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Performance of an OVT inverter reliant on the switching frequency of the filtering inverter

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Abstract. The paper presents an inverter based on the orthogonal space vectors theory (OVT inverter) and its performance. The OVT inverter consists of two constituent two-level 3-phase inverters: the main inverter (MI) and the auxiliary one (AI). The MI is controlled in a simple way to generate the stepped output voltage and the AI works as an active filter limiting the higher harmonics in the OVT output voltage. The filtering process is formed by the use of the orthogonal space vector theory. The output voltage of the OVT inverter takes the shape of a stepped voltage comparable to the voltage generated by multilevel inverters. The AI operates as a very effective active power filter (APF) of the OVT inverter output voltage. The AI power is significantly lower in comparison to the MI power nevertheless its switching frequency affects the OVT performance. The article describes studies in which the impact of changes in the switching frequency filter inverter on the operation of the orthogonal inverter and the output voltage THD. Increasing the filter inverter switching frequency improved performance and reduced the transformer size, which acts as a summing node.

Keywords. Active power filter; space vector; vector orthogonality; three-phase inverter; spectrum; THD factor.

1. Introduction

One of the most important targets of the power electronics domain defines the conversion of direct current into alternating current (DC/AC). A classic control system applied in AC drives includes a DC/AC converter. The inverter's output voltage takes the shape of rectangular pulses as a result of the applied PWM (pulse-width modulation) control method. Consequently, in order to receive a sine wave voltage, it is usually compulsory to use a filter that is able to select a fundamental harmonic voltage component. Photovoltaic sources, as well as fuel cells, deliver electric energy, such as a DC voltage, of different levels. This voltage is not suitable to be directly connected to the grid. In consequence, it is obligatory to use voltage conversion DC/DC as well as DC/AC converters. The DC/DC and subsequent DC/AC conversion is indispensable in many applications. Three diversified examples of the DC/DC conversion in regard to their principle of operation have been presented in [1–3]. They are able to deliver a very high voltage gain; therefore, they are particularly suitable for use as an interface between photovoltaic sources and the grid. Other appropriate DC/DC converters destined to be used in fuel cell power systems are also greatly de-bated [4–6]. These converters generate the DC voltage to supply the inverters creating the DC/AC conversion. Multilevel converters have also to be considered because they generate a reduced amount of output voltage harmonics [7]. As well multi-input converters are efficient devices for grid-connected hybrid PV or wind power systems [8]. Correspondingly a very important problem of stability in future power systems is considered in [9]. The system stability depends significantly on the interfacing DC/AC converter structures and control methods.

Using standard control methods such as PWM or SVCM (space vector control method) is not particularly effective because an inverter output voltage is formed as a sequence of rectangular and diversified in width steep pulses and comprises great content of higher harmonics (high THD_U). For this reason, an alternative based on the amplitude modulation (AM) of the inverter output voltage has been carefully considered. As a consequence, many inverter circuit proposals have been devoted to solutions based on the AM control method. These works generally relate to multilevel inverters [10–13]. Inverters with seven or more levels have been designed as grid-connected inverters acting as the interface between photovoltaic systems and the grid network. In [12], a 17-level inverter is presented, and in [13], a 31-level inverter is proposed.

Another class of inverters is based on the switched capacitor rule of operation [14–19]. These inverters use capacitor units to switch the subsequent states of the inverter. The inverter state change requires the overcharging of the capacitor. This class of inverters is generally used to form multilevel structures, e.g., 7-level structures and those with more than seven levels [17].

The simplest way to control the VSI is to switch every 60° appropriate transistor pairs of the two-level inverter.

Then, the VSI generates a phase voltage that varies stepwise. This method of voltage generation has certain advantages, including a simple control system and high efficiency of the inverter due to the negligible switching losses. The ratio of the voltage fundamental harmonic frequency to the switching frequency is equal to 6 and relatively high compared to other control methods. The modulation index expressing the relation U_D/U_{h1} is the highest in two-level inverters. The biggest disadvantage of such a control method is the considerable content of harmonics in the output stepwise voltage. For example, the total harmonic distortion factor (THD_U) in a single-phase inverter controlled in this way is approximately 31%. Furthermore, it is not easy to regulate the fundamental harmonic value of the output voltage. In this case, it is necessary to adjust the U_D voltage supplying the inverter or to use other methods. Therefore, this control method is rarely used in practice, although its weaknesses are diminished in multiphase inverters. An example of the six-phase inverter with a 60-degree output voltage is presented in [20].

However, there are some interesting possibilities concerning DC/AC converters composed of two two-level inverters, which are labeled, for the purposes of this paper, as orthogonal-vector-controlled inverters (OVTs). The disadvantage of the basic control concept, which is based on orthogonal vectors and has been presented in various works [21, 22, 23, 24], is that the combiner system, which includes the transformer, has to carry a large amount of power both on the main inverter side and also on the auxiliary inverter side. Considering the material costs and the resulting high-power handling design problems, the primary control of the auxiliary inverter is not very efficient. In this paper, a concept for the auxiliary inverter control is developed that enables a significant reduction in the size of the transformer used as a summing node in an orthogonal inverter [25].

2. Construction and operation of the OVT inverter and filter inverter

This paper presents a novel, modified proposal regarding the converter control method. This modification relates to the idea of a converter based on the orthogonal vector theory [21, 22]. The basic structure of the converter consists of two conventional two-level inverters. The operational idea consists of summing the voltage space vectors of the two inverters. These vectors are mutually orthogonal. The resultant output voltage space vector is formed as a combination (sum or difference) of the orthogonal space vectors generated by the individual inverters. This idea has an ability for recurrence, meaning it is possible to add a third successive inverter, or even more, to improve the output voltage [23]. Comparative experimental results are found in certain voltage waveforms obtained during laboratory tests [24].

The paper presents a novel proposal concerning the control process of the filtering auxiliary inverter (AI). In the standard solution of the OVT control method, the pulses generated by the AI are transformed directly to the output circuitry of the OVT Invert-er. An encouraging alternative assumes that these pulses are specifically divided in order to increase their frequency. Higher frequency means lower losses and smaller transformers. A few cases of such a method as well as their effect on the filtering capability and performance of the OVT inverter are well thought-out and presented by the use of simulation research tests.

The basic block diagram of the OVT converter is shown in Figure 1a. It consists of two standard two-level inverters: a main (MI) and an auxiliary (AI) inverter. The outputs of the inverters are connected via a summing node (SN). The concept of the formation of the output voltage vector of the OVT converter is shown in Figure 1b. The output waveform is formed as a result of adding two defined component waveforms. The space vectors of these waveforms are mutually orthogonal. The meanings of the symbols used are as follows:
$V_{\_MIk}$ — the voltage vector of the main inverter;
$V_{\_AIk}$ — the voltage vector of the auxiliary inverter;
$V_{\_OVTk}$ — the voltage vector of the output OVT inverter.

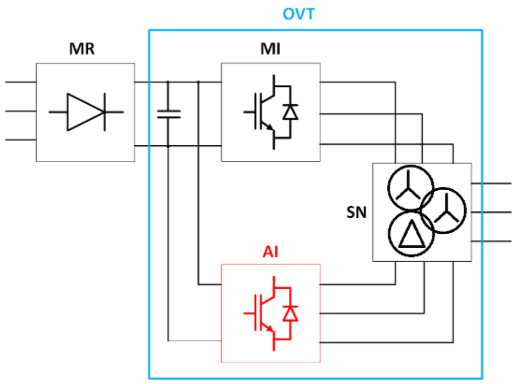


Fig.1. Scheme the OVT inverter.

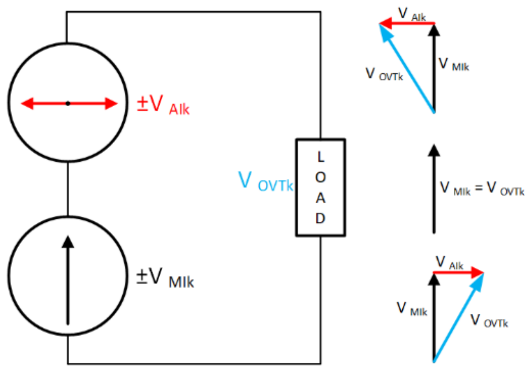


Fig.2. Concept of the vectors in the OVT inverter.

The (α, β) plane of the stationary coordinate system is divided into six equal k vectors corresponding to the active vectors V_{MIk} of the main inverter. Each sector of the plane accommodates three different output vectors V_{OVTk} generated by the OVT converter: two vectors as a result of the sum of the corresponding orthogonal vectors V_{MIk} and V_{AIk} one output vector equal to the vector V_{MIk} of the main inverter. In the latter case, the auxiliary inverter generates a zero vector. The output voltage waveform of the OVT converter is created by switching on successive sequences of three vectors: V_{OVT-}, V_{OVT}, V_{OVT+}, assigned to the k-th sectors of the plane (α, β).

The vectors are included in the order given in Equation (1):

$$
\begin{gathered}
V_{OVT-} = V_{AIk\oplus 3} + V_{MIk} \\
V_{OVT} = V_{MIk} \\
V_{OVT+} = V_{AIk} + V_{MIk}
\end{gathered}
\qquad (1)
$$

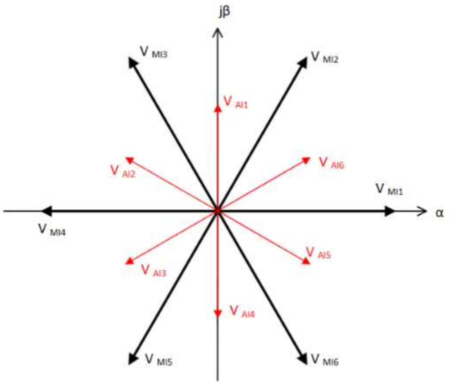


Fig.3. The active vectors of the main and auxiliary inverters.

Figure 4 shows a summary of the control vectors for the main and auxiliary inverters. The theoretical waveforms of the phase-to-phase voltages for each inverter are shown along with the vectors. In the basic configuration, the main inverter is connected to the load in a star configuration, but the auxiliary inverter is connected in a delta configuration. Figure 4 shows that the vectors of the auxiliary inverter are generated three times in one sector of the (α, β) plan, so the vector frequency of the AI is three times higher in relation to the vector frequency of the MI.

a)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
vectors / phases	v5	v5	v5	v4	v4	v4	v6	v6	v6	v2	v2	v2	v3	v3	v3	v1	v1	v1
a	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0
b	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	0	0	0
c	1	1	1	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1

b)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
vectors / phases	v3	v7	v4	v1	v0	v6	v5	v7	v2	v4	v0	v3	v6	v0	v1	v2	v0	v5
a	0	1	1	0	0	1	1	1	0	1	0	0	1	1	0	0	0	1
b	1	1	0	0	0	1	0	1	1	0	0	1	1	1	0	1	0	0
c	1	1	0	1	0	0	1	1	0	0	0	1	0	1	1	0	0	1

Fig.4. The theoretical waveforms (in black) of the phase-to-phase voltages corresponding to the control vectors for the main (a) and auxiliary inverters (b).

The time relationship between the MI and AI inverter vectors shown in Figure 4 applies to the basic control version. The modulator controlling the AI inverter, modified in [25], allows for an even greater increase in the auxiliary inverter frequency. The simulation studies presented below are intended to show the impact of the auxiliary inverter switching frequency on the orthogonal inverter operation.

3. Operation of the auxiliary inverter at different switching frequencies

In one period of time, the voltage sequence of the main inverter consists of 6 vectors, while the auxiliary inverter uses a sequence of 18 vectors at the same time. If we denote the nominal frequency of the orthogonal inverter by f_{OVT}, then the frequency with which individual vectors change in the auxiliary inverter can be calculated from the formula:

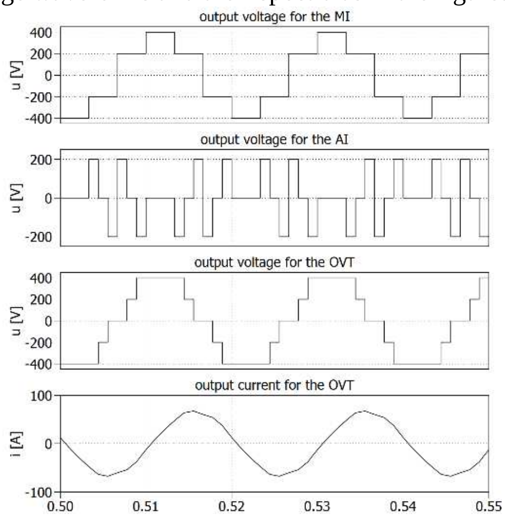
$$f_v = \frac{f_{OVT}}{v}, \qquad (2)$$

where v is the number of vectors used by the auxiliary inverter during one period, for example, where f_{OVT} = 50 Hz, frequency f_{AI} = 900 Hz.

Paper [5] describes three methods of modulation of the control signal for the auxiliary inverter, which will directly contribute to reducing the size of the summing transformer and improving the THD value. The presented solutions require verification of the changes' impact on the auxiliary inverter switching frequency on the orthogonal inverter operation and the signals parameters. The switching frequency (f_s) of the auxiliary inverter in the relation presented in [5] should be a multiple of the minimum frequency f_v given by relation (2).

$$f_s = nf_v, \qquad (3)$$

where n are the numbers 1, 2, 3…
Below are the results of simulation tests for fs from 900 Hz to 7200 Hz, which in terms of k gives values from 1 to 8. In addition to frequencies being an integer multiple of f_v, the influence of frequencies for which k = 0.5, 1.5, 2.5, 3.5, 4.5, etc. was investigated. Simulation tests were carried out for a summation node in the form of a set of transformers with a ratio of 200:600. The transformer ratio was selected due to the frequency fs = 2700 Hz. With this transformer ratio, the orthogonal inverter in the basic version presented in the figure 1 and in the publications [21,22,23] is characterized by current and voltage waveforms and their spectra as in the figures 5.



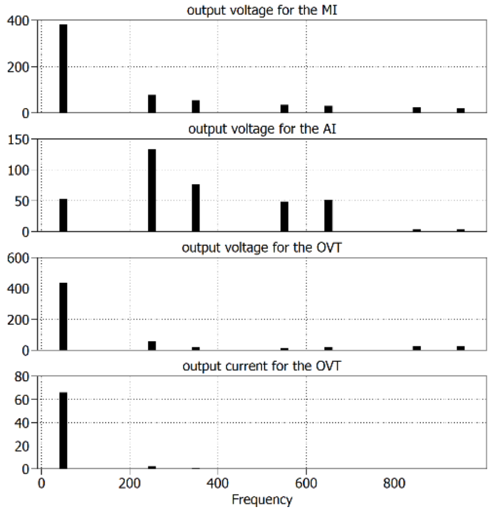


Fig.5. Voltage and current waveforms and their spectra for an orthogonal inverter without additional switching in the auxiliary inverter circuit.

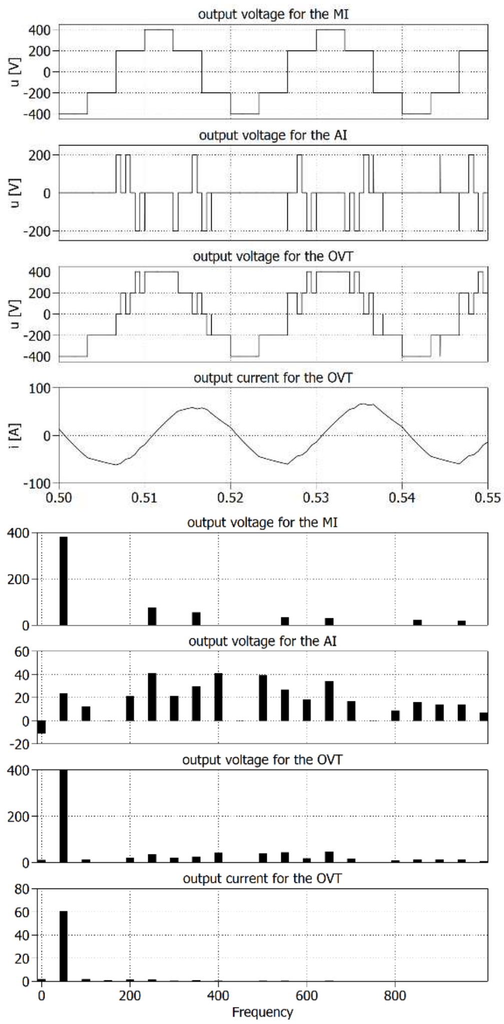


Fig.6. Voltage and current waveforms and their spectra for an orthogonal inverter with additional switching in the auxiliary inverter circuit at the frequency fs = 900 Hz.

If the switching frequency of the auxiliary inverter is too low, an irregular voltage shape can be seen in the voltage waveforms, which translates into the appearance of a constant component in the spectrum, which in the case of a transformer will cause a number of unfavorable phenomena (Figure 6).

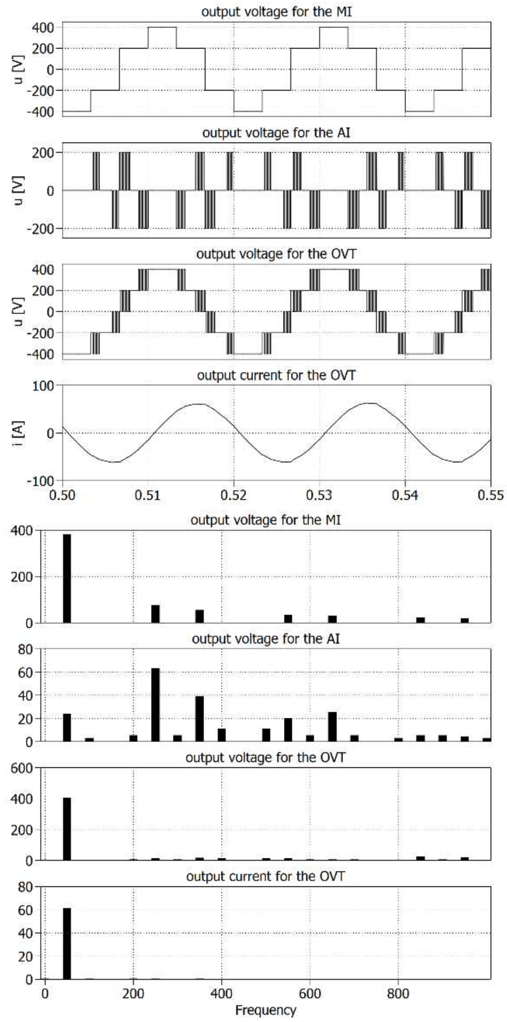


Fig.7. Voltage and current waveforms and their spectra for an orthogonal inverter with additional switching in the auxiliary inverter circuit at the frequency fs = 3600 Hz.

When increasing the switching frequency for the auxiliary inverter to 3600 Hz, that is, $f_s = 3f_v$, we already get a very satisfactory shape of voltages, currents and their spectra (Figure 7). On the other hand, Figures 8 through 10 show the distributions of THD coefficient and RMS values for main, auxiliary and orthogonal inverter currents and voltages as a function of frequency.

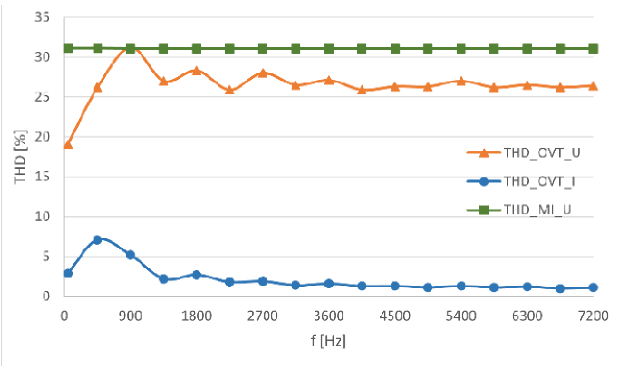


Fig.8. Changes in the THD factor as a function of the f_s frequency for the voltages and currents of the orthogonal and main inverter.

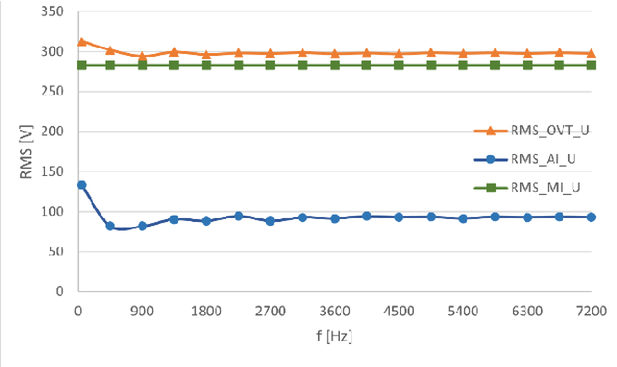


Fig.9. Changes in the RMS as a function of the f_s frequency for the voltages of the orthogonal, auxiliary and main inverter.

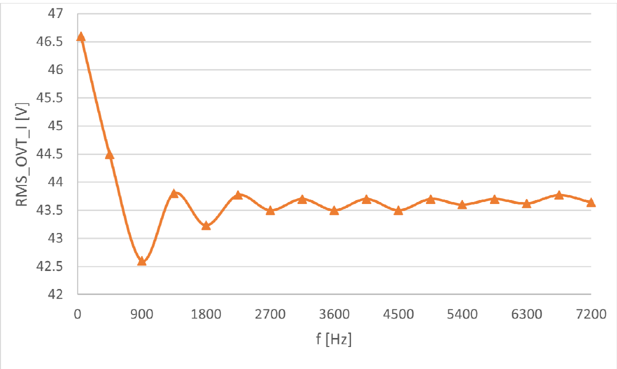


Fig.10. Changes in the RMS as a function of the f_s frequency for the orthogonal inverter current.

On the THD and RMS distributions shown as a function of the switching frequency of the auxiliary inverter, it can be seen that even at twice the switching frequency of the auxiliary inverter, the waveforms of its voltages and currents are acceptable - as are their spectra.

4. Conclusion

Należy uzupełnić wnioski końcowe.

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