

Efficiency Improvement of the Flyback Converter Based on High Frequency Transformer Winding Rearrangement

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Abstract- In this paper, a novel method for loss reduction and efficiency optimization of the high frequency flyback transformers is proposed based on rearrangement of the windings. According to detailed analysis of the high frequency flyback transformer using FEM technique, a novel and simple approach for its design improvement and loss reduction is introduced. It is shown that leakage flux scattering in core air-gap is one of the main reasons for hot-spot point generation in the windings. So, this problem and its possible solutions are analyzed in more detail. Moreover, FEM analysis is used for investigation of the developed method and rearrangement of the winding structure. In fact, some winding structures for efficiency improvement of the flyback transformer is presented and analyzed. Finally, in order to verify accuracy and effectiveness of the developed approach, simulation and experimental results are presented. Experimental results show 3.3% improvement in total efficiency of the converter and 41.78% loss reduction in the flyback transformer.

Keyword: High frequency transformer design, Winding rearrangement, FEM analysis, Transformer loss and flyback converter.

1. INTRODUCTION

DC-DC converters are widely used in Switch Mode Power Supplies (SMPS), battery chargers and renewable energy systems [1]. Considering recent advancements in development of the semiconductor switches, production of very fast microprocessors and invention of efficient controllers, application of SMPS has increased compared to conventional linear regulators. The main advantages of SMPS are low weight, high efficiency, good regulation, multiple isolated output generation and etc. [2-6]. In standard DC-DC converters, there is no electrical isolation between input and output ports. Also in forward converter, although output load is isolated electrically from the input power source, but multiple isolated feedback signals maybe required to regulate different outputs of the converter separately [6]. In low power application, electronic engineers are interested in flyback converter which is modified topology of the

standard buck/boost DC-DC chopper. In this converter, inductor of the buck/boost converter is replaced with a special high-frequency transformer. The core of the transformer is charged when the power switch of the converter is turned ON and then, stored energy is transferred to the output during OFF interval of the switching signal. In fact, magnetizing inductor of the transformer plays a vital role for appropriate performance of the chopper and this should be considered carefully during transformer design. Hence, operation and design of the flyback transformer is completely different compared with standard transformers which are used in high voltage transmission and distribution networks.

In order to harvest electric energy more efficiently in these application, it is clear that overall power loss of the converter should be minimized. For example, in Ref. [7], in order to limit voltage overshoot of the power switch and improve its efficiency, an adaptive snubber circuit is proposed. Considering optimum design of the converter, it is possible to improve power efficiency of the flyback DC-DC converter by using the mentioned adaptive snubber. However, modification of the high-frequency transformer layout for more optimization of the chopper isn't studied in Ref. [7]. Furthermore, in Ref. [8], application of the active clamp technique in

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high frequency flyback converters is investigated to fully recycle energy of the leakage inductance and achieve soft switching in converter's power switch. It can improve efficiency of the whole system either in light-load or heavy-load conditions. Effectiveness of the mentioned method is validated using 50W experimental setup. Moreover, performance of the developed active clamper is not affected by changes of the leakage inductance. Although it is well-known that application of the clamp circuits and snubbers may improve efficiency of the converter by limiting the switch voltage and current overshoots, modification of the high frequency transformer structure and windings rearrangement aren't studied for improvement of the power efficiency in Ref. [8]. This issue is the main objective of the present paper and in the following, it is studied in more detail.

Development of a simple and efficient method for analysis of the high-frequency transformers is one of the active research domains in power electronics field [4, 9-12] and different methods for design of the flyback transformer are presented. For example, in Ref. [9], evaluation of the high frequency transformers in common mode EMI noise conditions were analyzed. In Ref. [10], an exact model for a 3-winding flyback transformer using time domain system identification is extracted and model parameters are estimated using an appropriate adaptive analysis. An efficient method for winding loss analysis is developed according to phase shift difference between primary and secondary currents in Ref. [11]. Also, finite element method (FEM) is used for verification of the proposed analysis. On the other hand, detail design process and transformer modification are not studied in Ref. [11].

For periodic non-sinusoidal transformer current waveforms, some equations for primary and secondary winding power losses have been developed in Ref. [12]. A transformer has been designed for a flyback converter in continuous conduction mode (CCM) of operation and its performance has been verified during output power and DC input voltage changes [12].

In Ref. [13], a design method for improvement of the current waveform in the transformer is proposed to keep power switches in safe operating area. However in the mentioned approach, selection of the transformer turns-ratio is a completely challenging task. Also in Ref. [6], efficiency improvement considerations are studied in the flyback transformer design. In Ref. [6], iron and copper losses are minimized using an analytical approach. In spite of efficiency improvement, in this

reference, only DC resistance is used for loss calculation. It should be noted that in high frequency flyback transformer, skin effect and equivalent AC resistance play important role and must be taken into account for more accuracy of the model. Also, nominal frequency and input voltage of the converter are not used in primary winding design. This may result in magnetic core saturation of the flyback transformer in different frequencies and operational conditions.

In Ref. [5], a similar method is developed for flyback transformer design based on detailed specification of winding's core. In spite of design simplicity, proposed method of [5] cannot be used for transformer gap calculation.

Development of a high frequency transformer for a flyback converter with very high efficiency (up to 99%) in integrated circuit applications is presented in Ref. [14]. Mathematical analysis and design process of the transformer is not straightforward. In Ref. [15], application of the Nano-crystal material for elimination of the core air-gap is studied and an implemented transformer is used in flyback topology. Also, similar researches on planar transformers are reported recently [16-17]. Although application of these high frequency transformers has led to cost and weight reduction, however maximum output power rating of these transformers is limited to hundreds of mili-watts.

Considering well-known skin effect in AC currents, Dowell has proposed an analytical approach for calculation of the AC resistance in transformer windings in 1966 [18]. Also by only consideration of the DC resistance, a frequency-dependent factor is defined for modification of calculations in AC systems. According to proximity and skin effects, this factor has been formulated for sinusoidal current waveforms. Recently, Dowell's equation has been extended for non-sinusoidal waveforms as well for DC-DC converters [19-20]. Kazimierzuk has developed some expressions for estimation of the winding copper loss in buck [19], flyback [20] and forward [21] DC-DC converters. Also, a similar approach for the litz-wire windings has been proposed in Ref. [22]. It should be mentioned that in Refs. [19-22] Fourier series of the windings current waveforms should be used for determination of the copper losses at different harmonic frequencies. However, main drawback of the recent technique is complexity of model development for consideration of the fringing and by-pass fluxes in Dowell's equation. Hence, proposed approaches in Ref. [19-22] cannot be employed directly a in flyback transformer which

includes a defined air gap.

In recent researches, FEM technique is used for analysis of the power transformers. For example considering interaction between leakage fluxes and conductor current, this technique is employed to study electromagnetic forces in windings of the transformers [23]. Also, distribution of the electromechanical forces is investigated during electrical and mechanical faults. This study can be useful for determination of the electromechanical forces changes and distribution profile. Also, application of the FEM approach is reported in analysis of the high frequency transformers. For example in Ref. [24], three-dimensional (3D) analysis of the transformer with foil windings for copper loss calculations is studied using FEM. In engineering and mathematic applications, FEM technique is a powerful numerical approach for obtaining an approximate solution in boundary value problems. It uses vibrational methods to minimize an error function and produces stable solutions. Analogous to the idea of connecting many tiny straight lines which can approximate a larger circle, FEM encompasses all of the method for connecting many simple elementary equations over many small subdomains, named finite elements, to approximate a more complex equation over a larger domain. On the other hand, some studies are carried out to minimize power losses in flyback converter by using planar and surface mounting technologies [25-26]. However, output power of the mentioned approaches is limited to less than a 1 watt. According to our research, in higher power applications, standard transformers are more promising and can be employed widely. Moreover, there is no published report on efficiency improvement of the DC-DC power converters based on the windings rearrangement and reconfiguration. Considering vital importance of the loss reduction in SMPS, a novel approach for rearrangement of the transformer windings in flyback DC-DC choppers is proposed in this paper. In fact, a simple and effective method is proposed for high-frequency transformer of the flyback converter design. In the developed approach, winding turns are selected considering nominal frequency and winding voltages. Hence, core magnetic saturation problem is resolved. Then, FEM technique is applied to evaluate effectiveness and accuracy of the design. To improve high-frequency transformer of the flyback converter design, some modifications in winding structure are presented and analyzed. Finally, in order to verify the accuracy and effectiveness of the developed method, some simulations and experimental results are presented.

2. FLYBACK CONVERTER

The flyback converter is the favorite structure below 100-150 W because of its low cost and high efficiency [5]. Its circuit topology and related waveform are illustrated in Fig.1. When power switch is turned on, electrical energy is stored in magnetizing inductance of the high frequency transformer and considering polarity of the secondary voltage, the diode will be off. It is clear that, when the power switch is turned off, diode will be on and stored energy will be transferred to the output.

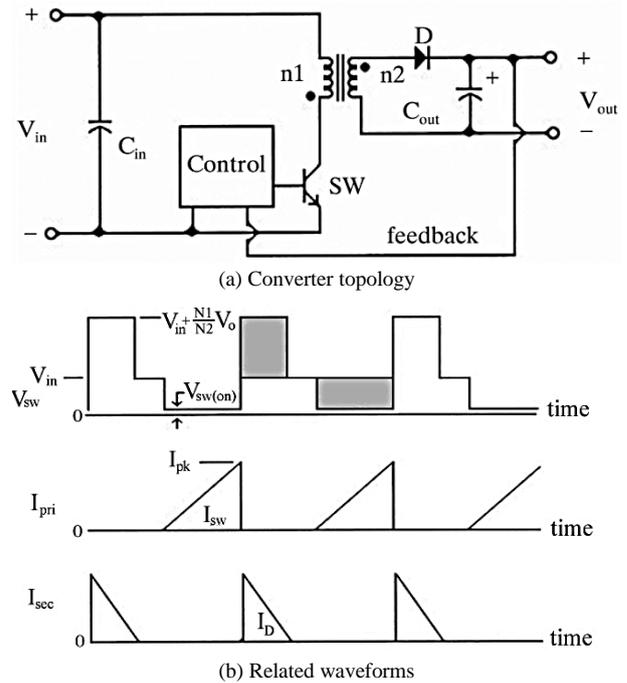


Fig.1. topology of the flyback DC-DC converter and related waveforms

During on-state of the power switch, stored energy in magnetizing inductance can be calculated as follows:

$$W_L = \frac{1}{2} L_m I_{PK}^2 \tag{1}$$

Where, L_m is magnetizing inductance of the transformer. Flyback transformer plays two main roles: energy storing and adjusting ratio of the primary and secondary voltages. Also, this transformer includes a parasitic series resistance in the input windings which reduces total efficiency of the converter. In ideal conditions, all of the stored energy in the magnetizing inductance is transferred to the output capacitor and its voltage is increased considering the following equation:

$$W_C = \frac{1}{2} C V_{out}^2 \tag{2}$$

On the other hand, it is possible to implement very high frequency flyback converters. Nowadays, considering recent progresses in development of semiconductor switches, these converters are developed

up to 1MHz. By increasing switching frequency, it is possible to supply required output energy using a small inductor. During off-state of the power switch, if all of the stored energy in the magnetizing inductance is transferred to the output, the converter will transit into Discontinuous Conduction Mode (DCM) which is desired mode of operation in practical converters. But considering simplicity of design, usually DC-DC converters are used in Continuous Conduction Mode (CCM) [6].

3. A SIMPLIFIED APPROACH FOR HIGH-FREQUENCY TRANSFORMER OF THE FLYBACK CONVERTER DESIGN

Usually DC-DC converters are designed in switching frequencies more than 20kHz. Obviously, in these ranges, high frequency ferrite cores must be used [3]. Permeability of these cores is in 1500-3000 range. Ferrite cores are saturated when magnetizing field density is around 0.3-0.4 tesla. Considering this limitation, ferrite cores can store relatively low energies. Value of this energy can be calculated simply using hysteresis curve. It should be noted that the area which is inside of the curve is related to hysteresis loss.

In flyback transformer design, first steps are selection of voltages of different outputs ($V_{01}, V_{02}, \dots, V_{0n}$) and switching frequency (f_s), determination of input voltage variations range ($V_{in(min)}, V_{in(max)}$) and acceptable efficiency (η) of the converter and selection of maximum applicable duty cycle (D_{max}). After selection of these parameters, the transformer maximum input power can be calculated as:

$$P_{in} = \frac{P_{out}}{\eta} = \frac{V_{01} \times I_{01} + V_{02} \times I_{02} + \dots + V_{0n} \times I_{0n}}{\eta} \quad (3)$$

Also, average and maximum current of the primary windings can be written as following:

$$I_{in} = \frac{P_{in}}{V_{in(min)}} \rightarrow I_p = \frac{2I_{in}}{D_{max}} \quad (4)$$

Using Eqns. (3) and (4), magnetizing inductance of the transformer can be formulated easily:

$$L_m = \frac{2P_{in}}{f_s I_p^2} \quad (5)$$

Considering available ferrite cores, a suitable core is selected. Using Faraday's law, transformer winding turns can be obtained by Eq. (6). In this equation, A_c , B_{max} and V_D are transformer core area, maximum magnetic field density and diode voltage drop respectively.

$$E_1 = N_1 \frac{d\phi}{dt} \rightarrow \begin{cases} N_1 = \frac{D_{max} V_{in(max)}}{f_s A_c B_{max}} \\ N_2 = \frac{(1-D_{max})(V_o + V_D)}{D_{max} V_{in(min)}} N_1 \end{cases} \quad (6)$$

To transit the flyback transformer into DCM region, diode on-time should be less than switch off-time. Hence:

$$L_s = \left(\frac{N_2}{N_1} \right)^2 L_m \quad (7)$$

$$t_d = L_s \frac{I_p \frac{N_1}{N_2}}{V_o + V_D} \leq \frac{(1-D_{max})}{f_s}$$

Where, L_s is transferred magnetizing inductance to the secondary winding. If above condition is not satisfied, transformer winding turns should be changed by variation of the selected core or B_{max} . Then, air-gap value can be calculated as following:

$$L_m = \frac{N_1^2}{\mathfrak{R}} = \frac{N_1^2}{\frac{1}{\mu \mu_r} \frac{l_c}{A_c} + \frac{1}{\mu} \frac{l_g}{A_g}} \approx \frac{N_1^2}{\frac{1}{\mu} \frac{l_g}{A_g}} \rightarrow l_g = \frac{N_1^2 A_g \mu_o}{L_m} \quad (8)$$

Where, \mathfrak{R} , l_c , l_g and A_g are equivalent reluctance of the core, average length of core, average length of air-gap and air-gap area. Finally, the designed transformer is acceptable if the following condition is satisfied:

$$\sum_{i=1}^{ith \text{ winding}} A_{Cui} \times N_i < k_w A_w \quad (9)$$

Where, A_{Cui} , A_w and k_w are i th winding's copper area, winding window area of core and window utilization factor. Usually k_w is selected between 50% and 70%. If Eq. (9) is not satisfied, core selection should be revised. Complete design flowchart of the flyback transformer is illustrated in Appendix I.

Considering the described algorithm, specification of the designed flyback transformer is presented in Table 1.

4. ANALYSIS OF THE FLYBACK TRANSFORMER USING FINITE ELEMENT METHOD

FEM is a numerical technique for obtaining approximate solutions to boundary value problems of mathematical physics. The method has a history of about 50 years. It was first proposed in the 1940s and its use began in the 1950s for aircraft design. Thereafter the method was developed and applied extensively to problems of structural analysis and increasingly to

problems in other fields. Today, FEM has become recognized as a general method widely applicable to engineering and mathematical problems. It should be noted that values of the leakage inductances, proximity effect of different winding layers, eddy current losses in windings are affected by winding structure. It is obvious that such a study cannot be accomplished using standard design techniques. Hence, we focus on the analysis of the designed flyback transformer considering FEM. In this paper, the effects of air gap on the amount of copper loss are studied in more detail.

Maxwell software is used for FEM analysis of the flyback converter. This is a high-performance interactive software package that uses Finite Element Analysis (FEA) to solve three-dimensional electric, magneto static, eddy current and transient problems. It is possible to use this software to compute static electric fields, forces, torques, and capacitances caused by voltage distributions and charges, static magnetic fields, forces, torques, and inductances caused by DC currents, static external magnetic fields, and permanent magnets, time-varying magnetic fields, forces, torques, and impedances caused by AC currents and oscillating external magnetic fields and finally transient magnetic fields caused by electrical sources and permanent magnets [5].

Table 1. Specification of the designed transformer and DC-DC flyback converter

Parameter	Determined value	Unit
$V_{in(min)}$ (min. input voltage)	24	V
$V_{in(max)}$ (Max. input voltage)	36	V
P_{out} (output power)	20	W
B_{max} (Max. magnetic field)	0.2	T
D_{max} (Max. duty cycle)	45	%
f_s (Max. switching frequency)	74	kHz
η (efficiency)	80	%
A_c (conductor area)	0.785	mm ²
L_m (magnetizing inductance)	32	uH
L_s (secondary inductance)	14	uH
l_g (air-gap length)	1	mm
N_1 (primary turns)	18	Turn
N_2 (secondary turns for $V_0=20V$)	12	Turn
A_{cu1} (copper area of the primary)	0.5	mm ²
A_{cu2} (copper area of the secondary)	0.785	mm ²
A_w (core window area)	77	mm ²

4.1. Magnetostatic analysis

In a magneto static solution, the magnetic field is produced by DC currents flowing in conductors/coils and by permanent magnets. The electric field is

restricted to the objects modeled as real (non-ideal) conductors. The electric field existing inside the conductors as a consequence of the DC current flow is totally decoupled from the magnetic field. Thus, as far as magnetic material properties are concerned, the distribution of the magnetic field is influenced by the spatial distribution of the permeability. There is no time variation effects included in a magnetostatic solution, and objects are considered to be stationary. The energy transformation occurring in connection with a magnetostatic solution is only due to the ohmic losses associated with the currents flowing in real conductors.

4.2. Copper loss calculations

According to proximity and skin effects, fringing and by-pass fluxes, it is well known that ac and dc resistance are completely different in high-frequency transformers. Using Dowell's equation [17], ac resistance can be calculated as a function of dc resistance:

$$R_{ac} = F_R \times R_{dc} \quad (10)$$

$$F_R = A \left[\frac{\sinh(2A) + \sin(2A)}{\cosh(2A) - \cos(2A)} + \frac{2(N_1^2 - 1)}{3} \frac{\sinh(A) + \sin(A)}{\cosh(A) - \cos(A)} \right] \quad (11)$$

Where, N_1 is number of winding layers and:

$$A = \left(\frac{\pi}{4} \right)^{0.75} \frac{d}{\delta_w} \sqrt{\eta} \quad (12)$$

In this equation, d is wire diameter. Also, δ_w (skin depth of the conducting wire) and η (porosity factor) can be defined as follows:

$$\delta_w = \sqrt{\frac{\rho_w}{\pi \mu_0 f}} \quad (13)$$

$$\eta = \frac{d}{p} \quad (14)$$

Where, ρ_w , p , μ_0 and f are winding conductor resistivity, distance between the centers of two adjacent conductors, free-space permeability and fundamental frequency of the ac current. According to these equations, it is clear that F_R is frequency depended factor. Hence, application of Dowell's equation for non-sinusoidal current waveform is not completely straightforward. On the other hand, in Dowell's method, fringing and by-pass fluxes are not modeled. To study this issue in more detail, application of FEM analysis is proposed in this paper. In this method, ohmic loss is given by the following equation:

$$P = \iiint \frac{\vec{j} \cdot \vec{j}^*}{2\sigma} dx dy dz \quad (15)$$

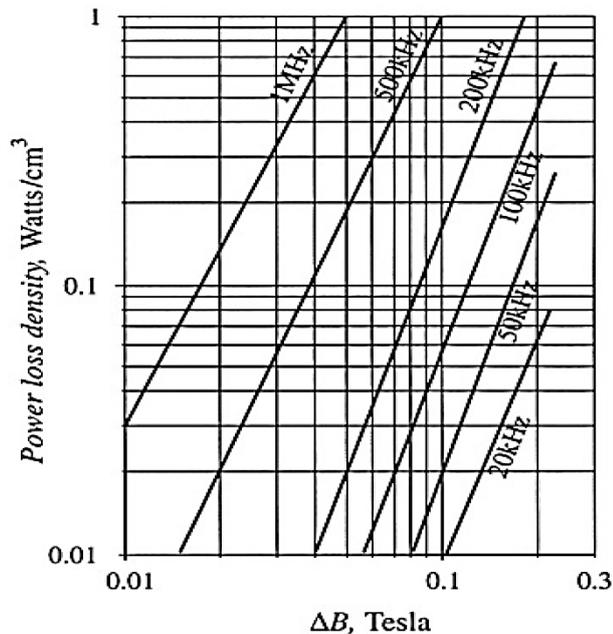


Fig. 2. Core loss versus flux density in different switching frequencies[6]

Where, \vec{j}^* is the complex conjugate of the current density and σ is the conductivity in siemens/meter.

4.3. Core loss analysis

Manufacturers utilize graphs that plot loss versus frequency of operation versus maximum operational flux density, which makes it easy to compare materials (refer to Fig. 2). It should be noted that during FEM analysis of the designed transformer, this curve is imported to the Maxwell software.

5. MODIFICATION, DISCUSSION, SIMULATION RESULTS

Using Maxwell software from Ansoft Co., designed transformer is simulated and modified according to transient analysis. In Fig. 3, two dimensional view of the transformer in the software is illustrated for five different cases. These simulations are related to standard design and some modifications in winding arrangement of the transformer for efficiency improvement. Ferrite core is selected from the default library of the software with relative permeability of 2000. Assuming 0.1 Siemens per meter for resistance of the core, eddy current loss is calculated and also, ferrite core loss is modeled using curves which are shown Fig. 2.

5.1. Proposed modification

To improve efficiency of the designed transformer, some modifications are proposed as following:

Case I: Standard design-in this condition, primary windings is placed in the internal part of the core. Also, secondary windings are packed externally.

Case II: Modification one-. Considering distribution of the magnetic leakage field around air gap, it has been decided to select empty area three times of the air gap length.

Case III: Modification two- in this case, in order to reduce proximity effect between primary and secondary windings of the transformer, a blank space between windings of the transformer is considered.

Case IV: Modification three- stranded wire may be used in transformer windings to reduce skin effect total efficiency of the converter can be improved considerably.

Case V: Modification four- this modification is used to reduce leakage inductance. In this case, primary windings are divided in to different parts and secondary windings are replaced between these parts.

5.2. Simulation results

To evaluate the performance of the modified transformers, flyback DC-DC converter is simulated considering transient analysis in Maxwell Software. Switching frequency is selected around 72 kHz. Also, open loop duty cycle of the converter is around $D=0.45$. Transformer's primary and secondary currents are shown in Fig. 4 during transient analysis.

Core magnetic field density for standard transformer is illustrated in Fig. 5 and current density distribution is shown in Fig. 6. It is completely well-known that, due to leakage flux around the air-gap, copper loss will increase in this segment. This case can lead to failure of the transformer especially in high voltage applications. In fact, in these transformers, usually low area wires which result in more coils around the air gap. Hence, it is completely reasonable to use no winding around the air gap.

To solve these problems, some modifications are done as illustrated in Fig.3. Core magnetic field densities for different modifications using FEM analysis are shown in Fig. 7.

From Fig. 7, it is completely obvious that leakage flux does not flow through the transformer windings and hence, related eddy current loss is eliminated totally. Considering Fig. 5, it is decided to select empty space around of the air gap 3 times of core gap. In fact, paying attention to presence of the leakage flux around the air gap, it has been decided to consider an empty $3\text{mm} \times 3\text{mm}$ square in the primary and secondary windings.

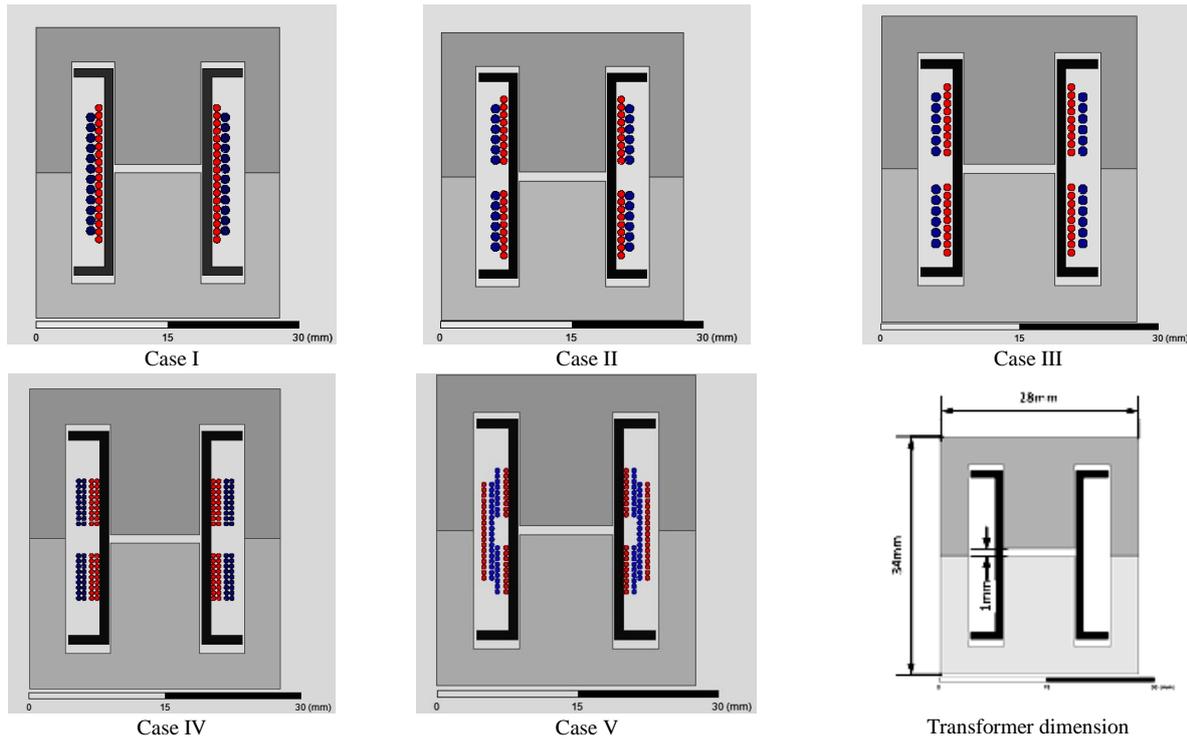


Fig. 3. Illustration of the designed transformers in the Maxwell/Ansoft. Primary and secondary winding are illustrated with red and blue colors respectively. Transformer core is selected in E-E shape and P material and transformer bobbin is shown with black color. Detailed dimension of the transformer is written in part f.

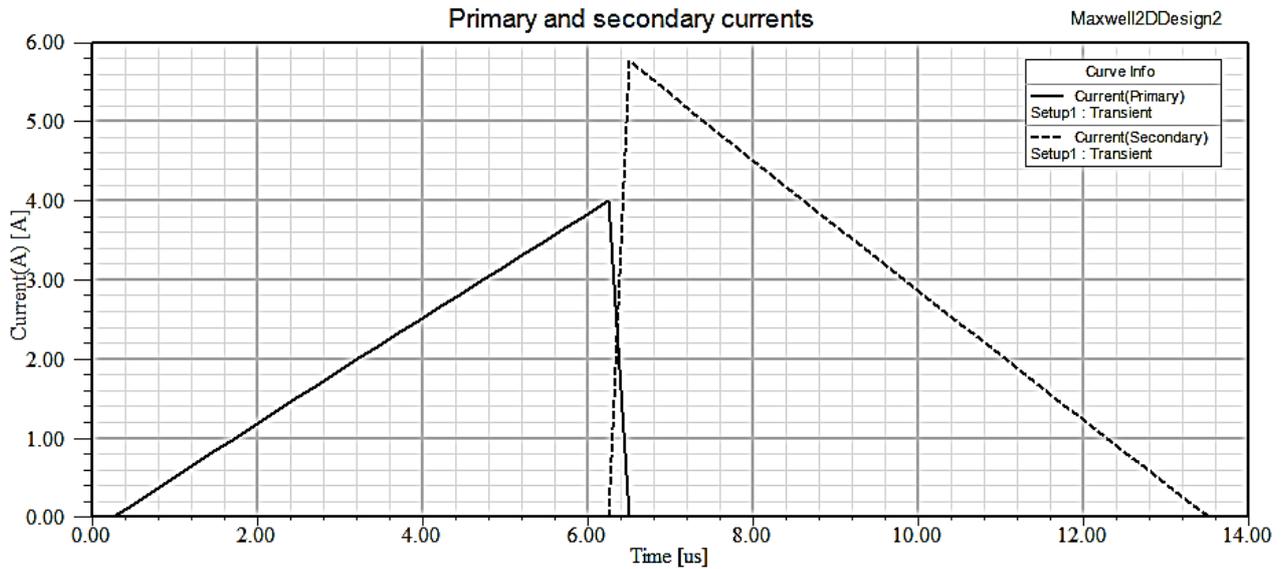


Fig. 4. Primary and secondary currents of the transformer during transient analysis (simulation)

More complete analysis of the previously described modifications is listed in Table 2. It is clear that, these modifications reduce ac resistance of the windings which can improve efficiency of the converter. So, copper loss is reduced as different modifications are applied. In case II, elimination of eddy current loss around air gap improves efficiency of the transformer. In case III, application of a black gap between layers (equal to 1 primary conductor diameter) reduces copper loss. It should be noted that, usually in high voltage applications, an isolator layer is used between different

layers which automatically result in blanking space. The length of blank space is around half of the primary conductor diameter (0.35mm). Paying attention to the values of the equivalent ac resistances of the windings in Table 2, it is obvious that electric current flows through outer portion of the coil.

In order to reduce ac resistances, two parallel conductors (with 0.5mm diameter) in primary side and three parallel conductors (with 0.5mm diameter) in the secondary windings are used in case IV.

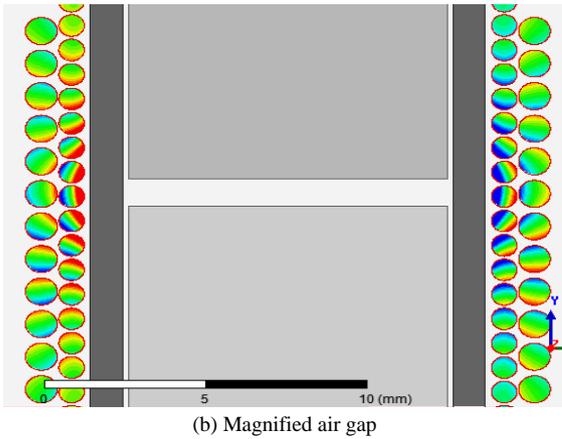
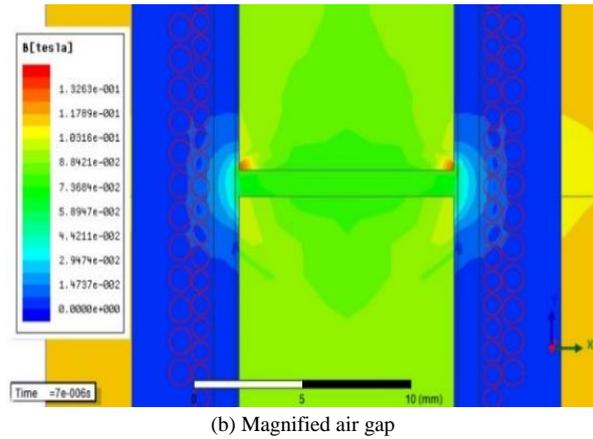
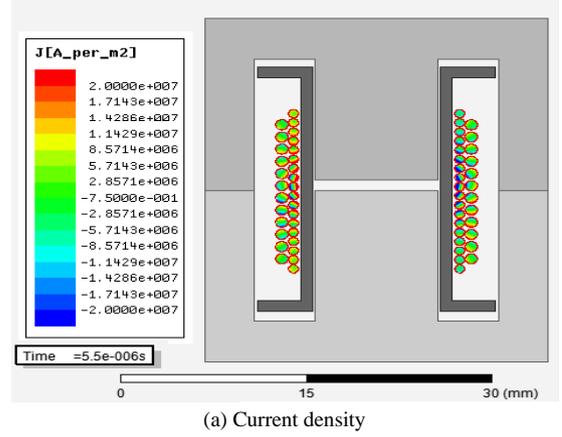
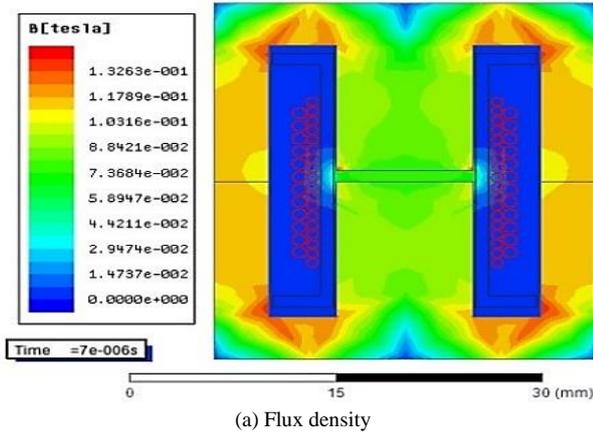


Fig. 5. Core magnetic field density for standard transformer

Fig. 6. Current density distribution in standard transformer

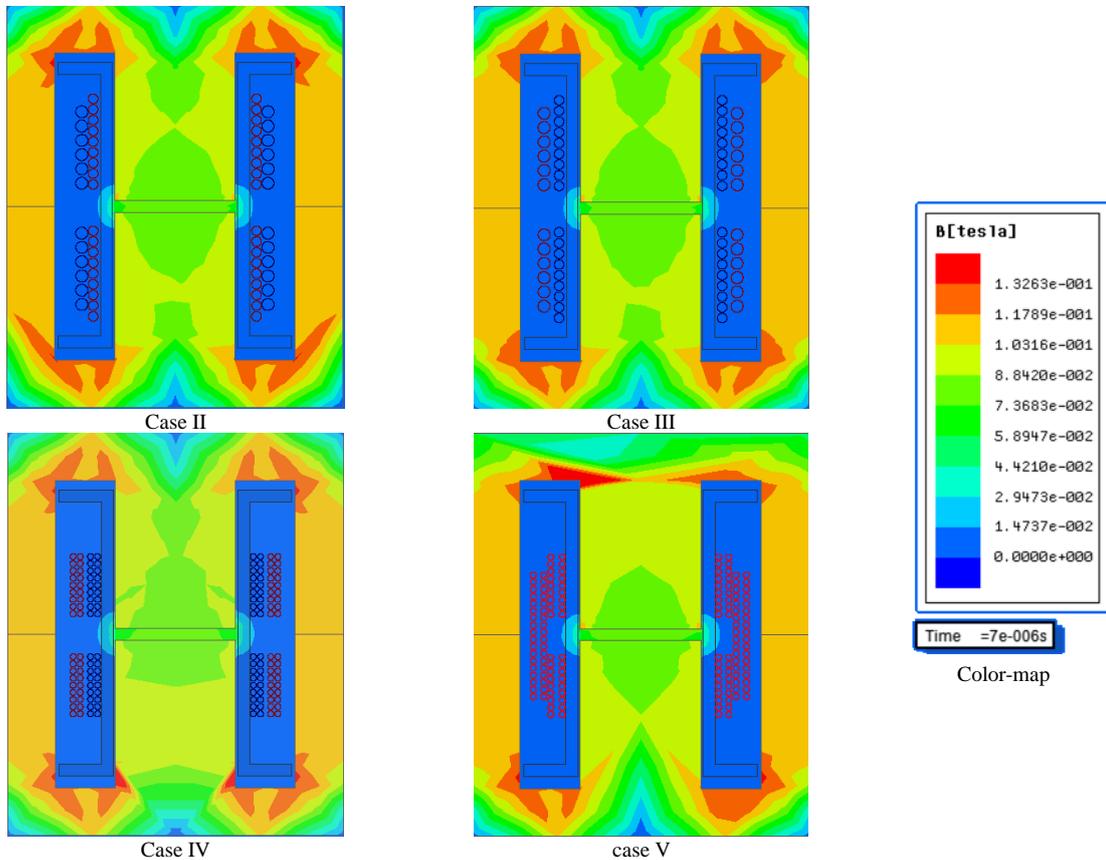


Fig. 7. Core magnetic field densities for different modifications

Table 2. Simulation of the standard transformer using FEM

	L_m (magnetizing inductance)	L₁₁ (Primary leakage inductance)	L₁₂ (secondary leakage inductance)	R_{ac1}/R_{dc1}	R_{ac2}/R_{dc2}	Core Loss (W)	Copper Loss (W)
Case I[27]	34.87286	0.069308	0.013706	5.349059	6.361941	0.036251	0.458310
Case II	35.67078	0.068024	0.013424	5.295865	5.255161	0.035120	0.4019
Case III	35.65241	0.123431	0.024407	5.301742	5.139775	0.03514	0.377987
Case IV	35.62332	0.251534	0.050194	1.139559	1.14921	0.03520	0.08335
Case V	35.36575	0.136115	0.027186	1.139541	1.113016	0.03246	0.085578

In fact, in case IV, use of stranded wires in transformer (2 parallel conductors in primary and 3 one in secondary windings) with the same equivalent conductor area improves efficiency of the flyback transformer. As efficiency is improved through case II-IV, leakage inductances are increased due to reduction of coupling factor between windings. In fact, such structure results in considerable leakage inductance in the primary and secondary windings which can deteriorate dynamic response of the converter and causes large voltage overshoot on the controlled switch. To solve this problem, case V is added. Here, this modification is used to reduce leakage inductance. To improve coupling factor, primary windings are divided in to different parts and secondary windings are replaced between these parts. Considering that overall structure of the transformer is not changed, magnetizing inductance is almost constant in different cases.

The effects of air gaps leakage fluxes as well as the proximity of the conductors on the density of the current through the conductor is one of the major issues in the flyback converters design. Considering Fig.5, it is clear that relatively large leakage flux can affect conductors around the air gap. This may result in considerable loss in conductors around the air-gap. To study this subject in more detail, conductor loss is calculated during a cycle in standard structure. Ohmic loss is always associated with conduction current distribution in conductors which are not perfect. Thus the resistivity of conductors is responsible for the ohmic power loss when current flows in such conductors. There is always a heating effect due to the ohmic loss. In this study, solid loss value of the transformer conductor is considered. In order to study efficiency of the developed method, it is compared with conventional topology [27] according to copper and core losses, values of the parasitic DC and AC resistances, leakage and magnetizing inductances. It is shown that the proposed transformer structure has superior response compared to conventional one and it can improve total efficiency of the converter up to 3.3%.

6. EXPERIMENTAL RESULTS

To evaluate performance of the designed transformers, a 20W flyback DC-DC converter is implemented using an open-loop PWM controller. The practical setup is shown in Fig.8. Also, nominal values of the converter power circuit are listed in Table 3. In this section, standard and modified-4 transformers are tested practically. The waveforms related to these transformers are illustrated in Fig.9 and Fig.10 respectively. Results for steady-state operation of the converter are presented in Table 4 using practical measurements.

It is clear that total efficiency of the converter can be improved using proposed modification. In order to find total improvement in the efficiency, switching and transformer losses must be separated. It is clear that switching loss can be calculated analytically using measured parameters.

Table 3. Nominal values of the implemented flyback converter

Parameter	Values
Cin (input capacitor)	1000uF
Co (output capacitor)	940uF
Power Mosfet switch	IRF640 (N - CHANNEL 200V - 0.150W - 18A - Ron < 0.18 Ω)
Power diode	1N5822 (3.0A schottky barrier rectifier, Vd(on) = 0.522V)

Table 4. Results for steady-state operation of the converter using standard and modified-4 transformers

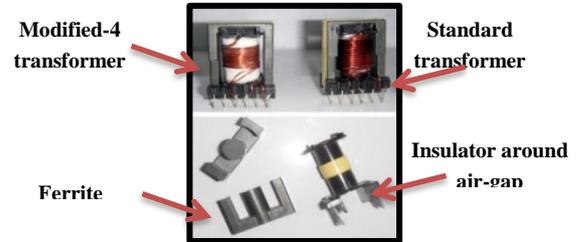
Parameter	Values		Unit
	Standard transformer	modified-4 transformer	
V _{in} (input voltage)	24	24	V
I _{in} (input current)	0.95	0.91	A
P _{in} (input power)	22.8	21.84	W
V _o (output voltage)	12.02	12.03	V
I _o (output current)	1.267	1.273	A
P _{out} (output power)	15.23	15.314	W
η (efficiency)	66.80	70.12	%
Total loss (switching and transformer loss)	7.57	6.526	W



(a) Test bench

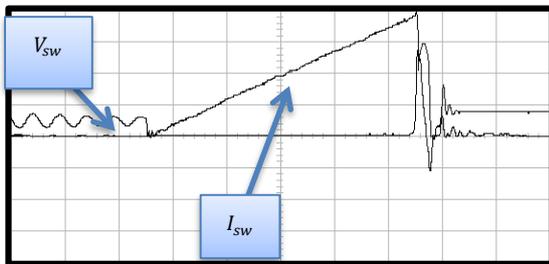


(b) DC-DC flyback converter



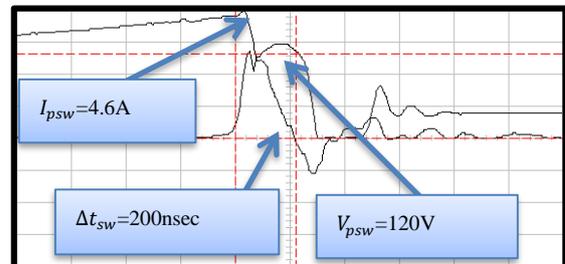
(c) Standard and modified-4 transformers

Fig. 8. Practical setup, (a) test bench (b) DC-DC flyback converter, (c) Standard and modified-4 transformers

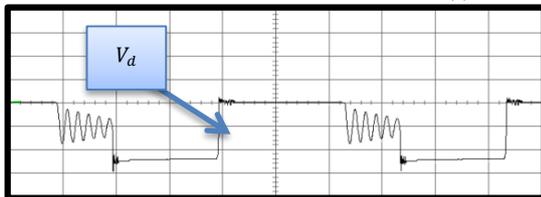


Vol/div=50V, A/div=1.22A, time/div=1usec

(a) Power switch current and voltage

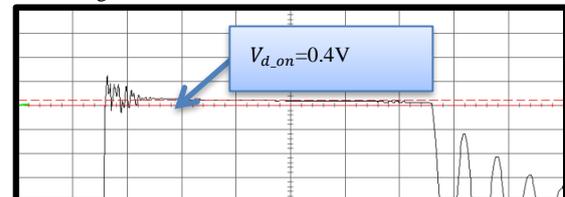


Vol/div=50V, A/div=1.22A, time/div=100nsec

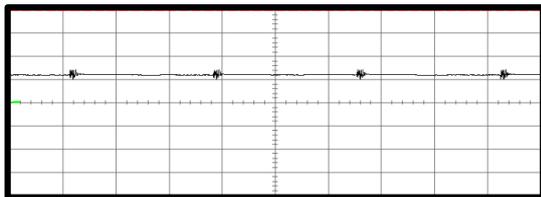


Vol/div=10V, time/div=2.5usec

(b) Power diode voltage

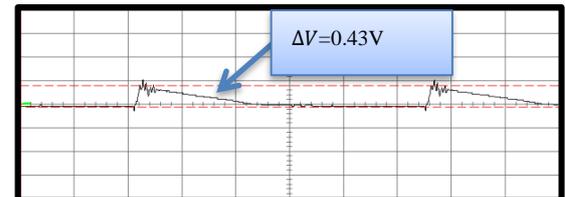


Vol/div=2V, time/div=500nsec

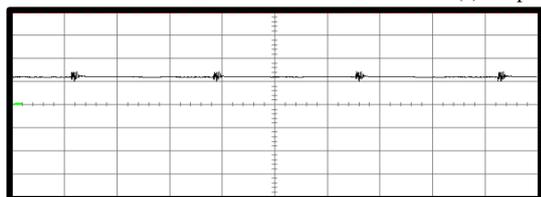


Vol/div=10V, time/div=5usec

(c) Output voltage of the converter

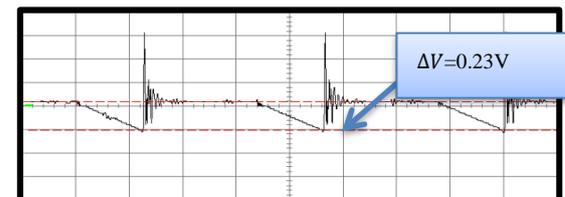


Vol/div=0.5V, time/div=2.5usec



Vol/div=20V, time/div=5usec

(d) input voltage of the converter



Vol/div=0.2V, time/div=4usec

Fig. 9. Switching waveforms of the flyback converter using standard transformer
(a) power switch voltage and current, (b) power diode voltage, (c) output voltage and (d) input voltage of the converter

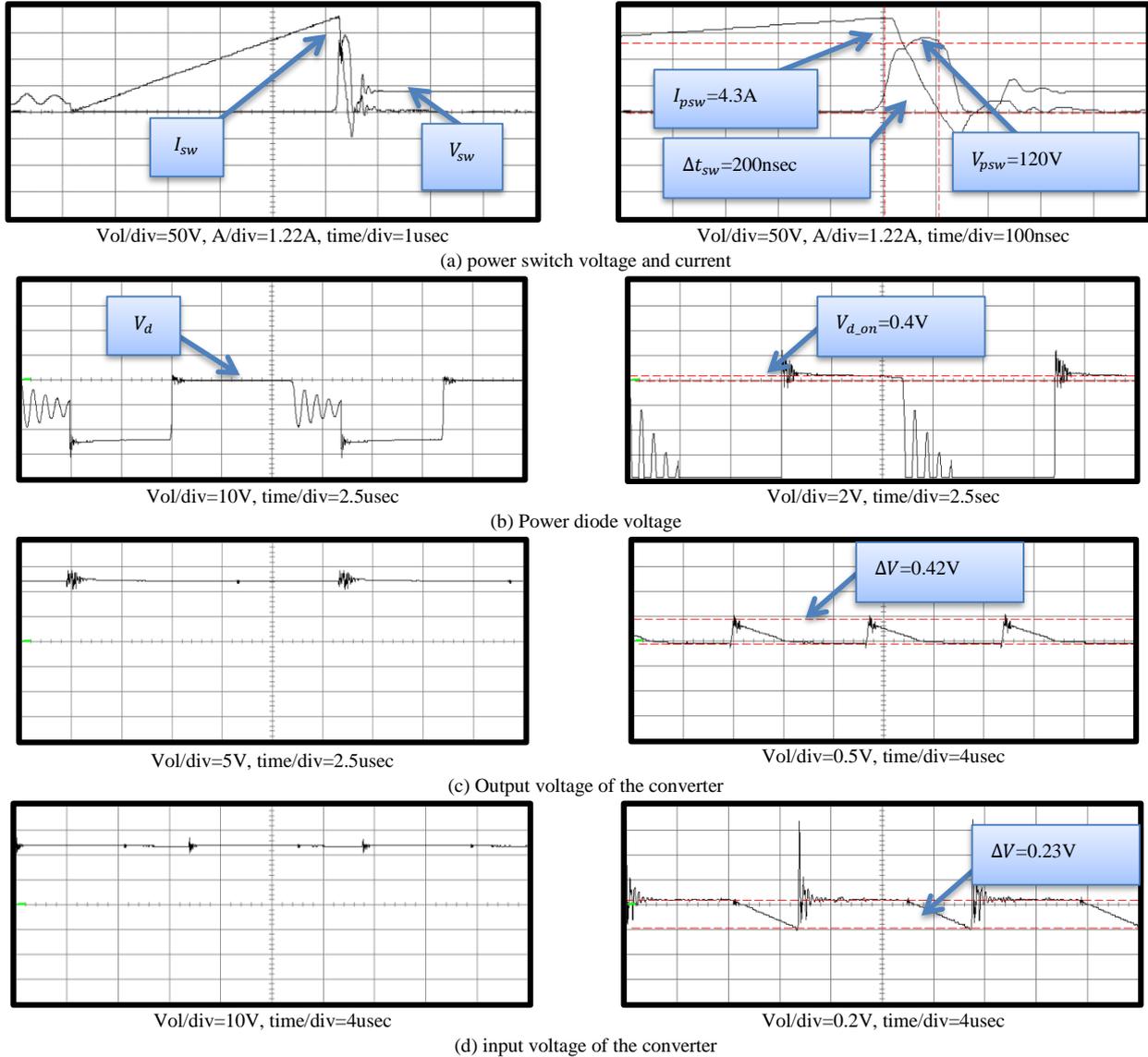


Fig. 10. Switching waveforms of the flyback converter using modified-4 transformer
 (a) power switch voltage and current, (b) power diode voltage, (c) output voltage and (d) input voltage of the converter

In standard transformer, the switching loss of power switch can be calculated using waveform which is illustrated in Fig. 9. Here, I_{rms_sw} , P_{loss_sw} , Δt_{sw} , I_{p_sw} , V_{p_sw} , f_{sw} , R_{on} are RMS value of switch current, total power loss of power switch, switching time duration, switch peak current, switch peak voltage, switching frequency and switch ON resistance respectively.

$$I_{rms_sw} = I_{p_sw} \sqrt{\frac{D}{3}} = 4.6 \sqrt{\frac{0.35}{3}} = 1.57 \quad (16)$$

$$P_{loss_sw} = \text{switching loss} + \text{conducting loss} = \frac{t_{sw} \times V_{p_sw} \times I_{p_sw}}{2} f_{sw} + R_{on} I_{rms_sw}^2 = \frac{200 \times 10^{-9} \times 120 \times 4.6}{2} 73964 + 0.14 \times 1.57^2 = 4.43W \quad (17)$$

If the diode switching loss is neglected, total power loss of the diode can be calculated as follows:

$$I_{rms_D} = I_{Psw} \frac{n1}{n2} \sqrt{\frac{D_2}{3}} = 4.6 \times \frac{18}{12} \sqrt{\frac{0.437}{3}} = 2.63 \quad (18)$$

$$P_{loss_D} = V_{D(on)} I_{rms_D}^2 = 0.4 \times 2.63 = 1.05W \quad (19)$$

Where, I_{rms_D} , P_{loss_D} , $V_{D(on)}$ are RMS value of the diode current, total power loss of the power diode and diode forward bias voltage respectively.

Due to presence of Equivalent Series Resistance (ESR) in output capacitor, variation of capacitor current direction result in step changes in output voltage of the converter during switching intervals. According to Fig.9c, ESR of the output capacitor and capacitor power loss can be calculated as:

$$\Delta i_c = i_{sw} \frac{n1}{n2} - i_o = 6.9 - 1.267 = 5.63A \quad (20)$$

$$ESR = \frac{\Delta V}{\Delta i_c} = \frac{0.43}{5.63} = 0.0763 \quad (21)$$

$$i_{ac} = \sqrt{I_{rms}^2 - I_o^2} = \sqrt{2.63^2 - 1.267^2} = 2.3 \quad (22)$$

$$P_{loss_ESR} = ESR \times (i_{ac})^2 = 0.0763 \times (2.3)^2 = 0.403W \quad (23)$$

Where, Δi_c , ΔV , i_{ac} and P_{loss_ESR} are capacitor current ripple, output voltage ripple, capacitor ac current and power loss of the capacitor respectively.

Using similar approach, ESR of the input capacitor and its related power loss can be calculated as:

$$\Delta i_c = i_{psw} - i_{in} = 4.6 - 0.95 = 3.65A \quad (24)$$

$$ESR = \frac{\Delta V}{\Delta i_c} = \frac{0.23}{3.65} = 0.063 \quad (25)$$

$$i_{ac} = \sqrt{I_{rms}^2 - I_{in}^2} = \sqrt{1.57^2 - 0.95^2} = 1.25 \quad (26)$$

$$P_{loss_ESR} = ESR \times (i_{ac})^2 = 0.063 \times (1.25)^2 = 0.0984W \quad (27)$$

Considering Table 3 and Eqns. (17, 19, 23 and 27), transformer total power loss would be calculated as :

$$P_{Loss_Trans_standard} = P_{Loss} - P_{Loss_sw} - P_{Loss_D} - P_{Loss_ESR} = 7.57 - 4.43 - 1.05 - (0.403 + 0.0984) = 1.5886 W \quad (28)$$

Practical waveforms for modified-4 transformer are shown in Fig.10. Repeating the same approach, power losses in different elements of the converter can be calculated using modified-4 transformer:

$$P_{loss_sw} = 4.14 W$$

$$P_{loss_D} = 1 W$$

$$P_{loss_ESR} = 0.461 W$$

$$P_{Loss_Trans_standard} = P_{Loss} - P_{Loss_sw} - P_{Loss_D} - P_{Loss_ESR} = 6.526 - 4.14 - 1 - 0.461 = 0.925$$

Which shows 0.6636 W reduction in loss of the proposed transformer for flyback converter:

$$P_{Loss}(\text{modified.trans}) - P_{Loss}(\text{standard.trans}) = 0.925 - 1.5886 = -0.6636 W$$

On the other hand, according to simulation results which are presented in Table 2, it is clear that power loss of the transformer can be reduced considerably

without large increment in leakage inductance. In fact from simulation results, power loss difference between transformers is:

$$(P_{Loss}(\text{modified trans}) - P_{Loss}(\text{standard trans})) = 0.458310 - 0.085578 = 0.3727W$$

Relative error between simulation and experimental results is around 43% which is related to measurement errors and ideal assumptions during simulation. These results clearly show 41.78% power loss reduction in modified-4 transformer compared with standard transformer.

7. CONCLUSIONS

In this paper, a simple design technique and different winding rearrangement and layout changes are introduced for efficiency improvement of the high frequency transformers. FEM technique is used for analysis of the designed transformers. Using this method, it is shown that the current density is relatively large- around core air gap. FEM is also used to develop the desired layout of the transformer. Modifications are developed based on removal of windings in (and around) the air-gap with consideration a blank space between primary and secondary windings. It is shown that, there is trade-off between loss and stray inductance reduction in high frequency transformers. In order to analysis the transformer experimentally, DC-DC flyback converter is implemented using an open loop controller. Experimental results prove that the proposed high frequency transformer improves efficiency of the converter considerably. In order to study efficiency of the developed method, it is compared with conventional topology according to copper and core losses, values of the parasitic DC and AC resistances, leakage and magnetizing inductances. It is shown that the proposed transformer structure has superior response compared to conventional one and it can improve total efficiency of the converter up to 3.3%.

Appendix A

See Fig. I.

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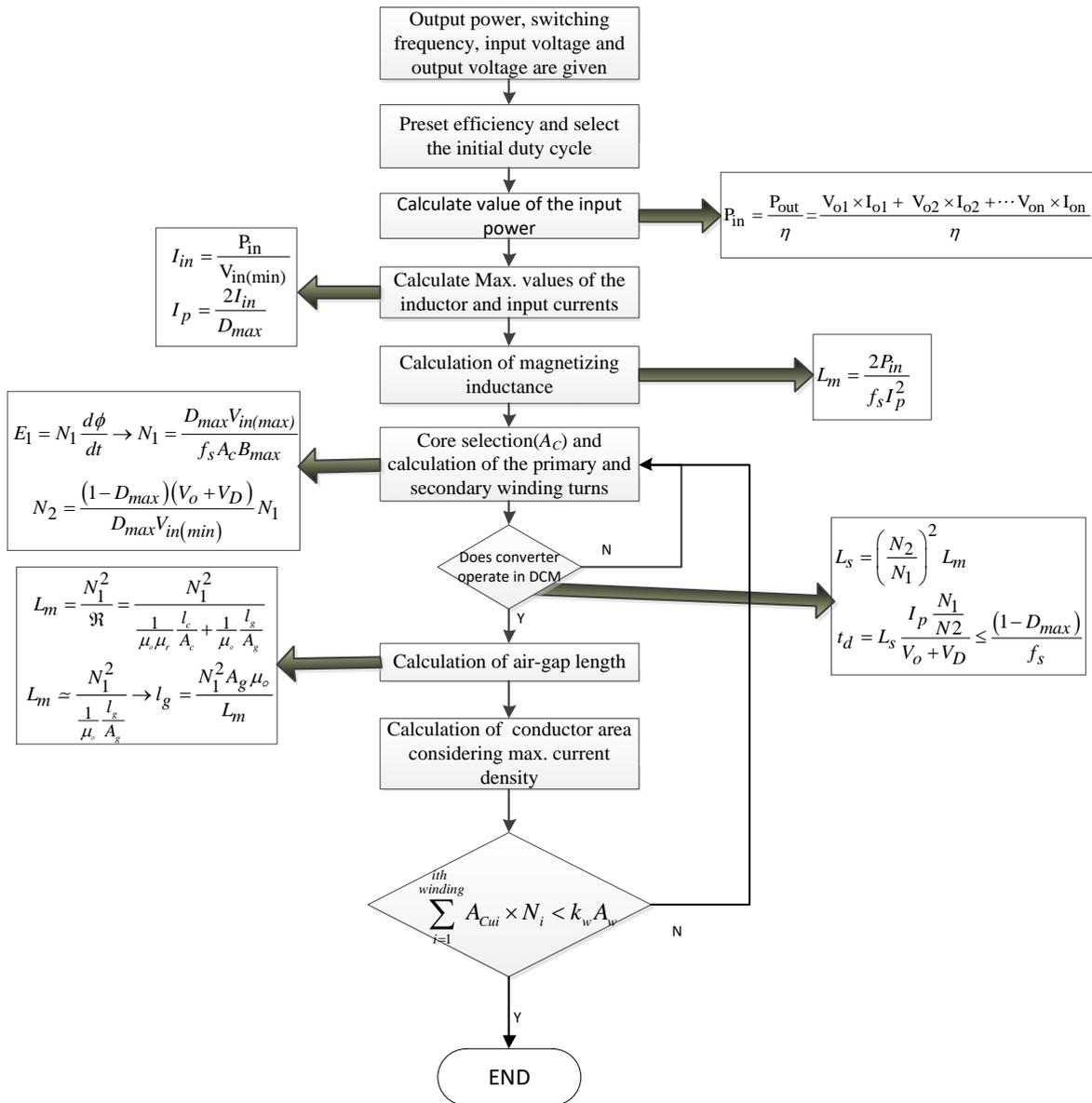


Fig. 1. Complete design flowchart of the high-frequency transformer of the flyback converter

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