Zero Voltage Switched Full Bridge Converters for the Battery Charger of Electric Vehicle

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Abstract—This paper illustrates the study of three isolated zero voltage switched (ZVS) PWM full bridge (FB) converters to charge the high voltage battery in the charger of electric vehicle (EV). EV battery chargers have several challenges such as high efficiency, high reliability, low cost, isolation, and high power density. The cost of magnetic and filter components in the battery charger is reduced when switching frequency is increased. The increase in the switching frequency increases switching losses. ZVS is used to reduce switching losses and to operate the converter in the battery charger at high frequency. The performance of each of the three converters is evaluated on the basis of ZVS range, dead times of the switches, conduction losses of switches, circulating current stress, circulating energy, duty cycle loss, and efficiency. The limitations and merits of each PWM FB converter are reviewed. The converter with broader ZVS range, high efficiency and low switch stresses is selected for battery charger applications in EV.

Keywords—Electric vehicle, PWM FB converter, zero voltage switching, circulating energy, duty cycle loss, battery charger.

I. INTRODUCTION

The vehicle industries are nowadays working to reduce exhaust emissions, acoustic noise, and vibrations in order to get high conversion efficiency. This is a difficult task for the vehicle industries to achieve all these characteristics in vehicles that run on fossil fuels. Conventional vehicles, which consume fossil fuels and emit green house gasses, lead to climate changes and causes global warming. Vehicle manufacturers are diverting towards the EVs because EVs have the ability to remove the drawbacks of conventional vehicles. The electricity needed to store in the batteries of EVs is obtained from the AC grid as shown in Fig. 1 [1].

The battery charger of EV consists of a rectifier, a DC/DC converter and a battery pack. The rectifier takes its input from an AC grid while the DC/DC converter generates the required voltage for the battery pack. The battery life and charging time depends upon the characteristics of modules used in the battery charger [2], [3]. These modules are manufactured worldwide by various vehicle industries for EVs. The design and charging pattern of the battery module determines the performance of the charger. High efficiency, high reliability, low cost, isolation, and high power density are the major challenges for EV battery chargers.

EV is electrically disconnected from the AC grid through galvanic isolation. This galvanic isolation in the battery charger of EV is performed using high frequency transformer in DC/DC converter.

The cost of magnetic components and filter components in the battery charger is reduced by increasing the switching frequency of the DC/DC converters. A limit will also come on the maximum switching frequency due to the increase of switching losses. However, incorporation of soft switching methods reduces switching losses and operates the converter in battery charger at high frequency [4]. The conventional FB converters are typically hard switched, and the hard switching converters are not suitable to achieve high efficiency. Soft switching is incorporated in FB converters to solve the above problems. Soft switching technique i.e. zero voltage soft switching and zero current soft switching turn on/off converters at zero voltage and current, respectively.

ZVS PWM FB converters utilize the stored energy in the leakage inducance of the primary winding of power transformer and output filter inductor for obtaining ZVS [5]. Conventional ZVS PWM converters output rectifier diodes suffer from hard-switching, results in severe voltage spike and ringing across the output rectifier diodes, high switching losses, circulating current, and low efficiency [6], [7]. ZVS and ZCS reduce switching losses in converters. Conduction losses are decreased by eliminating circulating currents. Consequently, a high efficiency can be achieved for the on-board battery charger of EVs [8], [9]. Main focus of the paper is to design a 2 kW ZVS DC/DC converter to charge the high voltage battery in the on-board charger of EV. Simulation of the converters has been done in PSIM to verify the design. In this paper, three isolated 2 kW DC/DC converters namely, ZVS PS PWM FB converter using leakage inductance, ZVS PS PWM FB converter using saturable inductance, and ZVS zero PS PWM FB converter using leakage inductance have been selected and designed for battery charger applications of EV. The characteristics of these converters are compared to select the suitable converter for battery charger system of EV.

The remaining paper is organized as follows: Section II discusses literature review of various ZVS PWM FB converters. Section III presents operation principles and analysis of ZVS PWM FB converters. Section IV includes the designed parameters of the selected converters for the given specifications. Section V provides the discussion on the comparison of the characteristics and simulation results of the converters. Section VI concludes the paper with future work.
II. LITERATURE REVIEW

ZVS PWM FB converters are broadly used in medium to high power DC/DC conversion applications such as EVs battery chargers, DC motor drives, computers, telecommunication systems, DC distributed systems, and welding machines etc [10].

Efficiency, power density, reliability and cost are the important parameters in these types of converters. In order to get high power density and small size for the converters, it is usually required to operate the converter at high frequency. However, switching power loss is proportional to high transistor switching frequency which lowers converter efficiency. Therefore, ZVS or ZCS topologies allow for high frequency operation while minimizing the switching loss. The size and cost of isolated DC/DC converters can be reduced by using high fixed frequency transformer [11]. The ZVS topologies operate at high frequency can improve the converter efficiency resulting high power densities [12].

Various types of ZVS PWM FB converters are reviewed with the objective of identifying converters with high efficiency and low circulating current, duty cycle loss, conduction losses and voltage ringing of rectifier diodes. Several ZVS topologies exist. However, not all of these ZVS topologies are feasible for the battery charger of EV.

In [13], ZVS FB PWM converter achieves ZVS with the help of transformer primary leakage inductance and the parasitic capacitances of the semiconductor switches. The energy stored in the output filter inductor and transformer primary leakage inductor help in ZVS for leading leg. ZVS in lagging leg is lost under low load condition because of the low energy stored in small primary leakage inductance [14]–[16].

When ZVS is required at low load currents, the transformer primary leakage inductance is intentionally increased and/or large external resonant inductor is connected in series with primary leakage inductance of transformer, resulting in high duty cycle loss and rectifier diodes parasitic voltage ringing [17].

A saturable resonant inductor is used to improve the performance of the converter rather than using a large linear external resonant inductor. ZVS in lagging leg is obtained over a wider load range. The duty cycle loss on the secondary side of transformer also reduces. However the saturable inductance limits the switching frequency and produces parasitic ringing across rectifier diodes [18].

In order to eliminate these problems, a classical converter in [19], [20] is proposed. Two primary clamping diodes are introduced, which clamp the voltage across the diodes present in the rectifier circuit to the reflected input voltage and the voltage oscillations are removed. The diodes in the secondary may be used with lower voltage ratings. Thus the converter efficiency is improved. The transformer primary one terminal is attached with the bridge leading leg and the primary inductor is attached with the bridge lagging leg. In this converter in one switching period, the clamping diodes conduct two times, but for voltage clamping one time conduction of the clamping diodes are necessary. The primary inductor current is freewheeling and produces higher conduction losses in zero state.

An improved ZVS FB PWM converter is proposed in [21], and the transformer and resonant inductor positions are interchanged. The lagging leg of the inverter is attached with the transformer. This topology not only reduces the voltage oscillations but the clamping diodes in the primary conduct once and reduces current of the resonant inductor in zero state, which reduces conduction losses in the primary. The clamping diodes conduct for half switching period at low load current and produces severe reverse recovery due to hard turned off of clamping diodes. In high input voltage applications, the clamping diodes are easily damaged. It is essential for clamping diodes to reset its current quickly to zero in zero state.

An enhanced ZVS FB PWM converter is proposed with extra auxiliary transformer [22]. This auxiliary transformer forces the current of clamping diode quickly to zero over a wider load current, results in low conduction losses of clamping diodes and in the leading leg.

III. ZVS PWM CONVERTERS OPERATION AND ANALYSIS

A. ZVS PWM PS Converter Using Leakage Inductance

Converters with low switching losses are used in high frequency power conversion [13]. The circuit shown in Fig. 2 operates under ZVS by using parasitic components. To get ZVS, the primary bridge inverter legs are operated with a phase shift. This operation discharges the MOSFET parasitic capacitance and later on forces the conduction of the MOSFET body diode. Fig. 3 demonstrates the primary current and voltage waveforms of ZVS PS FB PWM converter.

The energy stored in leakage inductor at time \( t_2 \) is used for discharging the output capacitor of switch \( Q_4 \) and charging the output capacitor of switch \( Q_2 \), and has to satisfy (1):

\[
E = \frac{1}{2} L_{ik} I_2^2 > \frac{4}{3} C_{MOS} V_{in}^2 + \frac{1}{2} C_{TR} V_{in}^2
\]  

where \( I_2 \) is the current flowing at time \( t_2 \) (or \( t_3 \)) in Fig. 3, \( C_{MOS} \) is the effective output capacitance of the MOSFET and \( C_{TR} \) is the winding capacitance of the transformer. To turn on switch \( Q_4 \) with zero voltage, a dead time is needed between the turn off of switch \( Q_2 \) and turn on of switch \( Q_4 \), such that switch \( Q_4 \) diode conducts before to turn on switch \( Q_4 \). The resonance between the leakage inductance of primary winding of transformer \( L_{ik} \) and the equivalent output capacitances of switches \( (C_{MOS} + C_{MOS}) \) and transformer winding capacitance \( C_{TR} \) produces sinusoidal voltage across switches \( Q_2 \) and \( Q_4 \) that reaches to maximum value at one fourth of the resonant period. The dead time between switches in the lagging leg can be calculated at one fourth of the resonant period as given in (2) [13]:

\[
t_{d24} = \frac{\pi}{2} \sqrt{\frac{L_{ik}}{C_{eq}}}
\]  

where \( C_{eq} = C_{MOS} + C_{MOS} + C_{TR} \).

The rising voltages across switch \( Q_4 \) at time \( t_2 \) for three different load currents are shown in Fig. 4. The first waveform in Fig. 4 (a) shows the case when the energy stored in \( L_{ik} \) is greater than the energy required to charge or discharge the output capacitors. Switch \( Q_4 \) output capacitor is charged in
Fig. 2 ZVS PWM FB converter using leakage inductance

Fig. 3 ZVS PS FB PWM converter key waveforms

less than \( t_{d24} \). Thus, the voltage across switch \( Q_4 \) is clamped to \( V_{in} \). Fig. 4 (b) shows the case when the energy in the \( L_{lk} \) is equal to the energy needed to charge or discharge output capacitors of switches. The last voltage waveform in Fig. 4c shows the condition when the energy in \( L_{lk} \) is less than the energy needed to charge or discharge the parasitic output capacitors and hence ZVS is lost. After \( t_{d24} \), switch \( Q_4 \) or \( Q_2 \) is on and the primary voltage sharply clamped to \( V_{in} \).

At low load currents, the energy stored in \( L_{lk} \) at time \( t_2 \) or \( t_6 \) is not sufficient to turn on switch diode \( D_2 \) or \( D_4 \) of the lagging leg [13], [23]. In leading leg, switch \( Q_1 \) at time \( t_5 \) is turned off and the energy needed to charge \( Q_1 \) output capacitance and discharge \( Q_3 \) output capacitance is the energy in \( (L_{lk} + L_f) \) [13]. The dead time \( t_{d13} \) needed between switches \( Q_1 \) and \( Q_3 \) may be calculated from (3):

\[
4C_{MOS}V_{in} + C_{TR}V_{in} = I_P t_{d13}
\]  

(3)

The term \( 4C_{MOS}V_{in} \) in (3) is the charged stored on two nonlinear output capacitors of MOSFETs. The charge stored on one nonlinear output capacitor of MOSFET is \( 2C_{MOS}V_{in} \).

The phase shift between switches \( Q_1 \) and \( Q_2 \) is determined from Fig. 3 and may be written as (4):  

\[
\phi_{12} = \left( 1 - D - \frac{2t_{di3}}{T} \right) 180^\circ
\]  

(4)

1) Requirement of ZVS for Leading and Lagging Legs:

Switches \( Q_1 \) and \( Q_3 \) can easily achieve ZVS even at low load currents because the reflected output filter inductor current always turn on body diodes \( D_1 \) and \( D_3 \) [13]. ZVS for switches \( Q_2 \) and \( Q_4 \) can be achieved at a primary current greater than the critical current \( I_{crit} \). The critical current in primary at time
\( t_2 \) (or \( t_6 \)), required for ZVS of switches \( Q_2 \) and \( Q_4 \) is obtained from (1) and may be written as (5):

\[
I_{cri} = \sqrt{\frac{2}{L_{ik}} (\frac{4}{3} C_{MOS} V_{in}^2 + \frac{1}{2} C_{TR} V_{in}^2)}
\]  

(5)

The current in the primary at time \( t_2 \) may be determined from Fig. 3 and is given by (6):

\[
I_2 = N_s \left( \frac{I_{out} + \Delta I}{2} - \frac{V_{out}}{L_f} \right) (1 - D) \frac{1}{2f_s}.
\]  

(6)

where \( D \) is the converter primary duty cycle, \( L_f \) is the output inductance, \( V_{out} \) is the average output voltage of the converter, \( f_s \) is switching frequency, \( I_{out} \) is converter average output current, \( \Delta I \) is the peak-peak output inductor current ripple, and \( N_p \) and \( N_s \) are the primary and secondary turns, respectively.

ZVS for lagging leg at time \( t_2 \) (or \( t_6 \)) is achieved when the primary current is greater than the primary critical current. The relation for ZVS at time \( t_2 \) (or \( t_6 \)) is given by (7). ZVS for switch \( Q_2 \) and switch \( Q_4 \) at \( t_2 \) (or \( t_6 \)) has to satisfy (7) and (8):

\[
I_2 > I_{cri}.
\]  

(7)

\[
\frac{N_s}{N_p} \left( \frac{I_{out} + \Delta I}{2} - \frac{V_{out}}{L_f} \right) (1 - D) \frac{1}{2f_s} > I_{cri}.
\]  

(8)

The voltage conversion ratio of ZVS PS PWM converter may be written as given in (9):

\[
\frac{V_{out}}{V_{in}} = \frac{N_s}{N_p} D_{eff}
\]  

(9)

where \( D_{eff} \) is the secondary voltage duty cycle.

\( D \) is set by the gate signals of the primary switches and expressed as (10):

\[
D = D_{eff} + \Delta D
\]  

(10)

In (10), \( \Delta D \) is the duty cycle loss produced by \( L_{ik} \).

From Fig. 3, the steady state equation for duty cycle loss \( \Delta D \) is given by (11):

\[
\Delta D = \frac{2L_{ik} f_s (I_1 + I_2)}{V_{in}}
\]  

(11)

\[
\Delta D = \frac{2L_{ik} f_s (2I_{out})}{V_{in}}
\]  

(12)

Using (1) and (12) duty cycle may be written as (13):

\[
\Delta D = \frac{32C_{MOS} f_s V_{in} I_{out}}{3I_{cri}^2}
\]  

(13)

In Fig. 3, \( I_1 \) is the primary current at time \( t_4 \) and may be written as (14):

\[
I_1 = \frac{N_s}{N_p} (I_{out} - \frac{\Delta I}{2})
\]  

(14)

The substitution of (6) and (14) into (11) leads to the (15) for duty cycle loss:

\[
\Delta D = \frac{N_s}{N_p} \left( \frac{2I_{out} - V_{out}}{L_f} (1 - D) \frac{T}{2} \right)
\]  

(15)

The substitution of (15) into (10) leads to (16):

\[
D = \frac{1 + 4 \frac{L_{load} R_{load}}{L_f}}{1 + \frac{L_{load}}{L_f} D_{eff}}
\]  

(16)

where \( R_{load} = \frac{N_s}{N_p} R_{load} \), \( L_f = \frac{N_s}{N_p} L_f \). When the term \( \frac{L_{load}}{L_f} (1 - D) \frac{T}{2} \) is much smaller as compared to \( 2I_{out} \) in (15), then (15) may be simplified to (17):

\[
\Delta D = \frac{N_s}{N_p} \left( \frac{2I_{out} - V_{out}}{L_f} (1 - D) \frac{T}{2} \right)
\]  

(17)

2) Conduction Losses: The conduction losses of the primary switches and body diodes may be determined from Fig. 5 as (18)-(21):

\[
P_{Q2.4} = R_{on} \left[ \frac{A + B + C}{2} \right]
\]  

(18)

where \( A = \left( \frac{I_{ach}}{\sqrt{2}} \right)^2 \frac{\Delta D}{4} \), \( B = \frac{\Delta I^2}{12} D_{eff} \frac{T}{2} \), and \( C = \left( I_{ach} + \Delta I \right)^2 \frac{D_{eff}}{2} \)

\[
P_{Q1.3} = R_{on} \left[ \frac{I_{ach}}{\sqrt{2}} \left( \frac{\Delta D}{4} + (I_{out} + \frac{\Delta I}{2}) \frac{D_{eff}}{2} \right) \right]
\]  

(19)

\[
P_{D2.4} = \left( \frac{I_2}{2} \right) V_{diode} \left( \frac{\Delta D}{4} \right)
\]  

(20)

\[
P_{D1.3} = V_{diode} \left( \frac{D_{eff}}{2} I_{out} + \frac{\Delta D}{4} I_2 \right)
\]  

(21)

where the first and second term used in the brackets of (18) and (19) are the rms currents during intervals \((t_3 - t_4)\) and \((t_4 - t_5)\) in Fig. 3, respectively. The third term in the bracket of (18) is the rms current during interval \((t_4 - t_2)\) or \((t_5 - t_6)\). There is no conduction loss during state \((t_1 - t_2)\) or \((t_5 - t_6)\) for switches \( Q_1 \) and \( Q_3 \), respectively. During the operation of converter, a high circulating current flows during the intervals \((t_1 - t_2)\) and \((t_5 - t_6)\) shown in Fig. 3. In these intervals, two upper or lower switches in the primary bridge are on at the same time in one cycle and clamp the transformer primary voltage to zero and increases conduction losses. All secondary diodes are on during these intervals and no power is delivered to load. For wider ZVS range of lagging leg, primary leakage inductance is increased or large linear resonant external inductor is used in series with \( L_{ik} \) [21]. The minimum energy stored in the linear resonant inductor at critical current is given by (22):

\[
E_{min} = \frac{1}{2} L_{crit} I_{cri}^2
\]  

(22)

The stored energy in the large linear resonant inductor at maximum output current is much more than is required for ZVS of the primary bridge switches as shown in Fig. 6. During intervals \((t_2 - t_4)\) and \((t_6 - t_8)\) in Fig. 3 energy is returned to the source known as circulating energy and is given in (23):
This circulating energy is very high and helps in achieving ZVS, though it also increases switch conduction losses and duty cycle loss. The maximum energy stored in the linear resonant inductor at maximum output current is given by (24).

$$E_{\text{max}} = \frac{1}{2} L_{ro} I_{\text{out}(\text{max})}^2$$  \hspace{1cm} (24)$$

B. ZVS PS PWM FB Converter Using Saturable Inductor

The large linear resonant inductor in the primary over a broad ZVS range produces high duty cycle loss, high switch conduction losses, high current and voltage stresses [18]. The converter output voltage with large linear resonant inductor may be written as (25):

$$V_{\text{out}} = \frac{D V_{\text{in}}}{N} - \frac{4 L_{ro} f_s I_{\text{out}}}{N^2}$$  \hspace{1cm} (25)$$

It is observed from (25) that the converter output voltage depends on the output current. \(V_{\text{out}}\) is more sensitive to variation in the output current for a given primary duty cycle and resonant inductor. A large resonant inductor causes low output voltage. To achieve the required output voltage, smaller turns ratio is needed. Conversely a smaller turns ratio increases the primary current stress, \(I_{\text{out}}\), which increases the rectifier diode voltage stress, \(V_{\text{in}}\), and primary conduction losses. These major limitations in the ZVS PS PWM converters mentioned above can be removed by using saturable inductor in place of resonant inductor as shown in Fig. 7.

The stored energy in saturable inductor is unchanged if the primary current increases above \(I_{\text{cri}}\) as shown in Fig. 9. The minimum stored energy in saturable inductor must fulfill (22). At \(t_2\) (or \(t_b\), the saturable inductor is saturated and the inductor current reaches to critical saturation current . Then the primary current, \(I_{\text{pri}}\), reaches rapidly to \(\frac{I_{\text{out}}}{N}\), the converter voltage in the secondary reaches to \(\frac{V_{\text{in}}}{N}\), and in half period, \(\Delta D T/2\) is reduced by \(\Delta D/2\) as shown in Fig. 8. Switch \(Q_1\) at time \(t_4\) is turned off and the current drops rapidly to critical saturation current \(I_{\text{cri}}\). During intervals \((t_0 - t_1)\) and \((t_4 - t_5)\) in Fig. 8 the current stresses of primary switches are decreased. Fig. 8 also shows that when primary current exceeds \(I_{\text{cri}}\) then the duty cycle loss depends upon the critical current which may be written as (26):

$$\Delta D = \frac{32 C_{\text{MOS}} f_s V_{\text{in}}}{3 N I_{\text{cri}}}$$  \hspace{1cm} (26)$$

The converter output voltage using saturable inductor may be written as (27) or (28):

$$V_{\text{out}} = \frac{D V_{\text{in}}}{N} - \frac{4 L_{ro} f_s I_{\text{out}}}{N^2}$$  \hspace{1cm} (27)$$

when \(I_{\text{out}} > I_{\text{cri}}\)
Fig. 7 ZVS PWM FB converter circuit using saturable inductor

\[ V_{\text{out}} = \frac{D V_{\text{in}}}{N} - \frac{\Delta L_{rs} f_s I_{\text{cri}}}{N^2} \]  \hspace{1cm} (28)

when \( \frac{I_{\text{out}}}{N} > I_{\text{cri}} \)

It is seen from (28), that the converter output voltage using saturable inductor become independent of the load current when the reflected output current referred to primary is greater than critical current. The circulating energy is greatly reduced by saturable inductor as shown in Fig. 10 which, in turn, reduces duty cycle loss and conduction losses of switches.

When saturable inductor is used for ZVS in the converter, the circulating energy is equal to the minimum energy required for ZVS and is given by (29):

\[ E_{\text{cir}} = E_{\text{min}} \]  \hspace{1cm} (29)

1) Conduction Losses: From Fig. 8, the primary bridge switches and body diodes conduction losses are obtained and may be written as (30)-(33):

\[ P_{Q2,4} = R_{\text{on}}[C + D + E] \]  \hspace{1cm} (30)

where \( C = \left( \frac{I_1}{\sqrt{3}} \right)^2 \frac{\Delta D}{2} \), \( D = (I_{\text{out}}^2 + \frac{\Delta I_{\text{out}}^2}{12}) \frac{D_{\text{eff}}}{2} \)
and \( E = \frac{I_{\text{in}} D}{2} \)

\[
P_{Q1,3} = R_{\text{on}} \left( \frac{I_{\text{cri}}}{\sqrt{3}} \right)^2 \frac{\Delta D}{2} + (I_{\text{out}}^2 + \frac{\Delta I_{\text{cri}}^2}{12}) \frac{D_{\text{eff}}}{2} \]  

(31)

\[
P_{D1,3} = V_{\text{diode}} \frac{D'}{2} I_{\text{cri}} + \frac{\Delta D}{8} I_{\text{cri}} \]  

(32)

\[
P_{D2,4} = V_{\text{diode}} \frac{\Delta D}{8} \]  

(33)

where the first and second term used in the brackets of (30) and (31) are the rms currents during states \((t_3 \rightarrow t_4)\) and \((t_4 \rightarrow t_5)\), respectively. The third term in the bracket of (30) is the rms current during state \((t_1 \rightarrow t_2)\) or \((t_5 \rightarrow t_0)\) and depends upon the critical current not upon the output current.

C. Zero PS ZVS PWM FB Converter Using Leakage Inductance

In zero PS converter, there is no phase shift between the diagonal switches in Fig. 2. The gate signals, switch current and voltage waveforms of zero PS ZVS converter are shown in Fig. 11, with \( D = 0.7 \) and \( f_s = 100 \text{ KHz} \). When this converter operates on small primary duty cycle and all the MOSFETs are turned off, then the stored energy in \( L_{\text{in}} \) causes ringing with output capacitances of MOSFETs. This will increases the conduction losses of the switches. This is a big disadvantage of this converter.

IV. DESIGN OF CONVERTERS

The discussed three ZVS FB PWM converters are designed for the following given specifications: Input voltage, \( V_{\text{in}} = 300 \text{ V} \); output voltage, \( V_{\text{out}} = 180 \text{ V} \); switching frequency, \( f_s = 100 \text{ KHz} \); output power, \( P_{\text{out}} = 2 \text{ kW} \); and output inductor current ripple, \( \Delta I_{\text{out}} = 10\% \) of \( I_{\text{out}} \). To make the discussion more easy, the ZVS PS PWM converter with leakage inductance will be consider as approach A, the converter with saturable inductor is consider as approach B and Zero PS converter with leakage inductance will be referred to as approach C. Based on the given specifications, power components in the primary bridge are \( IRFP460 \) and \( BYV54V200 \) for the secondary rectifier were selected. The output filter inductance was measured about \( 324 \mu\text{H} \) and the output capacitor about \( 1.54 \mu\text{F} \).

In approach A, a leakage/resonant inductance with a value of \( 13.5 \mu\text{H} \) is selected with a duty cycle of 0.8 and secondary effective is 0.6 to achieve ZVS from 20.34\% of load to full load. The phase shift between switch \( Q_1 \) and \( Q_2 \) is 35.46°.

In approach B, the linear external inductor is replaced with saturable inductor with a value of \( 13.5 \mu\text{H} \) for the same ZVS range as given in approach A. To get the required output voltage, the primary duty cycle is 0.64 and secondary effective duty cycle is 0.6. The phase shift between switch \( Q_1 \) and \( Q_2 \) is 63.54°.

In approach C, the leakage/resonant inductance with a value of \( 23.62 \mu\text{H} \) is selected to achieve ZVS from 21.78\% of load to full load. To get the required output voltage, the primary duty cycle is 0.9 and secondary effective duty cycle is 0.6. The phase shift between the switch \( Q_1 \) and \( Q_2 \) is zero.

V. SIMULATION RESULTS AND COMPARISON OF CONVERTERS

All the discussed three converters are simulated in PSIM software. After the successful simulations in PSIM, the generated waveforms of output voltages and currents waveforms, primary, secondary voltages and currents waveforms, and switch voltages and currents waveforms have been shown in Figs. 12-20. The purpose of these waveforms shows duty cycle loss, circulating current stresses and switching loss. From the simulation results, it is clear that the desired output voltage and current is achieved for each converter. These results also show that converter with saturable inductor produces low duty cycle loss and operated the converter with less conduction losses, while the other two converters with leakage inductances produces higher duty cycle loss which increases the conduction losses. ZVS is achieved for switch \( Q_2 \) using approach A, B and C as shown in Figs. 14, 17 and 20.

The ZVS range, dead times of the switches, duty cycle loss, circulating energy, circulating current stresses, conduction losses of primary bridge switches, body diodes and rectifier diodes are the main parameters for each ZVS PWM FB converter. The comparison of the converters in this paper are based on the same primary bridge switches, rectifier circuits,
frequency, filter inductances and capacitances, transformer and transformer turns ratio. A detail comparison of the parameters of the discussed and simulated converters is given in Table I.

Table I shows that ZVS PS PWM FB converter using leakage inductor and ZVS PS PWM FB converter using saturable inductor have the same ZVS range, which is 20.34% of full load current for the same value of inductance. To obtain ZVS in zero PS ZVS converter which is 21.78% of full load current the $L_{ik}$ is increased which increases the circulating energy. The circulating energy of the converter with saturable inductor is 34.48 $\mu J$, which is lower than that of 821.65 $\mu J$ of ZVS PS PWM converter and 1456.80 $\mu J$ of zero PS ZVS converter. The saturable inductor after saturation does not store much more circulating energy.

The converter duty cycle loss increases with high circulating energy. The duty cycle loss of the converter with saturable inductor is 0.04, which is much smaller than that of 0.2 and
Three isolated 2 kW ZVS PWM FB converters have been studied for battery charger applications of EV. The PS PWM and zero PS PWM converters with leakage inductances are not suitable for battery charger applications of EV with wider ZVS range. These converters have higher circulating energy, duty cycle loss, and lower efficiency. However, the converter employing saturable inductor with wider ZVS range has lower circulating energy, duty cycle loss, conduction losses, and high efficiency. Because of these characteristics, the ZVS PS PWM FB converter with saturable inductor is preferable for the battery charger applications of EV.

In future work, we will perform AC analysis of the converters to get more accurate results. Since ZVS of the converters is required from no load to full load in order to reduce switching losses, it also needs to be analyzed in future.

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