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Research Article

Design and Construction of a High-Frequency Transformer of a Power Inverter

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ARTICLE INFO | **ABSTRACT**

Research has been done on the design of transformers at a variety of power densities and operating frequency ranges. The power level, efficiency and power density target are used to define the core material type, as well as the operating frequency. Also, the power converter topologies that were discussed previously call for the addition of inductors in order to function correctly. However, in most cases, if the transformer leakage inductance is designed appropriately, it is possible to do rid of this additional inductance requirement. This results in an increase in the system's power density as well as its efficiency and a decrease in its overall cost. As a result of this, and particularly at high power levels, it is possible to see that the design stages of a power converter and a transformer affect one another. So, the primary objective of this study is to carry out research on the design and construction of a high-frequency power inverter transformer. In this investigation, the design of a single-phase transformer with 330 kW of capacity (equivalent to 1 MW in three phases) that operates at 50 kilohertz is described. Core materials along with their performance at high switching frequencies are now under investigation. To simulate a transformer's behaviour, a 3D model is analysed using a Finite Element Analysis (FEA) programme. To simulate the intended transformer's magnetics, electrostatics, and transients, Maxwell-3D may be used. In respect to leakage inductance, along with voltage regulation, and also total transformer efficiency (98.608%), the results showed that the Shell-type transformer performed well. Additionally, a design that is compact and has a power density of 40.376 kW/L can be developed.

Keywords: High Frequency (HF); Power Inverter; Solid State Transformer (SST); Transformer; Finite Element Analysis.

INTRODUCTION

Since the turn of the century, renewable energy sources have been gaining popularity; using them more extensively as a grid component helps cut down on greenhouse gas emissions. It's a strategy to protect Earth from climate change, but there are a few obstacles that need fixing before the goal of increasing renewable energy consumption and meeting the smart grid's requirements can be realised. In order to meet the necessary utilisations of renewable resources, the International Renewable Energy Agency (IRENA) [1] has pinpointed the most crucial areas that have yet to be developed (Abu-Siada et al., 2018). The points identified by IRENA includes increasing energy storage capability, facilitating bi-directional energy flow, improving grid interconnection, and adopting technology that enhances existing systems. The transformer is one of the most vital components of the power grid since it is used at the power plant to boost voltage for more efficient

[1] chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://www.irena.org/ /media/Files/IRENA/Agency/Publication/2018/Apr/IRENA_Report_GET_2018.pdf

transmission. After that, it is put to use in the distribution grids to reduce the voltage as many times as necessary before it reaches the end users (Samad, 2019). The figure below illustrates the HF transformers.

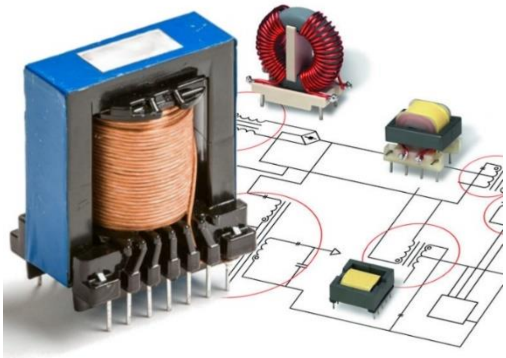

Figure.1 High Frequency Transformers[2]

Numerous studies (Sand, 2019; El Shafei et al., 2019; Tong et al., 2020) are currently being conducted on this asset in an effort to change it from the massive magnetic transformer that it currently uses to an intelligent Solid-State Transformer (SST). It consists of several power electronic converters and a high- or medium-frequency transformer (Khayamy et al., 2018). In addition to larger and more efficient transformers, they can perform better monitoring, along with control, and also grid support tasks, like supplying active/reactive power, when in comparison with Line Frequency Transformers (LFTs). Full-bridge PWM converters are used in SST utilisations, although their use is constrained by switching losses in high power and/or medium voltage utilisations. However, this limits the reduction in transformer size and the enhancement of the transformer's efficiency (Shamshuddine et al., 2020). Design power level can be enhanced by employing relatively lower switching frequency. As a result, converters such the Series-Loaded Resonant (SLR), Dual-Active Bridge (DAB), and also Phase-Shifted Full Bridge (PSFB) are being utilised in SST utilisations (Hannan et al., 2020). Zero-Voltage Switching (ZVS), a feature of these converters, raises the highest switching frequency value that may be achieved while maintaining a manageable switching loss. Higher values for efficiency and power density are therefore attained (El Shafei t al., 2019). The previous literature on this subject is thoroughly discussed in the section that follows.

[2] https://www.deangeliprodotti.com/en/articles/high-frequency-transformers-a-challenge-for-the-future-of-energy/

LITERATURE REVIEW

Table.1 Literature review

Tong et al., (2020)	Three different toroidal transformer designs were examined in this article, including design calculations, finite-element method (FEM) simulations, and loss analyses. The first design used nested toroids to couple the N^2 flux, the second used stacked toroids to couple the one-turn flux, and the third interleaved two windings.	Compared to hand-wound air-core components, the manufacturing process described in this article enables accurate modelling of the transformer's inductance matrix. Additionally, this research offered experimental examples, such as the use of these transformers in 100-W, 30-MHz resonant converters.
Guo et al., (2021)	Predesign, preliminary design, and optimal design make up the study's suggested optimal design process. To improve current carrying capacity and lower leakage inductance, the parallel-concentric winding arrangement is used in the preliminary design.	The DAB converter has a peak efficiency of 99.53% and a 200-kW efficiency of 98.85%. MFT has a maximum efficiency of 99.844% and a 200 kW efficiency of 99.842%.
Okeke et al., (2022)	The field-shaping method that was suggested in this work produces two skin-depths' worth of conduction by evenly distributing current on both sides of each conductor layer.	Conceptually proved this method using FEA simulation and an experimental prototype.
Yao et al., (2023)	For various high-power isolated DC-DC converters, this research presented a unique structure of integrated SiC MOSFETs with a high-frequency transformer (I-SiC-HFT).	Through FEM-based electromagnetic simulation and DC-DC converter tests, a small-scale 1.5 kW prototype I-SiC-HFT is used to show the fundamental structure and different performance indicators.
Daneshmandietal., (2023)	Transformers are being downsized and the design is being optimised using magnetic material production techniques including ferrite, amorphous, and high-frequency nanocrystals. A high-frequency transformer with a ferrite core and a power of 100 watts is built for use in high voltage charges in pulse power technology in this study using the finite element method (FEM), together with a frequency transformer over 5 kV.	The findings indicated that when compared to analytical methods, the finite element method appears to be more accurate. Due to the significance and difficulty of developing high-frequency transformers, utilising this method can benefit transformer designers by making parameter calculation and ideal design easier and more straightforward.

The operating frequency, along with the core material type are chosen based on the power level, along with power density, and also efficiency aim, according to previous research. Additionally, extra inductors are necessary for the effective operation of the given power converter topologies. However, this additional inductance requirement may typically be removed by using an adequate transformer leakage inductance design. In addition to increasing efficiency and lowering system costs overall, this increases power density. Therefore, it is clear that the design phases of power converters and transformers interact, particularly at high power levels. So, the primary goal of this study is to carry out research on the Design and Construction of a HF Transformer for a Power Inverter using SST.

METHODOLOGY

The Table 2 lists the suggested transformer specs. The transformer, which has a power rating of 330kW and runs at a frequency of 50kHz, as seen in the table, will exceed the limits of the standard values.

Table.2 System Speacification (EI Shafeiet al., 2019)

SYSTEM SPECIFICATIONS	VALUE
Output Rated Voltage (V)	1000
Output Rated Current (A)	330
Single Phase Output Power (kW)	330
Load Resistance (U)	3
Switching Frequency (kHz)	50

Fig. 1 shows the analogous circuit for a two-winding transformer. The transformer efficiency is impacted by the parasitic capacitance and leakage inductance found in both windings. Leakage inductance values inside HF transformers must always be carefully planned and selected. To transfer power straight into the secondary side, a low leakage inductance value is essential. A low inductance value, on the other hand, will result in an unfavourable high *di/dt* rate directly at the switching devices. Therefore, a trade-off between these two design goals should be made. Due to the amount of winding layers used in these high power, along with HF transformer utilizations, the leakage inductance value is previously very high. So, it makes sense to maintain this value as low as possible. Assuming that the *di/dt* rate is appropriate for the switches being used, this study aims to minimise the leakage inductance value. The following studies have been conducted in accordance with this design target:

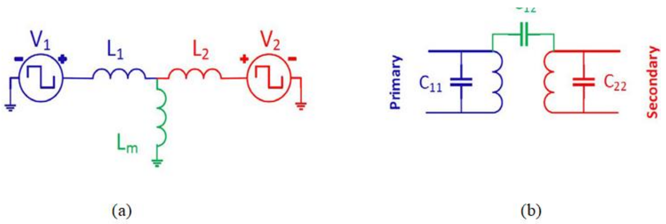

Figure.2 (a) Transformer Model Equivalent Circuit. (b) Transformer Capacitance Equivalent

Transformer Design Formulations

An essential design step is figuring out the dimensions and size of the transformer. Efficiency, power density, and cost of transformers are just a few of the aspects that will be impacted by this. Equation (1) provides a practical and well-known formula for estimating the transformer's size:

$$A_p = A_c W_a = \frac{S}{KfKcuBmfJ} 10^4 \quad (1)$$

here, A_c is the core Cross-Sectional Area (CSA), B_m maximum flux density, S rated apparent power, f operating switching frequency, W_a transformer window area, K_{CU} window utilization factor, K_f applied waveform coefficient, and J current density of the conductor.

Core Material: The initial and fundamental stage in transformer design is choosing the core material. The material types typically utilised for transformer core construction are ferrite, nanocrystalline, si-steel, and amorphous. These types always have trade offs and restrictions at various power levels along with operating switching frequencies, claimed El Shafei et al. (2019). Table 3 lists the material characteristics for each application of high power and high switching frequency taken into account in this investigation.

Table.3 Core Material Characteristics

Core Material	Power loss	Permeability	Bmax	Cost	Market
Ferrite	Low	High	Moderate	Low	High
Si-steel	High	High	High	Low	High
Nanocrystalline	Low	High	High	High	Low
Amarphous	High	High	High	Low	High

Parameter Analysis: The number of turns, core, magnetic flux density, frequency, and copper losses serve as their primary summaries. In order to determine the trade-offs and values of the optimal parameters, an optimisation algorithm was created for this purpose using MATLAB. Different core sizes and turn counts may be taken into consideration, subject to the design purpose. The main design target can be either cost, power density, or efficiency. Efficiency has been identified as the desired and main goal to be addressed for this transformer application.

RESULTS AND DISCUSSIONS:

ANSYS For the purpose of studying the physics, along with magnetics, and also transients, and also electrostatics of the system, Maxwell-3D/Simplorer FEA simulations have been run. In order to replicate the

full electrical system, the transformer was modelled in Maxwell-3D and loaded into Simplorer. The main winding is energised by a 50kHz switching HF inverter connected to a 1kV DC bus. The secondary winding is connected to a diode bridge rectifier that produces 1 kV of DC bus level for a 330-kW load. In this comprehensive transient - transient co-simulation, evaluating a physical transformer under real-world operating circumstances is duplicated. Results were then reviewed, including transformer efficiency, load voltage/current/power, and core magnetic flux distribution.
The leakage inductances for Type-A, along with Type-B, and also Type-C Core-type configurations have been computed to be 90.744 H, 1.283 H, and 2.512 H, respectively, after the self/mutual inductance matrices from Maxwell-3D have been extracted. There is no doubt that Type-A possesses an extremely great leakage inductance. This will no longer be discussed because it had a negative impact on the power transferred to the secondary side. The Type-C leakage inductance value caused an output voltage drop of 11.4% and prevented the secondary side from receiving the full amount of power. Consequently, this choice has also been ruled out. Last but not least, Type-B produced good results (Table 4) with a negligible voltage drop at the output and a minor leakage inductance. On the other hand, Table 5 lists the outcomes of the Shell-type simulation. The Shell-type transformer outperforms the values indicated in Tables 4 and 5 when considering efficiency and also leakage inductance.

Table.4 Core Type-B Results

Simulation Results	**Core Type – B**
Maximum Flux Density, ^{B}max (T)	0.288
Tranformer Leakage Inductance(uH)	1.283
Magnetizing Inductance (mH)	5.877
Tranformer Input Power (Kw)	340.313
Tranformer Ouput Power (Kw)	322.836
Effieciency	94.864

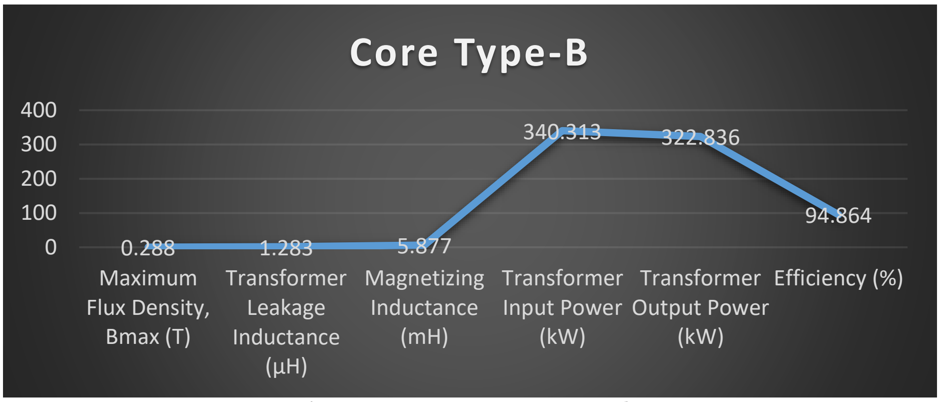

Figure.3 Core Type-B Results

Table.5 Shell Type Results

Simulation Results	**Shell Type - B**
Maximum Flux Density, ^{B}max (T)	0.26
Tranformer Leakage Inductance(uH)	1.25
Magnetizing Inductance (mH)	3.858
Tranformer Input Power (Kw)	338.443
Tranformer Ouput Power (Kw)	333.733
Effieciency	98.608

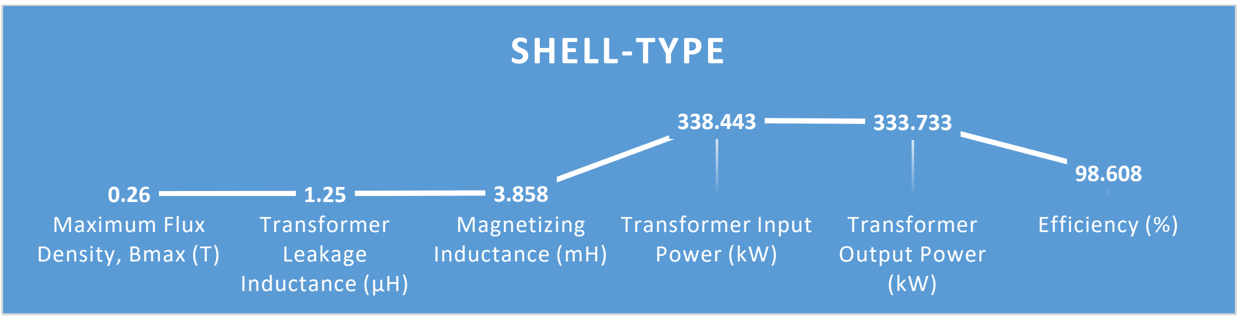

Figure.4 Shell Type Results

The voltage and current of a Shell-type transformer at the main and secondary sides are shown in Figs. 4, respectively. There is no indication of any core saturation, and the current waveform possesses a good and also smooth shape. The secondary voltage also attained the anticipated rated level of 1kV. According to calculations, the transformer's efficiency is at a level of 98.608%. For the chosen power, along with frequency, and also voltage levels, this figure is thought to be quite satisfactory. Finally, the load voltage and also current waveforms have reached their design levels, resulting in the full 330 kilowatts of power. The output rectifier and filter of the transformer are shown in this illustration to be functioning appropriately.

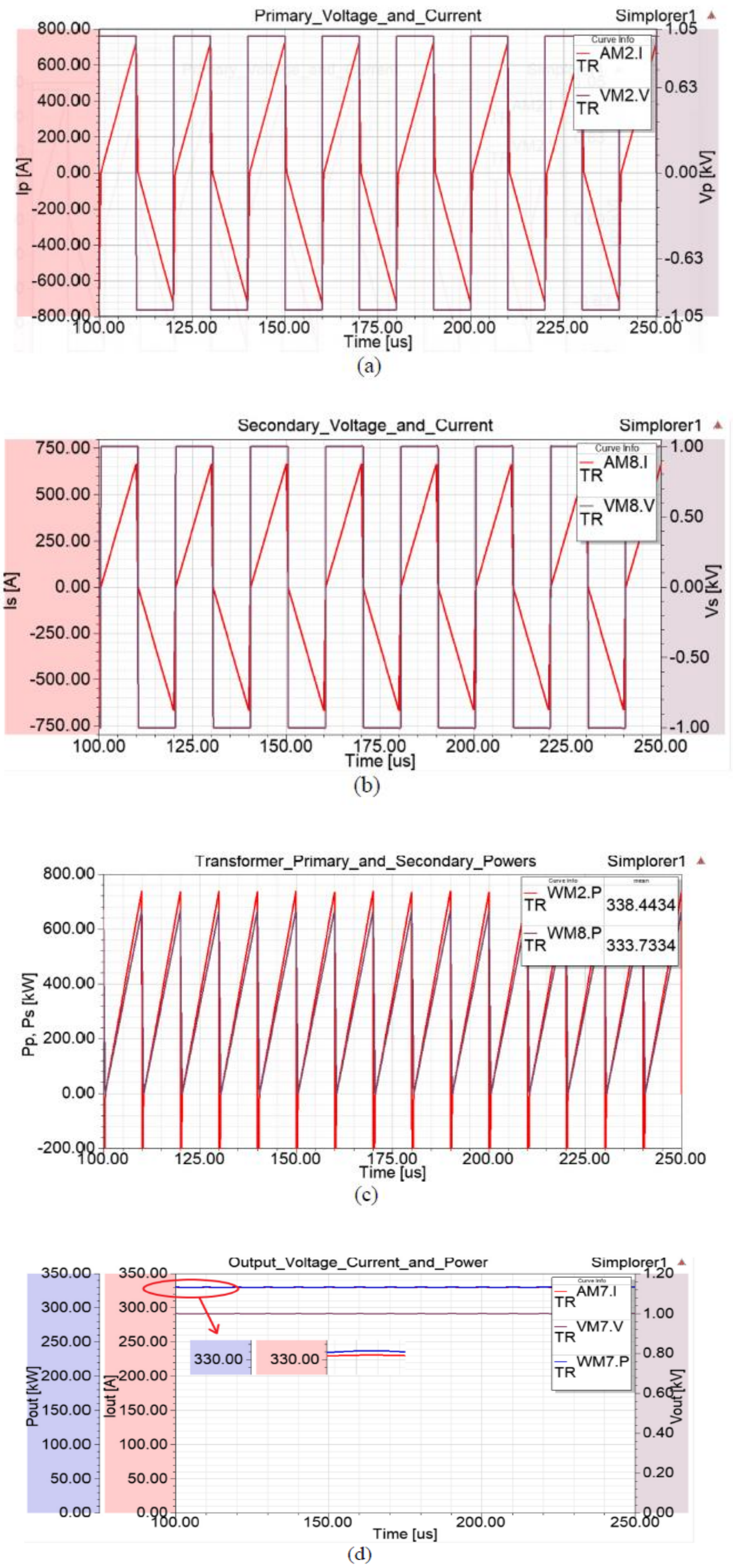

Figure.5 Proposed Shell-type transformer results. (a) Primary voltage and current (b) Secondary voltage and current (c) Primary and Secondary power (d) Load voltage and current (EI Shafei et al.,2019)

CONCLUSION

SSTs are now employed in HF utilisations requiring medium to low power or in low frequency utilisations requiring high power. A unique single-phase, 330kW, 50kHz transformer is constructed and modelled in this work. It can be used to create a 1MW three-phase system. In order to mitigate and reduce this leakage inductance, this work gave a thorough evaluation of the core construction, and also material, along with winding arrangement, and also coupling coefficients. In high-power, high-frequency utilisations, leakage inductors with large values might cause problems. Through the use of FEA software, theoretical analysis, computations, and findings were validated. To construct a transient-transient co-simulation, the designed transformer models were built using ANSYS Maxwell-3D and then combined with a power electronics circuit using ANSYS Simplorer. Different winding configurations have been simulated for Core-type and also Shell-type transformer models using the same CSA, wire size, along with core material, and also size factors. In respect to leakage inductance, voltage control, and transformer efficiency (98.608%), the simulation findings favoured the Shell-type transformer. Additionally, 40.376kW/L of power density is achieved in a small design.

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