Stray-Field Loss Modeling under Hybrid Excitation in Smoothing Reactors

Z.Cheng[1], B.Forghani[2], D.Lowther[3], Y.Liu[1], Z.Zhao[4], T.Liu[1], Y.Fan[1], and G.Han[1]

[1]R & D Center, Baoding Tianwei Group Co., Ltd, 071056, Baoding, CHINA, emlabzcheng@yahoo.com
[2]Infolytica Corporation, Place du Parc, Montreal, QC H2X 4B3, CANADA, forghani@infolytica.com
[3] McGill University, Montreal, QC H3A 0E9, CANADA, david.lowther@mcgill.ca
[4]Hebei University of Technology, 300130, Tianjin, CHINA, iamsam@hebut.edu.cn

The smoothing reactor in HVDC (High Voltage Direct Current) systems uses a DC-AC hybrid excitation with multiple harmonics. This paper investigates effective and practical approaches that can be used to confidently determine the stray-field losses in such systems. The proposals presented in the paper are validated using a well-established smoothing reactor model.

Index Terms— **Hybrid excitation, laminated frame, leakage flux, measurement and numerical analysis, stray-field loss.**

I. Introduction

The modeling and the prediction of the stray-field losses in very large electromagnetic devices are becoming increasingly important, especially, for smoothing reactors used in HVDC systems with special excitations, i.e., a DC-AC hybrid excitation. However, the multi-scale modeling, due to the huge overall size of the structure and the very thin penetration depth in the magnetic parts, or the large laminated core (or frame), and the modeling of the GO silicon steel material property, under DC-biasing and in the presence of multiple harmonics, become quite challenging [1]-[5].

The purpose of this paper is to systematically investigate efficient numerical and experimental approaches that can be used, with confidence, to determine the stray-field losses in conducting components under extreme excitations, and to validate the results on a smoothing reactor model with laminated frame.

II. Determination of Stray-Field Loss in Components under Hybrid Excitation

A. Direct Calculation of Components Loss (Solution I)

In the typical smoothing reactors, the air-core exciting coil is placed inside a square laminated frame, and the exciting current $i(t)$ contains a heavy DC and multiple AC harmonics, as shown in (1),

$$i(t) = I_{dc} + \sum_{k} i_m \sin(k\omega t + \phi_k) \tag{1}$$

In this DC-AC harmonic transient field computation, the electromagnetic material property modeling of all the components, under hybrid excitation, becomes very important. For example, the corresponding specific total iron loss of the laminated frame, as a key component of the smoothing reactor, is measured under different DC-biasing levels and different harmonic contents, using PE-View9, Mayway Labs co., Ltd, Japan. The comparison among the different kinds of magnetization curves has shown that the DC magnetization curve of the laminated frame's material can be used in the DC-biased harmonic field analysis.

The laminated frame acts, in fact, as a vertical-type magnetic shield, in which the induced eddy currents are rather weak; therefore the so-called additional eddy current loss [6] can be neglected.

The total iron loss of the laminated frame, P_{frame}, can be calculated based on the 3-D transient field solution and the measured specific total iron loss, i.e., the iron loss in each element is first calculated, $P_{iron}^{(e)} \cdot V^{(e)}$, and then summed up,

$$P_{frame} = \sum_{e} P_{iron}^{(e)} \cdot V^{(e)} \tag{2}$$

B. Indirect Determination of Components Loss(Solution II)

The measured total stray-field loss P_{total} usually includes two parts: the loss generated in all the components, referred to as $P_{components}$ and the loss generated in the exciting coils $P_{excitation}$. Accordingly, the stray-field loss in the components is indirectly determined, as shown in (3),

$$P_{components} = P_{total} - P_{excitation} \tag{3}$$

If the total stray-field loss, P_{total}, has been correctly measured, the problem is reduced to accurately determining the loss in the exciting coils, $P_{excitaion}$. In general, the coil's loss, $P_{excitation}$ is also divided into two parts: the induced eddy current loss, due to the leakage flux linked with the coils, P_{eddy}, and the coil's resistive loss, P_r.

In this paper, the total loss in the exciting coil, under extreme excitation, based on 3-D transient field solution, is investigated. To do this, each turn of the exciting coil is exactly treated as a bare solid conductor, in which case all the Ohmic loss, caused in the exciting coil, can be calculated using (4),

$$P_{excitation} = \int_{\Omega_{cu}} \frac{\boldsymbol{J} \bullet \boldsymbol{J}}{\sigma} dv \tag{4}$$

Where $\boldsymbol{J}$, σ and Ω_{cu} are the current density, the conductivity and the total volume of the copper wire of the exciting coil, respectively. Now (3) can be rewritten as (5),

$$P_{components} = P_{total} - \int_{\Omega_{cu}} \frac{\boldsymbol{J} \bullet \boldsymbol{J}}{\sigma} dv \tag{5}$$

C. *Smoothing Reactor Model*

The smoothing reactor model is well established, as shown in Fig.1. The square laminated frame parameters are: center distance limb to limb, 730mm; width of lamination, 100mm; thickness of limb, 20mm; GO steel, 30Q140, WISCO. The main specification parameters of the exciting coil are: number of turns, 408; size of copper wire, 3×9mm; conductivity of wire, $\sigma=5.7143\times10^7$ S/m.

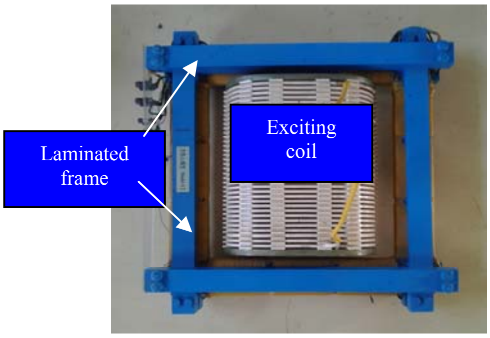

Fig.1. Smoothing reactor model.

Solutions I and II stated in Section II are validated based on the smoothing reactor model.

D. *Eddy Current Loss of Air-Core Exciting Coil*

The eddy current loss is calculated based on the air-core coil of the reactor model without the laminated frame. The total loss, including eddy current and resistive loss, generated in the air-core exciting coils is measured (by Power Analyzer WT3000, Yokogawa) and calculated (by MagNet, Infolytica) under different excitations (3 Cases).

The solved finite element model, 1/8th of the whole coil, is shown in Fig.2. The corresponding loss results are shown in Table I.

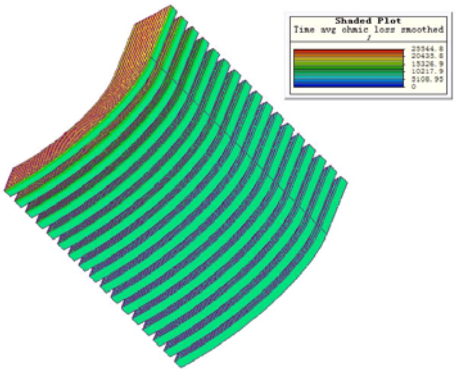

Fig.2. 3D FE model of air-core exciting coil.

Table I
LOSS IN AIR-CORE ELLIPTIC EXCITING COIL

Exciting currents (A)		Calculated (W)	Measured (W)
Case I	20.0 (DC)	119.03	118.57
Case II	20.0(AC)	127.06	126.99
Case III	6.9(AC) , 20.0(DC)	126.88	125.29

The good agreement between the calculated and measured loss results shows that the eddy current loss of the air-core exciting coil can be accurately and numerically calculated under different excitations.

E. *Basic Guarantee of Coil's Eddy Current Loss Analysis*

The leakage flux densities at the specified positions of the exciting coil of the reactor model under DC-AC hybrid excitation (AC:15.7A/50Hz, rms; DC:148.0A), have been measured (by Gauss/Teslameter 7010, F.W.Bell, AC/DC can shift) and calculated (by MagNet, Infolytica). See Fig.3. The good agreement between the calculated and measured results demonstrates that the leakage flux linked with the exciting coil inside the laminated frame is accurately calculated under hybrid excitation. This provides a basic guarantee for coil's eddy current loss analysis, which is closely dependent on the accurate calculation of the leakage-flux.

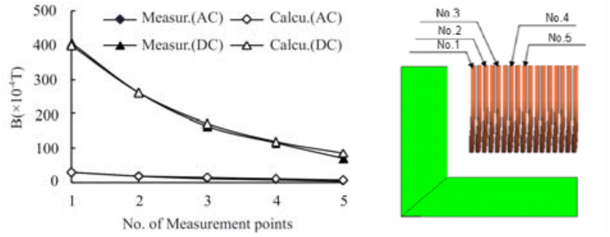

Fig.3. Results of leakage flux densities under hybrid excitations.

D. *Stray-Field Loss inside Laminated Frame*

The stray-field losses caused in the laminated frame have been obtained using two methods (Solutions I and II), as described in Section II. The loss results are shown in Table II.

TABLE II
LOSS IN SMOOTHING REACTOR–BASED MODEL

Exciting currents (A)		Coil's loss (W)	Total loss (W)	Stray-field loss in laminated frame (W)	
AC	DC	$P_{excitation}$	P_{total}	Solution I	Solution II
15	15	142.94	143.82	0.77	0.88
15	18	178.29	179.24	0.87	0.95
20	15	200.19	201.64	1.33	1.45

The stray-field loss results, inside the laminated frame, obtained by two methods, show good agreement.

The full paper will show the modeling and computation in more detail, including the measurement of the working properties of all the components under hybrid excitation with multi-harmonics.

VI. REFERENCES

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