U.P.B. Sci. Bull., Series C, Vol. 73, Iss. 2, 2011 ISSN 1454-234x

COMPARISON BETWEEN THREE LEVEL RECTIFIERS

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Se prezintă un studiu comparativ între mai multe structuri de conversie alternativ-continuu cu trei niveluri de tensiune. Sunt prezentate rezultate de simulare şi analize teoretice privind performanţele şi pierderile în dispozitivele semiconductoare de putere. Este descrisă o structură nouă de redresor cu trei niveluri de tensiune derivată din invertorul bidirecţional 3L-ASNPC.

It presents a comparative study between several ac-dc structures with three voltage levels. Also there are presented simulation results and theoretical analysis regarding the performances and power losses in the power devices. It is shown a new rectifier structure with three voltage levels derived from the bidirectional converter 3L-ASNPC.

Keywords: commutation losses, conduction losses, multilevel rectifiers

1. Introduction

To obtain high power rectifiers it was necessary to increase the current and voltage capability for the semiconductor devices. With the voltage increase, the performances drop and the price increase. Multilevel rectifiers were created as a solution to reduce the voltage stress of the semiconductor devices compared with classical solutions. The increase in the number of devices was justified by the increase in the performances and the reduction of the input filter size. Also in some structures it is possible to double the input voltage frequency.

These observations led to the development of several multilevel structures during the last years [1]-[3].

The development of unidirectional multilevel rectifiers started in 1996 with the structure called Vienna 1, proposed by Kolar [4]. The single phase bridge arm contains a single transistor that works on the entire cycle and six diodes. Following the principles given by this structure, several other structures were created that had double-boost effect, lower losses in the insulated gate bipolar transistor (IGBT) devices and the possibility to increase the maximum output

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power [5]-[7]. In [8] it was presented a comparison between several known three level and five level rectifiers and a new flying capacitor rectifier concept. The comparison was made regarding the total power losses and the total harmonic distortion factor. The main advantage of the new structure is its ability to withstand one permanent on-state failure without excessive voltage surge.

This paper presents two known three level rectifiers and a new structure. It is presented the operation method of these three structures and their performances shown both by simulation and by theoretical analysis. A power loss study for a STATCOM application will be presented.

The first presented structure was derived from the Neutral Point Clamped (NPC) converter, for which control strategies and advantages are described in [9]. The new structure is obtained from the Active Stacked NPC (ASNPC) converter whose characteristics are shown in [10].

2. Structures presentation

Rectifier structures that have an input voltage (u_i) with three or more voltage levels are obtained from the reversible multilevel converters. This is made after the elimination of some devices and leads to the reduction of the input filter.

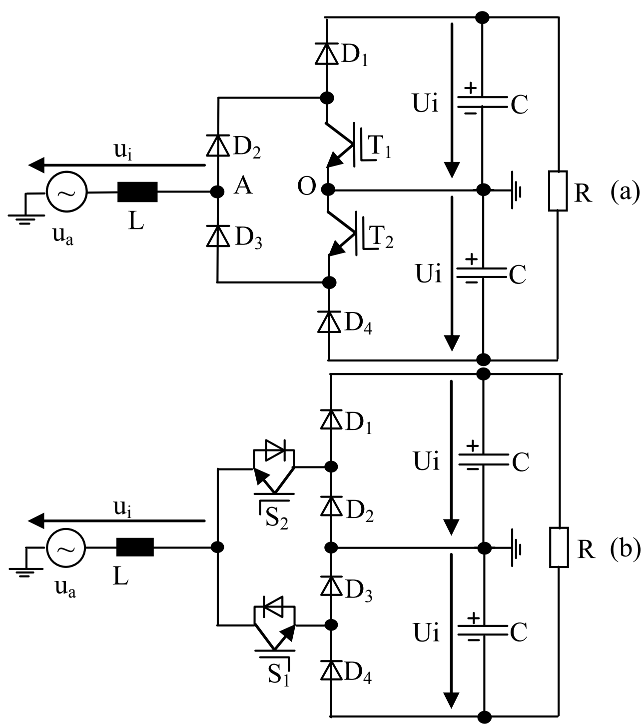

Fig. 1. Multilevel rectifiers: (a) Vienna 2; (b) NPC

Vienna 2 Rectifier

This structure is formed from two IGBT switches, T_1 and T_2, which form a commutation cell and four diodes, D_1, D_2, D_3 and D_4 (Fig. 1(a)). The two active switches have the purpose of charging the input inductivity, while the diodes have been used to transfer the energy from the input to the output capacitors and thus for making the alternative-continuous conversion.

To implement the PWM control there were used two carrier waves phase shifted by 180° compared with a sinusoidal reference wave (Fig. 2). The transistor T_1 is in conduction when the reference (α) is positive and greater than the carrier wave. When the reference is negative and smaller than the carrier wave, the T_2 transistor is on. While the mains voltage is positive and the T_1 switch is on, the energy increases through the coil. The current goes through the coil, the diode D_2 and the transistor T_1. While the T_1 switch is off, the current goes through the coil, the diodes D_1 and D_2, the upper capacitor and the load. When the main voltage is negative, the operation mode is similar and affects the transistor T_2, the diodes D_3 and D_4 and the lower capacitor.

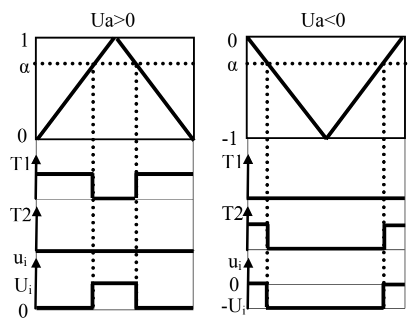

Fig. 2. PWM control for NPC and Vienna 2 rectifiers

This structure was implemented to improve the performances given by the Vienna 1 [5], by using two transistors that have the effect of reducing to half the conduction period and thus reducing the temperature stress of the two devices.

NPC Rectifier

This structure is made out of four diodes, D_1, D_2, D_3 and D_4, and two IGBT transistors with reverse diodes, S_1 and S_2 (Fig. 1(b)). The switches S_1 and S_2 are made from the transistor T_1 and the reversed diode D_{T1}, respectively from T_2 and D_{T2}. The multilevel NPC rectifier is obtained from the inverter structure with the same name. Similar to the previous structure, the transistors have the passive purpose of charging the filter inductivity, while the diodes have the active role of creating a path for the load current. The PWM control is the same as for the previous structure and the operation mode is the following: while the mains voltage is positive and the T_1 switch is on, the energy increases through the coil. The current goes through the coil, the transistor T_1 and the diode D_3. While the T_1 switch is off, the current goes through the coil, the reverse diode of S_2 (D_{T2}), the diode D_1, the upper capacitor and the load. When the main voltage is negative, the operation mode is similar and affects the transistor T_2, the reverse diode of S_1 (D_{T1}), the diodes D_2 and D_4 and the lower capacitor.

ASNPC Rectifier

By following the concepts given by the previous two structures and analyzing the converter structure 3L-ASNPC, results a new rectifier structure called ASNPC (Fig. 3).

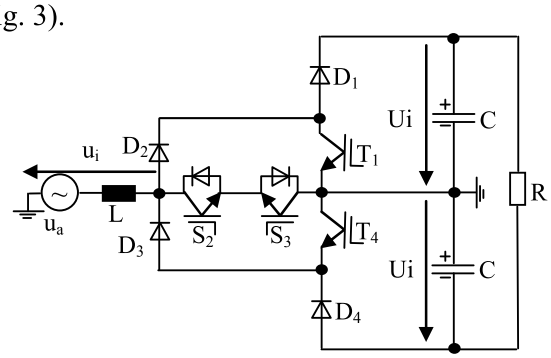

Fig. 3. ASNPC Rectifier

This structure is made out of two IGBT transistors with reverse diodes, S_2 and S_3, four diodes, D_1, D_2, D_3 and D_4, and two transistors, T_1 and T_4. The switches S_2 and S_3 are made from the transistor T_2 and the reversed diode D_{T2}, respectively from T_3 and D_{T3}.

The PWM control obtained by the comparison of two phase shifted carrier waves with a sinusoidal reference wave is presented (Fig. 4).

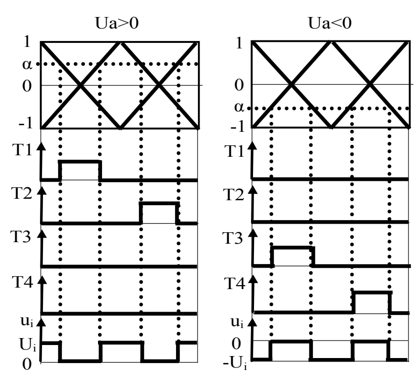

Fig. 4. PWM control for ASNPC rectifier

When the reference wave is positive, charging with magnetic energy the inductivity L is realized on two paths: through the transistor T_2 of S_2 and the reverse diode of S_3 (D_{T3}) or through the diode D_2 and the transistor T_1. The diodes D_1 and D_2 create the path for the load current. When the reference is negative, the path for the load current is given by the diodes D_3 and D_4. Because each device switches only a quarter of the total period, the total commutation power losses in the devices are smaller compared with the previous structures, leading to lower heat and greater maximum output power. Also by the PWM control it was obtained the doubling of the input voltage frequency leading to a smaller size for the filter inductivity. Reducing the inductivity leads to smaller current ripple and the increase in performances. The advantages of this structure are the existence of two paths for the input current and the balancing of the total power losses between the four transistors and six diodes. The power loss balancing will be shown in the following chapters. In comparison with the two level rectifiers, the NPC and Vienna 2 structures have the input filter reduced to half, while in the presented structure the filter is reduced four times by doubling the input voltage frequency.

In (Fig. 5) are presented the current through the active diodes D_1 and D_4 for a phase delay of 270° which describes a STATCOM application. It can be observed that each diode is in conduction on half a period and in commutation on a quarter of a period which leads to heat reduction and greater output power.

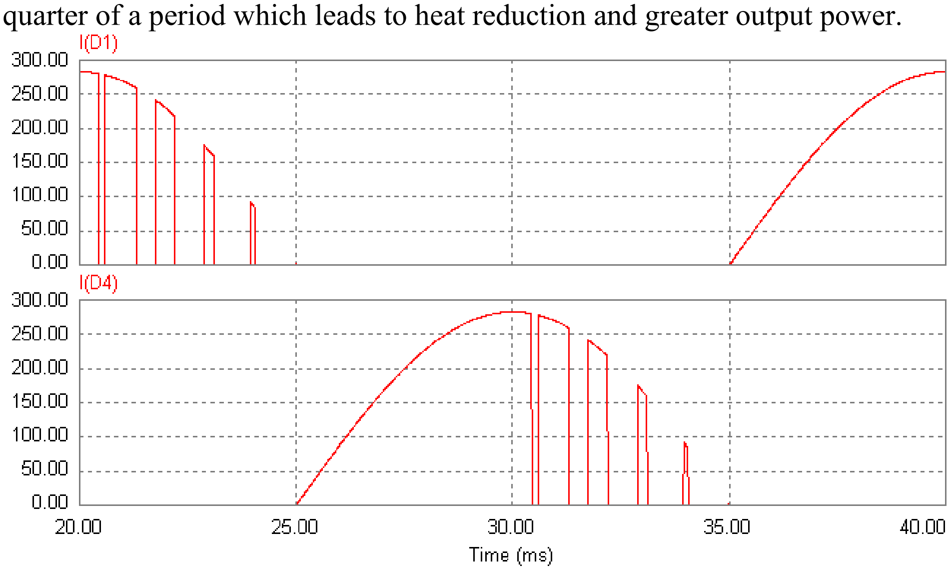

Fig. 5. Currents through diodes D_1 and D_4 from structure ASNPC

3. Method of estimating the power losses

The temperature of the power devices defines the maximum output power and is dependent to conduction and commutation power losses [11]. To know the maximum output power it is necessary to estimate the total power loss. This has been made by knowing the thermal and electrical parameters of each device. To make this calculus the following simplifying hypothesis were made:

- the input current is sinusoidal
- the dead time for the transistors is neglected

The total power losses, both in conduction and in commutation, represent the sum of the losses in transistors and diodes.

Conduction power loss

$$P_{TAV} = v_{T0} \cdot I_{TAV}^{T} + r_T \cdot I_{TRMS}^{2} \tag{1}$$

$$P_{DAV} = v_{T0} \cdot I_{FAV} + r_D \cdot I_{DRMS}^{2} \tag{2}$$

In equations (1) and (2), v_{T0}, r_{D0}, v_T, r_D are parameters for each device taken from the datasheet, while $I_{TAV}, I_{FAV}, I_{TRMS}, I_{DRMS}$ are the average and rms current through transistor T or diode D.

Commutation power loss

Commutation loss depends on the turning on energy, $E_{ON}(i_c)$, and turning off energy, $E_{OFF}(i_c)$. These are characteristics given in the catalog and are dependent on the switched voltage v_{sw} and switched current i_c. The total energy absorbed on a commutation period by a device represents the sum of these energies.

$$E_{vdef}(i_C) = E_{ON}(i_C) + E_{OFF}(i_C) \tag{3}$$

The equation (3) can be approximated by a parabola with constant coefficients, A, B, C which are obtained from the device characteristics. For a device that switches with the frequency f over a period of time Δ the following expression for the commutation power loss is resulted:

$$P = f \cdot \frac{v_{sw}}{v_{def}} \cdot (A \cdot \Delta + B \cdot I_{swAV} + C \cdot I_{swRMS}^{2}) \tag{4}$$

In (4) v_{def} is the maximum voltage supported by the device and is a datasheet value, Δ is the duty cycle, while I_{swAV}, I_{swRMS} are the average and rms commutation current for the used device. The expressions for the average and rms current depend on the rms value of the input current and are the following:

$$I_{AV} = \frac{1}{2 \cdot \pi} \cdot \int_{t1}^{t2} \sqrt{2} \cdot I \cdot \sin(x - \theta) \cdot f(x) \cdot dx \tag{5}$$

$$I_{RMS} = \sqrt{\frac{1}{2 \cdot \pi} \cdot \int_{t1}^{t2} (\sqrt{2} \cdot I \cdot \sin(x - \theta))^2 \cdot f(x) \cdot dx} \tag{6}$$

In (5) and (6), f(x) is the modulation function and is given by the dependency between the current that flows through the device in conduction and the reference wave. For these rectifier structures f(x) has a sinusoidal form and depends on the modulation index M.

In this paper the power losses were calculated taking into account the use of the power modules, IGBT EUPEC FF200R33KF2C having $v_{def} = 1800V$. The electrical parameters used were: I_i = 200A rms, U_i = 1250V rms, U_{DC} = 3000V, f_{sw} = 4000Hz. For the ASNPC rectifier, f_{sw} = 2000Hz.

4. Power calculus

Table I

Modulation functions and conduction period

Device	Conduction period			Modulation functions		
	Vienna 2	NPC	ASNPC	Vienna 2	NPC	ASNPC
D_1	$[0;\pi/2]$	$[0;\pi/2]$	$[0;\pi/2]$	$1-M\cdot\sin(x)$	$1-M\cdot\sin(x)$	$1-M\cdot\sin(x)$
	$[3\pi/2;2\pi]$	$[3\pi/2;2\pi]$	$[3\pi/2;2\pi]$	1	1	1
D_2	$[\pi/2;3\pi/2]$	$[\pi;3\pi/2]$	$[0;\pi/2]$	1	$M\cdot\sin(x)$	$1-\frac{M\cdot\sin(x)}{2}$
			$[3\pi/2;2\pi]$			1
D_3	$[\pi/2;3\pi/2]$	$[0;\pi/2]$	$[\pi;3\pi/2]$	1	$M\cdot\sin(x)$	$1+\frac{M\cdot\sin(x)}{2}$
			$[\pi/2;\pi]$			1
D_4	$[\pi;3\pi/2]$	$[\pi;3\pi/2]$	$[\pi;3\pi/2]$	$1+M\cdot\sin(x)$	$1+M\cdot\sin(x)$	$1+M\cdot\sin(x)$
	$[\pi/2;\pi]$	$[\pi/2;\pi]$	$[\pi/2;\pi]$	1	1	1
D_{T1}	—	$[\pi;3\pi/2]$	—	—	$1+M\cdot\sin(x)$	—
		$[\pi/2;\pi]$			1	
D_{T2}	—	$[0;\pi/2]$	$[\pi;3\pi/2]$	—	$1-M\cdot\sin(x)$	$\frac{M\cdot\sin(x)}{2}$
		$[3\pi/2;2\pi]$			1	
D_{T3}	—	—	$[0;\pi/2]$	—	—	$\frac{M\cdot\sin(x)}{2}$
T_1	$[0;\pi/2]$	$[0;\pi/2]$	$[0;\pi/2]$	$M\cdot\sin(x)$	$M\cdot\sin(x)$	$\frac{M\cdot\sin(x)}{2}$
T_2	$[\pi;3\pi/2]$	$[\pi;3\pi/2]$	$[0;\pi/2]$	$M\cdot\sin(x)$	$M\cdot\sin(x)$	$\frac{M\cdot\sin(x)}{2}$
T_3	—	—	$[\pi;3\pi/2]$	—	—	$\frac{M\cdot\sin(x)}{2}$
T_4	—	—	$[\pi;3\pi/2]$	—	—	$\frac{M\cdot\sin(x)}{2}$

The modulation functions and conduction intervals were presented for each device of the three structures (Table I). When the modulation function has the value one it means that device have only conduction losses.

The D_2 and D_3 device for the NPC structure, respectively the D_{T2} and D_{T3} for the ASNPC structure have no losses in commutation because they switch at zero voltage.

Table II

Total power loss for M=0.95

Structure	Conduction losses [W]	Commutation losses [W]	Total losses [W]
Vienna 2 NPC ASNPC	1125.2	1511.8	2637

Table III

Total power loss for M=0.05

Structure	Conduction losses [W]	Commutation losses [W]	Total losses [W]
Vienna 2 NPC ASNPC	1058.7	2015.7	3074.4

The repartition for the conduction and commutation losses in the ASNPC rectifier is presented for M=0.95 and M=0.05 (Fig. 6).

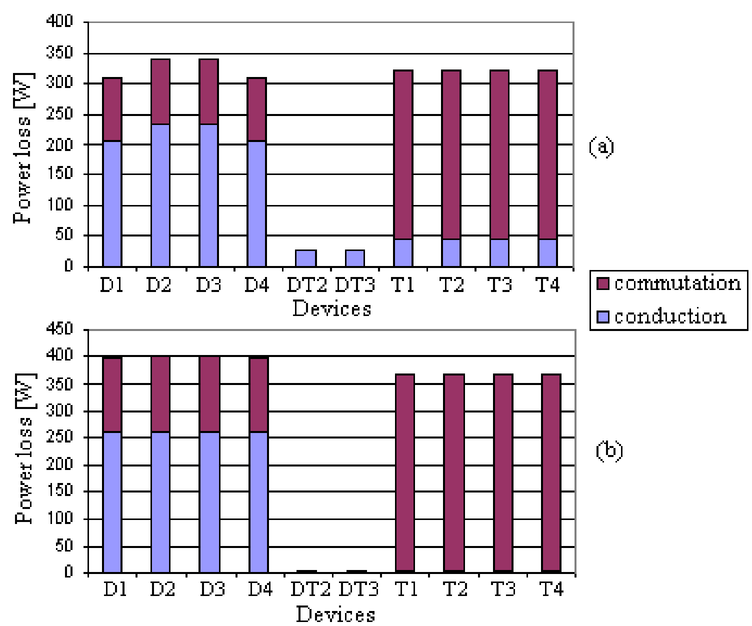

Fig. 6. Power losses repartition in the ASNPC rectifier: (a) M=0.95; (b) M=0.05

It can be seen that the total output power can be increased because the power losses have a better repartition. The conduction, commutation and total losses were presented for each structure, for two extreme modulation indexes, M=0.95 (Table I) and M=0.05 (Table II). It can be seen that all structures have the same conduction and commutation losses, the only difference being their repartition. The repartition for the conduction and commutation losses in the NPC and Vienna 2 rectifiers is presented for M=0.95 (Fig. 7). The transistors must support higher losses compared with the ASNPC rectifier.

A disadvantage of the new structure is represented by the increased number of devices.

The advantages of the new structure are the half reduction of the input inductivity and the possibility to increase the output power.

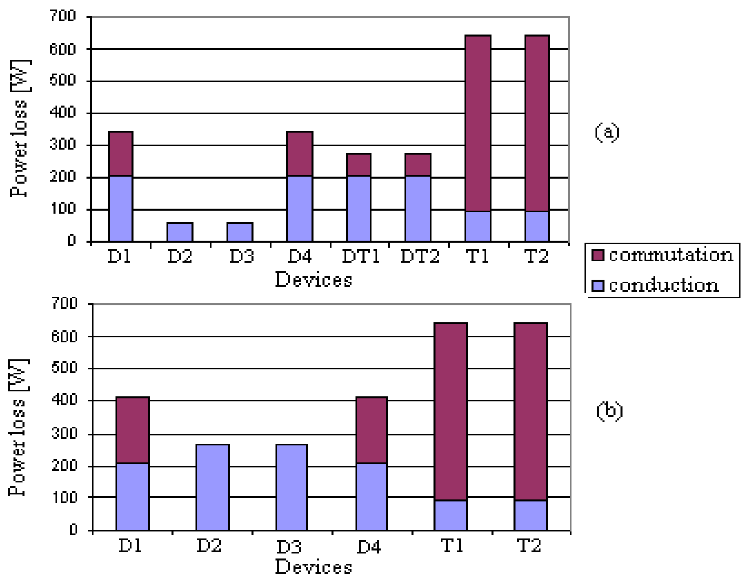

Fig. 7. Power losses repartition for modulation index M=0.95: (a) NPC; (b) Vienna 2

5. Conclusions

This paper has shown a theoretical and simulated analysis of the operation and performances for three alternative-continuous conversion structures. Theoretical loss calculations were presented for the used semiconductor devices. A new three level rectifier model was presented and compared with two known structures. The total conduction and commutation losses were described for the three structures. For the new model the power loss calculus was also made for each device at low and high modulation index and its advantages and disadvantages were shown.

Acknowledgment

The authors would like to thank the National University Research Council (CNCSIS) from Bucharest, Romania, for supporting this work under Project IDEI 75/01.10.2007 (ID_1037) and to the Sectoral Operational Programme Human Resources Development 2007-2013 of the Romanian Ministry of Labour, Family and Social Protection through the Financial Agreement POSDRU/88/1.5/S/60203..

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