A SINGLE-STAGE ZERO-VOLTAGE SWITCHED PWM FULL-BRIDGE CONVERTER WITH POWER FACTOR CORRECTION

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Abstract - A new single-stage converter is proposed in this paper. The converter operates with fixed switching frequency, and with a continuous input current that is sinusoidal and in phase with the input voltage. This is in contrast with most other single-stage converters, which are either resonant converters or must operate with a discontinuous input current. All converter switches operate with soft-switching due to a simple auxiliary circuit that is used for only a small fraction of the switching cycle. In the paper, the operation of the converter is explained and analyzed, and design guidelines are given. The feasibility of the converter is shown with results obtained from an experimental prototype.

I. INTRODUCTION

The process of converting the input ac mains voltage into an isolated and regulated dc voltage typically requires that two converters stages be used: an ac-dc conversion (rectifying) stage and an isolated dc-dc conversion stage. Since standards such as IEC 1000-3-2 require that the harmonics of the input line current of electronic equipment be below certain specified levels, it is becoming less acceptable to use a diode bridge rectifier by itself as the front-end converter. It is now customary, instead, to add a boost converter that performs power factor correction (PFC) so that the input current is sinusoidal and in phase with the input voltage. The presence of two switching converter stages, however, causes the overall efficiency of the two-stage converter to be low because it is the product of the efficiency of each individual stage.

In order to improve efficiency, several converters that integrate the functions of power factor correction and isolated dc-dc conversion into a single power stage have been proposed [1]-[9]. These single-stage converters, however, have at least one of the following drawbacks:

(1) The converter is complex.
(2) The converter can only be used in low power applications because the input current is discontinuous with a high triangular, pulsating waveform.
(3) The converter switches do not operate with soft-switching.
(4) The converter is a resonant converter and therefore operates with increased conduction losses due to higher rms currents, and variable frequency control.

A single-stage converter that operates with zero-voltage switching (ZVS) and PFC, but without the above-mentioned drawbacks is proposed in the paper (Fig. 1). The operation of the converter is explained, its features are discussed, and design guidelines are given. The feasibility of the converter is shown with results obtained from an experimental prototype.

II CONVERTER OPERATION

The proposed converter has sixteen distinct operation intervals for a single steady-state switching cycle. Only a half switching cycle will be shown here because its operation intervals are similar to those of the other half. The equivalent circuit for each half-cycle interval is shown in Fig. 2, and gating signal and auxiliary circuit waveforms are shown in Fig. 3. The equations that characterize the converter's behavior during each interval of auxiliary circuit operation are shown. The following assumptions have been made:

(1) The input current is a constant current I_{in} when the auxiliary circuit is operating.
(2) The output voltage is a constant voltage V_o when the auxiliary circuit is operating.
(3) The auxiliary switch, S_{aux}, has a resistance of R_r when it is turned on.
(4) All inductors and capacitors and full-bridge switches have negligible resistance.
(5) All diodes in the circuit have a negligible voltage drop.

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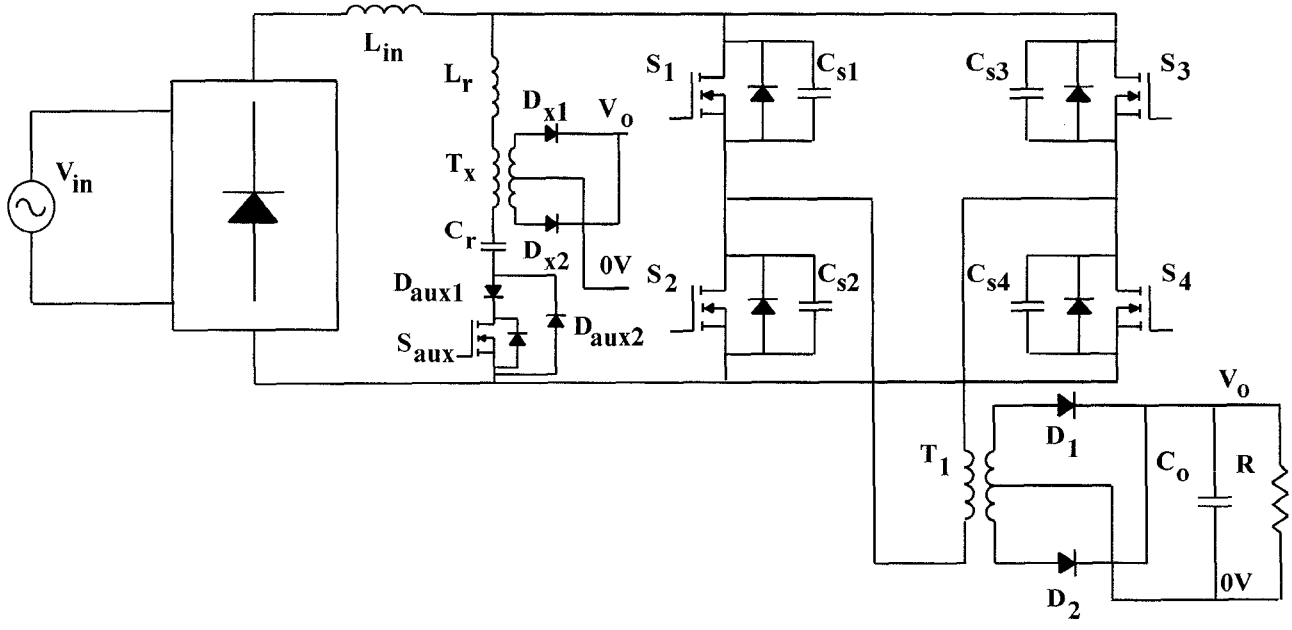


Fig. 1. Proposed single-stage converter.

(6) The output voltage reflected across the transformer primary is $V_{pri} = V_o/N$.
(7) The transformer, T_X, is clamped to $V_X = V_o/N_X$ when current is flowing in the auxiliary circuit. The polarity of V_X is dependent on the polarity of the current.
(8) Transformer T_1 is an ideal transformer in series with a primary leakage inductance L_{lk}, which affects the converter's operation only during the auxiliary circuit's first operating interval.

(a) Interval 0 [$t < t_0$]:

Switches S_1 and S_4 are on and power is being transferred to the load. The voltage across S_2 and S_3 is V_{pri}. The auxiliary circuit capacitor, C_r, is charged to a voltage, V_{Cr0}. The voltage across auxiliary switch, S_{aux}, is $V_{pri} - V_{Cr0}$.

(b) Interval 1 [$t_0 - t_1$]:

The auxiliary switch S_{aux} is turned on with ZCS as the resonant inductor L_r and the leakage inductance of T_1, L_{lk}, limit the rate of current rise. Current is diverted from the full-bridge as the current flowing through the auxiliary circuit rises. Voltage V_X is no longer zero volts but is clamped to $V_X = V_o/N_X$ while current is flowing through secondary diode D_{x1}. The equations for this interval are:

$$(L_{lk} + L_r)\frac{dI_{Lr}}{dt} = V_{pri} - V_X - \frac{1}{C_r}\int_0^t I_{Lr}\,dt - V_{Cr0} - I_{Lr}R_r \quad (1)$$

$$C_r\frac{dV_{Cr}}{dt} = I_{Lr}. \quad (2)$$

At the end of this interval, the current flowing through the auxiliary circuit is equal to the input current, and the voltage across the resonant capacitor is V_{Cr1}.

(c) Interval 2 [$t_1 - t_2$]:

Current does not flow through the full-bridge because the current flowing through the auxiliary circuit is greater than the input current. As I_{Lr} continues to rise, the current that exceeds the input current discharges C_{s2} and C_{s3}, through the anti-parallel diodes of S_1 and S_4. The equations for this interval are:

$$L_r\frac{dI_{Lr}}{dt} = V_{Cswp} - V_X - \frac{1}{C_r}\int_0^t I_{Lr}\,dt - V_{Cr1} - I_{Lr}R_r \quad (3)$$

$$C_r\frac{dV_{Cr}}{dt} = I_{Lr} \quad (4)$$

$$C_{swp}\frac{dV_{Cswp}}{dt} = -(I_{Lr} - I_{in}) \quad (5)$$

where

$$C_{swp} = C_{s2} + C_{s3}. \quad (6)$$

This interval ends when C_{s2} and C_{s3} have been fully discharged. At this moment, the current flowing through the auxiliary circuit is equal to I_{Lr2}, and the voltage across the resonant capacitor is V_{Cr2}.

(d) Interval 3 [$t_2 - t_3$]:

During this interval, the anti-parallel diodes of all the switches in the full-bridge are conducting, and S_2 and S_3 are turned on with ZVS. The equations are:

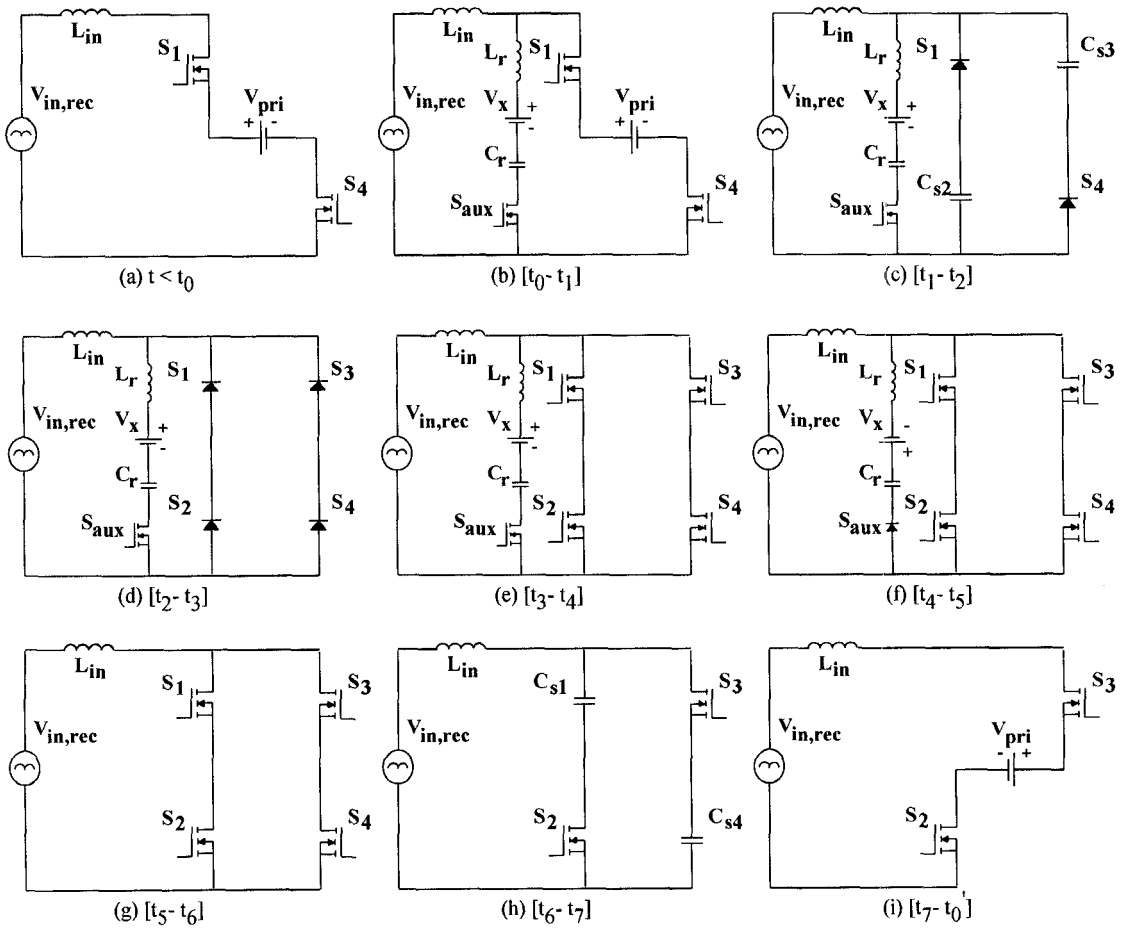


Fig. 2. Converter operation during a half switching cycle.

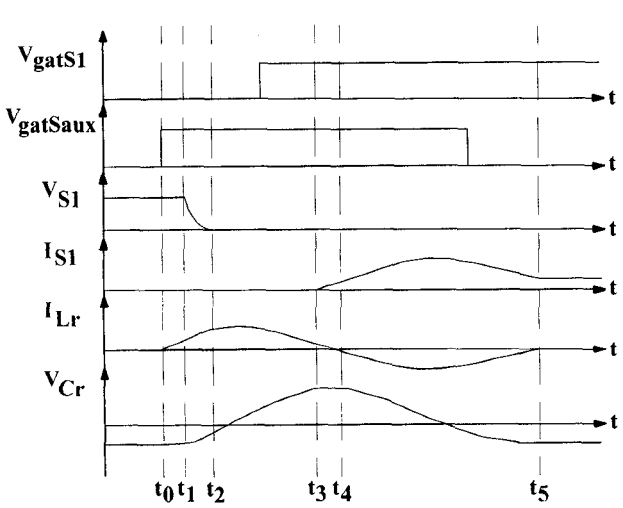


Fig. 3. Auxiliary circuit waveforms

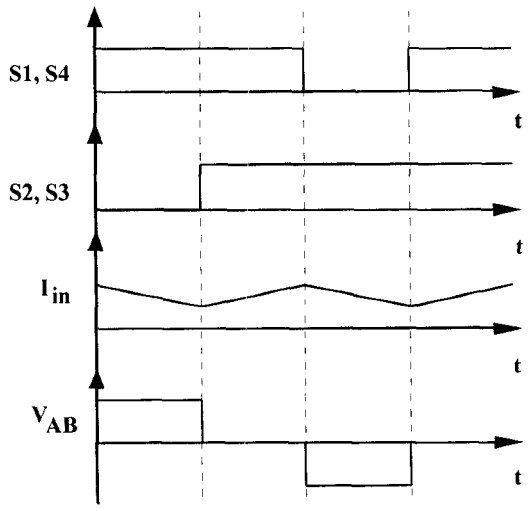


Fig. 4. Power circuit waveforms.

$$L_r \frac{dI_{Lr}}{dt} = -\left(V_X + \frac{1}{C_r} \int_0^t I_{Lr}\, dt + V_{Cr2} + I_{Lr} R_r \right) \quad (7)$$

$$C_r \frac{dV_{Cr}}{dt} = I_{Lr}. \quad (8)$$

The current flowing through the auxiliary circuit at the end of the interval is the same as the input current.

(e) Interval 4 [t_3 - t_4]:

Current starts flowing through all the full-bridge switches as the current flowing through the auxiliary circuit is still positive, but less than the input current. This mode ends when current I_{Lr} is zero. The voltage across C_r is V_{Cr4}.

(f) Interval 5 [t_4 - t_5]:

The current through S_1 is the sum of the input current and the current flowing through the auxiliary circuit through the body diode of S_{aux}. The polarity of V_X changes as current is flowing through secondary diode D_{X2}. Switch S_{aux} is turned off with ZVS during this mode. The equations are:

$$L_r \frac{dI_{Lr}}{dt} = V_X - \frac{1}{C_r} \int_0^t I_{Lr}\, dt - V_{Cr4} \quad (9)$$

$$C_r \frac{dV_{Cr}}{dt} = I_{Lr}. \quad (10)$$

Under steady-state conditions, the value of V_{Cr} after this interval is the same as it was before the auxiliary circuit was activated: $V_{Cr} = V_{Cr0}$.

(g) Interval 6 [t_5- t_6]:

The operation of the circuit during this time is identical to that of a current-fed PWM converter.

(h) Interval 7 [t_6- t_7]:

Switches S_1 and S_4 are turned off with ZVS due to capacitors C_{s1} and C_{s4}. These capacitors are charged until the voltage across each capacitor is equal to V_{pri}.

(i) Interval 8 [t_7- t_8]:

Current flows only through the diagonally opposite pair of switches S_2 and S_3 until the auxiliary circuit is reactivated.

The waveforms in Fig. 4 show how both PFC and dc-dc conversion can be performed by the full-bridge with the proper sequencing of the switch gating signals.

III. Converter Features

The features of the proposed converter can be summarized as follows:

(i) *Soft-switching:* The full-bridge switches can be turned on with ZVS by simply activating the auxiliary circuit whenever a pair of switches is about to be turned on. The auxiliary switch has a ZCS turn-on and a ZVS turn-off.

(ii) *PWM operation:* Unlike resonant-type single-stage converters, the proposed converter acts like a PWM converter except when the auxiliary circuit is operating for a small portion of the switching cycle. The converter can operate with a fixed switching frequency and with any PWM technique that can be used for a boost PFC converter.

(iii) *Power factor correction with a continuous input current:* Since the converter can operate with any PWM technique, it is therefore possible to produce a continuous input current that is sinusoidal and in phase with the input voltage. This can be done by simply controlling when the input current should rise or fall. This is in contrast to other single-stage converters that must have a discontinuous input current because the converter switches have difficulty in simultaneously performing PFC and dc-dc conversion.

(iv) *Simplicity:* The above features are obtained with a simple auxiliary circuit requiring only one additional switch and a few passive components.

IV. Design Guidelines

Guidelines for the selection of auxiliary circuit components are given in this section.

A. Characterisitc Curves

The equations for the operation intervals in Section II can be solved and used to generate characteristic curves like the ones shown in Fig. 4. These curves can be used in the design of the converter. Since the auxiliary circuit is activated just before the full-bridge switches are turned on, its operation is dependent on the input current value at that instant and the output voltage V_o. The curves shown in Fig. 5 have thus been generated with respect to the ratio:

$$Z_{rb} = \frac{V_o}{I_{in}}. \quad (11)$$

The values of Z_{rb} in Fig. 5 have been chosen in accordance with the design example presented later in this paper.

Fig. 5(a) shows the relationship between the voltage across the auxiliary switch, V_{saux}, and the impedance of the auxiliary resonant components

$$Z_r = \sqrt{\frac{L_r}{C_r}} \quad (12)$$

for various values of $K = C_r / C_{swp}$. This voltage is greater than V_O (1 pu) because of the negative voltage that exists across T_X and C_r when the auxiliary circuit is inactive. Fig. 5(b) shows the relationship between the peak current of the auxiliary switch $I_{saux,pk}$ and Z_r for various values of K.

B. Selection of Transformer Turns Ratio N_x and Diodes

The voltage across the primary of T_X is clamped to $V_X = V_O / N_X$ when the auxiliary circuit is operating. The higher the value of V_X is, the lower the auxiliary circuit currents and voltages are. If V_X is set to too large a value, however, the full-bridge switches will not turn on with ZVS as there will not be sufficient energy to discharge the switch capacitances. N_X should therefore be set at the minimum value at which the full-bridge switches can turn on with ZVS.

The maximum voltage that a transformer secondary diode experiences is twice the output voltage when the other diode is conducting current. The diode currents are the auxiliary circuit currents divided by N_X.

C. Selection of Auxiliary Switch S_{aux}

The power rating of auxiliary switch S_{aux} is considerably lower than that of a full-bridge switch because it is on for a small fraction of the switching cycle and handles very little power. This allows the use of a device that is smaller and less costly than the main switch to be used. The peak current and voltage, however, are higher than the input current and output voltage respectively.

Current flows through the anti-parallel diode across S_{aux} during auxiliary circuit operation. It is recommended that a fast recovery diode be used instead of the device's body-diode because it has a slow recovery that may cause the auxiliary circuit to reset improperly for the next switching cycle.

D. Selection of Full-Bridge Switches

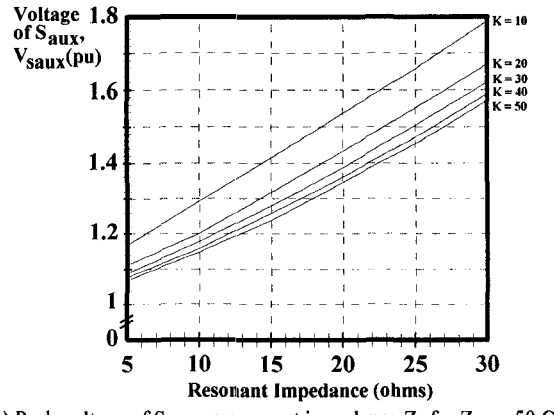
The voltage and current stresses of the full-bridge switches are the same as those for the switches in the conventional PWM converter except for the peak current. This will not be more than 1.25 pu. for the range of Z_r and K shown in Fig. 5.

E. Selection of Resonant Components L_r and C_r

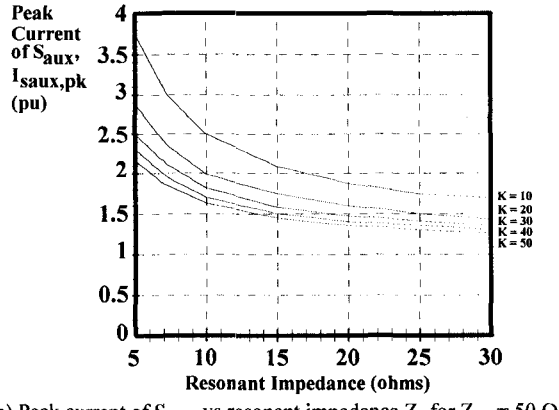
The time that the auxiliary circuit is in operation is dependent on the resonant cycle T_r, which is defined as

$$T_r = 2\pi\sqrt{L_r C_r} = 2\pi C_{swp} Z_r K \qquad (13)$$

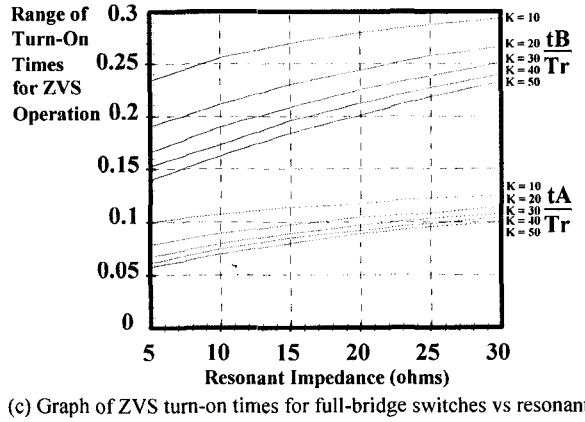
The values of L_r and C_r should be as low as possible to keep T_r small in order to minimize auxiliary circuit conduction losses, and maximize the converter duty cycle. If L_r and C_r, however, are too low then there can be excessive auxiliary circuit voltages and currents, and the full-bridge switches will not turn on with ZVS. Values of L_r and C_r should therefore



(a) Peak voltage of S_{aux} vs resonant impedance Z_r for Z_{rb} = 50 Ω.



(b) Peak current of S_{aux} vs resonant impedance Z_r for Z_{rb} = 50 Ω.



(c) Graph of ZVS turn-on times for full-bridge switches vs resonant impedance Z_r for Z_{rb} = 500 Ω.

Fig. 5. Graphs of characteristic curves with turns ratio N_X = 1.5.

be found from characteristic curves by looking for low values of Z_r and K that keep the peak auxiliary switch voltage and current from being very large and that still allow the converter to operate with soft-switching.

F. Time Interval for ZVS Turn-On of the Full-Bridge Switches.

The full-bridge switches turn-on whenever the input inductor is to be energized, after S_{aux} has been turned on at time t_0. These switches can turn on with ZVS only after the

switch capacitances have been discharged at time $t = t_A$, but before the current through the resonant circuit drops below the input current at $t = t_B$. Fig 5(c) shows times, t_A and t_B, defined with respect to the resonant cycle of the auxiliary circuit, T_r for Z_{rb} = 500 Ω. This value of Z_{rb} is representative of the case when the input current is very small, and the ZVS time interval is the narrowest. A ZVS turn-on for the full-bridge switches is guaranteed for all operating points if it occurs between t_A and t_B for this large value of Z_{rb}.

G. Output Capacitor

Just like a boost PFC circuit, the converter's output current has a 2nd harmonic component that must be filtered. Since the converter has only one stage with a low output voltage, this current harmonic is large. The output capacitor that must be used is therefore large (≈ 5mF), much larger than that needed for a two-stage converter.

V. Design Procedure and Example

The following example is given to demonstrate the design procedure used to determine the values of the auxiliary circuit components, and the ZVS time interval t_A-t_B. Since this procedure is an iterative process, only the last iteration is shown here. The converter is to be designed with output power: P_O = 500 W, output voltage: V_O = 48 Vdc, input voltage: V_{in} = 100 - 240 Vrms, switching frequency f_{sw} = 50 kHz. It is assumed that the input inductor is large enough so that the input current has little ripple, and that a value of 1 nF is sufficient switch capacitance to minimize turn-off losses and noise in each full-bridge switch. It is also assumed that converter efficiency is $\eta >= 92\%$. The values are to be selected so that the voltage across the auxiliary switch, V_{saux}, does not exceed 1.2 pu. The turns ratio of the isolation transformer is N = 8. The turns ratio of the auxiliary circuit transformer is N_X = 1.5, which results in V_X = 48 / 1.5 = 32 V.

(1) Determine the average voltage across the primary of the isolation transformer:

$$V_{pri} = NV_O = 8 \cdot 48V = 384V. \qquad (14)$$

(2) Determine the value of $Z_{rb} = V_{pri} / I_{in}$ where the input current is at its peak. The peak switch voltages and currents occur at this point. The input current is at its maximum value when V_{in} = 100 V and is

$$I_{in,max} = \frac{\sqrt{2}\,\frac{P_O}{\eta}}{V_{in,min}} = \frac{\sqrt{2}\,\frac{500}{0.92}}{100} = 7.68A. \qquad (15)$$

The minimum value of Z_{rb} is $Z_{rb,min}$ = 384 / 7.68 = 50 Ω. The curves in Fig. 5(a) - (b), which are for Z_{rb} = 50 Ω, will be used in this example.

(3) Use the characteristic curves in Fig. 5 to determine the values of L_r and C_r. According to Fig. 5(a), a value of K = 15 and Z_r = 10 Ω will result in an auxiliary switch voltage that is 1.2 pu. Since C_{swp} is 2 nF (twice the switch capacitance), the value of C_r is C_r = 2 nF x 15 = 30 nF. Since Z_r = 10 Ω, then L_r is

$$L_r = Z_r^2 C_r = (10\Omega)^2 30\,nF = 3\mu H. \qquad (16)$$

It can be seen from Fig. 5(c) that the full-bridge switches can operate with ZVS with these values of K and Z_r.

(4) Using K and Z_r, find V_{saux} and $I_{saux,peak}$ from Figs. 5(a) and (b). For K = 15 and Z_r = 10 Ω, V_{saux} = 384 V x 1.2 pu = 460 V and $I_{saux,pk}$ = 7.68 A x 2.25 pu = 17.3 A. The peak current for a full-bridge switch is 7.68 A x 1.25 pu = 9.6 A.

(5) Calculate the value of T_r using equ. (13) then find the values of t_A and t_B from Fig. 5(c). T_r is 1.88 μs. The values of t_A/T_r and t_B/T_r for Z_r = 10 Ω and K = 15 are 0.1 and 0.23 respectively. Multiplying these values by T_r gives t_A = 183 ns and t_B = 432 ns. This is the narrowest ZVS time interval that is encountered by the converter.

(6) The peak voltage stress across the transformer diodes is 2 pu or 2 x 48 V = 96 V. The peak current is $I_{saux,pk}$ / 1.5 = 11.5 A.

VI. Experimental Results

The feasibility of the converter was verified with results obtained from an experimental prototype. The input voltage was 60 - 100 V_{rms}, the output voltage was V_O = 20 V, and the switching frequency was 50 kHz. The component values that were used were L_r = 3 μH, C_r = 30 nF, C_{swp} = 2 nF, N = 8, and N_X = 1.5.

Fig. 6(a) shows the voltage across a full-bridge switch, and the combined current through the switch, its body diode, and its capacitance. It can be seen that the negative current, which is due to the auxiliary circuit, brings the voltage across the switch down to zero. This results in a ZVS turn-on. The ringing that appears in these waveforms is due to the interaction of leakage inductance of the isolation transformer and the full-bridge switch capacitances whenever two switches are turned off. A transformer with a large leakage inductance was used because it was the most suitable transformer availiable at the time when the experimental results were recorded. Transformers having lower values of leakage inductance can be manufactured, and the ringing in the waveforms decreases if they are used instead. The severity of this ringing prevented results at higher voltages from being obtained.

Fig. 6(b) shows the same pair of waveforms as Fig. 6(a), but on a different time scale. The zero-crossing points and the resonant peaks in the current waveform are due to the operation of the auxiliary circuit. The portions of the voltage and current waveforms that contain substantial ringing occur during the time when only a pair of diagonally opposite switches conduct the full input current.

Fig. 6(c) shows a typical switch gating signal and the input current. The input current rises and falls just as a typical boost converter input current waveform does. It can be seen that the input current falls whenever the switch gating signal is low. It also falls whenever there is only a pair of diagonally opposite pair of switches conducting current.

VII. Conclusion

A new single-stage converter was presented in this paper. Its features include soft-switching for all switches, fixed frequency operation, and power factor correction with a continuous input current. The auxiliary circuit that allows the converter to operate with soft-switching is simple and requires only one active switch.

The operation of the converter was explained and design guidelines were given. The feasibility of the proposed converter was verified experimentally with a 50 kHz prototype. Experimental results showed that the converter switches can in fact turn-on with ZVS, and that the converter itself is essentially a boost converter that can operate with power factor correction.

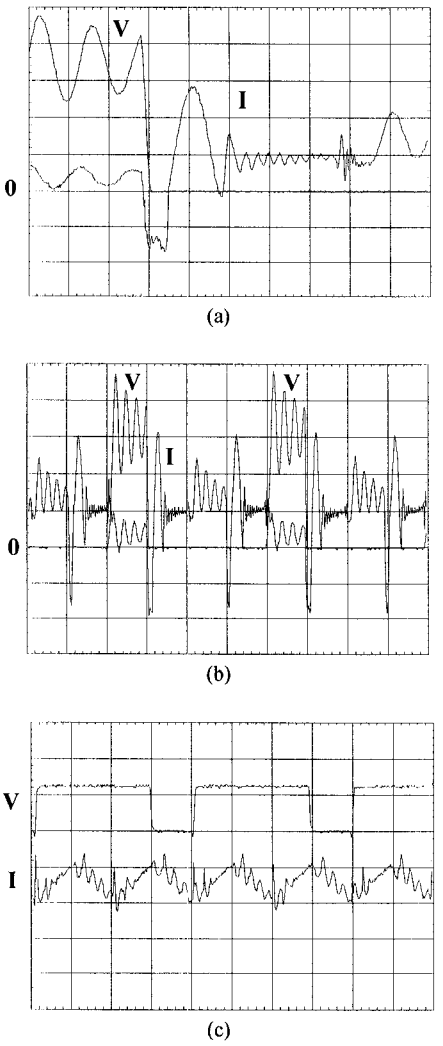


Fig 6. Experimental results. (a) Full-bridge switch turn-on (V: 50 V/div., I: 0.5 A/ div., t: 500 ns/div.). (b) Full-bridge switch waveforms (V: 50 V/div., I: 0.5 A/div., t: 5 μs/div.). (c) Full-bridge switch gating signal and input current ripple (V: 10 V/div., I: 0.1 A/div., t: 5 μs/div.).

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