Available online at www.sciencedirect.com
ScienceDirect
Electric Power Systems Research 78 (2008) 765–776
ELECTRIC POWER SYSTEMS RESEARCH
www.elsevier.com/locate/epsr

Method for effects evaluation of some forms of power transformers preventive maintenance

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Received 13 April 2006; received in revised form 7 May 2007; accepted 31 May 2007
Available online 23 July 2007

Abstract

The paper suggests a method for effects evaluation of a few activities and measures, undertaken as a part of preventive maintenance of power transformers. The method enables calculation of expected failures repair cost and load curtailment cost. The method identifies minor and major failures. Power transformer is a complex system, consisting of five components (functional parts). It is assumed that each component has two independent, competing failure modes: wear-out failure mode, modeled by two-parameter Weibull distribution, and a chance failure mode, characterized by an exponential distribution. The application of the method is demonstrated for one transformer station (TS) 110/*x* kV/kV with 2 × 31.5 MVA transformers. Also, by applying the method, influence of system for condition monitoring of transformer windings and oil on failures repair cost and load curtailment cost is evaluated.

Keywords: Power transformer; Preventive maintenance; Failures repair cost; Load curtailment cost

1. Introduction

With regard that equipment in substations is growing older, maintenance organization in each electric power company has one of the most important functions.

The goal of effective preventive maintenance is minimizing the unplanned outages, i.e. reduction of long and expensive failures repair and load curtailment cost. Having in mind their functions, purchase costs, number of installed units and techno-economical consequences of unplanned outages, preventive maintenance of power transformers has an essential importance.

The aim of this paper is to propose a model enabling the evaluation of effects of a few activities and measures, undertaken as a part of power transformers preventive maintenance.

In the following sections, a model for calculation of expected failure repair cost and a model for calculation of load curtailment cost are formulated.

2. Basic assumptions

At any point of time, status of power transformer can be classified as either operating or failed. Failed status is a result of minor failures and/or major failures. Minor failures can be repaired for $t \leq 24$ h.

Hence, probability that the component "*k*" of power transformer is in operating status equals

$$R_k(t) = \mathrm{e}^{-(\lambda_{k,\mathrm{mf}}+\lambda_{k,\mathrm{MF}})t}\,\mathrm{e}^{-(t/\alpha_k)^{\beta_k}} \tag{1}$$

i.e. we assume that the component has two independent failure modes: a chance failure mode, characterized by the exponential distribution, and a wear-out mode, modelled by two-parameter Weibull distribution.

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0378-7796/$ – see front matter
doi:10.1016/j.epsr.2007.05.024

Power transformer consists of five components-functional parts [5,7,10,14]: (1) Windings and Core + Oil, (2) Bushings, (3) Tank, (4) On-load tap-changer, and (5) Other accessories.

The main failures occurring on each functional part of power transformer are as follows [6,15]:

- *Windings, core, oil*. Partial discharges, abnormal oil and cellulose ageing, loose connections, oil contamination, excessive water content, overheating of laminations, overheating due to circulating currents, turn-to-turn failures, phase-to-phase failures, mechanical failures, open winding, and external faults.
- *Bushings*. Moisture contamination due to deterioration of gasket material or cracks in terminal connections, and partial discharges.
- *Tank*. Poor tank weld, corrosion, and external damages.
- *On-load tap-changer*. Local hotspots due to contact overheating, significant increase in required torque, sparking, oil leaks, and partial discharges.
- *Other accessories*. Arcing, local overheating, electrical failures of pumps and fans, and internal or external blocking of radiators resulting in poor heat exchange.

With regard to the failure repair time, there are three failure classes:

- ($i=1$) failures which can be repaired for $t \leq 1$ day (minor failures),
- ($i=2$) failures which can be repaired for 1 day $< t <$ 30 days,
- ($i=3$) failures which can be repaired for $t \geq 30$ days.

3. Model development

Six forms of power transformer preventive maintenance will be analyzed:

(3.1) Operation with non-preventive maintenance (*run to failure*);
(3.2) One-day preventive maintenance (practically, 8 h)—visual examination, checking the state of the transformer and replacing worn-out parts (without tank opening-windings, core and oil are not involved);
(3.3) Oil regeneration + (3.2). These activities will be performed in 5 days;
(3.4) Insulation system regeneration + (3.2). These activities will be performed in 10 days;
(3.5) Power transformer refurbishment. After this, transformer will be "as good as new". After each year of operation, transformer value goes down for $0.015 \times C_{\text{new}}$/year. Process of refurbishment will be performed in 28 days;
(3.6) Installing of system for condition monitoring of windings and oil. Expected life-time of commercially available systems is 10 years. Detection rate is about 80% [10,11]. Detecting of failures in the early stage of development prevents an outage of power transformer and reduce cost and time of repair. Neglecting of detected failures repair cost seems to be too optimistic. Because of reasons of certainty, an assumption is adopted: all detected major failures on windings and oil will be treated as faults, which can be repaired in 5 days and for €5000.

(3.1) If the transformer operates without performing preventive maintenance expected cost per year during period of length T equals [1,4]

$$C_{\text{ET}}(0,T) = \frac{[1-R_{\text{tot}}(T)]\sum_{k=1}^{b}\left(\sum_{i=1}^{f_k} p_{k,i}C_{k,i}\right)}{\int_0^T R_{\text{tot}}(t)\,\mathrm{d}t + (1-R_{\text{tot}}(T))\sum_{k=1}^{b}\sum_{i=1}^{f_k} p_{k,i}r_{k,i}}, \qquad R_{\text{tot}}(t) = \prod_{k=1}^{b} R_k(t) \tag{2}$$

The numerator in Eq. (2) is the expected cost of failures repair during time period T. First term in denominator is the mean time to failure and second term is the expected time of failures repair during period T.

An average unavailability of transformer during period of length T equals

$$U_{\text{ET}}(0,T) = \frac{[1-R_{\text{tot}}(T)]\sum_{k=1}^{b}\sum_{i=1}^{f_k} p_{k,i}r_{k,i}}{\int_0^T R_{\text{tot}}(t)\,\mathrm{d}t + (1-R_{\text{tot}}(T))\sum_{k=1}^{b}\sum_{i=1}^{f_k} p_{k,i}r_{k,i}} \tag{3}$$

For planning of preventive maintenance activities, it is more convenient to calculate an average failure repair cost during time interval (T, N):

$$C_{\text{ET}}(T,N) = \frac{[1-(R_{\text{tot}}(N)/R_{\text{tot}}(T))]\sum_{k=1}^{b}\sum_{i=1}^{f_k} p_{k,i}C_{k,i}}{\int_T^N R_{\text{tot}}(t)\,\mathrm{d}t + [1-(R_{\text{tot}}(N)/R_{\text{tot}}(T))]\sum_{k=1}^{b}\sum_{i=1}^{f_k} p_{k,i}r_{k,i}} \tag{4}$$