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A new control method for the three level active neutral point clamped converter for low speed applications

***Abstract**. This paper presents a new control method for the Three-level Active Neutral Point Clamped (ANPC) converter. The advantages of this method are presented and a power loss analysis is made for an extreme modulation index. The results obtained are compared whit those obtained for two other control methods. Simulation and experimental results are presented in order to validate the theoretical studies made for this method.*

***Streszczenie.** Zaprezentowano nową metodę sterowania trzypoziomowym aktywnym przekształtnikiem typu ANPC. Wykazano zalety tej metody oraz oceniono straty mocy przy ekstremalnej wartości indeksu modulacji. Przestawiono też wyniki symulacji oraz rezultaty badań. (**Nowa metoda sterowania trzypoziomowym przekształtnikiem typu ANPC**)*

Keywords: NPC converter, ANPC converter, switching losses, conduction losses.
Słowa kluczowe: przekształtnik NPC, straty przełączania

Introduction

Multilevel conversion structures constitute a solution to improve the performances given by the classical structures with two voltage levels. For medium voltage applications, the cost of the semiconductor devices is increased. Multilevel structures offer a reduction of the voltage stress that compensates for the increased number of devices. Also this structures offer the advantage of reducing the size of the output filter by lowering the total harmonic content.

The development of these structures began with the solution given by Bhagwat in 1980 called Stack Cell Converter (SC) [1]. This solution gave a reduction to half of the voltage stress in the semiconductor devices but had the disadvantage of an unequal loss distribution that represented a limitation to the maximum output power that could be achieved.

In order to solve this problem, several multilevel structures were developed. Among them the most utilized in industrial applications is the Neutral Point Clamped Converter (NPC) because of the low number of devices used comparative with the other structures [2, 3].

This structure has a wide industrial spread mostly in medium voltage applications in the range 2kV-8kV. The main disadvantage of this converter is the operation at small modulation index (M) when the devices must cope with various thermal stresses. This structure was followed by the Active Neutral Point Clamped Converter (ANPC) developed by Bruckner in 2001. It presents the advantage of an increased number of degrees of freedom [4]. This advantage leads to the possibility to use more control methods [5, 6, 7]. These methods differs by the performances given and were compared from the point of view of the losses in the semiconductor devices [8, 9].

This paper presents a comparative study between the losses obtained for the NPC structures and those for two control methods for the ANPC structure. Also one of the controlled methods is proposed for the first time in this article and presents the advantage of increased performances at low modulation index. Simulation and experimental results will be presented in order to validate the theoretical studies performed for this new control method.

Power loss estimating method

The temperature of the power devices defines the maximum output power and is dependent to conduction and commutation power losses [9]. 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 output 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

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

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

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.

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

The equation (3) can be approximated by a parabola with constant coefficients, A, B, C which are obtained from the device characteristics [8]. 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:

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

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 output current and are the following:

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

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

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 the converters structures presented in this article, f(x) has a sinusoidal form and depends on the modulation index M.

Three-level NPC Converter

This structure is made from four Insulated Gate Bipolar Transistor (IGBT) modules and two clamped diodes (Fig. 1). The transistors are complementary controlled: S_1-S_{1C}, S_2-S_{2C}. Every switch S is made from a transistor T and a reversed diode D.

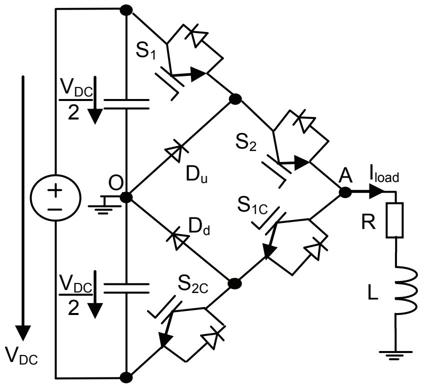

Fig. 1. Three-level NPC Converter

The control is made by comparing a sinusoidal reference wave Sr with two triangular carry waves S_{p1} and S_{p2} phase shifted on the y-axis (Fig. 2).

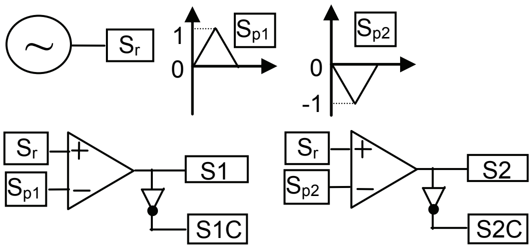

Fig. 2. PWM Control for the NPC converter

The main disadvantage of this structure is the presence of a single zero stage that leads to an unequal loss distribution. For this reason it is presented a power loss analysis at a small modulation index for the structure working as an inverter. This is the critical operating point for this structure (Fig. 3).

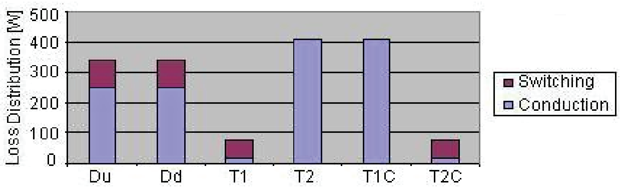

Fig. 3. Simulated distribution of losses for NPC using FF200R33KF2C IGBT devices (V_{DC}=3000V, I_{RMS}=200A, f_{sw}=1000Hz) at M=0.05.

Three-level ANPC Converter

This structure is made from six IGBT modules that create three switching cells: S_1-S_{1C}, S_2-S_{2C} and S_3-S_{3C} (Fig. 4).

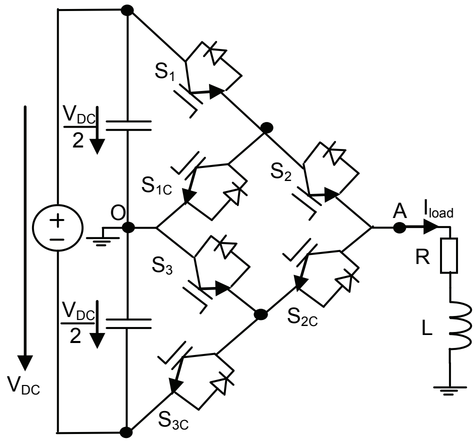

Fig. 4. Three-level ANPC Converter

In this chapter is presented two PWM control methods that lead to a different power loss distribution in the semiconductor devices. A similar comparison was made in [10], but at a low modulation index the presented structures worked as rectifiers. In that article the total amount of power losses was the same for each structure and control method because at any given time there were in conduction exactly two devices. This new control method creates two parallel current paths that leads to a reduction of the total power loss and therefore to an increase in efficiency.

1) Strategy PWM-1

This control method was presented in [8]. The reference wave S_r is compared with two triangular carrier waves phase shifted by half a switching cycle (Fig. 5). Following this comparison results four switching states: P ($V_{DC}/2$ voltage level), O_1 and O_2 (zero voltage level) and N ($-V_{DC}/2$ voltage level). To obtain the P state must be in conduction the devices S_1, S_2 and S_3, while for the N state the S_{1C}, S_{2C} and S_{3C} must be on.

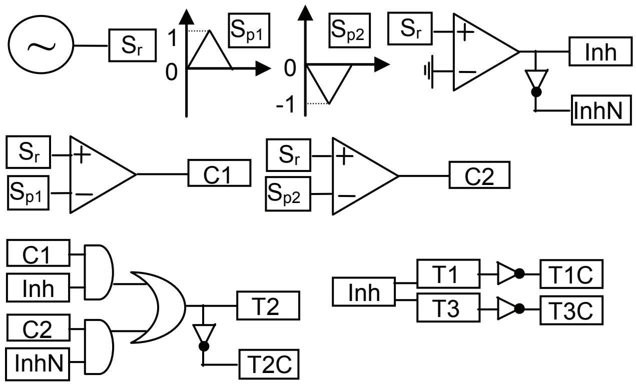

Fig. 5. PWM1 Control for the ANPC converter

The power loss distribution is given by the zero states O_1 and O_2. In Fig. 6 is presented the power loss distribution considering that the ANPC structure works as an inverter.

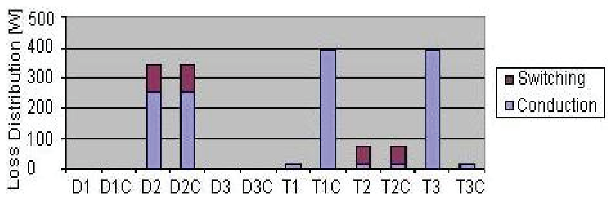

Fig. 6. Simulated distribution of losses for PWM 1 using FF200R33KF2C IGBT devices (V_{DC}=3000V, I_{RMS}=200A, f_{sw}=1000Hz) at M=0.05.

The most stressed devices are T_{1C} and T_3 which have only conduction losses because they switch at zero voltage. These devices limit the maximum output power level. To compensate this drawback it is necessary for each device to have similar power losses.

For this reason a new control method is proposed in this article, called PWM-2.

2) Proposed PWM-2 strategy

This is a new control method that has the effect of dividing the current taken by the devices S_{1C} and S_3 by creating two parallel current paths for the zero voltage switching states.

The sinusoidal reference wave S_r is rectified and compared with a triangular carrier wave S_p (Fig. 7). Following the comparison process, results four switching states: P, O_1, O_2 and N. To obtain the O_1 state (zero voltage level when the reference wave in positive), S_{1C}, S_2 and S_3 must be on, while for the O_2 state (zero voltage level when the reference wave is negative) the S_{1C}, S_{2C} and S_3 must be on.

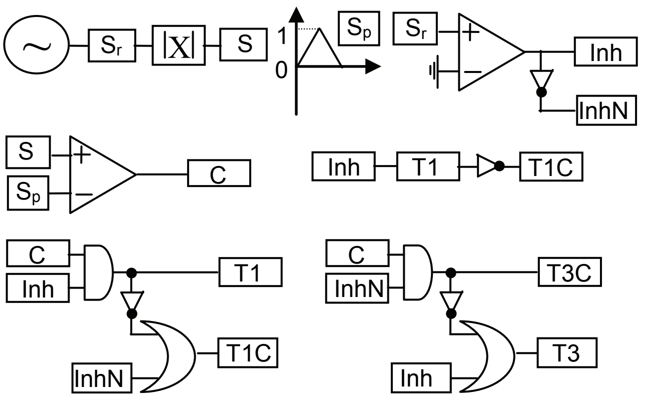

Fig. 7. PWM-2 Control for the ANPC converter

To describe this control method, in Table 1 are presented the moments when each device is in conduction.

Table 1. Switching sequences of ANPC PWM-2

Output Voltage (V_{AO})	Switching State	Switch Sequence					
		S_1	S_{1C}	S_2	S_{2C}	S_3	S_{3C}
$V_{DC}/2$	P	1	0	1	0	1	0
0	O_1	0	1	1	0	1	0
	O_2	0	1	0	1	1	0
$-V_{DC}/2$	N	0	1	0	1	0	1

To show the advantages of this control method, simulation waveforms are presented for the output voltage, the current through different devices and the voltage taken by the T_2 device (Fig. 8).

The resulted load current has a rms value of 200A while the current through the devices T_1 and T_{3C} has a value of 100A, which leads to the reduction of the current for this devices and therefore to the reduction of the total power losses. The T_2 transistor has only conduction losses because it is in conduction at zero voltage.

Fig. 9 shows the power loss distribution for the ANPC converter working as an inverter controlled with the PWM-2 strategy. As it can be seen the power loss levels are reduced and are better distributed among the power semiconductors. The T_1 and T_{3C} transistors have the lowest power losses, while the T_2 and T_{2C} devices support the greatest conduction currents. The power losses for the T_{1C} and T_3 transistors are reduced with 173.4% compared with the PWM-1 control strategy, while for D_2 and D_{2C} the losses are reduced with 161.5%.

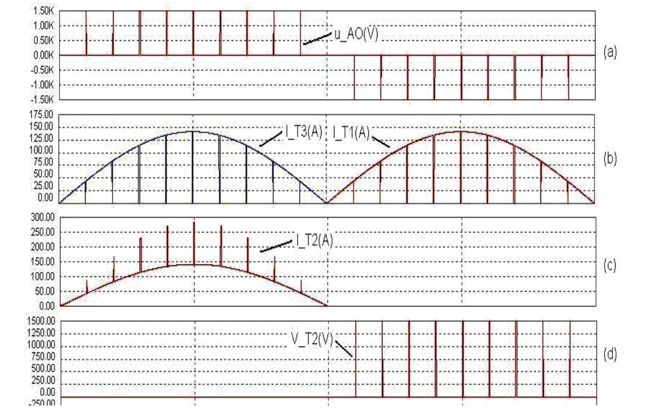

Fig. 8. Simulated wave forms for PWM-2 (M=0.05, V_{DC}=3000V, I_{RMS}=200A): (a) output voltage; (b) current through T_{1C} and T_3 devices; (c) current through T_2 device; (d) switched voltage by device T_2.

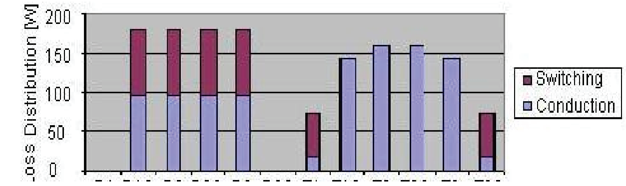

Fig. 9. Simulated distribution of losses for PWM-2 using FF200R33KF2C IGBT devices (V_{DC}=3000V, I_{RMS}=200A, f_{sw}=1000Hz) at M=0.05.

On the O_1 switching state, the load current flows through the following devices: D_{1C}--T_2 and T_3--D_{2C} forming two parallel current paths. Similar on the O_2 switching state the following devices creates the parallel paths: D_2--T_{1C} and T_{2C}—D_3. For the NPC and ANPC with PWM-1 there were exactly two devices in conduction on any switching state. Because of this reason, for the PWM-2 control method the total losses obtained are different than for the other control methods presented.

Table 2 depicts the values for the total power losses, in conduction and in commutation for the three control methods.

Table 2. Total power losses (FF200R33KF2C IGBT devices (V_{DC}=3000V, I_{RMS}=200A, f_{sw}=1000Hz) at M=0.05

	Conduction [W]	Switching [W]	Total [W]
NPC	1358.2	302	1660.2
PWM-1	1358.2	302	1660.2
PWM-2	1029.2	447.8	1477

As it can be seen the proposed method leads to smaller total losses and to increased efficiency.

An important parameter of the power conversion is its efficiency (7).

$$\eta = \frac{P-(P_{CON}+P_{SW})}{P}\times 100 \ [\%] \quad (7)$$

In this equation, η=efficiency, P=total active power, P_{CON}=conduction losses, P_{SW}=switching losses.

The smallest efficiency value appears at the critical modulation index point, at M=0.05 where the power loss distribution were presented for the three control methods (Fig. 10). When the modulation index is almost one, the conversion efficiency is 99%.

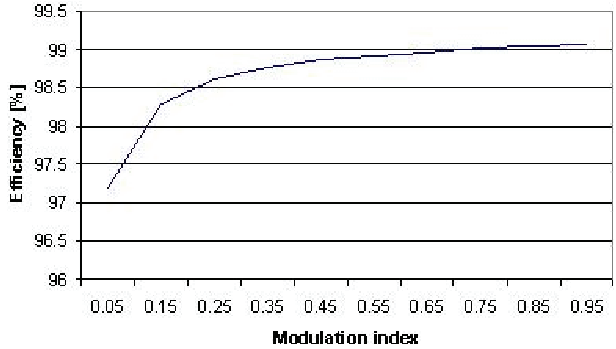

Fig. 10. Efficiency for PWM 2 using FF200R33KF2C IGBT devices (V_{DC}=3000V, I_{RMS}=200A, f_{sw}=1000Hz)

Another important parameter of power conversion is the total harmonic distortion factor (THD) described in (8), (9).

$$THD = \frac{\sqrt{\sum_{n=3}^{\infty} V_n^2}}{V_1} \tag{8}$$

$$\sum V_n^2 = V_{RMS}^2 - V_1^2 \tag{9}$$

In these equations, THD=total harmonic distortion, V_1=rms value of the first harmonic, V_n=rms value of the n-order harmonic, V_{RMS}=total RMS value of the waveform.

Using these equations and the results obtained by simulation, results the dependency of THD and the modulatuion index M (Fig. 10). The total harmonic content results for a small modulation index.

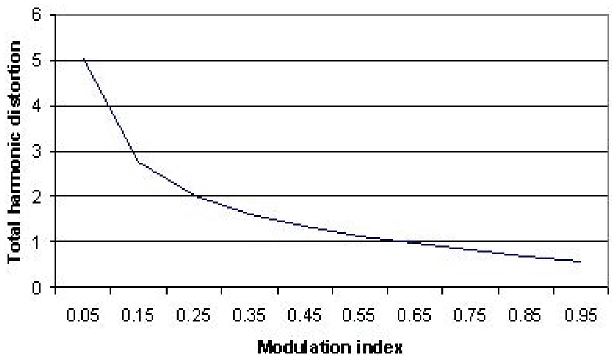

Fig. 10. Total harmonic distortion for PWM 2 using FF200R33KF2C IGBT devices (V_{DC}=3000V, I_{RMS}=200A, f_{sw}=1000Hz)

In order to validate the proposed control method, an experimental bench was developed, having a RL load with the value of 10Ω+4mH connected between A and O (Fig. 11).

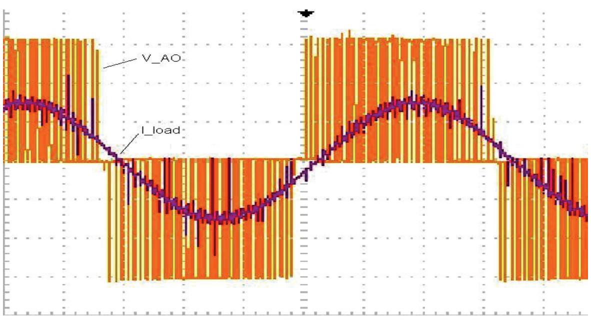

Fig. 11. Experimental results for PWM-2: Output voltage, V_AO (50V/div) and load current, i_load (2A/div).

Conclusions

In this paper the NPC and ANPC structures were presented. All the analysis presented was made with the PSIM simulation environment. For the NPC structure, the power loss analysis was presented at a low modulation index and the result was an unbalanced loss distribution that leads to a limitation of the maximum output power level.

For the ANPC converter, two control methods were presented. For both methods, the power loss distribution was given at the critical modulation index considering that the ANPC converter was working as an inverter.

The PWM-2 control method was described for the first time in this article and presents the following advantages:

- a better loss distribution
- reduces power losses in conduction
- increased efficiency
- divided current in the middle devices
- increased maximum output power

In order to show the performances of the new control method, the dependencies of the total harmonic distortion factor and of the efficiency with respect to the modulation index were presented.

This control method provides better results at a small modulation index and it is best suited for low speed industrial applications.

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