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Assessing mechanical deformations in two-winding transformer unit using reduced-order circuit model

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ABSTRACT

Certain level of mechanical deformations in winding does not hamper the normal performance of power transformer. However, such incipient deformations if unattended could result in permanent failure of transformer. To this end, an approach is proposed to assess the severity of mechanical deformations in transformer winding. These deformations get reflected as changes in its high frequency behaviour. Hence, characterising the high frequency behaviour is essential. This requires building physically realisable ladder circuit corresponding to each winding. Thus, *n*-winding transformer is represented by *n* electrically and magnetically coupled ladder networks. In such scenario, the objective of fault diagnostics becomes very challenging. In this effort, realising the multi-winding unit by reduced-order ladder circuit model is explored. This approach essentially involves energising one winding at a time. Then, reduced-order ladder circuit of considered unit is synthesised from its measured driving-point impedance data. It is shown how these circuit models could be used for identifying mechanical deformations. To demonstrate capability of the method, two-winding model transformer is considered and deformations are introduced in its outer winding. Then, reduced-order circuit models are synthesised corresponding to healthy and faulty state of model transformer. The location of fault is identified by the changed parameter in the circuit. Further, the amount of change reveals the severity of introduced deformation. In all the cases, synthesised reduced-order circuit model agrees with that of model transformer with regard to driving-point impedance plot and results are found satisfactory.

Motivation

Power transformer is a vital component of power system. Hence its uninterrupted functioning is of utmost importance. The mechanical integrity of a transformer is challenged by excessive electromagnetic forces generated in axial and radial direction due to short circuit current [1–3]. Apart from this, lightning and switching surges, transportation and rough handling of transformers are also responsible for reducing mechanical strength of the transformer. Cumulative effect of exposure to such abnormality would alter winding geometry. Such mechanical deformations are initially incipient faults. Eventually such fault-like condition grows and would lead to catastrophic failure. Therefore, identifying mechanical deformation and assessing its severity is paramount for smooth functioning of transformer and power system.

Usually, changes in the mechanical structure of power transformer get reflected in the frequency range starting from few kHz to 1 MHz [4]. Hence, its high-frequency behaviour can be considered. To this end, frequency response analysis (FRA) can be performed on transformer [5–14]. The acquired FRA data can be converted into network function by deploying curve fitting techniques [15,16]. A detailed analysis of such network function can be useful to detect deformation in transformer. Once, mechanical deformation is detected, the subsequent crucial task becomes identifying location of fault and its severity. To this end, it is necessary to look for some approach that is capable of addressing the goal of localisation. This becomes motivation for the research effort.

Literature survey

In order to locate deformation, it appeared worthwhile to have complete representation of the winding. This can be achieved if a physically realisable circuit model is built. The circuit should be synthesised such that it characterises accurately the high-frequency behaviour of transformer winding. Since most of the flux passes through air for high frequency excitation, linear circuit representation can be considered [17,18]. Such circuit models can be found in [10–12] [19–23]. Further, circuit model for two-winding transformer is shown in subsequent section (Fig. 1).

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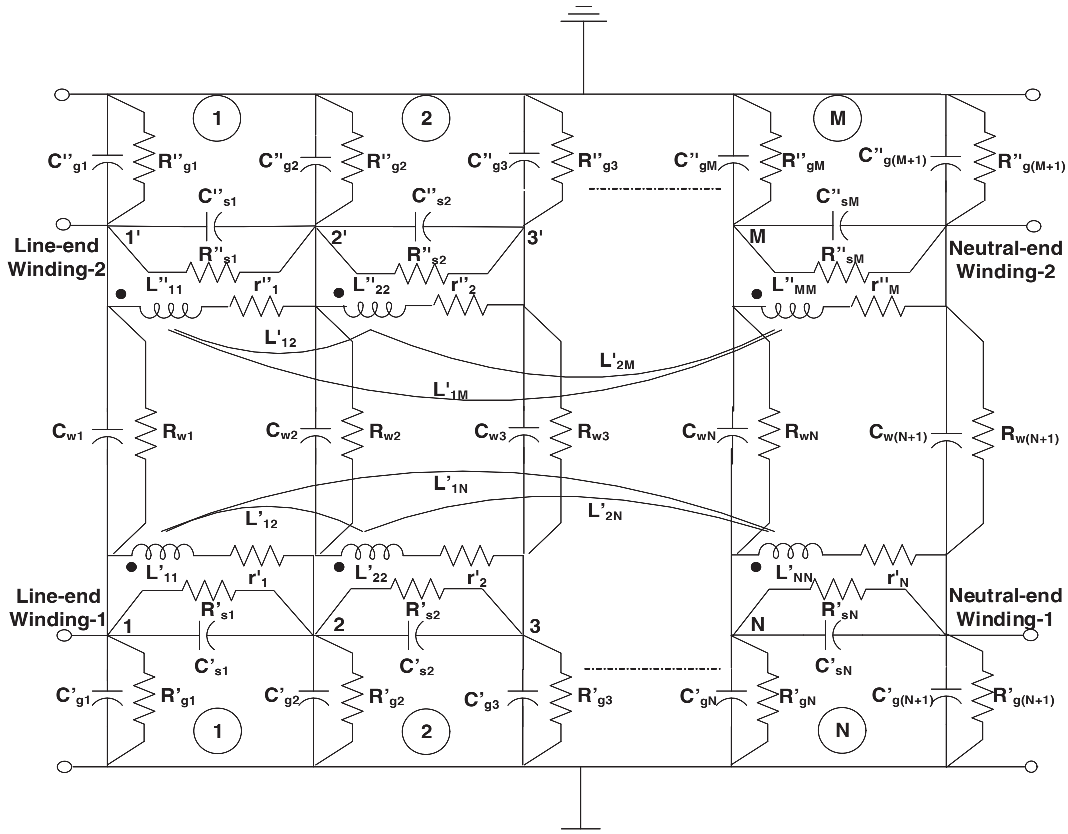

Fig. 1. High frequency circuit model of two-winding transformer.

The ladder circuits were used in [10–12,19,20] for the purpose of locating faults. In these publications, initially circuit corresponding to healthy transformer winding was synthesised. Later, some changes were introduced and then corresponding to faulty winding, one new circuit was synthesised. Then, these circuits were compared and faults were identified. Thus, the principle of identifying the changes remains the same.

However, in [19,20], the ladder network was developed using design details. Whereas, in [10–12], terminal voltage and current data are utilised. Then, driving-point impedance (DPI) function was obtained. Utilising which physically realisable ladder network was synthesised. Thus, these two approaches are different. Further, there exists discrepancy with regard to test-arrangement as indicated below:

- In [10,12], single winding is considered. Then, discrete changes in capacitances were introduced in the winding and these changes were viewed as deformations. In [11], inductive changes were also introduced by shorting few discs along with the discrete capacitive changes.
- In [19,20] two-windings are considered. Then, axial displacement is introduced by moving one winding with respect to other. Further, radial deformations are introduced by deforming one of the windings.

Thus, it is clear that the approach based on design details was validated considering "physical deformations" in the winding. Further, the test unit comprised of "two-windings". On the other hand, the terminal measurement based approach was demonstrated considering "discrete changes" in "isolated winding". Nonetheless, it is completely non-invasive.

From the above discussion, it is understood that there is a need to identify physical deformations through terminal measurement in two-winding unit. Hence, it becomes objective of the work. For this purpose, FRA is deployed.

Reduced-order circuit model

The high frequency circuit model of two-winding transformer unit is comprised of two-ladder networks as in Fig. 1 with each ladder network corresponds to a winding. Further, the electric and magnetic coupling between these windings can be accounted by inter-winding capacitances and mutual-inductances respectively.

The considered equivalent circuit has N and M sections corresponding to winding-1 and winding-2 respectively. The capacitances and inductances per section are represented as series capacitances (C'_{si}, C''_{si}), shunt-capacitances (C'_{gi}, C''_{gi}), resistances (r'_i, r''_i), self inductances (L'_{ii}, L''_{ii}) and inter-winding capacitances (C_{wi}). Mutual inductances between any two sections 'i' and 'j' can be denoted by L'_{ij}, L''_{ij}. The dielectric losses could be represented by large values of resistances $(R'_{gi}, R''_{gi}, R'_{si}, R''_{si}, R_{wi})$ in parallel to capacitors.

Thus, transformer with n-windings would be represented by n-ladder networks; coupled electrically and magnetically. Hence, it is clear that the number of variables (circuit parameters) to be estimated will increase with increase in number of windings. Thus, complexity increases during circuit synthesis. This problem could be simplified if the entire system is equivalently be represented by single ladder network. With this, it is possible to reduce number of variables significantly. Further, applicability of the diagnostic method would not be restricted with regard to number of windings in transformer.