

# A Novel AC-DC Interleaved ZCS-PWM Boost Converter

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**Abstract**—A new interleaved AC-DC boost converter is proposed in this paper. The converter uses just a single active auxiliary circuit to assist all the main converter switches operate with ZCS and operates with ZCS itself. This circuit does not increase the peak voltage or current stresses of the main switches and can be deactivated from the main pwr circuit if necessary. In this paper, the operation of the converter is fully explained, its features are discussed, and guidelines for the design of key auxiliary circuit components are given. Results obtained from an experimental prototype are presented to confirm the feasibility of the proposed converter.

**Keywords**—Switch mode power supplies, AC-DC conversion, soft-switching, ZCS-PWM converter

## I. INTRODUCTION

AC-DC converters with input power factor correction (PFC) that consist of two or more interleaved boost converter modules are popular in industry [1]-[15]. PFC is required in today's AC-DC converters as their input current must meet harmonic standards set by regulatory agencies. With interleaving, the input current of each module can be made to be discontinuous and the size of their input inductors reduced. Interleaving can reduce the high ripple in each module and produce a net input current with a ripple that is comparable to that achieved with a single boost converter module with a large input inductor. Moreover, there is less current stress on the converter components as they handle a fraction of the overall current and the control is easier as more sophisticated control methods needed for continuous current mode (CCM) operation are avoided.

Soft-switching methods for these converters can either be zero-voltage switching (ZVS) if they are implemented with MOSFETs or zero-current switching (ZCS) if implemented with IGBTs. The focus of the paper is on ZCS methods for IGBT converters [13]-[23], such as the ones shown in Fig. 1. Most of these, like the converters in Fig. 1, use an auxiliary circuit that is activated whenever a main converter switch is about to be turned off, gradually diverting current away from the switch so that it can turn off with ZCS. ZCS is beneficial for IGBTs as it eliminates the current tail that would otherwise exist when turning off. This current tail overlaps with the switch voltage and causes significant turn-off losses.

ZCS methods in boost converters have at least one of the following drawbacks:

- The auxiliary circuit causes the main converter switch to operate with a higher peak current stress that creates a need for a higher rated device for the main switch.
- The auxiliary circuit creates circulating current in the main part of the converter that increases conduction losses, thus offsetting the gain in efficiency caused by the reduction of switching losses.
- Auxiliary circuit components must be placed in the main part of the converter so that the auxiliary circuit is not completely separated from the main converter. This means that conduction losses can be increased so that higher current rated components need to be used.
- Each module of an interleaved AC-DC boost converter must have its own ZCS auxiliary circuit to help its main switch turn off with ZCS. This adds cost to the overall interleaved converter.

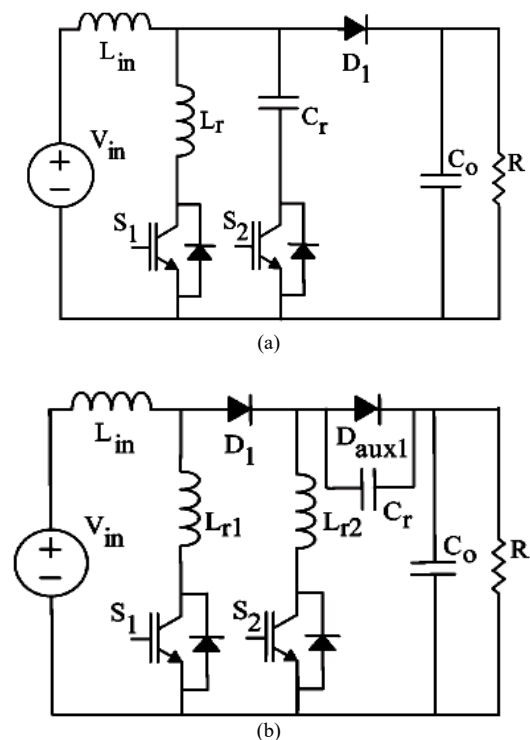


Fig. 1. ZCS-PWM boost converters (a) Converter proposed in [22]. (b) Converter proposed in [23].

A new interleaved ZCS AC-DC boost converter consisting of two boost converter modules is proposed in the paper. The proposed converter has none of the drawbacks mentioned above and uses only one auxiliary circuit to help the main switches turn on with ZCS.

In this paper, the general principles behind the operation of the proposed converter are discussed and its modes of operation are explained. The features of the converter are stated and guidelines for the design of key auxiliary circuit components are given. The feasibility of the proposed AC-DC converter is confirmed with results obtained from an experimental prototype.

## II. CONVERTER PRINCIPLES

ZCS-PWM IGBT converters that use an auxiliary circuit to help the main converter switch turn on with ZCS are generally less efficient than hard-switching converters at light loads. The main reason for this is that the auxiliary circuit losses dominate when the converter is operating under these conditions. Auxiliary circuit losses include the turning on and off of the auxiliary switch and additional conduction losses as there can be an increased amount of circulating current flowing in the converter. ZCS-PWM converters achieve their improved efficiency over hard-switching converters at heavier loads when the main switch switching losses that are eliminated (especially the IGBT current tail losses) are greater than the auxiliary circuit losses.

Ideally, the auxiliary circuit used to achieve ZCS operation in a ZCS-PWM converter should be activated only when the converter is operating with heavier loads and not used when the converter is operating with light load. Operating the converter in such a manner would ensure the optimal efficiency profile over the entire load range. This, however, generally cannot be done with ZCS-PWM converters because of the presence of an inductor placed in series with the main switch. As can be seen in the example converters shown in Fig. 1, an inductor is typically placed in series with the main switch so that it can turn on with ZCS. The series inductor slows down the rate of rise in current after the switch has been turned on so that the overlap between voltage and current in this switch can be reduced.

Although the presence of this series inductor in a ZCS-PWM converter is beneficial, it prevents the auxiliary circuit from being deactivated when the converter is operating under light load conditions. As long as this series inductor is in the converter, the auxiliary circuit must be used at all times, across the full load range – even when it is not necessary under light load conditions – because failure to do so would result in the damage of the main switch. Given the size of the series inductance, which may be relatively small compared to that of the input boost inductor but not insignificant, the energy in this inductance would result in the appearance of high voltage spikes across the switch when it is turned off as there would be no path for current to flow through.

There are several possible solutions to the problem of having an inductor placed in series with the main switch, but

none of them are satisfactory. It may be possible to place a bypass switch of some sort across the series inductor so that when the auxiliary circuit is not needed, the bypass switch would be turned on and current would bypass the inductor, but this would add cost and make the converter more complex.

Another possible solution is to implement the converter with an active auxiliary circuit and a passive snubber. With such a scheme, the active auxiliary circuit would be activated only when the converter is operating with heavier loads and the passive snubber would be used to deal with the series inductor energy when the main converter switch is turned off with the auxiliary circuit is deactivated. This approach would again increase the cost and the complexity of the converter.

If the main switch could somehow be made to turn on with ZCS without having an inductor in series with the main switch, then it would be possible to avoid using the auxiliary circuit when the converter is operating under light load conditions. This is, in fact, possible when the converter is operating with a discontinuous input inductor current. In such a case, the main converter switch would turn on with ZCS as initially there would be no current flowing through the switch. Current through the switch would rise gradually, given the size of the input boost inductor.

Discontinuous current mode operation is advantageous when a boost converter is implemented with two converter modules in parallel and the modules are interleaved with respect to each other with a phase difference of 180°. Interleaving is commonly used as a means of reducing current ripple in power converters. This is especially true for AC-DC converters where a continuous input boost inductor current can be achieved and high peak currents and EMI noise can be reduced if interleaving is implemented. In the scheme being described here, if the individual converter modules are ZCS-PWM converters, then it would be possible to deactivate the auxiliary circuit as there would be no need of a series inductance to help the main switch turn on with ZCS.

Using two ZCS-PWM converter modules, however, requires the use of two separate auxiliary circuits – one to help the main switch of an individual module turn on with ZCS. The cost of the overall converter can be reduced if it is possible to use the same auxiliary circuit to help the main switches in both modules turn on with ZCS. This may be possible given that the turn-on of these two switches never occurs at the same, but occurs a half switching cycle apart. If this can be done, then an interleaved ZCS-PWM converter that requires just a single auxiliary circuit for both main module switches that can be deactivated when the converter is operating under light load conditions to improve efficiency becomes possible. Such a converter is proposed in the next section of this paper.

## III. CONVERTER OPERATION

The proposed AC-DC converter, shown in Fig. 2, consists of two boost converter modules: one with  $L_1$ ,  $S_1$

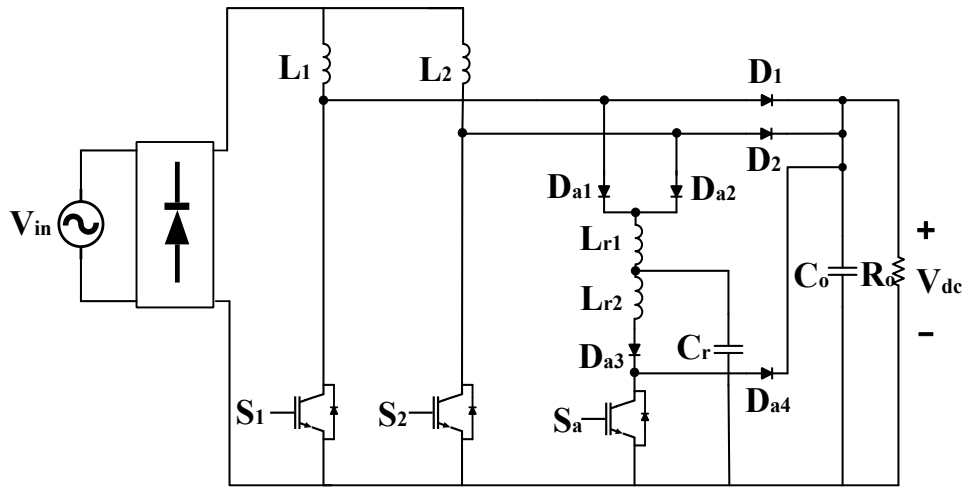


Fig. 2. Proposed interleaved AC-DC ZCS-PWM boost converter

and  $D_1$ , the other with  $L_2$ ,  $S_2$  and  $D_2$ . The gating signals of the two main switches,  $S_1$  and  $S_2$  are identical, but shifted  $180^\circ$  with respect to each other.

The currents in  $L_1$  and  $L_2$  are discontinuous and identical, but also shifted  $180^\circ$  with respect to each other. The two boost modules are connected to the same auxiliary circuit, which consists of connection diodes  $D_{a1}$  and  $D_{a2}$ , reverse blocking diode  $D_{a3}$ , switch voltage clamping diode  $D_{a4}$ , inductors  $L_{r1}$  and  $L_{r2}$  and capacitor  $C_{r1}$ . The auxiliary circuit is activated whenever one of the two main switches is about to be turned off and is active for only a fraction of the switching cycle.

The proposed converter has the following modes of operation for a half switching cycle when duty cycle  $D \geq 0.5$  and when  $S_2$  is turned on and  $S_1$  is turned off; typical converter waveforms are shown in Fig. 3 and circuit diagrams for these modes are shown in Fig. 4. The modes of operation for the other half-cycle when  $S_1$  is turned on and  $S_2$  is turned off are identical.

#### Mode 1 ( $T_0 < t < T_1$ ):

This mode begins when switch  $S_2$  is turned on. The rectified voltage is applied to  $L_2$  and the current through  $L_2$  linearly increases as does the input current in the input inductor  $I_{in}$ .

#### Mode 2 ( $T_1 < t < T_2$ ):

This mode begins when the auxiliary switch ( $S_a$ ) is turned on in preparation to turn off main switch  $S_1$  with ZCS.  $S_a$  turns on with ZCS because  $L_{r2}$  limits the rise of the switch current. After  $S_a$  is turned on,  $C_r$  starts to resonate with  $L_{r2}$  so that the current in  $L_{r2}$  rises while the voltage across  $C_r$  decreases.

#### Mode 3 ( $T_2 < t < T_3$ ):

This mode begins when the voltage across  $C_r$ ,  $V_{Cr}$ , is zero. During this mode,  $V_{Cr}$  is charged to a negative voltage and  $D_{a1}$  and  $D_{a2}$  begin to conduct. The voltage across  $D_1$  and  $D_2$  is limited to the output voltage. The current through  $L_{r1}$

increases, thus  $I_{L1}$  and  $I_{L2}$  flow through  $L_{r1}$ . The current in  $L_2$  is less than  $L_1$ , thus the current through  $S_1$  becomes zero and  $S_1$  can be turned off with ZCS. The current through  $S_2$  becomes negative and flows through its body diode.

#### Mode 4 ( $T_3 < t < T_4$ ):

This mode begins when the current in  $L_{r2}$  reaches zero because of its resonance with  $C_r$ ;  $S_a$  can then be turned off with ZCS condition. During this mode, energy in  $L_{r1}$  is transferred to  $C_r$ , thus increasing its voltage so that  $V_{Cr}$  becomes less negative and is in the process of eventually becoming positive.

#### Mode 5 ( $T_4 < t < T_5$ ):

This mode begins when the net voltage across the  $C_r$  and  $L_{r1}$  becomes positive, thus auxiliary diode  $D_{a2}$  stops conducting and  $I_{L2}$  flows through  $S_2$ .  $D_{a1}$  continues to conduct during this mode.

#### Mode 6 ( $T_5 < t < T_6$ ):

This mode begins when  $V_{Cr}$  reaches the output voltage  $V_o$ .  $D_4$  clamps the voltage across the auxiliary switch to  $V_o$  as well and the stored energy in  $L_{r1}$  is transferred to the output so that the current in the  $L_{r1}$  decreases. When the current through  $L_{r1}$  becomes less than  $I_{L1}$ , diode  $D_1$  starts to carry the current difference. The voltage across  $L_1$  becomes  $(V_o - V_{rec})$  and the current through  $L_1$  starts to decrease linearly.

#### Mode 7 ( $T_6 < t < T_7$ ):

This mode begins when the current in  $L_1$  reaches zero. This is the last mode of the half-cycle. The next half-cycle begins when  $S_1$  is turned on under ZCS.

## IV. CONVERTER FEATURES

The proposed converter has the following features:

- All the converter switches turn on and off with ZCS.

- There is only one active auxiliary circuit for both main switches instead of each main switch needing its own active auxiliary circuit to help it turn off with ZCS.
- The main switch does not have increased peak and rms current stresses as it the case with resonant type ZCS auxiliary circuits because no current from the auxiliary circuit flows into the main circuit.
- The voltage stress of the auxiliary switch is clamped to the output voltage and does not exceed this voltage.
- The main boost diodes do not have reverse recovery current as the input inductor currents are discontinuous.
- The auxiliary circuit does not interfere with the interleaving operation of the converter thus all the advantages of interleaving are maintained.
- The auxiliary circuit can be deactivated when the converter is operating under light-load conditions, unlike most ZCS methods, where the auxiliary circuit must always be in operation, regardless of the load; thus light-load efficiency is improved. This is because there is no auxiliary circuit component in the main power circuit.

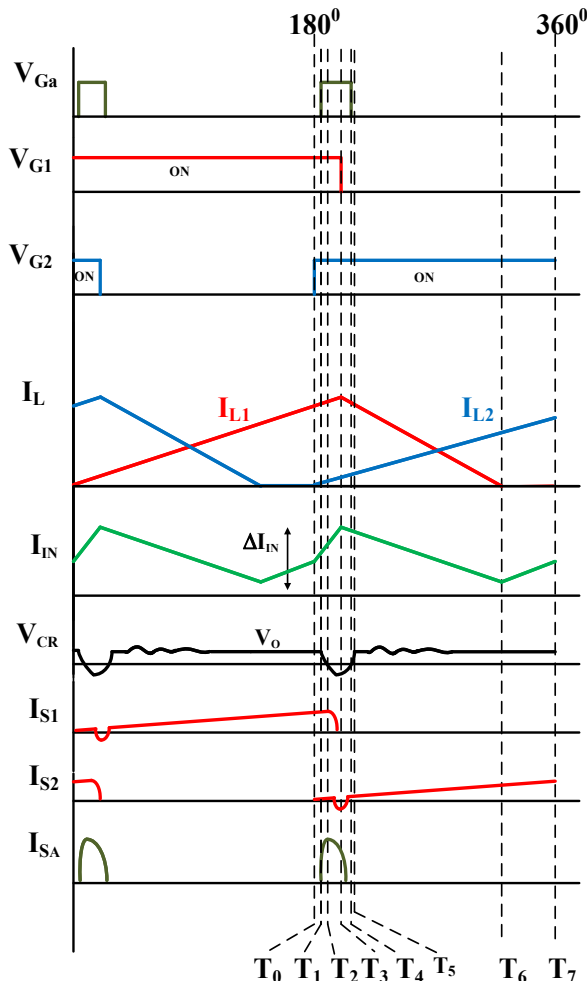


Fig. 3. Typical converter waveforms

## V. DESIGN CONSIDERATIONS

General considerations that should be taken into account for designing the auxiliary circuit of the proposed converter are discussed in this section. The key auxiliary circuit components that should be designed are the resonant capacitor  $C_r$  and the two auxiliary circuit inductors  $L_{r1}$  and  $L_{r2}$ .

### A. Resonant Capacitor ( $C_r$ )

The main function of the resonant capacitor is to impose a counter voltage across  $L_{r2}$  that allows current to be diverted away from the main switches so that they can turn off with ZCS. The value of this capacitor should not be too low as there will not be sufficient time for current to be diverted away from the main switches as the capacitor would quickly charge up and its voltage polarity would become positive. If the voltage across  $V_{Cr}$  becomes positive as current is being diverted away from a main switch, then current will stop flowing in  $C_r$  and thus the switch will turn on with ZCS. Moreover, a very low value of  $C_r$  will increase the voltage stress of the converter components.

If  $C_r$  is too large, then the transfer of current away from the main switch becomes very gradual. This will result in increased current stress and conduction losses of the auxiliary circuit components as they will be forced to conduct current for a longer amount of time. This may also interfere with the operation of the main circuit as a longer turn-off switching duration will result in a reduction of the effective duty cycle of the converter.

### B. Resonant Inductor ( $L_{r2}$ )

When the auxiliary switch is turned on, current flows through  $L_{r2}$  first even though  $C_r$  begins to discharge as this capacitor still has a positive voltage across it. Current will start to be diverted away from a main switch only when the capacitor voltage is sufficiently negative. As a result,  $L_{r2}$  should be sufficiently small to ensure that the current transfer from main switch to auxiliary circuit happens quickly. Moreover,  $L_{r2}$  should be small to reduce the time during which the auxiliary switch is on, thus reducing conduction losses in the switch.

If however,  $L_{r2}$  is too small, then several negative consequences can occur. The first is that the ZCS operation of the auxiliary switch  $S_a$  may be impacted. A very low value of  $L_{r2}$  will increase the rate at which current would rise after  $S_a$  is turned on so that this switch may not turn on with ZCS properly. Also, the resonant cycle related to the interaction between  $L_{r2}$  and  $C_r$  will become short so that current will not be diverted away from  $S_a$  gradually enough to ensure the elimination of the current tail when the switch is turned off. A second negative consequence would be that the peak current stress of the auxiliary switch would become high, given that the full resonant capacitor voltage is placed across this inductor.

### C. Resonant Inductor ( $L_{r1}$ )

The selection of  $L_{r1}$  is mainly based on two considerations. The first is the ZCS operation of the main switches. It is only after the voltage across  $C_r$  has become sufficiently negative that current flowing in a main switch

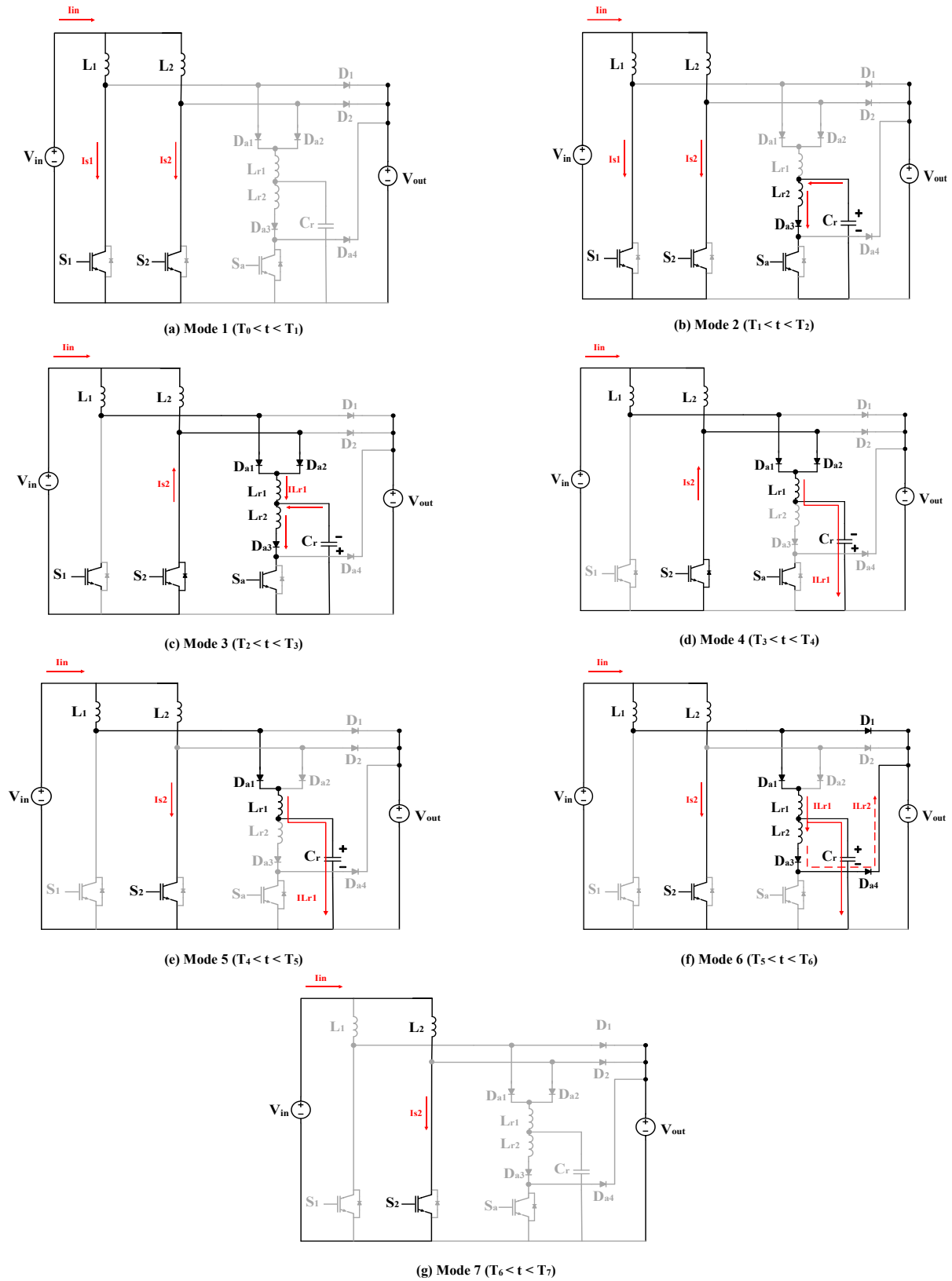


Fig. 4. Modes of operation

can be diverted into the auxiliary circuit. If  $L_{r1}$  is too small, then the rate of current transfer will be too sudden so that the current tail in the main switch would not be eliminated and the main switch will not be able to turn off with ZCS. The other consideration that should be taken into account in selecting a value of  $L_{r1}$  is the voltage across  $C_r$ . Lower values of  $L_{r1}$  result in higher voltages across  $C_r$  and thus a larger capacitor is needed.

The value of  $L_{r1}$  should be greater than that of  $L_{r2}$  because the current through  $L_{r1}$  should be less than current through  $L_{r2}$  in Mode 3 of operation to divert the current

from the auxiliary circuit and turn it off with ZCS. If  $L_{r1}$  is too large, however, then the duration of the turn-off switch transition becomes too gradual and the operation of the main circuit is affected as the effective converter duty cycle is increased as are auxiliary circuit component current stresses and losses.

## VI. EXPERIMENTAL RESULTS

A prototype of the proposed converter was built to confirm its feasibility. The prototype was built with the following specifications: Input voltage  $V_{in} = 85\text{-}265 V_{rms}$ ,

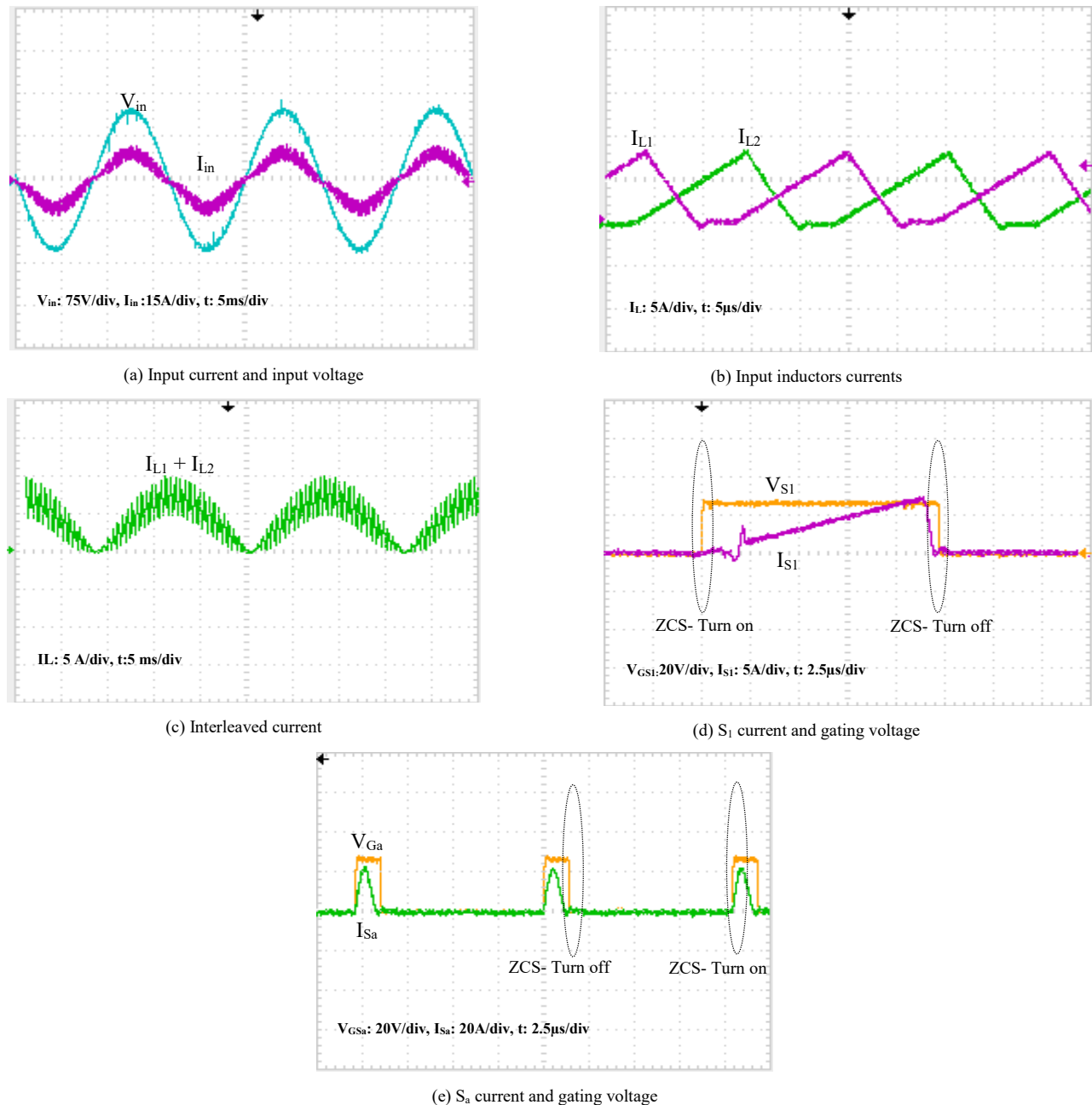


Fig. 5. Experimental results

output voltage  $V_o = 400 V_{dc}$ , switching frequency  $f_{sw} = 50$  kHz, maximum output power  $P_{o,max} = 1$  kW. Experimental results are shown in Fig. 5.

Fig. 5(a) shows typical input voltage and input current waveforms. It can be seen that the input current is sinusoidal and input phase with the input voltage and that the input current is continuous. Fig. 5(b) shows current waveforms for input boost inductors  $L_1$  and  $L_2$ . It can be seen that these currents are discontinuous and identical. Fig. 5(c) shows the interleaved current that is a sum of the current in  $L_1$  and  $L_2$ .

Fig. 5(d) shows typical current and gating signal waveforms for one of the main switches. It can be seen that the switch can be turned on with ZCS and can be turned off with ZCS, without a current tail, because the current through the switch goes to zero before turning it off. The same waveforms are shown in Fig. 5(e) for the auxiliary switch and it can be seen that the auxiliary switch turns on and off with ZCS as well.

## VII. CONCLUSION

A new AC-DC interleaved ZCS-PWM converter is proposed in this paper. Advantages of this converter include full ZCS operation of all converter switches, just one active auxiliary circuit for the two main switches, no additional voltage or current stresses on the main switches, no increased peak voltage stress on the auxiliary switch, and the auxiliary circuit can be deactivated from the main power circuit at any time. The feasibility of the converter was confirmed with results obtained from an experimental prototype.

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