PARTIAL-RESONANT FLYBACK CONVERTER ANALYSIS AND COMPARISON TO THE STANDARD FLYBACK CONVERTER

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Abstract- Pulse Width Modulation (PWM) is commonly used in power electronics applications thanks to its simplicity and effectiveness. However, it suffers from high switching losses, frequency limitation, and need for clamping circuits. Resonant and partial resonant converters are created to find solutions to these problems. Their main aim is to decrease the switching losses and enable higher frequency operation. A novel Partial-Resonant Flyback converter was presented in 2014 and its operation and advantages were explained in this referred paper. This paper aims to conduct a detailed loss analysis between this referred topology and PWMFlyback. Moreover, some practical issues such as semiconductor switch, inductor, output capacitor, and gating circuit selection were also compared between two topologies. A simulation model was used for this purpose and the results were presented.

Keywords- pulse width modulation; partial resonant; Flyback converter; loss analysis; reverse blocking IGBT.

I. INTRODUCTION

Pulse Width Modulation (PWM) is a widely used control scheme in power electronics, due to its simplicity and effectiveness. This method is mainly applied to basic isolated or non-isolated DC-DC converters. These converters are preferred because of their low cost and simple construction. However, their hard switching characteristics create high switching losses and brings frequency limitation to the converter design [1]. Moreover, the need arises for clamping circuits to avoid excessive voltages on semiconductor switches, which may damage the switches, for isolated converters [2].

Resonant or partial resonant converters are widely investigated in the literature and used as a solution to the problems of PWM converters. Additional components are used in these power converters to obtain zero voltage or current switching. They have low switching losses, higher frequency operation, and high power density. However they suffer from excessive peak voltages and currents in the circuit and low capability to work under flexible input voltage or output load conditions [3].

To combine the advantages of PWM and resonant converters, while avoiding their drawbacks, a novel circuit topology is proposed and presented by H. Keyhani and H. A. Toliyat [4]. In this paper, with small changes in the basic isolated or non-isolated converters, a novel Partial Resonant (PR) converter family is created. These PR converters guarantee zero voltage turn-on and turn-off by utilizing capacitors to create resonant transitions and using reverse blocking capable semiconductor switches.

In this paper, the focus is on Partial Resonance (PR) Flyback Converter. In the referred paper of Keyhani and Toliyat [4], a PR Flyback converter was designed and tested. The performance results under different load and voltage conditions were presented. However, a detailed comparison about losses was not conducted in the original paper. Therefore, this paper aims to investigate the detailed loss analysis of the referred topologyand comparison to the PWMFlyback converter, based on simulation analysis. Additionally, these two topologies will be compared in other aspects such as control complexity, switch ratings,gating circuits, inductorand capacitor selection.

II. CONVERTER DESIGN AND LOSS ANALYSIS METHODOLOGY

A. Converter Design

In this section, two different Flyback converters (partial resonant and PWM) were designed with the same specifications. Chosen specifications are given in Table 1.

Table 1.Specifications of the converters.

Parameter	Value
Vin – Input Voltage	200V
Vout – Output Voltage	300V
Pout – Output Power	750W
n –Turns Ratio	0.9

As indicated in [4], PR Flybackconverter has four switching modes, where two of them are resonant modes (Mode 2 and 4). In these modes, the magnetizing inductor and resonant capacitors form a parallel resonant circuitand the resonance frequencyis given with (1).

$$f_0 = \frac{1}{2\pi\sqrt{L_M C_R}} = \frac{1}{2\pi\sqrt{L_M (C_1 + n^2 C_2)}} \quad (1)$$

In Mode 2 and 4, capacitor voltage and magnetizing current oscillate with the resonance frequency, which is defined by the magnetizing inductor and equivalent resonant capacitor. This frequency was chosen to be

around35kHz. To obtain this frequency, transformer's magnetizing inductor and equivalent resonant capacitor were chosen to be 266µH and 82nF, respectively.

Although only one resonant capacitor is enough to create a resonance, two resonant capacitors on both sides of the transformer were used to avoid the voltage spikes because of the leakage inductance and capacitance of the transformer. Therefore, equivalent resonant capacitor value was split into two parts and placed as 56nF and 33nF capacitors on primary and secondary sides, respectively.

Using Matlab script, switching frequency and the duration of modes were calculated upon the specifications that given above. This script calculated the mode durations and the values are given in Table 2.

Table 2.Mode durations and switching frequency of the PR Flyback Converter.

Parameter	Value
t_1 – Mode 1	17.5µs
t_2 – Mode 2	2.45µs
t_3 – Mode 3	13.8µs
t_4 – Mode 4	19.1µs
T_s - Period	52.85µs
fs - Frequency	18.9kHz

These durations resulted with 33.2% duty cycle for S1 and 20.6% duty cycle for S2. Besides that, there is a delay between the starting points of these two signals, which is 20µs. Both of the signals are shown in Figure 3.

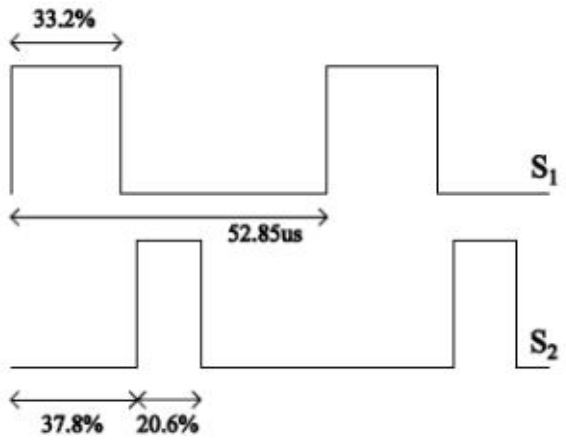


Figure 1.Switching signals for PR Flyback Converter.

To have a fair comparison between two topologies, the PWMFlyback converter was also designed with the same specifications that weregiven in Table 1. The switching frequency of the PWMFlyback converter was also chosen as 18.9kHz. Upon these specifications, the magnetizing inductor was calculated as 11mH. The duty cycle of the switching signal for the primary switch became 63% and the signal is shown in Figure 4.

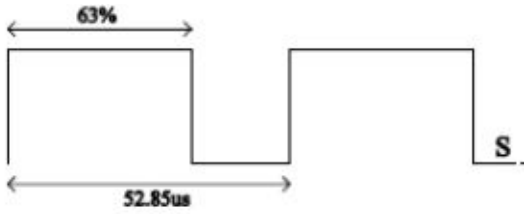


Figure 2.Switching signal for PWM Flyback Converter.

B. Semiconductor Component Selection

As stated before, PR Flyback converter makes the usage of reverse blocking IGBTs (RB-IGBT). This referred topology cannot be used without reverse blocking switches, because of the negative voltages on both of the switches (primary and secondary sides) that caused by the resonant transition.

RB-IGBT switches are not popular in the semiconductor market since most of the power electronics applications can be realized with unidirectional voltage blocking switches. A few applications require unidirectional current flow or reverse blocking capability from the switches. Therefore, only a fewcompanies produce them and they are mostly rated for high voltages as 1200V and high currents as 100A. Because of these reasons, there are not too many choicesof a suitable RB-IGBT for this type of low power and low current application. In this work, IXRH40N120 was chosen for the primary and secondary side switches in PR Flyback converter. This switch has 1200V and 40A rating.

Since the PWMFlyback converter doesn't need reverse blocking capability for primary side switch and controllability for secondary side switch, Mosfet and diode pair could be used for this converter. For this application, there were widely available switches in the semiconductor market and the component selection was easier and more appropriate. In the PWMFlyback converter, FCH077N65F and RURP1560 were selected for Mosfet and Diode, respectively. The Mosfet has 650V and 55A rating, while the diode has 600V and 15A.

C. Loss Analysis Methodology

First purpose of the referred topology is to lower the switching losses. The PR Flyback converter achieves this by assuring zero-voltage transition at turn-on and turn-off for both of the switches. However, like other resonant converter, this referred topology also suffers from high peak currents in the circuit. As a result, conduction losses are expected to be increased compared to thePWMFlyback converter.

Moreover, while PWMFlybacks are using Mosfet and Diode as primary and secondary side switches, PR Flyback converter makes the usage of RB-IGBTs at the both sides. Since the switching and conducting characteristics of all these switches are totally different, they would have different losses.

These points show the importance of detailed loss analysis and comparison between the referred

topology and PWM equivalent. To implement the loss analysis on simulation software, two realistic models for these topologieswere created in PLECS.This software has detailed functions for switching and conduction loss analysis of power switches.

In this paper, the components of the topologies are modeled with their parasitic properties. These could be described as follows;

- All of the passive components have parasitic resistances in series: magnetizing inductor wire resistance, output capacitor ESR, transformer winding resistances,
- All of the active devices have been modeled with their switching and conducting behaviors. All of these data are used from their datasheet figures.

For PR Flyback converter, the transformer was designed with the magnetizing inductor value of 266µH. As a result of being a partial resonant converter, the RMS current of the topology increased. Therefore, the transformer should have been designed with thicker wires. As a realistic value, wire resistance of the magnetizing inductor was chosen to be 50mΩ.

For PWMFlyback converter, transformer's magnetizing inductance is around 40 times bigger than the one for partial resonant equivalent. This is a result of low frequency and high voltage operation. To maintain small magnetizing current ripple ratio, the inductor value should be higher with high voltages. Besides that, since the RMS value of the magnetizing current would be smaller than partial resonant one, the wires would have higher resistance. The wire resistance of the magnetizing inductor for the PWMFlyback was estimated to be 130mΩ.

The output capacitors for both of the topologies are identical. An aluminum electrolytic capacitor with 100µF and 450V would be suitable for both of the topologies. These capacitors are suitable for bulky DC applications in power electronics and they provide higher capacity/size ratio. However, they have relatively higher equivalent series resistor (R_{ESR}) compared to other capacitor types. This resistor value was used as 0.1Ω in the simulation model.

In this work, thermal analysis is not included and temperature differences were not taken into account. In the model, the temperature of the switches were held at 90°C.The switching and conduction losses were obtained from the datasheets of the components and inserted into the model in a detailed manner. This procedure was done for every semiconductor switch in the model.

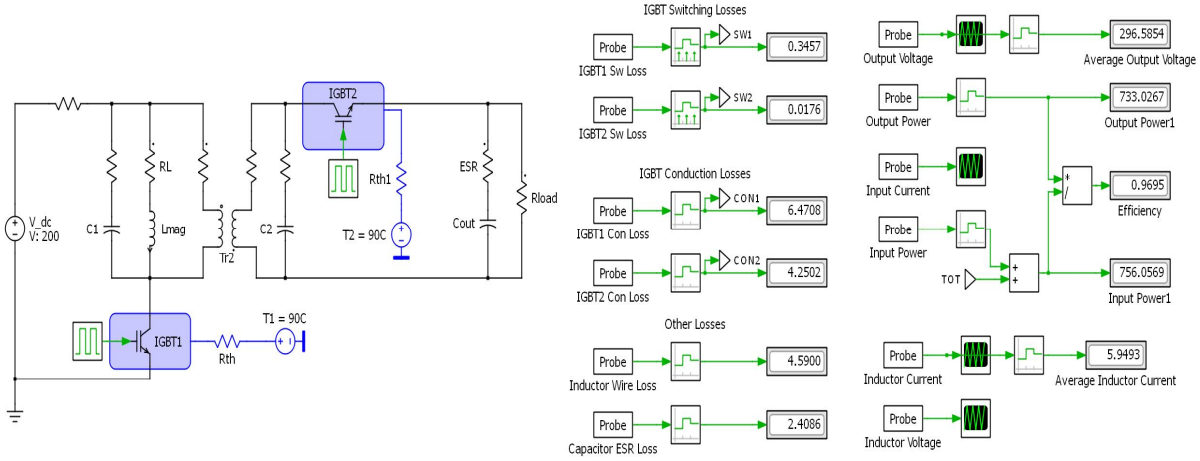


Figure 5. Model of the PR Flyback Converter in PLECS software.

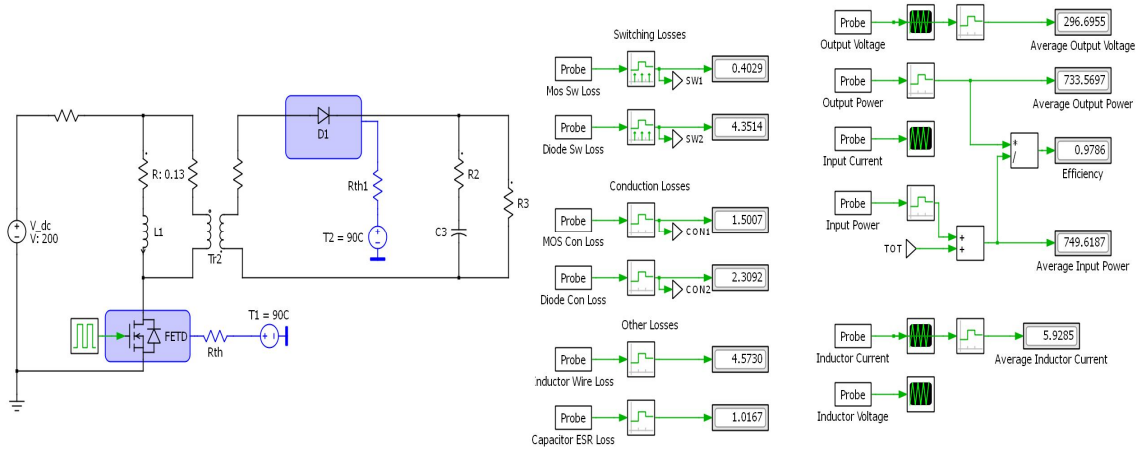


Figure 6. Model of the PWM Flyback Converter in PLECS software.

III. SIMULATIONS AND RESULTS

In this work, PLECS was used as the simulation software because of its special tools for power electronics applications, such as detailed switching and conduction loss analysis. These tools allowed to define the behaviors of semiconductor switches in detail and see the results in a more realistic way. In Figure 5 and 6, the simulation models for PR Flyback and PWMFlyback convertersare shown.

A. Switching Losses

In real life, semiconductor switches have some parasitic parts such as input capacitance, output capacitance, lead inductances, which are frequency dependent components. These parasitic components affect the dynamic behavior of the switch and result out the switching losses. Switching loss of a semiconductor switch is dependent on the voltage and the current at the moment of switching.

For PR Flyback converter, as seen in Figure 5, switching losses for both of the RB-IGBTs are very small (0.35W and 0.02W). This is a result of zero-voltage switching for both of the switches. With the help of resonant capacitors, the switch voltage increases and decreases not suddenly but with sinusoidal form, no hard switching occurs during the transition. Therefore, the switching losses were calculated too small.

On the other side, for PWMFlyback converter, as seen in Figure 6, switching losses are highercompared to the PR equivalent: 0.4W for Mosfet and 4.35W for Diode. The switching loss for Mosfet is reasonable but Diode suffers from the reverse recovery phenomena and Diode is the dominant factor in the switching losses for PWMFlyback.

B. Conduction Losses

IGBTs are minority carrier devices and the most striking property of them is to have low ON-state voltages at high current or high voltage ratings. But they switch slower than majority carrier devices. In contrast, Mosfets and Schottky diodes are majority carrier devices and they switch faster but suffer from high ON-state voltages when the current is high. However, PR Flyback converter requires RB-IGBTs and they have higher ON-state voltages than standard IGBTs.

Total conduction losses for PR Flyback is around 10.5W, while it is 3.80W for PWMFlyback. This big difference was caused by two things: 1) the power ratings of the converter allowed us to choose a better Mosfet and Diode for PWMFlyback. ON-state characteristics of the RB-IGBTsaren't suitable for this type of low power application. 2) As a result of having resonant transitions, PR Flyback has much higher peak currents than PWMFlyback. This increased the RMS value of the currents and resulted higher conduction losses.

C. Inductor Losses

Inductor losses can be divided into two parts: copper losses and core losses. Copper losses are caused by the resistivity of the wire on the inductor and core losses are a result of magnetic properties of the core material.For simplicity, only copper losses were taken into account in this work.

As seen from the Figure 5 and Figure 6, PR and PWMFlyback converters have almost the same inductor wire loss, around 4.5W. In the *"Loss Analysis Methodology"*section, it has been said that wire resistances are different for both of the topologies: 50mΩ for PR Flyback and 130mΩ for PWMFlyback. Although the resistivity of the wire is lower for PR Flyback, higher RMS current (9.6A) compared to PWM equivalent (5.95A) equalized the copper losses.

D. Output Capacitor Losses

Output capacitors of both of the switches were chosen identical. However, the current waveforms are different for two topologies. The output capacitor of PR Flyback suffers from high peak currents (around 20A), while the output capacitor of PWM equivalent has around 6A of peak capacitor current. This results out as different RMS values of capacitor currents: 5A and 3.2A. This is the reason for different losses in the capacitor and they were found as 2.4W and 1W for PR and PWMFlyback, respectively.

E. Total Losses and Efficiency

Whole losses of two converters were calculated by the simulation model and they are presented and compared in Figure 7. Other losses can be defined as the connection resistances between the components. Since the RMS currents increased in PR Flyback, it has much losses compared to the PWMFlyback. As seen in the figure, total losses of the converters are around 23W and 16W, for PR and PWM Flybacks, respectively.

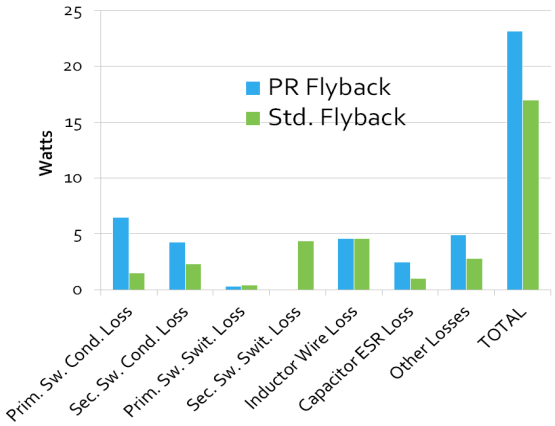


Figure 7. Overal loss comparison of the converters.

The efficiency of the converters was calculated by the modelsand wasgiven in (2). These efficiency values and the Figure 7 show that, the referred topology

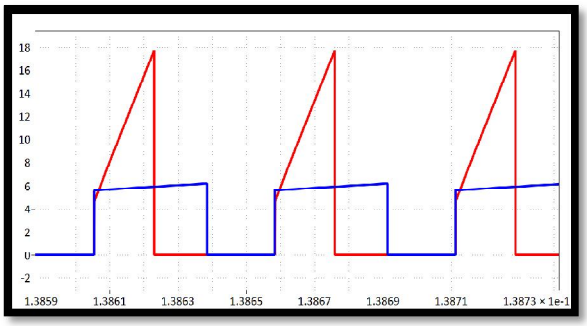
lowers the switching losses dramatically but suffers from high conduction losses due to the high peak currents in the circuit. As a result, under the simulation conditions, whole efficiency of the PR Flyback was calculated lower than the PWM equivalent.

$$\eta_{PR} = 96.95\% \qquad (2)$$
$$\eta_{STD} = 97.86\%$$

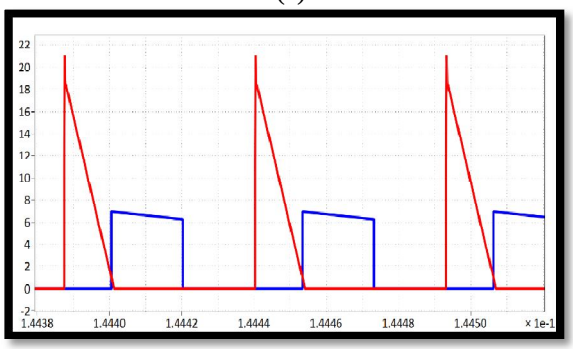
F. Switch Ratings

Both of the converter have the same operating specifications. However, because of the resonant transition, partial resonant converter suffers from high peak currents circulating in the converter. These peak currents also affect the switch selection. In Figure 8, switch currents for both of the converters are shown.

The average value of these currents are equal, however because of short switching duration for PR Flyback converter, the peak current value becomes around 18A and 20A for S1 and S2. As seen from the figure, the switch currents have rectangular shape which allows the peak and RMS currents to be lower compared to partial resonant equivalent.



(a)



(b)

Figure 8. Switch Currents (a)Primary and(b) Secondary Switches. PR Flybackin red, PWMFlybackin blue.

In Figure 9, primary switch voltages for both of the converters are shown. As seen in the figure, the peak voltage values are equal, however, negative voltage is seen on the switches of partial resonant converter. This shows the reason why RB-IGBTs should be used in the converter. The primary switch voltages have the same waveform, as well. Therefore they are not shown in the figure.

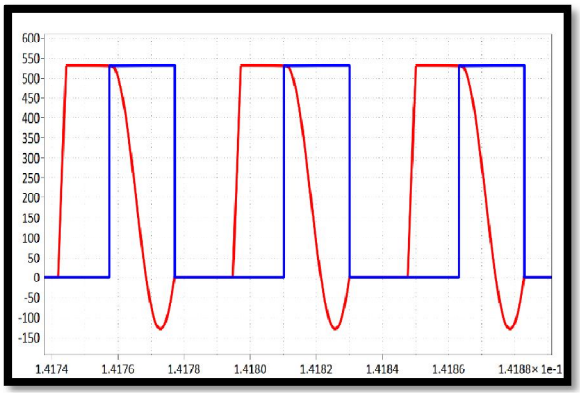


Figure 9. PrimarySwitch Voltages: PR Flybackin red, PWMFlybackin blue.

G. Control and Switch TypeComparison

These two topologies require different control schemes. Moreover, they have different needs on semiconductor devices. As shown in the previous section, PR Flyback converter requires RB-IGBTs for both sides of the converter. These are controlled semiconductor switches and therefore two different isolated gate drive circuits are needed.

On the other side, PWMFlyback converter utilizes Mosfet for primary and Diode for secondary side. Only Mosfets are controlled device from these two. Therefore, only one gate drive circuit is required. This will allow the cost of gate driving to be lower.

H. Inductor and Capacitor Comparison

The referred PR converter and PWM converter utilize the inductor in a different way. Figure 10 shows the inductor magnetizing current differences between two converters. Red waveform belongs to partial resonant Flyback converter and blue waveform is for PWMFlyback converter. As seen in the figure, red waveform swings between 16A and -6A with a sinusoidal like shape. On the other hand, blue waveform is almost DC current. This would bring difference in the inductor design for the converters and moreover, the core losses of these inductors would be different. Since the inductor current in PR Flyback swings from positive to negative, BH curve area is higher than the other. This would cause higher core losses for partial resonant inductor.

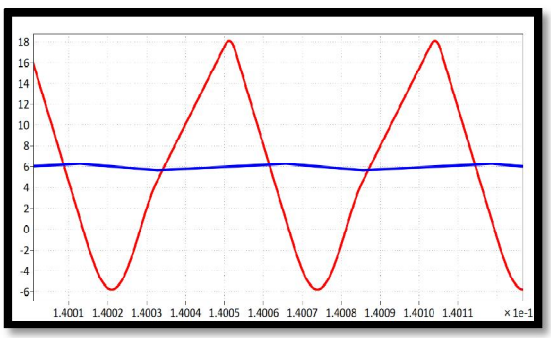


Figure 10.Inductor current comparison of PR (red) and PWM (blue) Flyback Converters.

In Figure 11, the output capacitor currents are compared for two topologies. Red waveform shows the current for partial resonant one while the blue waveform belongs to the PWM converter. Aluminum capacitors can handle sudden currents very well however RMS value of the repetitive current is an important factor for these capacitors.

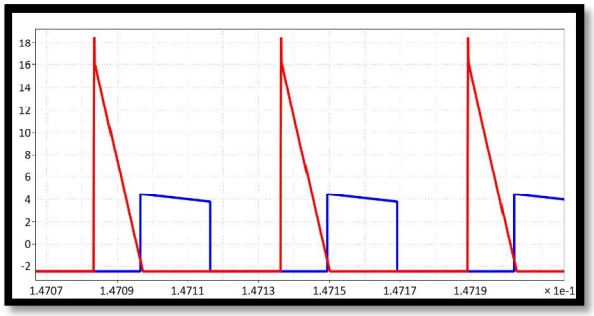


Figure 11. Output capacitor current comparison of PR (red) and PWM (blue) Flyback Converters.

As seen in the figure, output capacitor current of the PR Flyback converter has 18A peak value and RMS current were calculated around 5A. However, the same parameters for PWMFlyback converter are around 5A and 3.2A. This brings a difference in output capacitor selection and lifetime of the capacitor. Since high peak and RMS values degrade the lifetime of a capacitor, the output capacitor of the PR Flyback would have some reliability problems.

COMMENTS AND CONCLUSION

This paper aimed to conduct a detailed analysis over the losses and practical issues for two different Flyback converters: Partial Resonant (PR) and PWM. The novel PR Flyback converter is proposed by Keyhani and Toliyat [4]. Some reported advantages of this new topology were assuring zero voltage switching both turn-on and turn-off, applicable high frequency switching, no spike on the transformer windings, and low losses compared to the PWM equivalent.

In this work, the author referred to the original paper and designed a PR converter by using the theory from the referred paper. A PWMFlyback converter was also designed by the author with the same specifications of partial resonant one. A new simulation model on PLECS software for both referred topology and PWM topology were created. This software has helpful tools on loss analysis of power electronic switches. Switching and conducting behaviors of the switches were obtained from the datasheets and inserted into the software.

Software models of these converters calculated the detailed losses for every power component: semiconductor switches, inductors, and output capacitors. As expected, peak currents in the circuit, so the conduction losses of PR Flyback converter were calculated higher than PWM equivalent. However, it has almost zero switching losses due to the zero voltage switching transition. This allows designer to utilize higher frequencies.

On the other side, this referred topology had higher peak and RMS currents on both of the switches, which increases the conduction losses beyond the PWM version.Secondly, the referred topology requires two controlled RB-IGBT switches and two isolated gate drivers. These switches are not widely available in the electronic market. Thirdly, generation of the switching signals for PR Flyback converter is done by measuring the proper current and voltage values in the topology. This increases the cost of the electronic controller a lot and brings many difficulties.

In conclusion, Partial Resonant Flyback Converter would be a nice choice for low noise, high power DC-DC converter. It has better specifications compared to PWM equivalent such as lower switching losses and low noise operation. However, these are done with the price of high conduction losses, complex control circuitry, and high costs.

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