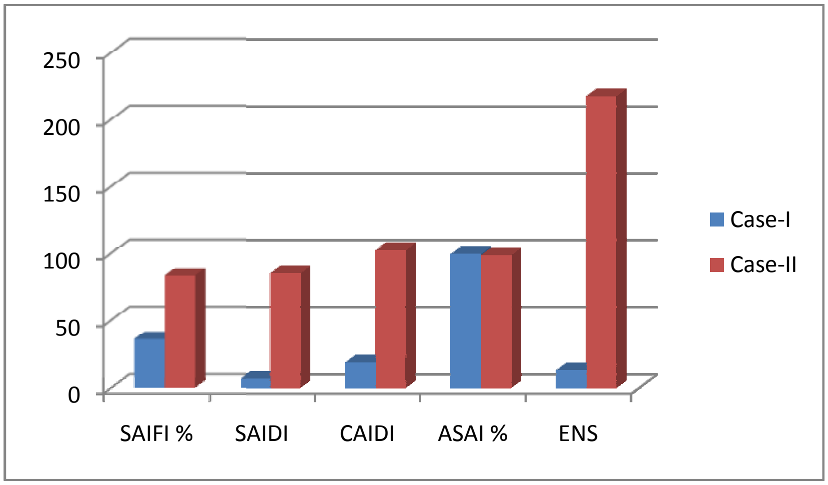

Fig. 7. System Reliability indices for case-I and II.

VI. DISCUSSION

The available historical data shows that the failure rates of the distribution transformer are differing for each circle and every year. Therefore, it is not possible to use an average failure rate of transformer to evaluate system reliability using a statistical analysis. Therefore, condition monitoring data of transformer is used to evaluate the system reliability. This work has focused on following important issues; condition assessment of transformer, condition based reliability of system and impact of the maintenances of transformer on system reliability. Our first objective was to assess the condition of the transformer. For this the conditions of different criteria's were investigated and then used to assign the scores on relative basis. This work identifies traditional criteria and nontraditional criteria. Based on the importance of a particular type of criteria for the healthy operation of the transformer a weight is assigned to each criterion. Once the weighted reliabilities of all criteria are estimated the condition of the transformer is determined.

The assignment of weight to each parameter is a very important step in the transformer condition assessment method. Weight assignment is more system specific and also need inputs from the maintenance expert and transformer manufacturers. Fuzzy analytical hierarchy process (FAHP) has been used for deciding and selecting the weights.

Analytical Hierarchy Process (AHP) is a process that helps us to pick up one of the options from a list of alternatives.

The present methodology deals with the application of Fuzzy Analytical hierarchy process (FAHP) to evolve the prioritized aesthetic attributes of transformer condition criteria. Subsequently, the transformer condition rank (TCR) is calculated by the summation of products of each weight and corresponding condition score of respective criteria. This TCR is normalized so that the values correspond to the following: best inspection outcome; and worst inspection outcome. The condition obtained of the transformer is classified into different categories from which the failure rate of the transformer is estimated. The distribution system reliability is then calculated by this condition dependent failure rate of transformer and for this calculation other components of the transformer are assigned their average failure rate. The different conditions of transformer were then used to study the effect on the distribution system (IEEE Reliability test system for electrical distribution BUS 4) reliability by using the system indices: SAIFI, SAIDI, CAIDI, ASAI, ASUI and ENS. In our study, we have considered three different conditions of transformer configurations. Case 1: All three supply point transformers in normal condition. Case 2: One critical, one defective and one transformer in normal condition.

Finally, all the configurations of system are compared on the basis of indices mentioned above.

Effects of Transformer Condition Parameters two cases are presented to illustrate the effects of transformer condition parameter on the unreliability indices. Case 1—Considering Normal Condition (considered average failure rate) Parameters: This is the base case in which constant average loads, costs, failure rates and restoration times are used. The load point failure rate, outage time, annual outage time, SAIFI, SAIDI, CAIDI, ASUI and ENS indices are calculated for comparison purposes. Case 2—considering condition based Failure Rates of transformer: Average loads, costs, and restoration times and condition based failure rates are used for transformer in these two cases. Load point failure rate, outage time, annual outage time, feeder & system indices SAIFI, SAIDI, CAIDDI, ASAI and ENS are shown in Fig. 2-7. In the case of an IEEE reliability test distribution system, the individual load point failure rates are determined by the average component failure rates. The load point failure rates will therefore be the different as those obtained using condition based failure rates.

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