Design of Wide Input Voltage Range High Step-Up DC-DC Converter based on Secondary-side Resonant Tank Full Bridge LLC

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***Abstract*—Battery are widely utilized in uninterruptible power supply (UPS) to provide the power temporarily during power failure. In applications up to a few kilo watts, low voltage battery stack are typically used since it is not economically feasible to use high voltage battery stack in such application. To interface the battery to the dc-link of the UPS, power electronic converter are widely used. Due to the wide voltage variation at battery terminal that are mainly caused by battery state of charge and battery stack current, power converter for battery application are required to be capable to interface with wide battery voltage range. In this paper, a wide input range high step up converter was designed based on LLC converter. To significantly reduce the resonant capacitor current, secondary side resonant tank LLC converter was proposed. Finally, a 2 kW prototype was designed for 36 V~ 72 V input voltage and 410 V output voltage, built, and from experimental test 93.59% peak efficiency was measured.**

***Keywords*—high step up converter, wide input range converter, LLC converter, secondary side resonant tank**

I. INTRODUCTION

Uninterruptible power supply (UPS) are widely used to ensure continuous supply to the critical loads. The basic structure of UPS consisted of three components, a battery charger, a high step up dc-dc converter, and an inverter. The high step up dc-dc converter are used to supply the dc link of the inverter from battery in case of power failure. The high step up converter are required to interface the low voltage battery stack that are commonly used in UPS application with power rating up to a few kilo-watt. Due to the battery voltage to state-of-charge characteristic, a UPS front end converter must be able to perform power conversion at wide input voltage range to reliably supply the inverter dc-link. A lot of research focused on high step up dc-dc converter has been done in the past. High step up converter based on modified boost converter structure was presented in [1-3]. High step up converter based on resonant converter was presented in [4-5]. However, [4] only present the design of high step up LLC converter for low power design where high power step up LLC converter suffers from high current stress at the resonant. While [5] describe the design for high step up converter based on LLC converter with push-pull structure at the primary side. The push-pull structure are not very suitable for wide input voltage range due to very high voltage stress at the MOSFET requires selection of at least V_{DS} rating of $2V_{IN}$ which is disadvantageous for higher MOSFET Rdson. This paper presents a design of high step up dc dc converter with full bridge primary MOSFET utilizing LLC resonant tank for wide input range and also a simple approach to reduce the current stress using secondary-side resonant tank structure. Using this technique, the high current are of the converter are limited to the primary side MOSFET and the transformer primary side and the current stress at the resonant components are reduced significantly resulting in improved efficiency and also allowing the use of off-the-shelf component for the resonant circuit.

II. LLC CONVERTER

Resonant tank is widely used in converters to reduce the switching losses by forcing the switches to commutate under soft-switching, improving the overall circuit efficiency. LLC resonant tank are one of the most commonly used resonant converter for its high efficiency and its gain characteristic of greater and less than one, allowing for great power conversion flexibility.

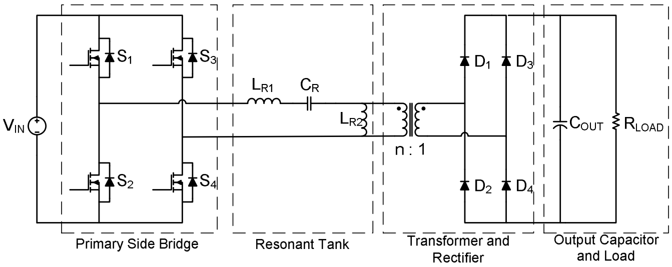

Fig. 1 Full bridge LLC converter

A LLC converter consisted of primary side bridge, resonant tank, and transformer and rectifier. In this paper, the primary side bridge utilize full bridge circuit, the rectifier use full bridge diode rectifier circuit, and the resonant tank formed by the L_{R1}, L_{R2}, C_R, and the R_{LOAD} . In typical application, L_{R2} is formed by the transformer magnetizing inductance.

A. *Modes of Operation*

There are three modes of operation for a LLC converter, depends on its current operating frequency for the particular resonant tank configuration, the characteristic of each operation mode is described as following:

- Mode I ($F<F_P$)

In this mode, the converter operates with wide gain range from $M_G > 1$ to $M_G < 1$. However, since the resonant tank impedance in this mode is dominated by the resonant capacitance, the MOSFET operate in ZCS. This operation condition are typically avoided under normal operation due to higher EMI issue and lower efficiency.

- Mode II ($F_P<F<F_R$)

Mode II, also called LLC mode, operate at gain $M_G > 1$ allowing the converter to boost the output voltage. The MOSFETs work in ZVS condition, resulting in high converter efficiency. This mode has relatively higher circulating loss compared to mode III, thus care should be taken to achieve optimum converter efficiency.

- Mode III ($F \leq F_R$)

The mode III, also called as SRC mode, operates at gain $M_G < 1$. The resonant in this mode are dominated by L_{R1} and C_{R1}. The MOSFETs works in ZVS condition, thus results in high conversion efficiency.

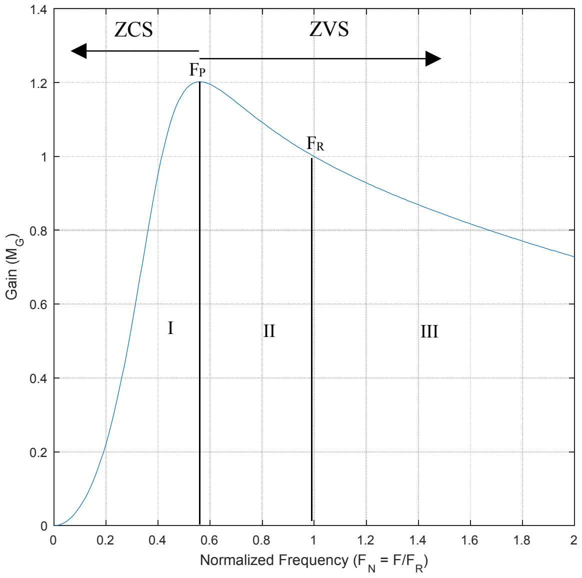

Fig. 2 LLC gain curve characteristic for $L_N = 5$ and $Q = 5$

B. Modeling of LLC Resonant Tank

First harmonic approximation (FHA)[6] is widely used to model the LLC converter with good approximation especially at the operation of the converter near its resonant frequency since the resonant current only composed of purely first harmonic current. Based on that assumption, as shown in fig. 2, the FHA equivalent model of LLC are consisted of voltage source V_{IN}, and the resonant components L_{R1}, L_{R2}, C_R, and R_{AC}. R_{AC} is ac equivalent resistance for the load reflected to the primary side of the transformer.

$$R_{LOAD} = \frac{V_{OUT}^2}{P_{OUT}} \tag{1}$$

$$R_{AC} = \frac{8n^2}{\pi^2} \times R_{LOAD} \tag{2}$$

From the equivalent circuit, then a converter gain (3), defined as the output voltage to input voltage ratio, was derived (4). Using the definition of L_N (5), Q (6), and normalized frequency to the resonant frequency F_N (7), then substitute them into (4), then a more convenient derivation of gain M_G can be derived as (9).

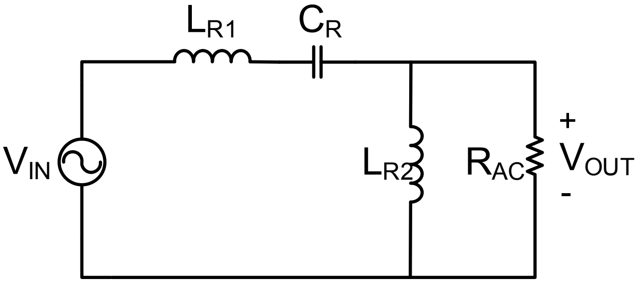

Fig. 3 FHA model of LLC converter

$$M_G = \frac{V_{OUT}}{V_{IN}} \tag{3}$$

$$M_G = \frac{s^2 L_{R2} R_{AC}}{R_{AC} + sL_{R2} + s^2 C_R R_{AC}(L_{R1} + L_{R2}) + s^3 L_{R1} L_{R2} C_R} \tag{4}$$

$$F_R = \frac{1}{2\pi\sqrt{L_{R1} C_R}} \tag{5}$$

$$L_N = \frac{L_{R2}}{L_{R1}} \tag{6}$$

$$Q = \frac{\sqrt{L_{R1}/C_R}}{R_{AC}} \tag{7}$$

$$F_N = \frac{F}{F_R} \tag{8}$$

$$M_G = \left| \frac{F_N^2 L_N}{F_N^2 (L_N + 1) - 1 + j\big((F_N^2 - 1) F_N L_N Q\big)} \right| \tag{9}$$

From the equivalent circuit, then a converter gain (3), defined as the output voltage to input voltage ratio, was derived (4). Using the definition of L_N (5), Q (6), and normalized frequency to the resonant frequency F_N (7), then substitute them into (4), then a more convenient derivation of gain M_G can be derived as (9).

III. SECONDARY SIDE RESONANT TANK LLC CONVERTER

In high current power converter such as high step up dc-dc converter, LLC resonant tank are rarely utilized in the converter due to very high current stress at the resonant components for the conventional structure. However, the fact that most typical off-the-shelf film capacitor are only capable to handle current stress of approximately three to five amperes [7]. This very high current stress then require high number of typical off-the-shelf capacitors connected in parallel to handle the required current stress. In the end it forces the engineer to either utilize expensive specialty capacitor that are rated for high current stress or inconveniently high number parallelly connected off-the-shelf capacitor.

To significantly reduce the current stress at the resonant converter, simple structure modification of conventional LLC resonant which then called secondary side resonant tank LLC (SSRT-LLC) converter was implemented in this paper. The main idea of this modification is by placing the resonant tank at the low current side of the transformer (secondary side) then the current stress at the resonant circuit will be a fraction smaller to the conventional design proportional to the transformer turn ratio. Some advantages of this modification are: (1) lower current stress at the resonant circuit components allowing for the of typical off-the-shelf film capacitor, (2) reduce the area of high current stress of the converter limited to the primary MOSFETs and primary side of the transformer resulting in lower conduction losses, and (3) since the modification is very simple the calculation of the resonant tank design is practically remaining similar compared to the conventional LLC.

Fig. 4 shows the structure of secondary side resonant tank LLC converter. In this paper, the converter was designed to utilize full bridge MOSFET at the primary side and full bridge diode rectifier at the secondary side to handle the required power rating, however another bridge configuration should also be working for the secondary side resonant tank LLC converter.

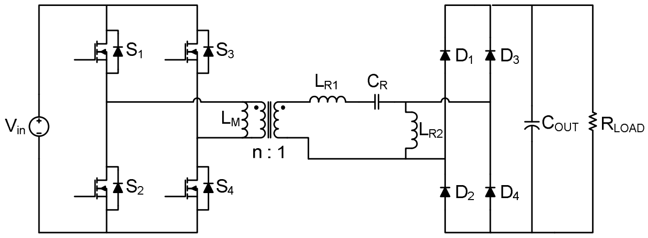

Fig. 4 Secondary side resonant tank LLC converter

The equivalent FHA circuit for secondary side are shown in fig. 5 which consisted of L_{R1}, L_{R2}, and C_R of the resonant circuit tank, R_{AC} the AC-equivalent of the converter load, and L_M to represent the transformer magnetizing inductance. In this paper, the transformer was implemented using ungapped EE ferrite core which has magnetizing inductance value of a few mH at the primary side. The high transformer magnetizing inductance, low voltage across the transformer primary side, and high switching frequency resulting in very small negligible currents flowing. Therefore, the L_M in the FHA for SSRT-LLC can be ignored, then the equivalent circuit of SSRT-LLC became essentially similar to the conventional LLC. Thus, the design procedure of SSRT-LLC also mostly similar to the conventional LLC, making this design attractive for its steep learning curve.

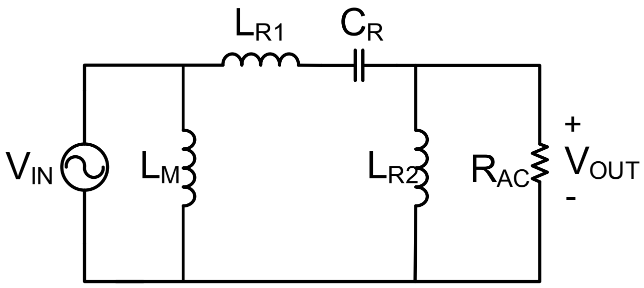

Fig. 5 Secondary side resonant tank LLC converter equivalent FHA model

IV. Design Procedure of SSRT-LLC

Finally, a 2-kW prototype with 36 V ~ 72 V input voltage and 410 V output voltage were designed to verify the feasibility of the presented structure. The design procedure for SSRT-LLC was based on [6] with slight modification on the last procedure to obtain the final component value. A complete design procedure is described as follows:

1. Determine transformer ratio (n)

$$n = \frac{V_{IN(NOM)}}{V_{OUT(NOM)}} \tag{10}$$

$$n = \frac{66}{410} = \frac{1}{6.21}$$

$$n \approx \frac{1}{6}$$

Select the transformer turn ratio with that will yield integer turn number for both primary and secondary side of the transformer

2. Determine the required gain (M_{MIN} and M_{MAX})

$$M_{MAX} = \frac{nV_{IN(MIN)}}{V_{OUT(MAX)}} \tag{11}$$

$$M_{MIN} = \frac{nV_{IN(MAX)}}{V_{OUT(MIN)}} \tag{12}$$

$$M_{MAX} = \frac{1}{6} \times \frac{410}{72} = 0.949$$

$$M_{MIN} = \frac{1}{6} \times \frac{410}{36} = 1.898$$

3. Determine L_N and Q_{MAX}

There is not any exact guidance to determine the L_N and Q_{MAX} for LLC resonant tank, thus some trial and error may be required. As a rule of thumb, following characteristic might be useful for the engineer to help the design iteration.

   a. Decreasing Q_{MAX} for same L_N increase the converter gain peak, but it also narrows the operating frequency range.

   b. Decreasing L_N for same Q_{MAX}, will increase the converter gain peak, but it will also increase the L_{R2} current, resulting in increased conduction losses.

According to [6], L_N=5 and Q_{MAX}=0.5 could be a good start for the design iteration. In this paper, L_N = 8, and Q_{MAX} = 0.2 was finally selected to achieve the desired gain range.

4. Determine resonant frequency and calculate the C_R, LR1, and L_{R2}

$$R_{AC(SEC)} = \frac{8}{\pi^2} \times R_{LOAD} \tag{13}$$

$$C_R = \frac{1}{2\pi F_R R_{AC(SEC)} Q_{MAX}} \tag{14}$$

$$L_{R1} = \frac{1}{(2\pi F_R)^2 C_R} \tag{15}$$

$$L_{R2} = L_N L_{R1} \tag{16}$$

$$R_{LOAD} = \frac{410^2}{105\% \times 2000} = 80\Omega$$

$$R_{AC(SEC)} = \frac{8}{\pi^2} \times 80\Omega = 64.85\Omega$$

$$C_R = \frac{1}{2\pi(200 \times 10^3)(64.85)(0.2)} = 61nF$$

$$L_{R1} = \frac{1}{\left(2\pi(200 \times 10^3)\right)^2 (61 \times 10^{-9})} = 10.31\mu H$$

$$L_{R2} = 8 \times 10.32 \times 10^{-6} = 82.56\mu H$$

After all resonant component obtained, then the gain of the converter can be verified using (17) for various input voltage range.

$$V_{OUT} = \frac{V_{IN}}{n} \times \frac{j\omega L_{R2} R_{AC}}{R_{AC} + j\omega L_{R2} + (j\omega)^2 C_R (R_{AC}(L_{R1} + L_{R2}) + j\omega L_{R1} L_{R2})} \tag{17}$$

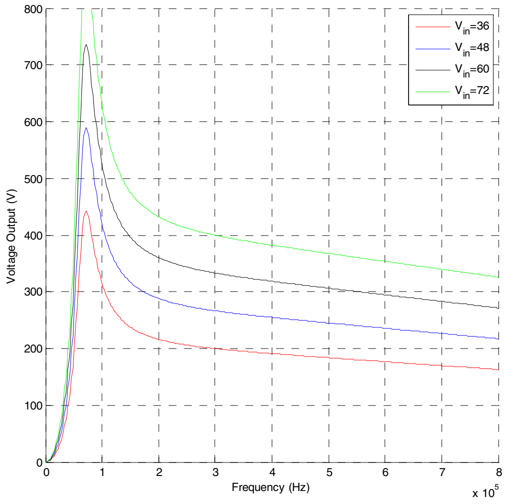

Fig. 6 Simulated output voltage at various input voltage

5. From the component parameter obtained at step 4, a simulation can be made to evaluate the circuit performance before making a hardware prototype. Some parameter from step 1-4 can then be adjusted if necessary.

V. EXPERIMENTAL RESULTS

Finally, a 2kW, 36V~72V input voltage and 410 output voltage secondary side resonant tank LLC converter prototype was built to demonstrate the feasibility of the modified structure. The design of the resonant tank structure was done using the procedure described in previous section. The circuit parameter used in the prototype presented in this paper is shown in table 1.

Table 1 Converter circuit parameter

Primary switch	IRFB4310 (100 V, 130 A, 5.6 mΩ)
L_{R1}	CM203060 (8 turns)
L_{R2}	CM330026 (38 turns)
Transformer	EE55 (Np : Ns = 2:12)
Secondary Rectifier	APT30D60BHBG
Controller	TMS320F38035

From the experimental test, a few key waveforms at input voltage V_{IN} = 36 V and V_{IN} = 72 V are shown in fig. 7 through fig. 10.

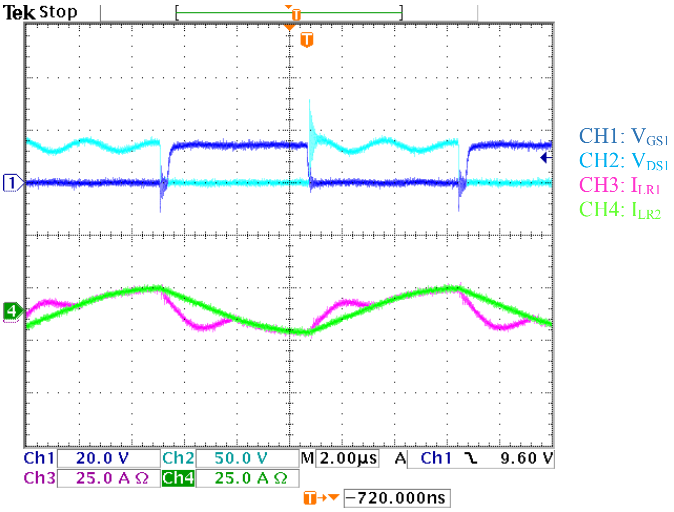

Fig. 7 Key waveform at V_{IN} = 36V (P_{OUT} = 1000 W)

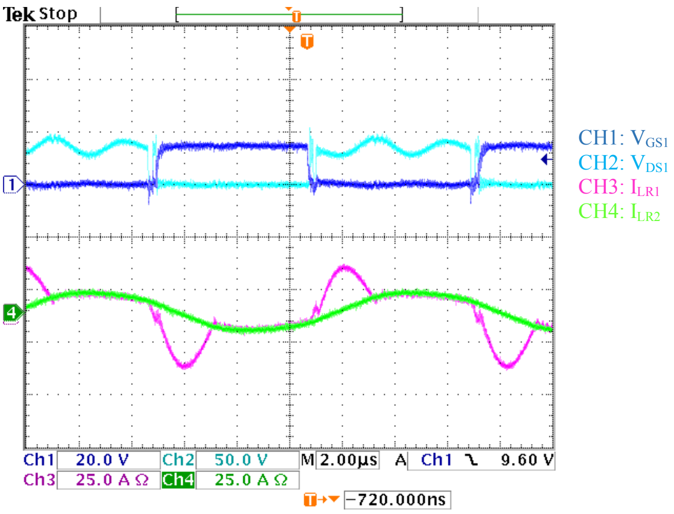

Fig. 8 Key waveform at V_{IN} = 36V (P_{OUT} = 2000 W)

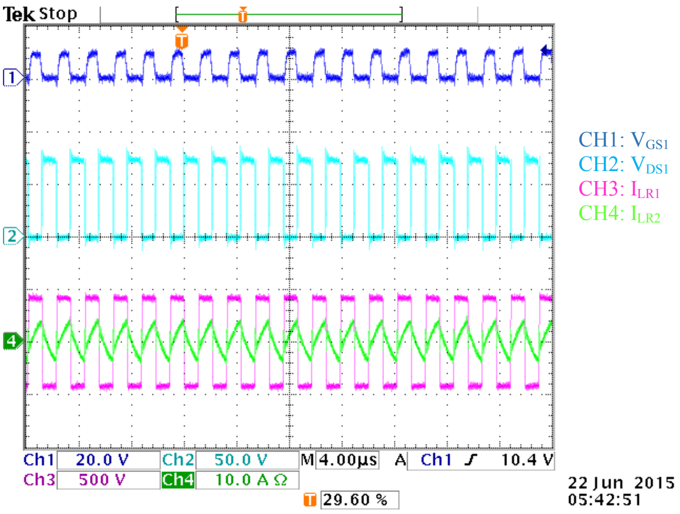

Fig. 9 Key waveform at V_{IN} = 72V (P_{OUT} = 1000 W)

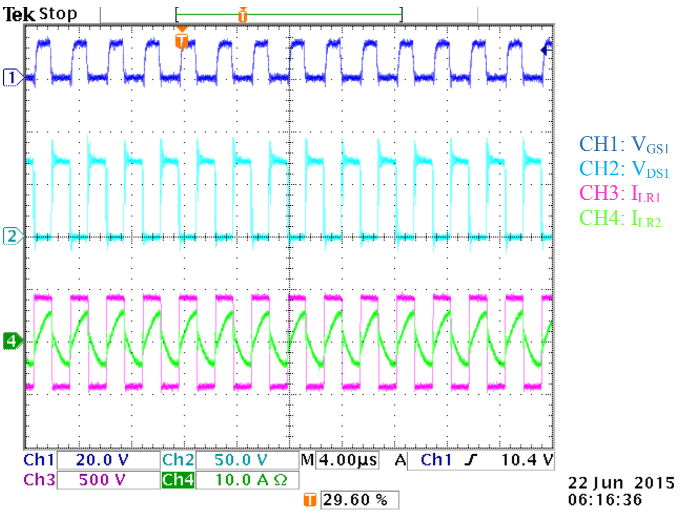

Fig. 10 Key waveform at V_{IN} = 72V (P_{OUT} = 2000 W)

From the converter test, then the efficiency measurement of the converter is shown in fig. 11. The efficiency of the converter can reach >90% for the required input voltage specification, and it peaks at 93.6% at input voltage 60V and 100% load.

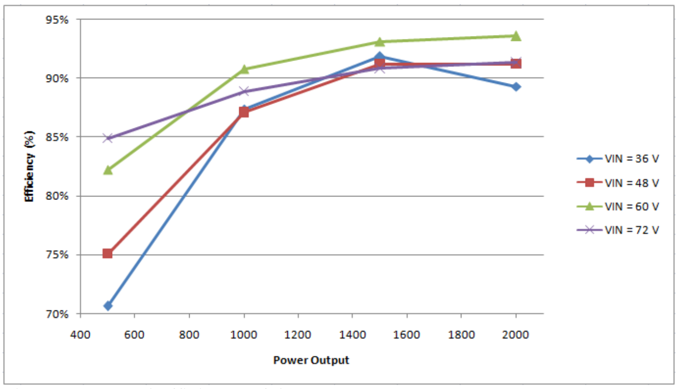

Fig. 11 Measured efficiency of the prototype

VI. CONSCLUSION

In this paper, a wide input voltage range high step up dc-dc converter based on secondary-side resonant tank LLC was proposed and tested. By utilizing simple modification, current stress of the resonant tank was significantly reduced to the fraction proportional to the transformer turn ratio and high current loop part of the circuit was limited to the primary side MOSFET and transformer resulting in lower conduction losses. From experimental measurement of the converter, 93.59% peak efficiency of the converter was achieved at 60 V input voltage and 100% load.

REFERENCES

[1] F. L. Luo and H. Ye, "Positive output cascade boost converters," in *IEE Proc. Electr. Power APpl.*, vol. 151, 2004, pp. 590-606.J. Clerk Maxwell, A Treatise on Electricity and Magnetism, 3rd ed., vol. 2. Oxford: Clarendon, 1892, pp.68-73.

[2] J. M. Kwon, E. H. Kim, B. H. Kwon, and K. H. Nam, "High efficiency fuel cell power conditioning system with input current ripple reduction," *IEEE Trans. Ind. Electron.*, vol. 56, no. 2, pp. 826-834, Mar. 2009

[3] S. K. Changchien, T. J. Liang, J. F. Chen, and L. S. Yang, "Novel high step-up DC-DC converter for fuel cell energy conversion system," *IEEE Trans. Ind. Electron.*, vol. 57, no. 6, pp. 2007-2017, Jun. 2010.

[4] Sam A. R., "Resonant LLC converter: operation and design," Infineon Technologies, Application Note AN 2012-19, 2012.

[5] W. Chen, Z. Y. Lu, F. Zhang, and S. S. Ye, "A novel ZVS step-up push-pull type isolated LLC series resonant DC-DC converter for UPS system and its topology variation," in *Proc. 23rd Annu. IEEE Appl. Power Electron. Conf. Expo.*, Feb. 2008, pp. 1073-1078.

[6] Huang H., "Designing an LLC resonant half-bridge power converter," Texas Intruments, Power Supply Design Seminar SLUP263, 2010.

[7] Rubycon. Metallized polypropylene film capacitors MPH series. PDF.