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A NEW COUPLED INDUCTOR MULTILEVEL AC CHOPPER

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The use of thyristors-based AC-AC converters present several disadvantages like non-sinusoidal output voltage and increased harmonic content on the input side. A solution to these problems is offered by AC choppers made with IGBT modules. Amongst the advantages offered by these converters are: increased efficiency, sinusoidal input and output currents, smaller input/output filters. In this paper is proposed a new solution capable of reducing the switched current by using two parallel choppers. In addition, the proposed structure is generalized for any number of voltage levels.

Keywords: AC choppers, coupled inductor, multilevel converters

1. Introduction

Due to the increase of industrial non-linear loads, AC-AC converters found a large use. Initially classical phase-controlled thyristors-based solutions were largely utilized. The reasons for creating new improved direct AC converters are: the absorbed current with high amplitude of low harmonics which restrict the use of passive filters, the reactive power absorbed by these converters is dependent on the control angle and passive elements are expensive. Furthermore, these solutions present electromagnetic compatibility issues [1].

Two-level pulse width modulation (PWM) AC chopper which use power semiconductor devices represent a valid alternative to the old solutions due to an important array of advantages: increased overall efficiency, no need of a dc intermediary circuit, input current and output voltage are almost sinusoidal and easy to filter [2]-[6].

The output voltage is obtained similar to classical dc-dc choppers having a constant duty cycle; thus, the control methods are simple and easy to implement.

The next step towards a flexible direct AC chopper is obtaining the ability to increase the output current / voltage and apparent frequency without using high current / voltage power devices that are expensive and bulky. In order to achieve this goal, multilevel AC-AC converters were proposed during the past years [7]-

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[11]. In [11] a flying capacitor multilevel AC chopper was introduced. It was made from several non-differential choppers connected by capacitors in order to enhance the output voltage without using high cost power devices. The main drawback of this class of AC choppers is the need to work at high switching frequencies otherwise the intermediary capacitor would have a significant size.

This paper presents a new class of AC choppers that use the concept of coupled inductors to increase the number of voltage levels at the output. In the second section of this paper, the basic AC choppers are described together with their main properties and control methods. In the third section, a new improved AC-AC direct converter is proposed for the first time and named Three-Level Parallel PWM AC Converter (3L-PPAC). The advantages of the proposed converter are the reduction of the switched current through the power devices and the increase of the apparent switching frequency. A calculation of the input and output filters for this converter is provided. In the fourth section, the N-level generalization of the proposed converter is provided together with the defining equations. Finally, conclusions about the merits of the new converter are presented.

2. Basic two-level AC choppers

Two types of two level (2L) AC choppers are commonly in use and are dependent on the supply mode: differential alternative chopper (2L-ADC) and non-differential alternative chopper (2L-NADC) topologies (Fig.1).

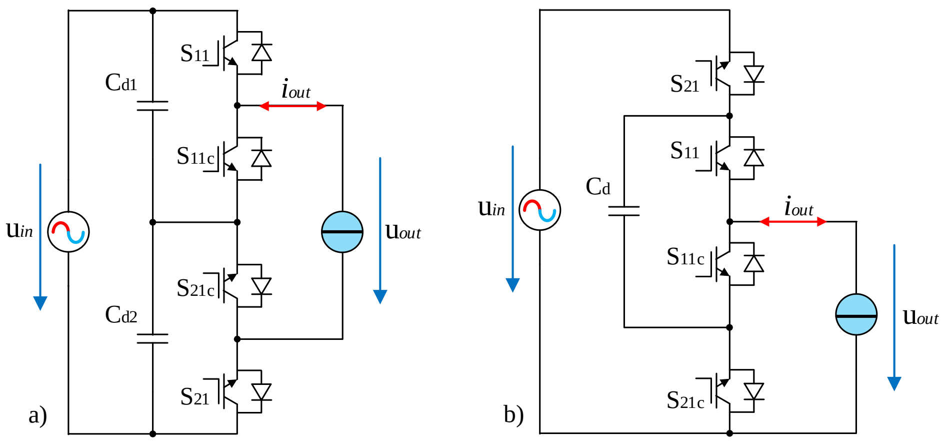

Fig.1. 2L AC-AC Choppers: (a) Differential chopper; (b) Non-differential chopper.

IGBT power switching devices are used together with simple DC snubbers attached to the switching cells in order to absorb the energy stored in the line stray inductance. The non-differential structure presents the advantage of neutral wire continuity, while the differential mode is used in three phase systems. The control method is the same for both converters and depends on the sign of the input voltage (u_{in}). If u_{in} is positive, two power devices have a PWM control with a constant duty cycle (α), while the other devices are always on.

When u_{in} is negative, the other two devices are PWM controlled while the first ones are turned on. The output voltage is obtained by the same law as in DC choppers (1).

$$U_{out} = \alpha \cdot U_{in} \tag{1}$$

where: α is the duty cycle, U_{out} is the rms voltage of the output voltage, while U_{in} is the rms voltage of the input voltage. The 2L AC-AC chopper present three working modes: active, freewheeling and bypass.

During the active mode, the output current i_{out} flows through both the input and output sides and provides output energy. The S_{11} and S_{21} switches are turned on and the current i_{out} conducts through S_{11} and the diode of the device S_{21} when the current is positive or S_{21} and the diode of S_{11} for the negative current.

The freewheeling mode is complementary to the active mode. The switches S_{11C} and S_{21C} are turned on so that the output current freewheels through the load.

The bypass mode is imposed by the non-linear regime of power devices.

In the next section, the main features of the new converter will be presented.

3. Proposed multi-level AC-AC converter

A solution to increase the power delivered to the load by an AC-AC PWM controlled converter can be done by paralleling multiple AC choppers connected by magnetically coupled inductors.

The proposed Three-Level Parallel PWM AC Chopper (3L-PPAC) is made of eight IGBT power devices and a coupled inductor. Each group of four devices forms a non-differential alternative chopper (Fig.2). The structure can be generalized for any number of voltage levels by adding NADC cells interconnected by coupled inductors.

The control of the new structure is made using two carrier waves instead of one in the case of the 2L-NADC. The carrier wave c_2 for the additional chopper is phase delayed with half of the period (T_{sw}) (Fig.3). When the input voltage is positive, the S_{11}, S_{11c}, S_{21} and S_{21c} power devices are PWM controlled with a constant duty cycle, while S_{12}, S_{12c}, S_{22} and S_{22c} are in conduction. For the negative input voltage, the S_{11}, S_{11c}, S_{21} and S_{21c} devices are on, while S_{12}, S_{12c}, S_{22} and S_{22c} are PWM controlled. For a half network cycle, there are always four power devices that have no commutations, thus the switching losses are considerably reduced.

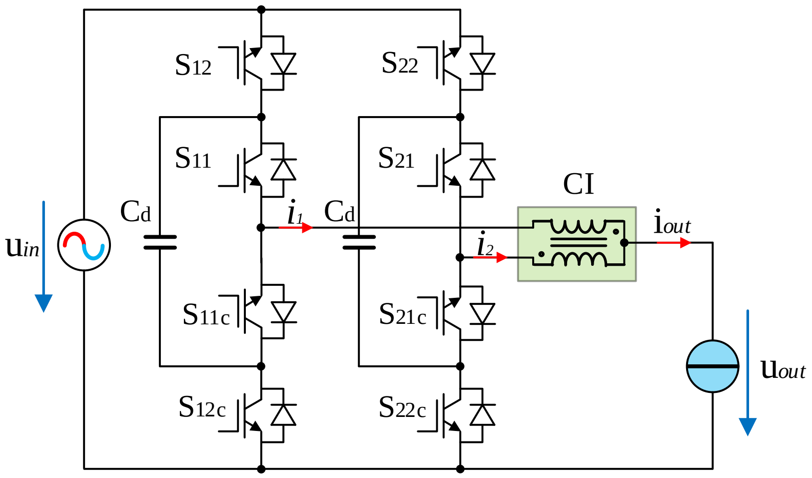

Fig.2. Parallel PWM AC Chopper.

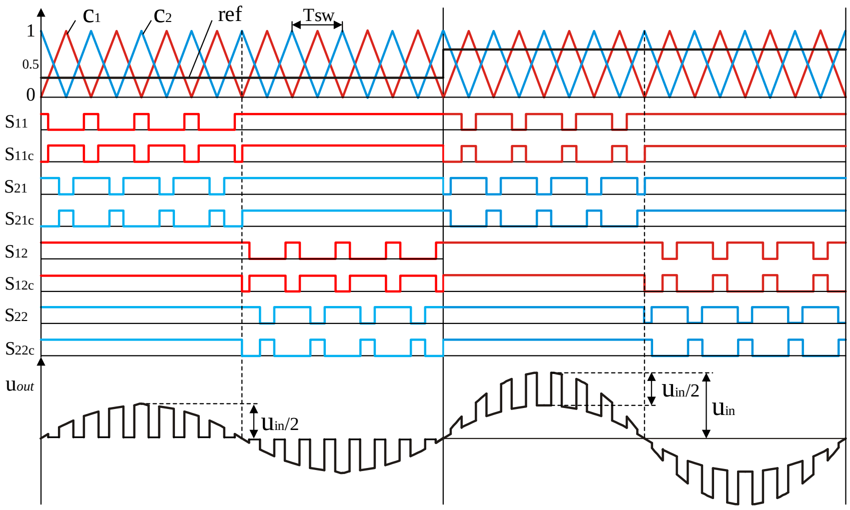

Fig.3. PWM control of 3L-PPAC converter.

When the duty cycle is lower than 0.5, the output voltage presents the 0, and $u_{in}/2$ voltage levels. When the duty cycle is larger than 0.5 the $u_{in}/2$ and u_{in} voltage levels are obtained (Table 1). Depending on the input voltage sign, two equivalent circuits are obtained (Fig.4).

Table 1

Switching states of the proposed converter

	S_{11}	S_{11c}	S_{21}	S_{21c}	S_{12}	S_{12c}	S_{22}	S_{22c}	Output voltage	
									$\alpha < 0.5$	$\alpha > 0.5$
$u_{in} > 0$	1	0	1	1	0	1	1	1	$u_{in}/2$	$u_{in}/2$
	0	1	1	1	0	1	1	1	0	-
	0	1	1	1	1	0	1	1	$u_{in}/2$	$u_{in}/2$
	1	0	1	1	1	0	1	1	-	u_{in}

$u_{in} < 0$	1	1	1	0	1	1	0	1	$u_{in}/2$	$u_{in}/2$
	1	1	0	1	1	1	0	1	0	-
	1	1	0	1	1	1	1	0	$u_{in}/2$	$u_{in}/2$
	1	1	1	0	1	1	1	0	-	u_{in}

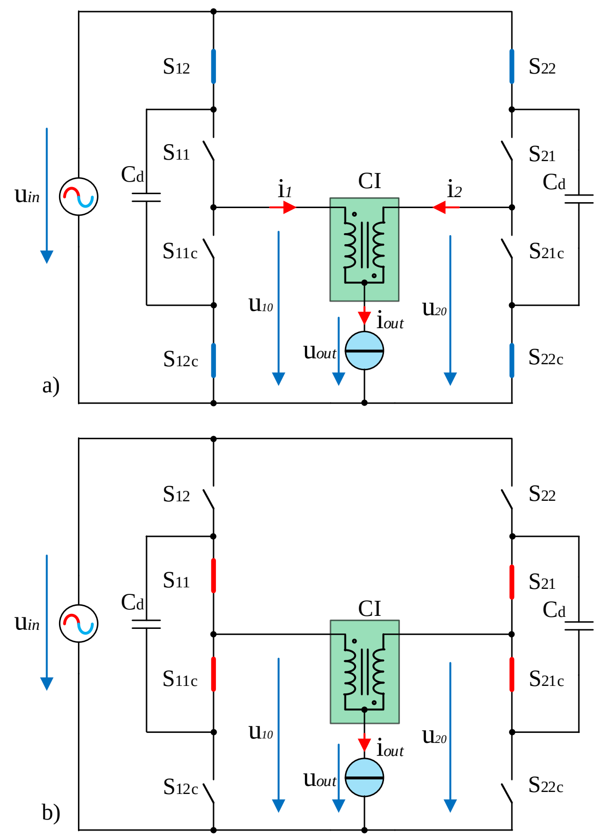

Fig.4. Equivalent magnetic circuit of proposed 3L-PPAC chopper:
(a) Positive input voltage ($u_{in} > 0$); (b) Negative input voltage ($u_{in} < 0$).

For $u_{in} > 0$ the devices S_{12}, S_{12c}, S_{22}, and S_{22c} are turned on and the other four devices are PWM controlled. The voltage applied to the parallel commutation cells, u_{10} and u_{20}, is positive and half of the input voltage (2). When $u_{in} < 0$ the devices S_{11}, S_{11c}, S_{21}, S_{21c} are turned on and the remaining devices are PWM controlled. The voltage applied to the parallel commutation cells is negative and half of the input voltage.

By analyzing the ideal equivalent magnetic structures, it can be observed that the relation between the output voltage and the voltage of the parallel commutation cells at any given time is:

$$u_{out} = \frac{u_{10} + u_{20}}{2} \tag{2}$$

In order to obtain a reduced harmonic content for the input and output waveforms, passive filters are needed for this converter (Fig.5).

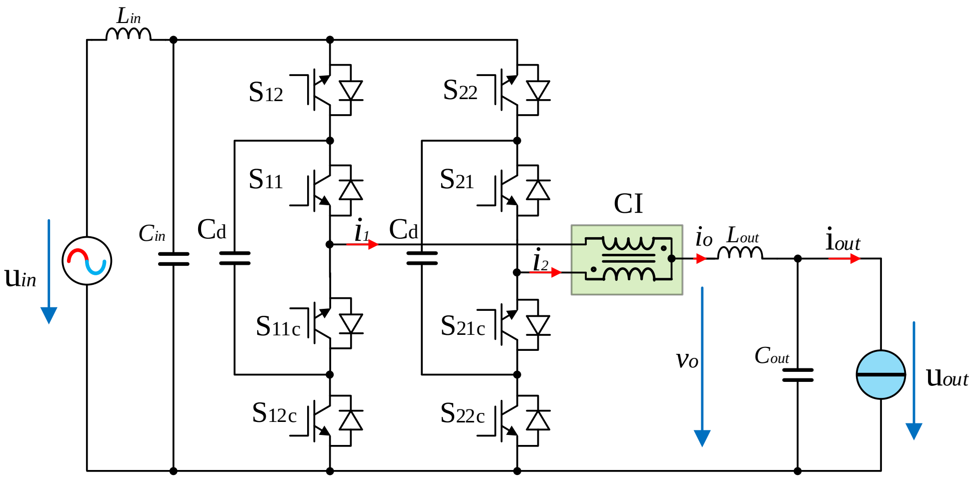

Fig.5. Proposed 3L-PPAC converter with input and output filters.

The input and output filters are obtained by using the same set of equations. A computation example for the output filter is provided (3)-(6). The output inductance L_{out} is dependant of the maximum output current ripple Δi_{out}^{max} (3).

$$L_{out} = \frac{U_{in}}{16 \cdot f_{sw} \cdot \Delta i_{out}^{max}} \tag{3}$$

where: f_{sw} is the switching frequency of the power devices and U_{in} is the input voltage.

The C_{out} capacitor is computed so that all harmonics lower than the cutting frequency (f_n) will pass (4). Harmonics larger than f_n will be attenuated by the factor X (5). In (4), ω_n is the angular frequency.

$$\omega_n = 2\pi f_n \tag{4}$$

$$X = \left(\frac{f_{sw}}{f_n}\right)^2 \tag{5}$$

The relation between the cutting frequency and the filter components is:

$$f_n = \frac{1}{2\pi\sqrt{L_{out}C_{out}}} \tag{6}$$

In order to prove the merits of the new converter, simulations results are provided using the PSIM 6.0 software (Fig.6). At the initial duty cycle of 0.3 the output voltage presents the low voltage levels (0, $u_{in}/2$). After a network period it is increased to 0.7 in order to obtain the superior voltage levels ($u_{in}/2$, u_{in}).

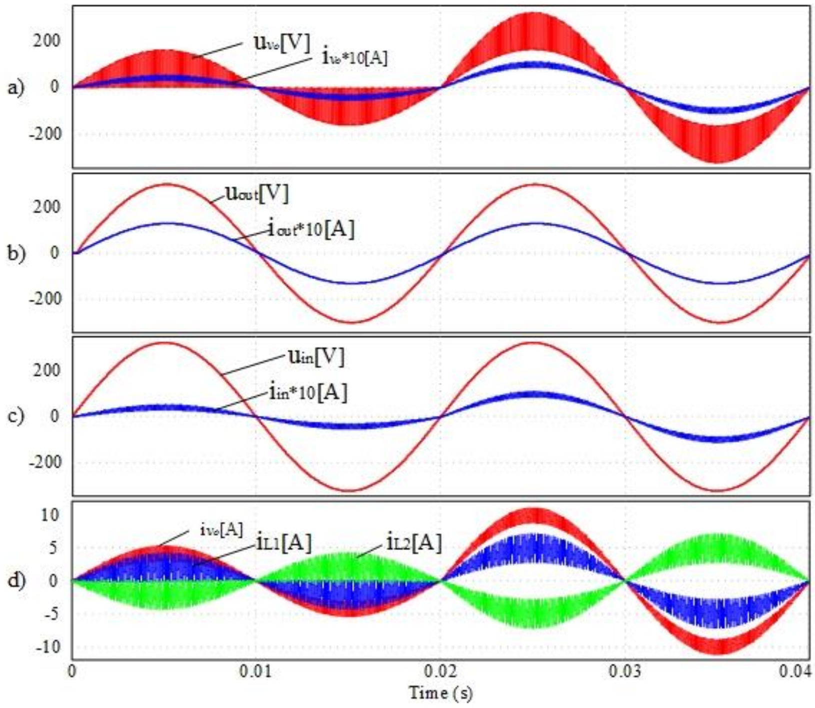

Fig.6. Simulation results for 3L-PPAC converter:
a) Output voltage u_0 and current i_0 before filter; b) Output voltage u_{out} and current i_{out} after filter; c) Input voltage u_{in} and current i_{in} before filter; d) i_0 and current in CI i_{L1} and i_{L2}.

The following set of parameters was used for the simulation model.
Input voltage $U_{in} = 230$ V
Output current $I_{out} = 10$ A
Duty cycle $\alpha = 0.93$
Output load 23 Ω + 1 mH
Decoupling capacitors $C_d = 100$ nF
Coupled inductor CI = 1 mH
Switching frequency $f_{sw} = 8$ kHz
Using the relations in (3)-(6), the filter values are provided.
$L_{in} = 1.8$ mH; $C_{in} = 5.54$ µF; $L_{out} = 1.67$ mH; $C_{out} = 5.97$ µF

The reduced harmonic content of the output waveforms after the filter can be observed (Fig.6b). The filter L_{in}, C_{in} is used in order to obtain a sinusoidal input current. The current through the coupled inductor is half of the output current (Fig.6d), a fact that allows the use of lower current devices compared to classical AC choppers.

4. Generalized structure

In order to increase the output current without using high current power devices, the number of voltage levels of the proposed Three Level Parallel PWM AC Chopper can be increased by adding NADC cells and coupled inductors. Thus the structure is generalized and named NL-PPAC Chopper (Fig.7).

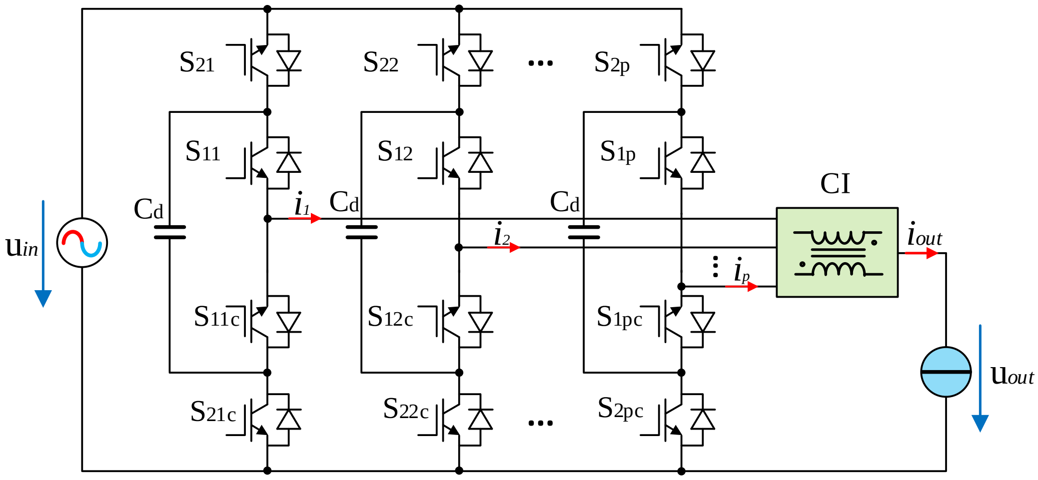

Fig.7. Generalized NL-PPAC converter.

By using this parallelization method that was first described in [10], each active device switches only a fraction of the output current, thus low current power devices can be used (7).

$$i_k = \frac{I_{out}}{p}, k = 1,2,\ldots, p \tag{7}$$

where p is the number of interconnected choppers and I_{out} is the rms value of the output current.

The resulting number of voltage levels (N) depends on the number of parallel non-differential choppers (8).

$$N = p + 1, p \geq 1 \tag{8}$$

The increase of the number of voltage levels leads to increasing the apparent output frequency (f_{ap}) compared to the switching frequency of the power devices (9). Thus, the switching losses in the active devices are reduced compared to using a lower number of parallel arms.

$$f_{ap} = p \cdot f_{sw} \tag{9}$$

The control is made using the phase shifted PWM strategy, where the phase delay between two consecutive carriers is equal to the switching period divided by the number of parallel choppers (Fig.8).

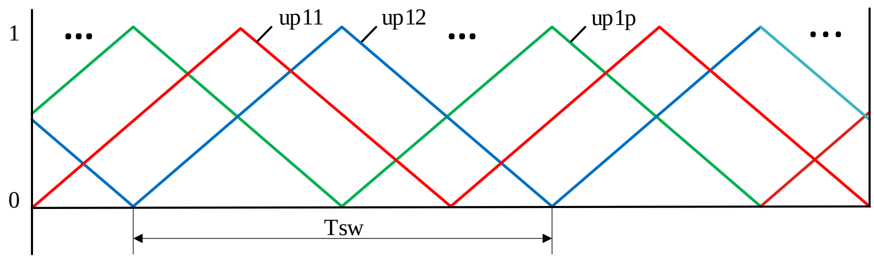

Fig.8. Carrier waves for the generalized structure.

5. Conclusions

In this paper a new structure of alternative-alternative converter, the Three-Level Parallel PWM AC Chopper was presented. The main features of the new converter are:

- the reduction of the switched current through the power devices
- the increase of the output voltage apparent switching frequency
- reduced switching losses

The novelty of the new concept consists in the use of coupled inductors to make a parallel connection between two 2L-NADC choppers.

The main drawback of this AC chopper is the need to work at a high switching frequency otherwise the coupled inductor would have a significant size

The proposed structure has been generalized for any number of voltage levels by adding non-differential alternative choppers and coupled inductors.

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