Inverse Updating Method of High-frequency Equivalent Circuit Model in Transformer for Winding Deformation Diagnosis

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This paper proposes a novel method for diagnosing winding deformation in transformer more accurately and intuitively, based on Equivalent Circuit Model Updating (ECMU) at a high-frequency range (10Hz ~10MHz). In fact, the ECMUM is an inverse method to determine the electromagnetic parameters states under FRA excitation. It is a challenge to find a unique and accurate solution during inverse updating operation. In our study, thanks to the ECMU and frequency selection, the certainty and qualitative relationship between FRA error data and electromagnetic parameter increments of transformer equivalent circuit model can be determined easily. Also, the maximum approximate unique solution can be obtained exactly. According to the parameter increments, we can estimate the transformer winding deformations much more intuitively and accurately, which may enhance the diagnosis precision for winding deformation.

***Index Terms*—Transformer, Winding deformation, Inverse Updating Method, Equivalent Circuit Model.**

I. Introduction

TRANSFORMER is one of the most essential equipment in the electric systems, which plays the role of electromagnetic energy conversion and transmission. Statistically, winding deformation produced by huge and dynamical electromagnetic forces under short-circuit fault is one of the most serious problem which may make the transformer fault.

In practice, the transformer is like to be a black-box. It is very hard to diagnose the winding deformation accurately by using the present approaches [1]-[2], such as the Correlation Coefficient Method (CCM). During the frequency response analysis (FRA) studies, the equivalent circuit model of transformer is usually used to solve the forward problem [3]-[6], as shown in Fig.1, but how to determine the increments of equivalent electromagnetic parameters, such as the inductance, capacitance and resistance, is an important inverse problem. The diagnosis of winding deformation for transformer is a typical inverse problem.

This paper proposes a novel method for diagnosing winding deformation in transformer more accurately and intuitively, based on Equivalent Circuit Model Updating (ECMU) at a high-frequency range (10Hz ~10MHz). In fact, the ECMUM is an inverse method to determine the electromagnetic parameters states under FRA excitation. It is a challenge to find a unique and accurate solution during inverse updating operation. In our study, thanks to the ECMU and frequency selection, the certainty and qualitative relationship between FRA error data and electromagnetic parameter increments of transformer equivalent circuit model can be determined easily. Also, the maximum approximate unique solution can be obtained exactly.

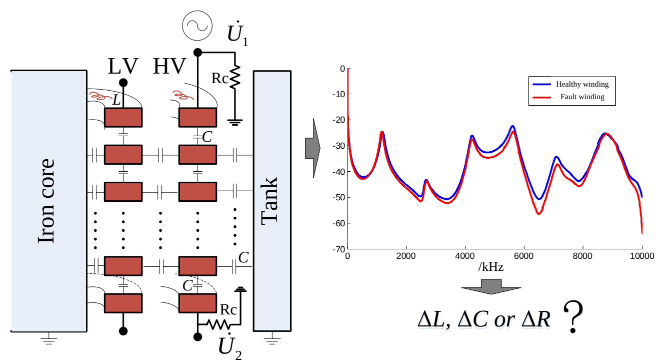

Fig. 1 Inverse problem in winding deformation diagnosis of transformer using FRA.

II. Derivation of Inverse Updating Equations

Similar to the vibrating equations in structural dynamic system [3], the dynamic governing equations in the circuit system can be given as:

$$\boldsymbol{L}\ddot{\boldsymbol{q}}(\boldsymbol{t})+\boldsymbol{R}\dot{\boldsymbol{q}}(\boldsymbol{t})+\boldsymbol{C}\boldsymbol{q}(\boldsymbol{t})=\boldsymbol{u}(\boldsymbol{t}) \tag{1}$$

where, $\boldsymbol{L}$, $\boldsymbol{R}$ and $\boldsymbol{C}$ are the parameter matrixes of inductance, resistance and capacitance.

Under harmonic excitation $\boldsymbol{u}(t)$, the dynamic stiffness matrix of circuit system in frequency domain can be obtained as:

$$\boldsymbol{G}(\omega)=-\omega^2\boldsymbol{L}+\mathrm{j}\omega\boldsymbol{R}+\boldsymbol{C} \tag{2}$$

where, ω and j are the frequency in rad/s and imaginary unit, respectively. In this study, absolute sensitivity of FRF with respect to the ith parameter Φ is used and defined as:

$$\boldsymbol{S}_{\phi}^{H(\omega)}=-\boldsymbol{H}(\omega)\frac{\partial\boldsymbol{G}(\omega)}{\partial\boldsymbol{\phi}}\boldsymbol{H}(\omega) \tag{3}$$

where, $\boldsymbol{H}(\omega)$ is the frequency response function (FRF). After calculating all the sensitivity at each frequency, the sensitivity matrix can be constructed. Finally, the model updating equation can be obtained as:

$$\boldsymbol{S}\Delta\boldsymbol{\phi} = \boldsymbol{\varepsilon} \tag{4}$$

Here, $\boldsymbol{S}$ is the sensitivity matrix; $\Delta\boldsymbol{\Phi}$ is the updating parameter vector, and $\boldsymbol{\varepsilon}$ is the output residual vector.

Then, the updating problem in (4) can be solved by [7]-[8]:

$$\Delta\boldsymbol{\phi} = [S]^{+}\boldsymbol{\varepsilon} \tag{5}$$

The updated parameters are can be determined iteratively by solving (5), until the residual, $\boldsymbol{\varepsilon}$, becomes sufficiently small.

III. Verification and Results

Fig. 2 describes the equivalent circuit corresponding to the physical discs, which is set as the original network in sensitivity analysis. All the parameters can be calculated by using analytical method or finite element method.

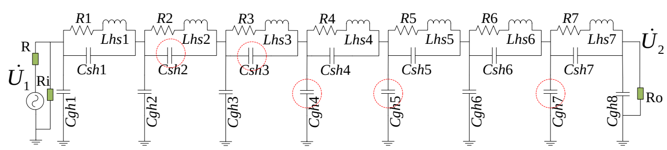

Fig. 2 The equivalent circuit model of transformer with single winding.

Fig. 3 and Fig.4 show the model updating results of FRF error after two iterations. Fig. 5 illustrates the variation of FRF error with respect to each frequency point. Table I presents the comparison results between the 1st and 2nd updating (*DP* is the updating precision). It can be seen that the updating algorithm has a high efficiency. Also, the parameter increments determined by solving model updated equations iteratively can qualitatively reflect the frequency response errors which are produced by winding faults. According to the parameter increments, we can estimate the transformer winding deformations much more intuitively and accurately. Besides, it is found that the updating precision can be improved by iteratively updating, where the residual of FRF may become sufficiently small.

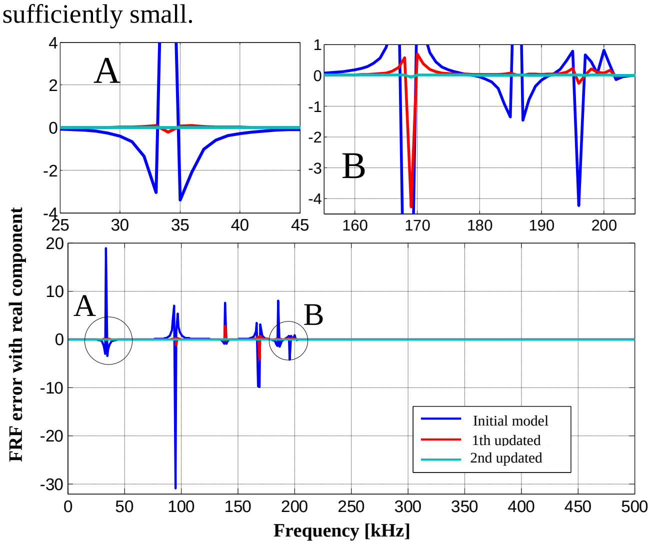

Fig. 3 Changes in the real part of FRF error under model updating

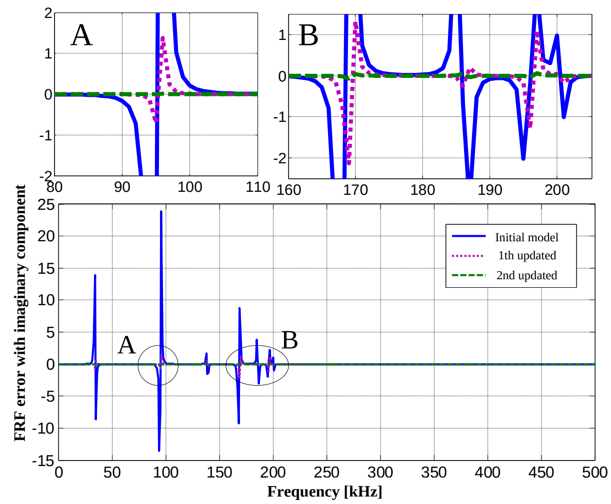

Fig. 4 Updating results of FRF error with imaginary part.

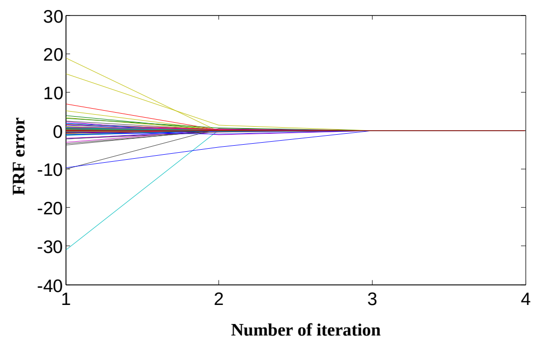

Fig.5 The convergence curve of the FRF error at each sampling frequency.

TABLE I
COMPARISON UPDATING RESULT AFTER 2ND UPDATED

Parameter	Cgh4	Cgh5	Cgh7	Csh2	Csh3
Simulated	-10%	-2%	-3%	-5%	+5%
Updated	-10.08%	-2.00%	-2.98%	-4.95%	5.18%
DP	99.2%	100%	99.3%	99.0%	96.4%

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