Combined HBM/POD Approach for Oil-Paper Insulation Assessment of Converter Transformer

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***Abstract* — The oil-paper insulation system of the converter transformer operates under composite AC-DC voltage. The insulation ability is affected by various coupling factors: the permittivity is related to the frequency, and the resistivity is dependent on the electric field intensity. These coupling parameters bring challenges for insulation assessment. In this paper, the harmonic balance method (HBM) is adopted in the finite element model, considering the harmonic dependence of permittivity. To reduce the computational burden, the proper orthogonal decomposition (POD) is combined with HBM to reduce the order of oil-paper system. Additionally, the electric field-dependent conductivity is updated using the fixed point iteration method. Finally, an oil-paper model is constructed to demonstrate the effectiveness of HBM/POD.**

I. Introduction

The insulation issue in the oil-paper insulation system is a crucial aspect for the safe operation of the converter transformer. The insulation capability is influenced by various coupling factors, such as temperature, moisture, pressure, as well as operation frequency and field intensity. Experiments shows that the paper's permittivity decrease dramatically with the rise of harmonic order, and its conductivity exhibits nonlinear dependence on the electric field intensity [1].

The coupling properties of physical parameters bring computational challenges to insulation assessment. To study effects of harmonics, the electric fields under different frequency voltages are usually computed separately [2]. The composite AC-DC condition cannot be properly studied. Additionally, the field-dependence of conductivity is nonlinear, which needs iterative computation in simulation. To decrease the computational complexity, some model order reduction (MOR) approaches were proposed [3], but the MOR in harmonic domain is seldom studied.

This paper puts forward a MOR by introducing POD into HBM. This approach allows for consideration of the harmonic dependence of permittivity and nonlinear conductivity, and can reduce the order of the governing equation with a high level of accuracy.

II. Harmonic Domain of EQS Field

The oil-paper insulation system withstands capacitive and resistive electric potential when works in composite AC-DC excitations. The governing equation to be considered is an electro-quasi-static (EQS) field, as given

$$\nabla \cdot \left(\epsilon \frac{d}{dt} + \gamma\right) \nabla \varphi = 0 \ \text{in} \ \Omega \, ; \ \varphi = u(t) \ \text{on} \ \Gamma_1, \qquad (1)$$

where φ is the electric potential, ϵ is the permittivity related to harmonic order, γ is the conductivity nonlinearly dependent with the electric field, and $u(t)$ is the periodic voltage excitation, namely $u(t+T) = u(t)$. Besides, Ω is the study domain with boundary Γ ($\Gamma_1 \subset \Gamma$).

The finite element method is conducted, with the semi-discrete form provided

$$\boldsymbol{K}_{\epsilon} \frac{\partial \boldsymbol{\varphi}(t)}{\partial t} + \boldsymbol{K}_{\gamma} \boldsymbol{\varphi}(t) = \boldsymbol{U}(t), \qquad (2)$$

where $\boldsymbol{K}_{\epsilon}$ is the permittivity coefficient matrix related to harmonic order, $\boldsymbol{K}_{\gamma}$ is the conductivity coefficient matrix that requires updating based on the electric field. $\boldsymbol{U}(t)$ is the excitation applied to Γ_1.

III. MOR Approach

A. Harmonic domain modeling of EQS field

To study in harmonic domain, the complex exponential Fourier is utilized to represent the voltage excitation :

$$U(t) \quad = u_0 + \sum_{k=1}^{\mathcal{N}} u_k e^{jk\omega t}, \qquad (3)$$

where $j = \sqrt{-1}$ and ω is the angular frequency, $\mathcal{N}$ is the order of the truncated harmonics, u_k is the k^{th} harmonic component and u_0 is the DC component.

Substituting equation (3) into equation (2) after Fourier transformation on (2) yields (4). It is a discrete form in k order harmonic:

$$\overbrace{(\boldsymbol{K}_{\gamma} + j\omega k \boldsymbol{K}_{\epsilon,k})}^{Ns\times Ns} \cdot \boldsymbol{\varphi}_k = \boldsymbol{U}_k \qquad (4)$$

where $\boldsymbol{K}_{\epsilon,k}$ is the permittivity coefficient matrix under k-order harmonic. $\boldsymbol{\varphi}_k \in R^{Ns\times 1}$ is the electric potential under k^{th} harmonic, $\boldsymbol{U}_k$ is the space discrete form corresponding to u_k. Ns is the degree of freedom of the finite elements discretisation.

B. SVD for sampling complex matrix

The first Nm order harmonics are calculated by harmonic balance method in full order, and we can obtain harmonic-domain snapshots $\boldsymbol{\varphi}_0, \boldsymbol{\varphi}_1, \dots \boldsymbol{\varphi}_{Nm}$ for POD model. Based on (4), we know $\boldsymbol{\varphi}_k$ is a column matrix with Ns complex numbers. $\boldsymbol{\varphi}_k$ can be expressed by one group of orthogonal basis vectors $[\boldsymbol{\zeta}_0, \boldsymbol{\zeta}_1, \dots \boldsymbol{\zeta}_{Nm}] \in R^{Ns\times Nm}$ as (5), where a_j represents the corresponding coordinate of orthogonal basis vectors [4].

$$\boldsymbol{\varphi}_{\mathscr{k}} = \sum_{j=1}^{Nm} a_j \boldsymbol{\zeta}_j \tag{5}$$

Performing SVD on the sampling matrix $\boldsymbol{A} = [\boldsymbol{\varphi}_0, \boldsymbol{\varphi}_1, \dots, \boldsymbol{\varphi}_{Nm}] \in R^{Ns\times Nm}$ is an effective way to obtain orthogonal basis vectors with a lower order, given as

$$\boldsymbol{A} = \boldsymbol{P}\begin{bmatrix} \alpha_1 & & \\ & \alpha_2 & \\ & & \ddots \end{bmatrix}\boldsymbol{V}^{\mathrm{H}} \tag{6}$$

where $\boldsymbol{P} \in R^{Ns\times Nd}$ is a matrix with Nd orthogonal basis vectors, and $\boldsymbol{V}$ is an orthonormal matrix . $Diag(\alpha_1, \alpha_2, \dots)$ contains Nd singular values capturing the most energy of the system, i.e., $Nd < Nm$.

Therefore, the unknown variable $\boldsymbol{\varphi}_{\mathscr{k}}$ is approximated by

$$\boldsymbol{\varphi}_{\mathscr{k}} = \boldsymbol{P}\boldsymbol{a}_{\mathscr{k}}, \tag{7}$$

where $\boldsymbol{a}_{\mathscr{k}} = [a_0, a_1, \dots a_{Nd}]^{\mathrm{T}}$, indicating that $\boldsymbol{a}_{\mathscr{k}}$ is a variable instead of $\boldsymbol{\varphi}_{\mathscr{k}}$ in equation (4).

C. HBM/POD scheme

The unknown variable $\boldsymbol{\varphi}_{\mathscr{k}}$ in HBM is replaced by $\boldsymbol{P}\boldsymbol{a}_{\mathscr{k}}$, based on (7), and $\boldsymbol{P}^{\mathrm{H}}$ is multiplied to both sides of (4), as given.

$$\overbrace{\boldsymbol{P}^{\mathrm{H}}(\boldsymbol{K}_{\boldsymbol{\gamma}} + j\omega\mathscr{k}\boldsymbol{K}_{\epsilon,\mathscr{k}})\boldsymbol{P}}^{Nd\times Nd} \cdot \boldsymbol{a}_{\mathscr{k}} = \boldsymbol{P}^{\mathrm{H}}\boldsymbol{U}_{\mathscr{k}} \tag{8}$$

Compared with governing equation (4) of full-order model, the order of HBM/POD model decreases from Ns to Nd.

D. Fixed-point iteration

For the field-dependent property of the oil-paper conductivity, the fixed-point iteration method is utilized to deal with this problem, dividing the nonlinear conductivity into two parts as γ_{FP} and γ_{NL} . γ_{FP} is a fixed-point conductivity, while γ_{NL} is a function of electric field and conductivity, i.e.,$\gamma = \gamma_0 + \gamma_{NL}$. The iterative form is given:

$$\boldsymbol{P}^{\mathrm{H}}(\boldsymbol{K}_{\boldsymbol{\gamma},FP} + j\omega\mathscr{k}\boldsymbol{K}_{\epsilon,\mathscr{k}})\boldsymbol{P} \cdot \boldsymbol{a}_{\mathscr{k}}^{(n+1)} = \boldsymbol{P}^{\mathrm{H}}(\boldsymbol{U}_{\mathscr{k}} + \boldsymbol{F}_{\mathscr{k}}^{(n)}), \tag{9}$$

where n is the iteration number; $\boldsymbol{K}_{\boldsymbol{\gamma},FP}$ is the coefficient matrix of fixed-point conductivity γ_0, and $\boldsymbol{F}_{\mathscr{k}}$ equals $\boldsymbol{P} \cdot \boldsymbol{a}_{\mathscr{k}}^{(n)} \cdot \boldsymbol{K}_{\boldsymbol{\gamma},\boldsymbol{NL}}$ after the fast Fourier transform.

IV. Results and Discussion

A transformer model with oil-paper insulation system is constructed, and the excitation is a composite voltage with 49 order harmonics [5], as in Fig.1. The permittivity is set according to harmonic order, and conductivity is nonlinearly dependent with electric field, as in Fig.2.

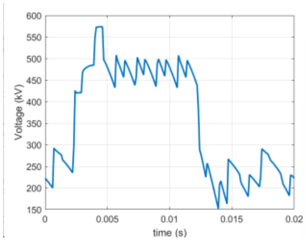

Fig. 1. Composite AC-DC voltage.

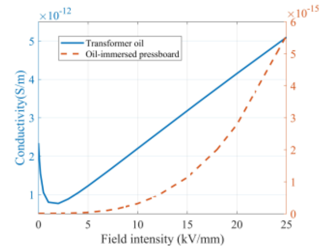

Fig. 2. Nonlinear conductivity.

The electric potential obtained with $Nd = 5$ is shown in Fig.3. The variation of electric field at a point near the winding end obtained by our HBM/POD method is compared with the HBM alone and the comparison is shown in Fig.4. It can be observed that changing trends are almost the same, and the maximum relative error is 0.003%. The computation time of HBM and HBM/POD are 2152s and 1792s respectively.

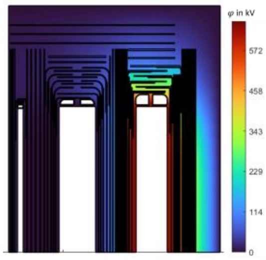

Fig. 3. Electric potential contour.

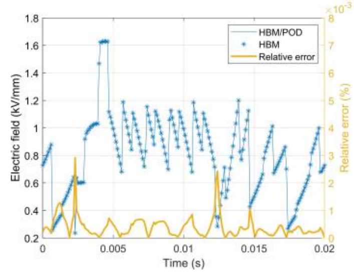

Fig. 4. Electric field and error variation.

V. Conclusion

HBM is used in the EQS problem to investigate the harmonic-dependent permittivity effect and combined with POD to reduce the degree of freedom of variable to be solved. The fixed point method is used to consider the nonlinear property of the conductivity. A transformer model is employed to validate the combined HBM/POD model. Comparing it with the full-order finite element method using HBM, the computation cost decreased while maintaining the accuracy.

References

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