THREE-LEVEL ZERO-VOLTAGE-SWITCHING PWM DC-DC CONVERTERS - A COMPARISON

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Abstract - This paper states a comparative study of six three-level zero-voltage-switching TL-ZVS-PWM dc-dc converters. All converters operate at fixed frequency and offer zero-voltage-switching for all active devices. The studied TL-ZVS-PWM converters are namely: TL-ZVS-PWM, TL-ZVS-PWM with one (1) commutation auxiliary circuit CAC, TL-ZVS-PWM with two (2) CAC, TL-ZVS-PWM Parallel-Resonant, TL-ZVS-PWM Series-Resonant and TL-ZVS-PWM Series-Non-Resonant.

The main features of the TL-ZVS-PWM converters are discussed and mentioned, some these are: number of power devices, current through components, load range under ZVS operation, output characteristics, output rectifier commutation, command circuit and efficiency.

The TL-ZVS-PWM dc-dc converters have been implemented. From the obtained experimental results was permitted to evaluate the main sources of losses, as well as to carry out analysis and comparison of the converters features. The TL-ZVS-PWM dc-dc converters greatest attribute is that the maximum voltage across the active switches is half of the input voltage.

Tables, abacus and experimental results are presented.

I. INTRODUCTION

New alternatives to obtain Three-level Zero-Switching-Voltage PWM dc-dc converter destined for high input voltage SMPS of high performance have been introduced in [9]. These techniques are based on PWM and resonant converter. Several soft-switching PWM techniques have been proposed introducing soft-switching without a significantly increase in circulating energy. In these converter classes, the commutation utilizes some form of resonant technique to perform a soft-switching, when this transition is completed the circuit behavior like the PWM conventional converter. As consequence, the switching losses can be reduced without to penalize signicantly the conduction losses.

In this work is carried out a comparison of six TL-ZVS-PWM converters, which are: TL-ZVS-PWM [5], TL-ZVS-PWM with one (1) commutation auxiliary circuit CAC [6], TL-ZVS-PWM with two (2) CAC, TL-ZVS-PWM Parallel-Resonant, TL-ZVS-PWM Series-Resonant [7] and TL-ZVS-PWM Series-Non-Resonant. The two later converters have one commutation auxiliary circuit. Every Three-Level converters operate at constant frequency, their active switches are commutated under zero-voltage and they can run over a large load range.

The TL-ZVS-PWM converters have been implemented using the same power semiconductor devices and transformer. The principal components of the structure are namely:

Power Switches: MOSFETS APT5040 Rd(on)=0,4Ω(25°C); Clamping Diodes: MUR440 (Motorola); Output Rectifier Diodes: MUR1540 (Motorola); HF Transformer: on ferrite core E-65/39

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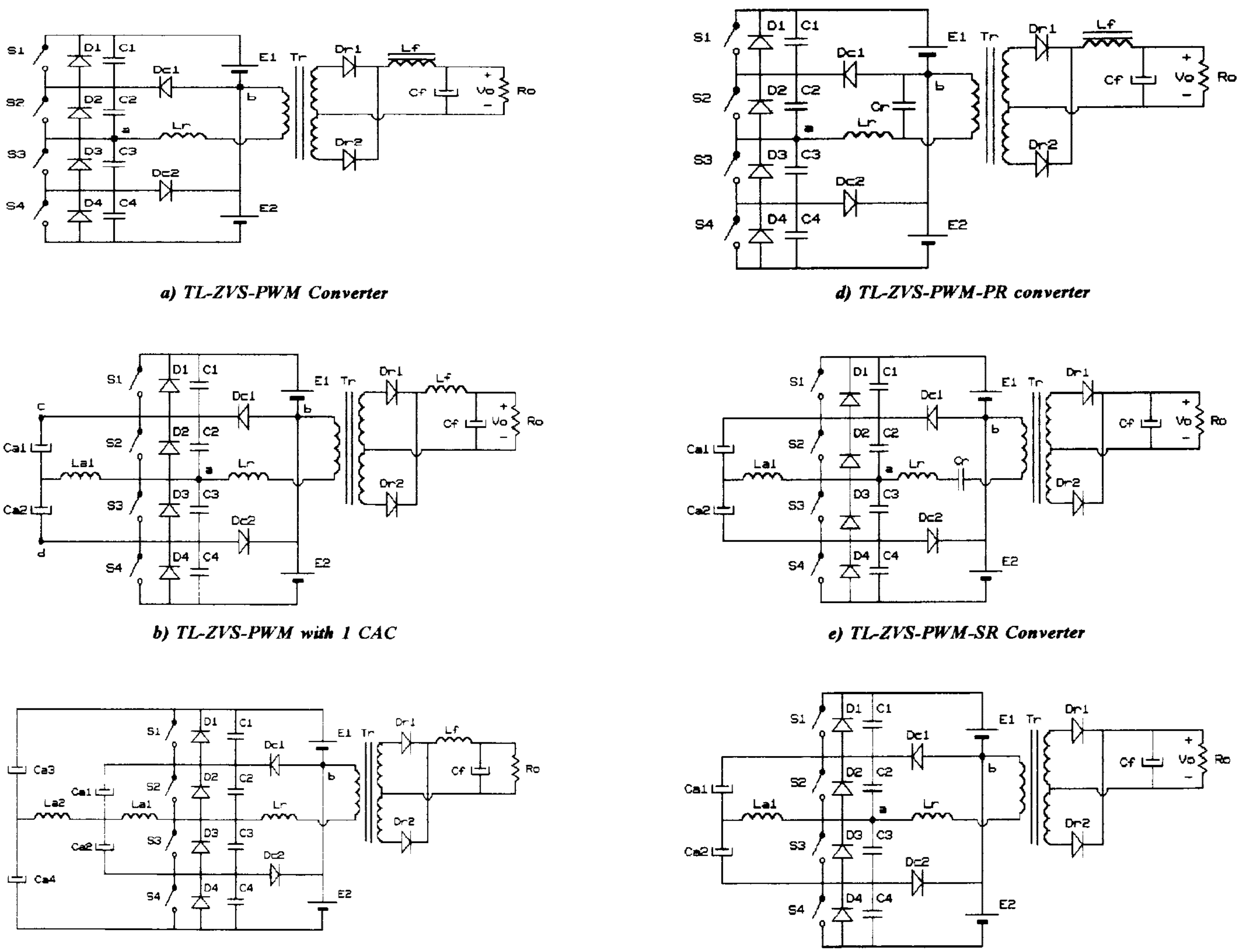


a) TL-ZVS-PWM Converter

d) TL-ZVS-PWM-PR converter

b) TL-ZVS-PWM with 1 CAC

e) TL-ZVS-PWM-SR Converter

c) TL-ZVS-PWM with 2 CAC

f) TL-ZVS-PWM-SNR Converter

Fig.1 Six TL-ZVS-PWM converters

(Thornton), primary: 15 turns, secondary: 10 turns center tapped.

In Fig. 1 are shown the six TL-ZVS-PWM converters, which will be discussed hereafter. In some converter the presence of the commutation auxiliary circuit is not necessary, as they operate within limited load variation range as the resonant tank has enough energy to perform the commutation independently of the load range maintaining the soft commutation characteristic.

II. Comparative Study

Some values of the principal parameters are presented in Table I for the six TL-ZVS-PWM converters operating at full load. Being E the input dc

TABLE I
PRINCIPAL PARAMETERS

	1	2	3	4	5	6
E	600V	600V	600V	600V	600V	600V
V_o	60V	60V	60V	60V	60V	60V
I_o	25A	25A	25A	20A	20A	20A
P_o	1500W	1500W	1500W	1200W	1200W	1200W
L_r	16μH	16μH	16μH	56μH	61μH	34μH
C_r	-	-	-	66nF	100nF	-
L_{a1}	-	225μH	225μH	-	225μH	225μH
L_{a2}	-	-	380μH	-	-	-
n_{tr}	3	3	3	3	3	3
I_{maxS14}	8,3A	8,3A	9,3A	16,1A	11,2A	12,6A
I_{maxS23}	8,3A	9,8A	9,8A	16,1A	12,8A	13,6A
I_{rmsS14}	3,9A	3,9A	4,2A	5,9A	4,3A	4,4A
I_{rmsS23}	5,4A	5,6A	5,6A	7,2A	5,5A	5,7A
I_{avgD14}	0,19A	0,19A	1,2A	0,83A	0,27A	0,23A
I_{avgD23}	0,19A	0,25A	0,24A	0,83A	0,43A	0,36A
P_{MOSFET}	46,1W	48,1W	52,3W	108,2W	60,1W	62,4W
I_{avgDc}	1,7A	1,7A	0,83A	1,2A	0,89A	1,76A
I_{avgDr}	12,5A	12,5A	12,5A	10,0A	10,0A	10,0A
$P_{cond\ Semic}$	77,2W	79,3W	81,7W	135W	86,2W	90,9W
E_{Lr}	0,55mJ	0,55mJ	0,55mJ	7,8mJ	3,9mJ	2,7mJ
E_{Cr}	-	-	-	3,0mJ	1,3mJ	-
E_{La1}	-		0,42mJ	-	0,42mJ	0,42mJ
E_{La2}	-	-	0,11mJ	-	-	-
$R_{ds(on)}$	0,5Ω	0,5Ω	0,5Ω	0,6Ω	0,6Ω	0,6Ω
V_{th}	1,1V	1,1V	1,1V	1,2V	1,2V	1,2V
V_{maxCr}	-	-	-	314,1V	159,7V	-
I_{maxLr}	8,3A	8,3A	8,3A	16,1A	11,2A	12,6A
P_{condDr}	27,5W	27,5W	27,5W	24,0W	24,0W	24,0W
P_{condDc}	3,7W	3,7W	1,8W	2,9W	2,1W	4,2W
Effic(25A)	93%	92%	90,5%	-	-	-
Effic(20A)	94%	93%	92%	84,5%	88%	87%

1-TL-ZVS-PWM Converter (Fig.1a)
2-TL-ZVS-PWM Converter with 1 CAC (Fig.1b)
3-TL-ZVS-PWM Converter with 2 CACs (Fig.1c)
4-TL-ZVS-PWM-PR Converter (Fig.1d)
5-TL-ZVS-PWM-SR with 1 CAC (Fig.1e)
6-TL-ZVS-PWM-SNR with 1 CAC (Fig.1f)

supply voltage, V_o the output dc voltage, I_o the output load current, P_o output load power, n_{tr} the transformer turns ratio, L_r the resonant inductance, C_r the resonant capacitance, L_{a1} and L_{a2} the auxiliary commutation inductances, I_{maxS14} and I_{maxS23} the maximum main switch currents, I_{rmsS14} and I_{rmsS23} the r.m.s. main switch currents, I_{avgD14} and I_{avgD23} the average main diode currents, P_{MOSFET} the dissipated MOSFET power, I_{avgDc} the average clamping diode current, I_{avgDr} the average rectifier diode current, $P_{cond\ Semic}$ the dissipated Semiconductor devices power, E_{Lr} the maximum resonant inductor energy, E_{Cr} the maximum resonant capacitor energy, E_{La1} and E_{La2} the maximum auxiliary commutation inductor energy, $R_{ds(on)}$ the conduction drain-source resistance, V_{th} the threshold rectifier diode voltage, V_{maxCr} the maximum resonant capacitor voltage, I_{maxLr} the maximum resonant inductor current, P_{condDr} and P_{condDc} the conduction loss power of the rectifier and clamping diodes, Effic(25A) and Effic(20A) the efficiency for load of 25A(1500W) and 20A(1200W). In Table II are presented some features of the converters.

TABLE II
COMPARISON OF TL-ZVS-PWM CONVERTERS

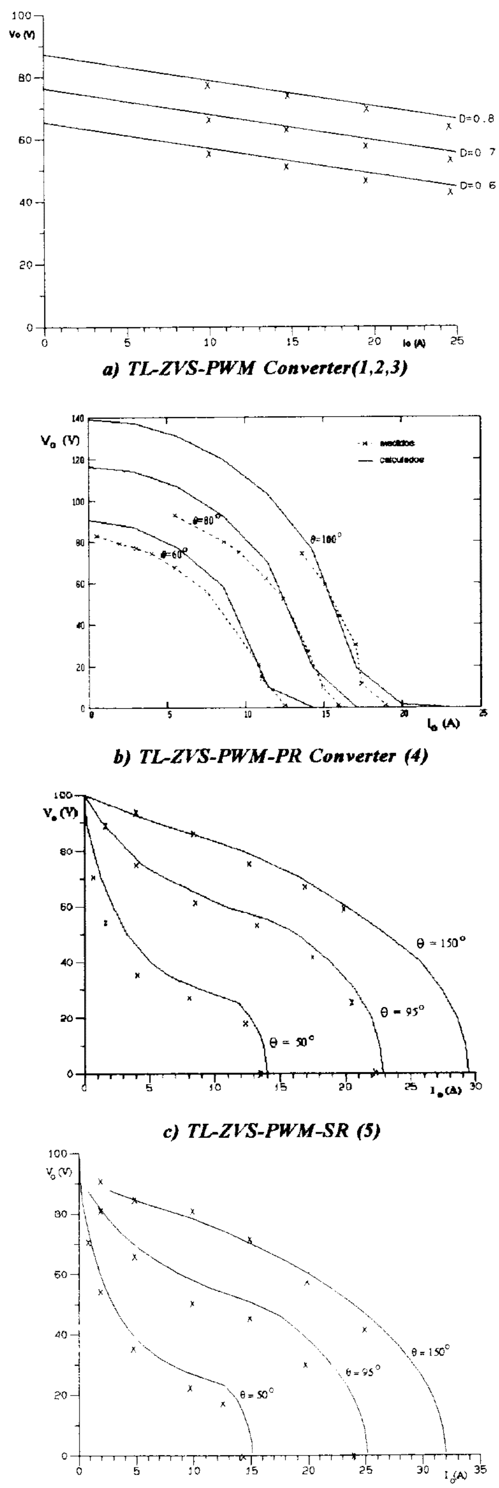
	1	*2*	*3*	*4*	*5*	*6*
Short-circuit	No	No	No	No	Yes	Yes
No load Regulation	Yes	Yes	Yes	Yes	Yes	Yes
Output Filter	LC	LC	LC	LC	C	C
Voltage Clamping Dr	Yes	Yes	Yes	No	No	No
Command	PWM	PWM or Phase-Shift	Phase-Shift	PWM	PWM	PWM
Components n° CAC + CR	1	3	4	2	5	4
Auxiliary circuit	No	Yes(1)	Yes(2)	No	Yes(1)	Yes(1)
ZVS Range	Partial	Full	Full	Full	Full	Full

From analysis and experimental results was observed that the converter *1* presented the highest efficiency (94%) and the smallest component number. On the other hand, it operates under ZVS in a limited load range.

It will present dissipative commutation to light load. As consequence of the dissipative commutation, there will be increase of the switching losses and the noise (EMI and RFI) and the impossibility of the use of dual thyristor. The employment of dual thyristor offers with a simple circuit a important feature of safety and robustness, beyond to protect against overcurrent and to prevent against short-circuit of the Three-level leg.

When the operating in a wide load range is desired, the converter *2,3* are the alternatives to be considered, because they present excellent performance even for high current and low output voltage applications, due to presence of the LC output filter. The converter *3* can guarantee ZVS commutation from no load to full load independently the converter to be incorporating insulation transformer or not. In the converters *1,2,3* appear overvoltage on the output rectifiers, due to the fact that the commutation is not under zero voltage and due to presence the transformer leakage inductance and output rectifier junction capacitance. This problem is the same to presented by FB-ZVS-PWM discussed in [2,3,4,8]. In this work was employed a RC clamping circuit to avoid high voltage level across the output diodes terminals.

The converter *4* (parallel-resonant) can be a alternative to overcome the overvoltage across the output diodes, this goal is achieved by placing the resonant capacitor to secondary. This procedure eliminate the use of clamping voltage circuits, since the output rectifier commutations occur under zero voltage. The converter *4* yields a circulating energy practically independent of the load, therefore it does not need of CAC to operate from no load to full load. It presented the lowest efficiency (84,5%) and the biggest resonant tank volume. A singularity of the converter *4* is the possibility to operate as voltage elevator, when the ω_{sn}



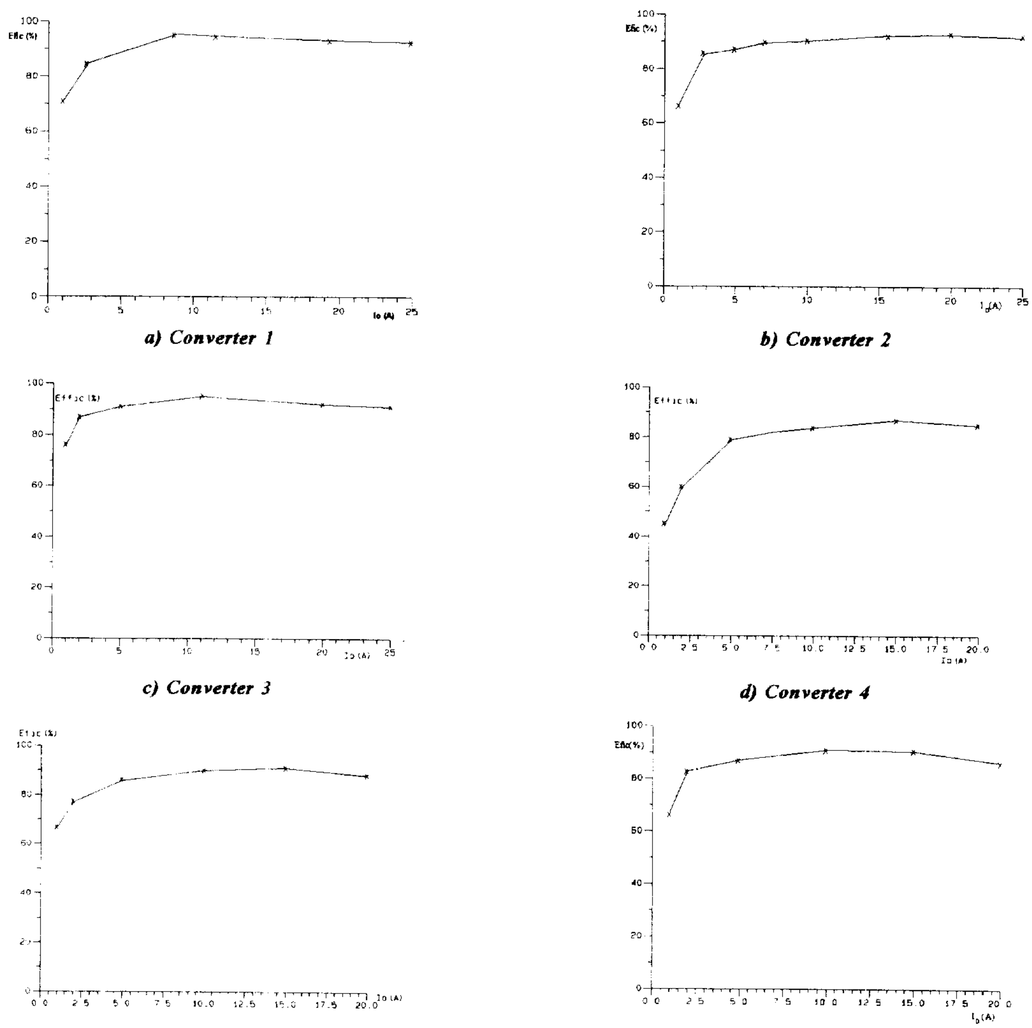
a) TL-ZVS-PWM Converter(1,2,3)

b) TL-ZVS-PWM-PR Converter (4)

c) TL-ZVS-PWM-SR (5)

d) TL-ZVS-PWM-SNR (6)

Fig. 2 Output Characteristics



a) Converter 1
b) Converter 2
c) Converter 3
d) Converter 4
e) Converter 5
f) Converter 6

Fig. 3 Efficiency versus output current for V_o=60V, f_s=100kHz

(normalized switching frequency) is equal to 1.4 or lower. The normalized switching frequency is defined as being the ratio between the frequencies of resonance and switching.

The converter ***4,5,6*** present "fall down" output characteristics, which can be considered such as output current source. Hence, they can offer a natural protection to short-circuit current.

The Series-Resonant and Series-Non-Resonant converter ***5*** and ***6***, respectively, have their output filter formed by a capacitor only, these one are indicated for both low output current and when there is not rigorous requirement of the output voltage ripple. These converters require CAC to operate in a wide load range. The converter ***4*** presented a higher efficiency than the ***5***, but the converter ***5*** presented a smaller resonant tank volume than the ***4***.

There is a considerable difference among the magnetic elements of the resonant tank. For instance, the resonant tank maximum energy of the converters ***1,2,3*** added to CAC is about 1.1 mJ, against 7.8mJ of the converter ***4***, 4.3 mJ of the converter ***5*** and 3.1 mJ of the converter ***6***.

In figure 2 are shown the output characteristics (theoretical and experimental results) of the six TL-ZVS-PWM converters.

The converters ***1,2,3*** present the same output characteristics, in he similar manner the converters ***5,6*** can present their output characteristics. We can affirm that the Series-Non-Resonant converter ***6*** is a particular case of the Series-Resonant one.

The converters ***4,5,6*** present higher output impedance than the converters ***1,2,3***, this characteristics may in many applications to be a interesting one, for instance, in following applications: batteries charger, current source, parallelism of dc-dc converters, electronic welding converter, distributed dc-dc sources. In Fig. 3 are illustrated the efficiencies versus the output current of the six TL-ZVS-PWM converters.

III.CONCLUSION

This work realizes a comparison of six different topologies of Three-level Zero-Voltage-Switching PWM dc-dc converters, they are: TL-ZVS-PWM, TL-ZVS-PWM with 1 commutation auxiliary circuit (CAC), TL-ZVS-PWM with 2 CAC, TL-ZVS-PWM Parallel-Resonant, TL-ZVS-PWM Series-Resonant and TL-ZVS-PWM Series-Non-Resonant.

The global point-of-view the TL-ZVS-PWM converter with 1 commutation auxiliary circuit presented the better performance, hence it can operate over a wide load range without to sacrifice the efficiency.

The TL-ZVS-PWM-SR and TL-ZVS-PWM-SNR converters presented good performance, therefore they can be an attractive choice when the robustness is a fundamental aspect, due to their ability to sustain an output short-circuit even without special protection circuit. As well as, every converter may be an interesting alternative whenever it is necessary to connect power switches in series. For instance, due to unavailability of the switches, which can be adequate to desired specifications, such as maximum voltage, switching frequency and r.m.s current.

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