Efficiency Improving Strategies on GaN-based LLC Converter with Non-uniform Air Gap Transformer

Ching-Guo Chen[1*], Shiu-Hui Lee[2], Wen-Nan Huang[1], Chih-Ming Yu[1]and Hsiang-Chi Meng[1]
1 Potens Semiconductor Corp. Zhubei City, Hsinchu County, Taiwan
2 Department of Electrical Engineering, National Taipei University of Technology, Taipei, Taiwan
*E-mail: tim@potens-semi.com

***Abstract*— Strict efficiency requirements for power supply unit (PSU) are certified by EPA, ErP/EuP, ENERGY STAR, etc. The manufacturers pay strong attention to these requirements and adopt new circuit topologies or control strategies for PSU design to meet high efficiency. In this paper, the adaptive driving strategies(ADS) on efficiency improvement are presented with the topologies of Gallium Nitride (GaN) based LLC converter utilizing non-uniform air gap transformer. The dynamic gate voltage control is effective for power saving at light load and for low switching losses at rated load. Furthermore, the LLC converter utilizing non-uniform air gap transformer is conducted through variation of magnetizing inductance to reduce power loss to perform light load efficiency improving. The experimental results are demonstrated on the LLC converter of 400V input voltage, 300kHz, 300W and 12V output voltage. The efficiency of the LLC converter can achieve 98.3% at rated output power and 92.3% at 10W output power.**

Keywords*— *Adaptive driving, dynamic gate drive, GaN-based LLC Converter, and non-uniform air gap transformer.

I. INTRODUCTION

Electronic product manufacturers are constantly demanded to reduce the power consumption of their products due to large increasing in consumer electronic products. The effective ways is to improve the efficiency of the power supply unit. For power supply unit (PSU) with rated output 150W~600W in desktop PC, TV, and game console applications, the performance on efficiency is generally the basic product requirement for energy saving. Among circuitry topologies, LLC converter are usually chosen as the main DC/DC topology, shown as Fig. 1. The LLC half bridge, for S_1 and S_2, also uses GaN as power device for performing high efficiency and high power density DC/DC conversion with soft switching and isolated function. In [1]-[2], though the advantages while applying LLC using GaN are presented, the parameter optimization for transformer in actual application needs further analyzed. In addition, focusing on efficiency improvement for whole loading range, especially at light load condition, is another topic needs to propose the upgrading design for making LLC converter perform with higher efficiency [3]-[4].

The proposed driving strategies are focusing on the adaptive design for the circuitries using a wide bandgap GaN to achieve the performance improving on efficiency. As follows, the contributions of the proposed driving strategies can be concluded:

1) Dynamic gate drive control is proposed for GaN-based circuit to improve the working in optimization according to characteristics of GaN semiconductors.
2) The transformer utilizing for LLC converter is designed with adaptive features through dimension of magnetic core to adjust air gap, hence, the inductance level becomes adaptive to make the converter working for optimization in conditions of heavy load and light load with a theoretical derivation for parameterization on magnetic design.
3) The proposed dynamic gate drive voltage, and the LLC converter applying non-uniform air gap transformer are designed and implemented to work as a platform topology successfully by performing high efficiency.

This paper introduces dynamic gate voltage control and GaN-based LLC converter with non-uniform air gap transformer. The next section presents operation principle of LLC converter. Section 3 presents dynamic gate voltage control for the efficiency improvement. The light load control strategy of LLC convert is discussed in Section 4. Experimental results are presented in Section 5 and the conclusion is given in Section 6.

II. OPERATION PRINCIPLE OF PROPOSED CIRCUIT

The LLC convert is a typical soft switching converter which is widely used in DC/DC conversions. The GaNs S_1 and S_2 are the power switches of half bridge and configured to output the square wave voltage. The MOSFETs S_3 and S_4 are the power switches of the secondary side synchronous rectifier for achieving high efficiency.

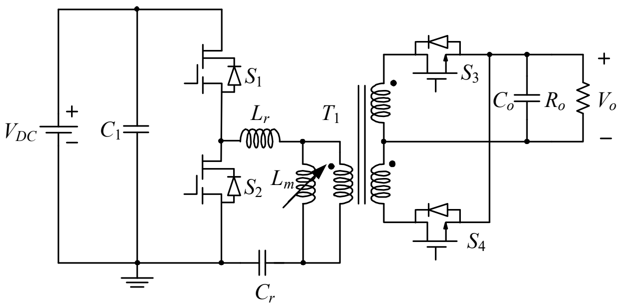


Fig. 1. Circuits of GaN-based LLC converter with non-uniform air gap transformer.

The fundamental harmonic approximation (FHA) method is used to simplify the voltage gain of the LLC converter [5]. By FHA method, the AC equivalent circuit of the LLC converter can be obtained. The resonant tank includes three main components which are resonant inductors L_r, magnetic inductor L_m and resonant capacitor C_r. The resonant frequency is given as

$$f_r = \frac{1}{2\pi\sqrt{L_r C_r}} \tag{1}$$

The voltage gain G of the LLC resonant tank can be expressed as

$$G = \frac{1}{\sqrt{\left(1+1/k(1-\ (f_s/f_r)^2)\right)^2 + Q^2(f_s/f_r - f_r/f_s)^2}} \tag{2}$$

where k is the ratio of inductance for magnetizing inductance to leakage inductance denoting as $k = L_m/L_r$; and f_s is the converter switching frequency, Q is the quality factor denoting as $Q = (\pi^2/8a^2 R_L)\sqrt{(L_r/C_r)}$, and R_L is the equivalent load resistance. According to (2), the voltage gain of the resonant tank under different load conditions.

III. Dynamic Gate Drive Control Scheme

GaN devices have shown high current carrying capability, lower on resistance and higher switching speed compared to Si devices. The driving of GaN devices is also different and with unique characteristics from Si devices. The gate driver optimization of GaN devices is proposed [6]-[7]. In [6], the drive losses and the switching characteristics of a capacitor type gate drive circuit for GaN devices are analyzed to improve the efficiency of the inverter. In [7], the capacitor-less gate driving of GaN devices shows that higher efficiency operation is obtained.

Fig. 2 is the output characteristics of PEB15GC65HDS (Ponens semi.) and shows a relationship between gate current and drain-source current [8]. For driving loss reduction at light load, small gate current should be kept minimum level during turn on period. For reduction of conduction power loss, bigger gate current injection is necessary during turn on period. The driving loss of gate operation can be expressed as below

$$P_{loss} = V_{cc}\, I_g \frac{t_{on}}{T_s} \tag{3}$$

where V_{cc} is the supply voltage, I_g is the gate current, t_{on} is the on-time of the drive, and T_s is the switching period.

Fig. 3 is the dynamic gate drive circuit for improving light load efficiency. There are two PWM signal driving paths at each switch to provide different constant gate currents are adaptive to load current. The selection of the paths is made by the level of the inductor current represents the load condition. The path for light load denotes by L and the other path for heavy load denotes by H. Fig. 4 is the measured waveforms of the gate voltage, the gate current and the driving loss during turn on and off transient by dynamic gate drive control scheme over a wide load range. The driving losses of the dynamic gate drive control are much lower than the driving losses of the conventional gate drive control at light load condition.

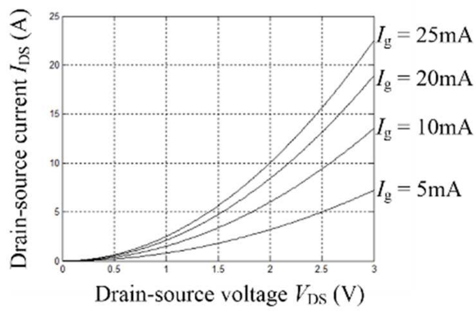


Fig. 2. Output characteristics of GaN.

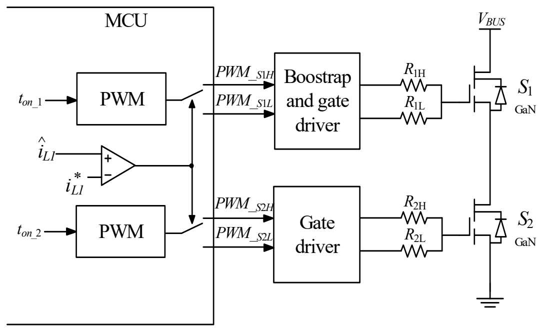


Fig. 3. Dynamic gate driving circuit.

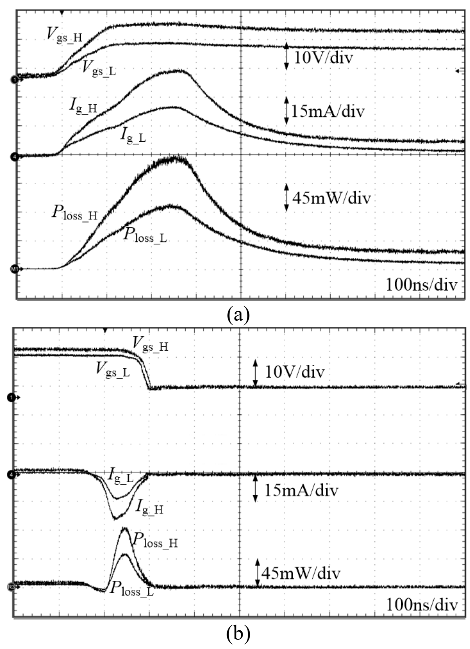


Fig. 4. Gate voltage, current and driving loss.
(a) Turn on, (b) Turn off

IV. Driving Technique of LLC Converter

The utilizing concept of the large leakage inductor for resonant operation which could affect heavy load efficiency is applied to achieve the ZVS switching for performing high efficiency under light load conditions [9]. In addition, an earlier version of this technique was presented at the Int. Power Electronics Conf. and was published in its proceedings [10]. In this paper, the previous work was expanded by:

1) Completing the theoretical derivation of the relation for core dimension and inductance's characteristics from two-state level variant inductance to three-state level variant inductance.
2) Enhancing the depiction of the design approach with the newly proposed core shape in convex type for generating distinctly non-uniform air gap of the transformer.
3) Enriching the implement explanation by more illustrations with the newly applied function circuits.

Hence, the control technique of the LLC converter utilizing a transformer with the step-type air gap with designed core shape performing the variant inductance in three states is proposed to reduce power losses by adjusting the magnetizing current at light load. In this application, a narrower switching frequency range is obtained for better control of transient response at light load and the efficiency is increasing at first-state inductance region. Regarding resonant operation of the LLC DC/DC conversion, the magnetizing inductance is applied herein as the main design parameter of this adaptive driving strategy.

According to the basic LLC operation relation, the adjustable magnetizing inductance L_m in a circuit model is shown in Fig. 5. Further illustration as Fig. 6, a close to three-state inductor with non-uniform air gap is designed to improve efficiency through the adjusting of magnetizing inductance to a larger inductance which means that less magnetizing current to be drawn. Therefore, there would be a reduction on power loss due to smaller of squares of current caused for power losing, and the improving effect is obvious to be gained during light load.

The succeeding explanation of the design for the inductance analysis is given as follows. The variation of adaptive feature for the inductance is implemented by setting the dimension and outline of the air gap for the transformer in LLC circuit. The design of this core applied in this transformer is shown as Fig. 6. It is called as a non-uniform air gap transformer with variant magnetizing inductance for LLC converter in this paper. Meanwhile, Fig. 6 represents the magnetic flux diagram that has saturation characteristics depending on their shape. The magnetic equivalent circuit (MEC) can be drawn by the magnetic flux diagram. The reluctances are shown as

$$R_{c1} = \frac{l_{c1}}{\mu_0\,\mu_r\,A_{c1}} \tag{4}$$

$$R_{c2} = \frac{l_{c2}}{\mu_0\,\mu_r\,A_{c2}} \tag{5}$$

$$R_{c3} = \frac{l_{c3}}{\mu_0\,\mu_r\,A_{c3}} \tag{6}$$

$$R_{g1} = \frac{l_{g1}}{\mu_0\,A_{g1}} \tag{7}$$

$$R_{g2} = \frac{l_{g2}}{\mu_0\,A_{g2}} \tag{8}$$

$$R_{g3} = \frac{l_{g3}}{\mu_0\,A_{g3}} \tag{9}$$

where μ_0 denotes as permeability of air, and μ_r is the relative permeability of the core material. l_{C1}, l_{C2}, and l_{C3} are the effective core length. l_{g1}, l_{g2}, and l_{g3} are the effective air gap length. A_{C1}, A_{C2}, and A_{C3} are the effective core area. A_{g1}, A_{g2}, and A_{g3} are the effective cross-section of air gap. As Fig. 6, the reluctance of the first state the flux goes through R_{g1} is

$$R_{s1} = R_{c1} + R_{g1} + R_{c2} + R_{c3} \tag{10}$$

The reluctance of the second state the flux goes through R_{g1} and R_{g2} is

$$R_{s2} = R_{c1} + R_{g2}\,//\,\left(R_{g1} + R_{c2}\right)\,//\,R_{g2} + R_{c3} \tag{11}$$

The reluctance of the third state the flux goes through R_{g1}, R_{g2}, and R_{g3} is

$$R_{s3} = R_{cl} + \mathrm{R_{g3}}//\left(\mathrm{R_{g2}}//\left(\mathrm{R_{g1}}+\mathrm{R_{c2}}\right)//\mathrm{R_{g2}}+\mathrm{R_{c3}}\right)//\mathrm{R_{g3}} \tag{12}$$

Fig. 7 shows the MEC in the three states. Hence, first, second, and third corner currents while L_m starts turning from one state to another state can be easily obtained.

$$L_{corner1} \cong \frac{B_{sat}\,R_{S1}\,A_{C1}}{N} \tag{13}$$

$$L_{corner2} \cong \frac{B_{sat}\,R_{S2}\,A_{C2}}{N} \tag{14}$$

$$L_{corner3} \cong \frac{B_{sat}\,R_{S2}\,A_{C3}}{N} \tag{15}$$

where B_{sat} denotes as the saturated magnetic flux density. And N is the number of turns in a coil. According to the derivation for the relation between air gap and inductance, the designed magnetizing inductance versus corner currents' settings is plotted in Fig. 8.

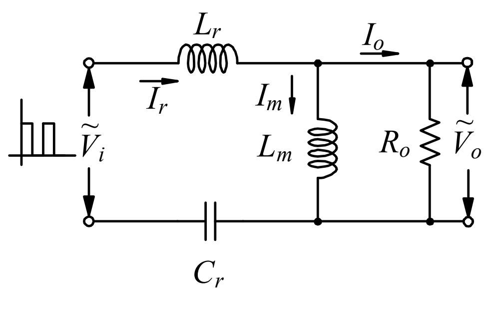


Fig. 5. Equivalent circuit of the proposed LLC converter.

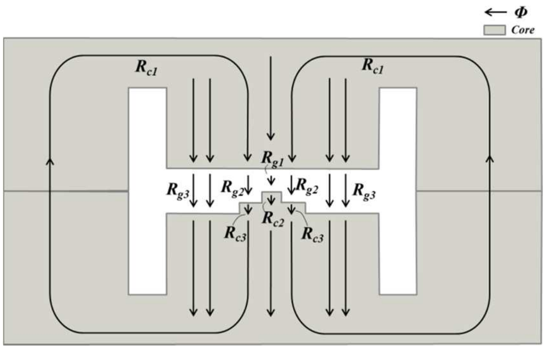
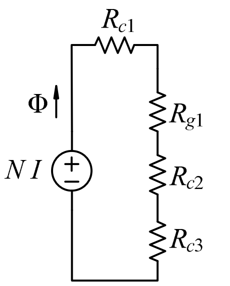
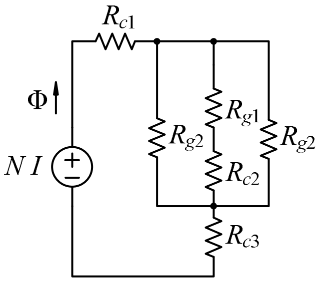


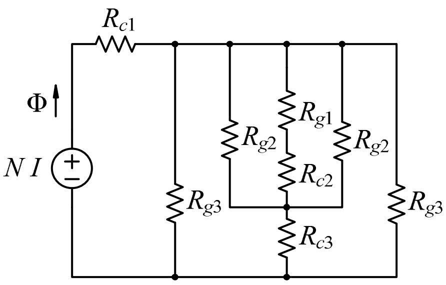
Fig. 6. The non-uniform air gap transformer core shape and magnetic flux diagram.



(a)



(b)



(c)

Fig. 7. The MEC of non-uniform air gap transformer

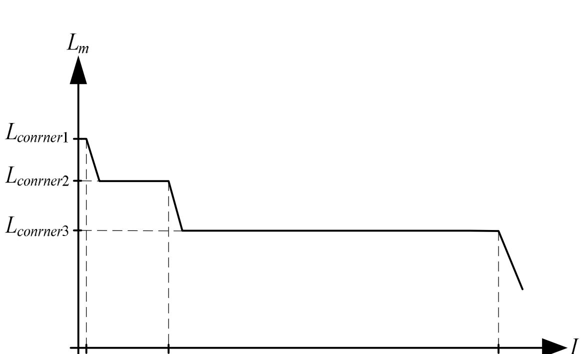
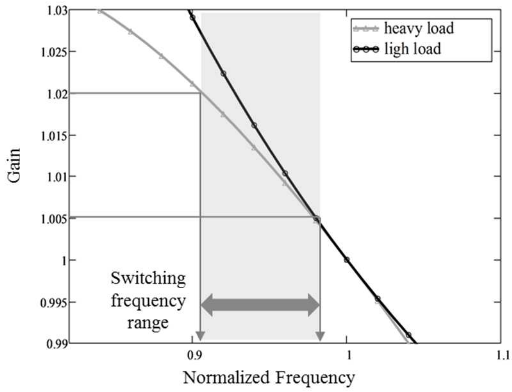
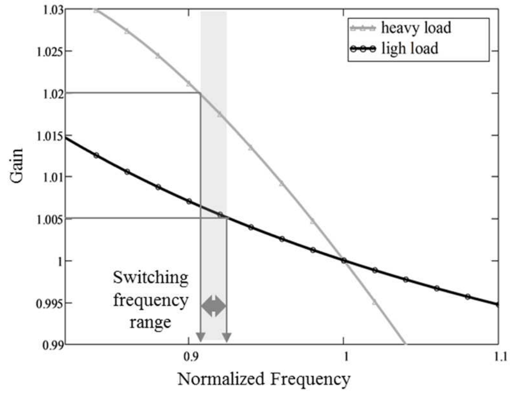


Fig. 8. Derivation of variable inductance.



(a)



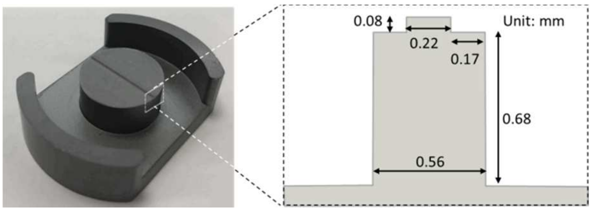
(b)

Fig. 9. Comparison of the working switching frequency range.
(a) Conventional gain response, (b) Proposed gain response

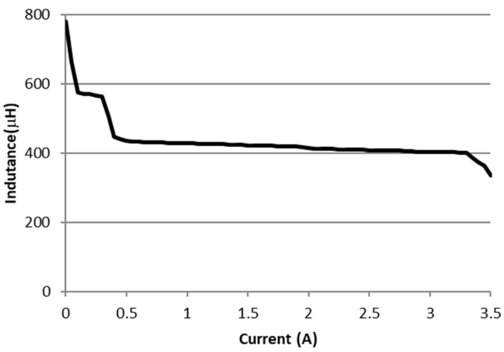
Brief remark is given as follows. This control technique is applied using the setting of the required magnetizing inductance which is the critical parameter to improve light load efficiency as well as letting the change of the transient switching frequency shift in a narrower band as this variance of magnetizing inductance is set for regulating the gain to meeting output voltage during dynamic loading of this LLC resonant conversion. Based on the principle of LLC resonant energy conversion, the magnetizing inductance is shown in Fig. 8, as aforementioned the converter switching frequency would be narrower. Fig. 9 presents the effectiveness from the gain of LLC converter versus the frequency ratio, denoting as LLC switching frequency fs divided by the resonant frequency f_r. This variant inductance based driving technique is implemented to optimize the LLC resonant operation among different load conditions. From (2), the three-state inductances for the magnetizing inductance L_m can be determined.

$$L_m = \frac{L_r\left(1-\ (f_s/f_r)^2\right)}{\sqrt{1/G^2-\ Q^2(f_s/f_r-f_r/f_s)^2-1}} \qquad (16)$$

The LLC resonant transformer with variable magnetizing inductance in this paper is shown as Fig. 10. CC33 core is chosen while Fig. 10(a) shows actual pictures of the core structure, and Fig. 10(b) shows the actual measured results of the variant inductance. At the first state, the output voltage of the LLC converter can keep in the range of voltage regulation by large inductance of the LLC converter and the power loss would be reduced at light load condition.



(a)



(b)

Fig. 10. Non-uniform air gap transformer design for light load efficiency improving
(a)The core structure, (b) Measurement of variable inductor

V. Experimental Results

To demonstrate the effectiveness of the proposed adaptive driving strategies, a 300W platform is chosen for demonstration by taking dynamic gate drive control scheme, and the adaptive driving strategy with magnetizing inductance of the LLC converter into account. Fig. 11 is the prototype of LLC converter with driving, feedback circuit. The main component selection and circuit parameters are given in Table I.

Fig. 12 illustrates the comparison in efficiency between the conventional and adaptive gate drive. It can be inferred that the dynamic gate drive method can improve the efficiency by 2%~5% at light load.

Fig. 13 shows the comparison of the efficiency test results of LLC resonant converter applying a conventional driving method without adaptive parameters and the proposed driving strategies. Obviously, the LLC resonant converter utilizing adaptive gate drive and non-uniform air gap transformer demonstrates the effectiveness of the improving on efficiency at light load.

Fig. 14 shows the measured efficiency of the conventional and the proposed LLC converter at 25%, 50%, 75% and 100% load condition. The proposed PSU is 1.3%, 1.3%, 1.6% and 2.2% higher efficiency at 25%, 50%, 75% and 100% load conditions compared with the conventional LLC converter due to reduced losses of GaN switches as well as the improving from dynamic gate driving for optimization on operation.

VI. Conclusion

In this paper, driving strategies applying with dynamic gate drive and the LLC converter with adaptive variant magnetizing inductance, is proposed to upgrade the efficiency of the converter. The operation principle of the proposed approach is experimentally implemented and verified through LLC converter platform utilizing the adaptive variant magnetizing inductance transformer in non-uniform air-gap core design performing a close three-state variant inductance.

In addition, the theoretical analysis of circuit operation and design for reference is derived and introduced. Furthermore, the LLC converter utilizing non-uniform air gap transformer is conducted through variation of magnetizing inductance of LLC converter to further reduce power loss and performing the efficiency improving at light load conditions. Regarding heavy load condition, LLC converter can also operate with original optimization of the switching and conduction losses without the impact of side effects while utilizing the proposed adaptive driving strategies.

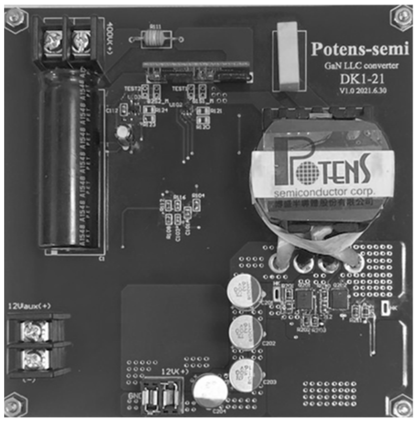


Fig. 11. Proposed circuit board.

TABLE I
Parameters of Main Circuit

Parameter	Value	Description
C_1	220uF	450V electrolytic capacitor
S_1, S_2	PEB15GC65HDS	650V, 15A, GaN
T_1	L_m=420μH, L_r=28μH	CC33, N_p:N_{s1}: N_{s2} = 34:2:2
C_r	10nF	1kV film capacitor
S_3, S_4	PDC49E8BX	40V, 170A, MOSFET
C_o	2200uF × 2	16V electrolytic capacitor

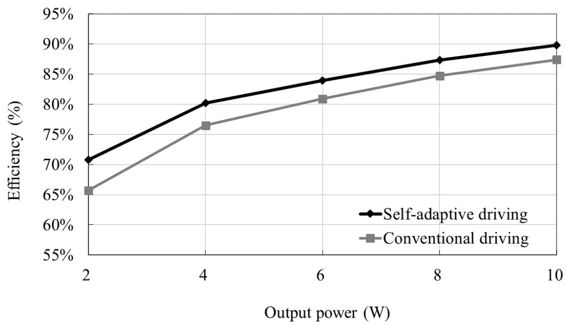


Fig. 12. Efficiency comparison of dynamic gate drive versus conventional fixed gate drive at light load.

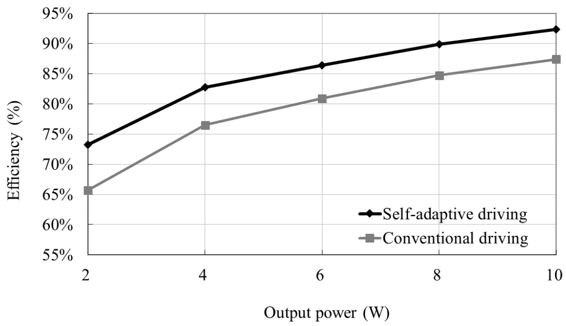


Fig. 13. Efficiency comparison of LLC converter at light load.

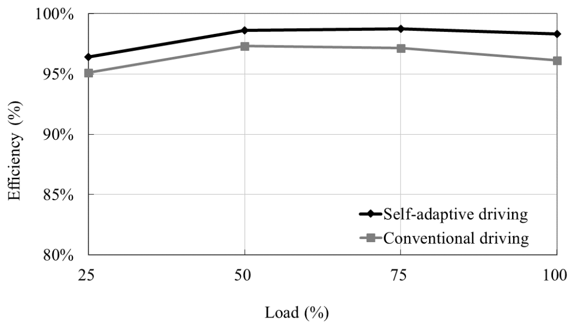


Fig. 14. Efficiency comparison of whole PSU at 25%, 50%, 75% and 100% rated load.

REFERENCES

[1] W. Zhang, F. Wang, D. J. Costinett, L. M. Tolbert, and B. J. Blalock, "Investigation of Gallium Nitride Devices in High-Frequency LLC Resonant Converters, " *IEEE Trans. Power Electron*., vol. 32, no. 1, pp. 571-583, Jan. 2017.

[2] P. He, A. Mallik, G. Cooke, and A. Khaligh, "High-power-density high-efficiency LLC converter with an adjustable-leakage-inductance planar transformer for data centers" *IET Power Electron*., vol. 12, no. 2, pp. 303-310, 2019.

[3] J. H. Kim, C. E. Kim, J. K. Kim, J. B. Lee, and G. W. Moon, "Analysis on Load-Adaptive Phase-Shift Control for High Efficiency Full-Bridge LLC Resonant Converter Under Light-Load Conditions, " *IEEE Trans. Power Electron*., vol. 31, no. 7, pp. 4942-4954, Jul. 2016.

[4] C. Fei, M. H. Ahmed, F. C. Lee, and Q. Li, "Two-Stage 48 V-12 V-6 V-1.8 V Voltage Regulator Module With Dynamic Bus Voltage Control for Light-Load Efficiency Improvement, " *IEEE Trans. Power Electron*., vol. 32, no. 7, pp. 5628-5636, Jul. 2017.

[5] H. Pan, C. He, F. Ajmal, H. Chen, G. Chen, "Pulse-width modulation control strategy for high efficiency LLC resonant converter with light load applications, " *IET Power Electron*., vol. 7, no. 11, pp. 2887-2894, 2014.

[6] A. Q. Cai and L. Siek, "A 2-kW, 95% Efficiency Inductive Power Transfer System Using Gallium Nitride Gate Injection Transistors, " *IEEE Trans. Power Electron*., vol. 5, no. 1, pp. 458-468, Mar. 2017.

[7] F. Hattori, H. Umegami, and M. Yamamoto, "Capacitor-Less Gate Drive Circuit Capable of High-Efficiency Operation for Non-Insulating-Gate GaN FETs, " *IEEE Trans. Electron Devices*, vol. 60, no. 10, pp. 3249-3255, Oct. 2013.

[8] PEB15GC65HDS datasheet, Potens, Hsinchu County, Taiwan, 2021. Available: https://www.potens-semi.com/upload/product/PEB15GC65HDS.pdf

[9] B. C. Hyeon, and B. H. Cho, "Analysis and Design of the L_mC Resonant Converter for Low Output Current Ripple, " *IEEE Trans. Ind. Electron*., vol. 59, no. 7, pp. 2772-2780, Jul. 2012.

[10] W. N. Huang, S. H. Lee, and C. G. Chen, "Light-Load Efficiency Improvement Strategy for LLC Resonant Converter Utilizing a Step-Gap Transformer, " in *Proc. 2014 int. Power Electron. Conf.* (IPEC-Hiroshima 2014 - ECCE ASIA), May 2014, pp. 1734–1737.