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Transformer risk modelling by stochastic augmentation of reliability-centred maintenance

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ABSTRACT

This paper reviews the literature and then applies power transformer case studies to develop a risk assessment model that augments the probabilistic capabilities of Reliability-centred maintenance (RCM). It is usually very difficult to assess the effectiveness of the RCM at its inception, when data is inadequate or when it is implemented on a large population of assets, especially when most of them are small in size as in the distribution systems. Thus, the major contribution of the study rests on applying a key performance indicator (KPI) for assessing the effectiveness of the RCM programmes, obtained by trending the profile of the mean-time-to-first-failure (MTTFF) and the average annual repair costs. The MTTFF, determined using Markov analysis, is inversely proportional to the costs. Besides, the method of moments is applied to statistical, historical data to generate a failure probability distribution comparative model, which lacks in the current practices for conducting a failure mode effect and criticality analysis (FMECA). Finally, the Markov derives complement of uptime-steady-state probability as input for FMECA, using limited data; which is an improvement on the current approaches. The overall approach developed offers a cost effective risk-priority-screening model for transformers, which can be applied prior to rigorous testing and inspection procedures on individual items during the RCM application.

1. Introduction

Many electric power utilities install Reliability-centred maintenance (RCM) programs for establishing maintenance requirements [1,2]. Much data and long (vast) experience is needed to successfully conduct the RCM [3]. Despite being around for a long time, its application in the power sector is still at an infancy stage [4].

Significant changes in business environment make electric power utility decision making and risk management, especially the need for improved risk characterisation, increasingly challenging [5]. Every stage of the physical asset management process should incorporate and build on the best attributes of the RCM for the process to succeed [6,7].

Section 2 provides a critical examination of the RCM and challenges faced during its implementation with respect to risk characterisation, data requirements and reliability modelling. Then, Section 3 outlines the methodology. Thereafter, Section 4 presents and discusses the results. Finally, Section 5 provides the conclusions.

2. Critical review of the RCM

2.1. Merits, demerits and opportunities

The RCM, initially applied to the aviation industry, establishes maintenance and refurbishment needs in complex, critical assets [2,7] based on constant failure and repair rates [8]. Critical assets are those for which the financial and service level impacts of failure justify proactive assessment and restoration [1]. The main value of the RCM is in answering the seven questions about the functions, functional failures and their causes as well as remedial actions needed to determine the most appropriate maintenance strategies [2,9].

The RCM has been described as a structured methodology and maintenance organisation or process for establishing the most cost effective level of reliability [9–12]. The RCM is claimed to reduce 11 kV transformer maintenance costs by 30–40% and routine preventive maintenance costs by up to 50% [13]. The US navy reported the following tangible benefits of the RCM: life cycle cost reductions

Abbreviations: FMECA, failure mode effect and criticality analysis; FMEA, failure mode effect analysis; ICT, information and computer technology; MOM, method of moments; MTTR, mean time to repair; MTTFF, mean time to first failure; RCM, reliability-centred maintenance; RPN, risk priority number.

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of 15%, representing $1.7 billion; increased availability by 17%; and an 8-year ship life extension [6].

The major flaws of the RCM are as follows: it lacks prioritisation needed for general industrial application [6], it is costly to implement and requires components of Total Productive Maintenance (TPM) to sustain its full capability [14]. Furthermore, it lacks the flexibility and full merits of probabilistic models [15]. Finally, it is unable to quantify the benefits of maintenance on system reliability and costs [16,17].

Risk Based Inspection (RBI) may be incorporated in the RCM to fortify it [1,6]; thereby helping to select appropriate condition monitoring methods [12]. However, the RBI is neither able to quantify costs of inspection/condition monitoring nor indicate the alternative risk treatment options [12]. The RCM's fault root cause analysis usually comprises a Failure mode effect analysis (FMEA) which is used to analyse potential failure modes and their impacts; and the Failure Mode Effect and Criticality Analysis (FMECA) which extends the FMEA to include measures to rectify the faults [18]. Major concerns in the FMECA are the tendency to eliminate cascade failures [19], and the use of simple uptime/downtime data to compute risk indexes which can affect the validity of the results [20]. For power transformers, a risk index is given as the product of consequence factor and failure probability [21,22]. Sections 2.2, 2.3 and 2.4 critically examine challenges pertaining to the risk characterisation, data requirements and reliability modelling, respectively.

2.2. Risk characterization

Physical asset management centres on optimisation of risks, cost and reliability [23]. The risk management process consists of the following seven stages [1]: risk contextualisation, risk identification, risk exploration, risk assessment, risk treatment, risk monitoring and review, and risk reporting. Risk characterisation refers to a synthesis of the seven stages, to provide a conclusion about the risk, the nature of the inherent and residual risk; and a rethink in strategy or policy due to changes in the risk profile over time.

The success of the risk characterisation process requires a comprehensive database of faults, failures, operations, and maintenance as in a surveyed breakdown strategy; whereby a fault and damage database is combined with Supervisory Control and Data Acquisition (SCADA), Enterprise Resource Planning (ERP) software and Geographical Information System (GIS) [24]. The cost implications and integration challenges tend to limit the application of such strategies in the power sector.

2.3. Data requirements

The RCM is one of the proactive equipment management practices, with probabilistic inferences, that have characterised the current asset management paradigms [7,24]. Data requirements for probabilistic concepts are huge, and it is usually difficult to get the data [3,24]. The validity of the risk evaluation processes by line managers, who normally conduct the risk analysis [25], can be adversely affected by the data unavailability.

Parameters for probabilistic models include mean times to failure, inspection rates and probabilities of state transitions [26,27]. Information and computer technology (ICT) models are useful for capturing these parameters, but power utilities have applied the models inconsistently, in a fragmented way and face challenges in integrating them in the data mining process [28]. Open System Architecture Condition-Based Maintenance (OSA-CBM) and Machinery Information Management Open Systems Alliance (MIMOSA) initiated the integration of standard ICT protocols in condition monitoring (CM) and maintenance, but most organisations have not embraced their use [28]. The Institute of Electrical and Electronics Engineers (IEEE) standardised the protocols to incorporate CM transducers [6], and also developed a standard for the FMECA and fault root cause analysis [22].

2.4. Reliability modelling

Models that quantify effects of maintenance on reliability in the power systems are few [26]. The RCM has been applied to critical systems and equipment [6], however, it is heuristic and requires judgement and experience which can take long before enough data is collected for the decision making purposes [3]. The Markov analysis can use a few data sets to cost effectively derive mean-time-to-first-failure (MTTFF), model reliability and measure the effectiveness of strategies, based on component failure and repair rates [27,29]. These rates are assumed constant [26,27]; a notion viewed as flawed [30], but it simplifies the analysis [31]. Section 3 presents an analytical model that exploits the opportunities and addresses the challenges that have been outlined in Section 2.

3. Risk modelling methodology

This section proposes a multi-method approach involving statistical data analysis and simulation of the MTTFF using stochastic Markov processes, as a way of determining probability of failures with reduced level of physical equipment inspection and testing; and even where limited data is available. The probabilities determined can be used to compute risk indexes within the FMECA stage of the RCM.

3.1. Comparison of methods and overall approach

There are four main methods for reliability and or statistical data analysis, namely: least squares method (LSM), maximum likelihood estimation (MLE), method of moments (MOM) [30,32], and Markov process [27,29]. The LSM gives accurate results for large sample sizes and for non-censored data, whereas the MLE and MOM yield accurate results for all sample sizes and even when the data is censored [32]. The results from the MLE and MOM are usually almost the same although the MLE is preferred to the MOM because its analytical approach is simple. In electric power systems, data is likely to be censored; hence either the MLE or the MOM can be applied. However, it has been shown that the application of the MOM yields more satisfactory standard errors than the MLE, thus the MOM can be used to validate the results of the MLE [33]. Unlike the LSM, MLE and MOM, the Markov technique is not suitable for drawing statistical inference, but its advantage over the other methods is that it can resolve state probabilities and simulate the MTTFF, using data from a very short time span (horizon) [27]. Based on the above background, this study applies the MOM to process statistical data to draw the relevant statistical inferences; and the Markov analysis to deal with the computation of transitional probabilities and MTTFF.

3.2. Overall analytical approach

Fig. 1 outlines the overall methodology, whereby the risk analyst must decide whether the equipment has a long history, with a reasonable quantity of data, or not. If yes, the MOM should be applied, otherwise the Markov simulation models should be used.

Fig. 1 (dotted) also shows that existing models on spare part contingency plans should be applied and the optimum number of spares determined to reduce the mean time to repair (MTTR) [22]. A new way of doing this was presented by [34]; it uses the Poisson distribution to satisfy the minimum requirements on mean time between failure, reliability and statistical economics. The statistical economics model is the best as it reduces the total system costs as well as the cost of spares carried in the system [34]. Besides,