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Design and analysis of a 35 kVA medium frequency power transformer with the nanocrystalline core material

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ABSTRACT

Medium frequency power transformers embedded into power electronics converters are frequently encountered in many applications such as electrical transportation and renewable energy systems and power supplies. Thus, researchers have been focused on soft magnetic materials such as amorphous and nanocrystalline materials to obtain smaller and more efficient transformer designs with the improvements on manufacturing technologies of the high frequency core materials. In this study, the transformer design methodology is proposed with the finite element analysis method, and a 35 kVA medium frequency transformer with nanocrystalline core material is designed. After the sizing stage, three-dimensional model of the transformer is created with finite element analysis software, and then co-simulations of this electromagnetic transformer model with a power electronics converter circuit are performed for practical operation conditions. Furthermore, thermal behavior of the prototype transformer is determined with the thermal coupling analysis, and temperature distribution of the prototype transformer is visualized with a thermal imaging camera. The transformer efficiency, exact equivalent circuit of the transformer and flux distributions in the transformer core are obtained from these simulation studies. In addition, the prototype of the designed transformer is produced and tested. The design conditions and simulation results are validated with experimental studies.

Introduction

Transformer that is a highly efficient and static electrical machine makes significant contributions in the area of energy conversion and has a very useful and effective role in daily life. Basic operating principle of the transformers is based on the theory of electromagnetic induction, and it consists of primary and secondary windings structurally dependent on each other via the magnetic coupling. There is an effective role of the transformer inside the power systems with the basic functions such as galvanic isolation and/or change the voltage amplitude. Hence, transformers of various power levels and operating frequency are used in many devices [1].

Although conventional applications of the transformers are usually at grid frequency, high frequency transformers

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embedded in power electronic converters are recently used in modern power systems such as uninterruptible power supplies, electrical transportation systems and motor drives, and grid interfaces of renewable energy sources such as wind turbines and fuel cells. Number of the power electronics applications and their power levels are increasing day by day, and this requires to transfer very large power levels. Generally, high frequency switching can be performed easily at low power levels (<10 kW). However, power electronics systems at medium and high power levels (generally ≥10 kW) are designed to operate at medium frequency (MF) values because of some limitations about voltage and current values of semiconductor switches especially at high frequency levels. This provides better performance in terms of losses and temperature at medium and high power levels. Transformers are embedded into MF power converters structures for different purposes, and therefore, a compact transformer designs should be obtained. These transformers are usually called as "medium frequency transformer" in isolated DC–DC converters, but they are also called as "power electronic transformer (PET)" or "solid-state transformer (SST)" [1–8].

The operating frequency value is a key parameter in determining the magnetic material for the transformer design. While silicon steel alloys are used in line frequency transformers, soft magnetic materials such as amorphous, nanocrystalline and ferrites are commonly preferred in medium and high frequency transformers [1]. The magnetic materials can be operated close to saturation point (such as 1.7 T at 50 Hz) for line frequency transformers. However, in the MF transformer design, the flux density in the core should not exceed a certain value (0.2 T at 20 kHz for nanocrystalline material) to limit losses. Therefore, operating frequency of the transformer and the specific core loss value which is related with saturation flux value of the preferred core material at the operating frequency are two most important design factors which influence the size and efficiency of designed transformer. When two transformers at same power and operating frequency values are designed with different core materials, different volume and efficiency values are obtained. Mechanical performance of the core material in kVA/kg which is decreasing with increasing operation frequency is also different for each material [9,10]. In addition, the coercivity force and magnetic permeability of the core materials are different from each other. High permeability and lower coercivity force requirements in transformers or inductors used in high frequency power electronics systems can be achieved with the use of soft magnetic materials. Besides, both permeability and specific core loss values of the core material are negatively affected with the increasing frequency values [11].

Since transformers are static electrical machines, the most important factor that determine the transformer performance is total power losses. Because winding and core losses result in heat, this heat may increase the winding temperature and cause number of problems (such as degradation of insulation materials and permeability deterioration of the core material). Ideally, core losses are not desirable, but in practice, each material has different specific core losses values which depend on their characteristics, and these losses increase with frequency. The AC resistance value and losses of the medium/high frequency transformer windings also increase with increasing frequency because of the skin and the proximity effects. In addition, non-sinusoidal excitation signals and harmonic components increase core losses and core temperature. The resulting heat is transferred to its surface and then to its environment through radiation and convection. The temperature rise worsens performance of the transformer by disrupting its magnetic and electrical parameters. Therefore, performing thermal analysis during the design stage of the transformer, and estimating the temperature rise are very important. After the thermal behavior of the transformer is determined, suitable cooling system can be determined. The natural cooling, the forced air-cooling and the fluid cooling methods are used as transformer cooling methods [12–19].

In the past literature, MF power transformer designs have been proposed with silicon steel alloys for 2 kHz and lower operating frequencies [8,9]. In recent years, researchers have focused on the new generation core materials such as amorphous and nanocrystalline core materials with the growing interest because of their improving mechanical and electromagnetic performances. Two different core materials are used in design of a MF power transformer embedded into the power system of the electric train. While in the first design, the silicon core material was used at 1 kHz operating frequency, the nanocrystalline core material was used at 5 kHz operating frequency in the second design. It is seen that, the volume and weight of the power system designed with nanocrystalline core materials for the electric train have decreased by about eight times when compared the transformer designed with the silicon core material [20].

Additionally, the performances of the MF transformer with ferrite and nanocrystalline core materials for power distribution system with the DC–DC resonant converters have been compared and it has been reported that the transformer with nanocrystalline core is advantageous in terms of efficiency and volume [9,21–26]. Before about 25 years, the ferrite core materials were used in the MF transformer designs, because the nanocrystalline core materials had not been commercially available yet. Although, ferrite materials are advantageous especially at high frequency levels, their limited sizes restrict the high power transformer designs [27]. However, the nanocrystalline material has been used for a high frequency transformer core (200 kHz and 30 kW), and the performance of the designed transformer has been reported as satisfactory [22]. In addition, the nanocrystalline core materials were used for 36.3 kVA power transformer operating at 2 kHz switching frequency, and core losses of the proposed transformer was tested at different frequencies. The thermal equivalent circuit of this medium-frequency transformer was also obtained and analyses of the temperature rise were performed [8,20].

In this study, a transformer design methodology by using modern design techniques is presented, and a 35 kVA transformer is designed and its prototype is produced. According to the design methodology, if an undesired condition about electromagnetic or electrical parameters of the transformer and/or a situation that is outside the specified limits is faced, modifications on core material type and mechanical specifications such as sizing the transformer and the winding structure can be made easily. The transformer is designed and