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F.C.Y. Lee
Virginia Polytechnic Institute and State Univ…

Milan M Jovanovic

An Improved Full-Bridge Zero-Voltage-Switched PWM Converter Using a Saturable Inductor

Guichao Hua, Fred C. Lee, *Fellow, IEEE,* and Milan M. Jovanović, *Senior Member, IEEE*

Abstract— **The saturable inductor is employed in the full-bridge (FB) zero-voltage-switched (ZVS) pulsewidth-modulated (PWM) converter to improve its performance. The current and voltage stresses of the switches as well as parasitic oscillations are significantly reduced compared to those of the conventional FB-ZVS-PWM converter. The qualitative analysis is presented and is verified on a 500 KHz, 5 V/40 A converter.**

I. Introduction

Recently, many new techniques have been proposed for high-frequency power conversion to reduce the switching losses in traditional pulsewidth-modulated (PWM) converters. Among them, the full-bridge (FB) zero-voltage-switched (ZVS) resonant-transition PWM technique [1]-[4] is deemed most desirable for many applications since it combines the benefits of both the ZVS quasi-resonant converter (QRC) and PWM techniques, while avoiding their major drawbacks. The primary switches in the FB-ZVS-PWM converter are zero-voltage switched and are subjected to a relatively low current stress. As a result, switching losses are significantly reduced without the penalty of a significant increase in conduction loss. Furthermore, the converter operates with a fixed frequency, enabling the design optimization of the circuit to be easily attainable.

Since ZVS of the FB-ZVS-PWM converter is achieved by utilizing the resonant inductor energy to discharge the output capacitance of the power switches, the load range under which ZVS is maintained is strongly dependent on the resonant inductance. This may not be a limitation for some applications where loss of ZVS can be tolerated at relatively light loads. In these cases, the leakage inductance of the transformer is sufficient to achieve ZVS at nearer full load ever for a wide input range. However, for some applications which are sensitive to light load efficiency, a considerably large resonant inductor will be required to ensure ZVS at light load. Due to this large resonant inductor, the FB-ZVS-PWM converter operates with high circulating energy, which substantially increases the conduction losses and current and voltage stresses of the switches compared to its PWM counterpart. In addition, this resonant inductor interacts with the diode junction capacitances, causing severe parasitic oscillations, and increasing switching loss and switching noise. These are the major limitations of the FB-ZVS-PWM converter.

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The authors are with the Virginia Power Electronics Center, The Bradley Department of Electrical Engineering, Virginia Polytechnic Institute & State University, Blacksburg, VA 24061.

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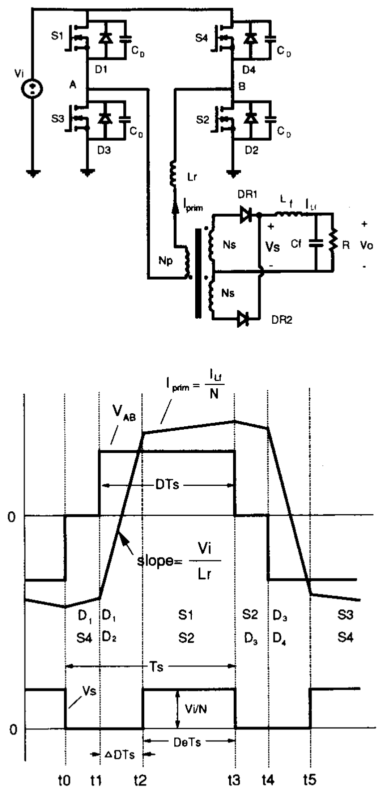


Fig. 1. FB-ZVS-PWM converter and its key waveforms.

This paper presents a simple and effective method to overcome the above-mentioned drawbacks of the ZVS-PWM technique. By using a saturable reactor as the resonant inductor during the switching transition, the performance of the FB-ZVS-PWM converter is improved.

II. Limitations of the FB-ZVS-PWM Converter

Fig. 1 shows the circuit diagram and the key waveforms of the FB-ZVS-PWM converter. Its operation is fully described in [1]-[4]. This converter uses the same topology as the FB-ZVS-QRC. Employing phase-shift control [5], it creates a freewheeling stage within the quasi-resonant operation which enables constant-frequency operation by controlling the time interval $(t0 - t1)$of this freewheeling stage [6].

Compared to its PWM counterpart, the FB-ZVS-PWM converter uses a resonant inductor (Lr) to achieve ZVS for the primary switches. The size of the inductor is determined by the load and input voltage range under which ZVS is maintained. To reduce the switching losses for a wide load and input voltage range, a large resonant inductance is required. However, a large resonant inductance causes higher circulating energy that significantly increases the conduction loss. Therefore, the load current under which ZVS is maintained is relatively limited in practical circuits [2]–[4].

The amount of the circulating energy determines a loss of duty cycle at the secondary side, ΔD:

$$\Delta D = D - D_e, \tag{1}$$

where D and D_e are the duty cycles of the primary-voltage and secondary-voltage, respectively. This ΔD is caused by the finite time $(t1 - t2)$ necessary to change the direction of primary current due to the presence of the large resonant inductor, as shown in Fig. 1. Referring to Fig. 1, ΔD can be obtained as:

$$\Delta D = \frac{2L_r f_s I_o}{NV_i}, \tag{2}$$

where $f_s = 1/T_s$, is the PWM switching frequency of the converter, and N is the turns ratio of the transformer. Thus the output voltage of the converter can be given by:

$$V_o = \frac{DV_i}{N} - \frac{2L_r f_s I_o}{N^2} \tag{3}$$

It can be seen that the output voltage of the converter is load current dependent, which is not the case for an ideal PWM converter ($L_r = 0$). For given duty cycle, a larger L_r value makes the output voltage more sensitive to load current variation. In a real circuit, a larger L_r value leads to a lower output voltage, which in turn requires a smaller transformer turns ratio (N) to meet line regulation. Consequently, the primary current, I_o/N, is increased, leading to higher conduction losses. At the same time, the voltage stress of the secondary diodes, $2V_i/N$, is also increased, requiring the use of rectifier diodes with higher voltage rating and higher forward voltage drop.

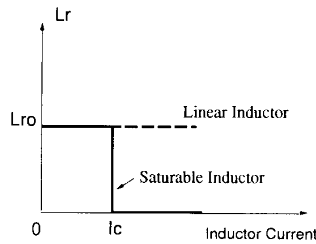
Another drawback of the FB-ZVS-PWM converter is the severe parasitic ringing between the diode junction capacitances and the resonant inductor [4], [7]. It is more severe than that in the FB-PWM converter since the resonant inductance in the ZVS-PWM converter is considerably larger than the transformer leakage inductance of the conventional PWM converter. The ringing frequency is:

$$f_r = \frac{N}{2\pi\sqrt{L_r C}}, \tag{4}$$

where C is the equivalent capacitance of the rectifier diode and the transformer windings. For large value of L_r, the ringing frequency is low, causing higher diode voltage stress, higher snubber loss, and higher switching noise [4],[7].

III. Improvement of the FB-ZVS-PWM Converter

The saturable inductor has been successfully applied to ZVS-QRC's [8] and a new class of ZVS-PWM converters [6] to improve their performances. It is shown in this paper that the incorporation of a saturable inductor to the FB-ZVS-PWM converter, a particular member of the ZVS-PWM converters [6], can minimize the above-mentioned drawbacks, resulting in a significant improvement in the converter performance.



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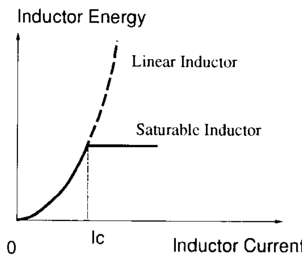


(b)

Fig. 2. Characteristics of an ideal saturable inductor and a linear inductor: (a) inductance versus current. (b) inductor energy versus current.

The energy stored in a linear inductor is proportional to the square of the inductor current. Thus the circulating energy in a FB-ZVS-PWM converter is proportional to the square of the load current. For instance, if the converter is designed to achieve ZVS above 20% load, the circulating energy at full load will be 25 times as that needed for discharging the FET capacitances (achieving ZVS for FET's). The situation is different when the linear resonant inductor is replaced by a saturable inductor. The inductance versus current curve of an ideal saturable inductor is shown in Fig. 2(a), where I_c is the critical saturation current. As illustrated in Fig. 2(b), the energy stored in the saturable inductor remains constant when the inductor current exceeds I_c. Theoretically, if the converter is designed to have the saturable inductor saturated at 20% load (i.e., $I_c = I_o^{\max}/5N$, with the output filter inductor considered as a current source), and the inductor saturation energy is equal to that needed for discharging the FET capacitances [4], i.e.:

$$\frac{1}{2}L_{ro}I_c^2 = \frac{4}{3}C_D V_i^2 \tag{5}$$

then the converter will operate with ZVS above 20% load, while imposing minimum circulating energy. With the employment of a saturable inductor, the FB-ZVS-PWM converter can achieve ZVS for a wider load range without increasing the circulating energy.

The circuit diagram and the key waveforms of the proposed FB-ZVS-PWM converter with a saturable inductor are shown in Fig. 3. It should be noted that a power transformer with a minimum leakage inductance is preferred in this case. The operation of the modified circuit is slightly different from that of the previously discussed FB-ZVS-PWM converter.

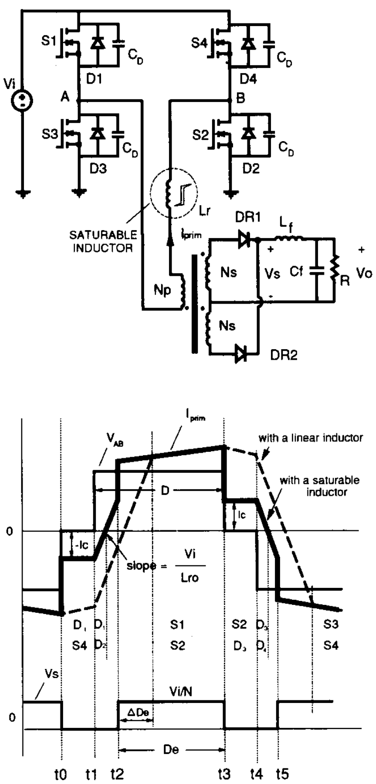


Fig. 3. FB-ZVS-PWM converter incorporating a saturable inductor and its key waveforms.

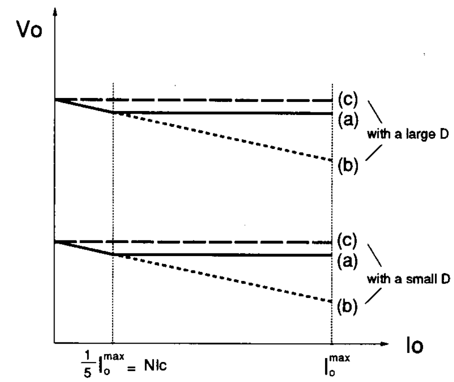


Fig. 4. Comparison of the typical ideal output characteristics for three cases: (a) FB-ZVS-PWM using a linear inductor; (b) FB-ZVS-PWM using a saturable inductor; and (c) Conventional FB-PWM converter.

At time t_2 or t_5, the inductor current reaches its critical saturation current, I_c, and the inductor is saturated. Then the inductor current rises abruptly until it reaches the reflected filter inductor current, I_L/N, at the same time the secondary voltage also jumps to V_i/N. Consequently, the loss of duty cycle (ΔD) of the converter is reduced by ΔD_e, as shown in Fig. 3. Assuming an ideal saturable inductor, when switch $S1$ is turned off at t_3, the inductor current will decrease quickly until it reaches I_c and the inductor gets out of saturation. Thus the switch current stress during the freewheeling stage is decreased, reducing the conduction loss of the primary switches.

Due to reduced loss of duty cycle, the output voltage of the converter using a saturable inductor is less sensitive to load change. Referring to Fig. 3, the output voltage of the converter is given by:

$$V_o = \frac{DV_i}{N} - \frac{2L_r f_s I_o}{N^2}; \quad \text{when } \frac{I_o}{N} < I_c, \tag{6}$$

$$V_o = \frac{DV_i}{N} - \frac{2L_r f_s I_c}{N^2}; \quad \text{when } \frac{I_o}{N} > I_c, \tag{7}$$

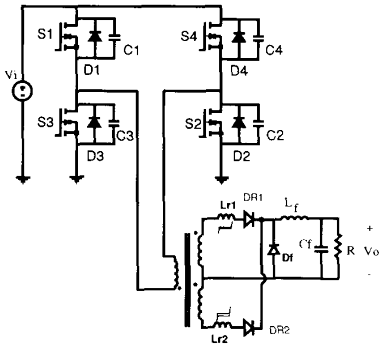
It can be seen that when the reflected output current exceeds I_c, V_o becomes load current independent. Assuming that $I_c = I_o^{\max}/5N$, the typical ideal output characteristics of the FB-ZVS-PWM converters using a linear resonant inductor and a saturable resonant inductor with the same inductance are shown in Fig. 4. It can be seen that the output characteristics of the FB-ZVS-PWM converter using a saturable inductor are closer to those exhibited by the conventional FB-PWM converter.

Another benefit of using a saturable inductor is greatly reduced parasitic oscillations between the diode junction capacitances and the resonant inductor. When a linear resonant inductor is used, the diode junction capacitances starts to resonate with the inductor at time t_2 and t_5, when the diodes suffer from a prompt reverse voltage. The large resonant inductance produces low-frequency ringing that increases rectifier voltage stress and switching noise. With a saturable inductor, this parasitic ringing is dramatically reduced, since the resonant inductor gets saturated at time t_2 and t_5, and its inductance is much reduced before the abrupt voltage is applied to the rectifier diodes. The much reduced inductance does not introduce significant ringing with the junction capacitances of the diodes.

The advantages of the FB-ZVS-PWM converter incorporating a saturable resonant inductor are summarized as following:

- reduced conduction loss of the switches due to reduced circulating energy;
- increased effective duty cycle resulting in the use of a larger transformer turns ratio to minimize the current in the primary circuit and the voltage in the secondary circuit;
- improved output characteristics;
- reduced secondary parasitic ringing and rectifier voltage stresses, so that rectifier diodes with lower voltage rating and lower forward voltage can be used; and
- wider load range can be achieved with ZVS without increasing the circulating energy.

The size of the saturable inductor is very small since magnetic material with very high permeability can be employed. Nevertheless, due to a large flux change in the core (from negative saturation area to positive saturation area), the switching frequency range of the converter might be limited to several hundred KHz, which is mainly determined by the thermal tolerance of the core material.



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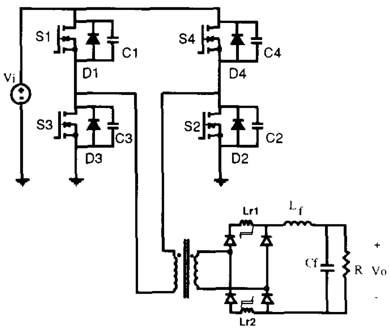


(b)

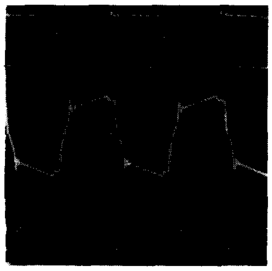
Fig. 5. FB-ZVS-PWM converter using saturable inductors at secondary with: (a) a half-bridge rectifier; (b) a full-bridge rectifier.

Another way to implement the proposed scheme is to move the resonant inductor from the primary to the secondary, as shown in Fig. 5(a). The operation of this converter is identical to that of the FB-ZVS-PWM converter with the saturable inductor in the primary, since the secondary inductor can be reflected to primary during each operation stage. It also works for the circuit with a FB rectifier, as shown in Fig. 5(b). However, the flux in $Lr1$ or $Lr2$ only operates in the first quadrant instead of travelling from negative saturation to positive saturation as was the case in circuit shown in Fig. 3; thus the core loss is significantly reduced compared to the circuit operating at the same switching frequency in Fig. 3.

IV. Experimental Verifications

A 500 KHz, 200 W FB-ZVS-PWM converter using a saturable inductor was implemented. It was regulated at 5 V output with a 250–350 V input and a 0-40 A load range. The power stage in Fig. 3 consists of the following components:

S1-S4	IRF740 (International Rectifier);
DR1,2	60CNQ030 (International Rectifier);
Lf	core: H7C4-RM7Z52B, 5.5 turns;
Lr	core: H7F-ER9.5/5Z, 6 turns;
TR	core: half 3F3-782E272 (Philips);
	primary: 58 turns of 100/44 Litz wire;
	secondary: 2 turns, center tapped, 3 mil Cu foil;
Cin	0.33 μF / 400 V metal polypropleme;
Cf	4 $\times$ 15 μF tantalum & 3 $\times$ 0.33 uF ceramic.



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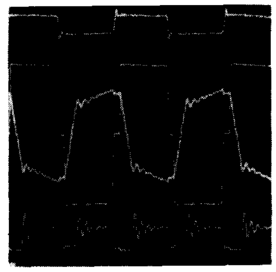

(b)

Fig. 6. Experimental waveforms of the 500 KHz, 200 W FB-ZVS-PWM converter with: (a) a saturable resonant inductor; (b) a linear resonant inductor, at Vi=250 V and D=0.9.

The transformer turns ratio was designed at Np/Ns=29 to get 5 V/40 A output with 0.9 duty cycle at 250 V input. The saturable inductor is implemented with six turns on a small ungapped H7F-ER-9.5/5-Z core. Fig. 5(a) shows the experimental waveforms of the FB-ZVS-PWM converter using the saturable resonant inductor on the primary side. If a linear resonant inductor were used, the transformer turns ratio would have to be decreased to $Np/Ns = 24$ to get the same output under the same input and duty cycle conditions. This results in a significant increase in the primary conduction loss (about 40%) and rectifier voltage stresses [shown in Fig. 6(b)]. The increased rectifier voltage stress necessitates the use of a Schottky diode with higher voltage rating (45 V) and higher forward voltage drop. Here both circuits are designed to maintain ZVS above 65% load at norminal line (Vi =300 V). In addition, the secondary parasitic ringing in the circuit with a saturable inductor is much less than that with a linear inductor, as can be seen from Fig. 6.

To reduce core loss of the saturable reactor and to further extend the load range for ZVS, another design was attempted with the saturable inductors in the secondary. The converter was designed to maintain ZVS above 45% load at 300 V input. Each saturable inductor was implemented with 1.5 turns on half H7F-ER-9.5/5-Z core. Fig. 6 gives the overall efficiency of the breadboarded converter. Due to reduced saturable core loss, this circuit has higher efficiency (about 0.7%) over that with the saturable inductor in the primary. Including the control circuit and driver losses, a maximum overall efficiency of 88.4% is achieved. Table I gives the estimated loss breakdown of three converters at full load and 300 V input.

V. Conclusion

High-frequency, high efficiency operation of dc-dc converters requires a essential decrease of switching losses in conventional PWM converters while avoiding a significant increase of conduction losses. Among a number of recently developed converter technologies, the FB-ZVS-PWM converter is deemed favorable for many applications since it features the benefits of both PWM and ZVS-QRC techniques while

TABLE I
LOSS OF BREAKDOWN AT FULL LOAD AND 300 V INPUT

	case 1	case 2	case 3
component losses	linear inductor	saturable inductor at primary	saturable inductor at secondary
S1-S4 cond.	3.9 W	2.7 W	2.7 W
D1,D2 cond.	17.6 W	15.2 W	15.2 W
transformer	3.4 W	3.4 W	3.4 W
resonant inductor	0.6 W	3.3 W	1.6 W
diode snubber	1.8 W	0.9 W	0.7 W
control	1.8 W	1.8 W	1.8 W
filter	1.8 W	1.8 W	1.8 W
others	0.5 W	0.5 W	0.5 W
total	31.4 W	29.6 W	27.7 W
efficiency	86.4 %	87.1 %	87.8%

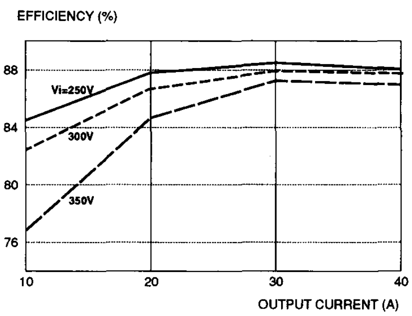

Fig. 7. Overall efficiency of the 500 KHz, 200 W FB-ZVS-PWM converter with the saturable inductors in the secondary.

avoiding their respective shortcomings. It utilizes the leakage of the power transformer and the parasitic capacitances of the MOSFET's to achieve ZVS for the power switches. The switching losses are significantly reduced. Nevertheless, due to the use of a large resonant inductor, this converter still imposes additional circulating energy that increases the conduction losses of the primary switches, voltage stresses of the rectifiers, and parasitic oscillations in the secondary side.

The limitations of the FB-ZVS-PWM converter can be alleviated by the use of a saturable inductor. The saturation of the resonant inductor effectively reduces the circulating energy of the converter, thus leading to an increase of the effective duty cycle. Hence the power transformer with a maximized turns ratio can be used, reducing the current stress of the power switches and the voltage stress of the rectifier diodes. In addition, the saturation of the resonant inductor also results in a substantial reduction of the secondary parasitic oscillations, reducing snubber loss and switching noise. Since a saturable inductor can effectively extend the load range of ZVS without significantly increasing the circulating energy, the FB-ZVS-PWM converter using the saturable inductor best benefits the applications which are sensitive to light-load efficiency.

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Guichao Hua received the B.S. and M.S. degrees in electrical engineering from Zhejiang University, China in 1985 and 1988, respectively. He is currently working towards the Ph.D. degree at Virginia Polytechnic Institute and State University (VPI&SU).

From 1988 to 1989 he was employed as a research engineer with Watt Power Supply Corp., China. Since 1989, he has been with the Virginia Power Electronics Center (VPEC) at VPI&SU. Currently, he is a research associate at VPEC. His research interests include high-frequency power conversion, new converter topologies, power-factor correction circuits, and UPS systems.

Fred C. Lee (S'72–M'74–SM'87–F'90), for a photograph and biography, see p. 119 of the April 1993 issue of this TRANSACTIONS.

Milan M. Jovanović (S'85–M'88–SM'89) , for a photograph and biography, see this issue, p. 422.