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A Markovian model for power transformer maintenance

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ABSTRACT

The condition of the insulation paper is one of the key determinants of the lifetime of a power transformer. The winding insulation paper may deteriorate aggressively and result in the unexpected failure of power transformers, especially under the presence of high moisture, oxygen, and metal contaminants. Such types of scenarios can be prevented if the deterioration is detected on time. Various types of condition monitoring techniques have been developed to detect transformer condition such as dissolved gas analysis (DGA) and frequency response analysis (FRA). They are non-intrusive and provide early warning of accelerated deterioration both chemically and mechanically. However, the accuracy of those techniques is imperfect, which means periodic inspection is still indispensable. In this paper, we discuss the value of continuous condition monitoring for power transformers and present a way to estimate this value. Towards this, a continuous-time Markov decision model is presented to optimize periodic inspections, so that the cost is minimized and the availability is maximized. We then analyze the performance based on the information from both discrete inspection and continuous condition monitoring using DGA and FRA. The result shows the dissolved gas analysis can improve the availability and operation cost, while frequency response analysis can only improve the availability of power transformers.

1. Introduction

Power transformers are critical assets in a power transmission network. A failure of a power transformer also may cause cascading failure and catastrophic blackout in the power grid. The necessity of increasing reliability and availability of power transformers can be analyzed directly from a financial point of view. Between 1997 and 2001, the total losses caused by power transformer failure in the US were over 286 million [1]. Moreover, the aging population of power transformers has increased since 1975 [2]. These imply that it is expected to have an increase in power transformer failure, and the resulting load curtailment if the maintenance strategy remains the same.

In literature, various types of maintenance models have been developed to address the problem of power transformer maintenance. Aldhubaib and Salama have developed a reliability centered maintenance and replacement approach to optimize maintenance and replacement to increase the lifetime of power transformers and reduce annual cost [3]. Dhople et al. proposed a set-theoretic method for capturing the uncertainty in Markov reliability and reward model to maximize the availability of power transformers [4]. Abu-Elanien et al. developed a decision support system to determine the life expectancy of transformers from techno-economic perspective [5]. Lima et al. designed a two-level framework of fault diagnosis and decision making for power transformers with considering the loss for life caused by overload condition [6]. Abiri-Jahromi et al. have developed a two-stages maintenance management model that contains both mid-term and short-term maintenance to maximize the serviceability of power transformers [7]. Koksal and Ozdemir have improved the power transformer maintenance using a Markovian model [8].

As to the condition state of a power transformer is considered to be discrete, most of the developed models are based on the Markovian deterioration model. However, the deterioration of power transformers is oversimplified and modeled by Markov chain with a single deteriorating path. Such an approach is inaccurate because it overlooks the complexity of the deterioration of power transformers, such as the acceleration deterioration of insulation paper caused by high moisture. Because of this, the effective of condition-based maintenance that solely relies on the periodic inspection is over-estimated. Therefore, to re-estimate the value of continuous monitoring, it is essential to improve the deterioration model of power transformers. In practice, the accuracy of the condition monitoring is imperfect and may be interfered by operation signals and external signals. Therefore, even for the power transformers that have already installed the condition monitoring devices, periodic inspection can still provide additional value to triangulate the estimated condition information by condition monitoring. The objective of the paper is twofold: optimize the condition-based maintenance for power transformers; explore the value of online monitoring from the perspective of the lifecycle of power transformers.

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Nomenclature

π_{ij}	steady state probability of state (i,j)
λ_a	infant mortality rate of power transformers
	the deterioration rate of winding insulation paper from state (i,0) at normal deterioration process
$\lambda_{di,1}$	the deterioration rate of winding insulation paper from state (i,1) in the accelerated chemical deterioration
$\lambda_{di,2}$	the deterioration rate of winding insulation paper from state (i,2) in the accelerated mechanical deterioration
$\lambda_{fi,1}$	the transition rate from state (i,0) in the normal deterioration to state (i,1) in the accelerated chemical deterioration
$\lambda_{fi,2}$	the transition rate from state (i,0) in the normal deterioration to state (i,2) in the accelerated mechanical deterioration
λ_F	the sudden failure rate of power transformer in the normal deterioration process
λ_{Fd}	the sudden failure rate of power transformer in the accelerated deterioration process
λ_{ol}	the rate of successfully detected malfunctions by online monitoring device
$1/\mu_{in}$	the duration of periodic inspection
$1/\mu_c$	the duration of minor maintenance
$1/\mu_M$	the duration of major maintenance
$1/\mu_F$	the duration of corrective maintenance
$1/\mu_R$	the duration of replacement
C_u	the downtime penalty cost due to unexpected failure
C_p	The downtime penalty cost due to maintenance and inspection
C'_{in}	the cost of periodic inspection
C'_C	the cost of minor maintenance
C'_M	The cost of major maintenance
C'_F	the cost of corrective maintenance
C'_R	the cost of replacement
C_{ol}	the annual cost of online monitoring device

To achieve the objectives, in the second section, we use cause-effect analysis on different subsystems of the power transformer to identify the potential risk of acceleration deterioration of insulation paper caused by the malfunction of different subsystems. In section three, we develop a continuous-time Markov chain model to optimize the maintenance of power transformers based on the information from inspection and continuous monitoring. Section four analyzes the value of different types of online monitoring numerically. Section five summarizes the concluding remarks of the paper.

2. Deterioration of power transformers

To systematically analyze the deterioration of power transformers to identify the information that can be used to improve the modeling of the power transformer. According to functionality and structure, power transformers can be classified into seven subsystems: winding, magnetic core, insulation oil, bushing, tap changer, tank and cooling equipment. In practice, the condition of winding insulation paper is usually regarded as the index for power transformer condition [9] and [10]. The deterioration of the winding insulation paper may accelerate under the presence of high moisture, oxygen, and metal contaminants.

In this section, we aim to identify the potential risks of the accelerated deterioration of winding insulation paper caused by the malfunctions of other subsystems using cause-effect analysis. In general, the deterioration of winding insulation paper may accelerate in two ways: accelerated chemical aging and accelerated mechanical aging. The accelerated chemical deterioration is a combination of three interactive processes: pyrolysis, hydrolysis, and oxidation [11]. Hydrolysis is the dominant process in the accelerated chemical degradation. The rate of hydrolysis is dependent on the content of moisture and catalyzes by the acidity [12]. The increase of acidity is caused by the sludge formation as the result of oxidation. The sludge will also increase the temperature and accelerate the pyrolysis. The accelerated chemical deterioration starts with the occurrence of contamination and moderate partial discharge. During the deterioration process, dissolved gas will be generated. Eventually, the partial discharge will result in treeing, tracking or even breakdown the winding insulation. The accelerated mechanical deterioration is usually initialized by the loss of clamping force or distortion of winding geometry, which is mainly caused by abrasion under electric-magnetic forces [13]. Under accelerated mechanical deterioration, the partial discharge will proceed to creeping and result in the breakdown of winding insulation.

The aging of winding insulation is related to the moisture, acidity, oxygen, containment level, and clamping forces. Empirically, abnormality in these factors is usually caused by malfunctions of other subsystems. For example, inelastic gasket on bushing can increase the risk of excessive moisture, oxygen, and containment level and in turn accelerate the rate of winding insulation aging and reduce the life of the power transformer. Malfunctions such as inelastic gasket can be repaired with a minor cost if it is detected on time. However, the resulting deterioration of the insulation paper is irreversible and will significantly reduce the service lifetime of the power transformer.

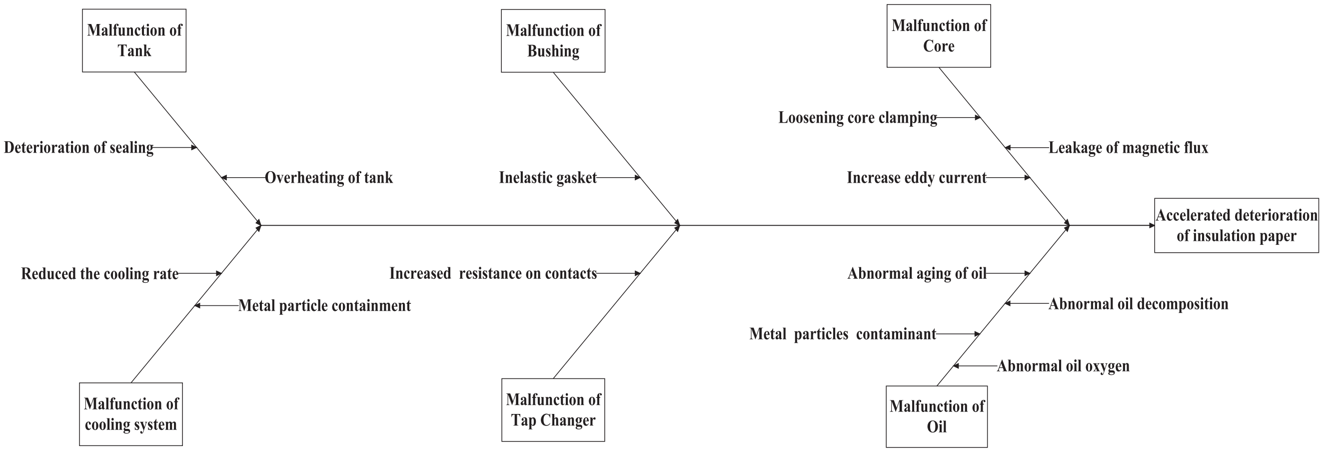

Fig. 1. Malfunctions of subsystems that can cause an accelerated deterioration of winding insulation.