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Probabilistic model for planning keeping of power transformer spare components with general repair time distribution

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ABSTRACT

The paper suggests a method to optimize the quantity of spare power transformer components. The presented sparing policy is conceived to provide minimum annual cost consisting of expected capital cost for spares, failures renewal and load curtailment costs. The method identifies minor and major failures. Power transformer is a complex system, consisting of six 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. Duration of failure renewal is not a deterministic variable. It is assumed that failure state residence time of each power transformer component is Weibull distributed (renewal times of power transformer components may follow any probability distribution, Weibull distribution being only a special case).

The application of the method suggested and the benefits it provides are demonstrated for one transformer station (TS) 110/x kV/kV with 2 × 31.5 MV A transformers in case of radial supplying of customers and when outage of one power transformer does not affect customers supplying. In addition, the influence of power transformer refurbishment on expected total cost has also been analyzed.

1. Introduction

Equipment failures in distribution substations may cause interruptions in the power supply, which increases costs to both a power distribution company and customers. The most severe consequences occur after power transformer failures, because the time for renewal of a damaged transformer can be very long and renewal process can be expensive. Depending on the nature of damage, the time for renewal of a damaged power transformer may last from one day to eight months.

Failures of power transformers are classified as either repairable or unrepairable. A repairable failure is a failure which can be fixed by any repair action other than replacing the entire system (component). Renewal time of repairable failures is not usually long and spare parts are not necessary. An unrepairable failure is a failure which can be fixed only by replacing the entire system (component). Unrepairable failures require spare parts, therefore renewal time depends on necessary spare parts availability. Purchase of spare parts substantially reduces unrepairable failures renewal time, however it involves considerable investment cost.

To render purchasing of spare parts or performing any other activities acceptable a cost/benefit analysis is done. In [1,2] models for determining optimal quantity of spare parts for high-voltage substations were based on the assumption that the lifetime and renewal time of all substation components are exponentially distributed. In [3–6] the reliability performance of sets of units supported by spares has been modeled by the Poisson distribution based on the assumption that the lifetime of units is exponentially distributed. As it is known, failure rate increases with the aging of equipment. In [7] to account for age-induced wear out, normally distributed transformer lifetime was assumed for individual units, characterized as having increasing failure rate. In [3–7] the renewal time was taken to be a deterministic variable of typically 1-year duration. In [8] a new model for the optimum sparing for a set of distribution substation transformers is developed, based upon the binomial distribution of the probabilities of power transformer states. This model can cover any transformer unit lifetime as well as renewal time probability distribution.

If the used reliability models are not sufficiently precise, the results of the analysis will be pessimistic, which will consequently lead to unnecessarily high costs. As regard the statistical data on failure rates, it is quite reasonable assumption that purchasing only some components is necessary, not the entire spare power transformer. In [9] a method to optimize the quantity of spare power transformer components is developed. In [10] the combinations of different types of preventive maintenance, keeping of spare power

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Table 1
Power transformer components reliability data.

k		P_k (%)	Failure class i	$P_{k,i}$ (%)	$r'_{k,i}$ (day)	$r''_{k,i}$ (day)
1	Windings	26.4	2	14.54	30	15
			3	85.46	250	15
2	Core	2.4	2	50	30	15
			3	50	180	15
3	Bushings	12	1	14.82	1	1
			2	51.85	40	3
			3	33.33	40	15
4	Tank	7.9	1	58.82	1	1
			2	23.53	3	3
			3	17.65	90	15
5	On-load tap-changer	40.7	1	25.61	1	1
			2	52.44	3	3
			3	21.95	40	3
6	Other accessories	10.6	1	65.22	1	1
			2	17.39	15	15
			3	17.39	40	15

transformer components and installation of condition monitoring systems of power transformer individual components are considered. In [9,10] renewal time is exponentially distributed, so the probability of renewal during time interval (t_1,t_2) does not depend on time already spent for renewal, which is not realistic even for a quite inexperienced repair crew. For this reason, in the model suggested the renewal time is not considered as deterministic but as Weibull-distributed, with parameters $\alpha_{k,i}$ and $\beta_{k,i}$. Life time for each component is modeled by the mixture of exponential distribution, with parameters $\lambda_{k,m,f}$ and $\lambda_{k,MF}$, and Weibull distribution, with parameters α_k and β_k.It is important to emphasize that the proposed procedure is valid for general distributions of operating and renewal time of power transformer components.

2. Basic assumptions

Power transformer consists of six functional parts: (1) windings + oil, (2) core, (3) bushings, (4) tank, (5) on-load tap-changer, and (6) other accessories.

Probability that the component k of power transformer will not fail before time t equals:

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

i.e. it is assumed that the component has two independent failure modes: a chance failure mode, characterized by the exponential distribution, and a wear-out mode, modeled by two-parameter Weibull distribution.

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 (*major* failures), and ($i = 3$) failures which can be repaired for $t \geq 30$ days (*major* failures).

According to CIGRE [11], major failure is a failure of 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. Minor failure is a failure of 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.

Relevant reliability data for power transformer components are presented in Table 1 [12].Given the average value of power transformer failure rate during the planned exploitation period, it can be concluded that probability of a failure of any power transformer component more than once during the analyzed period is very low.Based on the conclusion above, at a point of time t for each power transformer component we can observe three periods: operating period before failure, period of failure renewal and operating period after failure renewal.

Relevant transition-state diagram of any power transformer component is displayed in Fig. 1. For diagram in Fig. 1 we can write:

$$\lambda_{k,1}(t) = p_{k,1} \cdot \lambda_{k,s}(t),\ \lambda_{k,2}(t) = p_{k,2} \cdot \lambda_{k,s}(t),\ \lambda_{k,3}(t) = p_{k,3} \cdot \lambda_{k,s}(t) \tag{2}$$

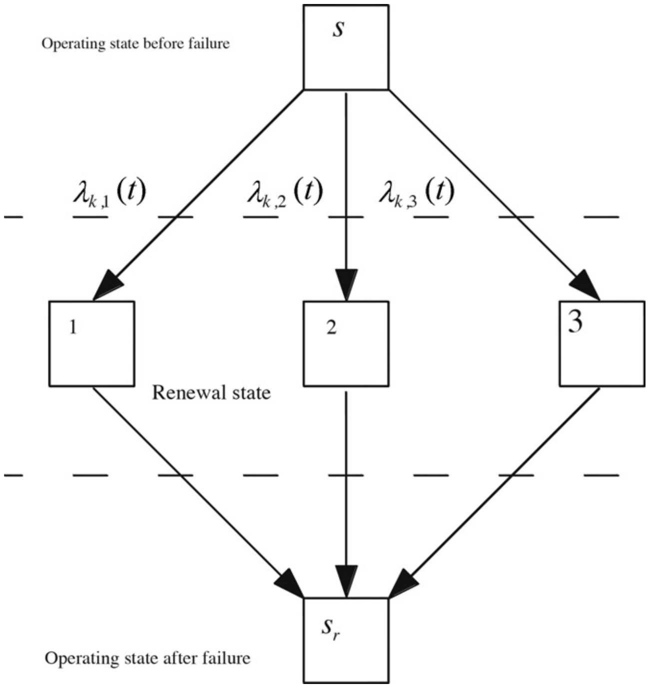

Fig. 1. Power transformer component transition-state diagram with three failure classes.