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Lifetime characterization via lognormal distribution of transformers in smart grids: Design optimization

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HIGHLIGHTS

- A tool for choosing the transformer rating under highly-intermittent loads is proposed.
- Analytical formulation for the aging of transformers in smart grid scenarios is presented.
- Randomness of loading profiles are addressed in terms of stochastic processes.
- The robustness of the Wiener process is validated for modeling load variability.

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ABSTRACT

In this paper, the problem of the optimal rating of transformers in smart grids is properly discussed with respect to the specific load characteristics. The design is based on the accurate prediction of the lifetime degradation of mineral-oil-immersed transformers subject to highly intermittent loads. In fact, by investigating the nature of the loads in the smart grid scenario, it clearly appears that the intermittent nature of the power demand increases drastically. In this context, specific tools for the characterization of the lifetime duration are required, since severe reduction of the transformer's life can be observed due to overloads, even in the case of short-duration overloads. The classical approaches based on using the equivalent thermal current to predict the transformer's lifetime might result in incorrect estimates, thus requiring advanced models that can deal with the time variability of the load. In this paper, the randomness of the load powers is addressed in terms of stochastic processes. In particular, the Wiener process is demonstrated to provide robust modeling of load variability. By starting from this assumption, it was demonstrated analytically that the hot-spot temperature, which is a major contributor to the degradation of the transformer's lifetime, also is a stochastic process. Then, in spite of the nonlinearity of the thermal model, the hot-spot temperature can be represented as a Wiener process, the robustness of which has been verified adequately. By taking into account the nonlinear relationship between the hot-spot temperature and the lifetime, the authors verified that the transformer's lifetime is modeled as a lognormal, stochastic process. Hence, a novel, closed-form relationship was derived between the transformer's lifetime and the distributional properties of the stochastic load. The usefulness of the closed-form expression is discussed for sake of design, even if a few of the considerations also are performed with respect to operating conditions. The aim of the numerical application was to demonstrate the feasibility and the easy applicability of the analytical methodology.

1. Introduction

Transformers are recognized universally as basic devices in electrical power systems, as confirmed by their extensive use from the transmission side to the end-user side. Also, in the new smart grid (SG) scenario, transformers, which are among the most expensive components in distribution systems, will continue to have a central role. In this context, however, the change in the philosophy of the operation of the power system requires the reexamination of some of the classical topics related to transformers. In particular, predicting their lifetimes is one of the most crucial topics from both economic and technical perspectives. In the environment of

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SGs, the expected increased penetration of new types of loads will imply highly-intermittent loading profiles and, probably, the use of transformers beyond to their ratings. Given this likelihood, the effects of plug-in and plug-in hybrid electric vehicles on the degradation of transformers' lifetimes currently are being investigated extensively in the literature [1–7]. In order to limit the effect of these loads on the transformers' lifetimes, specific operation strategies based on the demand response have been proposed, and these strategies provide emerging tools that can be used to control different loads and resources connected to SGs [8–10]. However, the most promising application of such a tool is known as price-based demand response, which focuses on the reduction of the costs related to the electricity usage of the end-users, thus allowing, in some cases, increased peaks of the load. Moreover, the optimal coordination of loads, as discussed in [11] with reference to the charging of electric vehicles, has some beneficial effects on the reduction of peak loads only in the case of a limited number of plugged in vehicles. If there are very high penetration levels of such vehicles, the coordinated charging strategies will not be able to fully mitigate severe increases in the load demand, thus allowing temporary overloading of transformers. Note that, by shifting the load demand (e.g., the charging of the vehicles) to the hours when the price of energy is lower (i.e., during the night), the unfavorable transformer loading conditions possibly could be extended over the entire day. Then, in the context of SG and, in particular, when there are large numbers of plugged-in electric vehicles, it is expected that the resulting daily aggregated loading profiles of the distribution transformers will be characterized by mean values close to the transformer rating, likely resulting frequent overloading peak demand. In these cases, the traditional methods used to predict the lifetimes of transformers might not be accurate, because, generally, they are based on the equivalent thermal current [12].

Transformer overloading requires the very accurate determination of the extent of the deterioration of the insulation depending on the types of transformers. In this paper, we focused on mineral-oil-immersed transformers that have insulation systems that consist of thermally-upgraded oil-mineral insulation. The prediction of the lifetime of this type of transformer as a function of loading rate has been investigated extensively in the literature [7,13–18]. Note that the lifetime depends on several aspects that affect the degradation of the transformer's insulation. These aspects refer mainly to heat (i.e., hot-spot temperatures in the windings and partial discharge), chemical mechanisms (oxidation process and moisture), and the presence of impurities in the oil. However, it is accepted extensively that, relative to the optimal transformer rating, hot-spot temperature is the factor that has the most significant effect on reducing the lifetime of the insulation [19–24]. The characterization of the features that affect lifetime should be based on historical data. The effects on the aging of transformers due to well-known parameters that affect the loading profile, such as ambient temperature, can be analyzed based on historical data and statistical methods, such as those presented in [7]. This natural approach is not suitable for the components and systems of the new generation of smart grids because no reliable historical data are available.

The probabilistic assessment of the reduction of the life of transformers has been proposed in the relevant literature, e.g., [25]. In this report, ambient temperature and transformer loading are handled as uncertain variables. The Monte Carlo procedure was used to derive the probabilistic features of hottest temperatures of the windings and to predict the rate at which transformers age.

As highlighted in [26], a probabilistic assessment of the reduction of a transformer's lifetime can be used to describe the uncertainties related to the overloading of the transformer. In [7], the Monte Carlo method was used to analyze the impact of electric vehicles in combination with the conventional residential load profile. According to the standards that usually are used [24], the method analyzes models that predict the lifetimes of transformers by considering only their thermal loading. A statistical analysis based on historical reliability data was proposed in [7]. In particular, the transformers' thermal lifetimes were studied by verifying the conditions of the insulation of a large number of transformers that were actually used in real distribution networks. Furthermore, a probabilistic approach was proposed to investigate the impact of the charging of electric vehicles on the distribution network [6]. In fact, as discussed in [5], the loads associated with charging electric vehicles must be treated by stochastic processes due to the different behaviors of the drivers.

The high level of intermittency of loads implies a certain difficulty in the choice of the most convenient modeling of the equivalent total power flowing through the transformer. The aim of the paper was to provide a tool to aid designers in choosing the optimal rating of transformers that incur highly-intermittent loading profiles. Based on the thermal models that usually are used in the design stage for the evaluation of the optimal rating of transformers [23–25], the main contribution of this paper is an analytical formulation of the aging of transformers based on the use of a stochastic loading profile described in terms of the Wiener process (WP). From this perspective, the assumption of using the WP for modeling the transformer's load is justified by keeping in mind the central limit theorem. This kind of modeling is particularly suitable for actual scenarios, which will become more familiar in the next few years, since it is expected that there will be an increased number of intermittent loads with intermittences that are not affected by seasonal variations. On the basis of WP characterization for load modeling, it is demonstrated that the hot-spot temperature also can be described as a WP. Thus, the relative aging factor can be modeled effectively as a lognormal process. Concerning the aim of verifying the robustness and suitability of the WP in describing the transformer's load, the authors demonstrated a substantial equivalence of the involved aging mechanism, even in the case in which a stochastic Poisson process (PP) was assumed. The PP, in fact, has been used extensively in the literature for handling the randomness of loads and the generation of electricity [27]. Since the WP is an ergodic process [28–32], the lifetime can be described as the mean value of this process, as will be demonstrated in the paper. Hence, a closed-form expression is derived for the estimation of the lifetime as a function of the first and second moment of the load power or, equivalently, as a function of the mean value and standard deviation of the load power. The simple form of the proposed analytical expression is useful in the following activities:

– design procedure, since it is able to choose the transformer's rating while guaranteeing a desired lifetime against the fast variations related to the highly-intermittent load;
– control actions, since it allows the dynamic adjustment of the mean value of the load power profile at a convenient level related to the maximum allowable hottest-spot temperature that is compatible with the desired lifetime.

This paper is organized as follows. In order to highlight the relationships between the lifetime and the hot-spot temperature, Section 2 summarizes the thermal model of the transformer. A probabilistic framework is developed in Section 3, in which the WP is used to describe the transformer's load profile; the validity and robustness of the WP hypothesis also are investigated by means of an alternative model that is based on the PP model for characterization of the load; moreover, the probabilistic characterization of the transformer's lifetime is reported and discussed.