High-Frequency Transformer Design with Hollow Core for Solid State Transformer

Haitham A Obaid 1* and Yasir M Y Ameen 2

1 Dept. of Electrical Engineering University of Mosul.
2 Dept. of Electrical Engineering University of Mosul.

emails: haithamahmed1996@gmail.com, Yasir_752000@uomosul.edu.iq

Abstract. Solid-state transformer (SST) is one of the new technologies that has kept pace with the development of renewable energy sources such as the solar energy and wind turbines. The SST consists of a high-frequency (HF) transformer and power electronic converter at both ends of the HF transformer. Despite the high efficiency of the traditional transformers, they are quite large in size and also very heavy. In order to reduce the size and weight of the transformers, SST is used as an alternative for the conventional transformer which also brings along other advantages. The type of core material, the type of wire used, and the method of winding the coils on the HF transformer core affects the core losses, copper losses, the cost, efficiency, and power density of the HF transformer. In this paper a new method has been proposed to form the core of the HF transformer used in SST where a hollow core is used, thus reducing the size and weight of the HF transformer along with the reduction in the core loss. The proposed core is designed using ANSYS Maxwell 3D software in addition to calculating the inductance matrix and the coupling coefficient. Finally, the proposed model of a high-frequency transformer was simulated using MATLAB Simulink software.

Keywords—Solid state transformer, Renewable energy sources, High frequency transformer, Power electronic converter, Hollow core, ANSYS Maxwell

1. Introduction
A solid-state transformer (SST) is actually a AC/AC transformer. It is an electrical power transformer that replaces the conventional transformers used for distributing AC electrical power. SST is one of the modern technologies that is expected to provide development in multiple fields, like the smart grid systems, traction systems, and renewable energy sources system [1]. The electric power system primarily consists of generating stations, transmission lines, and loads as shown in figure 1. To transmit electrical energy with minimal losses, we need to raise the voltage to a specific level and then reduce it to other standard levels. The transformer performs this function. The traditional transformers are limited to managing (increasing or decreasing) the voltage levels only, but they are unable to deal with power quality cases, such as harmonics, sagging, swelling, etc. It is this function that made researchers to look towards SST which has multiple advantages over conventional transformers. Some of the advantages are their smaller size, DC link, the power direction can be one-way or two-way, low weight, fault isolation, voltage regulation, reactive power compensation, etc. [2]. Nowadays Solid-state transformers have evolved very quickly and can be a viable alternative to conventional low-frequency current inverters (50/60 Hz). When their weight and scale is reduced, there is a significant increase in their performance and cost savings can be achieved [3]. The transformer size decreases when the operating frequency is increased, but as the frequency increases,
the switching losses of the switches also increase. Therefore, the high-frequency transformer must be
designed in such a fashion that they obtain the required efficiency, power density and cost. There will
be different effects on the transformer depending on the specific structure to achieve SST. They need
to be taken into account when designing a high-frequency transformer (i.e. the various requirements
for induction current, voltage, and leakage). To design an HF transformer, a set of design
considerations are presented. The material used to manufacture the core is specified to have an
acceptable saturation flux density, low core losses. The type of wire, the method for placing the coils
in the core to obtain the highest coupling coefficient, the value of leakage inductance, and Insulation
requirements, etc. are also specified [4][5].

Several research papers and studies have been presented on the solid-state transformer and high-
frequency transformer design method. Van der Merwe et al [6] He studied the concept of a solid-state
transformer as a practical alternative to a conventional transformer in distribution circuits and
presented the benefits of solid-state transformers in terms of improvements in problem areas in
distribution networks. Tiefu Zhao and others [7] proposed a solid-state transformer 20KVA and a 6.5
KV with a voltage of 12 KV distribution system. Ahmad and others [8] presented a design for a
330kW single-phase transformer operating at 50 kHz, and examined potential core materials and their
performance under high switching frequency process. Akram and others [9] described a high-
frequency transformer design and presented two prototypes of a high-frequency transformer, one using
an amorphous material and the second using a Nano-crystalline material to make a core. Muhammad
et al [10] presented three considerations when designing a high-frequency transformer, the first was
the method of placing the coils, as it presented four models for placing the coils in the core and
determining which method gives the highest coupling coefficient between the coils, the second was
the type of wire used, and the third was the type of core material used.

Most of the previous studies in the design of high-frequency transformers used in the SST that are
mentioned above focused primarily on the material used to manufacture the core and the type of wire

![Figure 1. The components of the electric power system](image-url)
used to obtain a high saturation flow density with the lowest possible losses, with the appropriate size and cost. In this paper a new proposal is being presented for the manufacture core, where the size of the core is reduced by using a hollow core. This proposal will take less volume, have less weight, and reduce core losses.

2. Classification of Solid State Transformers

SST can be classified depending on the number of stages that compose it into a single-stage, two-stage and three-stage. Each type is characterized by specific characteristics, the type of SST chosen according to the application used for it, the required efficiency, and other factors, for example, the direction of energy is two-way or one-way, the dc link possibility, etc. Figure 2 shows the classification of the topology for SST.

![Figure 2. Topology classification of solid-state transformer.](image)

The single-stage topology is simple in terms of design and control and is characterized by a low number of switches, so losses in this type of transformer are lower and has better efficiency than others. In this type, since there is no DC link, it is used in limited applications [2][12].

A two-stage SST contains a DC link, but is not suitable for power storage and distributed energy resource (DER) applications. In addition, large filters are required to reduce ripple current [3].

Three-stage SST are extensively used. They contain a rectifier (AC/DC) at the front end, a DC-DC converter, and an inverter (DC/AC) at the other end for user interface. In this type as the power direction can be two-ways and there is a DC link for high voltage and low voltage, it is widely used in power transmission systems to address the problems of power quality, compensate for VAR, improve power factor, and is also widely used with renewable energy sources [2][3].
3. Design high frequency transformer

The dc/dc stage is the most important stage in a SST, as it contains the HF transformer. The high-frequency transformer is characterized by small size and light weight. However, with increasing frequency, the core losses increase in the HF transformer. The core losses, copper losses, and switching losses reduce the efficiency of the SST. In this paper, several considerations are presented for designing a HF transformer so that the core losses are minimized with good saturation flux density and acceptable cost.

3.1 Core material

The selection of core materials is very important as the core material affects the cost, efficiency, and size of the HF transformer [13]. There are certain factors that are considered while choosing the base material [14]. These factors include core loss, saturation flow density, relative permittivity, and operating frequency. In this paper, four magnetic materials used to make the core will be covered. The first of these is silicon steel, which has a high saturation flux density and good permeability for high-frequency applications, but entails high core losses, especially at high frequencies [15]. The second material is ferrite. When compared to others, it has low core losses and low cost, but also low saturation flux density [15]. The third material is amorphous; it has high saturation flux density but the core losses are also high when compared to ferrite [5]. The fourth material is a Nano-crystalline material; it has good flux density but less than amorphous and has less core losses than amorphous [5]. Table 1 shows the difference between the properties of the materials used to make the HF transformer core.

| Material         | Saturation flux density | Core losses | Cost | Permeability |
|------------------|-------------------------|-------------|------|--------------|
| Silicon steel    | high                    | high        | low  | high         |
| Ferrite          | low                     | low         | low  | medium       |
| Amorphous        | high                    | high        | medium | high         |
| Nano-crystalline | high                    | low         | high  | high         |

It is evident from the above and from Table No.1 that the ferrite material gives better performance at high frequencies because it is characterized by low core losses and low cost, although the saturation flux density is less than the rest of the materials. In this paper, a ferrite material was chosen to make a high-frequency transformer core, as it is consistent with the frequency at which the transformer operates.

3.2 Cable selection

In high-frequency transformers, the effective resistance of the wires increases due to the increase of skin and proximity effects, the skin effect is the tendency of high-frequency currents to circulate on a conductor's surface. The proximity effect is the current that flows in loops or localized distributions due to the presence of magnetic fields created by nearby conductors. To solve the problem of skin and proximity effects, Litz wire was used in this experiment [4].

3.3 The shape of the core and the arrangement of the coil on the core

One of the major advantages of the solid-state transformer is its small size and reduced weight compared to a conventional transformer. In order to increase the efficiency of the solid-state transformer and determine the best shape of the core and the best formats for arranging the coil on the core, four models of the core shape and the arrangement of coil on the core were made and compared. The factors considered for comparison are the coupling coefficient between the coils, the size and the weight of the core. To obtain the lowest weight and volume of the SST, the HF transformer core has to be hollow.

By using ANSYS Maxwell, simulations of the proposed four states of core shape and coil arrangement in the core were performed. Green represents the source of nutrition (primary) and red represents the load (secondary).

The first case is the non-hollow core and the coil is arranged as shown in Figure 3, case 1. In the second case, the coil is arranged in the same order as in the first model, but the core in this case is hollow as shown in Figure 3, case 2.

The third case is the non-hollow core and the coils are arranged as shown in Figure 3, case 3. In the fourth case, the coil is arranged in the same order as the third model, but the core is hollow as shown in Figure 3, case 4.

**Figure 3.** ANSYS Maxwell simulation of the arrangement of coil on the core in the four cases.
In case 2 and case 4 the core is hollow, so the HF transformer volume is less than the volume in case 1 and case 3. The core losses are also less.

**Table 2.** Coupling coefficient between wire 1 and wire 2 for each case

| Case | Coupling | Wire 1 | Wire 2 |
|------|----------|--------|--------|
| Case 1 | Wire 1 | 1 | 0.931037 |
| | Wire 2 | 0.931037 | 1 |
| Case 2 | Wire 1 | 1 | 0.911522 |
| | Wire 2 | 0.911522 | 1 |
| Case 3 | Wire 1 | 1 | 0.991769 |
| | Wire 2 | 0.991769 | 1 |
| Case 4 | Wire 1 | 1 | 0.989147 |
| | Wire 2 | 0.989147 | 1 |

From Table 2, it is evident that the coupling coefficient of the hollow core is less than the coefficient of the non-hollow core conductivity, but in a very small proportion.

It is evident from the results that the best core shape and arrangement of coil is in case 4, as it is characterized by smaller core size, low cardiac losses, and good coupling coefficient.

4. Simulation and results

The proposed model of a high-frequency transformer was simulated in MATLAB Simulink software. Fig. 4 shows block diagram of the model of DC to DC stage, which is the second stage of a SST. The input voltage is 1000V DC, and the turn ratio of the HF transformer is one. IGBT switching device is chosen with frequency operation of 25 kHz. Table 3 shows the parameters that were used in the simulation.

**Figure 4.** Block diagram for dc to dc stage with High-Frequency Transformer
Figure 5 shows the input voltage and the input current of a high-frequency transformer (primary voltage and primary current), while Figure 6 shows the voltage and current output of a high-frequency transformer (secondary voltage and secondary current). Figure 7 shows the output dc voltage. The voltage is depicted in blue and the current in red.

| Table 3. Simulation parameters |
|-------------------------------|
| parameters    | value |
| Input voltage (V)         | 1000  |
| Mutual inductance (mH)    | 22.2  |
| Leakage inductance (µH)   | 30    |
| Turn ratio (n1/n2)        | 1     |
| Switching frequency (kHz) | 25    |
| Input capacitor (µF)      | 500   |
| Output capacitor (µF)     | 200   |

**Figure 5.** Primary Voltage (Vp) and Primary Current (Ip) for High-Frequency Transformer
Figure 6. Secondary Voltage (Vs) and Secondary Current (Is) for High-Frequency Transformer

Figure 7. Output dc voltage

Figure 6 shows the voltage and current coming out of the HF transformer, which is running smoothly as expected. In addition, the waveform for dc voltage emerging from the rectifier is also without distortion as shown in Figure 7.

5. Conclusion

This paper elucidates the concept of a solid-state transformer and the benefits of using power electronic convertors with a high-frequency transformer, as the use of power electronic convertors provide good control advantages and connection methods in the power transmission system. Also, the use of a high-frequency transformer reduces the size and weight of the transformer as compared to the conventional transformer, so a new model for the core shape of a high-frequency transformer is proposed, where a hollow core is used, which reduces the size and weight of the high-frequency transformer in addition to lowering the losses of the iron core. Simulations result of ANSIS Maxwell and MATLAB show the validity of the proposed model.

6. References

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