J Electr Eng Technol.2015;10(1): 288-294
http://dx.doi.org/10.5370/JEET.2015.10.1.288

ISSN(Print) 1975-0102
ISSN(Online) 2093-7423

Optimal Design of High Frequency Transformer for 150W Class Module-Integrated Converter

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Abstract – Recently, the module-integrated converter has shown an interest in the photovoltaic generation system. In this system, the high frequency transformer should be compact and efficient. The proposed method is based on the correlation characteristic between the copper and core loss to minimize the loss of transformer. By sizing an effective cross-sectional area and window area of core, the amount of loss is minimized. This paper presents the design and analysis of high frequency transformer by using the 3D finite element model coupled with DC-DC converter circuit for more accurate analysis by considering the nonlinear voltage and current waveforms in converter circuit. The current waveform in each winding is realized by using the ideal DC voltage source and switching component. And, the thermal analysis is performed to satisfy the electrical and thermal design criteria.

Keywords: High Frequency Transformer, DC-DC Converter, Coupled analysis

1. Introduction

Module-integrated converter (MIC) research has shown an interest in small-scale photovoltaic (PV) generation systems. The converter is capable of more efficient output power control of each PV module, and offers installation convenience, compared with a centralized converter. It needs a transformer to achieve a large voltage conversion ratio because of the low output voltage from PV module.

However, the high frequency transformer is the most dominant component to decide the power conversion efficiency of the system, because of the high frequency effect in the core and windings. In this paper, the design optimization procedure of the high frequency transformer is studied to achieve the high power conversion efficiency in compact size.

The proposed design method is based on the correlation characteristic of copper and core loss [1-2]. The total loss of transformer is minimized when the copper loss is approximately equal to core loss regardless of operating frequency.

In order to minimize the loss of transformer, the effective cross-sectional area and window area of core are changed in the optimization procedure by using a parametric 3-dimensional (3D) computer aid design (CAD) model. This method requires high accuracy analysis to find an optimal design point of core. However, in general studies, the analysis is done by using the approximated sinusoidal or square voltage and current waveform for the convenience of analysis [3-7].

In this study, the analysis model is performed by using the 3D finite element (FE) model considering the converter circuit to improve the accuracy of analysis. In order to calculate the copper loss in high accuracy, the current waveform in each winding is realized by using the DC voltage source and ideal switching component of the converter circuit.

The confirmation of thermal characteristics is very important because the operating temperature is definitely relevant to the amount of energy transferred in a transformer. Thus, the thermal characteristics of transformer should be analyzed to satisfy the electrical and thermal design criteria [8-9]. In this study, the thermal characteristics of transformer are analyzed by using a finite element analysis (FEA). The heat sources are based on core and copper loss analysis result.

2. Initial Design Procedure

2.1 Required specifications of transformer

The module-integrated converter is usually attached to the backside of PV module for the easy installation and downsizing the volume of total system. The height of MIC should be under 20[mm] to be placed within the PV

Table 1. Required specifications of transformer

Parameter	Value
Input DC voltage, V_g [V]	30
Rated output voltage [V]	310
Rated output power [W]	150
Rated operating frequency, f_o [kHz]	100
Turn ratio	1:5
Total height [mm]	≤ 15
Efficiency [%]	≥ 95

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Received: September 4, 2014; Accepted: November 12, 2014

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module package. For this, the height of transformer has to be designed under 15[mm]. Table 1 shows the required specifications of the transformer for the MIC. Input DC voltage (V_g) is given as an average output voltage of PV module.

2.2 Initial core structure

In order to select the smallest standard core, the minimum window area W_a and effective cross-sectional area of core A_c should be determined.

The total conduction area of winding A_w is determined by the maximum current density J_{max} and number of turns in each winding N_p and N_s from (1). The range of maximum current density is determined as 4-5A/mm^2.

$$A_w = N_p \left(\frac{I_{p\_\max}}{J_{\max}} \right) + N_s \left(\frac{I_{s\_\max}}{J_{\max}} \right) \tag{1}$$

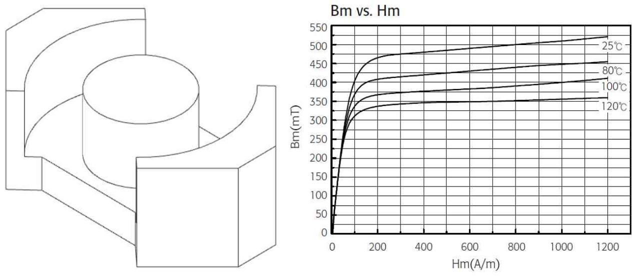
The minimum window area is calculated from (2). The window area should be considered the size of insulator between the windings and core through the utilization factor K_u.

$$W_a = \frac{A_w}{K_u} \tag{2}$$

From (3), the maximum flux density of core B_{max} is calculated by the maximum current I_{max} instead of non-linear voltage waveform. The maximum flux density of core should be lower than B_{sat} which is saturation flux density of core material by sizing the cross-sectional area of core.

$$B_{\max} = \frac{L_p I_{\max} \times 10^8}{N_p \times A_c} \tag{3}$$

Fig. 1 shows a half structure of rectangular modulus (RM) type core and B-H curve of core material. The RM type core has an advantage because it can be highly integrated into the printed board circuit.



(a) (b)

Fig. 1. (a) Half structure of core, (b) B-H curve of core

3. Modeling & Result

3.1 Modeling of initial model

In order to analyze the operating characteristics of initial model, the 3D FE model is used as shown in Fig. 2. The non-isolated boost converter is used as shown in Fig. 3.

The current waveform in windings is realized by using a converter circuit without control part.

The minimum time step interval is determined as the greatest common divisor of turn-on and turn-off time to obtain the current waveform of each winding in high accuracy. If the time step is too larger than switching period, the turn-on and turn-off operation of switch component is ignored in FEA.

The analysis result is compared with the measurement result of initial model to check the accuracy of analysis model. The current waveform in the primary winding is compared in Fig. 4 to verify the accuracy of proposed

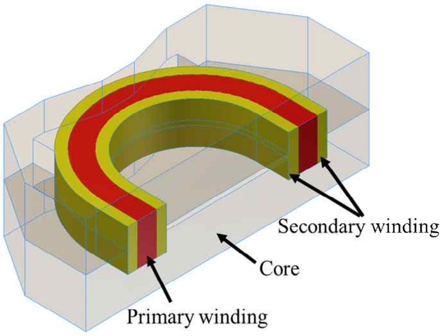


Fig. 2. 3D FE model of transformer

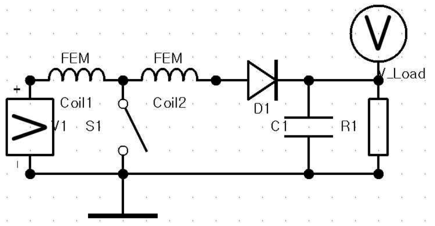


Fig. 3. Non-isolated boost converter circuit

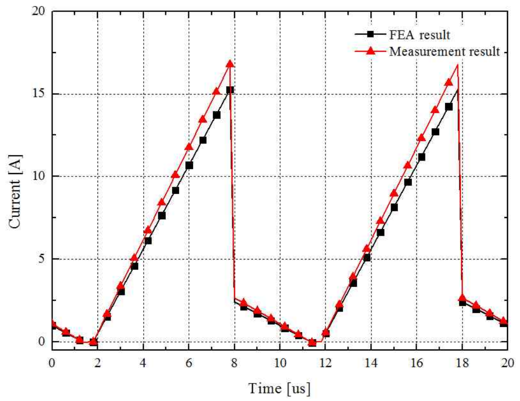


Fig. 4. Comparison of current in primary winding

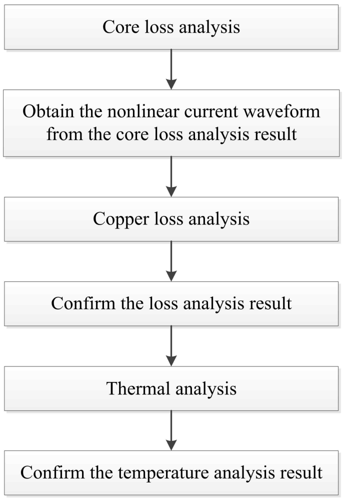


Fig. 5. Thermal analysis procedure

Table 2. Analysis conditions for thermal analysis

Material	Air	Core	Copper	Unit
Density	1.275	4900	8960	kg/m^3
Thermal conductivity	0.026	5	400	w/m/℃
Specific heat	1007	800	380	J/kg/℃

analysis model.

The temperature characteristics of transformer should be analyzed to satisfy the electrical and thermal design criteria because the operating temperature is definitely relevant to the amount of energy transferred in a transformer.

In this paper, the thermal analysis model is based on the amount and distribution of loss in each part of transformer.

Fig. 5 shows the thermal analysis procedure. Firstly, nonlinear current waveforms of primary and secondary windings are obtained by core loss analysis.

Then, copper loss is analyzed by using the current waveforms. Applying the result of core and copper loss, the thermal analysis is executed. The thermal analysis requires thermal conductivity, specific heat and density of each material. The ambient and initial temperature of each part are defined as 20[℃] in an analysis model. The analysis conditions are summarized in Table 2.

3.2 FEA result

In the Table 3, the loss analysis result is displayed. The portion of copper loss is larger than core loss. In addition, the core is partly saturated as shown in Fig. 6.

Fig. 7 and 8 show the core loss density and current density distribution of initial model. This model has a high current density at the edge of flat wire because of skin

Table 3. Loss analysis result of initial model

Model	P_{in} [W]	P_{out} [W]	P_{core} [W]	$P_{cu\text{-}1}$ [W]	$P_{cu\text{-}2}$ [W]	η [%]
Initial	170.3	152.9	5.4	9.7	2.3	89.8

P_{core} = Core loss, $P_{cu\text{-}1}$ = Copper loss of primary winding, $P_{cu\text{-}2}$ = Copper loss of secondary winding, η = Efficiency of transformer

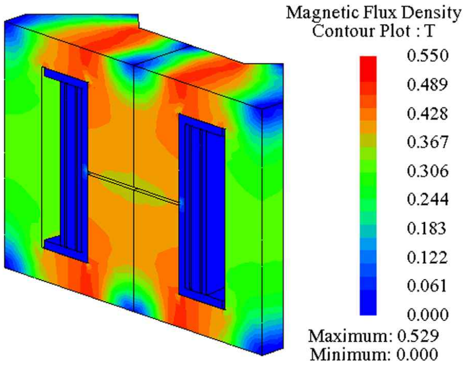


Fig. 6. Flux density distribution of initial model

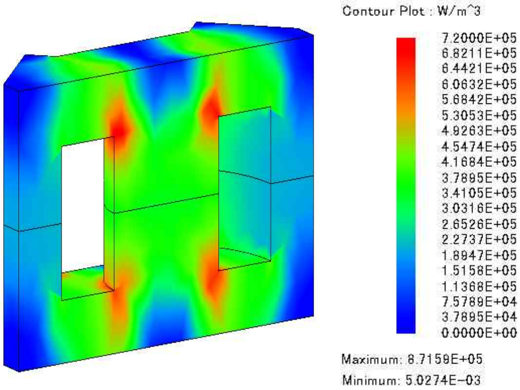


Fig. 7. Core loss density distribution of initial model

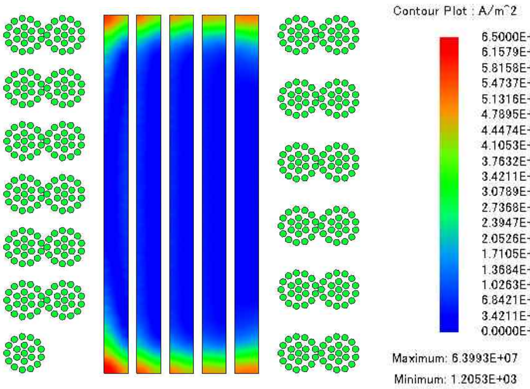


Fig. 8. Current density distribution of initial model

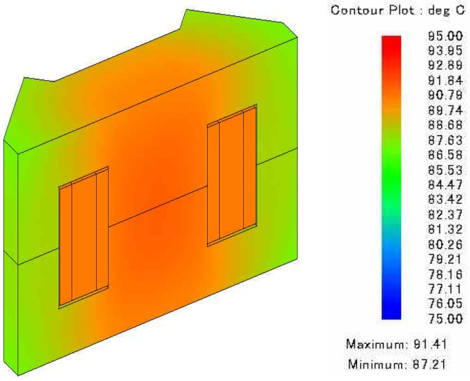


Fig. 9. Temperature distribution of initial model

effect. Due to the high current density, the average temperature is 91[℃] as shown in Fig. 9.

4. Design Optimization Procedure & Result

4.1 Design optimization procedure

The total loss of transformer is minimized when the copper loss is approximately equal to core loss regardless of operating frequency as shown in Fig. 10 [2].

The proposed optimization procedure is based on the correlation characteristics between the core and copper loss to improve the efficiency of transformer.

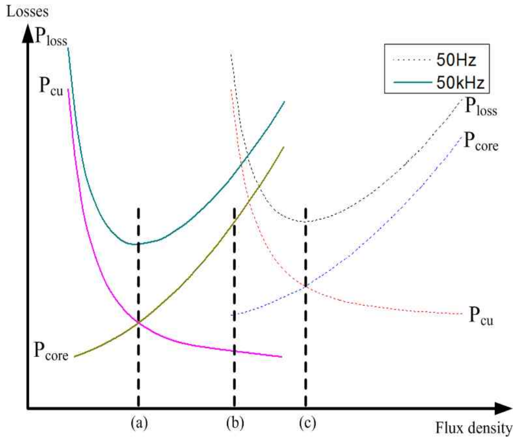


Fig. 10. Correlation characteristics between core and copper loss according to operation frequency variation

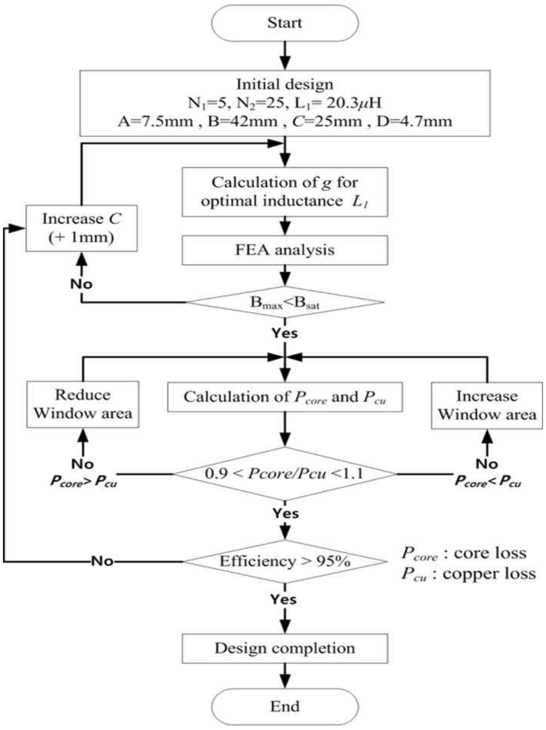
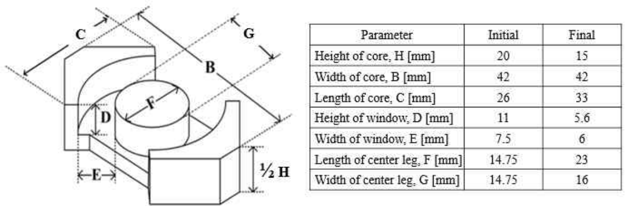


Fig. 11. Proposed design optimization procedure



Parameter	Initial	Final
Height of core, H [mm]	20	15
Width of core, B [mm]	42	42
Length of core, C [mm]	26	33
Height of window, D [mm]	11	5.6
Width of window, E [mm]	7.5	6
Length of center leg, F [mm]	14.75	23
Width of center leg, G [mm]	14.75	16

Fig. 12. Parametric 3D CAD model for optimization and design optimization result

In this procedure, the window area of core is major factor for the optimization instead of the flux density as shown in Fig. 11. The air-gap calculation is based on the amount of energy stored in the primary winding during the switch component turned on in order to prevent a saturation current in the primary winding. The parametric 3D CAD model for optimization and design optimization result are displayed in Fig. 12.

4.2 FEA Result of optimized model

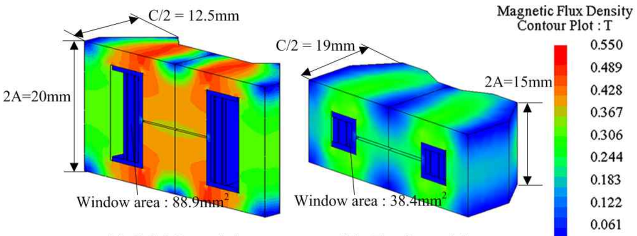
The core structure and flux density distribution of optimized model are compared with initial model as shown in Fig. 13. The wire type is changed flat to litz, this is because of the uniform current density distribution. As a result, the minimum window area of core is reduced. Whereas the effective cross-sectional area of core is expanded to remove local saturation points in the core.

As a result of optimization, the core and copper loss is reduced. In the Table 4, the loss of initial and optimized model is compared.

The efficiency at the rated output power is improved about 6[%] compared with initial model. The volume of optimized core is reduced about 13[%].

Due to the reduced core size, the core loss density of optimized model is increased as shown in Fig. 14 but the amount of core loss is lower than the initial model. The uniformed current density of optimized model is shown in Fig. 15.

The average temperature of optimized model is reduced



(a) Initial model (b) Final model

Fig. 13. Comparison of flux density distribution

Table 4. Comparison of loss analysis result

Model	P_{in} [W]	P_{out} [W]	P_{core} [W]	P_{cu-1} [W]	P_{cu-2} [W]	η [%]
Initial	170.3	152.9	5.4	9.7	2.3	89.8
Final	161.7	154.2	3.5	2.2	1.8	95.4

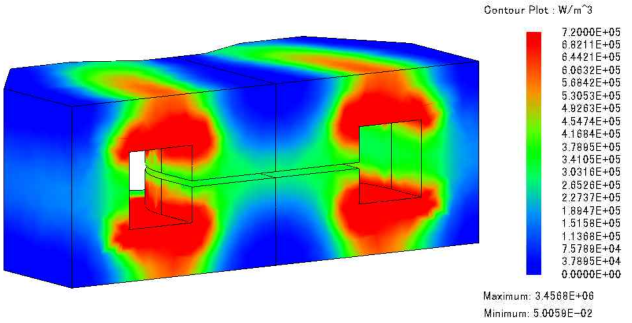


Fig. 14. Core loss density distribution of optimized model

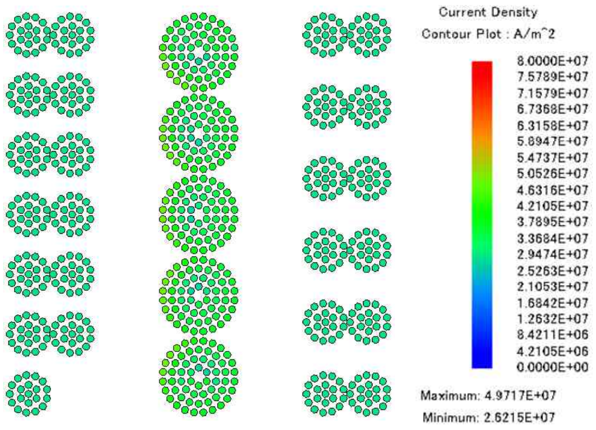


Fig. 15. Current density distribution of optimized model

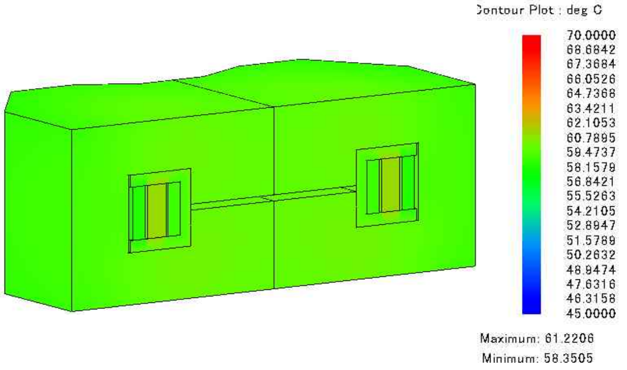


Fig. 16. Temperature distribution of optimized model

(a) Initial model

(b) Final model

Fig. 17. Prototypes for test

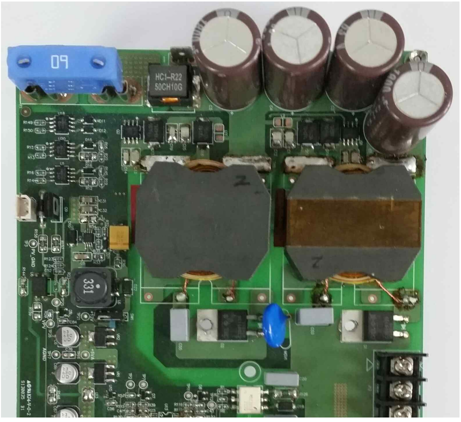


Fig. 18. PCB for test

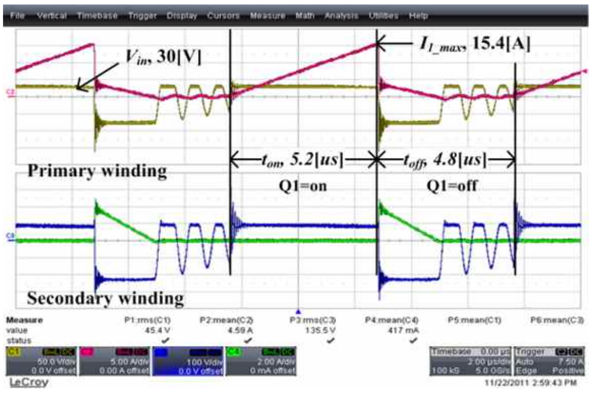


Fig. 19. Measurement result of voltage and current waveform of each winding

about 33[%] compared with initial model. The temperature distribution of optimized model is shown in Fig. 16.

5. Experiment result

Figs. 17 and 18 show the prototypes and PCB for the efficiency and thermal test. The tested PCB has two parallel connected converters. However, the only one of converters on the PCB is used in this paper.

Because of outer case, the temperature of each part are measured by using the thermocouple.

Fig. 19 shows the measurement result of voltage and current waveform of converter. The efficiency at the rated output power is improved about 6[%]. The overall efficiency is also improved as shown in Fig. 20.

Fig. 21 shows the temperature of each part. In order to maintain a constant ambient temperature, the test is done in a chamber. The temperature of winding and core are saturated at 61[℃], 57.5[℃] respectively after 1 hour.

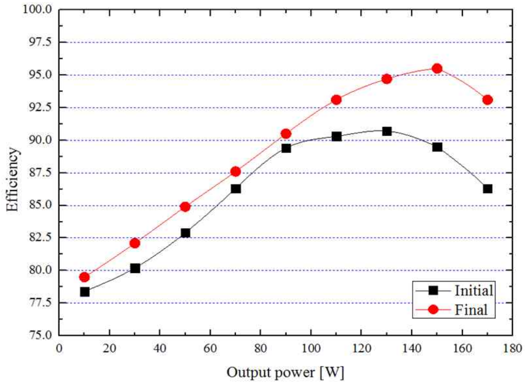


Fig. 20. Measurement result of efficiency according to output power variation

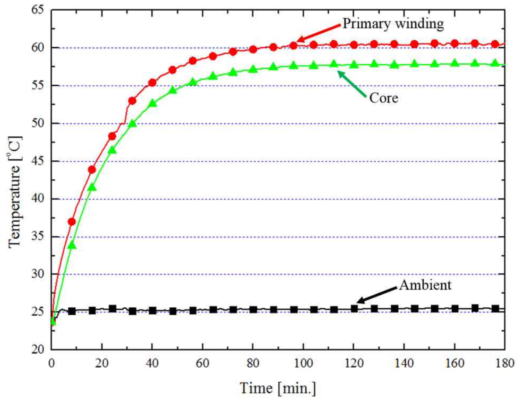


Fig. 21. Measurement result of temperature at rated output power

6. Conclusion

In this study, the optimization procedure and modeling method are proposed to design the high efficiency transformer in compact size. We demonstrated the proposed procedure to test its validity.

The proposed design procedure is based on the correlation characteristics between the core and copper loss. This method can be applied to any kind of transformer regardless of the operating frequency according to correlation characteristics between the core and copper loss.

In order to compare the component ratio of losses, the 3D FE model is also proposed in this paper. Instead of losses, the current waveform in the primary winding is compared to validate the accuracy of proposed model.

In addition, the thermal analysis model is proposed to satisfy the thermal design criteria. By using the proposed procedure, the core volume is reduced about 13 [%] and the efficiency is improved about 6 [%]. The average temperature of each part is decreased by changing the wire type about 33[%].

Acknowledgements

This work was supported by the Kyungnam University Foundation Grant, 2013.

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