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PWM for Single Phase 3L Z/qZ-Source Inverter with Balanced Power Losses

C. Roncero-Clemente[1], O. Husev[2], T. Jalakas[2], E. Romero-Cadaval[1], J. Zakis[3], V. Minambres-Marcos[1]
[1]*Power Electrical and Electronic Systems (PE&ES) Research Group, University of Extremadura, Spain*
[2]*Department of Electrical Engineering, Tallinn University of Technology, Estonia*
[3]*Institute of Industrial Electronics and Electrical Engineering, Riga Technical University, Latvia*

***Abstract*—This paper presents a new modified carrier based single phase modulation technique with maximum constant boost control for three level Z or qZ-source inverter topology. The proposed technique is explained, analysed and compared with the previous one in simulation as well in experimental way. Obtained results are compared from the point of view of power losses in the electronic switches. Advantages and disadvantages of the converters performance based on the proposed modulation techniques implementation are discussed.**

***Index Terms*—Power conversion, pulse width modulation converters, solar energy, power semiconductor switches.**

I. INTRODUCTION

There are several modulation techniques or shoot-through control methods in the literature for single phase or three-phase two level Z source inverters [1]–[4]. Mainly, these controls are classified in: simple boost (SBC) [1], maximum boost (MBC) [2], maximum constant boost (MCBC) [3] and modified space vector modulation (MSVMBC) [4]. They have been used for controlling converters in several applications such as PV solar energy and fuel cells among others [5]–[6]. In addition, all those techniques can be used for qZ voltage source inverter [7].

In order to select the most appropriate one, it is necessary to take into account many key aspects as: shoot-through (Ds) states must be carefully and centrally added (uniform distribution), size of the passive elements (direct connection with the cost of the converter), THD of the output voltage, DC-link voltage ripple, switch voltage stress, inductor current ripples, efficiency, boost capabilities and the final application of the energy conversion. In [8], a deep experimental comparison between different modulation techniques for three-phase two levels Z-source inverter is discussed according to some aforementioned criteria. The main comparative results are represented in Table I. MCBC method is presented as a best option among the others.

Focusing now the attention on multilevel inverter topologies, modulation and control methods have had a high level of dedication by researchers in the last years [9]–[15].

A perfect comparison between different modulation methods was presented in [11]. They divide the modulation methods for multilevel converter in two main groups: space vector based methods and carrier based methods. Fig. 1 illustrates such classification just in case of high frequency applications.

TABLE I. MODULATION TECHNIQUES FOR Z OR QZ SOURCE INVERTER [8].

Modulation technique	SBC	MBC	MCBC	MSVMBC
Criteria				
Line voltage harmonic	-	+	0	+
Phase current harmonic	0	0	+	-
DC-Link voltage ripples	0	-	+	0
Switch voltage stress	0	+	0	-
Inductor current ripples	0	-	+	-
Efficiency	0	+	+	-
Obtainable AC voltage	0	0	+	-
Total	-	+++--	+++++	+----

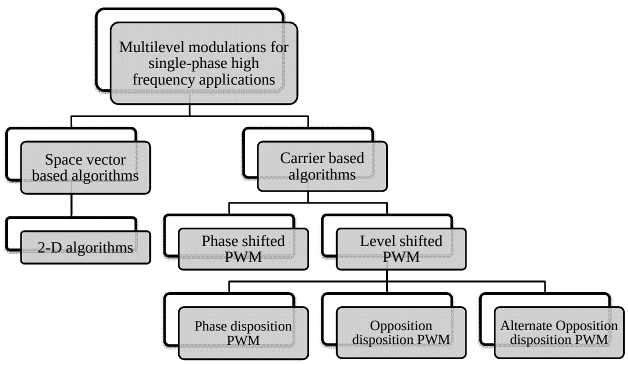

Fig. 1. Classification of multilevel high frequency modulation techniques.

Due to the aforementioned characteristics and recommendations, a new level shifted PWM (LS-PWM) in phase opposition disposition with MCBC was proposed in [16] for controlling a single-phase 3 level Neutral-Point-Clamped quasi-Z source Inverter (3L NPC qZSI) (Fig. 2). This modulation technique and its switching signal generation are depicted in Fig. 3. Also, it is explained in details in [16].

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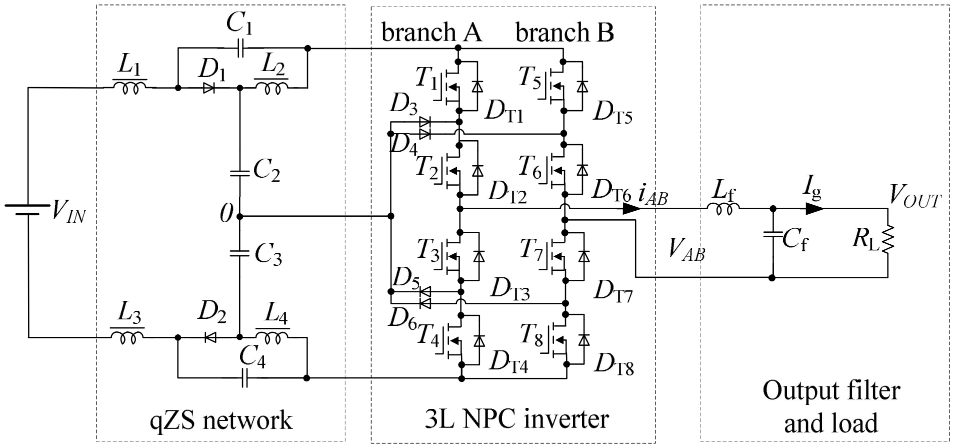

Fig. 2. Single-phase 3 level Neutral-Point-Clamped quasi-Z source inverter topology.

This modulation technique has been implemented and used in different works with success [7], [17]. But, at the same time, it is observed that switching signals and duty cycles (directly connection with power losses) of switches are quite unbalanced inside of each branch. This phenomenon can be observed in Fig. 3. In this technique, four carrier signals (C1, C2, C3 and C4) are required to generate the switching signals and C3 and C4 are shifted their level the amount of Ds/2 in order to compensate the average output voltage [16] when the Ds is applied.

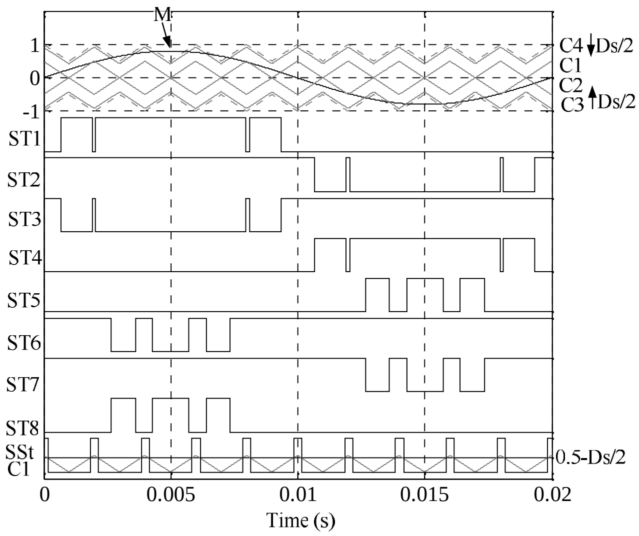

Fig. 3. Asymmetrical carrier-based PWM switching generation.

This paper proposes a new LS-PWM in phase disposition with MCBC which improves to the previous one from the point of view of balancing the power losses between branches. The new modulation technique can be used for Z-source or qZ-source 3 level topologies in single phase applications. Both modulation techniques have been compared and analysed as in simulation as experimentally. Such comparisons demonstrate that by using the new modulation technique, the proposed goal is achieved, presenting a better distribution of the power losses between branches and even between switches of each branch.

II. NEW BALANCED MODULATION TECHNIQUE

As it was exposed in previous chapter, the goal of developing a new modulation technique is to improve the previous one by means of balancing the power losses between branches. Those power losses are produced during switching states (switching losses) and also during on states (conduction states) in each electronic switch. Both losses must be taken into account in order to distribute them among branches of the converter. In this way different rates of the converter are improved such as: Mean Time to Failures (MTTF) and Mean Time between Failures (MTBF). As consequence, the reliability and the useful life of the converter will increase.

Figure 4 shows a simulated generation without and with shoot-through switching states based on new modulation technique. It has been used a modulation frequency index (m_f) equal to 10 (for a better representation), shoot-through duty cycle equal to 0.16 and the modulation index (m) is 0.84. Figure 5 illustrates the implementation sketch of the proposed modulation technique.

Two modulating sinusoidal waves (M1 and M2, one per branch) are compared with two level shifted triangular carriers (C1 and C2) in phase disposition. The result of this operation is obtaining the normal states of T1, T2, T5 and T6. T3, T4, T7 and T8 have the complementary states of the others, respectively. It is easy to detect in Fig. 4 that switching states of analogous switches are the same in both branches so power losses will be also the same.

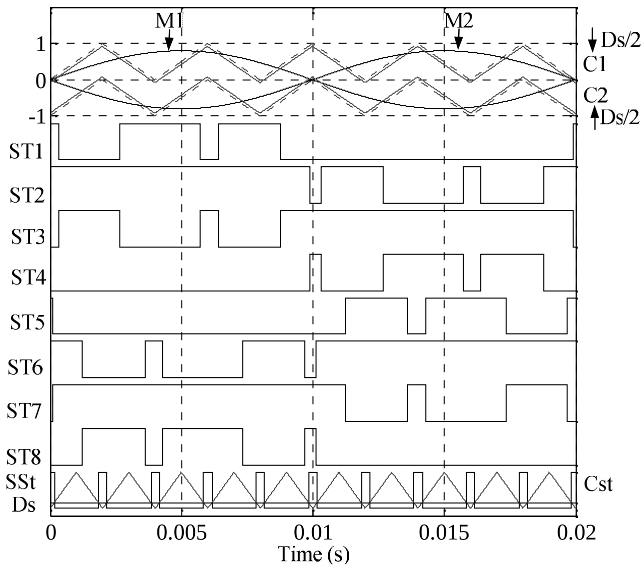

Fig. 4. Switching signals generation of the balanced modulation technique.

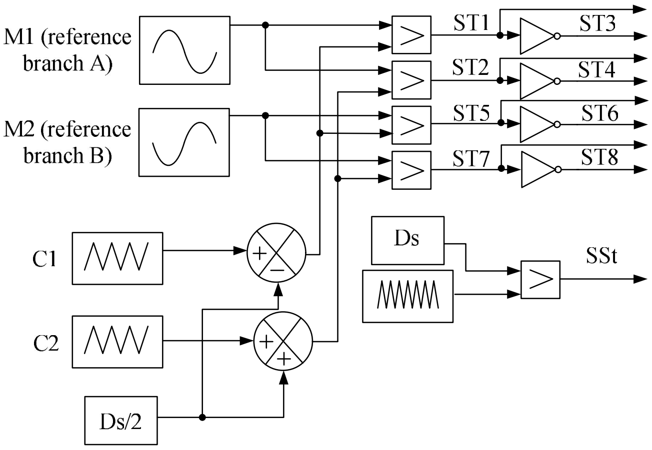

Fig. 5. Sketch of the implementation of the modulation technique.

The generation of the shoot-through states (SSt) is done by means of the comparison between Ds and one triangular carrier (Cst) at twice frequency than C1 and C2. Operating in this way, the symmetry of the output voltage is maintained and also MCBC is achieved. At the same time it is required to compensate the average output voltage (V_{ab}) when the shoot-through states are applied. It is done by shifting C1 and C2 quantities -Ds/2 and Ds/2 respectively.

III. ANALYTICAL COMPARISON BETWEEN PWM TECHNIQUES

In order to compare the previous and the proposed PWM in a quantitatively way, a comprehensive simulation study was performed in PSCAD.

First of all, the number of switching transitions (times) per switch during one fundamental period (defined at 50 Hz) were analysed in both PWM (Table II). These numbers or parameters are related to the switching losses and it are represented in Fig. 6(a) and Fig. 6(b) for each modulation technique as a function of m_f respectively (Ds is equal to 0.16).

TABLE II. ANALYSIS OF NUMBER OF SWITCHING SIGNALS PER SWITCH.

Previous modulation technique / Proposed modulation technique	Switching times at 100 kHz and Ds to 0.16	Switching average times per branch at 100 kHz ($\overline{T}_i$)	Standard deviation per branch ($\pm_{Ti}$)	Standard deviation of full converter
T1	3325	2658.5	769.6	1631
	3830			
T2	1992			
	1984			
T3	1992	2907	1065.8	
	1984			
T4	3325			
	3830			
T5	5308	3308	2309.4	987.1
	3830			
T6	1308			
	1984			
T7	1308	2907	1065.8	
	1984			
T8	5308			
	3830			

We can see as in Fig. 6 as well in Table II that in previous modulation technique, branch B presents higher internal unbalance between switching numbers (T5 and T8 switch 4 times more than T6 and T7). Branch B also presents more switching numbers unbalance in comparison with branch A than in proposed modulation technique (see $\pm_{Ti}$ in Table II). It is due to branch B just deals with compensating V_{ab} by changing the voltage V_{bo}. The compensation of the V_{ab} is done by both branches of the converter in the proposed PWM.

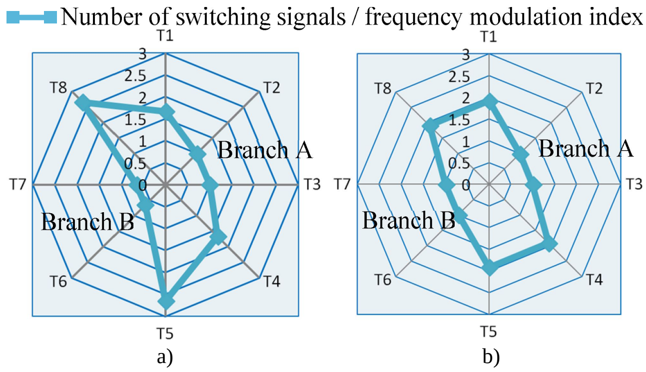

Fig. 6. Number of switching signals per switch/frequency modulation index in one fundamental period. Unbalanced modulation technique (a). Proposed modulation technique (b).

TABLE III. ANALYSIS OF T_{ON} PER SWITCH.

Previous modulation technique / Proposed modulation technique	T_{on} (ms)	Average Ton per branch ($\overline{T}_{ON,i}$)	Standard deviation per branch ($\pm_{TON,i}$)	Standard deviation of full converter
T1	10.161	11.6	1.66	4.06
	8.291			
T2	13.039			
	14.9095			
T3	13.039	11.6	3.82	
	14.9095			
T4	10.161			
	8.291			
T5	6.4239	11.6	5.97	3.53
	8.291			
T6	16.7763			
	14.9095			
T7	16.7763	11.6	3.82	
	14.9095			
T8	6.4239			
	8.291			

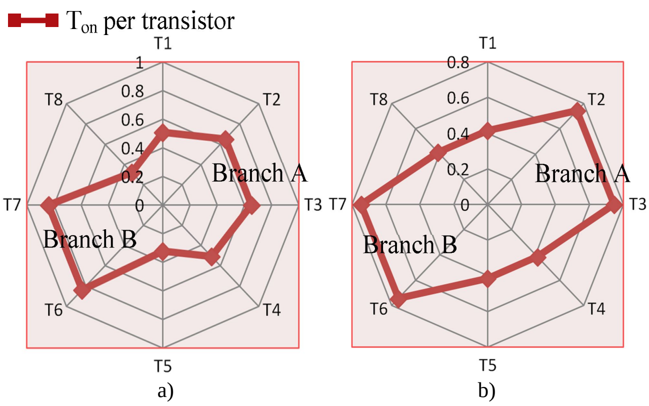

Fig. 7. T_{on} per switch during one fundamental period: Unbalanced modulation technique (a); Proposed modulation technique (b).

Secondly, the duty cycle of each switch (T_{on}) was calculated (Table III).

These values are related to the conduction losses and are represented in Fig. 7. The same conclusions are produced in the case of previous modulation technique. Branch B has a high level of conduction unbalance between its switches (T6 and T7 conduct 2.6 times more than T5 and T8) and also a different duty cycles with the analogous switch from branch A. New proposed PWM provides the same T_{on} of each analogous pairs of switches between branches and less unbalance within the branch.

We can conclude that by using the proposed modulation technique, both branches are symmetrically balanced from the point of view of switching and conduction losses. Also this balanced situation is inherited by the clamped diodes (D1, D2, D3 and D4) because their switches are the same than T1, T4, T5 and T8 respectively. Therefore, rates as MTTF, MTBF and reliability of the converter are improved.

IV. EXPERIMENTAL VERIFICATIONS

In order to prove all theoretical assumption the experimental investigation were carried out. The experimental prototype was deeply described in [17]. All tests were performed under 1.2 kW output power. Switching frequency was 100 kHz.

Figure 8 illustrates the gate-source switching signals of the first and second modulation techniques.

Figure 8(a) and Fig. 8(b) demonstrate the first modulation technique without and with shoot through correspondently. It is evident that all transistors are working in a different way. In all subfigures from up to down the switching signals of transistors correspond to T1, T2, T5 and T6. Figure 8(c) and Fig. 8(d) show the similar switching signals for second modulation techniques. In this case the switching signals of both branches are balanced.

Figure 9 shows the thermal pictures of the power board where driver circuits along with transistors terminals are located. Figure 8 demonstrates the gate resistors (R_G) of the transistors T1, T5 under first (a) and second (b) modulation strategies. Higher temperature of the gate resistors T5 confirms higher switching numbers of this transistor in the first modulation.

In case of second modulation technique branches are balanced from the point of view of switching signals and T_{on}.

Figure 10 illustrates the temperatures of the transistors chip that are located under the board on the radiators.

In the first case (Fig. 10(a)) difference between the temperatures of the difference branches is presented. This difference is mitigated under second modulation strategy (Fig. 10(b)).

It should be mentioned about total converter efficiency with different modulation strategies. This parameter was measured with YOKOGAWA DL850 V equipment. In the boost mode the efficiency was measured about 94,5 % for the first approach and 95 % for the second one. In case of buck operation the efficiency was around 97 % in both cases (Fig. 11) [17]. It is possible to conclude that the whole efficiency of the converter is practically the same (defined it as (P_{out}/P_{in}) by using both PWM techniques but, the stress of each branch is totally different, as thermic analysis and simulations have showed.

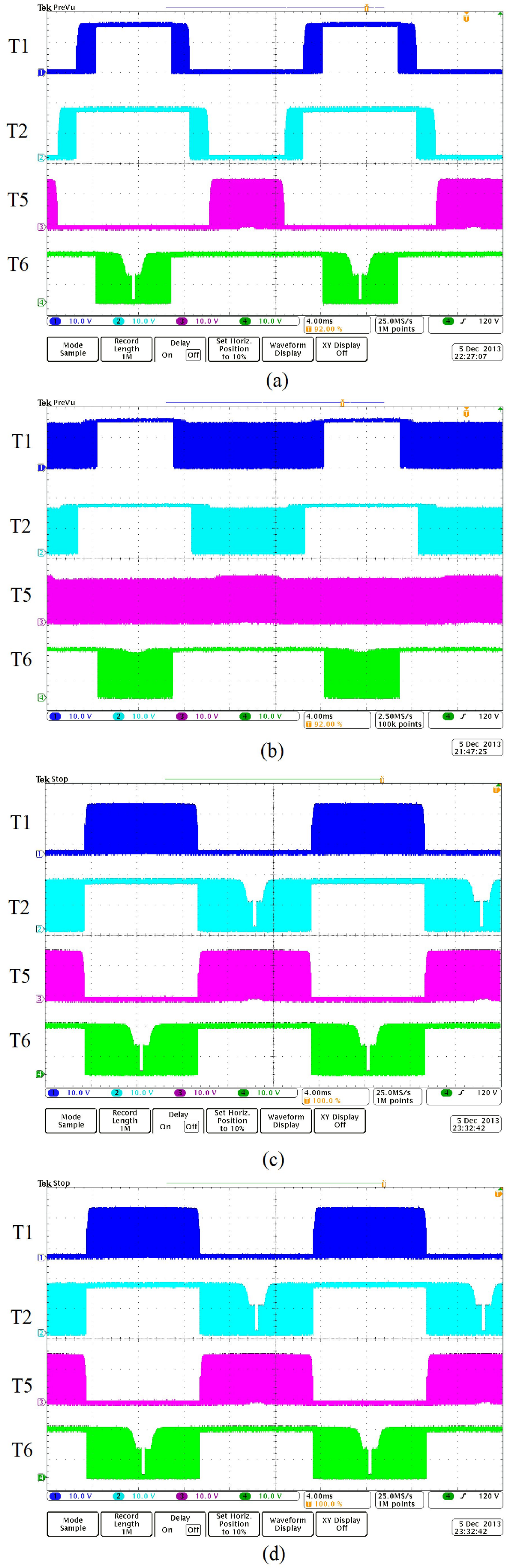

Fig. 8. Gate-source switching signals of the unbalanced (a, b) and balanced (c, d) modulation techniques without (a, c) and with (b, d) shoot-through generation.

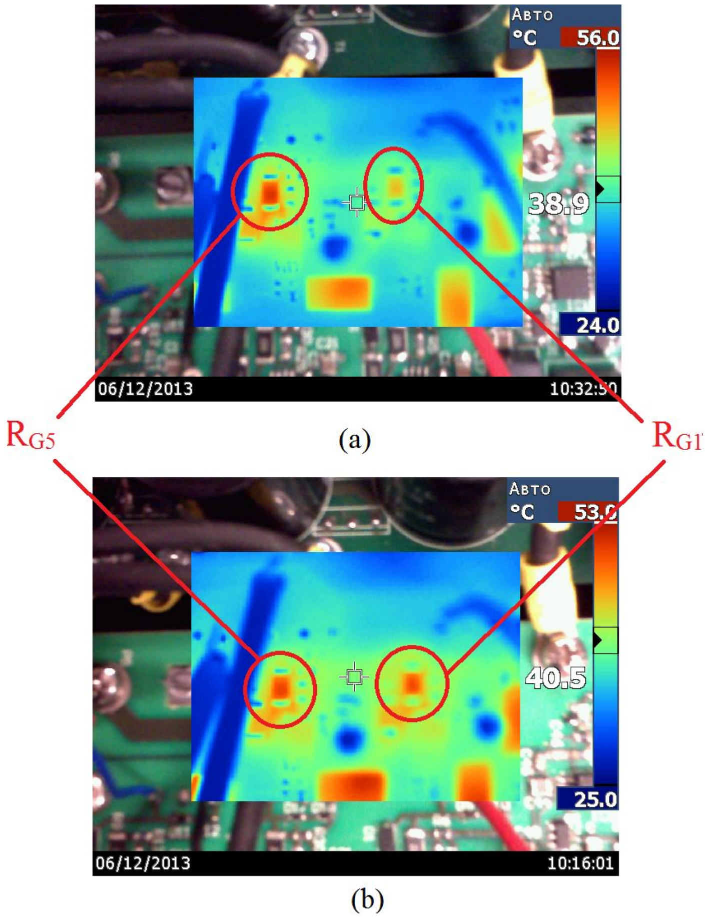

Fig. 9. Thermal picture of the gate resistors of the transistors T1, T5 under first (a) and second (b) modulation strategy.

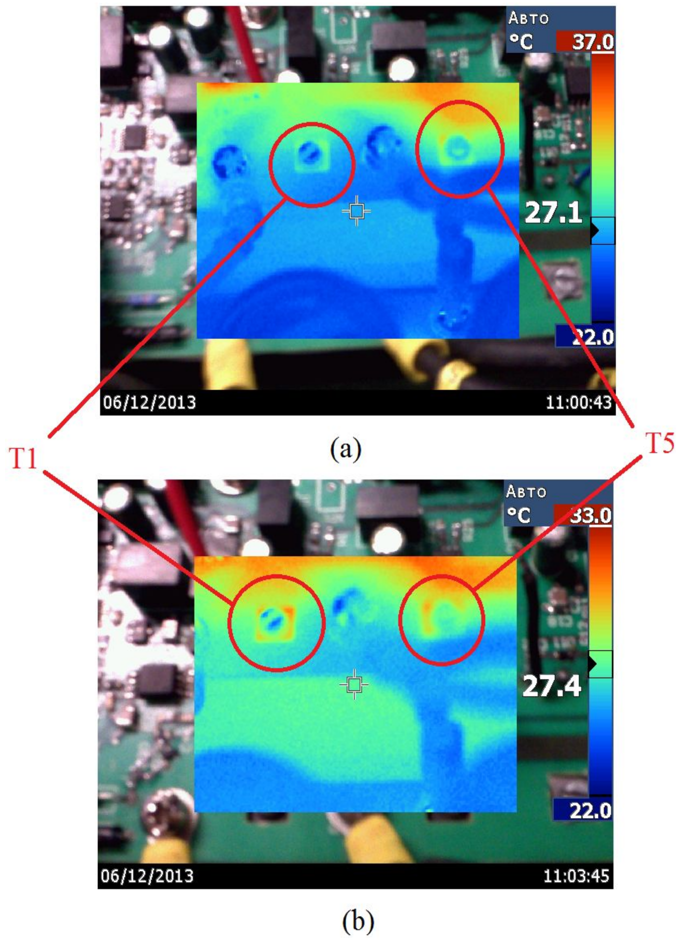

Fig. 10. Thermal picture of the chip transistors T1, T5 under first (a) and second (b) modulation strategy.

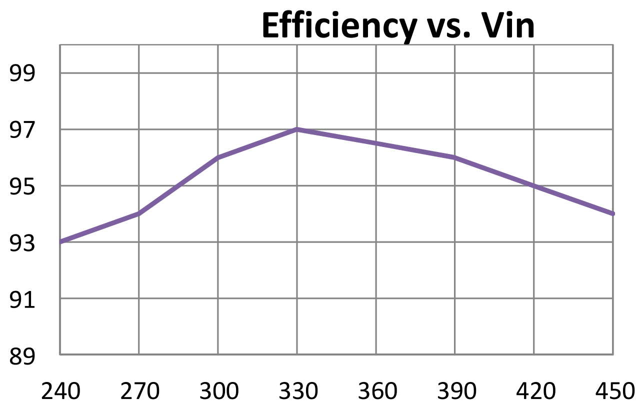

Fig. 11. Experimental measurements about efficiency versus input voltage.

V. CONCLUSIONS

This paper presents a new modified carrier based single phase modulation technique with maximum constant boost control for three level Z or qZ-source inverter topology.

The main advantage of the new proposed technique consists in equally distributed switching and conduction losses among two branches. Since the total converter efficiency remains approximately the same, the application of the two control strategies could be defined by thermal design of the converter.

Sometimes it is difficult to provide uniform heat sink for all transistors. It means that unbalanced thermal resistors for each transistor can be compensated by means of unbalanced modulation technique. And vice versa, balanced modulation technique is an appropriate control strategy for balanced thermal design.

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