Simplified loss analysis and comparison of full-bridge, full-range-ZVS DC-DC converters

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Abstract. The loss of zero-voltage-switching (ZVS) of active switches has been a serious limitation of full-bridge (FBZVS) converters. Many techniques have been proposed in the past to extend the range of ZVS operation over the wider and also the full range of operation. However, in these techniques ZVS is achieved at the expense of additional conduction loss in active switches and losses in the auxiliary components. In this paper, the analysis for the additional losses in various full-range FBZVS DC–DC converters and their comparative evaluation is reported. Closed form expressions are derived for average value of device currents and losses. The loss curves for various topologies are plotted and compared. The analytical results are found to be consistent with the experimental efficiency tests performed on 500 W, 100 kHz prototype. It is concluded that a recently proposed new topology has the least penalty of additional losses.

Keywords. Auxiliary current; full-bridge DC–DC converters; loss analysis, ZVS.

1. Introduction

The full-bridge (FB) zero-voltage-switching (ZVS) converter (FBZVS converter) is a preferred topology for high power dc–dc converters due to fixed switching frequency, ZVS operation, high efficiency, low circulating reactive energy and moderate device stresses. The major limitation of the FBZVS converter has been the limited range of operation over which ZVS can be achieved. When the load current is low, the ZVS of the lagging-leg switches is lost as the energy stored in the leakage inductance of the transformer is insufficient to discharge the switch and transformer capacitances. The loss of ZVS results in increased switching losses and electromagnetic interference (EMI). In the case of high-power converters using IGBT (which is a slower device than MOSFET and exhibits current tailing at turn off), an external snubber capacitor is connected to reduce the rate of rise of voltage and turn-off losses. Therefore, in high-power converters, the loss of ZVS additionally results in the discharge of snubber capacitor in IGBT. The resulting surge current gives rise to EMI problem and stresses

on IGBT and capacitor. Further, the resonant voltage overshoots due to resonance between the snubber capacitor and wiring/lead inductance can exceed IGBT voltage rating. Therefore, it is important to maintain ZVS operation over the entire range of operation or the conversion range. To extend the range of ZVS operation, various methods have been proposed in the past. ZVS range can be increased by utilizing the energy stored in leakage inductance, magnetizing inductance or using a saturable core inductor (Watson & Lee 1994, Jang Yungtak *et al* 2003, Hua Guichao *et al* 1993). However, these methods do not provide complete range of ZVS operation as energy required for the ZVS still depends on either load current (when utilizing the energy of leakage inductance or employing saturable inductance) or duty cycle (when using the energy of magnetizing inductance). In order to obtain complete range of ZVS, configurations have been proposed in which, an auxiliary energy source is incorporated in the FBZVS converter, by circulating additional current in the converter. However, due to additional circulating current, these methods increase the conduction losses and other losses in additional magnetic components. Therefore, it is important to estimate the penalty of additional losses. The objective of this paper is to compare additional losses in some of these topologies. Configurations providing complete range of ZVS operation have been chosen for the study. They are:

- (i) Conventional FB-PSPWM converter (Sabate *et al* 1990) [figure 1a]
- (ii) FBZVS converter with pole on lagging leg (Watson & Lee 1994) [figure 1b]
- (iii) FBZVS converter with pole on both legs (Jain *et al* 2002) [figure 1c]
- (iv) FBZVS converter with passive auxiliary circuit with 'adaptive' auxiliary current (Borage *et al* 2005) [figure 1d]
- (v) New FBZVS converter with 'adaptive' auxiliary current (Borage *et al* 2008) [figure 1e].

In order to realize the comparison, analytical expressions of additional losses in each topology have been derived and total theoretical loss has been estimated. The conventional FBZVS converter has been chosen as the reference model, as it has no additional losses. Efficiency tests have been conducted to confirm the trend. The expressions for the average device currents are derived for simplified loss analysis with IGBT switches. Loss analysis for MOSFET switches can be done on the similar lines. The only difference would be to derive the expressions for rms currents in the switches to calculate MOSFET on-state losses.

1.1 Assumptions and methodology of the simplified loss analysis

IGBTs are used for the high-power application of proposed FBZVS converter. To calculate the conduction losses in the IGBT switches and anti-parallel diodes as well as the losses in the auxiliary inductor over the entire conversion range, following simplifying assumptions are made:

- (a) The output current is ripple-free, therefore transformer primary current is square-wave.
- (b) Transformer leakage inductance is small, therefore the slew interval (during which the transformer primary current reverses its direction) is absent.
- (c) The average power loss in an IGBT and a diode is proportional to the average current flowing through them.

Total additional losses in the converter include conduction losses in the devices, core and resistive losses of the additional magnetic components. Core losses and the resistive losses are significant due to increased number of magnetic components in the converter.

In order to calculate average device currents, the currents flowing through the midpoints of the legs in any of the converter configurations (points *A* and *B* in figure 1a–e or bridge points), i.e. I_A and I_B , are first calculated. These currents are either the sum or difference of the transformer primary current (I_{pri}) and auxiliary current (or the current through the auxiliary inductance; I_a), if any. Then the current waveforms through the individual switch/diode can be obtained depending upon the gate pulses and the positive/negative value of the current flowing

Figure 1. Various converter configurations under study (a) Conventional PSPWM converter; (b) Converter with pole at lagging leg; (c) Converter with pole at both the legs; (d) Converter with passive auxiliary circuit and 'adaptive' current; (e) New FBZVS Converter with 'adaptive' current; (f) Secondary side current doubler for converters (a)–(d); (g) secondary side current doubler for converter (e).

through the midpoints of the legs. Average values of the individual currents are calculated and an expression for conduction loss in each switch and the body diode is obtained. Core losses and the resistive losses in the additional magnetic components are derived in the respective topologies. Total loss, which is the sum of the conduction loss in all the devices and the core and resistive losses in the magnetic components, is then plotted for each topology for comparison.

2. Conventional FBZVS converter

For the conventional FBZVS circuit [figure 1a, f] the device current-waveforms are shown in figure 2. In figure 2, transition from S_2 to S_1 will be soft switched for higher values of duty ratio, as the energy of the leakage inductance will be sufficient to produce ZVS in the lagging leg switches. For lower values of duty cycle this transition will be hard switched causing switching losses. $i_{s1} - i_{s4}$ are the switch currents in the switches $S_1 - S_4$ whereas $i_{d1} - i_{d4}$ are diode currents in the diodes $D_1 - D_4$, respectively. The dotted curve [figure 2] (in waveform $I_A = -I_B$) shows the primary current with ripples due to output filter inductance (L_{f1} and L_{f2}) [figure 1f]. The dotted waveform has been approximated to square-wave (solid curve in $I_A = -I_B$), for the ease of analysis, according to assumption 1 in § 3. The expressions for average value of device currents can be derived as:

$$I_{D1+2} = 0 \quad (1a)$$

Figure 2. Device current waveforms in conventional FBZVS converter.

$$I_{s1+2} = \frac{I_o}{2N} \quad (1b)$$

$$I_{D3+4} = \frac{I_o}{2N}(1 - D) \quad (1c)$$

$$I_{s3+4} = \frac{I_o}{2N}D. \quad (1d)$$

Here I_o , the output DC load current, can be written as $V_d D / (2NR)$. The conduction loss can be given as:

$$P_{conduction} = \frac{V_d}{4N^2 R} [D(V_{on} + V_{di}) + D^2(V_{on} - V_{di})]. \quad (1e)$$

As mentioned in § 3, transformer leakage inductance is neglected in this analysis. Therefore, the slew interval (during which the transformer primary current reverses its direction) is absent and current reverses its direction instantaneously. Since diodes D_1 and D_2 normally come into conduction during the part of this slew interval (which is assumed to be absent), $I_{D1+2} = 0$ and the waveforms of i_{d1} and i_{d2} are not shown in the figure 2.

3. FBZVS converter with pole at lagging leg

In converter with pole circuit at lagging leg (figure 1b, f), ZVS operation in the lagging leg for low values of primary current, I_{pri} , is assisted by additional triangular inductor current (I_a) through the pole inductance, L_a . Waveform of I_A , being sum waveform of I_a and I_{pri} , will be different for the cases $I_{pri} > I_{La}$ and $I_{pri} < I_{La}$, as shown in figures 3(a) and (b), respectively, where, I_{La} is the peak value of I_a . The boundary condition $I_{pri} = I_{La}$ can be expressed in the form of parameter $D_{boundary} = (N^2 R / 2F_s L_a)$. The expressions for the device average currents for $D > D_{boundary}$ are similar as obtained in conventional converter [equations (1a)–(1d)]; for the case $D < D_{boundary}$ the expressions for average device currents in terms of load current $I_o = V_d D / (2NR)$ and peak auxiliary current $I_{La} = V_d / (8L_a F_s)$ are derived as:

$$I_{D1+2} = \frac{1}{2} \left(I_{La} - \frac{I_o}{2N} \right) \frac{t_x}{T_s/2} = \left(I_{La} - \frac{I_o}{2N} \right) \frac{t_x}{T_s} \quad (2a)$$

$$I_{s1+2} = \frac{1}{2} \left(\frac{I_o}{2N} + I_{La} \right) \frac{\{T_s/2 - t_x\}}{T_s/2} = \left(\frac{I_o}{2N} + I_{La} \right) \left(\frac{1}{2} - \frac{t_x}{T_s} \right) \quad (2b)$$

$$I_{D3+4} = \frac{I_o}{2N}(1 - D) \quad (2c)$$

$$I_{s3+4} = \frac{I_o}{2N}D. \quad (2d)$$

The time interval t_x (figure 3b for definition) is derived as,

$$t_x = (T_s/4) - (DL_a/2N^2 R). \quad (2e)$$

Since I_{La} is independent of duty ratio (D), as $I_{La} = V_d / (8L_a F_s)$, winding loss ($P_{winding_La}$) and core loss (P_{core_La}) in auxiliary inductor L_a are constant over the entire range of duty

ratio and are decided by the design. The expressions for various losses are summarized in table 1 for both the cases. These losses are added at all duty cycle operations. This constant addition of loss may be justified at lower duty cycle operation due to attainment of ZVS, but degrades the converter efficiency at higher duty cycle operation.

4. FBZVS converter with pole at both legs

To obtain additional losses in this converter (figures 1c, f), similar method is adopted and average value of current in each body diode and switch is calculated. As there are two new circulating currents (one in each leg [figure 1c]) and $D_{boundary}$ will be different for the two legs, the analysis is done separately for leading and lagging the legs. The waveforms for the lagging leg current (I_A) in this converter remains same as I_A in converter with pole at lagging leg [I_A in figure 3], but leading leg waveform is the difference of I_a and I_{pri} .

Figure 4 shows the leg waveform (I_B) in the cases when $I_{pri} > I_{La}$ and $I_{pri} < I_{La}$, I_{La} being the peak auxiliary current. Average values of currents in each device are calculated for both conditions of D using the waveforms I_A and I_B . Expressions for the average currents in

Figure 3a. (Continued)

Figure 3b. Device current waveforms in FBZVS converter with pole at lagging leg for (a) $D > D_{boundary}$, and, (b) $D < D_{boundary}$.

the devices for the leading and lagging legs in terms of load current $I_o = V_d D / (2NR)$ and peak auxiliary current $I_{La} = V_d / (8L_a F_s)$, where, $I_{La1} = I_{La2} = I_{La}$, are given in equation set 3.

For $D > D_{boundary}$,

$$I_{D1+2} = 0 \quad (3a)$$

$$I_{s1+2} = \frac{I_o}{2N} \quad (3b)$$

$$I_{D3+4} = \left(I_{La} D + \frac{I_o}{2N} \right) (1 - D) \quad (3c)$$

$$I_{s3+4} = \left(I_{La}(1 - D) + \frac{I_o}{2N} \right) D. \quad (3d)$$

And, for $D < D_{boundary}$,

$$I_{D1+2} = \left(I_{La} - \frac{I_o}{2N} \right) \frac{t_{x1}}{T_s} \quad (3e)$$

$$I_{s1+2} = \left(\frac{I_o}{2N} + I_{La} \right) \left(\frac{1}{2} - \frac{t_{x1}}{T_s} \right) \quad (3f)$$

$$I_{D3+4} = \left(I_{La} + \frac{I_o}{2N} \right) \left(\frac{1 - D}{2} - \frac{t_{x2}}{T_s} \right) \quad (3g)$$

$$I_{s3+4} = \frac{I_o}{2N} \left(D - \frac{t_{x2}}{T_s} \right) + I_{La} \left(D - D^2 + (1 - 2D) \frac{t_{x2}}{T_s} \right). \quad (3h)$$

The time interval t_{x1} corresponds to the case of lagging leg and is same as t_x in equation 2(e) (figure 3b). The time interval t_{x2} for leading leg is defined in equation 3(j) (figure 4b for definition).

$$t_{x1} = 1/4F_s - (DL_a)/(2N^2R) \quad (3i)$$

$$t_{x2} = 1/4F_s - (DL_a)/(2N^2R) - D/(2F_s). \quad (3j)$$

Finally, the expressions for the conduction losses in each leg are derived. These losses along with core and winding loss are listed in table 2. It can be observed that core and winding losses are doubled, which severely degrade the converter performance as shown later in sections.

Table 1. Expressions for conduction loss, core loss and winding loss in converter with pole at lagging leg.

$P_{conduction}$	$D^2 \left(\frac{V_d}{4N^2R} \right) (V_{on} - V_{di}) + D \left(\frac{V_d}{4N^2R} \right) \left[V_{di} \left(1 - \frac{t_x}{T_s} \right) + V_{on} \left(\frac{1}{2} - \frac{t_x}{T_s} \right) \right]$
for $D \leq \frac{N^2R}{2F_sL_a}$	$+ \frac{V_d}{8L_aF_s} \left[V_{di} \frac{t_x}{T_s} + V_{on} \left(\frac{1}{2} - \frac{t_x}{T_s} \right) \right]$
$P_{conduction}$	$\frac{V_d}{4N^2R} [D(V_{on} + V_{di}) + D^2(V_{on} - V_{di})]$
for $D > \frac{N^2R}{2F_sL_a}$	
P_{core_La}	Decided by the design
$P_{winding_La}$	$\left(\frac{V_d^2}{192L_a^2F_s^2} \right)_{coil}^R$

5. Converter with passive auxiliary circuit

The device current waveforms for the converter with auxiliary passive circuit (figure 1d, f) with ‘adaptive’ current, is shown in figure 5. As the converter incorporates an ‘adaptive’ auxiliary current (I_{La} decreases with increase in I_{pri}), the device conduction loss reduces for higher duty cycle operation as compared to previous two configurations, tending to attain loss profile of conventional FBZVS converter for $D \geq D_{boundary}$, where $D_{boundary} = N^2 R / (N^2 R + 2F_s L_a)$. Expressions for the average currents in the devices for the leading and lagging legs in terms of load current $I_o = V_d D / (2NR)$ and auxiliary current $I_{La} = V_d(1 - D) / (8L_a F_s)$ are given in equation set (4).

For $D > D_{boundary}$:

$$I_{D1+2} = 0 \quad (4a)$$

$$I_{s1+2} = \frac{I_o}{2N}(1 - D) + \left(\frac{I_o}{2N} - I_{La} \right) D = \frac{I_o}{2N} - I_{La} D \quad (4b)$$

$$I_{D3+4} = \frac{I_o}{2N}(1 - D) \quad (4c)$$

$$I_{s3+4} = \left(I_{La} + \frac{I_o}{2N} \right) D. \quad (4d)$$

For $D < D_{boundary}$:

$$I_{D1+2} = \frac{1}{2} \left(I_{La} - \frac{I_o}{2N} \right) \frac{t_x}{T_s/2} + \left(I_{La} - \frac{I_o}{2N} \right) D = \left(I_{La} - \frac{I_o}{2N} \right) \left(D + \frac{t_x}{T_s} \right) \quad (4e)$$

Figure 4a. (Continued)

Figure 4b. Device current waveforms for the leading leg in FBZVS converter with pole at both legs for (a) $D > D_{boundary}$, and, (b) $D < D_{boundary}$.

$$I_{s1+2} = \frac{1}{2} \left(\frac{I_o}{2N} + I_{La} \right) \frac{\{(1-D)T_s/2 - t_x\}}{T_s/2} = \left(\frac{I_o}{2N} + I_{La} \right) \left(\frac{1-D}{2} - \frac{t_x}{T_s} \right) \quad (4f)$$

$$I_{D3+4} = \frac{1}{2} \left(\frac{I_o}{2N} + I_{La} \right) \frac{\{(1-D)T_s/2 - t_x\}}{T_s/2} = \left(\frac{I_o}{2N} + I_{La} \right) \left(\frac{1-D}{2} - \frac{t_x}{T_s} \right) \quad (4g)$$

$$\begin{aligned} I_{s3+4} &= \frac{1}{2} \left(I_{La} - \frac{I_o}{2N} \right) \frac{t_x}{T_s/2} + \left(I_{La} + \frac{I_o}{2N} \right) D \\ &= \left(I_{La} - \frac{I_o}{2N} \right) \frac{t_x}{T_s} + \left(I_{La} + \frac{I_o}{2N} \right) D. \end{aligned} \quad (4h)$$

The time interval t_x (see figure 5b for definition) is derived as,

$$t_x = \frac{1}{4F_s} - D \left(\frac{1}{4F_s} + \frac{L_a}{2N^2 R} \right). \quad (4i)$$

Table 2. Expressions of conduction loss, core loss and winding loss in converter with pole at both legs.

$P_{conduction_lagging}$ for $D \leq \frac{N^2 R}{2F_s L_a}$	$D \left(\frac{V_d}{4N^2 R} \right) \left[V_{on} \left(\frac{1}{2} - \frac{t_{x1}}{T_s} \right) - V_{di} \frac{t_{x1}}{T_s} \right] + \frac{V_d}{8L_a F_s} \left[V_{on} \left(\frac{1}{2} - \frac{t_{x1}}{T_s} \right) + V_{di} \frac{t_{x1}}{T_s} \right]$
$P_{conduction_lagging}$ for $D > \frac{N^2 R}{2F_s L_a}$	$V_{on} \frac{V_d D}{4N^2 R}$
$P_{conduction_leading}$ $D \leq \frac{N^2 R}{2(N^2 R + F_s L_a)}$	$\frac{V_d}{4N^2 R} \left[D^2 \left(V_{on} - \frac{V_{di}}{2} \right) - D \frac{t_{x2}}{T_s} (V_{di} + V_{on}) + D \frac{V_{di}}{2} \right]$ $+ \frac{V_d}{8L_a F_s} \left[-D^2 V_{on} + D \left(V_{on} - \frac{V_{di}}{2} \right) + \frac{V_{di}}{2} + \frac{t_{x2}}{T_s} [V_{on}(1 - 2D) - V_{di}] \right]$
$P_{conduction_leading}$ $D > \frac{N^2 R}{2(N^2 R + F_s L_a)}$	$\frac{V_d}{4N^2 R} [D^2 (V_{on} - V_{di}) + D V_{di}]$ $+ \frac{V_d}{8L_a F_s} [(D - D^2)(V_{on} + V_{di})]$
P_{core_La}	Decided by the design
$P_{winding_La}$	$2 \left(\frac{V_d^2}{192 L_a^2 F_s^2} \right) R_{coil}$

The expressions for the conduction losses in each leg are derived. These losses along with core and winding loss are listed in table 3.

The core loss of ferrites is often expressed in the form of following curve-fit equation.

$$P_{core} = k F_s^\alpha B^\beta, \quad (5)$$

where k , α and β are the constants and their values depend on the material grade. In the auxiliary inductor of the proposed converter, F_s is constant and B is proportional to I_{La} , which is proportional to $(1 - D)$. Therefore, core loss in the auxiliary inductor can be expressed as,

$$P_{core_La} = P_{core_max_La} (1 - D)^\alpha. \quad (6)$$

The winding loss in the auxiliary inductor are given by,

$$P_{winding} = I_{La,rms}^2 R_{coil-La} \quad (7)$$

$$I_{La,rms} = \frac{V_d(1 - D)}{8\sqrt{3}L_a F_s} \sqrt{2D + 1}. \quad (8)$$

Similarly, for auxiliary transformer, the core loss and winding loss are given by,

$$P_{core_Tr} = P_{core_max_Tr} (1 - D)^\alpha \quad (9)$$

$$P_{winding_Tr} = \frac{1}{4} I_{La,rms}^2 R_{core_Tr}. \quad (10)$$

6. New FBZVS converter

Figures 1e and g show the circuit of the new FBZVS topology (Borage *et al* 2008). The gate pulses in the converter, generated by the control circuitry, are similar to the basic model of PS-PWM converter. Voltages V_d and zero appear at the midpoint of the leg 1 (point A), when switch S_1 and S_2 are on, respectively. The DC blocking capacitor C_{cd1} blocks the DC components in this pulsed voltage at point A and a $\pm V_d/2$ appears at left terminal of L_a . Similarly, at the other end of L_a , $V_d/2$ and $-V_d/2$ appears when switches S_3 and S_4 are on,

Figure 5a. (Continued)

Figure 5b. Device current waveforms in converter with Auxiliary circuit and ‘adaptive’ current (a) $D > D_{boundary}$, and, (b) $D < D_{boundary}$.

respectively. During the time interval $DT_s/2$, switches S_1 and S_3 are on providing $+V_d/2$ across both transformer primaries, producing positive output pulse. Next, during $(1 - D) \cdot T_s/2$ period, switches S_1 and S_4 are on, producing voltages $+V_d/2$ and $-V_d/2$ across the transformer primaries, which add up to zero at the secondary. During this period, net voltage of V_d is obtained across L_a , producing auxiliary current which rises during $(1 - D) \cdot T_s/2$. Similar operation with opposite voltage polarities is obtained for next $D \cdot T_s/2$ and $(1 - D) \cdot T_s/2$

Table 3. Expressions of conduction loss, core loss and winding loss in converter with auxiliary circuit with adaptive current.

$P_{conduction}$	$\frac{V_d}{16F_s L_a} (V_{on} - V_{di}) - D^2 \left[\frac{V_d}{4N^2 R} (V_{di} - V_{on} - (V_{di} + V_{on}) \frac{L_a F_s}{N^2 R}) \right.$
for $D \leq \frac{N^2 R}{N^2 R + 2F_s L_a}$	$\left. + \frac{V_d}{16F_s L_a} (V_{on} - V_{di}) \right]$
$P_{conduction}$	$\frac{V_d}{4N^2 R} [D(V_{on} + V_{di}) + D^2(V_{on} - V_{di})]$
for $D > \frac{N^2 R}{N^2 R + 2F_s L_a}$	
P_{core_La}	$P_{core_max_La} (1 - D)^\alpha$
P_{core_Tr}	$P_{core_max_Tr} D^\alpha$
$P_{winding_La}$	$\frac{V_d^2 (1-D)^2}{192L_a^2 F_s^2} (2D + 1) R_{core_La}$
$P_{winding_Tr}$	$\frac{V_d^2 (1-D)^2}{768L_a^2 F_s^2} (2D + 1) R_{core_Tr}$

periods. Since the auxiliary current rises in the complementary duty cycle period, I_{La} is high for lower duty ratio operation and vice-versa.

Figure 6 shows the device currents waveforms for the new FBZVS converter (figures 1e, g). Table 4 gives the summary of calculated additional losses incurred in the new converter in order to attain full range ZVS. As extra circulating current (I_a) in the converter is ‘adaptive’ (i.e. it decreases with increasing I_{pri}), additional conduction losses, core loss and winding loss all tend to reduce with increasing duty cycle. Due to this, the conduction losses in the converter tend to converge with conduction losses in the conventional converter for higher duty cycle operation. Expressions for the average currents in the devices for the leading and lagging legs in terms of load current $I_o = V_d D / (2NR)$ and auxiliary current $I_{La} = V_d (1 - D) / (4L_a F_s)$ are given in equation set (11).

For $D > D_{boundary}$:

$$I_{D1+2} = \frac{(1 - D)(T_s/2)(I_o/2N)}{T_s/2} = \frac{I_o}{2N} (1 - D) \quad (11a)$$

$$I_{D3+4} = 0 \quad (11b)$$

$$I_{S1+2} = \left(\frac{I_o}{2N} + I_{La} \right) D \quad (11c)$$

$$I_{S3+4} = \left(\frac{I_o}{2N} - I_{La} \right) D + \frac{I_o}{2N} (1 - D) = \frac{I_o}{2N} - D I_{La}. \quad (11d)$$

For $D < D_{boundary}$:

$$I_{D1+2} = \frac{1}{2} \left(I_{La} + \frac{I_o}{2N} \right) \frac{(1 - D)T_s/2 - t}{T_s/2} = \left(I_{La} + \frac{I_o}{2N} \right) \left(\frac{(1 - D)}{2} - \frac{t_x}{T_s} \right) \quad (11e)$$

$$\begin{aligned}
 I_{D3+4} &= \left(I_{La} - \frac{I_o}{2N} \right) D + \frac{1}{2} \left(I_{La} - \frac{I_o}{2N} \right) \frac{t_x}{T_s/2} \\
 &= \left(I_{La} - \frac{I_o}{2N} \right) D + \frac{t_x}{T_s} \left(I_{La} - \frac{I_o}{2N} \right)
 \end{aligned} \tag{11f}$$

$$\begin{aligned}
 I_{S1+2} &= \left(I_{La} + \frac{I_o}{2N} \right) D + \frac{1}{2} \left(I_{La} - \frac{I_o}{2N} \right) \frac{t_x}{T_s/2} \\
 &= \left(I_{La} + \frac{I_o}{2N} \right) D + \frac{t_x}{T_s} \left(I_{La} - \frac{I_o}{2N} \right)
 \end{aligned} \tag{11g}$$

Figure 6a. (Continued)

Figure 6b. Device current waveforms in new FBZVS converter for (a) $D > D_{boundary}$, and (b) $D < D_{boundary}$.

$$\begin{aligned}
 I_{S3+4} &= \frac{1}{2} \left(I_{La} + \frac{I_o}{2N} \right) \left((1-D) - \frac{2t_x}{T_s} \right) \\
 &= \left(I_{La} + \frac{I_o}{2N} \right) \left(\frac{(1-D)}{2} - \frac{t_x}{T_s} \right). \quad (11h)
 \end{aligned}$$

Table 4. Expressions of conduction loss, core loss and winding loss in new converter with auxiliary circuit with adaptive current.

$P_{conduction}$	$\frac{V_d}{8F_s L_a}(V_{on} + V_{di}) - D^2 \frac{V_d}{4N^2 R}(V_{di} - V_{on} - (V_{di} + V_{on}) \frac{L_a F_s}{2N^2 R})$
for $D \leq \frac{N^2 R}{N^2 R + F_s L_a}$	$-D^2 \frac{V_d}{8F_s L_a}(V_{on} + V_{di})$
$P_{conduction}$	$\frac{V_d}{4N^2 R}[D(V_{on} + V_{di}) + D^2(V_{on} - V_{di})]$
for $D > \frac{N^2 R}{N^2 R + F_s L_a}$	
P_{core_La}	$P_{core_max_La}(1 - D)^\alpha$
$P_{winding_La}$	$\left(\frac{V_d^2(1-D)^2}{48L_a^2 F_s^2} (2D + 1) \right) R_{core_La}$

The time interval t_x (see figure 6b for definition) is derived as,

$$t_x = \frac{1}{4F_s} - D \left(\frac{1}{4F_s} + \frac{L_a}{4N^2 R} \right) \quad (11i)$$

$$D_{boundary} = \frac{N^2 R}{N^2 R + F_s L_a}. \quad (11j)$$

Next, the expressions for the conduction losses in each leg are derived. These losses along with core and winding loss in L_a are listed in table 4.

7. Comparison

Figures 7–10 show the plots of device conduction losses, core losses, winding losses and total conduction losses, respectively, with changing duty cycle, for all four configurations. The only source of conduction loss in conventional FBZVS converter, i.e. device conduction loss has been included in figure 7, in order to lay a reference level of device conduction loss. This level represents the minimum possible conduction loss in any FBZVS converter, as conventional FBZVS converter does not incorporate any additional auxiliary current. The parameters, chosen for the plots, are listed in table 5. In order to justify the comparison, choice of these parameters is such that respective peak primary currents and peak auxiliary currents are same in all configurations. For example, since the voltage across the L_a in the new FBZVS converter is $\pm V_d$, the L_a chosen is double as compared to other configurations, so that peak auxiliary currents in all configurations are same.

7.1 Higher duty cycle operation

At higher duty ratio operation, the converter with pole circuit at lagging leg shows increased conduction losses due to core and winding losses in auxiliary inductor [plot (1) in figures 8 and 9]. Converter with pole at both the legs also shows the same trend, with losses further increased, due to presence of two inductors [plot (2) in figures 8 and 9]. In the converter with passive auxiliary circuit, the additional device conduction loss and winding loss in the auxiliary inductor are minimal [plot (3) in figures 7 and 9], but the core losses in the auxiliary transformer make the total losses higher than the conventional FBZVS converter [plot (3) in

Figure 7. Device conduction losses in FBZVS converters. (1) Converter with pole at lagging leg ($L_a = 120 \mu\text{H}$), (2) Converter with poles at both legs ($L_a = 120 \mu\text{H}$), (3) Converter with passive auxiliary circuit ($L_a = 120 \mu\text{H}$), (4) New FBZVS converter ($L_a = 240 \mu\text{H}$), (5) Conventional converter.

figure 8]. In the new FBZVS converter configuration, the additional losses are minimal in all three forms [plot (4) in figures 7–9] and the loss curve converges to that of conventional FBZVS converter [plots (4) and (5) in figure 10], for higher duty cycle operation. Thus new FBZVS converter exhibits minimum conduction loss penalty with full-range ZVS operation.

Table 5. Design parameters for plots in figure 7. #: for new FBZVS converter; *: for other converters.

Parameter	Value	Parameter	Value
V_d	250 V	$P_{core,max}^\#$	2 W
V_o	0–10 V	$P_{core,max}^*$	1 W
I_o	0–50 A	$P_{core,max,Tr}$	2 W
F_s	100 kHz	α	2.5
N	9	$R_{coil}^\#$	100 mΩ
R	0.2 Ω	$R_{coil}^* = R_{coil,Tr}$	50 mΩ
$L_a^\#$	240 μH	V_{on}	2.5 V
L_a^*	120 μH	V_{di}	1.5 V

Figure 8. Core losses in FBZVS converters. (1) Converter with pole at lagging leg ($L_a = 120 \mu\text{H}$), (2) Converter with poles at both legs ($L_a = 120 \mu\text{H}$), (3) Converter with passive auxiliary circuit ($L_a = 120 \mu\text{H}$), (4) New FBZVS converter ($L_a = 240 \mu\text{H}$).

Figure 9. Winding losses in FBZVS converters. (1) Converter with pole at lagging leg ($L_a = 120 \mu\text{H}$), (2) Converter with poles at both legs ($L_a = 120 \mu\text{H}$), (3) Converter with passive auxiliary circuit ($L_a = 120 \mu\text{H}$), (4) New FBZVS converter ($L_a = 240 \mu\text{H}$).

Figure 10. Total conduction losses in FBZVS converters. (1) Converter with pole at lagging leg ($L_a = 120 \mu\text{H}$), (2) Converter with poles at both legs ($L_a = 120 \mu\text{H}$), (3) Converter with passive auxiliary circuit ($L_a = 120 \mu\text{H}$), (4) New FBZVS converter ($L_a = 240 \mu\text{H}$), (5) Conventional converter.

7.2 Lower duty cycle operation

At lower duty cycle, the converter with lagging leg pole has low conduction losses [plot (1) in figure 7], but again this converter does not operate in ZVS mode for leading leg when I_{pri} reduces below critical level, causing switching losses. FBZVS converter with passive auxiliary circuit and new FBZVS converter have the similar loss profile [plots (3, 4) in figure 7] and the losses in the FBZVS converter with poles at both legs has the highest losses in this region [plot (2) in figures 7–10].

8. Practical confirmation—Efficiency tests

Conversion efficiencies of converters are measured on an experimental 500 W prototype converter operating at 100 kHz. The converter operates from a 250 V dc input and delivers 50 A maximum in a load resistance of 0.2Ω . The output current variation is specified in the range of 2 A to 50 A. The switches $S_1 - S_4$ are IRF840 MOSFETs. In the transformer, $N = 9$. The output filter is: $L_{f1} = L_{f2} = 22 \mu\text{H}$ and $C_f = 10 \mu\text{F}$ [figure 1f, g]. The value of inductor is $L_a = 120 \mu\text{H}$ for the converters in figure 1a–d and $L_a = 240 \mu\text{H}$ for figure 1e with $C_{dc1} = C_{dc2} = 1 \mu\text{F}$ [figure 1e]. The values of L_a have been chosen such that peak auxiliary current remains equal in all configurations.

Figure 11 shows the efficiency test results for the converters. The efficiency of FBZVS converter with pole on lagging leg is shown as plot (2). From full-load to approximately 20% part-load, efficiency of the new FBZVS converter [plot (3)] is observed to be higher.

Figure 11. Efficiency of the 500 W prototype FBZVS converters. (1) Conventional converter, (2) Converter with pole at lagging leg, (3) New converter, (4) Converter with pole at both legs.

(a)
Figure 12a. (Continued)

(b)

Figure 12b. Experimental Waveforms for the new FBZVS converter at (a) $D = 0.9$, and (b) $D = 0.1$. (1) Input voltage for the current doubler rectifier (20 V/div), (2) I_{Pri} (2.5 A/div), (3) V_{La} (200 V/div) and, (4) I_a (2.5 A/div). X-scale: 2.5 μ s/div.

This is because the auxiliary current in the new FBZVS converter is lower than that in the FBZVS converter with pole on lagging leg. For lower output power, the efficiency of the new FBZVS converter is observed to be lesser. The reason is- in the FBZVS converter with pole on lagging leg, the auxiliary current is circulating in only two switches, providing ZVS in only lagging leg, whereas in the new FBZVS converter auxiliary current is circulating in all the four switches causing more conduction loss.

The efficiency of this FBZVS converter with poles on the both legs is shown as the plot (4) in figure 11. The efficiency is observed to be further degraded at full-load and also over the entire range as compared to the efficiency of the new FBZVS converter.

In summary, we can conclude that the fixed circulating current of FBZVS with pole on lagging leg and FBZVS converter with pole on both the legs degrades their full-load efficiency as compared to conventional FBZVS converter. Due to adaptive circulating current in new FBZVS converter, circulating current is low near full-load operation. Therefore, the full-load efficiency of the new FBZVS converter is the same as conventional FBZVS converter. The improvement in efficiency with the described full-range-ZVS techniques with respect to the conventional FBZVS converter at part-load operation depends on the trade-off between switching losses saved by maintaining ZVS operation and the additional conduction loss in the switches due to circulating current plus losses in the auxiliary inductor. The savings in the switching losses will be larger if either switching frequency is high (typically 300–500 kHz in low-power applications, e.g. up to 1–2 kW, using MOSFET) or the snubber capacitors are

larger (tens of nano-farads) in high-power converters (e.g. up to 5–20 kW, using IGBT). With the chosen parameters of the prototype converter, the saving in the switching loss seems to be less than additional conduction losses. Therefore, for part-load operation, the efficiency of conventional FBZVS converter is observed to be higher. Nevertheless, the full-range ZVS operation of new FBZVS converter with minimum additional loss penalty remains as a major advantage since apart from efficiency improvement, there are other important reasons as explained in the introduction of this paper for ensuring full-range ZVS operation.

Illustratively, figure 12 shows the experimental waveforms of secondary voltage, primary current, voltage across L_a and I_a for the new FBZVS converter [figure 1e], (Borage *et al* 2008). The waveforms clearly demonstrate the adaptive auxiliary inductor current, which is high when the load current is low and vice versa resulting in full-range ZVS without increasing the full-load conduction losses.

9. Conclusion

Simplified analysis of losses in the full-bridge, full-range-ZVS circuits is presented and comparative assessment is made. Closed form expressions are derived for average value of device currents and losses. The loss curves for various topologies are plotted and compared. The analytical results are found to be consistent with the experimental efficiency tests performed on 500 W, 100 kHz prototype. It is concluded that a recently proposed new topology has the least penalty of additional losses. The improvement in efficiency is expected in high frequency, high power operation wherein the switching losses saved exceed the additional losses incurred.

Nomenclature

C_{dc1}, C_{dc2}	DC blocking capacitors
C_f	Output filter capacitance
D	Duty cycle with respect to primary of transformer
$D_{boundary}$	Value of D at which I_{La} and I_{pri} are equal
$F_s (= 1/T_s)$	Switching frequency
I_A	Current flowing away from left leg at its midpoint
I_a	Current flowing through the auxiliary inductance (auxiliary current)
I_B	Current flowing away from right leg at its midpoint
I_{D1+2}	Total average current in diodes D_1 and D_2
$i_{d1} - i_{d4}$	Current through diodes $D_1 - D_4$, respectively
I_{D3+4}	Total average current in diodes D_3 and D_4
I_{La}	Peak value of I_a
I_o	Output dc current
I_{pri}	Primary current of the isolation transformer
I_{s1+2}	Total average current in switches S_1 and S_2
I_{s1+4}	Total average current in switches S_3 and S_4
$i_{s1} - i_{s4}$	Current through switches $S_1 - S_4$, respectively
L_a	Auxiliary inductance
L_{f1}, L_{f2}	Output filter inductances
L_s	Leakage inductance of the isolation transformer (measured at the primary)
N	Transformer turns ratio (primary to secondary)
$P_{conduction}$	Total conduction losses in the switches and diodes
$P_{core-La}$	Core loss of inductor L_a

$P_{core_max_La}$	Maximum core loss of inductor L_a
P_{core_Tr}	Core loss of coupled inductor (transformer) T_r
$P_{core_max_Tr}$	Maximum core loss of coupled inductor (transformer) T_r
$P_{winding_La}$	Copper loss of inductor L_a
R	Output load resistance
R_{coil_La}	Winding resistance of inductor L_a
R_{coil_Tr}	Winding resistance of coupled inductor (transformer) T_r
t_x	Parameter representing the time during which I_{La} equals $-I_{pri}$ since the start of the cycle
V_d	Input DC supply voltage
V_{di}	On-state voltage drop in diode
V_o	Output voltage
V_{on}	On-state voltage drop in IGBT

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