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Optimal Design of Medium-Frequency Transformers for Solid-State Transformer Applications

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***Abstract*—One of the most challenging problems of the electrical engineering in recent years is to replace conventional low-frequency distribution transformers with Solid-State Transformers (SSTs). The SST advantages make future smart grids flexible and cost effective. However, due to some main drawbacks such as low efficiency, it is not adopted in the distribution systems yet. In this paper, optimal design of Medium Frequency Transformers (MFTs) for a 20/0.4 kV 315 kVA solid-state transformer is done. The objective is to maximize the efficiency (η) and the power density (ρ), and to minimize weight of the MFT. The designed MFT reaches the efficiency > %99.70 and the power density > 13 kW/dm^3.**

Keywords—medium frequency transformer; optimal design; maximum efficiency; power density; minimum weight;

I. Introduction

In recent years, tremendous progresses in the power semiconductor devices bring numerous capabilities to manage the energy conversion in the different parts of the power systems. In one hand, power distribution systems are more prone to integrate with power electronics as the distributed generation policies try to decentralize power generation in the customer locations. On the other hand, the demand for reducing the weight, volume, and environmental concerns of the conventional distribution transformers empowers the SST probable applications.

Generally, Medium Frequency Transformers (MFTs) are the key elements in the SSTs, traction systems and electrical vehicle chargers. MFTs can reduce the size of bulky conventional low frequency distribution transformers by incorporating power electronic converter capabilities. However, power rating and switching frequency of the power IGBTs and MOSFETs limit the power density and the operating frequency of the MFTs.

In the past decade until now, power electronic researches trend to compact, slight and energy efficient design of power converters [1] and also their relevant component such as MFTs [2] and harmonic filters [3]. A 25 kW MFT was designed using Metglas magnetic materials in [4] in the frequency range of 1~3 kHz as a part of Universal and Flexible Power Management (UNIFLEX-PM) project in Europe [5]. In this design, the power density and efficiency were obtained as 2.5 kW/dm^3 and %99.13, respectively. In this work, probable application of the other materials such as ferrites and nanocrystallines are not discussed. In [2], ferrite materials were discussed and for LLC resonant converter based MFT the power density and efficiency were obtained as 7.7 kW/dm^3 and %99.68, respectively. also, a core type MFT with high isolation requirements is designed in [6].

In this paper, an optimal design procedure is proposed for MFTs. In the proposed method, weight of the MFT is minimized and the efficiency and power density are maximized. The control parameters of the optimization problem are core magnetic materials and core geometrical dimensions, diameter and the number of strands of the used litz wires, inter-winding isolation thickness, and air gap length of the magnetic path. In this paper, maximum allowable temperature rise is considered as an inequality constraint and desired values of leakage and magnetizing inductances are considered as equality constraints. Final optimal results show that the higher efficiency and power density is attainable using Nanocrystalline materials.

II. Optimizatiom Procedure

Manufactures provide a wide range of magnetic core geometries that are proper for building MFTs. Among the available core geometries, UU, UI, EE, and EI cores are commonly used in the Design of MFT [2, 4, 7, 8]. Fig. 1 (a) shows the UU-core geometry, and its related dimension. A sample MFT that is built of 8 U-cores is shown in Fig. 1 (b).

A. Objective Functions

In recent years, enhancing the efficiency and power density of power conversion devices have drawn an increasing attention [1]. Efficiency is critical in any engineering design and a suitable objective has to include it. Starting from efficiency, the total losses have to be minimized. Therefore, the first objective is:

$$\min P_{TL} = P_{CUT} + P_v \rho_c V_c \quad (1)$$

Where P_{CUT} is the total copper losses of the primary and secondary windings, P_v is the magnetic core loss density in W/kg, ρ_c is the density of the core material in kg/m^3 and V_c is core volume in m^3. Also, efficiency can be obtained as $\eta = 1 - P_{TL} / P_n$ where P_n is the MFT power rating. The calculation procedure of the copper and core losses are presented in section III of the paper. The second objective is to maximize the MFT power density that is attainable by minimizing the overall Volume of the MFT as:

$$\min V_T = 2EF\left(B + N_{CP} D\right) \quad (2)$$

Where B and D are core geometrical dimensions as shown in Fig. 1. E and F are calculated as shown in Fig. 2. N_{CP} is the number of parallel cores in the MFT. For example, N_{CP}=2 in the sample MFT that is shown in Fig. 1 (b). Power density can be obtained as $\rho = P_n / V_T$.

The third objective is to minimize overall weight of the MFT. This objective is defined as:

$$\min W_T = W_C + W_W \quad (3)$$

Where W_W and W_C are the winding and magnetic core weights, respectively.

B. *Optimization Constrains*

Optimization constraints include equality and inequality constraints. Maximum allowable temperature rise is the only inequality constraint. Thermal resistance can be used for the temperature rise considerations as:

$$\Delta T_{\max} - R_{th} P_T \geq 0 \quad (4)$$

Where R_{th} is the thermal resistance as in [7] and ΔT_{max} is the maximum allowable temperature rise.

Equality constraints are considered for magnetizing inductance and leakage inductance as follows:

$$\begin{aligned} L_\sigma - L_{\sigma SCH} &= 0 \\ L_m - L_{mSCH} &= 0 \end{aligned} \quad (5)$$

Where

$$L_m = \frac{\mu_0 N_p^2 A_c}{2 l_{gap} + \dfrac{l_c}{\mu_r}}$$
$$L_\sigma = \mu_0 \left(\frac{N_p}{S_M}\right)^2 \left(\frac{l_w}{h_w}\right)\left(S_M t_{iw} + \frac{1}{3}\sum_{i\in\{p,s\}} m_i d_{z,i}\right) \quad (6)$$

Where L_{mSCH} and $L_{\sigma SCH}$ are scheduled values for magnetizing and leakage inductances, respectively. l_w, h_w, m_i, A_c, *and* l_c are defined in Fig. 2 based on core and winding geometry. S_M is the number of magnetic sections. N_p is the number of primary winding turns. t_{iw} is the inter-winding isolation thickness. m_i is the number of winding layers in the primary and secondary windings. In fact, Fig. 2 shows the required computational procedure for obtaining weight and volume of the MFT.

General Relativity Search Algorithm (GRSA), that was presented in [9], has been used to obtain the optimal solutions of the MFT design. A new hybrid version of GRSA, proper for optimizing problems that include continuous and discrete variables, has been developed to this aim. Hybrid GRSA details will be presented in the future work. The objective function is transformed from a constraint optimization problem to an unconstraint optimization problem using penalty terms. This makes the usage of GRSA quite simple and straight forward.

III. Copper and Core Losses Calculation

Main loss components in a MFT are copper and core losses. Copper losses are a function of current waveforms through the primary and secondary windings. While, core losses are a function of flux density waveform in the core magnetic materials. In the following, these losses are discussed.

A. *Copper Losses Calculation*

Voltage and current waveforms of a typical DAB converter are shown in Fig. 3.

Square voltage waveform induces a nonlinear current in the primary and secondary winding of the MFT. This nonlinear current can be rewritten in the form of sum of its fundamental and higher order harmonics using Fourier series. Therefore, superposition theorem can be used to compute copper losses. The harmonic contents for the current waveform that is shown in Fig. 3 are

$$i(t) = I_0 + \sum_{n=1,3,}^{\infty} I_n \sin(2\pi f_s t + \phi_n)$$
$$= \begin{cases} \dfrac{I_{m1} + I_{m2}}{t_1} t - I_{m1} & 0 \leq t < t_1 \\ \dfrac{I_{m1} - I_{m2}}{t_2 - t_1}\left(t - t_1\right) + I_{m2} & t_1 \leq t < t_2 \\ \dfrac{-I_{m1} - I_{m2}}{t_3 - t_2}\left(t - t_2\right) + I_{m1} & t_2 \leq t < t_3 \\ \dfrac{-I_{m1} + I_{m2}}{t_4 - t_3}\left(t - t_3\right) - I_{m2} & t_3 \leq t < t_4 \end{cases} \quad (7)$$

Where f_s is the current frequency, t_2=T_s/2 and t_4=T_s. In the steady-state operating point I_0 is zero. I_{m1} and I_{m2} are as follows: