Design of high frequency transformers in different shape of core using matlab program

Reem Falah Hassan, Kassim Rasheed Hameed
Electrical Engineering Department, Collage of Engineering, Mustansiriyah University, Iraq

Article Info	ABSTRACT
	This paper deals with the design, simulation and implementation of the high-frequency transformer for a push-pull converter. It also includes transformer design and simulation for two switches, two outputs forward converter. Design these transformers by building a program, this program is designed in MATLAB software using a graphical user interface (GUI). The program is aimed to reduce the efforts and reduce the time compare with the manual design which takes time and effort. This paper provided the shape and geometry of the core that can influence the efficiency of the converter by designing these transformers in two types of core. The design results were validated by simulation in power simulation software (PSIM), and compare the results of simulation and design.

Corresponding Author:

Reem Falah Hassan,
Electrical Engineering Department,
Mustansiriyah University,
Palestine Street, Baghdad, Iraq.
Email: reemfalah1994@gmail.com

1. INTRODUCTION

The magnetic components such as transformer and inductor are necessary parts of power electronic converter. They provide energy transfer and energy storage. Transformers and inductors are indispensable elements of modern power electronic converters. Often, they are the bulkiest and the costliest components in a power converter. In addition, they can incur considerable losses, which may be similar or even greater than the semiconductor device switching and conduction losses. Therefore, the design related to the magnetic component is considered to be very important for avoiding general design regarding power electronic converters being less efficient or impracticable. The continuing evolution of higher power switching devices and higher frequency magnetic materials allow for continually increasing the switching frequency of the converters. However, this continuing increase in switching frequency makes the design of magnetic components a more and more challenging task, since the increasing levels of higher frequency losses need to be taken into account and minimized [1]. Also, the size of a magnetic component can be reduced by operating at high frequency. High frequency magnetic components such as high frequency transformers have the same function as low frequency transformers but high frequency transformers are smaller, lighter, and cheaper than low frequency transformers, making them ideal in applications where minimal space, weight, and cost are at a premium. However, they are not commercially available in a wide range of properties but are typically designed and constructed for a particular application. Although magnetic ferrite and powder cores have improved in the past, transformers and inductors are major obstacles to high frequency operation. A parasitic element such as leakage inductance, winding capacitance, skin and proximate effects, make it difficult to design high frequency magnetic components [2-3]. The main issue for high frequency magnetic components design is that the winding loss increases considerably due to skin and a proximity effect. Also, the magnetic flux density has to be reduced in order to keep the core loss at acceptable levels [4].

This paper focuses on building the design program and there are three main methods in computer-aided design, namely the analysis method, the synthesis method, and the hybrid method. Where in the analysis method the use of the computer is made only for analysis and leaving all the decision making to the designer. In the synthesis method, the logical decisions are taken by the computers instead of the designer. The required performance of the high frequency transformer and inductor is fed as the input to the computer [5]. In this paper, the hybrid method was followed in the program, which combines the methods of analysis and synthesis. The program helps the designer to obtain the optimal design through design in more than one core in a few times.

2. MAGNETIC MATERIAl USED IN POWER ElECTRONIC

The evolution of soft magnetic materials for industrial aim began with laminated iron and continues with carbonyl iron, powdered, ferrite, amorphous, and nanocrystalline materials. There are two major groups of materials in power electronics, these materials used for the magnetic core for inductors and transformers.

− Alloys of iron and they include some quantities of other elements like nickel (Ni), silicon (Si), cobalt (Co) and chrome (Cr) are the first group of materials, these materials indicate to ferromagnetic materials. The values to reach the saturation of these materials begin to 1.4Tesla and some of the materials the saturation value is near to 1.9Tesla. These alloys have electrical resistivity a little higher than good conductors like aluminum or copper.

− Ferrites (ferrimagnetic materials), the most commonly used materials and available in the market. The characteristics of ferrite materials are high resistivity, at the least 10^6 greater than the first group [6].

3. MAGNETIC CORE AND ITS POWER HANDLING ABILITY

Over the years, numeric codes are given by manufacturers to cores. These codes demonstrate the ability to deal with energy. This method specified the number of each core is called area product. The area product is the product window area and core cross-section area. These numbers are used by primary suppliers, to sum up, the electrical properties and dimensional in their catalogs.

$$A_p = W_a \ A_c \tag{1}$$

There is another equation that relates to the power handling capability of the core called core geometry K_g. The core geometry is related to copper losses or regulation. Each core has its own K_g.

$$K_g = \frac{W_a \ (A_c)^2 \ K_u}{MLT} \tag{2}$$

This equation looks similar to the area product equation but an exception of two additional terms window utilization (K_u), and mean length turn (MLT) is the average turn of copper wire. These factors have to do with regulation. The relationship between power handling capability and regulation in the following equation [7-8].

$$K_g = \frac{P_t}{2 \ K_e \ \alpha} \tag{3}$$

$$K_e = 0.145 \ (K_f)^2 \ (f_s)^2 \ (B_m)^2 \ (10)^{-4} \tag{4}$$

P_t : The apparent power.
K_e: The constant is set by electric and magnetic operating conditions.
K_f: Wafeform coefficient, defined as the ratio of RMS voltage to average voltage. For square wave equals 4.
B_m: Operating flux density.

4. WIRE DETERMINATION

The major challenge in the case of designing high frequency transformer is minimizing problems like skin and proximity effects. The skin effect is the phenomenon where AC current tends to flow only in outer skin regarding the conductor and not through the whole cross-sectional area. The impact results from eddy currents in a conductor acting to cancel out the current flow in the middle and to reinforce the current flow on

the outside of a conductor. The skin effect can be significant in two ways; firstly for high current inductors, increasing gauge of wire to reduce the copper losses may not be as effective as ohm's law would lead you to believe because the skin effect prevents the whole cross-section of the wire from carrying the current, and secondly, high frequency signals and switching spikes are blocked by the skin effect from traveling far along any conductor [9-10].

Losses because of skin effect could be reduced via using Litz wire. Litz wire can be created through "weaving" many smaller conductors for the purpose of making equivalent large wire gauge. The size regarding each strand is decided via the proposed operating frequency, as the small strands being utilized for higher frequencies, the weaving enables all the strands to take a space near outside (or skin) of Litz wire at certain point in wire's length, permitting the current to flow more evenly throughout all the strands. Select the proper wire gauge according to the following equations [7-11].

$$\varepsilon = \sqrt{\frac{\rho}{\pi f_s \, \mu_r \, \mu_o}} \tag{5}$$

where:

ρ: Resistivity of the materials (for copper $\rho = 1.72 \times 10^{-4} \Omega \, . \, cm$).
μ_r: Relative magnetic permeability of medium (for copper $\mu_r = 1$).
μ_o: The permeability of free space which equals $4\pi \times 10^{-7}$

$$Wire\ diamter = 2\varepsilon \tag{6}$$

$$A_w = \frac{\pi (wire\ diamter)^2}{2} \tag{7}$$

$$A_{wp} = \frac{I_{p(rms)}}{J} \tag{8}$$

$$S_{np} = \frac{A_{wp}}{\#\ wire\ gauge(bare\ area)} \tag{9}$$

Where ε , A_w, A_{wp}, S_{np} ,$_J$ are skin depth ,the wire cross sectional area needed due to thef_s, the wire cross sectional area needed due to the$I_{p(rms)}$, number of primary winding strands and current density.

The relationship between the skin depth and frequency for copper wire is shown in Figure 1. Noted that with an increased frequency the skin depth decreased according to (5).
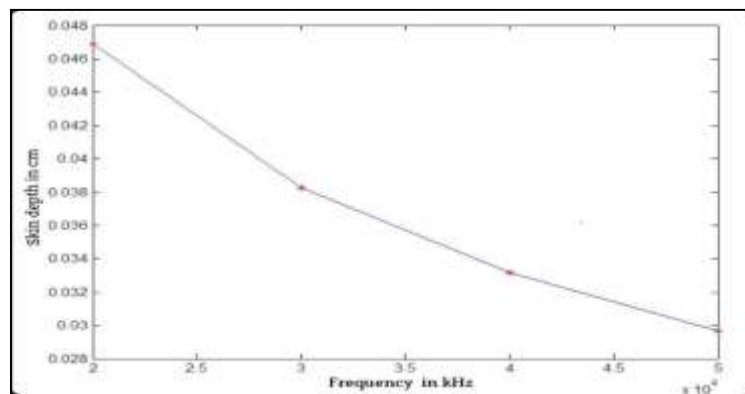

Figure 1. Curve between the skin depth and frequency

5.   WINDING LOSSES AND REGULATION

Copper losses are involved in total transformer losses. Winding coil losses resulting from the proximity effect, skin effect, effects from fringing flux intersecting windings near the core gap, edge effects, and extraneous conductor effects may be important and must be considered. For simplicity, any additional losses will be ignored and take into account copper losses (I^2R). From the following equations, the resistance of each winding can be calculated [12-13].

$$R_p = MLT\ (N_p)\left(\frac{\mu\Omega}{cm}\right).\,10^{-6} \tag{10}$$

$$R_s = MLT\ (N_s)\left(\frac{\mu\Omega}{cm}\right).\,10^{-6} \tag{11}$$

The conductor resistivity at maximum operating temperature is shown in the following equations.

$$R_p = MLT\ (N_p)\left(\frac{\mu\Omega}{cm}\right)10^{-6}\,[1 + \alpha 20(T_{max} - 20\ ^oC)] \tag{12}$$

$$R_s = MLT\ (N_s)\left(\frac{\mu\Omega}{cm}\right)10^{-6}\,[1 + \alpha 20(T_{max} - 20\ ^oC)] \tag{13}$$

The regulation is calculated from:

$$\alpha = \frac{P_{cu}}{P_o}100\% \tag{14}$$

6. CORE LOSSES

The reason for the temperature rises of the transformer is the core losses. Eddy current, hysteresis loss and residual loss all of these have to do with total losses. Hysteresis losses are usually dominant, at low frequencies and high flux densities. Eddy current losses usually dominate, at high frequencies. Eddy current losses arise from a change induction that generates electromotive forces, which cause a circular current within a magnetic material. Core losses are given in watt per kilogram, this is in general and for specific material.

$$P_{fe} = \rho_c\,V_c\,K_c(f_s)^m(B_m)^n \tag{15}$$

Where ρ_c is the mass density of the core material, V_c is the volume of core, and K_c, m, n are constants which can be set up from the manufacture's information. However, the manufacturer's information is ordinarily estimated for sinusoidal excitation. Moreover, the test sample size may diverge from the designed component. Losses are depending on the size of the core [13].

7. HEAT DISSIPATION

Through the transformer surface, the combined losses in winding losses and core losses should be dissipated. The predominant heat transfer mechanism is via convection of the transformer surface. The equation of newton's convection joins heat flow to temperature rise T_r, surface area A_t and the coefficient of heat transfer.

$$P_{total} = hA_t\,T_r \tag{16}$$

P_{total}: The copper losses and core losses.
h: Heat transfer coefficient.
For normal heat convection, h is a function of the height, A, of the transformer.

$$h = 1.42\left(\frac{T_s - T_a}{A}\right)^{0.25} \tag{17}$$

The difference between the surface temperature of the transformer or inductor T_s and the ambient temperature T_a is the temperature rise. The prediction of temperature rises of transformer by calculating winding losses and core losses. A blend of radiation and convection dissipates this heat from the uncovered surfaces of the transformer. Thus, heat dispersal is dependent upon the total uncovered surface of the core and the total uncovered surface of the windings. One approach to predict temperature rise is to sum both winding losses and core losses, where the thermal energy is presumed to be dissipated homogeneously throughout the surface area of winding and the core at all ambient temperatures. At the expected operating temperature through suitable core material selection, core losses of a transformer may be minimized [13-14].

8.   DESIGN PROGRAMMING

This program is not the only one; it is continuity and improvement for other programs built in other programming languages. Where the MATLAB software is used to build this program. The two main considerations required for building this program are: firstly, needed an easy to use GUI, that would display a large amount of data and secondly, the ability to access various manufactures core datasheet and wire datasheet. This program contains many controls or objects in design interfaces including (edit text for input and output calculations, pushbutton to select applications and to calculations, the pop-up menu that allows the user to choose from several options, table, panel, and static text to describing each edit text).

8.1.   Possibility and tasks of the design program

The design of the transformers and inductors with the help of the program is similar to the traditional design method in terms of the laws and relationships that govern the design, but the program provided us with an easy and fast way to complete complex and repetitive calculations, especially when the process requires access to a good design. The designer needs to complete many designs by modifying the value of the variables and repeat the calculations for analysis and impact study, which is difficult to verify during manual calculations that need a long time to complete the calculations. The procedures design of transformer and inductor by using the MATLAB software have the following advantages.
   a.   It has the capability to store large amount of design data.
   b.   A large number of loops can be incorporated in the design program.
   c.   Arithmetic operations during design can be performed at appreciably high speeds, which results in reducing the time.
   d.   High accurate and reliable designs are obtained.
   e.   It is possible to optimize the design, with a reduction in overall cost and improvement in performance.
   The tasks of the program are that multiple inputs increase the likelihood of an error, so the program is designed in a way that protects users from making a mistake when entering data as follows:
   a.   When a user skips a point of inserting data without any entry, the results will be zero it means the software doesn't do any calculations.
   b.   When inserting an unexpected value, a warning message will appear.

9.   STEPS OF WORK THE PROGRAM

There are steps ranging in the program from entering specifications to calculating loss, regulation, efficiency, temperature rise and window utilization. An overview of each of these steps is shown as follows.

9.1.   Main menu

In the main menu as shown in Figure 2, the user chooses one of the applications. This program includes fourteen applications, in this paper, the push-pull with one output and forward converter with two switches, two outputs were taken for design and simulation.

Figure 2. Main menu

9.2.   Specifications

After selecting the application from the main menu, the specification interface will appear as shown in Figure 3 then required from a user to enter the following specifications:

- Output current
- Input voltage
- Frequency
- Duty cycle
- Temperature rise
- Ambient temperature
- Desired efficiency

After entering the specifications, the user can choose from same interface the material specification which is suitable with frequency and application.
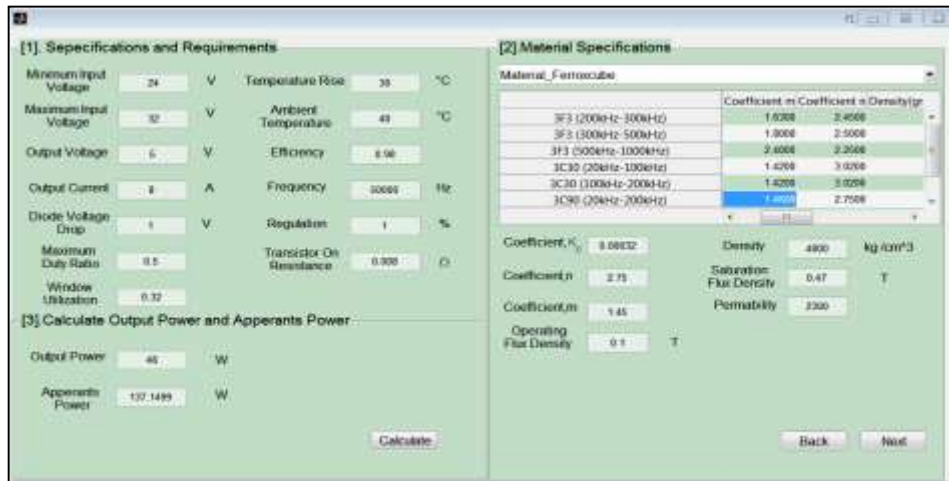

Figure 3. Interface for specifications and calculate output power and apperants power

9.3. Core data determination

The second interface is illustrated in Figure 4. The left side of this interface with the title "Calculate Electrical Condition and Core Geometry" used to calculate core geometry, K_g. After calculating K_g then the next step in design process is to select suitable core with the core geometry close to that calculated. At first, the user selects the shape of core from the pop-up menu section with the title "Choose the Core Shape", this pop-up menu contains core shapes such (EFD, EE, RM and PQ…etc.). The right side with the title "Core Information" contains the following information (weight of copper(W_{tcu}), weight of core(W_{fe}), mean length turn (MLT), mean path length (MPL), surface area(A_t), cross section area(A_c), window area(W_a), area product(A_p), core geometry(K_g) inductance factors(A_L) and dimension of core). This information is displayed by the program after selecting the shape of the core.
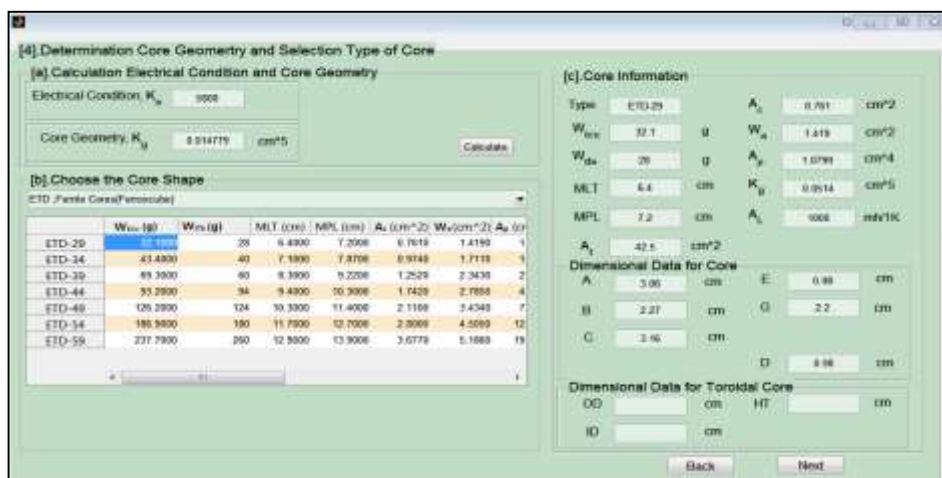

Figure 4. Interface for core data

9.4. Determination skin depth and wire gauge

The third interface includes the determination skin depth and wire gauge, also includes calculations (current density, wire area, number of turns and wire strands). In this interface, as shown in Figure 5, the program has the ability to compare the value of the calculated wire area with the wire area in the table to select value equal to or greater than 10% of calculated value according to the principle of the hybrid design method. All these parameters are calculated and wire is selected through the click on the calculate button.
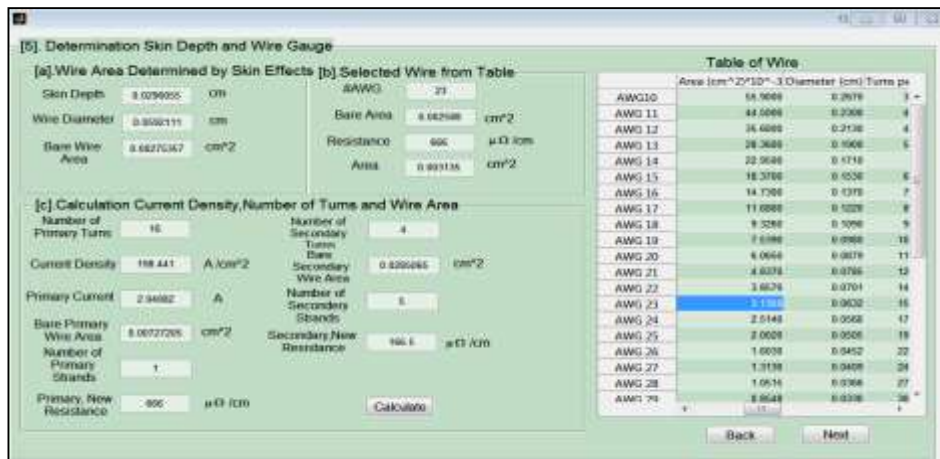

Figure 5. Interface for determination skin depth and wire gauge

9.5. Losses, efficiency and regulation

The fourth interface includes performance calculations which are described as follows:
a. Calculation of resistance of primary and secondary windings.
b. Calculation of copper losses and core losses.
c. Calculation of regulation, which depends on the value of copper losses.
d. Calculation of watt per kilogram which is dependent on (frequency, maximum flux density and core loss coefficients)
e. Calculate core losses.
f. Calculation of watt per unit area, which is dependent on total losses and surface area of the core, from this the temperature rise and heat transfer can be calculated which depends on core height and temperature rise.

These parameters are calculated by click on the calculate button as shown in Figure 6.
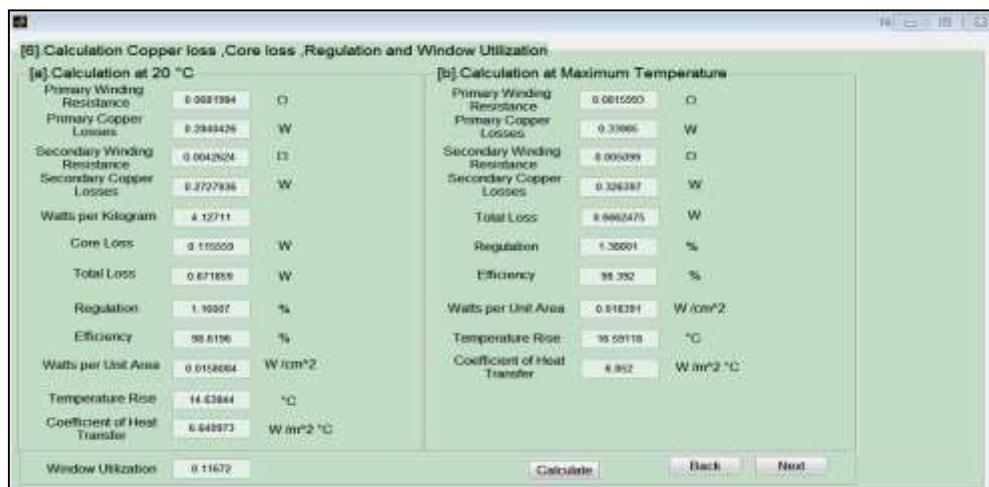

Figure 6. Interface for calculate losses, efficiency and regulation

10. CIRCUIT OF SWITCH-MODE POWER SUPPLY

The circuit of switch mode power supply can be divided into two parts. Where parts require isolation between the output and the input circuit, and other parts don't require isolation. An isolated topology utilizes a transformer to give DC isolation between the output and the input voltage. The non-isolation circuit more often utilizes an inductor. The topologies of DC-DC converter are designed to meet the specific demands of DC loads. There are several types of DC to DC converter that can be function as switching mode regulator [15-16]. The high frequency transformer used in DC-DC converters is described as follows:

10.1. Push-pull converter

Push-pull converter consists of two forward converters, magnetizing core in this type of converter be in both directions, that's mean in B-H loop both the positive (quardrant1) and negative (quardrant3) are used periodically. The push-pull transformer is much smaller than a forward converter transformer, in push-pull utilizes the core of transformer much more efficiently than forward converter. The scheme of push-pull converter shown in Figure7. When switch 1 is "ON" and switch2 is "OFF" diode D1 becomes forward biased, and diode D2 becomes reverse biased. The diode D1 becomes reverse biased and diode D2 becomes forward biased when switch 2 is "ON" and switch 1 is "OFF". Two diodes become forward biased when both switches are "OFF"[17-18].
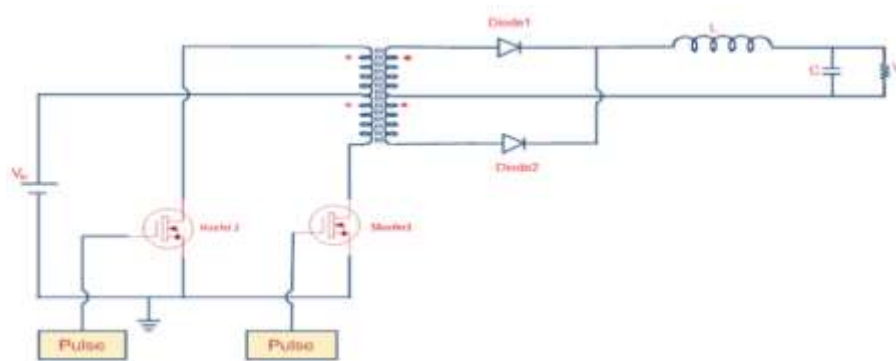

Figure 7. Basic circuit of push-pull converter

In this circuit, the current flowing in both the primary and secondary windings is interrupted because of using center tap circuit. The effective RMS current value changes if the current in the rectifier transformer becomes interrupted. Thus, the size of the transformer is not only specified by the load demand but furthermore, by the application because of copper losses produce due to the current waveform. The RMS current is the peak current time square root duty ratio [19]. The primary voltage, average input current and peak current are shown in the following equations.

$$V_p = V_{in}.2D_{max} - I_{in}R_{Ds} \tag{18}$$

$$I_{in} = \frac{P_o}{V_{in}\eta} \tag{19}$$

$$I_{p(peak)} = \frac{I_{in}}{2D_{max}} \tag{20}$$

According to the number of turns of the center-tapped transformer, the number of turns in the primary side are same, these windings are wound in the same direction. As well as the secondary side. The formulas for calculate number of turns for primary and secondary are given by (21) and (22) [7-19].

$$N_p = \frac{V_p \, D_{max} \cdot 10^4}{f_S A_c B_m} \tag{21}$$

$$N_s = \frac{N_p(V_o+V_d)}{V_p D_{max}} \left(1 + \frac{\alpha}{100}\right) \tag{22}$$

10.1.1. Transformer Design Results and Simulation

Design this transformer with the following specifications as shown in Table 1. With the increase in frequency, the magnetic material produces energy losses. In this example to reduce these losses, a material with low conductivity is used, like ferrite. For the same specification used two shapes of the core with the same material. The shapes of the core that used are ETD-29 and EPC-25, to show that the geometry of the core influences the efficiency of the converter. The results of design by using these cores are shown in Table 2.

Table 1. Transformer specifications for push-pull converter

Parameter	Value
Minimum input voltage	24V
Maximum input voltage	32V
Output voltage	5V
Output current	8A
Diode voltage drop	1V
Maximum duty ratio	0.5
Frequency	50 kHz
Regulation	1%

Table 2. Variables parameter of push-pull transformer

Parameters	Core shape ETD-29	Core shape EPC-25
Core geomtriy coefficient	0.0514 cm^5	0.014416 cm^5
Number of primary turns	16	26
Number of secondary turns	4	7
Wire gauge of strand	23#	23#
Primary bare wire area	0.0072720 cm^2	0.0026152 cm^2
Secondary bare wire area	0.0285065 cm^2	0.0102519 cm^2
Number of primary strands	1	1
Number of secondary strands	4	4
Copper losses	0.556835 W	0.73356 W
Regulation	1.16007 %	1.52825 %
Core losses	0.11559 W	0.053652 W
Total losses	0.671859 W	0.787212 W
EffIciency	98.619 %	98.38 %
Temperature rise	14.638°C	30.34 ℃
Window utlization	0.11672	0.3339

As can be seen in the Table 2, the higher number of turns by using EPC-25 core compared to ETD-29 core resulted in high copper losses. The core losses of design in the ETD-29 core are high because of the area product of the core. EPC-25 core has a surface area less than a surface area of ETD-29 core, therefore the temperature rises of the transformer in case of using EPC-25 core is high than the temperature rises of the transformer in case of using ETD-29 core. The best design was obtained using ETD-29 core, although adjustments were done on the number of strands of wire to make the window of core accommodate the amount of copper.

The transformer of the push-pull converter was simulated by using ETD-29 core. Figure 8 (a) shows the circuit diagram for simulation and Figure 8 (b) shows the simulation results of primary voltage, secondary voltage and no-load current. Table 3 shows the comparisons between design values and simulation values, Simulation values are obtained after the transformer is loaded at (R=1.5Ω).

Table 3. Comparisons between design values and simulation values

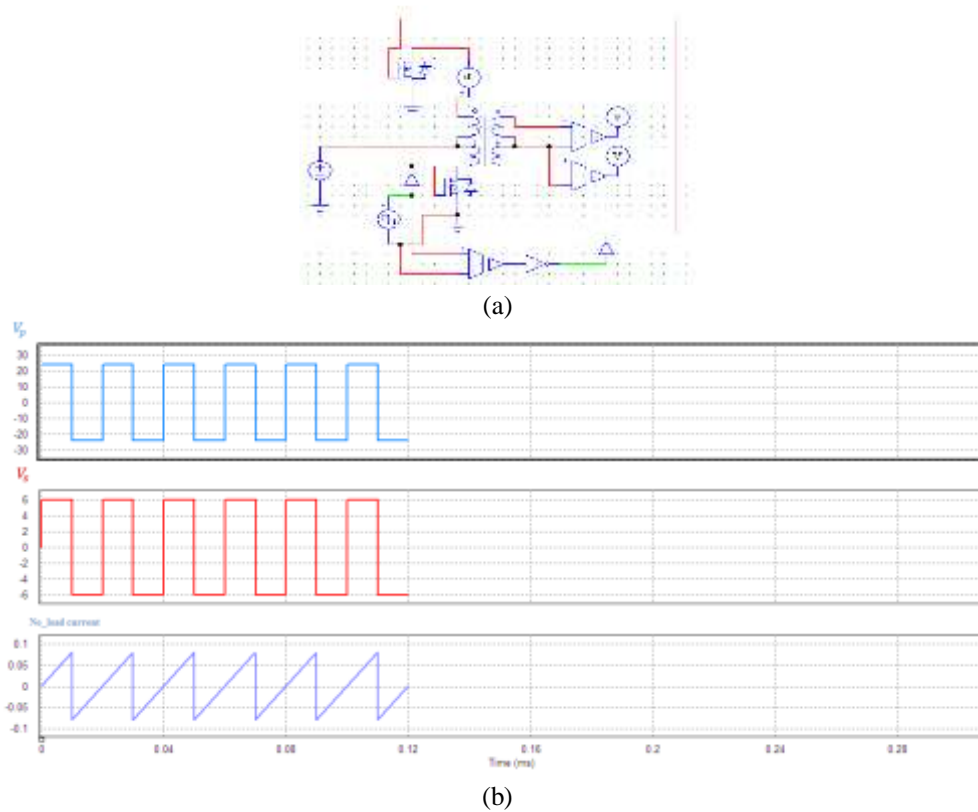|	Design values	Simulation values	Error
Output power	48 W	47.89 W	0.22916%
Copper losses	0.556835 W	0.561175 W	-0.779405%
Regulation	1.16007 %	1.1755 %	-1.33009 %
Efficiency	98.6033 %	98.123%	0.4871033%

(a)

(b)

Figure 8. (a) Push-pull circuit diagram, (b) Simulation results, primary voltage, secondary voltage and no-load current

10.1.2. Practical implementation and test result

For implemented transformer, ETD-29 core was used, and 23AWG was used for primary winding with number of strands 1, and 23AWG for secondary winding with number of strands 4. Push-pull converter was implemented to test this transformer as shown in Figure 9 (a). Where Hex Inverter Buffer IC 4049 was used to get 100 kHz from it, and D-type flip-flop (CD4013MS) was used to halves frequency to 50 kHz. Also, the MC34151 MOSFET drive was used. MC34151 MOSFET drivers are dual inverting high-speed drivers specifically designed for applications that require low current digital circuitry to drive large capacity loads. This device features low input current making it CMOS (complementary metal-oxide-semiconductor) and LSTTL (Low Power Schottky Transistor-Transistor Logic) logic compatible, input hysteresis for fast output switching that is independent of input transition time, and two high current pins outputs ideally suited for driving power MOSFET.

The appearance of a spike in practical results was due to leakage inductance in the winding. In addition, the transformer winding was done manually. The practical results are shown in Figure 9 (b), Figure 9 (c), and Figure 9 (d).
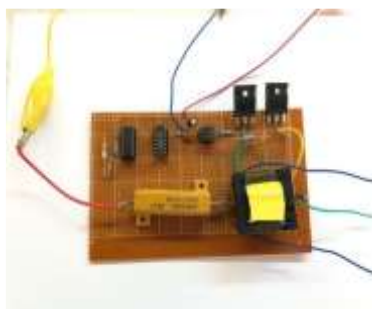
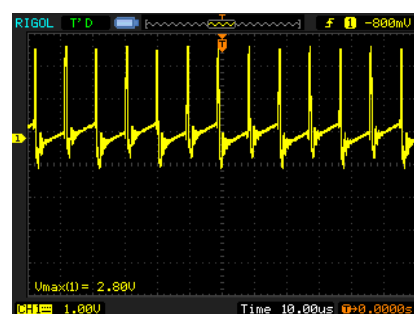

Figure 9(a). Practical circuit
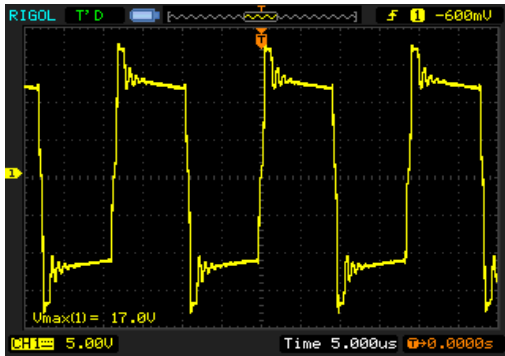

Figure 9(b). Primary voltage
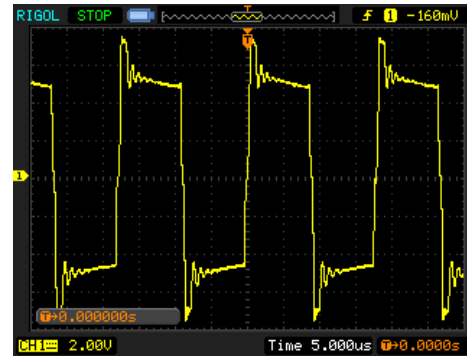
Figure 9(c). Secondary voltage

Figure 9(d). No-load current

10.2. Two switches forward converter

To get an isolated power power supply, two switches forward converter is one of the most suitable topologies [20]. Transformer in this converter has two winding rather than three winding compared with single ended forward converter. The scheme of this converter is shown in Figure 10.
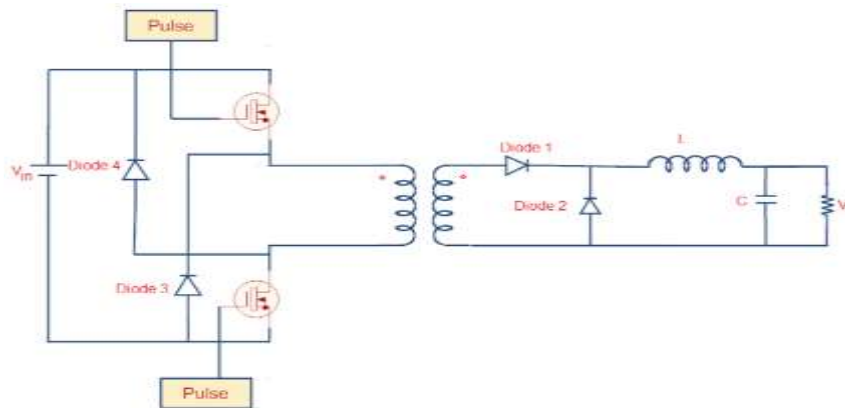

Figure 10. Circuit diagram of two switches forward converter

The input voltage connects to the primary winding when two switches are turned ON, with this case both primary and secondary winding starts conducting simultaneously. In case two switches are OFF, the magnetizing current flows through the diode in the primary side and back into the source. This type of converter offers the lower voltage across switches and the best efficiency. In this converter, the leakage inductance back to the input source without the needed snubber circuit [21-22]. Usually, a snubber circuit is used to reducing the voltage spike of the main MOSFET. There are many types of the snubber circuits are used to protect the main MOSFET from this problem such as RC snubber circuit, RCD snubber circuit or active clamped circuit [23]. As well as the leakage inductance can be reduced in some cases. One of these, on a long bobbin, the primary winding must be wound, with the secondary wound and by using minimum insulation to be as close as possible. In the second case, leakage inductance is directly proportional to the number of layers. Therefore, requires reducing the space between the layers. This needs the reduction of a number of winding layers. In the third case, primary winding divided into parts and then to sandwich winding between them. If there is an air gap, distribution of air gap along with the core structure is required to reduce the fringing flux [24-25].

10.2.1. Transformer design results and simulation

Design this transformer of two switches, two outputs forward converter with the following specifications as shown in Table 4.

Table 4. Transformer specifications for two switches forward converter

Parameter	Value
Minimum input voltage	118V
Output voltage, V_{o1}	5V
Output current, I_{o1}	2A
Output voltage, V_{o2}	12V
Output current, I_{o2}	2 A
Diode voltage drop	1V
Maximum duty ratio	0.45
Frequency	50 kHz
Regulation	1%
Efficiency	80%
Temperature rise	30℃

In this type, the possibility of a design transformer with two outputs each output has different watts. Table 5 shows a summary of the design results by using two cores.

Table 5. Parameters of transformer for two switches forward converter in two shapes of core

Parameters	Core shape ETD-34	Core shape PQ26/25
Core geomtriy coefficient	0.0914	0.0826
Number of primary turns	109	90
Secondary1, number pf turns	12	10
Secondary2, number pf turns	27	22
Wire gauge of strand	23#	23#
Primary bare wire area	0.00251073	0.00150207
Secondary1, bare wire area	0.00561347	0.00335832
Secondary2, bare wire area	0.00561347	0.00335832
Number of primary strands	1	1
Secondary1, number of strands	2	1
Secondary2, number of strands	2	1
Copper losses	0.35157 W	0.341689 W
Regulation	0.925185 %	0.899181 %
Core losses	0.0220234 W	0.019821 W
Total losses	0.373594W	0.36151 W
EffIciency	99.0264%	99.0576%
Temperature rise	7.46561 ℃	10.922℃
Window utlization	0.28285	0.373652

The similarity of the properties of the material 3C90and PC44 and the very slight difference in the value of the core geometry of two core will not make a significant difference in the results, as shown in Table 5. The efficiency and regulation by using ETD-34core and PQ26/25 core are good, but the window utilization in case of using PQ26/25 core is not acceptable due to an increase in the space occupied by windings to the space of the core window.

A simulation of the forward converter was performed to validate the results. The transformer was simulated by ETD-34 core. The circuit of the forward converter in PSIM software is shown in Figure11 (a). The simulation results of the primary voltage and current are shown in Figure11 (b). Figure11 (c) shows the secondary voltage and current, and Figure11 (d) shows the output voltage and current of the transformer. Table 6 shows the comparison between design values and simulation values.

Table 6. Comparison between design values and simulation values for two switches forward converter

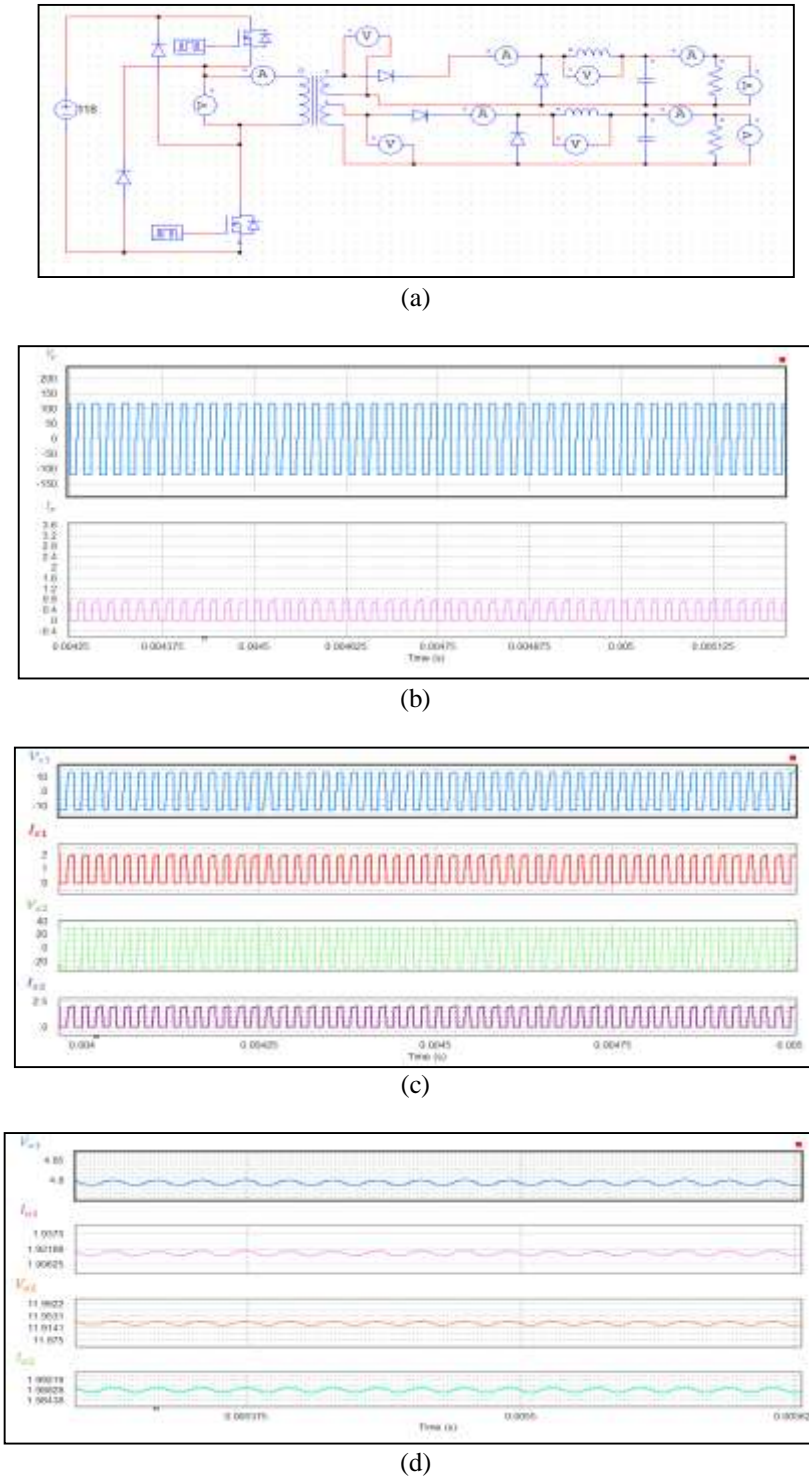|	Design values	Simulation values	Error
Copper losses	0.35157 W	0.345355 W	1.767784 %
Regulation	0.925185 %	0.9263789 %	-0.129044 %
Efficiency	99.0264%	98.6522 %	0.377879 %

(a)

(b)

(c)

(d)

Figure 11. (a) Two switches, two outputs forward converter, (b) Simulation results, primary y voltage and current, (c) Secondary voltage and current, (d) Output voltage and current

11. CONCLUSION

This paper considerably addressed the step by step design strategy for high frequency transformers and inductors by using a program, this program helped achieve design results fastly. From the design results of the push-pull transformer, the best design obtained by using ETD-29. The design results of the transformer for two switches forward converter show that the best efficiency and regulation were achieved by design transformer with ETD core.

ACKNOWLEDGEMENTS

REFERENCES

[1]   Samira Jonhorban, "Design of Inductors for Power Converters Operating at Intermediate Switching Frequencies," *Ph.D. Thesis, RMIT University, Australia,* 2016.
[2]   Wei Shen, "Design of High-Density Transformers for High-Frequency High-Power Converter," Ph.D. Thesis, Faculty of the Virginia Polytechnic Institute and State University, Virginia, 2006.
[3]   F. K. Wong, J. W. Lu, H. B. Harrison, and S. Dimitrijev, "Applications of High Frequency Magnetic Components for Switching Resonant Mode Power Supply,*"Proceedings of the IEEE International Conference on Industrual Technology*,pp. 406–410, 1996.
[4]   A.A.R.Aldana, O.E.B.Beltran, and R.Trjillo," Magnetic Design of a Push-Pull Converter," *IEEE Workshop on Power Electronics and Power Quality Applications (PEPAA)*, 2015.
[5]   Dr.V.N Mittle and Arvind Mittal, "Design of Electrical Machines," Book First Edition, *N.C,* 1971.
[6]   Alex Vanden and Vencislav Cekov Valchev, "Inductors and Transformers for Power Electronics," *Taylor and Francis Group,* London, 2005.
[7]   Colonel Wm.T.Mclyman, "Transformer and Inductor Design Handbook," Four Edition, *Taylor and Francis Group,*United State of America,2011.
[8]   Colonel Wm.T.Mclyman,"Magnetic Core Selection for Transformer and Inductors," Second Edition, *Marcel Dekker, Inc.*, New York, 1997.
[9]   Steve Roberts, "DC/DC Book of Knowledge Practical Tips for the User," Third Edition, *RECOM Engineering GmbH and Co KG,* Austria,2016.
[10] I. Manke, N. Kardjilov, M. Strobl, A. Hilger, and J. Banhart, "Investigation of the Skin Effect in the Bulk of Electrical Conductors with Spin-Polarized Neutron Radiography,"*Journal of Applied Physics* , vol. 104, no. 7, 2008.
[11] Charles R. Sullivan and Richard Y. Zhang, "Simplified Design Method for Litz Wire," *Conference Proceedings - IEEE Applied Power Electronics Conference and Exposition - APEC 2667–74,*2014.
[12] N.Ekekwe, J.E.Ndubah, K.White and O.Ben, "Practical Process in High Frequency Distribution Transformer Design," *IEEE*, pp. 121-128, 2003.
[13] W. G. Hurley, W. H. Wölfle, and J. G. Breslin, "Optimized Transformer Design: Inclusive of High-Frequency effects," *IEEE Transactions on Power Electron*, vol. 13, no. 4, pp. 651–659, 1998.
[14] George G.Orenchak, "Estimating Temperature Rise of Transformers," *Power Electronics Technology*,2014.
[15] Nor Hanisah Baharuding,Tunku Muhammad, Nizar Tunku Mansur,Fairuz Abdul Hamid,Rosnazri Ali and Muhammad Irwanto Misran, "Topologies of DC-DC Converter in Solar PV Applications," *International Journal of Electrical Engineering and Computer Sciences*, vol. 8, no. 2, pp. 368-374, 2017.
[16] Rajesh Thumma,Veera Venkata Subrahmanya Kumar Bhajana and Pramod Kumar Aylapogu, "Design and Simulation of a New ZVT Bi-directional DC-DC Converter for Electric Vehicles," *International Journal of Electrical Engineering and Computer Sciences*, vol. 7, no. 1, pp. 75-83, 2017.
[17] Issa Batarseh," Power Electronics Circuit, "First Edition, *John Wiley and Sons, Inc.*, 2003.
[18] J. G. Breslin and W. G. Hurley, "Computer Aided High Frequency Transformer Design Using An Optimized Methodology," *Conference of IEEE on Computer in power electronics* , pp. 277–280, 2002.
[19] Marian K.Kazimierczuck, "Pulse-Width Modulated DC-DC Power Converters ," First Edition, *John Wiley and Sons*, Dayton, 2008.
[20] Jianping Xu, Xiaohong Cao and Qianchao Luo,"An Improved Two-Transistor Forward Converter,"*IEEE 1999 International Conference on Power Electronics and Drive Systems*,PEDS'99,July,Hong Kong,1999.
[21] Perumal S,K.H.Sivanand and Rajashekar J.S, "Dual Switch Forward& Flyback Converter," *International Journal of Innovative Science,Engineering& Techology*, vol. 2, no. 4 Apr,2015.
[22] W. G. Hurley, W. H. Wölfle,"Transformers and Inductors for Power Electronics: Theory, Design and Application," First Edition, *John Wiley and Sons*, United Kingdom, 2013.
[23] Salam J.Yaqoob and Abdel A.obed, "Photovoltaic Flyback Micro-Inverter with Power Decoupling Technigue," *International Journal of Electrical Engineering and Computer Sciences*, vol. 15, no. 1, pp. 9-19,2019.
[24] Bunyamin Tamyurek and Bilgehan Kirimer, "An Interleaved High-Power Flyback Inverter for Photovoltaic Applications," *IEEE Transactions on Power Electronics*, vol. 30, no. 6, pp. 3228-324, 2015.
[25] Jun Liu, Licheng Sheng, Jinjiang Shi, Zhong Chao Zhang and Xiangning He," Design of High Voltage , High Power and High Frequency Transformer in LCC Resonant Converter,"*2009 Twenty-Fourth Annual IEEE Applied Power Electronics Conference and Exposition,* 2009.