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Short survey

Method for determining optimal power transformers exploitation strategy

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ABSTRACT

The paper suggests a procedure for determining an optimal combination of activities and measures to minimize the expected total costs during the planned exploitation period of power transformers.

Combinations of different types of preventive maintenance, spare parts keeping and installation of condition monitoring systems of power transformer individual components are taken into consideration. Power transformer is a complex system, consisting of six components (functional parts). It is assumed that each component has two independent, competing failure modes: a wear-out failure mode, modeled by two-parameter Weibull distribution, and a chance failure mode, characterized by an exponential distribution.The superposition of failures and planned maintenance are taken into account in the analysis of some forms of preventive maintenance.

The application of the method suggested and the benefits it provides are demonstrated for one transformer station (TS) 110/10 kV/kV with 2 × 31 500 kVA-110 kV Star-10 kV Delta transformers in case of radial supplying of customers as well as in case when outage of one power transformer does not affect the power supply to customers.

1. Introduction

Equipment failures in distribution substations may cause interruptions in the power supply, which result in cost increase on both power distribution company and customers. The most severe consequences arise after power transformer failures, because the time for renewal of a damaged transformer can be very long and renewal process can be expensive.

Power transformer failures are classified as repairable or unrepairable. Renewal time of repairable failures is not usually long and spare parts are not necessary. Unrepairable failures request using of spare parts, so the renewal time depends on necessary spare parts availability. Purchase of spare parts will substantially reduce the renewal time of unrepairable failures on the one hand, but, it implies considerable investment cost on the other.

Power transformer failure rate can be influenced by performing preventive maintenance of certain scope and/or by installing condition monitoring systems of power transformer individual components.

During the preventive maintenance of the first transformer failure of the second transformer is possible, which, depending of the concept of power supply, may result in the total interruption or reduction in power supply to customers.

The following sections will present a precise procedure for determining optimal combination of activities and measures that can ensure a minimum of expected total cost during the planned power transformers exploitation period.

2. Basic assumptions

At any point of time, the status of power transformer can be classified as either operating or failed. Failed status is a result of major failures and/or minor failures. According to CIGRE, major failure is a failure of a power transformer which causes the cessation of one or more of its fundamental functions. A major failure will result in an immediate change in the system operating conditions. A minor failure is a failure of a power transformer other than a major failure or any failure, even complete, of a constructional element or a sub-assembly which does not cause a major failure of the equipment.

Major failures can be repairable or unrepairable. Minor failures are repairable and can be repaired for $t \leq 24$ h.

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

$$R_k(t) = \exp(-(\lambda_{k,mf} + \lambda_{k,MF}) \cdot t) \cdot \exp\left(-\left(\frac{t}{\alpha_k}\right)^{\beta_k}\right) \quad (1)$$

i.e. it is adopted that the component has two independent failure modes: a chance failure mode and a wear-out mode [1]. Chance failures are those failures that cannot be improved with maintenance, such as human error, manufacture and design defects, and

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Nomenclature

t	time
C_{new}	purchase cost of new power transformer
$C_{new,k}$	purchase cost of power transformer component "k"
$C_{new,oil}$	purchase cost of new oil
C_u	cost of oil filtration and drying
C_{pm}	cost of material for performing 1-day preventive maintenance
$C_{reg.\text{-}oil}$	cost of oil regeneration
$C_{reg.\text{-}ins}$	cost of insulation system regeneration
b	number of functional parts-components of power transformer
f_k	number of failure classes of power transformer component "k" with regard to the failure repair time
p_k	probability that the failure occurs on power transformer component "k"
$p_{k,i}$	probability that the failure of class "i" occurs on component "k"
$C(t,t+1)$	average yearly failure renewal cost per transformer during time interval $(t,t+1)$
$C'_{k,i}$	renewal cost of class "i" failure on component "k" if spare component "k" is not available
$C^{CMS\text{-}b}_{k,i}$	renewal cost of class "i" failure on component "k" if condition monitoring system is installed and spare component "k" is not available
$r'_{k,i}$	renewal time of class "i" failure on component "k" if spare component "k" is not available
$C''_{k,i}$	renewal cost of class "i" failure on component "k" if spare component "k" is available
$r^{CMS\text{-}b}_{k,i}$	renewal time of class "i" failure on component "k" if condition monitoring system is installed and spare component "k" is not available
$r''_{k,i}$	renewal time of class "i" failure on component "k" if spare component "k" is available
$C_{s,k}$	purchase cost of condition monitoring system of power transformer component "k"
p^{CMS}	probability that the failure of class "i" occurs on power transformer component "k" after installing of condition monitoring system
$C_{m\text{-}cond.mon.sys.}$	yearly cost of condition monitoring system preventive maintenance
λ_{av}	average failure rate of power transformer
$\lambda_{k,MF}$, $\lambda_{k,mf}$	major failure rate and minor failure rate of component "k", respectively
$\lambda^0_{t,MF}$	initial (statistical) data for major failure rate at time t
α, β	the Weibull scale parameter and the Weibull shape parameter, respectively
$R(t)$, $U(t)$	reliability and unreliability, respectively
$W_1(t,t+1)$, $W_2(t,t+1)$, and $W_{dod}(t,t+1)$	expected yearly energy not delivered during time interval $(t,t+1)$ due to outage of one transformer, due to outage of both transformers and due to the superposition of failures and planned maintenance, respectively
C_{EN}	loss of revenue and load curtailment cost per kWh not delivered
N	duration of the planned period, expressed in years
P_{inst}	substation installed capacity
t_{pm}	duration of 1-day preventive maintenance performing
t_{oil}, t_{ins}, and t_{ref}	duration of oil-regeneration, insulation regeneration and power transformer refurbishment performing, respectively
$C_{ref}(T_{ref})$	cost of refurbishment performing at the point of time T_{ref}
d_k	degree of major failures detected by the condition monitoring system on power transformer component "k"
$Z(t,t+1)$	total expected cost during time interval $(t,t+1)$ (sum of investment cost, failures renewal cost and load curtailment cost)

bad weather such as lightning or ice storms. These failures generally have a constant failure rate over the transformer exploitation period and maintenance cannot reduce the failure rate. Wear-out failures are those failures whose probability increases with the service age or operations, so that maintenance can 'renew' the corresponding conditions and thus reduce the failure rate. A chance failure mode is characterized by the exponential distribution and a wear-out mode is modeled by two-parameter Weibull distribution.

Power transformer consists of six component-functional parts [2,3]: 1. Windings + oil, 2. Core; 3. Bushings; 4. Tank; 5. On-load tap-changer; 6. Other accessories.

The main failures occurring on each functional part of power transformer are as follows:

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

With regard to the failure repair time, there are three failure classes [2,3]:

$i=1$) failures which can be repaired for $t \le 1$ day,
$i=2$) failures which can be repaired for 1 day $< t <$ 30 days,
$i=3$) failures which can be repaired for $t \ge 30$ days.

Relevant data for power transformer components (p_k, $p_{k,i}$, $r'_{k,i}$, $r''_{k,i}$) are presented in Table 1 [2–5].

3. Model development [2–14]

In this section, the following individual cases and their combinations will be analyzed:

g_1) Operation without performing preventive maintenance (*run to failure*) and without keeping of spare components
g_2) One-day preventive maintenance (practically, t_{pm} = 8 h)—visual examination, checking the state of the transformer and replacement of worn-out parts