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Four Novel PWM Shoot-Through Control Methods for Impedance Source DC-DC Converters

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Abstract

This study proposes four novel pulse width modulation (PWM) shoot-through control methods for impedance source (IS) galvanically isolated DC-DC converters. These methods are derived from a PWM control method with shifted shoot-through introduced by the authors in 2012. In contrast to the baseline solution, where the shoot-through states are generated by the simultaneous conduction of all transistors in the inverter bridge, our new approach is based on the shoot-through generation by one inverter leg. The idea is to increase the number of soft-switched transients and, therefore, decrease the dynamic losses of the front-end inverter. All the proposed approaches are experimentally verified through an insulated-gate bipolar transistor-based IS DC-DC converter. Conclusions are drawn in accordance with the results of the switching loss analysis.

Key words: DC-DC power converters, Pulse width modulation converters, Pulse width modulation, Quasi-Z-source inverter, Shoot-through control methods, Switching losses, Zero current switching, Zero voltage switching

I. INTRODUCTION

Impedance source (IS) DC-DC converter (IS DC-DC) is a new type of step-up galvanically isolated DC-DC converter first introduced in [1] as a power conditioning system for renewable energy applications. The new topology is generally derived from a classical voltage source full-bridge isolated DC-DC converter [2] by adding a passive impedance network to its input terminals (Fig. 1). The impedance network is a two-port passive circuit that consists of capacitors, inductors, and diodes in a special configuration. The specific feature of the impedance network is that it can be short-circuited, which, in turn, will increase the voltage across the input terminals of the main converter (V_{DC} in Fig. 1) [3].

Given that IS DC-DC is a step-up converter, its operation is always connected to a low voltage and high current values at the input side, which can lead to high losses at the front-end inverter. The shoot-through switching states used for the stepping up of the input voltage are also associated with certain power dissipation. Therefore, special attention must be paid to the reduction in losses both in wiring and in the semiconductors of the primary (low-voltage) part of the converter. One of the benefits offered by IS DC-DC is the inherent soft-switching achieved by proper control methods [4]. The number of soft-switching transients depends on the selected modulation method. Both zero current switching (ZCS) and zero voltage switching (ZVS) can be achieved within a wide operation range [4].

This paper describes the results of the comparative study on the novel pulse width modulation (PWM) shoot-through control methods proposed by the authors for the family of IS DC-DC converters. The purpose is to minimize the switching losses of the front-end inverter.

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II. IS DC-DC CONVERTERS: OPERATING PRINCIPLE, REALIZATION POSSIBILITIES, AND BASIC CONTROL METHODS

A. Operating Principle

In the family of IS galvanically isolated DC-DC converters, quasi-Z-source converter (qZSC) is the most advantageous [Fig. 2(a)]. The impedance network of qZSC consists of two capacitors, two inductors, and one diode, all of which are connected in a specific configuration [outlined by the gray color in Fig. 2(a)]. The quasi-Z-source network was derived

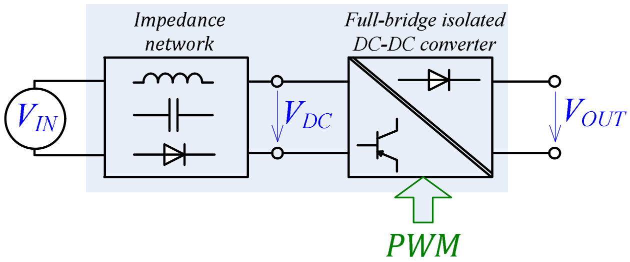

Fig. 1. Generalized block diagram of the IS galvanically isolated DC-DC converter.

from the baseline Z-source network [3] simply by changing the position of the input voltage source. Thanks to the presence of the input inductor L_{qz1}, the qZSC features continuous input current, which is especially important in renewable energy applications. Owing to the absence of a current path at start-up, qZSC has the feature of inrush-current limitation in contrast to Z-source-derived topologies. Other advantages of qZSC include the possibility of converterless integration of short-term energy storages (batteries) [5], bidirectional operation capability [6], and inherent short-circuit protection.

Regarding its operation principle, qZSC is similar to the galvanically isolated current-fed full-bridge boost converter [CFFBBC, Fig. 2(b)], which also uses shoot-through switching states for the stepping up of the input voltage [7]. In contrast to qZSC, CFFBBC has the disadvantage of inductive overvoltage across the inverter bridge, which leads to additional clamping circuits to be applied [8], [9]. Another issue of CFFBBC, the inrush current during start-up at a low output voltage, requires auxiliary start-up circuits to be implemented [10]. As a result, the introduction of these necessary sub-circuits increases the complexity of CFFBBC and can seriously affect its efficiency.

In both topologies, the peak voltage across the inverter bridge (V_{DC}) depends on the shoot-through duty cycle D_{ST}, that is,

$$D_{ST} = \frac{t_{ST}}{T}, \tag{1}$$

where t_{ST} is the cross conduction time of the switches in the inverter bridge, and T is the switching period. The idealized voltage boost across the inverter bridge in qZSC is

$$B_{qZSC} = \frac{V_{DC(peak)}}{V_{IN}} = \frac{1}{1-2\cdot D_{ST}}. \tag{2}$$

In the case of CFFBBC, the idealized voltage boost is

$$B_{\mathrm{CFFBBC}} = \frac{V_{DC(peak)}}{V_{IN}} = \frac{1}{1-D_{ST}}. \tag{3}$$

A comparison of idealized voltage boost properties shows that qZSC features a higher voltage step-up capability for the same shoot-through duty cycle D_{ST} than CFFBBC (Fig. 3). The twofold input voltage gain, typical for the power conditioners for renewable energy sources, can be obtained by D_{ST} of 0.25 and 0.5 for qZSC and CFFBBC respectively.

Given that the duty cycles of the shoot-through and active states are interdependent in both topologies ($D_A = 1 - D_{ST}$), this will result in a higher root mean square current through the primary switches of CFFBBC for the same operating conditions.

qZSC is theoretically possible to operate with shoot-through duty cycles up to 0.5. A high D_{ST} will lead to instabilities in the system. In practical applications at high step-up ratios, shoot-through duty cycles higher than 0.33 are not commonly recommended because they will lead to high conduction losses and a dramatic decrease in efficiency.

B. Realization Possibilities

IS converters have been actively studied during the last decade, and a number of new configurations of impedance networks have been proposed [3], [11]-[17]. All of them can be used to construct IS DC-DC converters. In several cases, the cascaded configurations of impedance networks and switched inductor or switched capacitor concepts can be used to increase converter performance [18]-[21]. An up-to-date comparative analysis of recently proposed impedance networks can be found in [22].

In galvanically isolated step-up DC-DC converters, a voltage-doubler rectifier (VDR) is the most efficient and simplest approach to obtain the highest possible voltage gain. The bridge VDR shown in Fig. 2 consists of two diodes (*D1* and *D2*) and two output capacitors (*C1* and *C2*). With the output capacitors connected in series, the output voltage V_{OUT} at every time instant will be the sum of the two capacitor voltages or twice the peak voltage ($V_{TX,sec}$) of the secondary winding of the isolation transformer. VDR can also be realized according to Greinacher topology, in which only one capacitor directly supplies the output load, and the second one serves as an intermediate energy storage element [23].

Recent research in the field of IS DC-DC converters focuses on the improvement of power conversion efficiency. In this context, methods such as resonant power conversion and synchronous rectification can significantly enhance the performance of IS DC-DC converters. The first series resonant IS DC-DC converter was proposed in [24]. Owing to the implemented series resonant LC circuit, a qZS-based DC-DC converter can be soft-switched in all operating points, except for minor power dissipation at the turn-off transients of the shoot-through states [25].

Another issue of IS DC-DC converters is the power conversion efficiency at high shoot-through duty cycle values because of the conduction losses in the diode D_{qz} of IS network. The diode D_{qz} is basically only needed to avoid short-circuiting the capacitors C_{qz1} and C_{qz2} during the shoot-through states. At the same time, the diode will noticeably increase conduction losses during the active states. To minimize such losses, N-channel metal-oxide-semiconductor field-effect transistor (MOSFET)

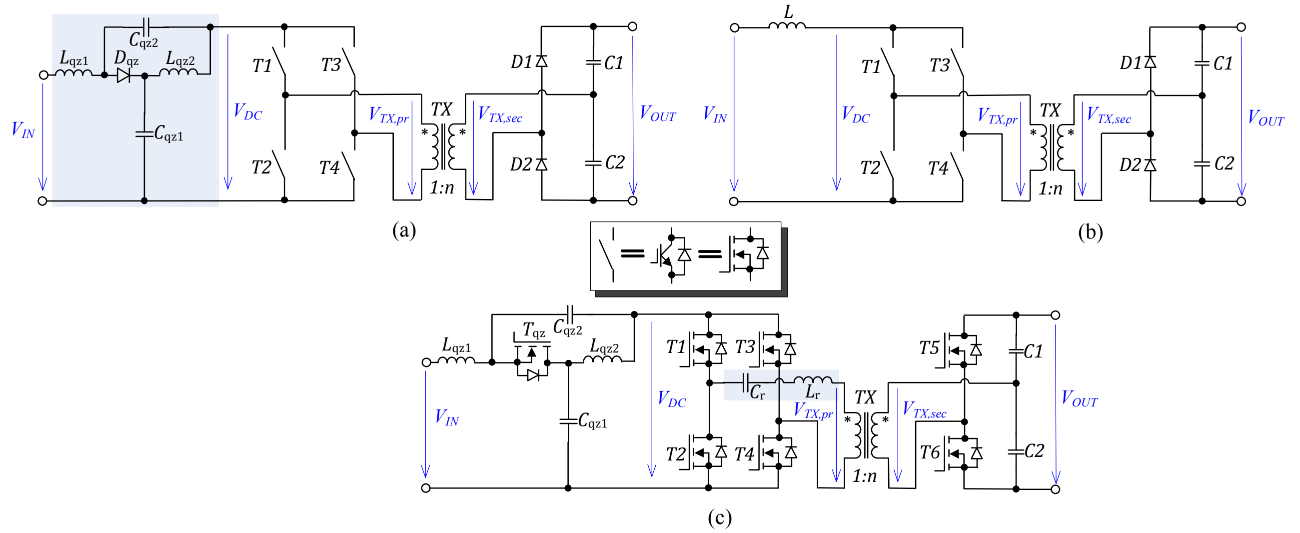

Fig. 2. Generalized topologies of the step-up galvanically isolated DC-DC converters. (a) qZSC, (b) CFFBBC. (c) High-performance qZSC with resonant power conversion and synchronous rectification.

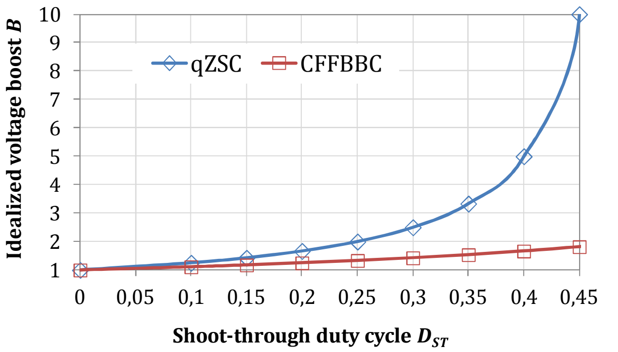

Fig. 3. Idealized voltage boost factor B as a function of the shoot-through duty cycle D_{ST} for qZSC and CFFBBC.

can be replaced by D_{qz} [26]. T_{qz} is synchronized with the inverter switches, and it only conducts during the active state and blocks the current during shoot-through.

Similar to the IS network, conduction losses can also be reduced in the diodes *D1* and *D2* of VDR. The implementation of transistors instead of diodes in VDR will result in the bidirectional operation capability of IS DC-DC converter. In consideration of all the mentioned modification possibilities, an example of a high-performance qZSC is presented in Fig. 2(c).

C. Basic Control Principles

In [27] and [28], two basic shoot-through control methods for IS DC-DC converters were proposed, namely, PWM and phase shift modulation (PSM). Shoot-through states [Fig. 4(a)] are typically generated within zero states [Figs. 4(d) and (e)], wherein the zero and shoot-through states are equally distributed over the switching period, so that the number of high harmonics in the transformer primary can be reduced. To minimize switch losses, the number of shoot-through states per period is limited to two.

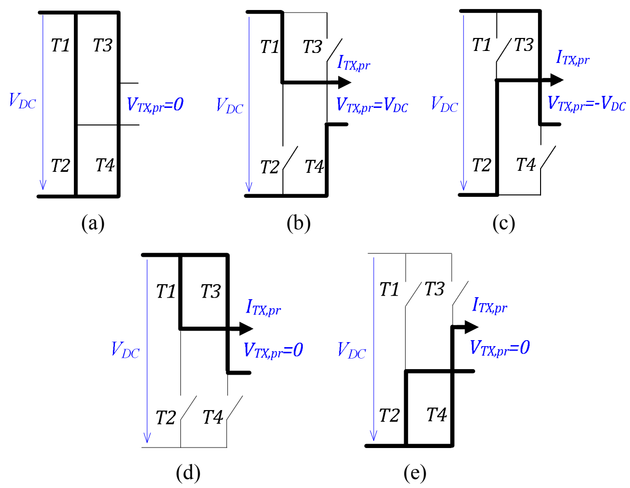

Fig. 4. Main operating states of the front-end inverter in qZSC: (a) Shoot-through state. (b), (c) Active states. (d), (e) Zero states.

Shoot-through current is also evenly distributed between both inverter legs by switching on all four transistors.

In consideration of conduction losses, both shoot-through control methods (PWM and PSM) are fairly identical because the number of conduction states and their duration will not be changed [29]. In case of the PSM shoot-through control method, the switching losses are increased by more than 20% because of an increased number of hard-switched commutations. PSM results in higher overvoltages in the system in comparison with the PWM shoot-through control method [28]. Hence, PWM shoot-through control seems to be a better method for IS DC-DC converters than PSM.

III. New PWM Shoot-Through Control Methods

All the proposed control methods were specially developed

TABLE I
METHOD A: SWITCHING-STATE SEQUENCE PER PERIOD

	Top transistors		Bottom transistors	
	T1	***T3***	***T2***	***T4***
active state		x	x	
shoot-through	x	x	x	x
zero state	x	x		
active state	x			x
shoot-through	x	x	x	x
zero state	x	x		

TABLE II
METHOD B: SWITCHING-STATE SEQUENCE PER PERIOD

	Top transistors		Bottom transistors	
	T1	***T3***	***T2***	***T4***
active state		x	x	
shoot-through	x		x	
zero state	x	x		
active state	x			x
shoot-through		x		x
zero state	x	x		

for the family of IS galvanically isolated DC-DC converters. IS DC-DC converter was based on the full-bridge single-phase inverter, where the top and bottom groups of transistors are denoted as *T1*, *T3* and *T2*, *T4*, respectively.

A. PWM Control with Shifted Shoot-Through (Method A)

This method was first introduced in [30] as an improved alternative to the conventional PWM shoot-through control. Two shoot-through states occur per period. To minimize the switching losses of transistors, one shoot-through state is shifted toward an active state until they merge, as shown in Fig. 5(a). This shift results in a reduced number of hard-switching transients for the bottom transistors (*T2*, *T4*), as shown in TABLE I. The states are shown for one period of the isolation transformer. The conducting switches are indicated by "x." ZVS is achieved for the bottom transistors (*T2*, *T4*) because of the merged shoot-through state. The shoot-through states are generated inside zero states to reduce the number of high harmonics in the transformer voltage. The experimental results prove that *Method A* enables the efficiency of a 1 kW full-bridge front-end inverter to be increased by 4% in comparison with the traditional PWM method [30].

B. PWM Control with Shifted Shoot-Through in One Leg (Method B)

This method is a new modulation technique derived from *Method A*. Instead of generating shoot-through with all four switches, only two switches of one leg are used at a time [Fig. 5(b)]. This technique eliminates two hard-switching transients of the bottom transistors.

The switching frequency of these transistors is reduced in comparison with *Method A*. As a result, in *Method B*, the switching frequencies of the top and bottom transistors are equal, as indicated in TABLE II.

TABLE III
METHOD C: SWITCHING-STATE SEQUENCE PER PERIOD

	Top transistors		Bottom transistors	
	T1	***T3***	***T2***	***T4***
active state		x	x	
shoot-through	x		x	
zero state	x	x		
active state	x			x
shoot-through		x		x

TABLE IV
METHOD D: SWITCHING-STATE SEQUENCE PER PERIOD

	Top transistors		Bottom transistors	
	T1	***T3***	***T2***	***T4***
active state		x	x	
shoot-through	x		x	
zero state	x	x		
shoot-through		x		x
active state	x			x
shoot-through		x		x
zero state	x	x		
shoot-through	x		x	

However, the amplitude value of the shoot-through current is increased, which leads to high power losses during the shoot-through state.

C. Asymmetric PWM Control with Shifted Shoot-Through in One Leg (Method C)

In *Method B*, a zero state is always placed between two subsequent active states (TABLE II). The idea of *Method C* is to shift active states toward each other, so that one of the two zero states can be eliminated [Fig. 5(c)]. An additional soft-switching state for transistor *T4* can then be introduced. The switching frequencies of the top and bottom transistors are equal, as indicated in TABLE III.

However, the frequency of shoot-through states in *Method C* is variable, which affects the input current ripple. The voltage of the isolation transformer is also asymmetrical, which will affect the output voltage ripple.

D. PWM Control with Shifted Double Shoot-Through in One Leg (Method D)

This modulation technique is a derivation from *Method B*. The shoot-through states are split into two and positioned on both sides of the active states [Fig. 5(d)]. As a result, the appearance of shoot-through states will be changed into an irregular one, which will reduce the input current ripple.

TABLE IV shows the switching sequences of the top and bottom transistors. The switching frequencies of the top and bottom transistors are equal, as shown in Fig. 5(d). However, no additional soft-switching states are introduced, and an increased shoot-through current is being switched during commutations.

E. Asymmetric PWM Control with Shifted Double Shoot-Through in One Leg (Method E)

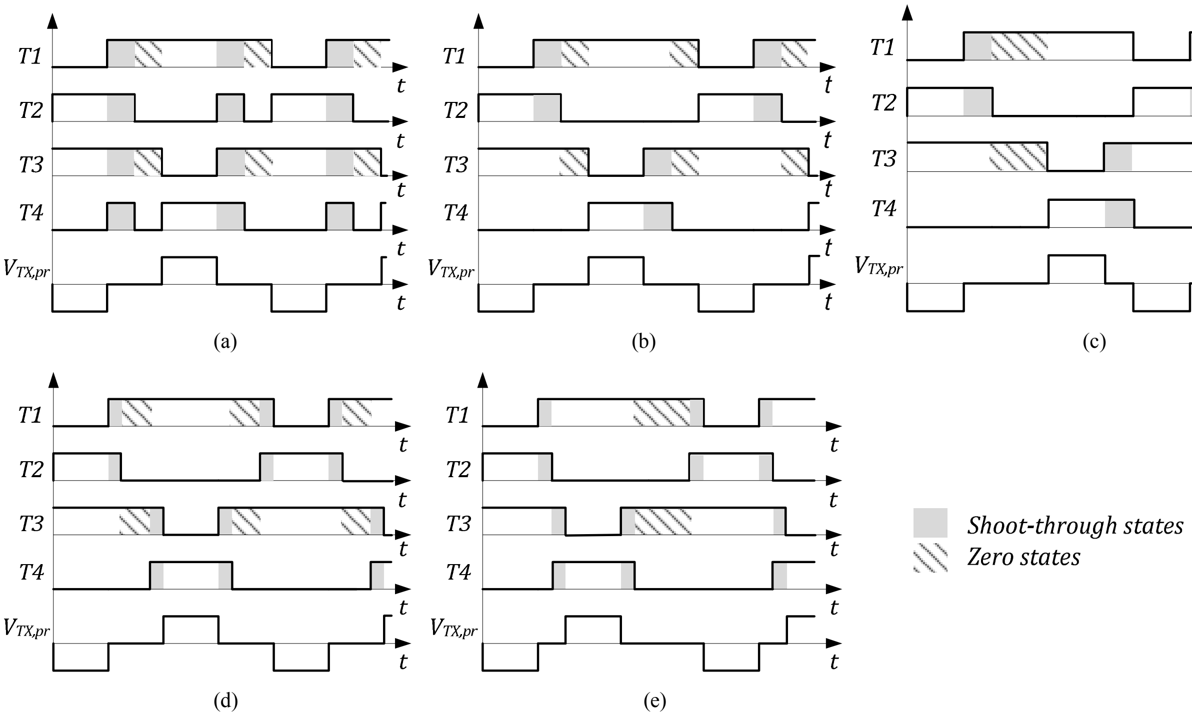

Fig. 5. Studied PWM shoot-through control methods: *Methods* (a) *A*. (b) *B*. (c) *C*. (d) *D*. (e) *E*.

TABLE V
METHOD E: SWITCHING-STATE SEQUENCE PER PERIOD

	Top transistors		**Bottom transistors**	
	T1	***T3***	***T2***	***T4***
active state		x	x	
shoot-through	x		x	
shoot-through		x		x
active state	x			x
shoot-through		x		x
zero state	x	x		
shoot-through	x		x	

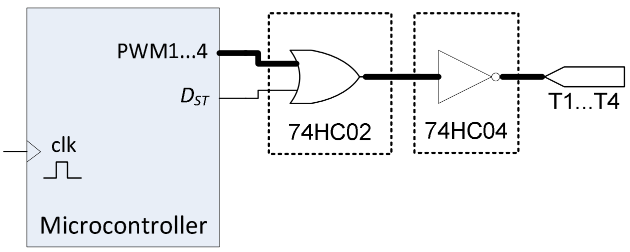

Fig. 6. Shoot-through generation principle by using a microcontroller combined with an external logic circuitry.

The asymmetric PWM control with shifted double shoot-through in one leg was derived from *Methods C* and *D*. The basic idea behind *Method E* is to shift active states toward each other, so that the shoot-through states around the active states can be merged [Fig. 5(e)]. An additional soft-switching state can then be introduced. *Method E* will also reduce the input current ripple in comparison with *Method A*. The switching sequences of each transistor are shown in TABLE V. The switching frequencies of the top and bottom transistors are equal, as indicated in Fig. 5(e).

IV. PRACTICAL GUIDELINES FOR BUILDING THE CONTROL SYSTEM

Microcontrollers generate PWM using timers and compare values. As a rule, conventional microcontrollers have only one or two compare values per timer, which are sufficient in most cases. Currently, the situation is complicated because of shoot-through states.

Up to five compare values are needed to generate PWM with shoot-through states. Consequently, PWM with shoot-through is impossible to implement on most microcontrollers. The following three methods can be considered as a solution to the problem:

1. Using a field-programmable gate array (FPGA).
2. Using a microcontroller combined with an FPGA.
3. Using a microcontroller combined with an external logic circuitry.

In the current project, price and development time were prioritized over flexibility. Thus, the third option was selected. The main idea was to generate the shoot-through state separately from PWM and mix signals through an external logic, as indicated in Fig. 6. We needed only one “NOR” logic block, such as 74HC02, to link PWM and shoot-through D_{ST} signals in the microcontroller output. “NOR” logic inverted the input signal. Additional hex inverters 74HC04 were used to obtain a signal in phase with the microcontroller

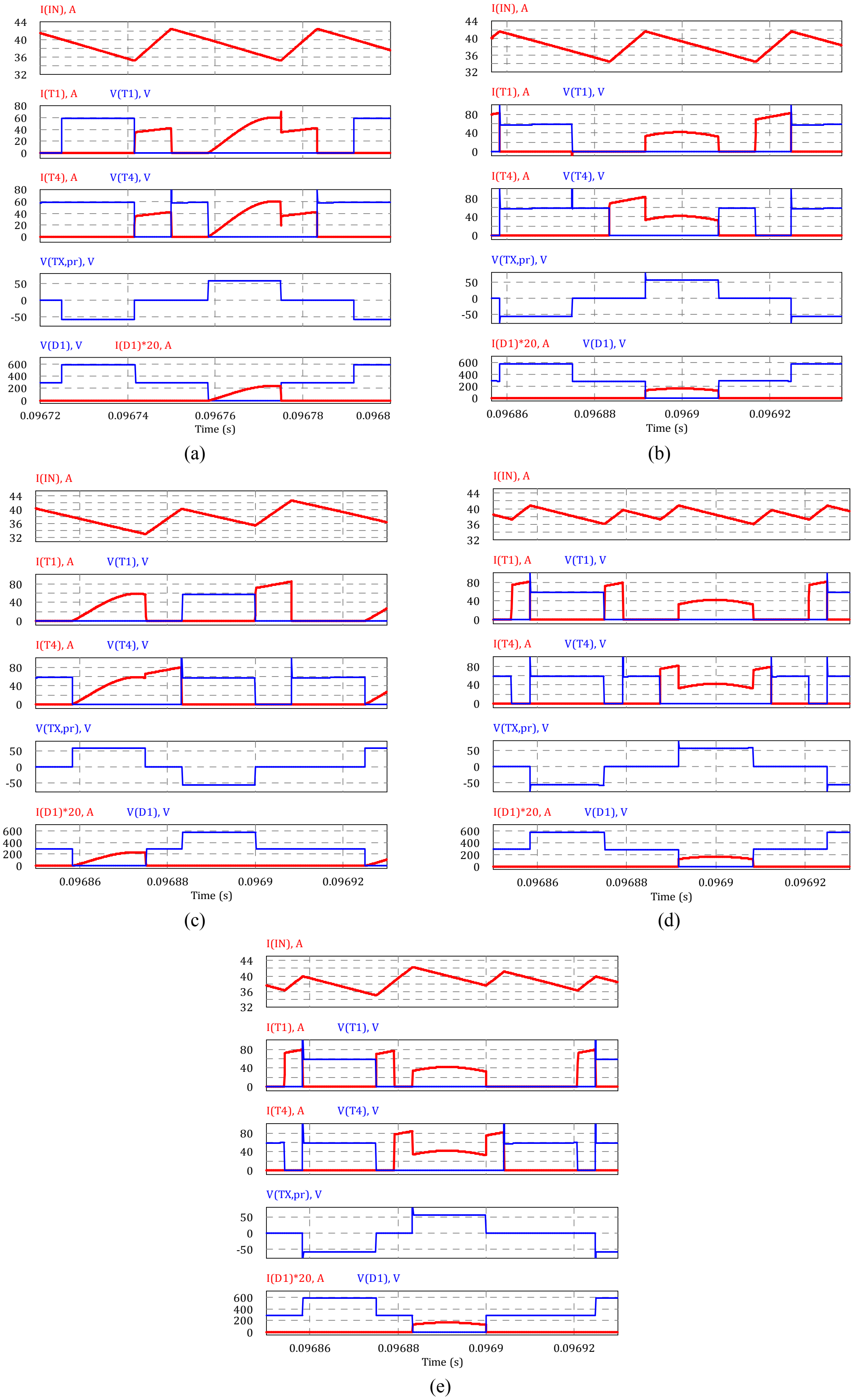

Fig. 7. Simulation results of *Methods* (a) *A*, (b) *B*, (c) *C*, (d) *D*, and (e) *E*.

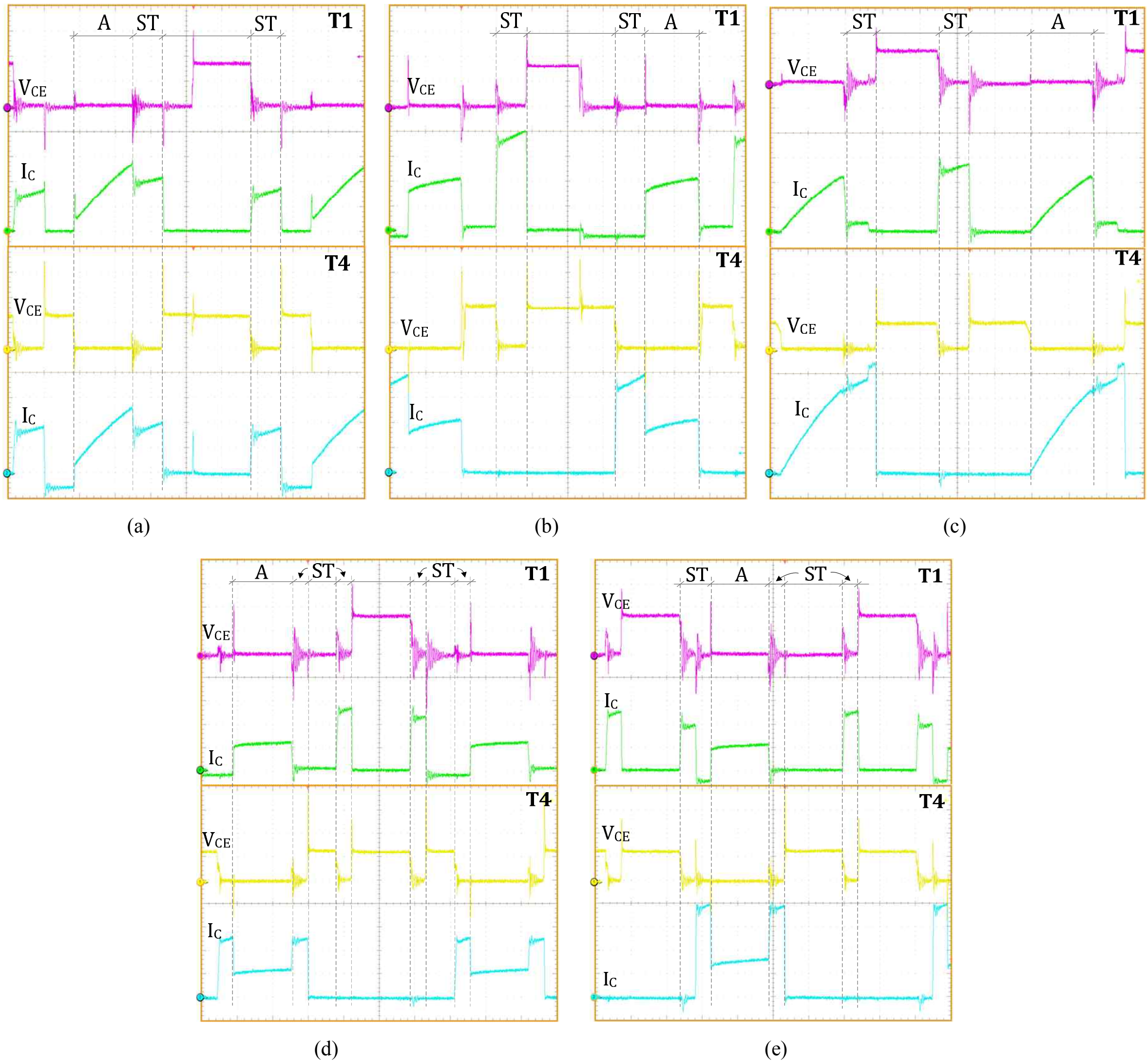

Fig. 8. Experimental waveforms of *Methods* (a) *A*, (b) *B*, (c) *C*, (d) *D*, and (e) *E*.

TABLE VI
OPERATING PARAMETERS OF THE CASE STUDY CONVERTER

Parameter	Value
input voltage, V_{IN}	30 V
desired DC-link voltage, V_1	60 V
output voltage, V_{OUT}	600 V
switching frequency, f	15 kHz
shoot-through duty cycle, D_{ST}	0.25
duty cycle of active state, D_Z	0.25
duty cycle of active state, D_A	0.5
load resistance, R_L	300 Ω
operating power, P	1 kW

output. This option is the cheapest and simplest of the three options.

V. SIMULATION STUDY

Lossless models were developed in the PSIM simulation software to evaluate and compare the proposed control methods. The following component values were assumed for the converter during simulations: $C_{qz1} = C_{qz2} = 700$ µF, $L_{qz1} = L_{qz2} = 50$ µH, and $C1 = C2 = 25$ µF. The turn ratio of the isolation transformer was 1:5. qZSC was studied at the operation point with the parameters presented in TABLE VI to demonstrate the basic operating waveforms with the different control methods.

The simulation results are shown in Fig. 7. Figs. 7(b)–(e) show that the proposed shoot-through generation by one inverter leg resulted in the twice-increased amplitude of the shoot-through current in comparison with the baseline approach, in which the shoot-through current was distributed between all of the transistors in the inverter bridge [Fig. 7(a)]. The double shoot-through approach introduced in *Method D* [Fig. 7(d)] decreased the peak-to-peak input current ripple by more than 6% in comparison with *Methods A* and *B* (12% for *Method D* vs. 19% for *Methods A* and *B*). The variable frequency of the shoot-through states in the asymmetric

TABLE VII
COMPARISON OF SWITCHING LOSSES GENERATED BY DIFFERENT PWM SHOOT-THROUGH CONTROL METHODS

	Losses during switching transients, W								Losses per diagonal, W	Total losses, W
	ST (ON)		ST (OFF)		A (ON)		A (OFF)			
	TOP	BOT	TOP	BOT	TOP	BOT	TOP	BOT		
Method A	3.0	3.7	0	27.9	0	0	0	0	34.6	69.2
Method B	0	8.8	18.3	0	0	0	0	11.1	38.2	76.4
Method C	17.2	0	0	17.3	0	0	0	0	34.5	69.0
Method D	14.9	9.5	9.7	18.8	0	0	0	0	52.9	105.8
Method E	11.9	0	9.3	19.6	0	0	0	0	40.8	81.6

PWM control (*Methods C* and *E*) seriously affected the input current ripple by increasing it by more than 6% in comparison with the alternative approach with the symmetric PWM control (*Methods B* and *D*). Therefore, the maximum peak-to-peak input current ripple of 25% was measured with the asymmetric PWM control with shifted shoot-through (*Method C*), which was more than double the case of the symmetric PWM control with the shifted double shoot-through (*Method D*).

In the diodes of VDR, *Methods A* and *C* featured the ZVS of rectifying diodes [Figs. 7(a) and (c)]; however, in *Methods B*, *D*, and *E*, the diodes were hard-switched.

VI. ANALYSIS OF EXPERIMENTAL RESULTS

To experimentally verify the proposed control methods, a 1 kW test setup of IS DC-DC converter was assembled. The front-end inverter was realized on the dual insulated-gate bipolar transistor (IGBT) modules Semikron SEMiX 202GB066HDs. Generalized parameters of the test setup are shown in TABLE VI. The control system was based on the microcontroller dsPIC 33FJ64GS606.

During the experiment, the collector–emitter voltage V_{CE} and the collector current I_C were simultaneously measured on the top (*T1*) and bottom (*T4*) transistors of one diagonal of the inverter bridge. Measured waveforms are presented in Fig. 8. The switching losses of IGBTs were calculated in accordance with the methodology presented in [29]. Losses were calculated for all the switching transients of the corresponding transistor (TOP or BOT) over one operating period, that is, turn-on (ON) and turn-off (OFF) of the shoot-through (ST) and active (A) states. The results are shown in TABLE VII. All the proposed PWM shoot-through control methods featured similar conduction losses and differed only by the number of soft-switching transients (TABLE VII). When considering inverter switching losses, *Methods A* and *C* had total switching losses of approximately 70 W, which was 34% less than that in the case of *Method D*. *Methods B* and *E* had intermediate switching losses of 76 and 82 W respectively.

In *Methods A–C*, two shoot-through states per period were generated; in *Methods D* and *E*, four were generated. *Methods D* and *E* clearly showed that considerable shoot-through states cause an increase in switching losses. However, the increased number of shoot-through states over an operating period also resulted in decreased input current ripple for the same inductance of the inductors in IS network.

Although *Method C* showed good results with respect to switching losses, it also introduced unsymmetrical transformer voltage. In some cases, this result can have some drawbacks, for example, DC-biased primary winding and additional magnetic losses.

VII. CONCLUSIONS AND FUTURE WORK

This study analyzed four novel PWM shoot-through control methods for IS DC-DC converters. The common feature of the new methods is the shoot-through generated by a single inverter leg. An overview of IS DC-DC converter was given, and the operating principle of each control method was explained through the switching-state sequence. Simulation results were verified by experiments. The proposed methods enable no considerable power loss reduction in the IGBT-based front-end inverter. However, they double the number of shoot-through states over one operating period without a significant increase in switching losses. A large number of shoot-through states will increase the effective frequency of the input current ripple, which in turn will result in a decreased value of the inductors and a compact design of the IS network. This issue will be addressed by the authors in detail in future publications.

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