Design of an Integrated Magnetics Structure for LLC Resonant Converter

Chul Wan Park
Power Electronics System Laboratory, POESLA
Kookmin University
77 JeongNeung-Ro, SeongBuk-Gu, Seoul, 02707, Korea(South)
E-mail : cjfdhks88@naver.com

Sang Kyoo Han
Power Electronics System Laboratory, POESLA
Kookmin University
77 JeongNeung-Ro, SeongBuk-Gu, Seoul, 02707, Korea(South)
E-mail : djhan@kookmin.ac.kr

***Abstract*—This paper, we propose IM (Integrated Magnetics) structure for LLC resonant converter. The IM technique can combine several components into one magnetic core, plus, utilizing a planar magnetic core is a suitable device to achieve high power density. Therefore, it can achieve high power density in Switch Mode Power Supply (SMPS) because the total volume is almost determined by the magnetic components. However, when adopting a planar magnetic core in LLC resonant converter, it is difficult to attain enough resonant inductance due to high coupling characteristics. This leads to using an additional inductor as a resonant inductor, thus, the total power density is decreased. To overcome this limitation, the proposed structure uses magnetizing inductances as resonant inductor so that all resonant parameters can be made equally in one magnetic core. Therefore, high power density can be achieved. Moreover, optimal design can be achieved easily because all of the resonant parameters are controllable. To verify the validity of the proposed structure, a magnetic analysis and an efficiency comparison are discussed, then, experimental results of 350W half bridge prototype are presented.**

Keywords—Integrated Magnetics, LLC Resonant Converter, High Efficiency, High Power Density, High Switching Frequency.

I. Introduction

In the current electric marketplace, most of the applications are becoming smaller and require high power density, high efficiency, and low cost. Considering the entire volume of a system, the magnetic components such as inductors and transformers take up the most space, so the development of power converter applications has moved toward achieving high switching frequency resulting in a reduction in magnetic volume. Although the switching losses are proportional to the frequency, the volume of the magnetic components can be dramatically reduced [1]. In this aspect, as shown in Fig. 1, the LLC resonant converter has generally been adopted in various applications to provides low switching loss and high efficiency in higher frequency operations [2].

The LLC resonant converter is constructed using three series of resonant parameters (magnetizing inductor L_p, resonant inductor L_s and resonant capacitor C_s) to control the output power. The output voltage can be regulated under wide load conditions around the point where the switching frequency and the resonant frequency are equal so that the output voltage can be controlled within a narrow switching frequency range under all load conditions. Furthermore, Zero Voltage Switching (ZVS)

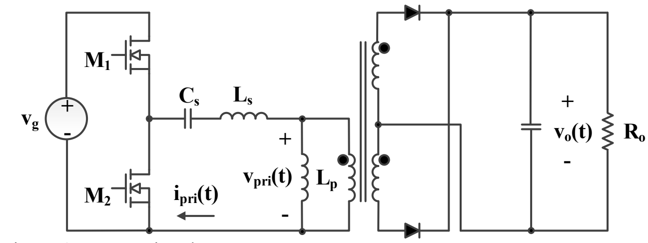


Figure 1. Conventional LLC resonant converter

can be achieved with the peak current of the magnetizing inductor under all load conditions so that the LLC resonant converter can operate in high switching frequency with low switching losses [3][4].

Even with the topology, to achieve higher power density, reducing the magnetic components is an intensive factor. Among the various options, planar magnetic core is a reasonable choice. Since planar magnetics use the PCB patterns as wire, the volume of magnetic components can be minimized. Apparently, compared to generally using ferrite magnetic under same conditions, planar magnetics has a lower and narrow structure, plus, the distances between line can be minimized due to its line structure and the characteristics in high frequency such as the proximity effect and the skin effect can be greatly reduced.

Moreover, parasitic inductance can be minimized because of planar magnetics' high magnetic coupling characteristic so that the circulating losses made by parasitic inductance can also be minimized. With these aspects, planar magnetics are optimal components to obtain high power density.

With planar magnetics, IM techniques have been presented to integrate several magnetic components into one magnetic core by sharing the magnetic flux path. Therefore, the total number of components can be greatly reduced. As a result, high efficiency and high power density can be achieved [5].

In this paper, the IM structure for LLC resonant converter is presented. The proposed IM structure adopts a planar magnetic core to achieve high power density. To overcome the shortage of leakage inductance, it uses a magnetizing inductor as a resonant inductor so that all resonant parameters can be made equally as conventional LLC resonant converter. Therefore, all parameters are controllable and optimal design is easily achieved.

Moreover, with the IM structure, the transformer and additional resonant inductor constructed into one magnetic core by sharing the magnetic flux path. Therefore, the number of component is reduced and high power density can be achieved.

To verify the validity of the proposed structure, the equivalent electrical models based on duality theory, and its loss analysis are discussed, and simulation and experimental results are presented.

II. Overview of the Conventional Magnetics for a High Power Density LLC Resonant Converter

A. Employing a Planar Transformer to Conventional LLC Resonant converter

As describe previously, a planar magnetic core is employed in LLC resonant converter to achieve high power density. Fig. 2 shows its magnetics structure. To maximize the characteristics of the planar magnetic core, primary windings are split in outer leg, and secondary windings are coupled in each leg. Therefore, the number of layers can be decreased by half, and the power density can be increased. In this structure, the flux in the center leg is canceled so that it decreases the magnetic core losses. Moreover, in outer legs, each flux is equal because its winding structure is symmetrical. Therefore, this structure is reasonable.

However, this structure has a limitation of getting enough resonant inductance because of its high coupling characteristic. Although in LLC resonant converter, the resonant inductance L_s is made by the leakage inductance of the transformer, thus in this structure, the leakage inductance is up to hundreds of nH, so that it is difficult to obtain enough resonant inductance. For this reason, an additional inductor is essential and used separately.

As a result, the power density is decreased and inverses the effectiveness of the planar magnetic core.

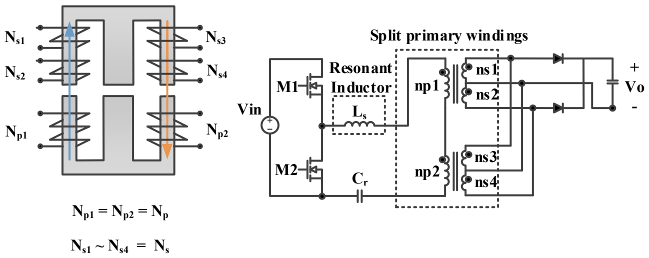


Fig. 2. Employing planar magnetics in conventional LLC resonant converter.

B. A Discrete Magnetics Solution for LLC Resonant Converter

To integrate resonant inductance and magnetizing inductance into one magnetic core, a lot of structures have been designed and presented. As described previously, resonant network of LLC resonant converter is constructed by inductor L_s and magnetizing inductor L_p. Therefore, both elements are need to be integrated into one magnetic core. Fig. 3, shows a discrete integrated magnetics model. To integrated all resonant parameters, each magnetic component is constructed separately in each outer leg so that the two magnetic components can be combined into one magnetic core. Flux from both the transformer and inductor is added in the outer legs, but in the center leg, the flux is cancelled. Therefore, the flux density is much smaller than the outer leg, and decreases core losses.

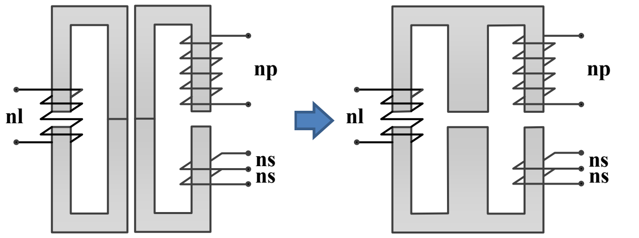


Fig. 3. Conventional integrated magnetics structure for LLC resonant converter.

However, in each outer leg, the currents of the resonant inductor and the magnetizing inductor are different, so the flux densities of each leg are different [6]. This will increase magnetic losses because of unbalanced flux density. Moreover, since all primary turns are built in one of the outer legs, the number of layers increases in proportion to the required primary turns. Therefore, the discrete magnetics solution is not suitable to obtain high power density.

III. The Proposed Integrated Magnetics structure for LLC Resonant Converter

A. Equivalent Inductance Model Analysis

The proposed IM structure for LLC resonant converter is shown in Fig. 4. In this structure, the magnetizing inductor is used as a resonant inductor so that the resonant inductor and magnetizing inductor can be combined into one magnetic core.

As shown in Fig. 4(a), the proposed structure consists of two primary windings, N_{p1} and N_{p2}, and two secondary windings, N_{s1} and N_{s2}. Each primary and secondary winding is wound on the outer legs of the magnetic core as a pair, and the primary windings are connected to each other. The total primary windings (N_{p1}+N_{p2}) act as the primary turn ratio of the transformer, and each secondary turn acts as a secondary turn ratio. For the symmetric operation in the LLC resonant network operation, N_{p1} and N_{p2} are the same as N_p, and N_{s1} is equal to N_{s2} (as N_s).

Fig. 4(b) shows the reluctance model of the proposed IM structure. In this model, each reluctance is determined as follows:

$$R_o = \frac{l_{g_o}}{\mu A_o}\ ,\ \ R_c = \frac{l_{g_c}}{\mu A_c}\ , \qquad (1)$$

where, A_c and A_o are the cross-sectional areas of the center and outer legs, respectively; l_{go} and l_{gc} are the magnetic path lengths of the center and outer legs respectively; and μ is the

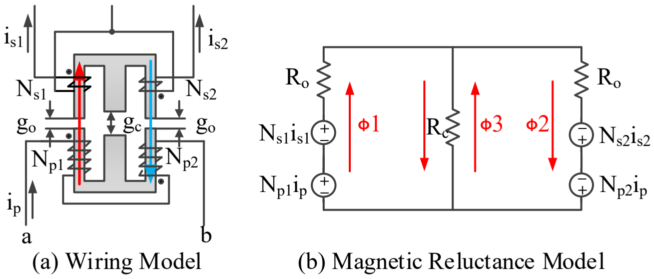
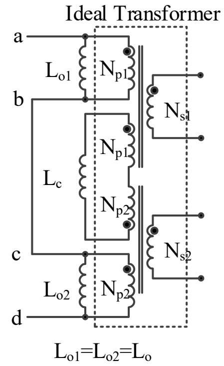


Fig. 4. The proposed magnetic structure for LLC resonant converter.



$$L_{o2} = \mu \frac{A_o N^2}{g_o} \quad (2)$$

$$L_{o2} = \mu \frac{A_o N^2}{g_o} \quad (3)$$

$$L_c = \mu \frac{A_c N^2}{g_c} \quad (4)$$

Fig. 5. The equivalent inductance model of the proposed IM structure.

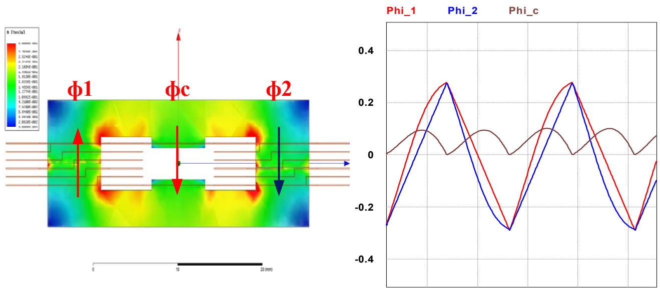


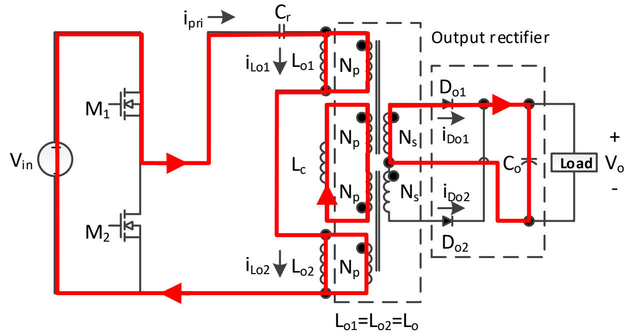
Fig. 6. The flux density of the proposed IM structure

permeability of air. Using the reluctances of the magnetics structure, the inductances are revealed as proportional to the square of the primary turns.

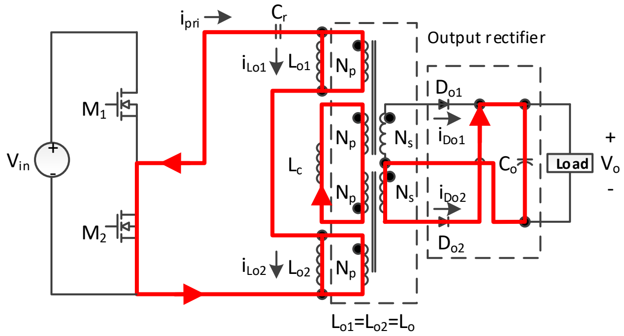
In the circuitry approach, the reluctance model can be derived into an equivalent inductance model using the duality modeling theory [7], [8]. Fig. 5 shows the equivalent inductance model of the proposed magnetics structure. In this model, the reluctance model is transferred to three types of inductances (L_{m1}, L_{m2}, and L_c) and two ideal transformers. L_{m1} is equal to L_{m2} (as L_m) because N_{p1} is equal to N_{p2}.As mentioned in equation (1), each inductance is affected by its air gaps (g_c and g_o), center and outer magnetic cross-sectional area (A_c and A_o), and the turn ratio of the transformer, so that all inductances are controllable by its magnetics structure.

Compare to the discrete magnetics solution model, two resonant components are structurally combined into one magnetic core. Since the resonant and transformer operations occur apart in each outer leg, each current is different and the flux density reveals asymmetry [6]. This leads to increased core loss, and an increase in the effective area of the magnetic component. Since the primary windings are constructed in one of the outer legs, the layers are directly proportional to primary windings. Therefore, the discrete structure is not suitable for high power density.

On the other hand, the proposed IM structure has a symmetrical structure based on the center of the core, so the flux density can be equaled in the outer legs. Since the proposed structure uses magnetizing inductance, the inductances in the outer legs (L_{o1} and L_{o2}) are equal. In each switching period, each magnetizing inductance combines with L_c and alternately becomes resonant inductance. Therefore, the flux density in the outer legs become symmetrical. In the center leg, flux cancelation occurs, and most flux flows to the outer legs. As shown in Fig. 6, the formation of flux density is symmetrical in



(a) Mode1



(b) Mode2

Fig. 7. Mode operations of the IM structure in LLC resonant converter

the proposed IM structure. Since flux in the center leg is smaller than the outer legs, the core loss is determined to the flux in the outer leg.

Moreover, split primary windings to the outer legs are adopted, so the proposed IM structure can decrease the number of primary turns by half and an additional inductor is not necessary. Therefore, high power density can be achieved [9].

B. Operation Analaysis

To apply the proposed IM structure to the LLC resonant converter operation, resonant capacitor C_r and output rectifiers are connected. Fig. 7 shows its mode operations, and equivalent circuits. In this paper, the primary side utilized a half bridge configuration and the secondary side adopted a center-tapped rectifier. The proposed IM structure can be used in a full bridge configuration as well.

In mode 1, the high side switch M1 is driving. During this period, the input voltage is applied to the dot terminal of the transformer and the output power is transferred through output rectifier D_1. Thus, the output voltage is applied to L_{o1} inductance, so that L_{o1} operates as a magnetizing inductance L_p in conventional LLC resonant converter, and the current increases linearly. At the same time, the L_{o2} inductance is parallel with L_c, and the transformer does not operate because output rectifier D_2 is reverse biased, so the combination inductance (L_{o2} and L_c) is resonant to primary capacitor C_r and transfer primary energy to output through N_{s1}. Therefore, the resonant inductance L_s can be represented as

$$L_s = \frac{L_o \cdot L_c}{L_o + L_c} . \quad (5)$$

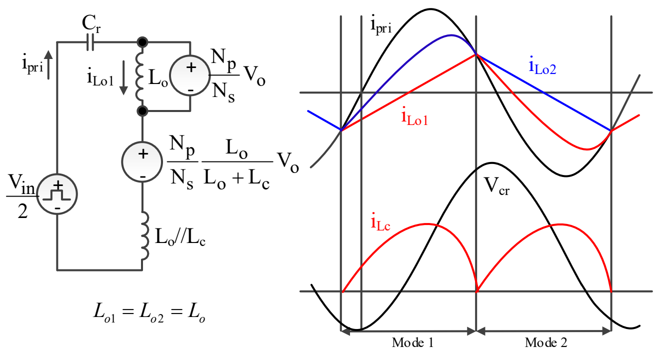


Fig. 8. Key waveforms of a resonant network

In mode 2, while the low side switch M_2 is driving, the voltage of the transformer is applied to the non-dot terminal, thus the operation is reversed; L_{o2} becomes the magnetizing inductance and L_{o1} is resonant to the primary capacitor with L_c in parallel. Therefore, the proposed IM structure can produce equivalent resonant parameters with three magnetizing inductances. In a resonant network, the equivalent inductance model can be simplified. Fig. 8, shows the equivalent circuit of a resonant network, and its key waveforms.

As shown in Fig. 8, the combination of magnetizing inductances can induce the resonant operation with a capacitor. Compared to conventional LLC resonant network, the proposed structure contains a voltage source. Therefore, magnetizing inductor L_c and the additional voltage source are considered, and its current and voltage are respectively as

$$i_{pri}(t) = \omega C\left(\frac{V_{in}}{2} - nV_o\left(1+\frac{L_o}{L_o+L_c}\right) - V_{c\_peak}\right)\sin(\omega t) \,, \tag{6}$$

$$\begin{aligned} V_c(t) = {} & \frac{V_{in}}{2} - nV_o\left(1+\frac{L_o}{L_o+L_c}\right) \\ & - \left(\frac{V_{in}}{2} - nV_o\left(1+\frac{L_o}{L_o+L_c}\right) - V_{c\_peak}\right)\cos(\omega t) \end{aligned} \,. \tag{7}$$

IV. Design Methodology

The main purpose of design methodology is to obtain the point of highest efficiency with the required maximum gain to ensure a wide operational range of LLC resonant converter.

As described previously, the resonant network of the proposed IM structure is constructed using three magnetizing inductances L_o (equal to L_{o1} and L_{o2}), L_c, and resonant capacitor C_r; all of the parameters are controllable. Therefore, all parameters can be selected optimally. As shown in Fig. 8, the proposed IM structure can make the equivalent conformation as LLC resonant converter.

In a resonant network, L_m is determined under the maximum gain condition in the hold-up time as

$$L_o = \frac{V_{in} n^2 2R_o L_n}{nV_o\left(F-\frac{1}{F}\right)\pi^3 f_r}\sqrt{1-\left(\frac{2nV_o}{V_{in}}\right)^2\left\{1+\frac{1}{L_n}\left(1-\frac{1}{F}\right)\right\}^2} \,, \tag{8}$$

where, n is the turn ratio of the transformer, the proportion of magnetizing inductance and resonant inductance is represented by L_n, and the rate of switching frequency and resonant frequency is represented by F. In practice, F and L_n are determined by designer.

According to the equivalent circuit of proposed structure, the turn ratio of the transformer can be selected as well. Using KVL, the turn ratio is represented by equation (9). Unlike a conventional LLC resonant converter, the turn ratio is affected by the resonant parameters (L_{o1}, L_{o2} and L_c).

$$n = \frac{V_{in}}{2V_o}\frac{L_o+L_c}{2L_o+L_c} \,. \tag{9}$$

Since in the proposed IM structure, the primary turn ratio is determined by the sum of the turns of outer legs, the total primary turn ratio is twice n and it has more turns than a conventional LLC resonant converter. Under the same conditions, the core loss is inversely proportional to the number of turns. Therefore, the proposed IM structure can reduce the magnetic loss compare to a conventional structure.

With the resonance parameters, the optimal operating point can be selected by loss analysis. For the highest efficiency point, total losses should be calculated. Each loss is determined by Table. I.

In the switching operation approach, the turn-on loss is zero because of the ZVS operation. Therefore, the turn-off losses and conduction losses are the majority in the switching losses.

In the turn-off operation, for hard switching, the current of the switch crosses to its voltage, which results in switching losses. During the turn-on operation, the rms current is obtained by equation (10), and the conduction losses can be determined with the $R_{ds(on)}$ value of the switch.

$$i_{sw\_rms} = \frac{\omega C_r}{2}\left(\frac{V_{in}}{2} - nV_o\left(1+\frac{L_o}{L_o+L_c}\right) - V_{cp}\right) . \tag{10}$$

On the secondary side, the current of the rectifier operates on the ZCS (Zero Current Switching). Therefore, the turn-on and turn-off losses are close to zero. Thus, the conduction loss is a large part of the losses from the rectifier.

In this paper, each loss is calculated under V_{in} = 390 V, V_o = 19.5 V (350 W) conditions. By the losses analysis, total losses can be calculated as efficiency, and the results are shown in Fig. 9. In the lower L_n values, 800kHz~1MHz has the highest efficiency. Therefore, this process can provide all of the resonant parameters at the optimal frequency point.

TABLE I. Equations for Loss Analysis

Loss Analysis Parameters		Equation
Switch	Turn off losses	$P_{turn-on} = \frac{1}{2} \cdot t_f \cdot V_{ds} \cdot i_v \cdot f_{sw}$
	Conduction losses	$P_{conduction} = i_{swrms}{}^2 \cdot R_{ds(on)}$
	C_{gs} losses	$P_{cgs} = 2\left(\frac{1}{2} \cdot C_{gs} \cdot V_{gs}{}^2 \cdot f_{sw}\right)$
Transformer	Core losses	$Pcv = k \cdot B^{\alpha} \cdot f^{\beta} \cdot V_e$, $B = \frac{L \cdot I_{PK}}{N \cdot A_e} 10^4$
	Wire losses	$R_{dc\_pri} \cdot I_{sw\_rms}{}^2 + R_{dc\_second} \cdot I_{d\_rms}{}^2$
Synchronous Rectifier	Conduction losses	$P_{SR\_conduction} = i_{SR\_rms}{}^2 \cdot R_{ds(on)}$

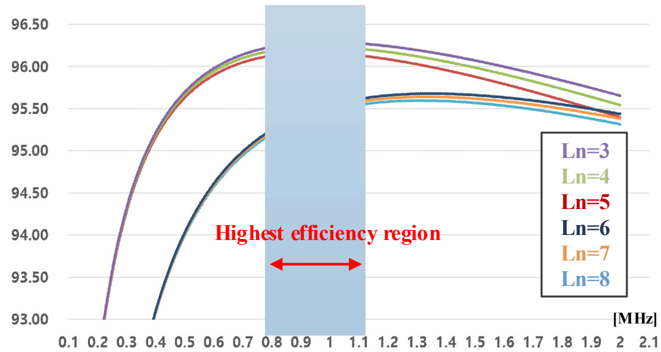


Fig. 9. Total efficiency in frequency variation according to Ln (Ln=Lp/Ls)

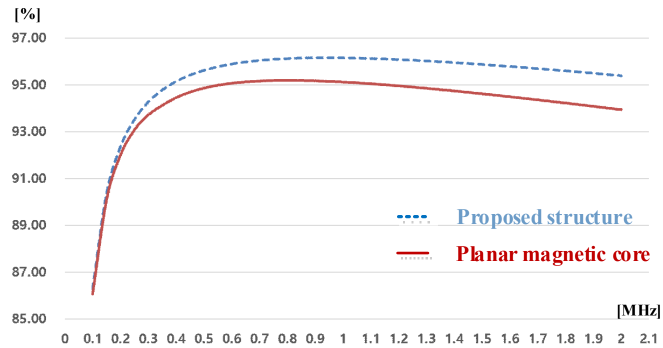


Fig. 10. Theoretical efficiency comparison in frequency variation

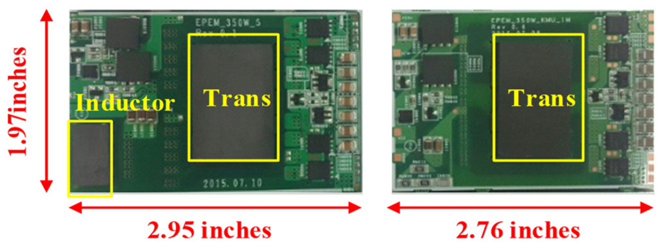
In the high frequency region, the turn ratio is 6:1, L_p = 18 uH, L_s = 8.9 uH, C_r = 6.6 nF, and 800 kHz resonant frequency are selected in this paper.

Fig. 10 shows the efficiency comparison of employing planar magnetics in LLC resonant converter and the proposed structure. As describe earlier, the IM structure can save the losses from an additional inductor, so it can obtain higher efficiency under frequency conditions.

V. Experimental Results

To verify the validity of the design and performance of proposed structure, a 350W prototype was implemented and tested. Fig. 11 shows a comparison of the proposed IM structure with the employing planar magnetics in LLC resonant converter.

As describe previously, the proposed structure uses a magnetizing inductor instead of an additional inductor to compensate for the resonant inductor L_s, so the additional inductor is not necessary. Therefore, higher efficiency and power density can be achieved. In the prototype, it is increased from 122 W/inch^3 to 131W/inch^3.



(a) Employing planar magnetics (b) Proposed structure

Fig. 11. 350W Prototype Comparison (Employing planar magnetics & proposed structure)

TABLE II : Experimental specifications

Parameter	Value	Unit
Input Voltage	320~390	V
Output Voltage	19.5	V
Output Power	350	W
L_o(=L_{o1}=L_{o2})	18	uH
L_c, L_s	8.9 / 5.5	uH
C_r	6.6	nF
f_{sw}	800	kHz
$f_{sw\_minimum}$	560	kHz
Number of turns	6:6:1:1	

The I/O specifications and all resonant parameters are shown in Table II, and the test results are presented.

Fig. 12 and Fig. 13 show the key waveforms at the normal and holdup time operation, respectively. In normal operation, the switching frequency and resonant frequency are closed at 800kHz. Under the hold-up time condition, the input voltage as minimum value, the switching frequency is reduced to the minimum frequency (567kHz) to compensate for the voltage gain.

While the load is changed, the operating frequency range is very narrow from 794 kHz to 567 kHz under all load conditions. Comparing the design consideration to the experimental results, the proposed structure operated closely to the design considerations.

Fig.14 shows the resonant current. Since the proposed IM structure uses a combination of inductances, comparing each parameter to the design is needed. In experimental results, the parameters are calculated as L_o = 17.41 uH, and L_s = 5.44 uH, and have a 1% error with the theoretical values. Therefore, this structure operates the same as the equivalent circuit analysis.

The results of efficiency are shown in Fig. 15. The efficiency varies from about 71.93% to 95.53% under all load conditions. Comparing these experimental results to the theoretical analysis, both results are very close and the error is less than 1%. Thus, the theoretical analysis is reasonable.

Moreover, the proposed IM structure can save additional losses in the resonant inductor. Therefore, it can provide higher efficiency than the employing planar magnetics in LLC resonant converter. As shown in Fig. 15 (b), the proposed IM structure has higher efficiency under all load conditions. Therefore, with the proposed magnetic structure, higher efficiency and higher power density can be achieved.

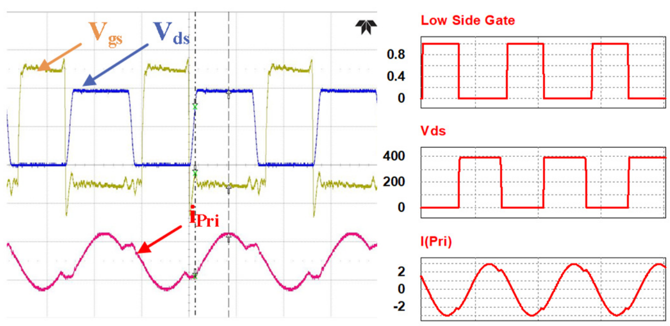


Fig. 12. Experiment waveforms & Simulation waveforms for 390 V input, 794 kHz, full load

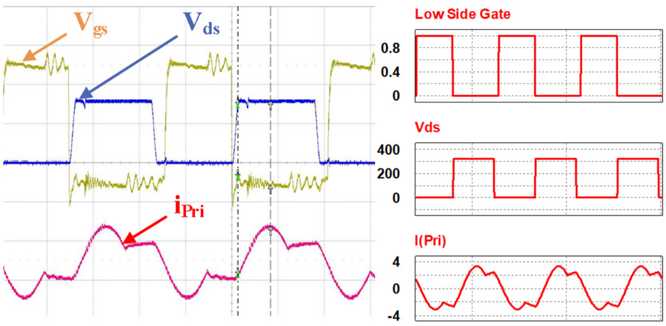


Fig. 13. Experiment waveforms & Simulation waveforms for 320 V input, 567 kHz, full load

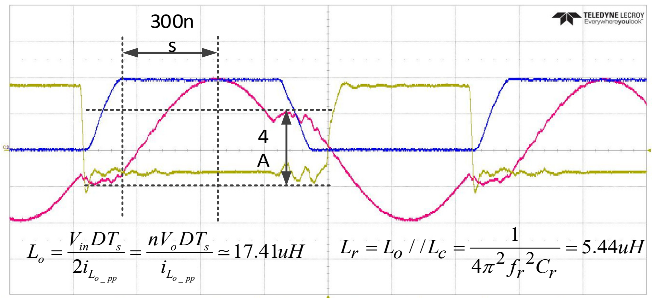
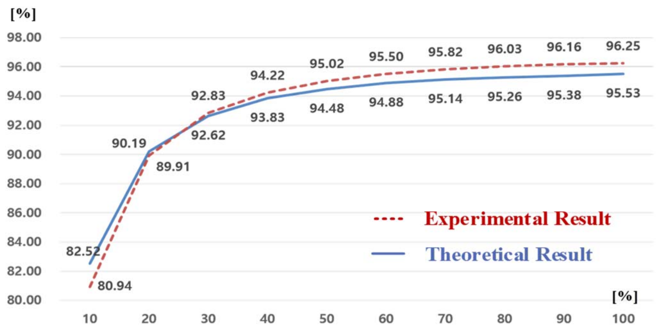
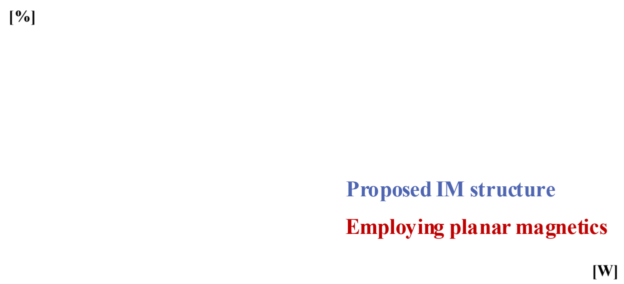


Fig. 14. Calculation of resonant parameter



(a) Experimental result vs Theoretical result



(b) Proposed IM structure vs Employing planar magnetics

Fig. 15. Efficiency comparison between proposed IM structure and employing planar magnetics

VI. Conclusions

To achieve high power density, IM structures for LLC resonant converter have been proposed. Moreover, planar magnetics is adopted for higher power density.

However, because of the high coupling characteristic, an additional inductor is essentially used separately to compensate for the lack of resonant inductances.

To overcome this limitation, proposed an IM structure uses magnetizing inductance as a resonant inductor so that making equivalent resonant and magnetizing inductance in one magnetic core is possible. Therefore, the number of components can be reduced and total power density increased.

Comparing to conventional discrete magnetic solution and employing planar magnetics model, the proposed structure can reduce the number of magnetic components and save the total loss. Therefore, higher power density and higher efficiency can be achieved.

Moreover, using magnetizing inductance as resonant inductor easily provides an optimal design, because all parameters can be controllable.

From the experimental results of the 350 W prototype, the proposed IM structure can operate equally as LLC resonant converter without an additional inductor. The overall power density was improved and the maximum efficiency was up to 95.53% under full load condition.

From these results, the proposed IM structure is not only an example, but also an expansion of guidelines for considering high power density converters.

Acknowledgment

This research was supported by the program ("Development of subminiature post power conversion system for next generation geostationary satellite" (NTIS-2011-0030431)), under the KARI (Korea Aerospace Research Institute).

References

[1] Bing Lu, Wenduo Liu, Yan Liang, Fred C.Lee, Jacobus D. van Wyk, "Optimal Design Methodology for LLC Resonant Converter" in IEEE-APEC 2006, pp. 533-538

[2] B.Yang, F.C. Lee, A.J. Zhang, G. Huang, "LLC resonant converter for front end DC/DC conversion," in IEEE-APEC 2002, pp. 1108-1112

[3] Cove, Samuel R., et al. "Integrated magnetic design of small planar transformers for LLC resonant converters." 2011 IEEE Energy Conversion Congress and Exposition. IEEE, 2011.

[4] Yanjun Zhang, Dehong Xu, "1MHz-1Kw LLC Resonant Converter wih Integrated Magnetics" in IEEE-APEC 2007, pp. 955-961

[5] Chen, Wei, et al. "Design of high efficiency, low profile, low voltage converter with integrated magnetics." Applied Power Electronics Conference and Exposition, 1997. APEC'97 Conference Proceedings 1997., Twelfth Annual. Vol. 2. IEEE, 1997.

[6] Yang, Bo, Rengang Chen, and Fred C. Lee. "Integrated magnetic for LLC resonant converter." Applied Power Electronics Conference and Exposition, 2002. APEC 2002. Seventeenth Annual IEEE. Vol. 1. IEEE, 2002.

[7] Hamill, David C. "Lumped equivalent circuits of magnetic components: the gyrator-capacitor approach." IEEE transactions on power electronics 8.2 (1993): 97-103

[8] Hamill, David C. "Gyrator-capacitor modeling: a better way of understanding magnetic components." Applied Power Electronics Conference and Exposition, 1994. APEC'94. Conference Proceedings 1994., Ninth Annual. IEEE, 1994.

[9] Valdivia, V., et al. "Improving the design of integrated magnetics for power electronics systems." Power Electronics Specialists Conference, 2008. PESC 2008. IEEE. IEEE, 2008.