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# Design of High-Power Isolated Boost DC-DC Converter for Renewable Energy Applications

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**Abstract:** Energy efficient DC-DC converters are essential to utilize the maximum power generated from renewable energy sources. The high frequency magnetic components, i.e. transformer and inductor contribute heavily to the poor conversion efficiency of any given DC-DC converter. In this paper, a full-bridge DC-DC converter is proposed with a novel design of its high-frequency transformer and inductor. The core loss effects, copper losses, proximity effects and the leakage inductances of the magnetic components are also analyzed to ensure maximum efficiency. The theoretical and simulation analysis of the converter design is also done and a full bridge topology with a voltage doubler circuit is used to acquire maximum voltage gain.

Foil windings are used and extensive interleaving is done for the primary and secondary winding of the high-frequency transformer in order to reduce the core losses and the leakage inductance. The turn ratio of 1:4 is set in order to step-up the voltage level at the secondary side of the transformer. For inductor design, the core material, shape and size are finalized for the given converter specifications after thorough analysis and simulation tests. The efficiency of 96.46 percent of the converter is achieved with the chosen design specifications for the transformer and inductor. The high frequency magnetic transformer is implemented physically and it is observed that the measured result resonates with the theoretical results. Also, it has been concluded that the turns-ratio of the converter transformer have no impact on its leakage inductance.

**Keywords:** DC-DC converter; voltage doubler circuit; foil winding; efficiency; core loss; interleaving; (key words)

## I. INTRODUCTION

In the recent years, high power low-voltage DC-DC converters have received considerable attention due to its wide applications in renewable energy systems. DC-DC boost converters are essentially required in order to scale the voltage level as per the system specifications especially in renewable energy based applications. Typically, in boosting application the voltage level of 12-15 V is scaled-up to 350-400 V so that it could be synchronized with the single-phase grid.

Many DC-DC boost converters have been presented in literature [2]-[6] which includes current-fed full bridge boost converter, partial paralleling based power converter, actively clamped converter design, isolated bidirectional boost converter design etc. Few characteristics are common in all the converter designs presented in the literature. In most cases, optimal result for the efficiency of the converter is obtained at highest input voltage and approximately medium output power. Minimum efficiency occurs at lowest input voltage and maximum output power. The converters that are reported in the literature usually have to face with the problem of poor conversion efficiency due to inefficient design of the high frequency magnetic components. However, in this research the issue of poor conversion efficiency is addressed.

In this paper, a converter design is presented which utilizes a full bridge topology. From the literature review, it has been concluded that the use of full bridge topology is essential for enhanced voltage gain. The full bridge topology also results in lower leakage inductance as each magnetic component experiences appropriate charging/discharging intervals. In addition to the chosen topology, a voltage doubler circuit is also used to double the voltage produced at the secondary side of the high frequency transformer which eventually reduces the secondary turns. The reduced number of turns helps in reducing the leakage inductance. Furthermore, it is also presented in this paper that the interleaving of primary and secondary turns of the transformer limits the transformer leakage inductance. The measurements corresponding to the switching and conduction losses are also done in this research and Schottky diodes and the most optimal MOSFETS are used for switching purpose in order to obtain the maximum efficiency. The chosen converter design is simulated using MATLAB Simulink software and it is observed that the simulation results resonates with the theoretical results.

The simulated results are then verified by implementing the high frequency magnetic components and upon its testing, extremely low leakage inductances and ac resistances have been witnessed. The maximum overall converter's efficiency was recorded to be 96.46 percent at maximum input voltage.

## II. ISOLATED FULL BRIDGE BOOST CONVERTER

The chosen isolated boost converter is illustrated in Fig. 1 below. This topology involves a voltage doubler circuit in parallel with the load of the converter. The corresponding waveforms are presented in Fig. 3.

In high-power converters, it is essential to use galvanic isolation to avoid any physical and electrical connection between the input and output side of the converter. Therefore, a high frequency transformer is also incorporated in every high-power converter as also illustrated in Fig. 1.

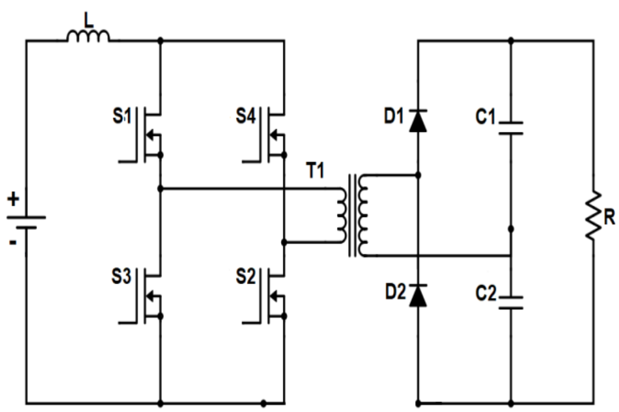


**Fig. 1** Full bride isolated boost converter

This paper presents the design of transformer and inductor given the chosen converter specifications as mentioned in Table I. Detailed theoretical and experimental analysis of the high frequency inductor and transformer of the proposed converter is done and the core and copper losses of the given magnetic components have been analyzed. The intensive technical details of high frequency transformer winding method are also presented. Furthermore, this paper concludes that upon interleaving the transformer's primary and secondary winding extensively, the conduction losses can also be reduced to minimal.

Voltage clamp circuit is generally required for the protection of converter switches in high power applications. However, advanced techniques have been introduced, such as Schottky diodes and MOSFETS that are rated for repeated avalanche [3]. Such components are used in order to eliminate the clamping circuits from the converter which results in reduced conduction and switching losses.

While selecting the appropriate MOSFET switch for the converter, the voltage rating of the switches were taken into consideration as their turn-on resistance ($R_{DSON}$) is proportional to approximately the square of the drain-to-source voltage rating of the switch. It is thus important to emphasize, that the use of switch having 2-3 times the voltage rating would not guarantee lower losses in fact results in higher losses.

## III. CONVERTER DESIGN AND OPERATION

The converter's specifications are listed in Table I. The inductor core is a Magnetics Kool Mu EE K4317E090. EE core was chosen because it has the least core losses among all the other core shapes. The transformer core is E41/17/12 in 3C91 material. The switching frequency is 50 kHz.

Table 1 Converter Specifications

| Parameter | Specifications |
|---|---|
| Input voltage range | 12-15 VDC |
| Output voltage | 150 VDC |
| Output current | 3.333 A |
| Output power | 500 W |
| Transformer turns ratio | 1:4 |
| Switching frequency | 50 kHz |
| Duty cycle | 68% |

The selected ferrite E core can provide the power of 500 W at varying 12-15V input. The turs-ratio of high frequency transformer is set as 1:4. Foil winding is used for both side of the transformer winding, with different thickness. Litz wire could also be used but given the sufficiently large current at the primary side and very low turns required at the primary side, Litz wire is not very affective.

A total of three operating modes including two energy transfer cycles are explained later in this section. The primary-side switches operate diagonally, i.e. $S_1$ and $S_2$ conducts simultaneously and in the subsequent switching state, switches $S_3$ and $S_4$ conducts. When all switches are on, due to duty cycle being greater than 50%, the inductor starts charging. During that interval, no voltage is supplied to the secondary side of the converter. The maximum overall converter's efficiency was recorded to be 97.46% at minimum input voltage.

The transfer function of the proposed design is:

$$\frac{V_o}{V_{in}} = \frac{n}{1-D}$$

And the inductor duty cycle and switching period is:

$$D_L = 2D - 1$$

$$T_L = \frac{T_{SW}}{2}$$

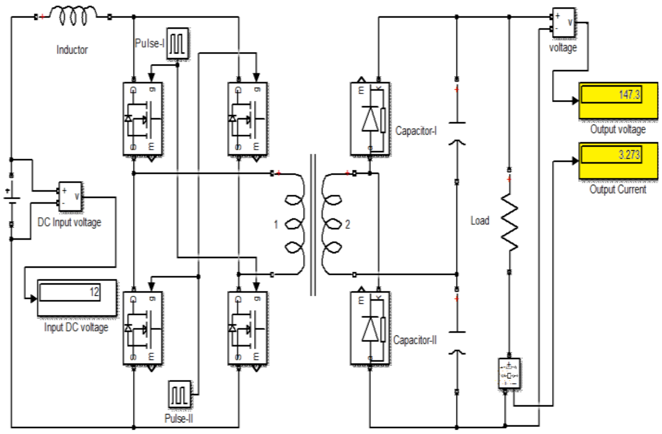


**Fig. 2(a)** Simulink simulation schematic

The zoomed-in image of converter's output result is presented below. The output voltage is recorded as 147.3 V and output current is 3.273 A based to the transformer experimental AC resistances and leakage inductances as shown is Fig. 8. Henceforth, from the simulation results, the converter power conversion efficiency is recorded to be 96.46 percent.

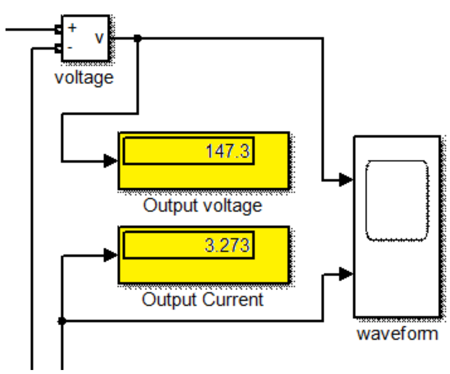


**Fig. 2(b)** Simulation output results

In Fig. 3, the basic time waveform during the converter operation is presented. All of the waveforms match with the expected results. The corresponding operating modes are presented below:

**Mode I:** Switches $S_1$ and $S_2$ are ON whereas $S_3$ and $S_4$ are OFF. In the first energy transfer cycle, the current start flowing through switch $S_1$, transformer, diode $D_1$, the load and therefore results in voltage drop across the connected load at the output. The current flows back to the input side via switch S2.

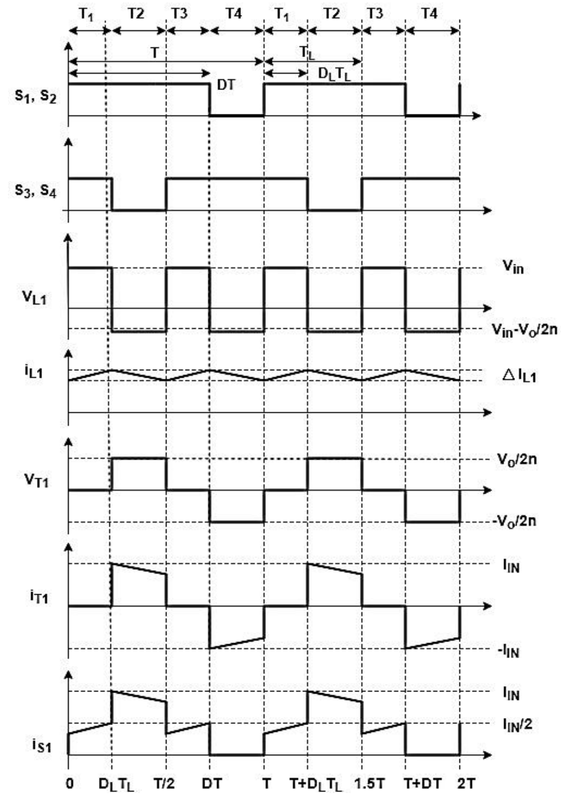

**Fig. 3** Operating waveforms of the chosen converter

**Mode II:** All four primary side switches are ON. In between the first and second energy transfer cycle, all four switches turns on for a certain time period which is utilized for the inductor to get charged. In this period, no current flows through the transformer and the capacitors of voltage doubler circuit provide current to the load.

**Mode III:** In this switching cycle, only the switches $S_3$ and $S_4$ are ON. The current passes through MOSFET switch $S_3$, transformer, diode $D_2$ and output capacitor hence the current reaches the output load before returning back to the input via switch $S_4$.

The output voltage and current values via MATLAB Simulink simulation has been presented below:

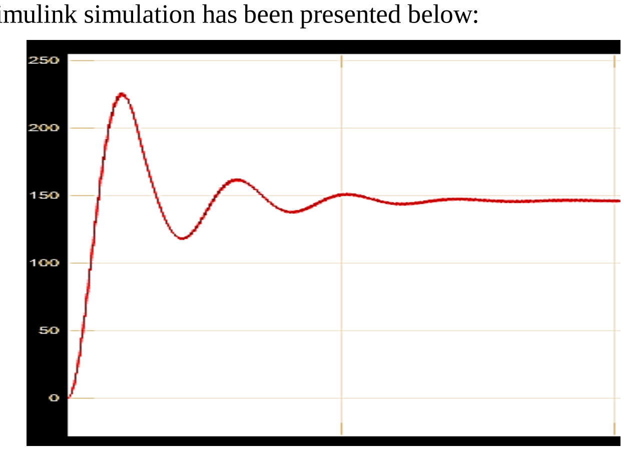


**Fig. 4(a)** Output voltage waveform on Simulink

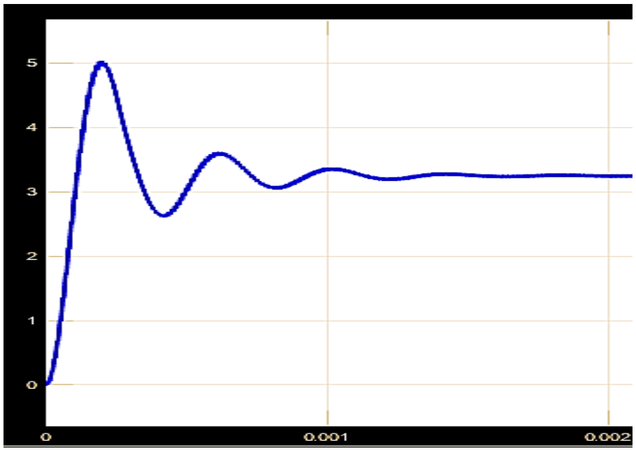


**Fig. 4(b)** Output current waveform on Simulink

## IV. DESIGN OF HIGH FREQUENCY MAGNETIC COMPONENTS

As mentioned above, DC-DC converters have to face with the poor power conversion efficiency due to the very nature of operation of its high frequency magnetic components. However, in this paper, a design method is presented for transformer and inductor that help in yielding maximum converter efficiency.

### *A.* Transformer Design

For the chosen boost type converter, the turns-ratio of 1:4 is selected for the the transformer. The switching frequency is 50 kHz. EE core E42/21/20 is used after theoretical calculations and their validation. The design concept of the transformer was considered to reduce the proximity effect so that the ac resistance factor could be reduced. Also, the transformer leakage inductance was also required to be kept minimal. EE shaped core is used so that the foil winding can be utilized as foil winding can provide large cross sectional-area. However, at very high power level, the foil winding approaches the penetration depth hence increased proximity effect.

In [4], the magnificent method to calculate the resistance factor presented by Dowell and Harley is presented. The equation derived by them is used widely to determine the ratio of ac and dc resistance. The ratio of ac and dc resistance is given by:

$$\frac{R_{ac}}{R_{dc}} = \emptyset \frac{sinh2\emptyset + sin2\emptyset}{cosh2\emptyset - cos2\emptyset}$$

Where for single layer winding, $\emptyset$ = h/δ. For winding with half layer, $\emptyset$ = h/2δ. In case of multi-layer winding, considerable level of proximity effects is also involved hence an additional term is taken into account, which is presented as follows:

$$F_R = \frac{R_{ac}}{R_{dc}} = \left(\frac{h}{\delta}\right)\left[\frac{\sinh 2\left(\frac{h}{\delta}\right) + \sin 2\left(\frac{h}{\delta}\right)}{\cosh 2\left(\frac{h}{\delta}\right) - \cos 2\left(\frac{h}{\delta}\right)} + \frac{2(p^2-1)}{3} * \frac{\sinh\left(\frac{h}{\delta}\right) + \sin\left(\frac{h}{\delta}\right)}{\cosh\left(\frac{h}{\delta}\right) - \cos\left(\frac{h}{\delta}\right)}\right]$$

Since the foil thickness is different for both primary and secondary windings therefore the proximity effect is recorded separately for both primary and secondary winding. Then, the average of both values of proximity effect is taken into consideration. The mean ac resistance ratio of primary and secondary winding of the proposed converter is calculated to be $R_{ac}/R_{dc}$ = 1.02, which is approximately 2% percent, i.e. extremely low.

*Winding Design I:* This is the single interleaving method which is widely used in the implementation of conventional high-frequency transformers. There are only two intersections which accounts for two layers per portion as evident in Fig. 4.

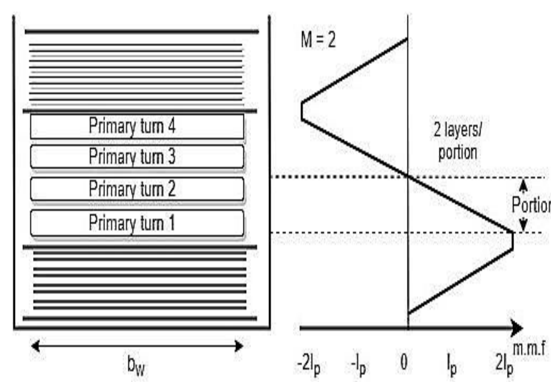


**Fig. 5** Conventional single interleaving transformer winding technique

*Winding Design II:* This is the double interleaving transformer winding method. This winding is also used in many design applications of high-frequency transformers. In this winding technique, there are four intersections which accounts for single layer per portion as evident in Fig. 5.

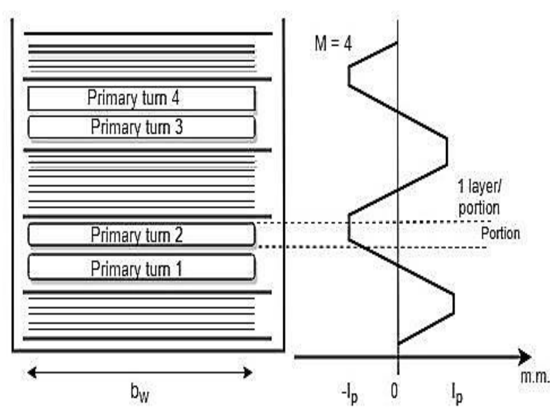


**Fig. 6** Conventional double interleaving transformer winding technique

*Proposed Winding Design:* This is the proposed transformer winding technique in which primary and secondary winding is extensively interleaved. There are total of eight intersections which accounts for half layer per portion as illustrated in Fig. 6.

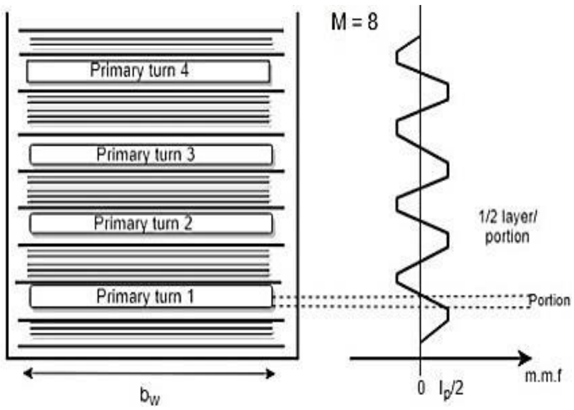


**Fig. 7** Proposed quadruple interleaving transformer winding technique

The leakage inductance is calculated from the given expression [1]:

$$L_{LK} = \frac{\mu_0(l_w h_w)}{3b} * \frac{N^2}{M^2}$$

The theoretical leakage inductance of secondary side with primary side shorted is calculated as 0.368 μH. The experimental results are presented in the figure below:

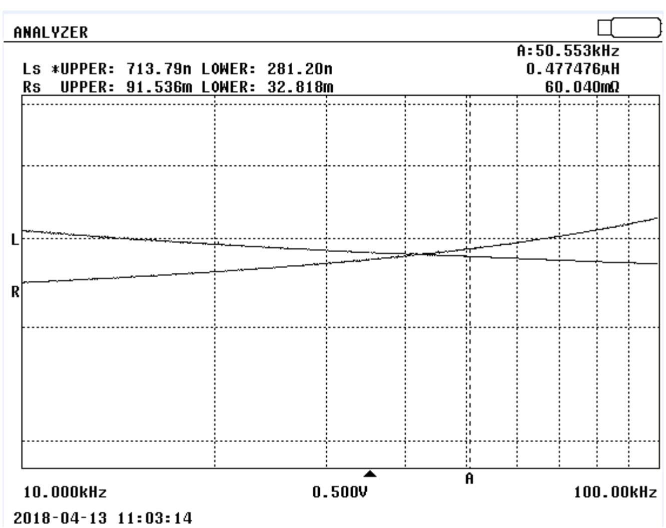


**Fig. 8** Measured ac resistance (R) and leakage inductance (L)

*Transformer Core Material and Shape:* In high frequency transformers, it is challenging to minimize the proximity effect and the other losses produced by eddy currents. Hence, the core material and shape corresponds proportionally to the obtained results of the transformer. Therefore, in high frequency applications, soft magnetic materials such as ferrite and nanocrystalline core are widely used. However, due to its high relative permeability, high saturation flux density and low coercivity, ferrite cores are more suitable for high-frequency operations.

Foil winding is effective in compact transformers as it provides maximum cross-sectional area with minimum wire thickness. Therefore, foil winding is used on E-shaped core. As extensive interleaving of primary or secondary winding is done in the proposed winding design, insulation is required between each turn of primary and secondary turn which is done using kapton tape. Kapton tape is manufactured using DuPont Kapton HN film and is capable of bearing the high temperature as high as approximately 600° C.

**Fig. 9** Implemented transformer design

The total power losses for transformer have been calculated and presented in the table below. It is observed that the transformer losses are very low which validates its design mechanism, and are presented in Table 2.

Table 2 Transformer Power Losses

| Parameter | Value [W] |
|---|---|
| Core loss | 0.740 |
| Copper/Wire loss | 0.3012 |
| **Total Losses** | **1.0412** |

## *B.* Inductor Design

The EE core is used for the inductor design of the proposed converter. After various iterations it was observed that EE core has the least core losses comparatively with the other core shapes. For magnetics E core K4317E090, total 7 no. of turns are required to achieve the inductance required. For the selected current density of 5A/mm^2, the foil height was chosen to be 15 mm and thickness as 0.6 mm.

The core loss and copper loss of the EE inductor and the selected foil winding is shown in Table 3.

Table 3 Inductor Power Losses

| Parameter | Value [W] |
|---|---|
| Core loss | 0.455 |
| Copper/Wire loss | 1.994 |
| **Total Losses** | **2.449** |

With the core losses being the least, EE core is taken chosen for inductor design. The winding factor is approximately 40 percent and all the measurements for losses are based on the above specified parameters.

## V. RESULTS

The overall power losses of the converter are calculated and it was observed that a total power conversion efficiency of 96.46% was achieved. The power loss of each component of the converter is presented in table 4 below:

Table 4 Total Converter Losses

| Component | Loss [W] |
|---|---|
| MOSFETs | 7.698 |
| Diodes | 2.8 |
| Transformer | 1.0412 |
| Inductor | 2.44 |
| **Total Converter Losses** | **13.979** |

## VI. CONCLUSION

An isolated boost high-power DC-DC converter with a novel design of high frequency magnetic components is proposed in this paper. A brief summary of in-depth literature review has also been done. The theoretical results were verified using Simulink and the simulation result confirms the validity of the theoretical results and proposed converter's design. Two capacitors are used at the output side of the converter which steps up the secondary side voltage level by two, the lesser number of secondary turns are thus required. It is proved that interleaving of primary and secondary winding of the high frequency transformer extensively, yields optimal performance as very low leakage inductance and ac resistance factor is recorded. The lowest leakage inductance of transformer is experimentally measured as 0.477 uH which resonates with the theoretical and simulation results.

## VII. ACKNOWLEDGEMENT

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