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Performance Comparison of Range Winding Technique, Asymmetrical Winding Asymmetric Half Bridge Converter and LLC Resonant Converter for Frond End DC/DC Converter

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Abstract: This paper presents the performance comparison of conventional range winding technique, asymmetrical winding asymmetric half bridge converter with LLC resonant converter. With range winding solution [1], the performance of front end DC/DC converter could be improved significantly at high input voltage condition. The drawback of range winding solution is that extra windings, diodes, switch and control circuit are needed, which makes this solution very complex. Asymmetric winding asymmetric half bridge converter does not require any additional components with wide input range. But the drawback is large capacitor is required to avoid discontinuous current. This problem is overcome by LLC resonant converter. Three advantages are achieved with this resonant converter. First, ZVS turn on and low turn off current of MOSFETs is achieved. The switching loss is reduced so we can operate the converter at higher switching frequency. Second advantage is that with this topology, we can optimize the converter at high input voltage. And last advantage is that with this topology, we can eliminate the secondary filter inductor, so the voltage stress on secondary rectifier will be limited to two times the output voltage, better rectifier diodes can be used and secondary conduction loss can be reduced. The efficiency comparison between this converter and asymmetrical winding asymmetric half bridge converter is given which shows a great improvement by using this topology.

Key words: LLC Resonant Converter · Asymmetrical winding · Distributed power System · Front End Converter · Switching losses and ZVS.

INTRODUCTION

The increasing efforts on pushing power converter to higher power density and lower profile have lead us to develop converters capable of operating at high switching frequency with high efficiency [2]. With high switching frequency, size of passive components could be reduced. However, traditional PWM converter will suffer efficiency with higher switching frequency, which will put more loads on thermal management and cannot meet the future requirements of power density and efficiency [3].

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Distributed Power System (DPS) is a widely adopted configuration in computer and communication power systems because of its high efficiency, high reliability and flexibility. The well-accepted DPS structure is shown in Fig. 1. The front-end converter includes Power Factor Correction (PFC), which converts AC line input into a 400V intermediate bus and Front-End DC/DC converters, which convert the 400V DC to an isolated 48V DC bus. For single-phase front-end converter, 1kW module is the most popular power level. For this application, one requirement is hold up time, which requires the system run at full power for 20ms when AC input is lost. During hold up time, the energy will draw from 400V bus cap, this will cause voltage drop on 400V bus. For a normal design, the front-end DC/DC converter input voltage range will be

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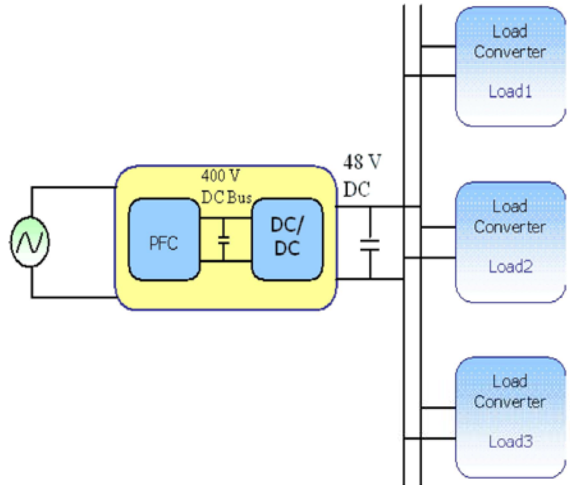


Fig. 1: Structure of Distributed Power System. Which is widely used in digital kits to supply the required power

300V to 400V. The circuit normally works under high input voltage, which is 400V. During hold up time, the input voltage will drop to 300V. This special requirement imposes lot of difficulties on the design of front-end DC/DC converter, since for many PWM topologies the efficiency will drop at high input voltage. An optimized design should have higher efficiency at high input voltage [4-7].

Most front-end DC/DC converter designs evolve around full-bridge, two switch forward and half-bridge converters. Among the possibilities and for the power level under consideration (1 kW), half-bridge converter and full bridge converter provide the best combination of simple structure, low device stress and soft switching capability. Most industry products use these two topologies.

However, these two methods don't come together easily. With high switching frequency, efficiency often will suffer. The reduced efficiency is because of high switching loss and also the reverse recovery of the secondary-side diodes. Another obstacle for front end DC/DC converter design is the hold up time requirement: when the input AC line is gone, system needs to work for 20ms with full power. With hold up time, the result is wide input range for front end DC/DC converter. To overcome these obstacles and develop a high switching frequency, high efficiency solution to achieve high power density and low profile, different techniques have been proposed [7].

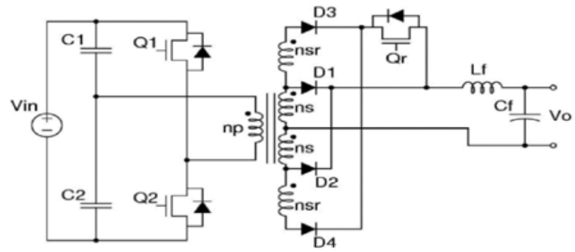


Fig. 2: Asymmetrical half bridge with range winding

In this paper performance of different converters for front end application. 1. Asymmetrical half bridge with range winding Range Winding 2. Asymmetrical winding asymmetric half bridge converter 3. LLC resonant converter are compared for the better performer.

Asymmetrical Half Bridge with Range Winding: The concept of range winding solution is to change the transformer turns ratio according to different input voltage so that the transformer could be optimized for high input voltage.

As shown in Figure 2, range-winding solution is built upon original asymmetrical half bridge converter by adding extra windings (n_{sr}), diodes (D_3 & D_4) and a switch (Q_r). By adding these extra components, the converter enjoys the freedom of extending its limits. With turn on or off the range switch Q_r, the transformer winding turns ratio could be changed. In this way, the gain of the converter could be regulated through two ways, the duty cycle (D) and the range switch.

When range switch Q_r is turned off, the converter will have a gain: $V_0 = \frac{V_{in}(1-D).D.n_S}{n_p}$

which is same as an asymmetrical half bridge with transformer turns ratio n_p: n_s.

With the range switch turned on, the range winding will be added to the secondary, the converter will have a different gain: $V_0 = \frac{V_{in}(1-D).D.(n_S + n_{sr})}{n_p}$

As given in the above equations, with range winding turned on, the transformer turns ratio will be reduced. The converter will have higher gain with lower turn's ratio. By detecting the input voltage of front end DC/DC converter, when it drops below the given level, the range switch will be turned on and the converter will have higher gain to cover lower input voltage. For the normal operation, the range switch is turned off and the range winding and diodes will not affect the operation.

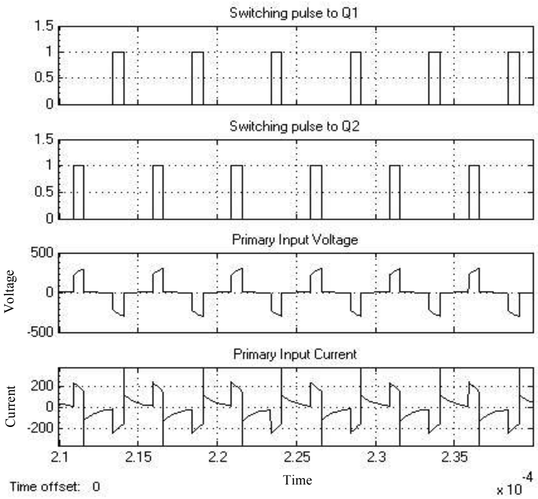


Fig. 3: Switching pulse Input current and Voltage of Range Winding Technique, When Vin=400V

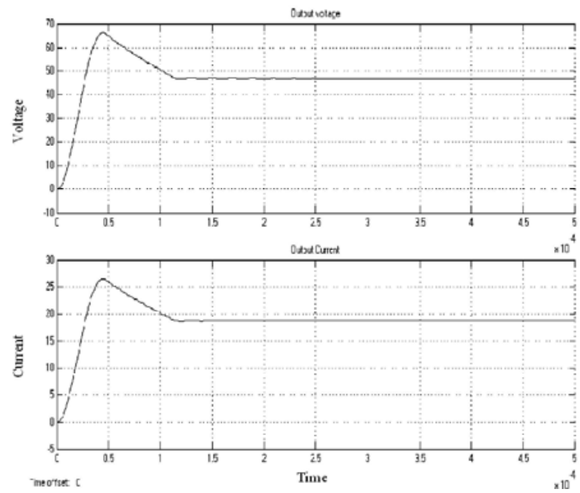


Fig. 4: Output Voltage and Current of Range Winding Technique, When Vin=400V

With range winding solution, the inner transformer turns ratio (n_p:n_s) could be optimized for high input voltage so that the converter will operate with large duty cycle at normal operation. At hold up time, the range switch will be turned on to increase the gain to cover wide input range.

In conventional asymmetrical half bridge, for input voltage range from 300V to 400V, the transformer turns ratio should be 10:7 (n_p:n_s). With this turns ratio, the duty cycle at 300V will be 0.45. The maximum duty cycle is set to 0.45 considering the duty loss caused by the leakage inductance for soft switching. When input voltage is 400V, duty cycle is less than 0.25.

For asymmetrical half bridge with range winding, the transformer turns ratio (n_p:n_s) is designed to be 10:6. The range winding n_{sr} is just one turn. With turn's ratio 10:6, the converter will be able to cover a input range from 360V to 400V. At 400V, the duty cycle is 0.34. When input voltage drops to below 360V, range switch will turn on and the converter will have same gain characteristic as traditional asymmetrical half bridge with turn's ratio of 10:7.

Figure 3 shows the switching pulse given to the switch Q1 and Q2 and also it shows the primary side transformer input voltage and current, when the DC input voltage V_{in} is 400V.

Figure 4 shows the output voltage and current when the DC input voltage V_{in} is 400V. It is clearly observed that the output settled at 0.12 msec during the initial stage.

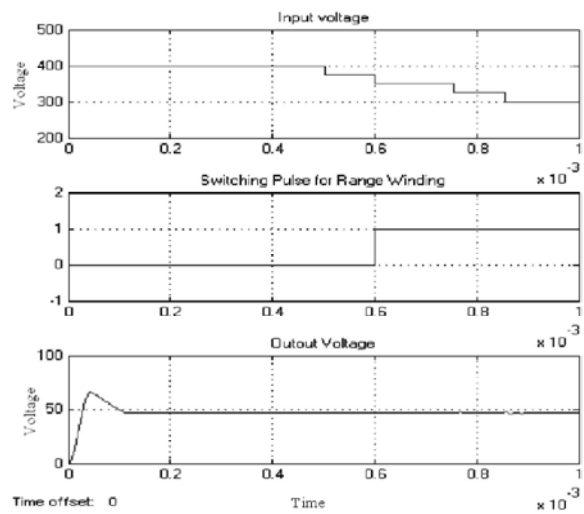


Fig. 5: Input and Output Voltage of Range Winding Technique, When Vin varies from 400V to 300V

Figure 5 shows that the output voltage V_0 (48V) is maintained constant for the input voltage variation in between 400V to 300V. The variation of the input voltage is shown in the first axis; switching pulse for the range winding is shown in the second axis and the output voltage in the third axis.

At t= 0.5 msec a step change is applied to the input to reduce it from 400 V to 375 V and the output tracks its final value (48V) within 1nano sec.

Range winding solution improves the efficiency at high input voltage and is used to cover wide input range. It enables the designer to be concentrated only on the

Fig. 6: Missing

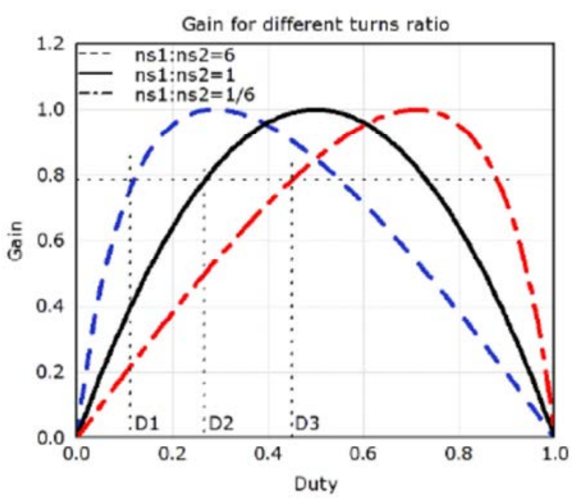


Fig. 7: Duty cycle Vs Gain for different turn's ratio

performance of interest and gives best performance possible. However, to implement range winding solution, extra components are needed which makes this solution very complex.

Asymmetrical Winding Asymmetric Half Bridge Converter: Fig.6 shows the circuit diagram of asymmetrical winding asymmetric half bridge converter. the operation and characteristic of this converter is similar to one transformer and two inductors. With two transformer different turns ratio can be achieved.

For traditional asymmetrical half bridge, the equation for duty cycle in relationship with input, output voltage and turns ratio is:

$$V_0 = \frac{V_{in}(1-D)D}{n_p}$$

For two-transformer asymmetrical half bridge, the duty cycle will be:

These equations are drawn in Fig 7. When the two transformers have same turn's ratio, maximum gain is achieved at duty cycle equals to 0.5.
This is same characteristic for one transformer asymmetrical half bridge. When the two transformers have different turn's ratio, the maximum gain will be shifted from duty cycle equals to 0.5. When np1 is larger than np2, the maximum gain will shift to smaller duty cycle. When np1 is smaller np2, the maximum gain will shift to larger duty cycle. The design goal for front end DC/DC converter is to optimize the performance at high input voltage. To achieve this goal, we would like to extend the duty cycle at high input voltage.

From this prospective, np1 smaller than np2 is preferred. With np1 smaller than np2, the maximum gain will shift to duty cycle larger than 0.5 and the DC characteristic will tilt toward right. With this effect, the duty cycle at high input voltage will be extended too. The duty cycle for the single transformer asymmetrical half bridge is:

$$D = \frac{V_{in} - \sqrt{V_{in}^2 - 4.V_{in}V_o.np}}{2.V_{in}}$$

The duty cycle for two transformers asymmetrical half bridge is:

$$D = \frac{V_{in} + V_o.(np2 - np1) - \sqrt{\begin{array}{l} V_{in}^2 + V_o^2.(np2 - np1) \\ -2.V_{in}.V_o.(np2 + np1). \end{array}}}{2.V_{in}}$$

In Fig 8 duty cycle range for different np1 to np2 ratio are shown. With smaller np1 to np2 ratio, the duty cycle at 400V could be shifted closer to 0.5.

Figure 9 shows the switching pulse given to the switch Q1 and Q2 and also it shows the primary side transformer input voltage and current, when the DC input voltage V_{in} is 400V. Figure 10 shows the output voltage and current, when the DC input voltage V_{in} is 400V. It is clearly observed that the output settled at 0.3 m sec during the initial stage.

Figure 11 shows that the output voltage V_0 (48V) is maintained constant for the input voltage variation in between 400V to 300V. The variation of the input voltage

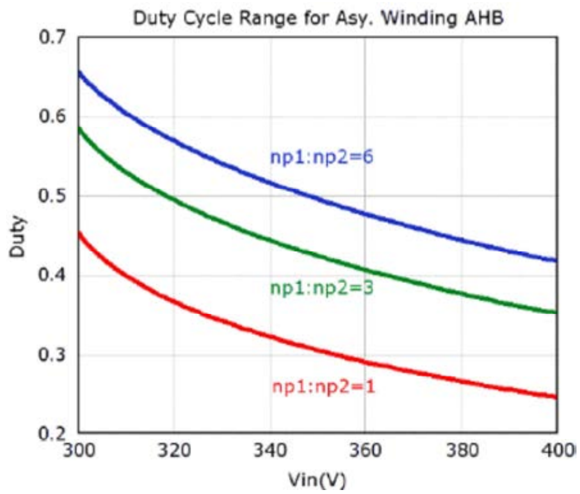


Fig. 8: Input voltage Vs Duty cycle for different turns ratio

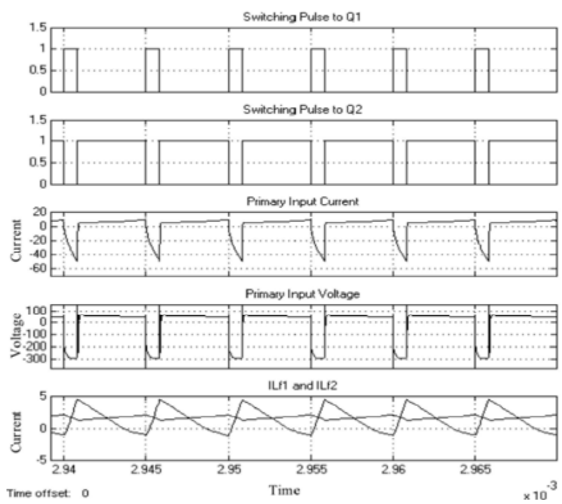


Fig 9: Switching pulse Input current and Voltage of Asymmetrical Winding Asymmetrical Half Bridge, When Vin=400V

is shown in the first axis and the output voltage in the Second axis. At t= 2 msec a step change is applied to the input to reduce it from 400 V to 375 V and the output tracks its final value (48V) within 15 nano sec.

From the test result it can be seen that efficiency could be improved by 1.5% for Asymmetrical Winding Asymmetrical Half Bridge. The performance improvement of this solution is not as good as range winding solution, but because of its simplicity, it is a good solution for asymmetrical half bridge converter.

Llc Resonant Converter: Fig. 12 shows circuit diagram of LLC resonant converter. Without the magnetizing inductance Lm, this converter is the same as series

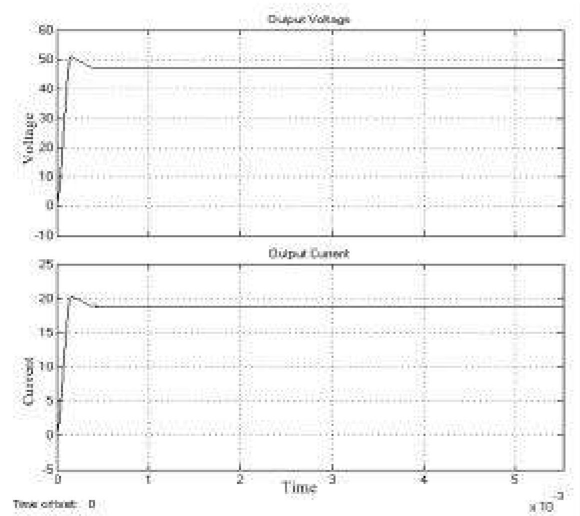


Fig. 10: Output Voltage and Current of Asymmetrical Winding Asymmetrical Half Bridge, When Vin=400V

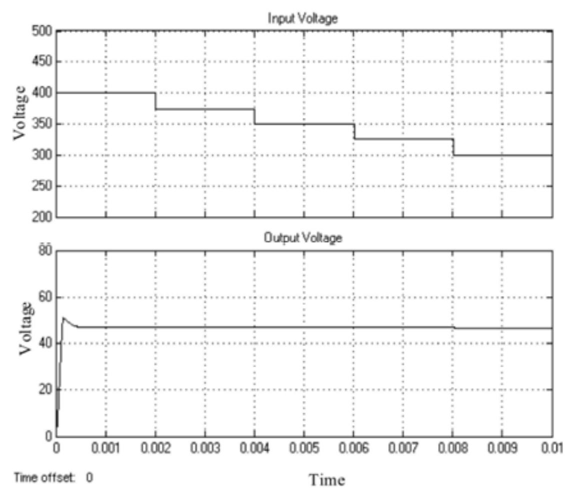
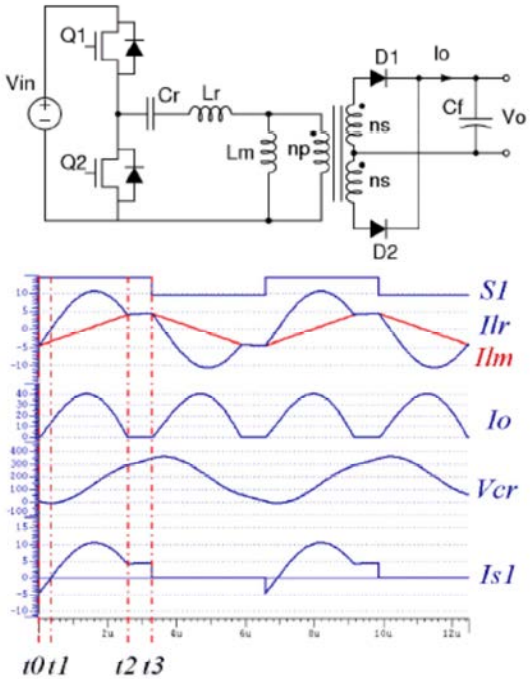


Fig. 11: Input and Output Voltage of Asymmetrical Winding Asymmetrical Half Bridge, When Vin varies from 400V to 300V

resonant converter. With participation of Lm, the operation and characteristic of this converter is very different from SRC then. The circuit has three passive components, Lr, Cr and Lm.

The secondary side is a center-tapped rectifier followed by a capacitive filter. The primary side of this diagram is a Half Bridge configuration; it could also be full bridge or other topologies. Since there is a capacitor in series with power path, automatic flux balancing can be achieved.



(a)

(b)

Fig. 12: a) LLC Resonant Converter b) Output Waveforms

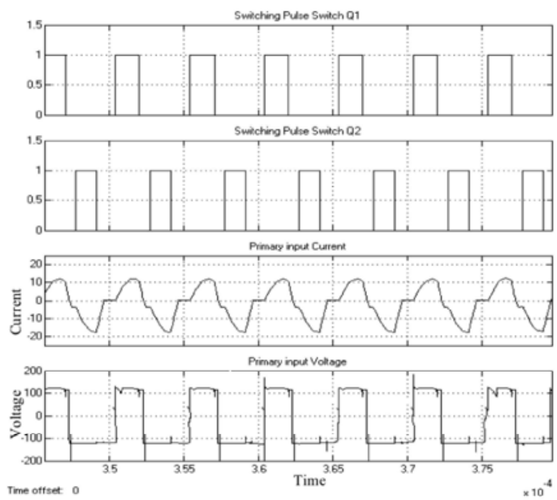


Fig. 13: Switching pulse Input current and Voltage of Half Bridge LLC Resonant Converter, When Vin=400V

Figure 13 shows the switching pulses given to the switches Q1 and Q2 and also it shows the primary side transformer input voltage and current, when the DC input voltage V_{in} is 400V. Figure 14 depicts the output voltage and current, at the same DC input voltage.

Figure 15 illustrates the variation of input voltage and the corresponding output voltage. It is observed that the output voltage V_0 (48V) is maintained constant for the input voltage variation of 400V to 300V.

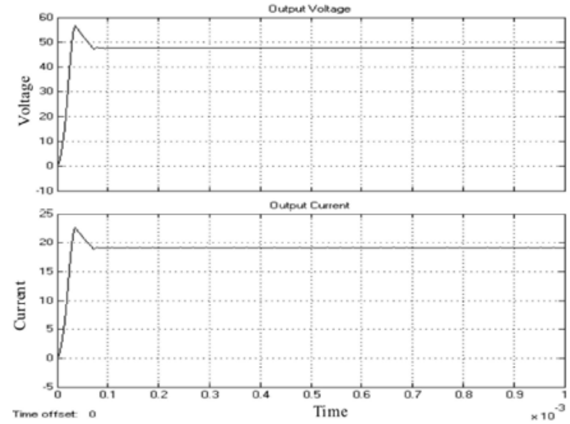


Fig. 14: Output Voltage and Current of Half Bridge LLC Resonant Converter, When Vin=400V

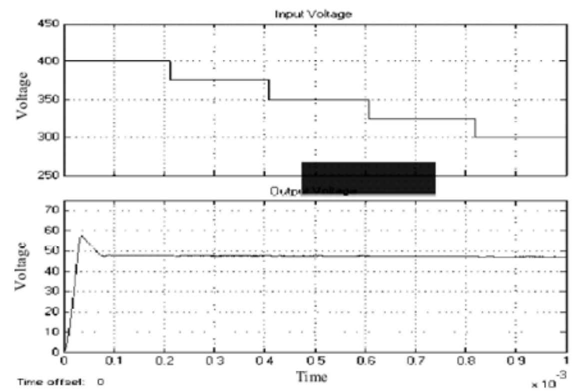


Fig. 15: Input and Output Voltage of Half Bridge LLC Resonant Converter, when Vin varies from 400V to 300V

Performance Comparison: In this part, the efficiency of LLC resonant converter is compared with Asymmetrical Half Bridge. Range winding technique is omitted due to the requirement of extra component and circuit complexity. Asymmetrical Half Bridge is choosing as candidate because this topology is simple and high efficiency. Comparison is based on simulation. Simulation models of both converters were built with same design specs.

The design specs for both converters are:

Vin = 300 to 400V, Vout = 48V and Pout = 1kW, switching frequency = 200kHz.

The devices we used for two converters are:

Primary switches: IXFN26N50 500V 21A MOSFET

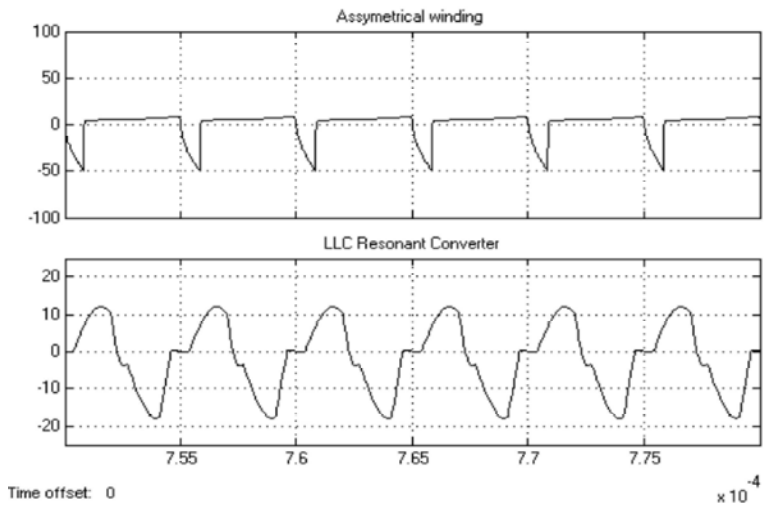


Fig. 16: Input current waveform of the two converters for input voltage 400V

Fig. 16. Shows the simulated input current waveform for two converters at input voltage of 400 at full load. It can be seen that for Asymmetrical Half Bridge converter, the current waveform is highly asymmetrical at high input voltage. This will increase both the conduction loss and switching loss when the converter works in this condition. So the efficiency of the converter will be hurt by wide input range. This asymmetrical duty cycle will also increase the voltage stress of the secondary rectifier. Higher voltage rating devices have to be used which have higher forward voltage drop. Secondary conducting loss will be a large part of total loss.

For LLC resonant converter, at high input voltage, the input current have lower peak value and RMS value, so the conduction loss is much lower at high input voltage. Also, the secondary side voltage stress is fixed at two times output voltage for LLC resonant converter. Low voltage schottky diodes can be used to reduce the secondary conduction loss. For resonant converter, high current stress or voltage stress is always a concern since the increase of conduction loss will compensate the benefit get from reduced switching loss.

Table 1. Shows the primary conduction loss and switching loss comparison based on the data sheet. Because for PWM converter, at high input voltage, the duty cycle is small, so the RMS current is even higher than LLC resonant converter. When the input voltage decrease, the duty will become more symmetrical and the resonant converter will show higher RMS current and higher conduction loss. But this is not a problem for this case since our normal working condition input voltage will be within 360V to 400V. Only during fault condition would the circuit work at so low input voltage. So even with LLC resonant converter, the increasing of conduction loss is not a problem.

Table 1: Loss Comparision

	Asymmetricalwinding	LLC Resonant Converter
Conduction Loss(W)	15.1707	3.2850
Switching Loss(W)	3.2886	2.2356
Total Losses (W)	18.4593	5.5206

Losses are calculated using following formulae

Conduction loss : $P_{con} = I_{rms}^2 \times R_{dsON} \times D$

Switching Loss : $P_{sw} = I_{rms} \times V_{ds} \times t_{sw} \times f_{sw}$

CONCLUSION

In this paper, performance of Asymmetrical winding asymmetrical half bridge converter is compared with LLC Resonant converter. This converter can achieve high efficiency at high input voltage. Besides of very low switching loss, the conduction loss of this converter is lower than PWM converter because of the elimination of secondary filter inductor. The efficiency comparison of this converter with asymmetrical half bridge shows that this converter can get 2 to 3% improvement on the efficiency

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