Design and Implementation of a Multi Winding High Frequency Transformer for MPSST Application

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Abstract— **Development of the new generation of high power and high frequency power electronic switches along with the need for compact controllable converters for utilization of distributed energy resources in the grid, have led to significant developments in the area of solid state transformers in the last years. The design process of a high frequency transformer as the main element in the solid state transformer is illustrated in this article. A multi winding transformer for multiport SST application is designed, studied and built in this research. In a MPSST several windings feed the core. As the result, coupling coefficient between each pair of windings, become an important factor which is studied in this study. Since the transformer is designed for high frequency applications, the power loss in the wire and core of the transformer increases as the result of higher skin effect and eddy current loss in high frequency. Three important factors in the design of HF transformer for MPSST are discussed in the paper. First, four different possible core materials are compared based on their flux density, frequency range, loss and price. Then the cable selection is illustrated and finally, different winding placement and distribution on the same core are suggested and the inductance and coupling coefficient matrices are calculated using ANSYS Maxwell 3D simulation. The transformer is built in the lab and the inductance values matches the expected values from the simulation.**

Keywords— ***ANSYS Maxwell 3D, core material, multi port high frequency transformer, coupling coeficient, solid state transformer, transformer design.***

I. INTRODUCTION

There are two major factors which drive the research efforts on solid state transformers. The development of high power and high frequency power electronic switches, and the need for compact controllable converters to utilize distributed energy resources within the electricity grid [6][11][15][17]. Conventional low frequency transformers, which provide galvanic isolation between the input and output side and change the AC voltage levels to match the voltage between voltage zones,[14] are simple, efficient and reliable components for long time service in the grid [6],[20]. However, large amount of metal is needed for the core of the low frequency transformers and consequently, size and weight of these transformers are relatively larger than the other components in the same power rating system which makes transportation, installation and maintenance of the low frequency transformers complicated and expensive. Also, the conventional passive transformers are not compatible with the needs of the new technologies, such as DC distribution systems, distributed generation (DG) and energy storage (ES) to utilize them in the power grid [12],[13]. Solid state transformer is a combination of active controllable power electronic converters and HF isolation transformer which makes the size of converter dramatically smaller [3],[4],[24].

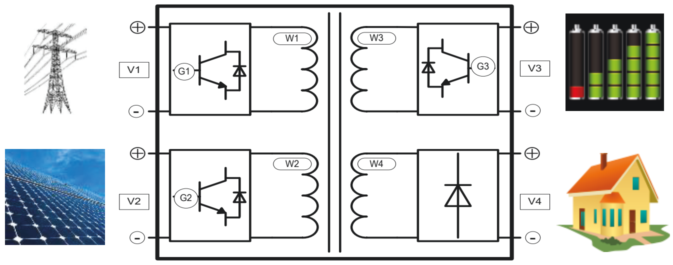


Fig. 1. MPSST configuration [6][16]

Fig. 1 shows the HF stages of a four-port SST configuration. All of the ports in this figure are DC ports. The stages of this converter at each port could be extended by adding inverters for AC connection. The high frequency stages of the converter includes HF inverters (rectifiers) and a HF transformer. Multiport SST (MPSST) (Fig. 1.b) is a type of SST with more than two ports. The four port MPSST [6] is designed to utilize DG and ES in a system with load and grid connection or in a zonal distribution using a one controllable converter [21].

Solid State Transformer (SST) has been formulated by several articles[3]-[6] Figure. 1 shows the HF stages of a four-port SST configuration The high frequency stages of the converter includes HF inverters (rectifiers) and a HF transformer. This HF configuration is common among different SST configurations. Multiport SST (MPSST) is a type of SST with more than two ports. The four port MPSST is used to utilize DG and ES in a distribution system [19] using multiple isolated controllable legs in one converter. This configuration enables the easy microgrid application and maximizes the power density of the converter, which dramatically decreases the size and cost of the system design.

The design process of any isolated converter includes two major steps, power electronic design and design of isolation transformer which is relatively more important for SST application. The focus of this paper is on the transformer design for multiport SST. In section II the design parameters of a transformer for high frequency application are discuss to find the best options for the defined power and frequency range of this application. In the section after that a simulation results of the designed transformer are shown and discussed. Section IV includes the final product and experimental results. The last section is conclusion.

II. Transformer Design Parameters

Three important factors are consider for optimal design of transformer in this paper. The firss factor is core material selection for HF application [10] to minimize the core loss and prevent core saturation for the nominal operation points[18]. The second factor is the selection of the wire to minimize the skin effect and wire loss caused by the HF applied voltage. The third factor is windings position to find the most efficient way of putting the windings on the core. These factors are more critical for the MPSST due to the application of high frequency and having more than two converters connected to the transformer. The relation between size of the transformer, power rating, core flux density and operation frequency is shown in (1). Equation shows that the size is inversely proportional to the frequency to the power of 1.16. This reverse relation between the frequency and size of the transformer drives most of the efforts for the design of SST at higher frequency [6][9].

$$W_a A_c = \left(\frac{\sum S \times 10^4}{K_f K_{cu} K_j f B_{pk}}\right)^{1.16} \quad (1)$$

In (1) W_a is the window area, A_c is the cross-sectional core area, K_f relates RMS voltage to volt-seconds, K_j relates area product to current density, f is the switching frequency and B_{pk} is the peak flux density in the core.

A. Core Material Selection and Design

The first stain transformer design is material selection of the core, as it affects the size, power density and power loss in the transformer [1]. Core material defines the boundary of the transformer frequency range. For a practical core material selection, four parameters including flux density, price and availability, frequency range, and core losses are studied in this research for different materials.

Four common materials for the design of HF power transformer for SST applications are studied here. Silicon steel, Ferrite, Amorphous and Nanocrystalline Silicon steel has high saturation flux density [1] and permeability which supports high frequency applications, with a drawback of high core losses. Ferrite has relatively lower saturation flux density (0.4 T) which increases the core size [2] but it is available commercially in different shapes and lower cost. Ferrite cores could be used in very high frequency with a moderate power loss. Amorphous, has good saturation flux density (higher than 1.5T), while the cost factor remains relatively low, but power loss is much higher than Ferrite for high power applications. Nanocrystalline has an acceptable saturation flux density in high frequency (1.2T), and relatively low losses in medium and high frequency but still for frequencies over 15 kHz the core loss is higher than ferrite. This material is relatively expensive and is not available commercially in the different shapes [2]. The material study shows that for 100 kHz switching frequency which is the target in design, ferrite material gives the best performance even though its saturation flux density is relatively lower than the three other studied materials. However it is important to mention that several researches are done on the new materials like advance silicon steels to improve there performance for high frequency applications, but these materials are not commercially available in the market or there price are still very high.

TABLE 1. Flux density and frequency range of the studied materials [1][2][7][8]

	Flux density (Tesla)	Frequency Range (Hertz) With reasonably low loss
Silicon steel	1.5-1.8	Audio frequency (20-20 kHz)
Ferrite	0.2-0.5	Audio frequencies to hundred megahertz
Amorphous	0.5-1.6	<300kHz
Nanocrystalline	1-2	<30 kHz

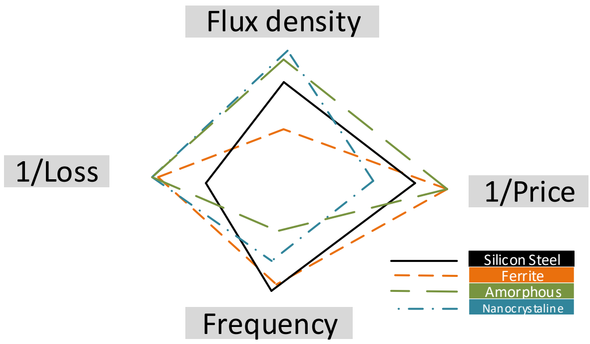


Fig. 2. Core material comparison for HF design

B. Cable Selection

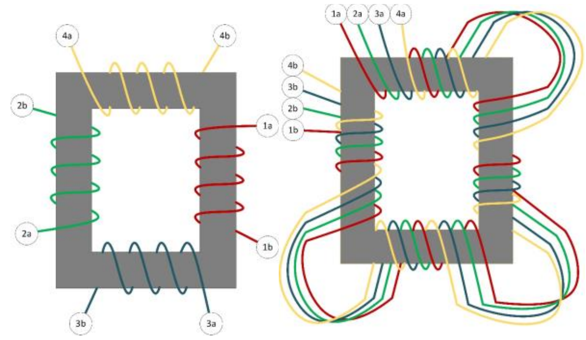
Another design factor is cable selection. Transformer losses vary when the frequency changes from low to high, since the effective resistance increases as the result of increasing of skin effect in high frequency. AC current distributes in a metal conductor in a way that the current density on the outer layer (skin) of the conductor is much higher than the core of the conductor. One solution to decrease the influence of skin effect on effective resistance is using Litz wire [22],[23]. Litz wire decrease this resistance by subdividing the conductor to smaller conductor strands with proper shields [5]. Each of very tiny strands in insulated from the other strands around it and several hundreds of them form a thicker wire with the thickness equal to the wire size which is calculated in volt power calculations. The thinner the strands of the wire the better high frequency characteristics could be achieved. The Litz wire strands are available in the market from 26 AWG to 50 AWG which is the thinnest strand. To achieve a proper resistance performance from the winding wire in 100 kHz for transferring up to 10 kVA in voltage range of <600V, 36 gage strands are used to form an equal size to 8 gage wire for our application.

C. Winding Placement

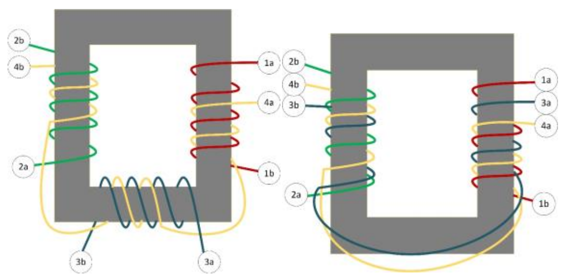
The winding placement on the core is important since it influences the mutual inductances and the coupling coefficients of the windings which directly affect the power loss and system efficiency. Winding placement is investigated in this paper for four possible configurations of placement of four windings on the core. The forth (yellow) wire is the load port winding and the design process in this study focuses on getting the best performance for power exchange with this port. Green wire is the third windings where energy storage is connected. The two other windings are defined as generation port windings. The winding placement configurations are shown in Fig. 3. The number of turns should be minimized since increasing the number of turns and the length of used wire increases the impedance and causes more loss which decreases the transformer efficiency even if the ratio is kept constant.

In case A, each of the windings is on one leg of the core. In winding configuration of case B all of the windings are wound around all of the legs of the core. In configuration C load winding is distributed between all of the other windings and in case D load and storage windings are distributed between the two other windings.

The cores with different winding configurations are simulated in ANSYS Maxwell 3D software (Fig. 3) with real dimensions and using ferrite material and Litz wire gage 8. The size of transformer is optimized based on the nominal voltage and power of MPSST which is built in the lab. The leakage inductance calculation of the simulation for the defined wire and other conditions is around 2μH. Also the coupling factor for the different winding positions which are shown in Table.2 are resulted from the simulation.



Case A Case B



Case C Case D

Fig. 3. Test cases of MPSST windings placement: (1) Grid (red). (2) DG (blue). (3) ES (green). (4) Load (yellow).

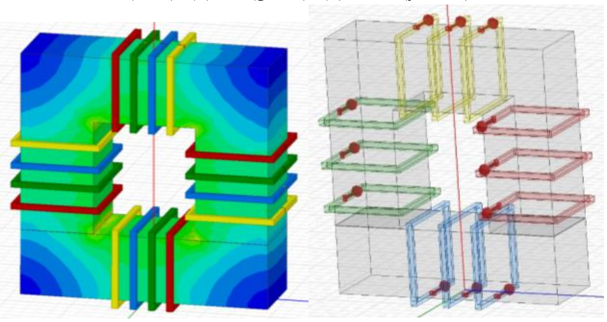


Fig. 4. ANSYS Maxwell 3D simulation of the designed core

The simulation is also done for the magnetic characteristics of the chosen material to verify the capability of transformer to operate in the defined operation range.

TABLE 2. COUPLING COEFFICIENT BETWEEN THE WINDINGS FOR THE DIFFERENT CASE STUDIES

Case A	W1	W2	W3	W4
W1	1	0.93208	0.94208	0.9426
W2	0.93208	1	0.94207	0.94253
W3	0.94208	0.94207	1	0.92272
W4	0.9426	0.94253	0.92272	1
Case B	**W1**	**W2**	**W3**	**W4**
W1	1	0.99029	0.98688	0.98549
W2	0.99029	1	0.99065	0.98692
W3	0.98688	0.99065	1	0.99013
W4	0.98549	0.98692	0.99013	1
Case C	**W1**	**W2**	**W3**	**W4**
W1	1	0.92104	0.93076	0.9662
W2	0.92104	1	0.93003	0.96594
W3	0.93076	0.93003	1	0.96992
W4	0.9662	0.96594	0.96992	1
Case D	**W1**	**W2**	**W3**	**W4**
W1	1	0.93229	0.96829	0.96862
W2	0.93229	1	0.96863	0.96797
W3	0.96829	0.96863	1	0.97094
W4	0.96862	0.96797	0.97094	1

From the results of the simulation in Table 1. case B gives the best coupling coefficients. However it needs longer length of wire which increases the impedance and loss. Also, since the design goal is defined based on the maximizing coupling coefficients for the forth winding with shorter length of wire the winding placement of case C is chosen for this application

III. TEST SETUP AND FINAL MANUSCRIPT DESCRIPTION

The designed transformer has the core area of 0.001 m^2 and uses ferrite material with flux density of 0.21T to transfer 10 kVA from each winding in the voltage range of 200-600 V. The transformer is built and tested in the lab. The measured leakage inductance from the test set up is 2.3 μH and the magnetizing inductance of the transformer is 75 μH. Figure. 5. Shows the built transformer in the lab.

Fig. 5. Final assembled multi winding HF transformer

IV. Conclusion

In conclusion this article describes the whole process of simulation, design and building of a multi winding HF transformer. The interest into this type of HF power transformers is increasing since they are compact, contorlable and modular devices which meet the requirments of the new generation of thegrids with DC loads, DER and smart. Three factors are studied in this paper. Material selection for the core which is the most important factor in the design of transformers in general is described and four different matrials are compared for the to find the best core material for 100 kHz aplication which is the goal of this design. Also, the wire selection for this HF application is illustrated and based on that a proper wire is selected for this transformer. Furthermore, different winding placements on the core are disscussed and simulated in Ansys Maxwell 3D to find the best placement from the point of maximum coupling factor. The transformer is built in the lab and tested and the primary test results mach the design expectations.

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