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# Transformer Condition Ranking Using Fuzzy AHP

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**ABSTRACT: Transformers are expensive devices used in power industry and its maintenance is also difficult and costly. Therefore, this is essential to plan cost effective maintenance polices. This paper proposes an effective transformer condition ranking technique. Hence, to prioritized for maintenance type and schedule of transformer. 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. There are number of condition monitoring techniques are utilized for monitoring transformer. Monitoring of transformer using all these method is expensive and time consuming. This is important to select few best methods to cover overall condition. But this selection method is depending on location, type of loading, operation life, manufacturers of transformer etc. Therefore this is very important to select best suitable method. For selection of suitable method Fuzzy analytic hierarchy process (AHP) is used. The Fuzzy AHP technique will be applied in transformer to analyze criteria for condition weight.**

**Keyword:** Transformer, Condition ranking, Condition monitoring, Fuzzy analytic hierarchy process (AHP)

## I. INTRODUCTION

Power distribution companies are under increasing pressure to provide higher levels of reliability at lower cost electrical power to customer. The optimized technical managers are used for the condition planning and operation of transformers. The failure of these can over and over again cause effects that range from inconvenience and irritation to a severe impact on society and on working environment. The objective of this work was to develop an effective condition assessment system so that faults can be detected at an early stage so as to improve the prospects for repairs. The objective of this paper first step to investigation of the available transformer condition assessment methodologies and developing a guideline that is more robust and generic so that all the utilities are able to adopt it. Second step to develop an adequate composite monitoring system for analyzing the performance with the condition of transformer. Fuzzy analytic hierarchy process (AHP) technique was applied in transformer to analyze criteria for condition weight.

In order to monitor and assess the transformer condition perfectly to improve the power system reliability. In addition the transformers operate under various uncertainties due to which it is difficult to determine the condition of transformers. McCalley *et al* (2006) [4] 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) [10]. They 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.

The fluid is an integral part of the transformer playing a dynamic role in the condition of the entire system as shown by Sokolov, V. V. (2006) [9]. Dielectric withstands strength of the oil and the level of oil contamination determines the dielectric safety margin of both new and service aged transformer insulation systems. The number of failures of transformers and shunt reactors, connected to copper sulphide ($Cu_2S$) formation.

Reactive sulphur was originated basically from non-inhibited oil containing presumably non-corrosive sulphur components as natural inhibitors. Unexpectedly Sulphur appeared to be a dramatic source of conductive contaminants badly affecting winding insulation. Other studies have confirmed that oil by-products dramatically accelerate cellulose decomposition and can be a decisive reliability-based factor in aged transformer fleet. These phenomena make a good reason to reconsider role of fluid in condition evaluation aspects of power transformers especially considering increased thermal and electric stresses.

Transformer is key component of power systems so preventive maintenance is performed to extend the equipment lifetime. The model parameters which are mean time in each stage, inspection rate of each stage, and probabilities of transition from one stage to others, have an effect on reliability and cost of maintenance. In order to establish a cost-effective maintenance process, analysis of model parameters should be conducted thoroughly as illustrate by Panida, J. *et.al.* (2004) [7]. They developed detailed models relating maintenance parameters to reliability and cost and then investigated the effect of varying model parameters. The analysis covers mean time to the first failure, maintenance cost, inspection cost, and failure cost.

The age of the majority of power transformers applied in the electricity network varies between 25 and 50 years. Depending on the load history and time of operation, replacement on short term is imminent. A technically sound policy concerning the replacement of these assets must be based on knowledge of (i) the life expectancy or reliability of individual components, (ii) how these failure probabilities cumulate to a replacement wave, and (iii) how to manage an expected replacement wave, as discussed by Schijndel, V. *et.al.* (2008) [8]. The population reliability is obtained from individual transformer reliabilities using Arrhenius based modeling of paper insulation degradation. This modeling technique includes measures to cope with inherent uncertainties in available data. Lorin, P. *et.al.* (2010) [6] discussed that Over the last decade there has been a renewed and increased interest in transformer life evaluation and monitoring. The main reason is that a large number of the transformers world population is approaching its expected end-of-life and the need increases for better methods to see whether the transformers are still fit for use or need to be retrofitted or replaced.

## II. CONDITION MONITORING AND ASSESSMENT

Power transformer is a complex and critical component of the power system. System abnormalities, loading, switching and ambient condition normally contributes towards increasing sudden failure. In the lack of transformer monitoring, the failure risk is always high. For early fault detection and real time condition assessment, online monitoring system in accordance with age and conditions of the asset would be an important tool. After being indicative of abnormality it is important to carry out offline tests/ diagnostics to ascertain the overall integrity and assessment to avoid unscheduled outages, financial/ revenue losses and environmental/ collateral damages.

Weidmann Technical Services Inc. reported that most of power transformers which are working in several of the transmission and distribution companies are more than 20 years old. The average load growth rate observed in developing country like India is approximately 2%. Transformer utilization has increased by 22% on an average, causing oil hot spot temperature to increase by approximately 48%, at normal peak load. Due to gradual increase in the temperature, peak load insulation life will be reduced by a factor of approximately 8. Economic pressures and factors such as an increasing proportion of aged power transformers are combining to dictate more efficient plant maintenance management. Condition assessment is becoming increasingly important as the average age of the asset increases. A Condition monitoring assessment would be an important tool towards higher reliability of the system and asset management. After determining the critical indicator responsible for early failure as well as asset technical assessment, the rate of failure can be reduced by implementing the correct operational and maintenance strategies. Better asset management system can be implemented and timely relocation/ replacement can be planned

### *A. Transformer Condition Measure*

Transformers are typically very reliable and durable components. 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

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

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

**Oil condition:** Gas in oil, Water in oil, Acid in oil and Oil power factor.

**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 are determined on the basis of field expert's opinion and finally applied to fuzzy AHP for calculating final weight for each criterion.

*B. 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 is selected in such a way that it highlights the criticality of particular parameter in the overall transformer condition assessment. Fuzzy analytical hierarchy process (FAHP) used has been for deciding and selecting the weights. Analytical Hierarchy Process (AHP) is a process that helps us pick up one of the options from 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 sometime very much vague or ambiguous and insufficient to interpret the results. To overcome these limitations the fuzzy based approach has been appropriate utilized to convert the customer emotion into usable design data. The present methodology deals with the application of FAHP to evolve the prioritized aesthetic attributes of transformer condition criteria. The proposed method has been illustrated using transformer expert survey data.

*C. Weight of Aesthetic Attributes*

A fuzzy AHP technique is used to evaluate the aesthetic attributes of transformer condition criteria. 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:

i) Weight judgments of aesthetic attributes of the transformer condition criteria.
ii) Their attitude toward the FAHP approach used by this study and
iii) Their suggestions in general.

All aesthetic attributes of transformer condition criteria were listed and 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.

After finalizing the assessment of relative importance 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 $\mu$. All initial individual fuzzy comparison matrices based on triangular membership function and α-cut were formulated.

The α-cut values and index of optimism $\mu$ incorporated into fuzzy AHP matrix take care of accuracy of the service quality measurement. Degree of satisfaction for the judgment matrices is estimated by the index of optimism $\mu$. The larger value of the index $\mu$ indicates the higher degree of optimism.

## III. TRANSFORMER CONDITION RANKING

After a transformer has been inspected, it is desired to score conditions according to their relative criteria. 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. 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 obtained, and a weighted average of 1 corresponds to the worst possible condition obtained. 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) and the final condition of transformer is obtained. 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.

### *A. Transformer Condition Assessment*

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, 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. 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.

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. 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. The best and worst condition of TCR (Transformer condition Rank) is used to normalize each transformer condition rank.

### *B. 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 [3]. 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 (2007) [2] 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. Since fuzziness and vagueness are common characteristics in many decision-making problems, the fuzzy AHP approach allows a more accurate description of the decision-making process [1]. The fuzzy AHP method in decision-making process can be applied in many different areas due to its accuracy. Kahraman *et al* (2003) [5] 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.

The comparisons are acceptable if consistency ratio is less than 0.1 and 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.

*C. Condition Ranking*

After a transformer has been inspected, it is desirable to score conditions according to their relative criteria. 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 1.

$$Transformer\ condition\ rank\ (TCR) = \sum W_i \times SC_i \quad (1)$$

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).

$$condition\ obtain = \frac{TCR(x) - TCR(1)}{TCR(0) - TCR(1)} \quad (2)$$

This approach using inspection items have guidelines that suggest scores for various inspection outcomes. The final condition of transformer is obtained by equation 2.

## IV. RESULT AND DISCUSSION

Due to limited availability of component data and transformer condition data, numerical analysis is done using assumed value for transformer.

**Table 1: 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 | Core and winding losses | 0.493 | 0.0986 | | |
| | | Transformer loading condition | 0.107 | 0.0212 | | |
| | | Experience with transformer type | 0.102 | 0.0202 | | |
| | | Age of transformer | 0.249 | 0.0493 | | |
| | | Noise level | 0.049 | 0.0097 | | |
| Winding condition | 0.576 | Condition of winding | 0.106 | 0.0611 | | |
| | | Condition of solid insulation | 0.596 | 0.3433 | | |
| | | Partial discharge (PD) test | 0.247 | 0.1423 | | |
| | | Winding turn ratio | 0.051 | 0.0294 | | |
| Oil Condition | 0.183 | Oil power factor | 0.094 | 0.0172 | | |
| | | Water in oil | 0.548 | 0.1003 | | |
| | | Acid in oil | 0.197 | 0.0361 | | |
| | | Gas in oil | 0.161 | 0.0295 | | |
| Physical Condition | 0.044 | Condition of bushing | 0.241 | 0.0106 | | |
| | | Condition of cooling system | 0.046 | 0.0020 | | |
| | | Condition of tank | 0.128 | 0.0056 | | |
| | | Condition of tap changer | 0.585 | 0.0257 | | |
| Transformer condition rank (TCR) | | | | | | |

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. 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 1.

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 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. The best and worst condition of TCR is used to normalize each transformer condition rank.

Once, the transformer has been inspected; it is desirable to score condition their relative criteria as in table-1. The summation of product of weighted and condition score of respective criteria is calculated. The result of transformer condition criteria shows that Best TCR value is 0.1140 and worst TCR value is 0.7614. These inspection item results is normalized each inspection.

**Table 2: 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 of transformer | 0.0493 | 0.0500 | 0.0025 | 0.0500 | 0.0025 | 0.5000 | 0.0247 | 0.8000 | 0.0394 |
| Experience with transformer type | 0.0202 | 0.1000 | 0.0020 | 0.8000 | 0.0162 | 0.2000 | 0.0040 | 0.1000 | 0.0020 |
| Noise level | 0.0097 | 0.0000 | 0.0000 | 0.5000 | 0.0049 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| Core and winding losses | 0.0976 | 0.2000 | 0.0195 | 0.2000 | 0.0195 | 0.6000 | 0.0586 | 0.8000 | 0.0781 |
| Transformer loading condition | 0.0212 | 0.0000 | 0.0000 | 0.5000 | 0.0106 | 0.5000 | 0.0106 | 0.7500 | 0.0159 |
| Winding turn ratio | 0.0294 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.5000 | 0.0147 | 0.7500 | 0.0220 |
| Condition of winding | 0.0611 | 0.0000 | 0.0000 | 0.5000 | 0.0305 | 0.5000 | 0.0305 | 0.5000 | 0.0305 |
| Condition of solid insulation | 0.3433 | 0.2500 | 0.0858 | 0.2500 | 0.0858 | 0.5000 | 0.1717 | 0.7500 | 0.2575 |
| Partial discharge (PD) test | 0.1423 | 0.0000 | 0.0000 | 0.5000 | 0.0711 | 0.5000 | 0.0711 | 0.8000 | 0.1138 |
| Gas in oil | 0.0295 | 0.2500 | 0.0074 | 0.5000 | 0.0147 | 0.7500 | 0.0221 | 0.7500 | 0.0221 |
| Water in oil | 0.1003 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.5000 | 0.0501 | 0.5000 | 0.0501 |
| Acid in oil | 0.0361 | 0.0000 | 0.0000 | 0.5000 | 0.0180 | 0.5000 | 0.0180 | 0.7500 | 0.0270 |
| Oil power factor | 0.0172 | 0.0000 | 0.0000 | 0.2500 | 0.0043 | 0.2500 | 0.0043 | 0.5000 | 0.0086 |
| Condition of tank | 0.0056 | 0.1000 | 0.0006 | 0.1000 | 0.0006 | 0.5000 | 0.0028 | 0.8000 | 0.0045 |
| Condition of cooling system | 0.0020 | 0.1000 | 0.0002 | 0.1000 | 0.0002 | 0.3000 | 0.0006 | 0.4000 | 0.0008 |
| Condition of tap changer | 0.0257 | 0.2000 | 0.0051 | 0.1000 | 0.0026 | 0.3000 | 0.0077 | 0.5000 | 0.0129 |
| Condition of bushing | 0.0106 | 0.1000 | 0.0011 | 0.1000 | 0.0011 | 0.3000 | 0.0032 | 0.5000 | 0.0053 |
| **TCR** | | **0.1242** | | **0.2825** | | **0.4947** | | **0.6907** | |
| **Condition Obtain** | | **0.0158** | | **0.2604** | | **0.5881** | | **0.8907** | |

Depending on various criteria score of transformer they are categorized into the following cases: Normal, Infant mortality, Defective and Critical condition. Using these values conditions of transformer was obtained is shown in table 2.

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