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Power transformers' condition monitoring using neural modeling and the local statistical approach to fault diagnosis

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ABSTRACT

On-line monitoring of electric power transformers can provide a clear indication of their status and ageing behavior. This paper proposes neural modeling and the local statistical approach to fault diagnosis for the detection of incipient faults in power transformers. The method can detect transformer failures at their early stages and consequently can deter critical conditions for the power grid. A neural-fuzzy network is used to model the thermal condition of the power transformer in fault-free operation (the thermal condition is associated to a temperature variable known as hot-spot temperature). The output of the neural-fuzzy network is compared to measurements from the power transformer and the obtained residuals undergo statistical processing according to a fault detection and isolation algorithm. If a fault threshold (that is optimally defined according to detection theory) is exceeded, then deviation from normal operation can be detected at its early stages and an alarm can be launched. In several cases fault isolation can be also performed, i.e. the sources of fault in the power transformer model can be also identified. The performance of the proposed methodology is tested through simulation experiments.

Introduction

Power transformers are among the most expensive equipment of the electric power transmission and distribution system and their condition monitoring is important for the uninterrupted and reliable functioning of the power grid. Transformer life management has been a topic of intensive research during the last years because of the need for operating the electric power grid under more harsh conditions and because of the increased demand for electric energy. According to an IEEE survey, oil immersed transformer failure rate per year is 0.00625. Therefore, in a fleet of 100 transformers, ten will have problem in the next 16 years. According to an international survey conducted by CIGRE, typical failure rates for power transformers are in the range of 1–2% per year for the large power transformers (operating voltages up to 300 kV). Load growth has contributed to an increase of the transformer's Hot Spot Temperature (HST), i.e. of a parameter that is directly associated to the ageing of the transformer and to the probability of failures of the transformer's components. The average HST a few decades ago was 50 °C, while under present operating conditions it is around 73 °C [1,2].

Transformers operating beyond their ratings exhibit the following symptoms: (i) increase in temperature of windings, insulation and oil, (ii) increase in leakage flux density outside the core, causing additional eddy current heating in the metallic parts, (iii) moisture and gas content increases with the increase in temperature, (iv) bushings, tap-changers, and cables are exposed to higher stresses, (v) deterioration of the windings insulation appears due to higher thermal stresses [3–5]. Obviously, there is a significant safety and environmental risk of operating aged transformer units close to their loading limits without surveillance and assessment. On the other hand, on-line monitoring of power transformers can provide a clear indication of their status and ageing behavior. Analysis of critical parameters collected from power transformers allows avoidance of irreversible failures and permits preventive maintenance.

During the last years research efforts have been carried out to develop thermal models of improved accuracy for power transformers [6–9]. The load-current profile, the top-oil temperature profile and the weather conditions (ambient temperature, solar heating, wind speed, rain conditions, etc.) are among the parameters that influence the transformer's thermal behavior. As mentioned, significant indications about the thermal condition of a power transformer and the associated failure risks can be obtained through monitoring the transformer's Hot Spot Temperature (HST). A deviation of HST from the anticipated temperature profile is

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probably an indication of ageing of the transformer or in some cases of pre-failure situations. Analytical, as well as numerical (neural/fuzzy) models for HST have been developed [10–12]. These models associate the hot spot temperature to inputs such as: the ambient temperature, the top oil temperature rise over the ambient temperature, and the maximum winding hot-spot rise over the top-oil temperature.

The development of a model of the power transformer's thermal behavior in the fault-free condition and the comparison of the outputs of such a model with online measurements of the real transformer output enables to implement fault detection and isolation (FDI). A statistical FDI method that can be used to find incipient failures in the transformer's components is the so-called Local Statistical Approach to change detection [13–17]. The proposed statistical fault diagnosis method can point out the existence of a fault through the processing of the residuals sequence, where the residuals are defined as the differences between the measured and the estimated HST values at every sampling instant. The proposed FDI method transforms the complex detection problem into the problem of monitoring the mean of a Gaussian vector. The local statistical approach consists of two stages: (i) the global χ^2 test which indicates the existence of a change in some parameters of the transformer's model, (ii) the diagnostics tests (sensitivity or min–max) which isolate the parameter affected by the change [13–17]. The local statistical approach is suitable for detecting incipient faults in the power transformer, thus enabling preventive maintenance.

The concept of the proposed FDI technique is as follows: the thermal profile of the fault-free power transformer system is learned by the neural-fuzzy network. At each time instant the neural network's output is compared to the real Hot-Spot Temperature of the power transformer. The difference between the real condition of the power transformer and the output of the neural network forms a residual. The statistical processing of a sufficiently large number of residuals through the aforementioned FDI method provides an index-variable that is compared against a fault threshold and which can give early indication about deviation of the transformer from the normal operating conditions. Therefore alarm launching can be activated at the early stages of power transformer failure, and repair measures can be taken. Under certain conditions (detectability of changes) the proposed FDI method enables also fault isolation, i.e. it makes possible to identify the source of fault within the power transformer model [20].

The current paper elaborates on and extends the results of [21]. The structure of the paper is as follows: in Section 'Transformers in the electric power grid' an overview of the main types of electric power transformers is given and their significance for the electric power grid is explained. The main types of failures in power transformers is overviewed. In Section 'Analytical thermal model of electric power transformers' the thermal model of oil-immersed electric power transformers is analyzed and the significance of the hot-spot temperature for condition monitoring and secure operation of power transformers is explained. In Section 'Neuro-fuzzy modeling of power transformers thermal condition' neuro-fuzzy modeling is proposed for describing the variations of the hot-spot temperature in electric power transformers as well as its dependency on parameters such as the top-oil temperature and the load current. In Section 'Fault diagnosis for electric power transformers' a systematic method is proposed for fault detection and isolation (FDI) in power transformers, through the monitoring of the variations of the hot-spot temperature. The considered FDI method is the *Local Statistical Approach* to fault diagnosis and is based on the generalized likelihood ratio criterion for change detection. It is explained that the method is suitable for incipient faults diagnosis and preventive condition monitoring. In Section 'Simulation tests' simulation experiments are performed to evaluate the efficiency of the proposed fault diagnosis method in detecting and isolating faults in power transformers. It is shown that despite the nonlinearities of the thermal model of the power transformer, the success rate of the proposed fault diagnosis method is remarkably high. Finally, in Section 'Conclusion' concluding remarks are stated.

Transformers in the electric power grid

Condition monitoring of transformers within the smart grid

Power transformers are the most expensive and strategic components of a power system. One can distinguish between several classes of power transformers using two major classification criteria. The first criterion has to do with the insulating material used in the transformer (e.g. oil-immersed, gas-immersed and dry-type transformers). The second criterion has to do with the incoming and outgoing voltage levels of the power transformers and their role in the electric power grid (e.g. power transformers in generation stations, power transformers in the transmission system, power transformers in the distribution system, distribution substation transformers or distribution network transformers) [1–5].

Fault detection and isolation (FDI) for power transformers aims at continuously assessing the transformer's condition through the monitoring of associated critical parameters and at determining if the transformer is on the verge of a failure (this can be due to an internal fault or due to aging). To implement FDI it is necessary to develop a model of the transformer's functioning that associates its internal state to environmental conditions thus (i) enabling the detection of incipient failures (ii) prohibiting the erroneous interpretation of the monitored critical parameters and (iii) avoiding the launch of false alarms (for example if the transformer is operating in a heat wave, its oil temperature could be expected to be unusually high, but the transformer's FDI system should ascribe the temperature rise to the environmental conditions rather than a transformer problem) [22,23].

Reasons for failures in electric power transformers

Common failures in power transformers are (see Fig. 1):

(i) *Insulation breakdown in windings*. As the transformer ages the windings insulation is weakened to the point that it can no longer sustain the mechanical stresses due to a fault (e.g. in case of a short circuit). Turn-to-turn insulation

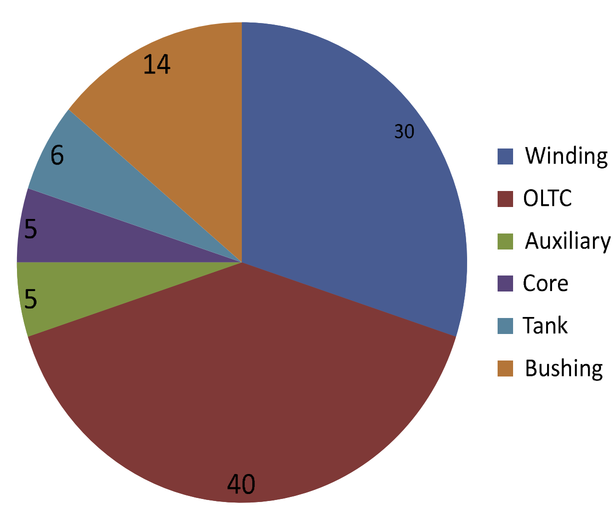

Fig. 1. Frequency of faults in components of electric power transformers [1].