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Analysing a power transformer's internal response to system transients using a hybrid modelling methodology

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ABSTRACT

This article presents a novel approach to analysing a power transformer's internal response to system transients. In this approach a hybrid modelling methodology is adopted which leverages the distinct advantages offered by both Black and Grey Box modelling techniques. The Black Box model of the transformer is used within the EMTP system study environment in order to take advantage of its mathematical flexibility and modelling accuracy. Transients derived from network switching operations within the study can then be used for injection tests within the Grey Box modelling environment. The Grey Box model, which is based upon the physical structure of the transformer, will facilitate analysis of the transformer's internal voltage response to the external stimulus. A fundamental difference between the approach described in this paper and more traditional approaches is that it does not require prior knowledge of the internal geometry of the transformer. All of the modelling parameters are derived from external tests, nameplate details and an intrinsic understanding of common transformer design principles. This can be a distinct advantage since in most cases a transformer's design specifications are not readily available outside of the laboratory due to the manufacturer's intellectual property restrictions. A study of a gas insulated substation within a hydroelectric power plant in Brazil is used to demonstrate the proposed technique.

Introduction

Electrical power system switching operations can generate a broad spectrum of transient frequencies [1]. The transient amplitude may not be sufficiently high to initiate a reaction by surge protection, however the frequency content of the transient may be such that there is a match with the natural frequency modes of equipment connected to the electrical network. A case in point is power transformers [2]. When a switching transient frequency component aligns with an internal resonance frequency within a power transformer, voltage amplification can occur which can result in a breakdown of the transformer's insulation system. This is an area of study with a long history [3], however the area is now receiving increased attention due to an increasing number of transformer failures which have been attributed to internal resonance overvoltage conditions [4,5].Working groups from both IEEE [6] and CIGRE [7] have been established to investigate ways of mitigating the problem.

Power transformers each have their own characteristic frequency response [8]. To predict how a power transformer will behave under different transient conditions, a modelling approach may be adopted. In fact, mathematical modelling of dynamic systems can generally be divided into two basic approaches, in terms of procedures for selecting the model structure and calculating the model parameters [9–11]: White-Box (or physical) modelling and Black-Box modelling. A methodology that is a compromise between these two approaches is the Grey-Box model. This terminology is associated with methods and models that can be put on a scale ranging from a pure White-Box physical model to a pure Black-Box parameterized model [9–11]. Therefore, this will be the nomenclature for transformer models used here.

A White Box model uses intimate knowledge of the internal geometry and material properties of the transformer to build a lumped parameter electrical network representation of the transformer [12–14]. Another common approach is to build a distributed electrical model which views the windings as multi-conductor transmission lines (MTL) [15]. Simple White Box models can be incorporated into an electrical system model within an Electromagnetic Transients Program (EMTP). However their application within EMTP becomes difficult when implementing a more

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comprehensive model which will be accurate across a broader frequency spectrum. Such a model will need to take into account various non-linear frequency dependent parameter properties such as the complex permittivity of the transformer's insulation system, magnetic skin effects associated with the transformer core, and the skin and proximity effects within the transformer's windings [16,8,17,18]. Another disadvantage of the White Box model is that their construction is directly based upon the transformer's design blueprint. Rarely is this information made available due to the manufacturer's intellectual property restrictions. This makes the construction of a true White Box model difficult outside of the laboratory or without close collaboration with the manufacturer.

In contrast to the physically representative White Box approach is the application of a Black Box model. The Black Box model is a purely mathematical representation of the terminal response of the transformer. Its parameters are derived using system identification methods on experimentally recorded time and/or frequency domain data in order to establish the dynamic behaviour of the system [19–22]. A Black Box model can achieve high levels of accuracy and can be readily incorporated into an EMTP electrical system model. The disadvantage is that this modelling approach does not provide any information regarding the internal behaviour of the windings.

A compromise between the Black and White Box modelling approaches is the Grey Box. Unlike the Black Box approach, both the White and Grey Box models are based on a transformer's physical structure. Like the White Box approach, a comprehensive Grey Box model can incorporate non-linear frequency dependent terms which will make it unsuitable for implementation within EMTP. The difference between these two methods is primarily in the determination of the model parameters. For the Grey Box model, many of the physical parameters may be unknown and will need to be estimated. One way of estimating the parameter values is by fitting the model's transfer function to external measurements, such as Frequency Response Analysis (FRA) [18,23,24]. It is critical however that the estimated parameters are representative of the transformer. An estimator that is not appropriately constrained can converge on a parameter set which may satisfy the objective function but is not physically representative of the transformer [23]. Such risks can be minimised by constraining parameter values using acknowledged transformer design principles supported by targeted external measurements [25]. The advantage of the Grey Box model is that the limitations associated with access to the transformer's construction details can be removed, however this will inevitably require modelling assumptions to be made which can lead to some modelling inaccuracy.

This article proposes a novel hybrid modelling methodology to facilitate the analysis of system transients within the internal winding structure of a power transformer. The hybrid approach leverages the advantages offered by both the Black and Grey Box modelling techniques. The high levels of modelling accuracy offered by the Black Box approach, together with its compliance within an EMTP system study environment are leveraged to determine worst case terminal transient conditions for the transformer. The nominal transient conditions are then injected into a Grey Box model which facilitates the determination of the resulting internal winding response. Unlike traditional transient study approaches, this methodology does not require access to the manufacturer's design specifications [26,27], but will facilitate a prediction for the transient response at nominal positions within the winding structure. The approach is demonstrated using data from a gas insulated substation (GIS) within a hydroelectric power plant in Brazil.

The paper is structured in the following manner. Section 'Hybrid modelling methodology' will discuss the proposed hybrid modelling methodology. A discussion on the Black Box modelling procedure for transient analysis is described in Section 'Black Box modelling for electrical system transient analysis'. The Grey Box modelling procedure and the estimation of an internal winding transient response is presented in Section 'Grey Box modelling to estimate the internal transient response'. The electrical system description and study results are presented in Section 'Example: generator transformer within a GIS substation'. Concluding remarks are given in Section 'Conclusion'.

Hybrid modelling methodology

Power transformer frequency response measurements are used to build both the Black and Grey Box transformer models used in the proposed methodology. The Black Box model is incorporated into an EMTP simulation of the electrical system under study. EMTP analysis will facilitate the determination of worst case system transient behaviour scenarios for the transformer terminals. These transients are then injected into the Grey Box model in order to estimate the internal response at nominal "nodal" points throughout the transformer's windings. This is accomplished by taking the Fourier Transform of the terminal transient signal and multiplying it by each of the Grey Box model's terminal to node transfer functions. This will provide an estimate for the transient output spectrum at each of the model's winding nodes. The application of an Inverse Fourier Transform on each nodal spectrum will then determine the transient voltage response at each of the Grey Box model's winding nodes. A diagrammatic representation of the proposed hybrid modelling methodology is given in Fig. 1.

The following sections will discuss the implementation of both the Black and Grey Box modelling approaches.

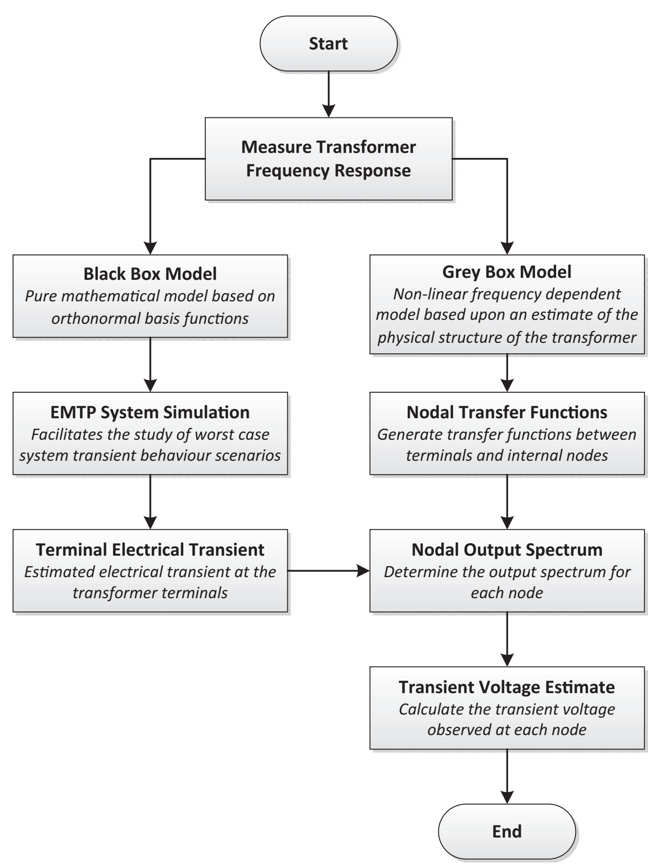

Fig. 1. Hybrid modelling methodology.