Amplitude Modulation – an Alternative Method of Generating the Convertor Output Waveforms

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Abstract

A novel approach to the generation of the convertor output waveforms, based on amplitude modulation is presented in the paper.

Key words

Multilevel convertor, recurrent convertor, amplitude modulation, orthogonal space vector.

1. Introduction

From the early years of Power Electronics the main effort has been concentrated on developing control methods for two-level voltage source inverters (**VSI**). The features and performance of this kind of **VSI**s have been largely recognized and verified in practice. The simplest way of the **VSI** control is just by subsequent switching consecutive inverter keys, which produces a step changing phase voltage at the output. The advantages of this method are simple control circuitry and negligible switching losses. The output frequency (of the voltage fundamental) to switching frequency ratio is relatively high as well as a modulation index. The greatest disadvantage of such a control method is a high harmonic content of the output voltage - the **THD** ratio amounts to 31 %. Besides the only possible way to decrease the output voltage fundamental is by adjusting the **DC** voltage of the inverter. Therefore this method is rarely applied in AC drives and many more sophisticated methods have been developed.

The most common control method for two level **VSI**s is based on pulse width modulation (**PWM**). This control method implies however a few drawbacks: reduction of modulation index, generated noise level, large voltage derivatives at motor clamps, high harmonic content of the output voltage. These features speed up the wearing out of the motor insulation and create new issues of electromagnetic compatibility. Further improvement of the output waveforms cannot be obtained by changing the control algorithm of the two-level **VSI.** Using special kind of inverter output filters it is possible to improve the two-level inverter's output waveforms. However these filters are rather bulky and expensive.

Another possible approach to the generation of the convertor output waveforms is based on an amplitude modulation. Actually this kind of modulation is rarely used in special purpose multilevel convertors. There are serious technical difficulties in the construction of such convertors. The control methods and convertor topologies permitting to increase the total output power and to improve output voltage waveforms are being intensively developed. There are solutions of complex convertors composed e.g. with several standard inverters and a transformer. The convertor proposed in [1] is destined to medium power applications and permits to limit the output voltage spectrum and to obtain better voltage waveforms.

The novel proposal, presented in this paper, is based on an idea of implementing the amplitude modulation by constructing a complex convertor consisting of few simple two-level inverters. Realised in this way the complex convertor generates the desired output waveform using a method called Additive Level Amplitude Modulation.

The solution is based on an **OVT** (Orthogonal Vectors Theory) convertor presented in [2] and [3]. The **OVT** convertor consists of two standard inverters. Its performance and the way of control are presented in the chapter 2. The solution presented in the paper is based on an observation that the idea of the **OVT** convertor has the property of recurrence. Adding a next **OVT** inverter (of adequately reduced power) it is possible to significantly improve the output voltage of the convertor. The idea and method of control of such a convertor, later called as recurrent **OVT** convertor (**RECOVT**), as well as simulation results are presented in the chapter 3.

2. Basic idea of the OVT Convertor

The block diagram and the idea of the **OVT** convertor control are outlined in Fig.1. The convertor consists of a mains rectifier (MR), a DC circuit, a main inverter (MI) and an auxiliary inverter (AI) The inverters are connected together with the help of a summing nod (S) which can be set up in a number of ways.

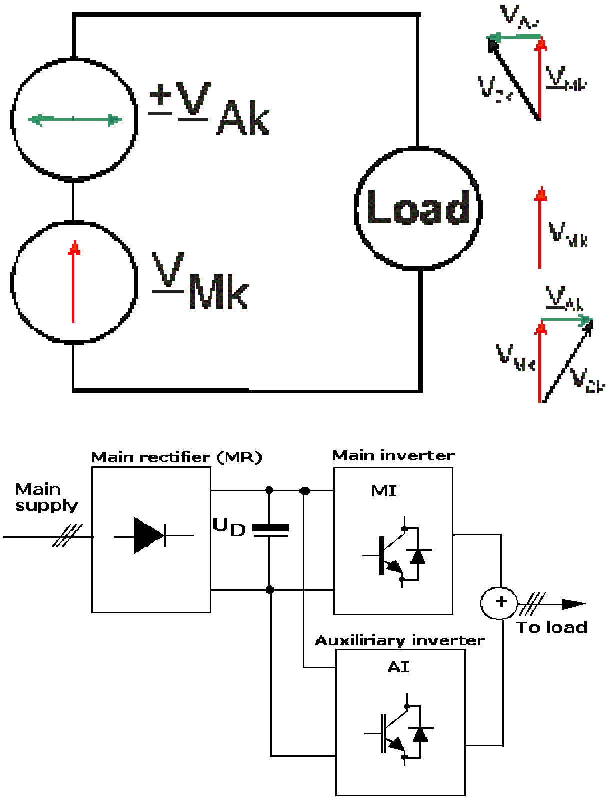


Fig.1. Idea and the block diagram of the OVT convertor: MR - mains rectifier, DC circuit (U_D), MI – main inverter, AI - auxiliary inverter, SN - summing nod.

The MI and AI units are two standard two level inverters. The main inverter MI produces space active vectors denoted as $\underline{V}_{Mk}$ while the auxiliary inverter generates space vectors $\underline{V}_{Ak}$ orthogonal to the MI vectors. The zero vectors $\underline{V}_{Ak}$ of the auxiliary inverter are used too. Convertor output voltage vectors are composed according to the idea presented above. The output space vector of the complex convertor is composed as a combination (a sum or a difference) of orthogonal vectors generating by two inverters. While a zero vector of the AI inverter is added to the space vector of the main inverter that means practically the only active vector of the MI is connected to the load. Thus the MI produces generally active power to feed the load whereas the AI provides relatively small disturbance power in order to filter the output voltage. Active space vectors of both inverters are presented in Fig.2.

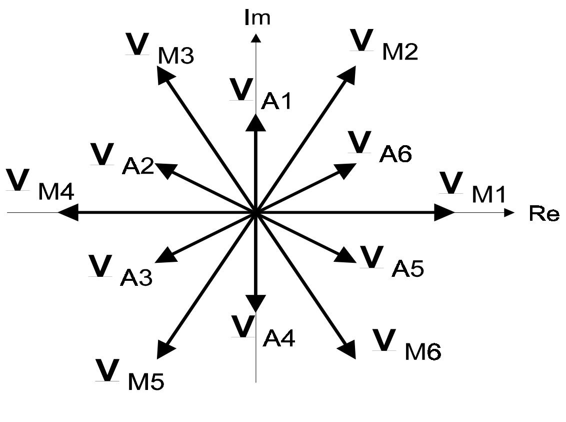


Fig.2. Active space vectors of both inverters.

All active vectors are described by the following expressions:

$$\underline{V}_{Mk} = \left|\underline{V}_{Mk}\right| e^{j\left[(k-1)\frac{\pi}{3} \pm 2\pi n\right]}$$
$$\underline{V}_{Ak} = \pm jm\underline{V}_{Mk} = \pm m\underline{V}_{Mk}\, e^{j\frac{\pi}{2}} \qquad (1)$$

where k=1,2,3,4,5,6; n=1,2,3... ; m – the ratio of vector lengths. As it was mentioned earlier zero voltage space vectors of the AI are also utilized.
The ratio *m* is defined as:

$$m = \frac{\left|\bar{V}_{Ak}\right|}{\left|\bar{V}_{Mk}\right|} = tg\left(\pi/9\right) = 0{,}364 \qquad (2)$$

As a result of proposed control method, the whole convertor is able to generate 42 output voltage space vectors assuming zero vectors of the MI are not considered. Among all vectors there are 18 vectors similar in length.

Taking into account only similar vectors the output space vector of the convertor is created in the way described below. In every surface sector of the stationary coordinates system (α-β), corresponding to the one of MI active vectors, the output vectors of the convertor are generated as a sequence of three vectors: $\underline{V}_{Ok-}, \underline{V}_{Ok}, \underline{V}_{Ok+}$. They are given as

$$\begin{cases} \underline{V}_{Ok-} = \underline{V}_{Ak \oplus 3} + \underline{V}_{Mk} \\ \underline{V}_{Ok} = \underline{V}_{Mk} \\ \underline{V}_{Ok+} = \underline{V}_{Ak} + \underline{V}_{Mk} \end{cases} \qquad (3)$$

The symbol k⊕3 denotes the modulo-6 sum of the index k and 3. The expression (2) describes the method of control based on the developed orthogonal vectors' strategy. The $\underline{V}_{Ok}$ vector is equal to a $\underline{V}_{Mk}$ vector of the main inverter. Then the auxiliary inverter generates a zero voltage vector. According to the rule (2) the convertor output vectors are given as

$$\underline{V}_{Ok-} = (1 - jm)\underline{V}_{Mk} = \sqrt{1+m^2}\,\underline{V}_{Mk}\, e^{-jarctgm}$$
$$\underline{V}_{Ok} = \underline{V}_{Mk} = \left|\underline{V}_{Mk}\right| e^{j\left[(k-1)\frac{\pi}{3} \pm 2\pi n\right]} \qquad (4)$$
$$\underline{V}_{Ok+} = (1 + jm)\underline{V}_{Mk} = \sqrt{1+m^2}\,\underline{V}_{Mk}\, e^{jarctgm}$$

While summing vectors according to the principle described, it is possible to obtain 18 non-zero vectors, that is three times as many as in case of conventional inverters. Having repeated the operation for any other vector $\underline{V}_{Mk}$ one arrives at 18 non-zero voltage space vectors. The length of twelve vectors, composed as a sum of active vectors of both inverters, is identical. And it is about 6 % more than the length of remaining six vectors which are generating by the main inverter. Fig.3 presents all vectors which have been described above.

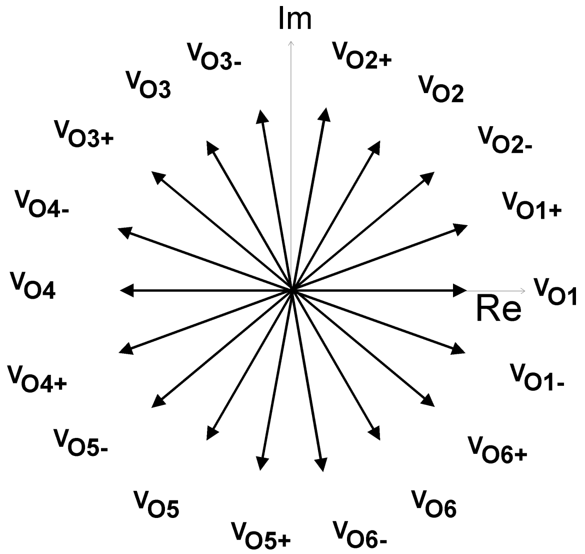


Fig.3. Output space vectors of the convertor.

Projection of these vectors on one phase axis permits to obtain an output phase voltage waveform of the OVT convertor. An example of such waveforms, obtained during simulation works is presented in Fig.4.

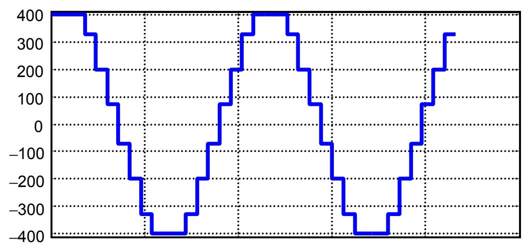


Fig. 4. Output voltage waveforms of the OVT convertor received during simulation works.

The OVT convertor has better performance and characteristics in comparison to the standard one. Due to the control method presented above the main inverter (MI) produces generally active power necessary to feed the load whereas the auxiliary inverter (AI) provides relatively small voltage pulses to the output terminals of the main inverter. As a result, the output voltage of the convertor takes a shape resembling more the shape of a sinewave voltage.

This step changing voltage, measured at the output of the OVT convertor, has a limited harmonic content. The harmonic spectrum is presented in Fig.5. The maximal value of the fundamental reaches 430 V that means more 300 V r.m.s. The THD ratio of the output voltage slightly exceeds 10,52 %.

The simulation results have been obtained with assumption that DC voltage was equal to 600 V.

Higher harmonics of the output phase voltage, in enlarged scale, are presented in Fig.6. The first significant harmonics appearing in the spectrum are of the 17-th and 19-th order and they reach respectively 24 and 22 V (amplitude). Besides 17th and 19th harmonics there are low level harmonics of the 5th, 7th and 11^{th}, 13-th order. The maximal value of the 5-th harmonic does not exceed 1,6 % of the fundamental and it is equal to 7,5 V. These harmonics are generated due to unequal length of the output voltage space vectors. The multiple of higher harmonics appears in the spectrum as well.

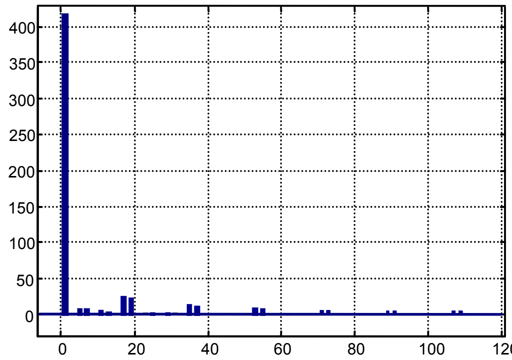


Fig.5. Harmonic spectrum of the convertor output phase voltage – maximal value.

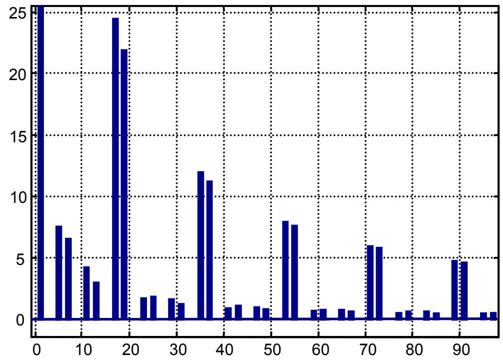


Fig.6. Harmonics of the output phase voltage in enlarged scale.

3. Experimental results

The OVT convertor has been verified during laboratory tests. The experimental research works have been done in AC Drives and Control Laboratory of the Electrotechnical Institute in Gdansk. The circuitry of the test conditions is presented in Fig.7 and its parameters in Table 1.

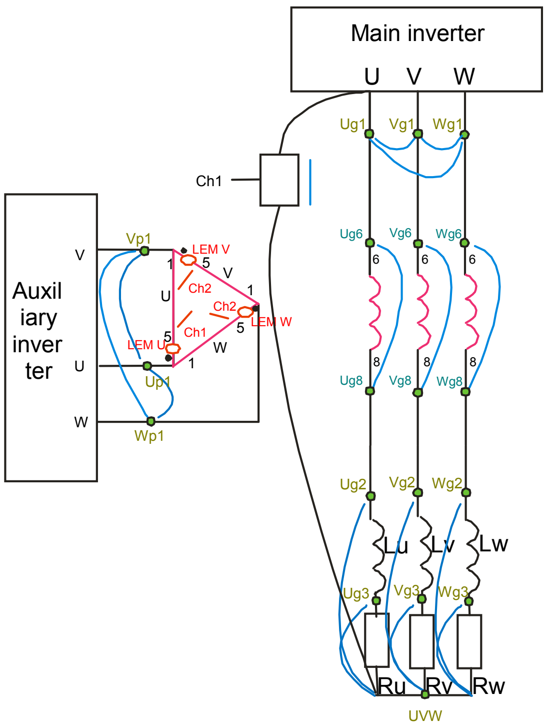


Fig.7. The test circuit diagram of the OVT convertor.

Table 1. Load parameters.

Resistors in Ω			Coils in mΩ		
R_u	R_v	R_w	L_u	L_v	L_w
10,7	10,5	10,3	0,022	0,022	0,022

A relatively small inductance component results in a resistive type of the load. The time constant was only 214 µs. These conditions were related to an UPS application of the OVT convertor. The voltage of the DC link circuit has been established on the level of 540 V. As measurement converters LEM devices have been used. Phase voltage converters have been got a defined 500 V/5 V ratio while current converters- 25 A/5 V. The connections between the inverters are made using three separate phase transformers (8,4 kVA rated power each). The transformers connecting two inverters are presented in Fig.8.

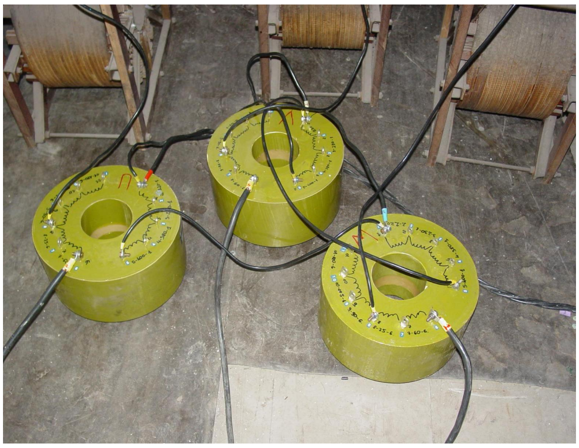


Fig.8. The summing transformers of the OVT convertor.

In Fig.9 ÷ 12 there are a few examples of the registered waveforms. The Fig.9 presents the phase voltage of the main inverter MI. The line to line voltage of the auxiliary inverter AI has a shape of short rectangular pulses and it is presented in Fig.10.

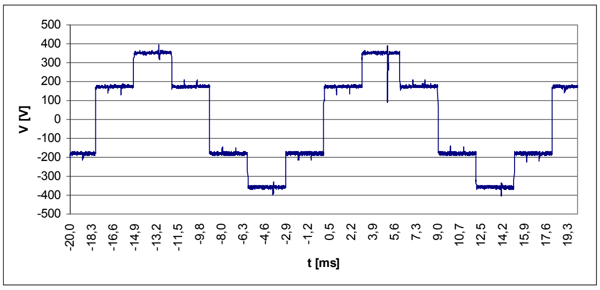


Fig.9. The phase voltage of the main inverter V_N.

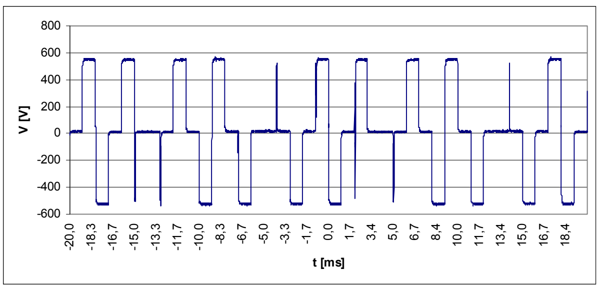


Fig.10. The line to line voltage of the auxiliary inverter.

The example of the phase output voltage V_O of the OVT convertor is presented in Fig.11 and phase output currents – in Fig.12.

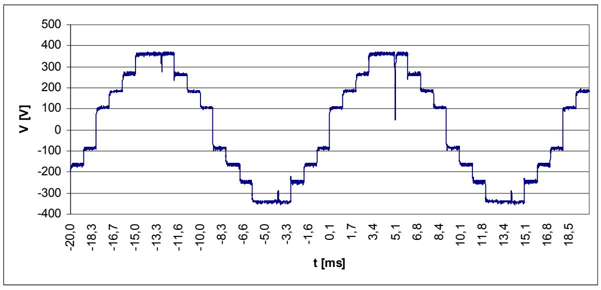


Fig.11. The phase output voltage V_O of the OVT convertor.

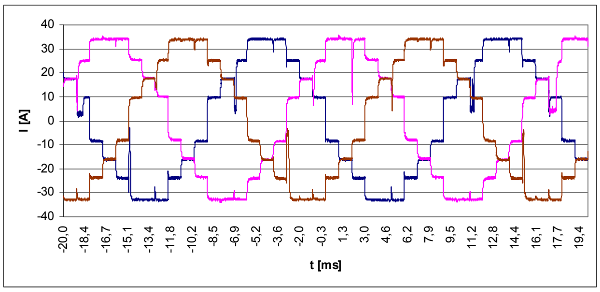


Fig.12. Phase output currents of the OVT convertor.

The power relations between main and auxiliary inverters (total power S, active power P and reactive power Q) are illustrated in Fig.13 ÷ 15.

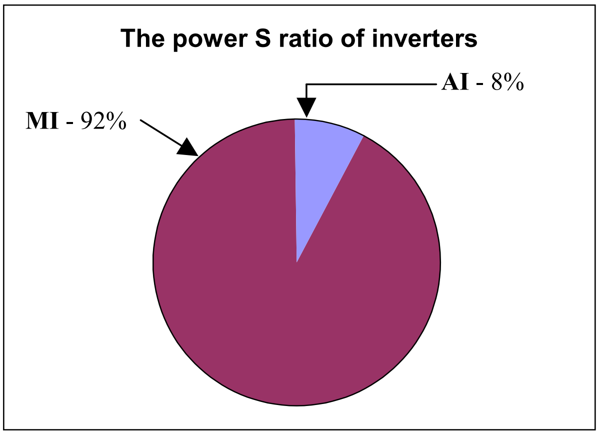


Fig.13. The relationship of inverters' total power.

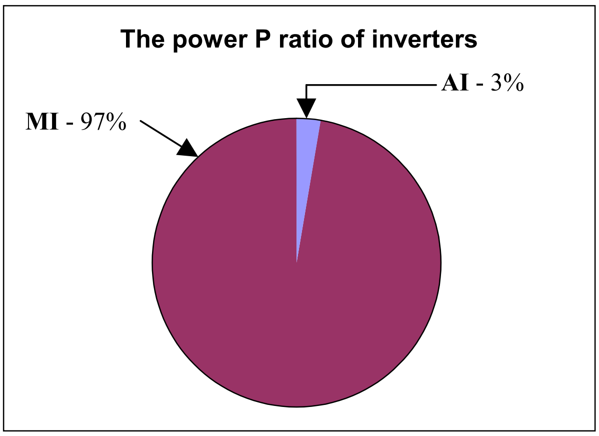


Fig.14. The relationship of inverters' total power.

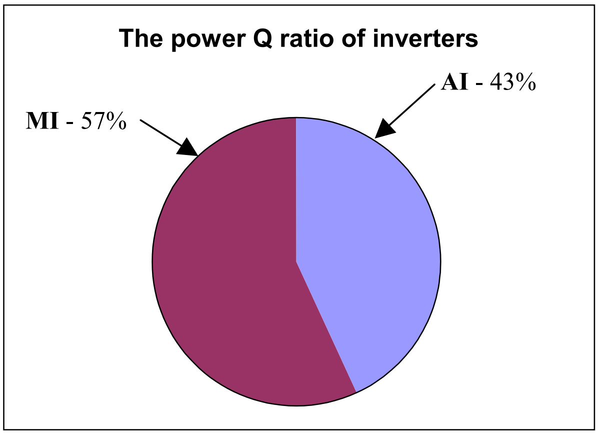
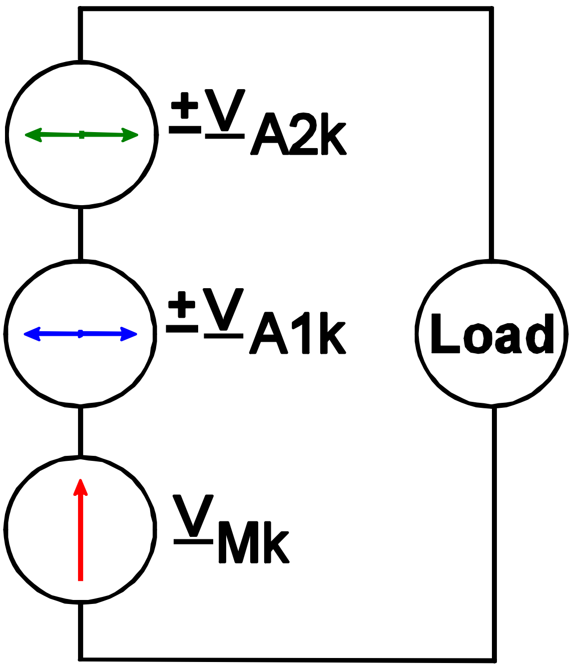


Fig.15. The relationship of inverters' reactive power.

4. The recurrent OVT convertor

The idea of the OVT control has the property of recurrence. It means that it is possible to duplicate the used mechanism of vector formation in order to assure better performance of the convertor. However it implies the use of another one inverter. The block diagram and the control idea of the recurrenced OVT convertor RECOVT are outlined in Fig.16. The convertor consists of a mains rectifier (MR), a DC circuit, a main inverter (MI) and two auxiliary inverters: AI1 and AI2. The inverters' outputs are connected together with the help of a summing nod SN. The SN nod can be set up in a number of ways and the ways are not discussed here. The connection of inverters results in a serial connection of generated output vectors. The vectors of the auxiliary inverters are orthogonal to the vectors of the main inverter. The modules of the AI2 vectors are respectively smaller than the AI1 ones. It has been assumed that the length of AI1 vectors is three times more than the length of respective AI2 vectors. So the total power of the AI2 inverter is considerably reduced in relation to the AI1 power.



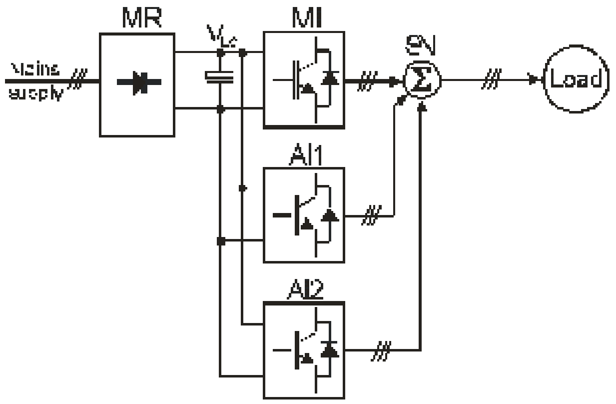


Fig. 16. The control idea and the block diagram of the recurrent RECOVT convertor.

The length of the AI1 vectors is defined by the ratio m_1 while the length of AI2 vectors by the ratio m_2 . The recurrence control method is based on the assumption that m_1 = 0,364 and m_2 = 0,121. The mutual angle position of the inverters vectors is presented in Fig.17. The figure demonstrates the angle relation between active space vectors of three inverters referenced to the *k*-sector of the surface. The length relations has not been saved.

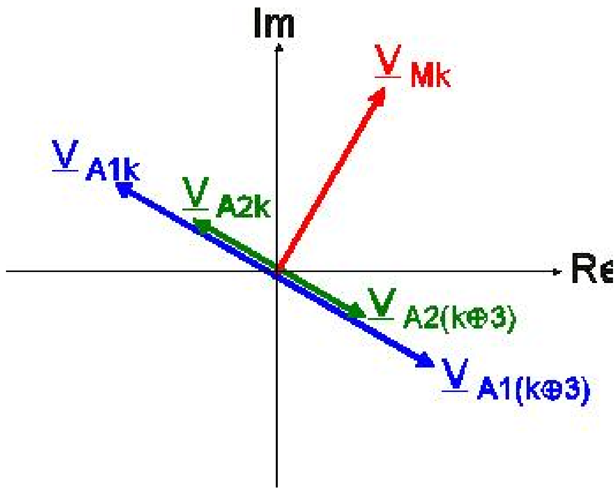


Fig.17. Active space *k*-vectors of three inverters.

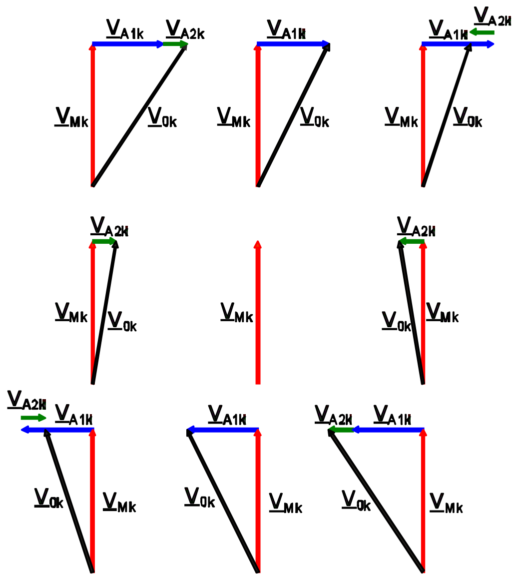


Fig.18. The sequence of nine active space vectors of the RECOVT convertor in one *k*-sector of the (α-β) plane.

In every (α-β) plane sector , corresponding to the one of MI active vectors, the output vectors of the RECOVT convertor are generated as a sequence of nine vectors. They are presented in Fig. 8. The vectors are denoted as it was shown in expression (5) and defined according to expression (6).

$$\underline{V}_{O4k-}, \underline{V}_{O3k-}, \underline{V}_{O2k-}, \underline{V}_{O1k-}, \underline{V}_{O0k}, \underline{V}_{O1k+}, \underline{V}_{O2k+}, \underline{V}_{O3k+}, \underline{V}_{O4k+} \tag{5}$$

$$\begin{cases} \underline{V}_{O4k-} = \underline{V}_{AI1k\oplus 3} + \underline{V}_{AI2k\oplus 3} + \underline{V}_{Mk} \\ \underline{V}_{O3k-} = \underline{V}_{AI1k\oplus 3} + \underline{V}_{Mk} \\ \underline{V}_{O2k-} = \underline{V}_{AI1k\oplus 3} - \underline{V}_{AI2k\oplus 3} + \underline{V}_{Mk} \\ \underline{V}_{O1k-} = \underline{V}_{AI2k\oplus 3} + \underline{V}_{Mk} \\ \underline{V}_{O0k-} = \underline{V}_{Mk} \\ \underline{V}_{O1k+} = \underline{V}_{AI2k} + \underline{V}_{Mk} \\ \underline{V}_{O2k+} = \underline{V}_{AI1k} - \underline{V}_{AI2k} + \underline{V}_{Mk} \\ \underline{V}_{O3k+} = \underline{V}_{AI1k} + \underline{V}_{Mk} \\ \underline{V}_{O4k+} = \underline{V}_{AI1k} + \underline{V}_{AI2k} + \underline{V}_{Mk} \end{cases} \tag{6}$$

The symbol k⊕3 denotes the modulo-6 sum of the index k and 3. The expression (6) describes the method of output vector composition of the RECOVT convertor. Such a method permits to obtain 54 similar output vectors shifted by the angle π/27. They are illustrated in Fig.19.

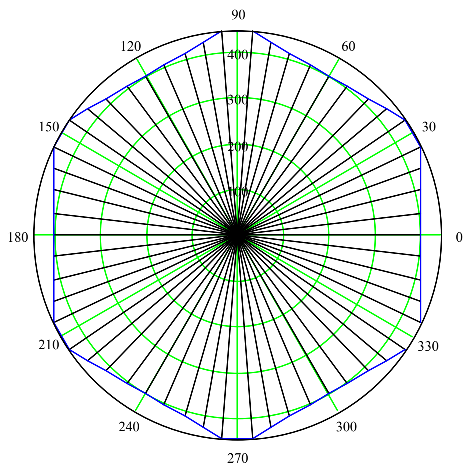


Fig.19. 54 available output voltage space vectors of the RECOVT convertor.

The longest output vector happens when all inverter vectors are to be added. Its length is about 11 % more than the length of the shortest vector. In this case it is the MI vector.

Projection of these vectors on one phase axis permits to obtain an output phase voltage waveform of the RECOVT convertor. An example of such a waveform is presented in Fig.20.

This step changing voltage has a very limited harmonic content. The THD ratio of the phase voltage does not exceed 5 %. It means that the RECOVT convertor satisfies requirements of the PN EN 51160 standard. First significant harmonics appearing in the spectrum are of the 53-rd and 55-th order that means more than 2 kHz in the frequency scale.

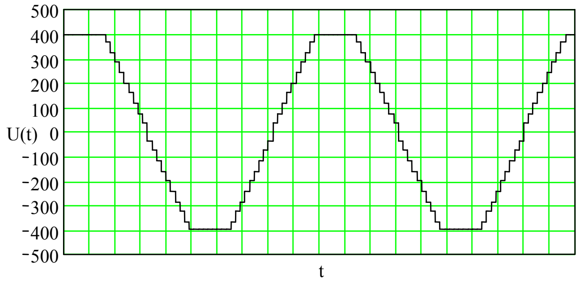


Fig.20. Output voltage waveform of the RECOVT convertor.

In Fig.21 - 23 three phase voltage waveforms of the main and auxiliary inverters have been presented. The main inverter is controlled by use of a rectangular wave which frequency is equal to the output voltage fundamental frequency of the RECOVT convertor.

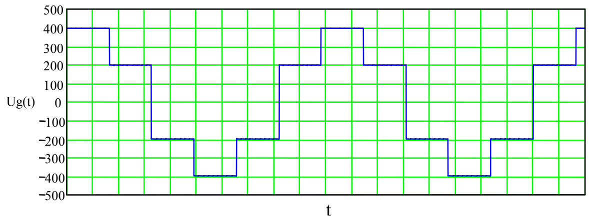


Fig.21. The output voltage waveform of the main inverter MI.

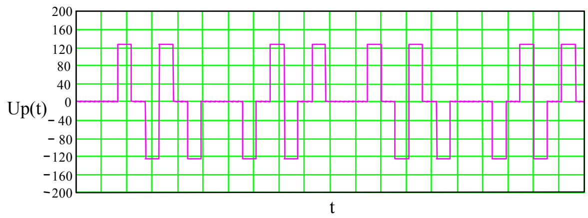


Fig.22. The voltage waveform at the output of the auxiliary inverter AI1.

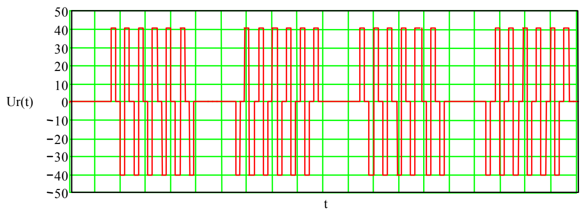
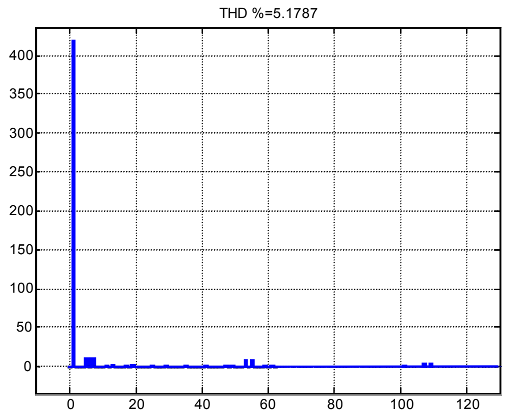


Fig.23. The output voltage waveform of the auxiliary inverter AI2.

The control signal waves of the auxiliary inverters are also very simple and respective to the output voltage presented in Fig.21, 22 and 23. It is important to mention that all inverters are to be switched with a very low frequency in comparison to i.e. PWM technique.

The harmonic spectrum for three inverters RECOVT is been presented in Fig.25. The THD ratio of the output voltage slightly exceeds 5 %. Higher harmonics of the



output phase voltage, in enlarged scale, are presented in Fig.26.

Fig.25. Harmonic spectrum of the RECOVT convertor output phase voltage – maximal value.

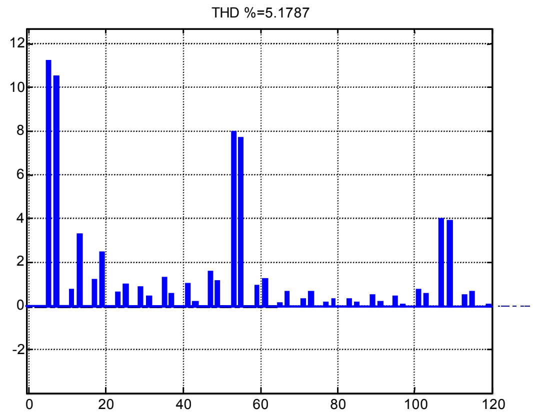


Fig.26. Harmonics of the RECOVT convertor output phase voltage in enlarged scale.

The recurrence control method can be applied farther - the complex convertor, built of i.e. four simple inverters, generates an excellent output phase voltage similar to a sine wave and containing a very low harmonic level.

The harmonics of the output voltage are shifted in the frequency scale to the value of 53 and 55 times of fundamental frequency - that is more than 2,5 kHz in Poland or 3 kHz in many other countries. All harmonics below that frequency are significantly reduced or eliminated.

Finally one can say that the RECOVT convertor is controlled with the help of 54 similar vectors which are almost equal (the modules). But the convertor built from three inverters makes it possible to receive 343 different output space vectors thus increasing the possibility of more sophisticated control.

5. Conclusions

The orthogonal vectors theory (OVT) has been used to develop the novel convertor topology. This topology permits to obtain output waveforms with amplitude modulation AM. Adding a third inverter (a second auxiliary one) to an OVT convertor it is possible to obtain 343 voltage space vectors on the output of complex convertor. 54 of these voltage space vectors are of the similar length. This second auxiliary inverter has adequately reduced power in relation to the first auxiliary inverter. The total power rating of the third inverter should not exceed 3 % of the MI power. In order to assure a proper connection and control of this inverter it is necessary to add an additional circuit i.e. a transformer between the auxiliary inverter and the MI output.

The idea of a novel proposal of the voltage source convertor as well as simulation results for this circuitry has been presented in the paper. The investigated convertor has the following features:

- some advantages of multilevel inverters,
- DC circuit not divided,
- similar vectors' lengths,
- low harmonic content of the output voltage,
- low switching frequency of all three inverters,
- relatively low power rating of two AI inverters,
- simple convertor control circuit.

The possible application area belongs mainly to higher power convertors especially in uninterruptible power suppliers (UPS). The idea of the presented convertor implies a novel approach to the problem of filtering of the output voltage. This new solution becomes an attractive alternative to a traditional output filtering technique utilizing passive components. The paper presents main features and contribution to the theory as well as the results obtained by simulation.

The solution of the summing nod (SN circuit) has not been considered in the paper. During experimental works concerning the OVT convertor the main and auxiliary inverter were connected by use of a three phase transformers. Other means are in statu of development.

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