PWM AC CHOPPERS: BASIC TOPOLOGIES AND APPLICATIONS

D. FLORICĂU*

In această lucrare sunt prezentate principiile de funcţionare pentru câteva structuri elementare de choppere de tensiune alternativă. Datorită avantajelor lor, acestea pot fi utilizate într-un număr mare de aplicaţii industriale. Sunt prezentate două tipuri de aplicaţii. Prima aplicaţie o reprezintă stabilizatoarele moderne de tensiune obţinute prin asocierea structurilor elementare cu transformatoare serie. Sunt prezentate compensatoare de tip coborâtor, ridicător, precum si cele de tip coborâtor-ridicător. A doua aplicaţie propune un cicloconvertor nou obţinut prin cascadarea chopperelor de tensiune alternativă elementare. Acesta este comandat pe principiul DPWM şi nu prezintă probleme de comutaţie.

In this paper the operation principles for some basic PWM AC choppers are presented. Due to their advantages, they can be used in a lot of industrial applications. Two types of applications are presented. The first one is represented by modern line conditioners, obtained by associating basic structures with serial transformers. They are presented buck, boost and the buck-boost compensators. The second application proposes a new type of cycloconverter made by cascaded basic PWM AC choppers. It is DPWM controlled and has not commutation problems.

Keywords: AC-AC converter, AC chopper, line conditioner, cycloconverter.

Introduction

AC voltage regulators have been widely used in applications such as industrial heating, line conditioners, lighting dimmers, soft-starting of induction motors and speed control of pumps. To realize the regulation, phase control technique is extensively utilized. This technique has the advantages of simplicity in main & control circuit, but suffers from poor power factor, high low order harmonic content in both of load and supply side. Bulk filters are essential and discontinuity of power flow is inevitable at both input and output sides. The AC voltage regulators can be replaced by pulse width modulation (PWM) AC choppers, which have better performances. In this case, the input voltage is

* Prof., Dept. of Electrical Measurements, Electrical Apparatus and Static Converters, University "Politehnica" of Bucharest, Romania

chopped into segments and the output voltage level is decided by controlling the duty cycle of the chopper switching function.

The AC choppers made by four segments switches were delayed due to the commutation problems [1]. To assure safe commutation without high voltage spikes, some PWM control principles were developed [2]-[3]. However, converters robustness depended on the control accuracy and kept high the risk of overvoltages and overcurrents appearance. Recently, different AC choppers topologies using a reduced number of switches [4]-[5] or standard commutation cells in two quadrants were developed [6]. To increase the converters robustness simple DC snubbers consisting of only a capacitor attached directly to commutation cells were proposed [7]-[16].

In this paper some basic topologies of direct and indirect PWM AC choppers are comparatively studied. Being different from the direct AC-AC conversion, the indirect one can produce a fast reversible phase of input voltage. This paper presents modern line conditioners with voltage up, down and up/down capability. They are based on serial compensation principle and use basic AC choppers. The progress realized in controlled power devices design and achievement allowed the appearance of so-called matrix converters made by four quadrants switches [17]. Numerous studies were developed for energy exchanges using such matrix converters. However, their use in practice is delayed due to the switches commutation problems [18]-[20]. This paper presents a new cycloconverter topology made by cascaded basic PWM AC choppers. The proposed cycloconverter has not commutation problems and it can be generalized in a multilevel topology.

1. Single-phase basic PWM AC choppers

1.1. Direct topology

By the supply mode, direct PWM AC choppers are classified in differential and non-differential topologies (Fig.1). Both structures are made by two standard commutation cells with IGBTs bidirectional in current and unidirectional in voltage.

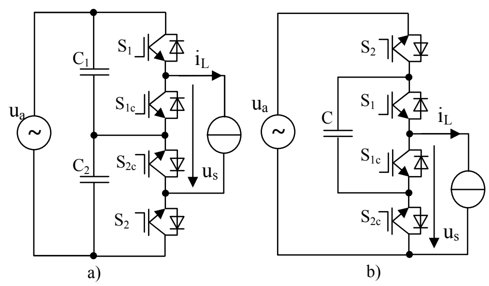


Fig.1. Basic single-phase direct PWM AC choppers, buck type:
a) differential topology; b) non-differential topology.

DC snubbers (C_1, C_2 and C) are attached directly to commutation cells to absorb the energy stored in line stray inductance. These snubbers have a very simple structure, consisting of only a capacitor, with no need for discharging resistors.

In differential topology (Fig.1a) the S_2 and S_1 switches, the voltage source and the load are serial connected. By moving S_2 switch between the voltage source and S_1 switch the non-differential topology is obtained (Fig.1b). This second structure presents the neutral wire continuity advantage.

Both converters have the same control, depending on the voltage source u_a sign. In this way, if u_a is positive, S_1 and S_{1c} switches are PWM controlled with a constant duty ratio (α), while S_2 and S_{2c} switches are fully turned on. When the sign of the voltage source is changed, the switching pattern is reversed, S_2 and S_{2c} being complementary PWM controlled with a constant duty ratio and S_1 and S_{1c} are fully turned on. In these switching patterns the current path always exits whatever the inductor current direction. Since two switches are always turned on during the half period of the voltage source the switching loss is significantly reduced. In the buck conversion topology the output voltage is proportional with the duty ratio:

$$u_s = \alpha \cdot u_a \tag{1}$$

During one switching cycle, PWM AC choppers present three possible operating modes: active mode, freewheeling mode and bypass mode (Fig.2).

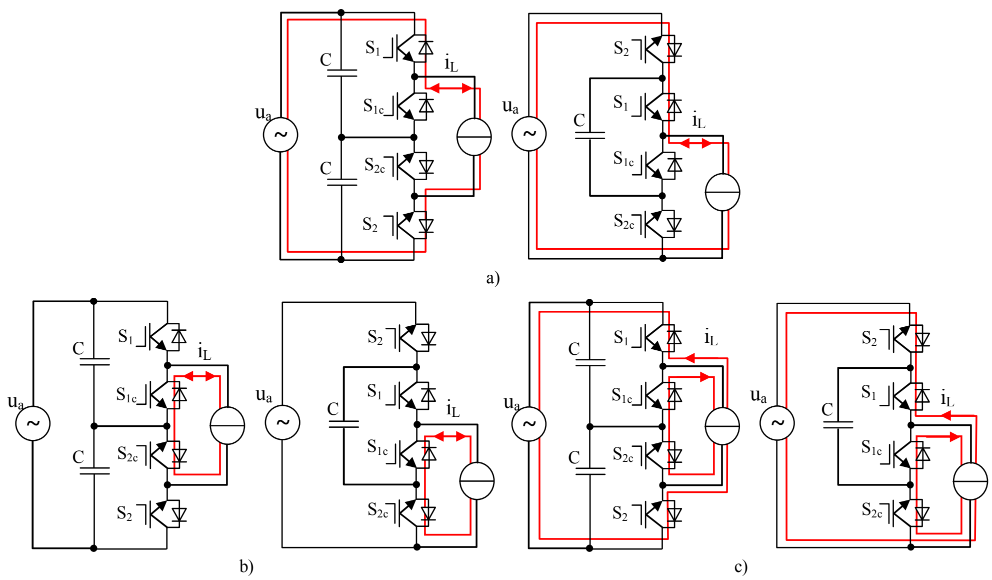


Fig.2. Current's paths for operating modes: a) active mode;
b) freewheeling mode; c) bypass mode.

In the active mode the inductor current i_L passes through input and output side and provides output energy. The S_1 and S_2 switches are turned on and the inductor current i_L passes through S_1 and the diode across S_2 for $i_L>0$ or S_2 and the diode across S_1 for $i_L<0$, as shown in Fig.2*a*.

The freewheeling mode is complementary to the active mode. During this mode the switches S_{1c} and S_{2c} are turned on, so that the inductor current freewheels through the output side, as shown in Fig.2*b*. The bypass mode is imposed by the non-linear regime of power devices. When the input voltage u_a is positive, the switches S_2 and S_{2c} are turned on for safe commutation. During the dead time the inductor current i_L passes in the positive direction through the load, the S_{2c} switch and the diode across S_{1c}. The negative inductor current i_L passes through the voltage source, the S_2 switch and the diode across S_1. Thus, a current path for the inductor current always exists in every current direction during the bypass mode. For $u_a>0$ the current's paths are shown in Fig.2*c*.

Table 1 presents the output voltage dependence on the switches control. The main restrictions for this control are the accuracy and the speed in detecting the voltage source sign.

Table 1.

Output voltage dependence on control.

	S_1	S_{1c}	S_2	S_{2c}	u_s	
					$i_L>0$	$i_L<0$
$u_a>0$	on	off	on	on	u_a	u_a
	off	off	on	on	0	u_a
	off	on	on	on	0	0
$u_a<0$	on	on	on	off	u_a	u_a
	on	on	off	off	u_a	0
	on	on	off	on	0	0

1.2. Indirect topology

The indirect PWM AC chopper's power circuit contains a rectifier, an inverter and a DC snubber (C) without discharging resistors (Fig.3).

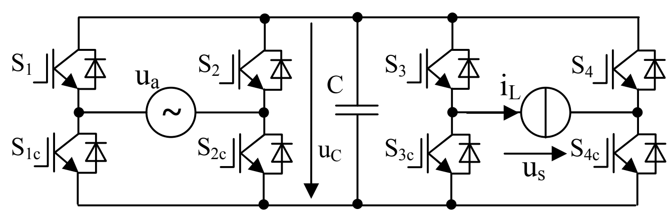


Fig.3. Power circuit of indirect PWM AC chopper.

Both converters have operation principles different from the classic structures. The rectifier realizes a bidirectional power transfer without PWM control. The switches S_1, S_{1c}, S_2 and S_{2c} are controlled at a low commutation frequency, when the input voltage is zero. The inverter works on PWM principle at a high commutation frequency with a constant duty ratio, similar with a continuous chopper. The switches S_3, S_{3c}, S_4 and S_{4c} are controlled depending on the input voltage polarity. The output voltage's effective value can be adjusted by modifying the duty ratio.

During one commutation period there are the same three possible operating modes. In the active mode, the inductive current i_L passes through input and output side and provides output energy. The S_3 and S_{4c} switches are turned on and the input voltage u_a is transmitted to the chopper's output, for both inductor current directions. The inductor current's paths are shown in Fig.4*a*. If $i_L>0$ the current passes through S_3 and S_{4c}, but when $i_L<0$ the current passes through the anti-parallel diodes of S_3 and S_{4c}.

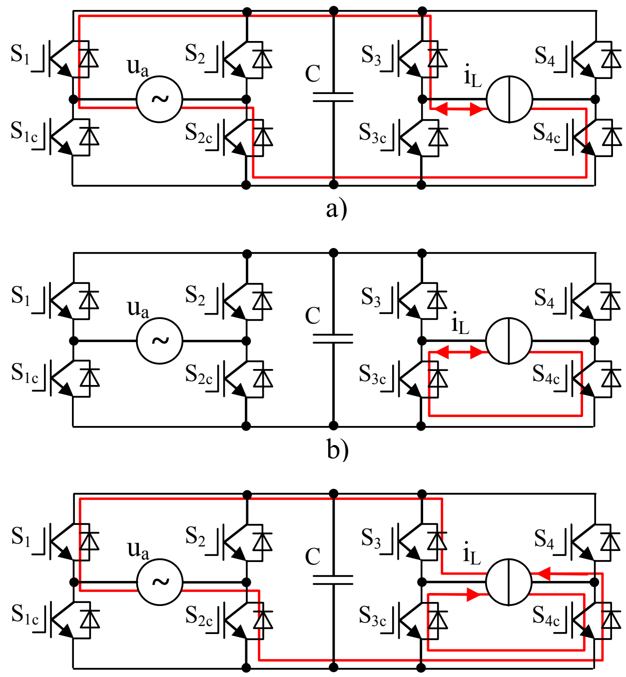


Fig.4. Operating modes for $u_a>0$: a) active mode; b) freewheeling mode; c) bypass mode.

The freewheeling mode is complementary with the active mode. S_{3c} and S_{4c} are turned on and allow the crossing of freewhelling inductor current through the load. The current's paths are shown in Fig.4*b*.

The bypass mode assures the load's inductor current passing during the dead time intervals. Thus, the appearance of overspikes and overvoltages through real switches is avoided. During these dead time intervals, the switches which compose commutation cells are turned off. When the input voltage u_a is positive and $i_L<0$, the inductor current passes through the anti parallel diodes of S_3 and S_{4c} switches, as shown in Fig.4*c*. For the other case, when $i_L>0$, the current passes through the load, the S_{4c} switch and the anti-parallel diode of S_{3c} switch.

This chopper presents the advantage of reversing almost instantaneous the output voltage's phase, by changing the control of commutation cells 3 and 4, as explained in Table 2.

Table 2.

Output voltage dependence on control.

	S_3	S_{3c}	S_4	S_{4c}	u_c	u_s	
						$i_L>0$	$i_L<0$
$u_a>0$	on	off	off	on		u_a	u_a
S_1, S_{2c}: on	off	off	off	on	u_a	0	u_a
S_2, S_{1c}: off	off	on	off	on		0	0
$u_a<0$	off	on	on	off		u_a	u_a
S_1, S_{2c}: off	off	on	off	off	$-u_a$	u_a	0
S_2, S_{1c}: on	off	on	off	on		0	0
$u_a>0$	on	off	on	off		$-u_a$	$-u_a$
S_1, S_{2c}: on	off	off	off	off	u_a	$-u_a$	0
S_2, S_{1c}: off	off	on	off	on		0	0
$u_a<0$	off	on	off	on		$-u_a$	$-u_a$
S_1, S_{2c}: off	off	on	off	on	$-u_a$	0	$-u_a$
S_2, S_{1c}: on	off	on	off	on		0	0

1.3 Experimental results

In the control system based on microprocessors, the software flexibility facilitates the development and updating of the control technique. More, the single-chip microcontroller can implements the controller with lower cost and smaller size than the general-purpose microprocessor accompanying environmental circuits. The control of the differential PWM AC chopper is implemented using a single-chip microcontroller PIC18F1320. The dead time intervals are implemented in software and PWM pulses are obtained from the pulse generator of the microcontroller.

The system is divided into two parts: the controller and the power circuit (Fig.5). The controller part includes the control algorithm. The power circuit consists of a differential PWM AC chopper. The rating of the converter is designed for up to 10kW with 50Hz/220V nominal input voltage. To handle this power range rating 40A/600V insulated gate bipolar transistors (IGBTs) are selected as the power semiconductor switches. These power semiconductor switches are operated with a fixed switching frequency f_{sw}=8 kHz and a dead time t_d=2.5µs. The input/output filters and DC snubber used for experiment had the following values: L_i=5mH, C_i=10µF, L_o=5mH, C_o=6µF and C_1=C_2=100nF.

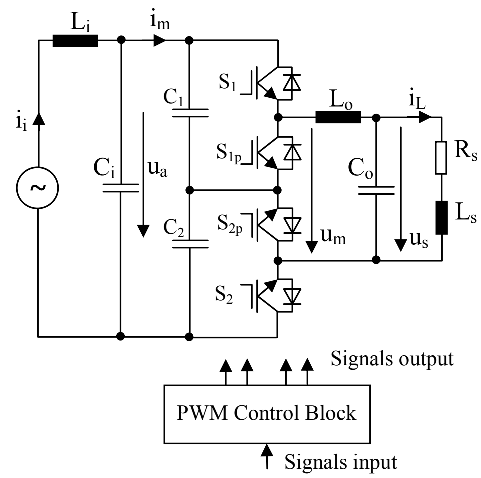


Fig.5. Experimental circuit of differential PWM AC chopper.

The experimental operation waveforms of the differential AC chopper are shown in Fig.6. Fig.6*a* shows the experimental waveforms of the input source voltage and snubber capacitors voltages and the Fig.6*b* shows the input currents (i_i, i_m) and output voltages (u_m, u_s).

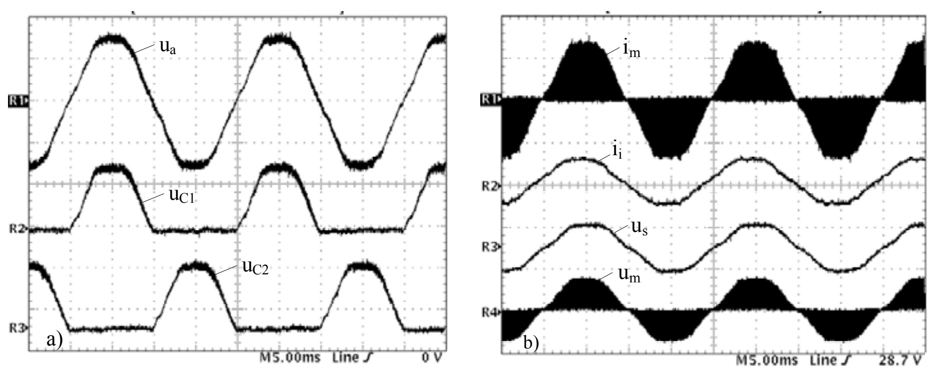
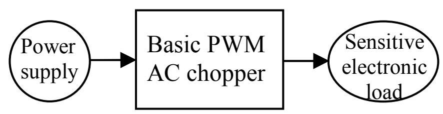


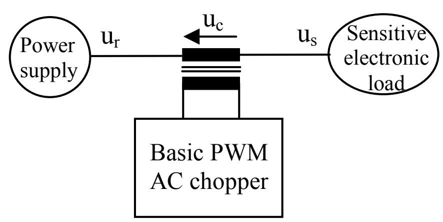
Fig.6. Operation of differential AC chopper : a) input source voltage u_a (100V/div); snubber capacitors voltages u_{C1}, u_{C2} (100V/div) ; b) input currents i_i, i_m (5A/div) and output voltages u_s, u_m (200V/div).

2. Modern line conditioners

Recent researches have shown the possibility to associate AC choppers with transformers, in order to obtain modern line conditioners. Line conditioners have been used in industry to provide and protect sensitive loads. There is a large variety of line conditioners which absorb one or more types of disturbances, like line conditioners with or without energy storage. Line conditioners with energy storage, for example uninterruptible power supplies (UPS), protect the equipments against a high number of disturbances, including short disconnections which are the most expensive. The line conditioners without energy storage include compensators which stabilize the voltage source by reactive power control and active filters. In the same category are included line conditioners made by basic PWM AC choppers. They operate at high commutation frequency and allow a fast and continue output voltage control. There are direct and indirect types of line conditioners without energy storage. In the direct type case one or more AC choppers are connected between the voltage source and the load (Fig.7*a*). The indirect type is made up of a PWM AC chopper and a transformer for series voltage compensation (Fig.7*b*).



a)



b)

Fig.7. Modern line conditioners: a) direct topology; b) indirect topology.

In the case of direct line conditioners differential AC choppers topologies are preferred, while indirect line conditioners use differential or non-differential AC choppers topologies. The serial voltage (u_c) given by the transformer is controlled by AC chopper in order to compensate the voltage source fluctuations. As a result is obtained a constant load voltage.

The serial voltage (u_c) is only a small part of the voltage source, which allows the line conditioner to absorb a reduced power. The direct AC chopper output voltage is in phase with the voltage source. The relative sign between the primary and the secondary of the series transformer (indicated by blackened points) allows to increase or to decrease the voltage delivered to the load ($u_s = u_r + u_c$), depending on the connection mode (Fig.8).

There are many possibilities to associate PWM AC choppers with serial transformers. Fig.9 presents some modern line conditioners with voltage up/down capability. The first topology (Fig.9*a*) is made by two non-differential AC choppers.

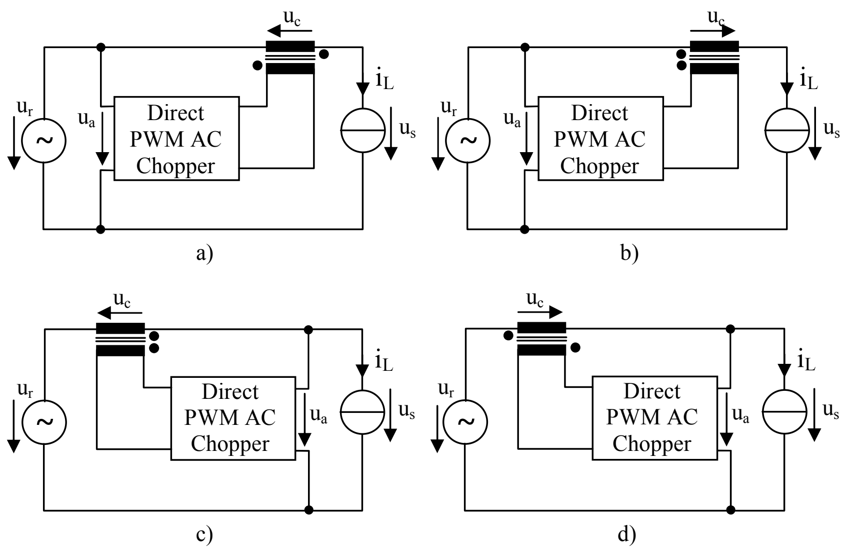


Fig.8. Modern line conditioners without energy storage: a) voltage up circuit with power supply from input side; b) voltage down circuit with power supply from input side; c) voltage up circuit with power supply from output side; d) voltage down circuit with power supply from output side.

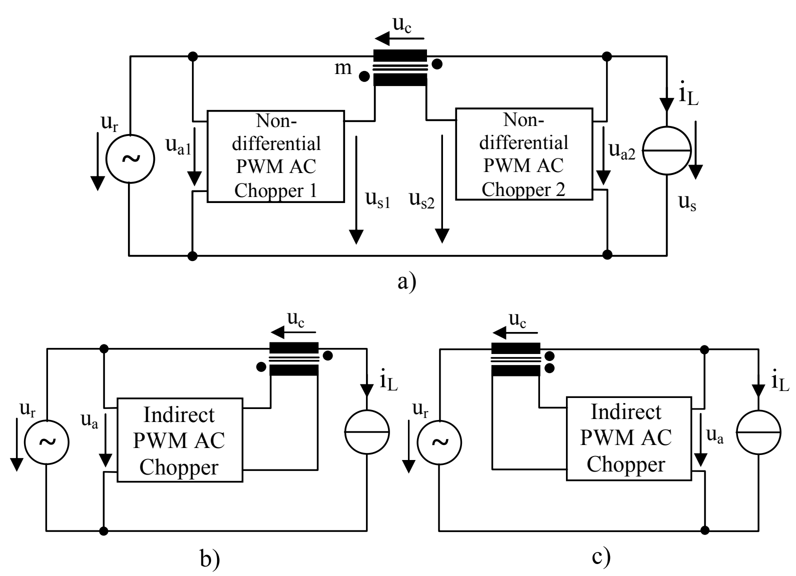


Fig.9. Modern line conditioners with up/down capability: a) with two direct non-differential topologies; b) with one indirect topology and power supply from input side; c with one indirect topology and power supply from output side.

The non-differential AC chopper 1 delivers the voltage u_{s1}, which have an increasing voltage effect, while the second one delivers the voltage u_{s2} with a decreasing voltage effect. As a difference between the two previous voltages (u_{s1}, u_{s2}) a compensation voltage (u_c) is obtained, which is serial injected with the voltage source. The voltage delivered to the load can be obtained as a function of the voltage source (u_r) and the AC choppers input voltages (u_{a1}, u_{a2}) by taking into account their duty ratio (α_1, α_2):

$$u_s = u_r + m \cdot (\alpha_1 \cdot u_{a1} - \alpha_2 \cdot u_{a2}) \qquad (2)$$

The other two structures (Fig.9*b*, *c*) use one indirect PWM AC chopper supplied from the input or output side and a transformer for series voltage compensation.

3. New single-phase cycloconverter

Single-phase AC choppers can be cascaded in different ways, by supplying them from a.c. voltage sources having the same phase, or having different phases. In both cases, a galvanic separation between the supply source and the load is required.

Fig.10 presents two new PWM AC choppers topologies with three voltage levels, supplied from the same source. Their control is based on the delay of carrier waves with 180°el, like in the case of the flying capacitor multilevel DC chopper. These structures have two important advantages: they decrease the voltage's fluctuations and increase the apparent output commutation frequency.

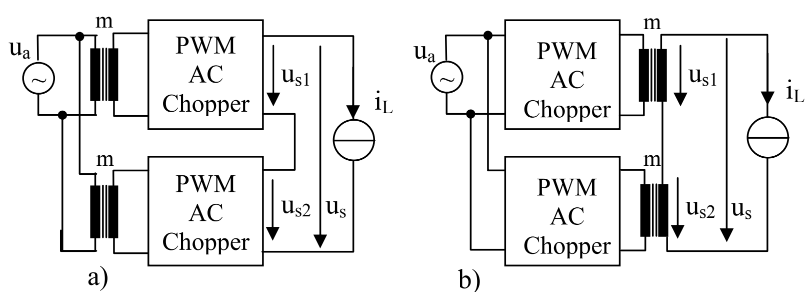


Fig.10. Direct PWM AC choppers with three voltage levels: a) galvanic separation on the input side; b) galvanic separation on the output side.

Fig.11*a* presents the proposed cycloconverter. It is made by three single-phase AC choppers, connected in cascade and supplied from three-phase ac voltage. It is considered that: $u_a=\sqrt{2}\,U_a\sin(\omega_r t)$, $u_b=\sqrt{2}\,U_a\sin(\omega_r t-2\pi/3)$ and $u_c=\sqrt{2}\,U_a\sin(\omega_r t-4\pi/3)$. The PWM AC choppers are controlled with duty ratio α_1, α_2 and α_3. The output voltage is obtained as a combination of the AC choppers output voltages (Fig.11*b*).

$$u_s = u_{s1} + u_{s2} + u_{s3} \qquad (3)$$

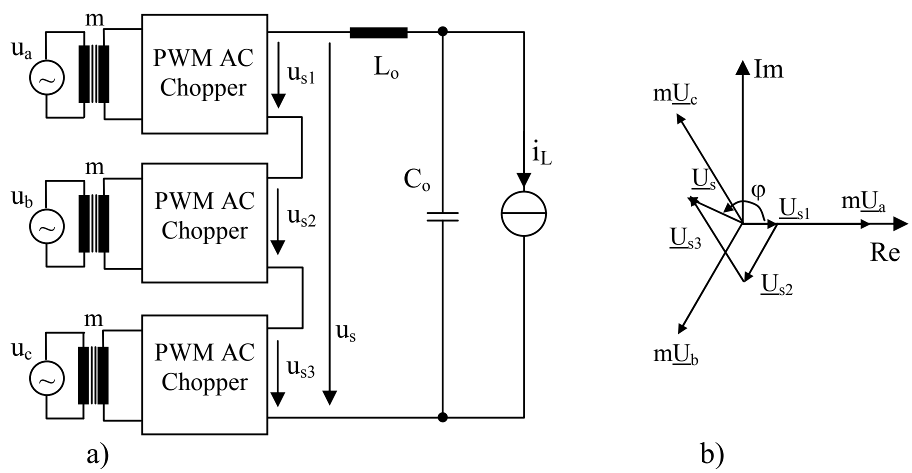


Fig.11. Structure of the proposed cycloconverter: *a* galvanic separation on the input side; *b* phasor diagram.

$$\begin{aligned} u_{s1} &= m \cdot \alpha_1 \cdot u_a \\ u_{s2} &= m \cdot \alpha_2 \cdot u_b \\ u_{s3} &= m \cdot \alpha_3 \cdot u_c \end{aligned} \tag{4}$$

where *m* represents the transformation ratio.

The effective value of the output voltage is equal to $mk\sqrt{3}U_a / 2$. The *k* coefficient represents the modulation index and it can take values between 0 and 1. There are lots of duty ratio combinations α_1, α_2 and α_3 which allow defining the output voltage of cycloconverter. In this paper is proposed a discontinuous pulse width modulation (DPWM) control in order to reduce losses in commutation. At every moment only two by three PWM AC choppers work. The non-switched chopper delivers a zero output voltage. The imposed control voltages (u_{c1}, u_{c2} and u_{c3}) have ω_i pulsation:

$$\begin{aligned} u_{c1} &= \cos(\omega_i t) \\ u_{c2} &= \cos(\omega_i t - 2\pi/3) \\ u_{c3} &= \cos(\omega_i t - 4\pi/3) \end{aligned} \tag{5}$$

The cycloconverter contains twelve switches in three segments among which only four are in commutation at every moment. The proposed control is defined as follows:

- when $u_{c1}<u_{c2}$ and $u_{c1}<u_{c3}$:

$$\begin{aligned} \alpha_1 &= 0 \\ \alpha_2 &= k \cdot (u_{c2} - u_{c1}) / \sqrt{3} \\ \alpha_3 &= k \cdot (u_{c3} - u_{c1}) / \sqrt{3} \end{aligned} \tag{6}$$

- when $u_{c2}<u_{c1}$ and $u_{c2}<u_{c3}$:

$$\alpha_1 = k \cdot (u_{c1}\text{-}u_{c2})/\sqrt{3}$$
$$\alpha_2 = 0 \qquad (7)$$
$$\alpha_3 = k \cdot (u_{c3}\text{-}u_{c2})/\sqrt{3}$$

- when $u_{c3}<u_{c2}$ and $u_{c3}<u_{c1}$:

$$\alpha_1 = k \cdot (u_{c1}\text{-}u_{c3})/\sqrt{3}$$
$$\alpha_2 = k \cdot (u_{c2}\text{-}u_{c3})/\sqrt{3} \qquad (8)$$
$$\alpha_3 = 0$$

The load voltage's pulsation (ω_s) is obtained as a difference between supply sources pulsations (ω_r) and the control signal's one ($\omega_s = \omega_r - \omega_i$).

By cascaded on each phase two or more basic AC choppers different structures of multilevel cycloconverters can be obtained. They have the advantages of being composed by standard commutation cells (inverter type) without commutation problems. The PSIM simulation waveforms of the proposed cycloconverter in two levels are shown in Fig.12. Fig.12*a-c* shows the simulation waveforms of the imposed control voltages u_{c1}, u_{c2}, u_{c3}, duty ratio α_1, α_2, α_3, input voltages u_a, u_b, u_c, output voltages of the three AC choppers u_{s1}, u_{s2}, u_{s3} and output voltage of the cycloconverter u_s. On the first interval (0.00s-0.05s) the control signal frequency was considered at 10Hz while on the second one the frequency was 40Hz. The three AC choppers were supplied at 50Hz frequency value. As a result the output voltage frequency is 40Hz on the first interval and 10Hz on the other one. The system parameters used for simulation are given by: k=0.8, f_{sw}=10kHz and t_d=2µs.

Conclusions

In this paper basic PWM AC choppers made by two quadrants commutation cells were presented. The most simple control principle to implement is the one based on the voltage source sign. More, it doesn't need devices to limit the current, which reduce losses. Structures based on two quadrants commutation cells are more robust than the ones based on four segments switches. Due to the simple snubbers attached directly to each commutation cell the basic PWM AC choppers do not have commutation problems. The non-differential AC chopper has the same robustness like the differential one and more, it presents the advantage of neutral wire continuity.

In accordance with standard CEM, the phase controls must be replaced by modern structures like the ones presented in this paper.

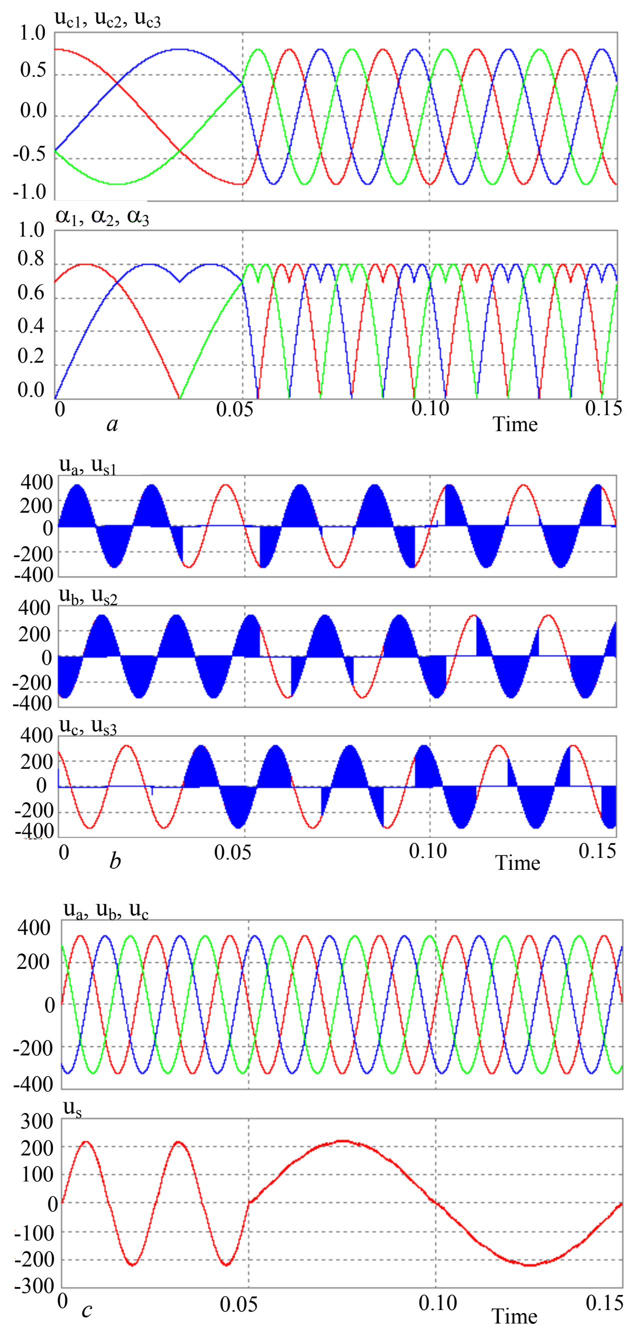


Fig.12. Operation of the proposed cycloconverter: a) imposed control voltages: u_{c1}, u_{c2}, u_{c3} and duty ratio: α_1, α_2, α_3; b) input voltages: u_a, u_b, u_c and output voltages of AC choppers: u_{s1}, u_{s2}, u_{s3}; c) input voltages: u_a, u_b, u_c and output voltage of cycloconverter: u_s.

PWM AC choppers have important advantages: sinusoidal current waveforms, better power factor, faster dynamics and smaller input/output filters. As a result, these modern converters can be used in a bigger number of applications. For the same apparent power transfer, a PWM AC chopper is more expensive than a transformer. In order to reduce the converter's apparent power and to increase the voltage supply quality the paper presented some modern line conditioners made up of basic PWM AC choppers.

The power converters cascade principle can be applied on the PWM AC choppers too. As a result new two levels or multilevel direct AC-AC converters are obtained. In this paper was proposed a new cycloconverter made by three AC choppers connected in cascade. These are supplied from ac three-phase source and each owns a transformer for galvanic separation. The cycloconverter delivers a sinusoidal voltage with an adjustable frequency and it has no commutation problems.

REFERENCES

1. *N.Burany*, Safe Control of Four-Quadrant Switches - Conference Record IEEE IAS Annual meeting, Vol.1, 1989, pp.1190-1194.
2. *G.-H.Choe, A.K.Wallace, M.-H.Park*, An improved PWM Technique for AC Choppers, IEEE Trans. on Power Electronics, Vol.4, no.4, Oct.1989, pp.496-505.
3. *D.H.Jang, G.-H.Choe, M.Ehsani*, A symmetrical PWM Technique with Harmonic Elimination and Power Factor Control in AC Choppers, IEEE Trans. on Power Electronics, Vol.10, no.2, March 1995, pp.175-184.
4. *D.Vincenti, J.Hua, P.Ziogas*, Design and implementation of a 25-kVA three-phase PWM ac-ac line conditioner, IEEE Trans.Power Electron., vol.9, July 1994, pp.384-389.
5. *B.-H.Kwon, B.-D.Min, J.H.Kim*, Novel topologies of AC choppers, IEE Proc.-Electr. Power Appl. Vol.143, No.4 July 1996, pp.323-329.
6. *F.Z.Peng, L.Chen, F.Ahang*, Simple Topologies of PWM AC-AC Converters, IEEE Trans.Power Electron. Letters, Vol.1, No.1, March 2003, pp.10-13.
7. *B.H.Kwon, B.D.Min, J.H.Kim*, Novel commutation technique of AC-AC converters, IEE Proc.-Electr. Power Appl. Vol.145, No.4, July 1998, pp.295-300.
8. *E.Lefeuvre, T.Meynard, P.Viarouge*, Robust two-level and multilevel PWM AC Chopper, EPE Graz, Proc.CD, 2001.
9. *Z.Fedyczak, R.Strzelecki, G.Benysek*, Single-phase PWM AC/AC Semiconductor Transformer Topologies and Applications, IEEE Power Electronics Specialist Conference PESC'02, Vol.2, June 2002, pp.1048-1053.
10. *D.Floricau, J.C.Hapiot*, Novel Topologies of DPWM multi-cells AC Choppers, 11th National Conference on Electrical Drives, Galati, 2002, pp.73-78.
11. *Y.Hongxiang, L.Min, J.Yanchao*, An advanced Elimination PWM Technique for AC Choppers, IEEE Power Electronics Specialist Conference PESC'04, Vol.1, June 2004, pp.161-165.
12. *D.Floricau, B.Dagues, M.Fadel, J.C.Hapiot, M.Dumitrescu*, PWM AC Choppers for high voltage applications, 7th International Conference on Applied and Theoretical Electricity, Băile Herculane, 2004, pp.200-205.
13. *B.-D.Min, B.-H.Kwon*, Novel PWM line conditioner with fast output voltage control, IEE Proc.-Electr. Power Appl., Vol.145, No.2, March 1998, pp. 85-91.

14. *B.-H.Kwon, J.H.Youm, J.H.Choi*, Automatic voltage regulator with fast dynamic speed, IEE Proc.-Electr. Power Appl. Vol.146, No.2, March 1999, pp.201-207.
15. *B.-H.Kwon, G.Y.Jeong, S.H.Han and D.H.Lee*, Novel Line Conditioner With Voltage Up/Down Capability, IEEE Trans.on Industrial Electronics, Vol.49, No.5, Oct.2002, pp.1110-1119.
16. *R.Strzelecki, H.Tunia, M.Jarnut, G.Meckien and G.Benysek*, Transformerless 1-Pase Active Power Line Conditioners, IEEE Power Electronics Specialist Conference PESC'03, Vol.3, June 2003, pp.1121-1126.
17. *M.Venturini, A.Alesina*, The generalized transformer: a new bi-directional sinusoidal waveform frequency converter with continuously adjustable input power factor, Proceedings IEEE Power Electronics Specialists Conference, 1980, pp.242-252.
18. *A.Alesina, M.Venturini*, Analysis and design of optimum amplitude nine-switch direct ac-ac converters, IEEE Trans.Power Electron., Vol.4, no.1, Jan 1989, pp.101-102.
19. *L.Zhang, C.Watthanasarn, W.Shepherd*, Analysis and comparison of control techniques for AC-AC matrix converters, IEE Proc.-Electr. Power Appl., Vol. 145, No.4, July 1998, pp.85-91.
20. *J.-H.Youm, B.-H. Kwon*, Switching Technique for Current-Controlled AC-to-AC converters, IEEE Transaction on Industrial Electronics, Vol.46, No.2, pp.309-317, April 1999, pp.85-91.