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Output voltage control of the OVT inverter

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Abstract. The paper presents the possibility of the output voltage control of an OVT inverter. The idea of the OVT inverter construction is based on the orthogonal space vectors theory. The OVT inverter is built of two components two-level three-phase inverters: the main inverter (MI) and the auxiliary one (AI). The output voltage of the OVT inverter takes the shape of a stepped voltage analogous to the voltage generated by multilevel inverters. The paper demonstrates possible control methods of the output voltage frequency and amplitude. The results obtained during simulation studies prove that the output voltage essential parameters may be a function of the DC voltage and the control circuitry permits easy defining a selection of voltage/frequency characteristics.

Keywords. Space vector; vector orthogonality; three-phase OVT inverter; fundamental harmonic.

1. Introduction

The conversion DC/AC of a direct into alternating current is one of the most essential targets of contemporary power electronics. Such a necessity is required in AC drives as well as in the area of renewable energy applications e.g. smart grids. In both domains, the critical parameters that should be regulated are voltage amplitude and frequency although the regulation range of these parameters is quite different. A typical control system applied in AC drives includes an inverter acting as a DC/AC converter. The most practical control method PWM (pulse-width modulation) causes the output voltage takes the form of rectangular pulses. Therefore, in order to receive a sine wave voltage, it is usually obligatory to use a low band filter which is capable to select a fundamental harmonic voltage component.

There are many thinkable sources of DC voltage. Usually, electric energy is taken directly from the mains but in the present day, a lot of energy is delivered from renewable energy sources. For instance, the DC voltage is generated by such sources as photovoltaic or fuel cells. But the level of the DC voltage they deliver is strongly different. Such a form is not suitable for many applications and is particularly inappropriate to be directly connected to the grid. In consequence, it is obligatory to use two-step voltage adaptation: the DC/DC and subsequent DC/AC conversion. 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. Additional applicable DC/DC converters designed to be used in fuel cell power systems are also greatly discussed [4–6]. They generate the DC voltage to supply inverters forming the DC/AC conversion.

The OVT subject inverter might be numbered to multilevel inverters because it generates a relatively reduced amount of output voltage harmonics [7], so the OVT inverter is very suitable to apply as an interface between DC sources and the smart grid. Multilevel inverters as well as multi-input converters are efficient devices for grid-connected hybrid PV or wind power systems [8].

If the OVT inverter works as an interfacing device standard control methods such as PWM or SVCM (space vector control method) are not particularly effective because the output voltage is formed as a sequence of rectangular and diversified in width steep pulses and comprises a great content of higher harmonics (high THD_U). For this reason, an alternative based on the amplitude modulation method (AM) of the inverter output voltage has been carefully considered. As a consequence, there are proposals devoted to solutions based on the AM control method. They generally relate to multilevel inverters and many of them have been designed as grid-connected inverters acting also as the interface between photovoltaic systems and the grid network [9–12].

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 some advantages, including a simple control system and high efficiency of the inverter due to the negligible switching losses. What is more the ratio of the 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%. In addition, 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.
However, there are some stimulating possibilities concerning DC/AC converters constructed of two two-level inverters, which are considered, for the purposes of this paper, as orthogonal-vectors-controlled inverters (OVTs). The main advantages and disadvantages of the control concept based on orthogonal vectors have been presented and discussed in [13, 14, 15, 16]. The original control method of the auxiliary inverter didn't remain very efficient. The use of a transformer transferring relatively long pulses was the main disadvantage of the presented solution. A novel idea of the auxiliary inverter control method has been developed and described in [17]. This paper presents a novel, modified proposal regarding the OVT inverter control method. The recommended control method brought a significant reduction in the transformer size used as a summing node of the OVT inverter.

2. The OVT inverter

The basic block diagram of the OVT inverter is shown in Figure 1a. The idea and performance of the inverter have been developed and presented in the aforementioned publications [13, 14, 15, 16] as well as the modified proposal [17]. Built from two standard two-level inverters: a main inverter (MI) and an auxiliary one (AI) the OVT inverter generates 18 similar in-length space voltage vectors. The component inverters are specifically connected and supplied from one DC voltage source. The block diagram is presented in Figure 1. The next Figure 2 determines the rule of vector creation. The vectors are denoted as:
V_{MIk} — the main inverter voltage vector k;
V_{AIk} —the auxiliary inverter voltage vector k;
V_{OVTk} — the OVT inverter voltage vector k
and $k = 1, 2, 3, 4, 5, 6$.
The vectors V_{MIk} and V_{AIk} are mutually orthogonal and presented in Figure 3.

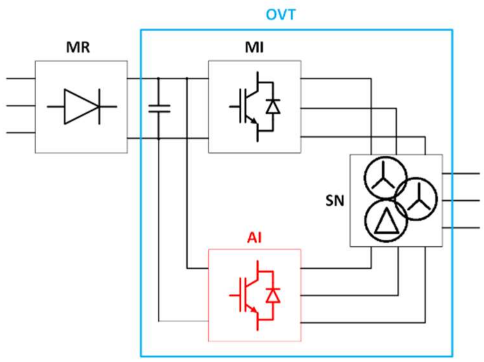


Fig.1. Scheme the OVT inverter.

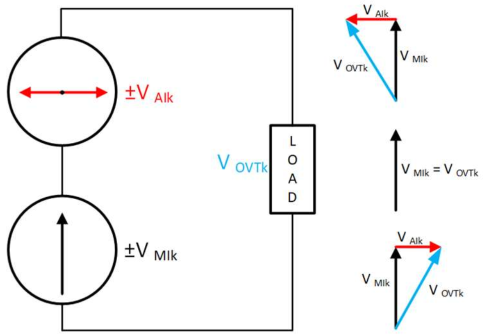


Fig.2. The formation concept of vectors V_{OVTk}.

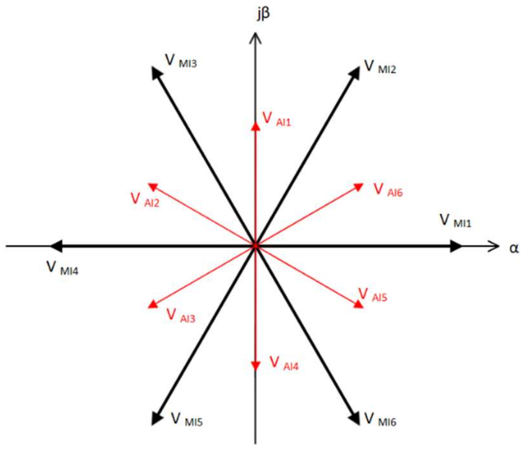


Fig.3. The active vectors of the main and auxiliary inverters.

In every of six k-sectors of the stationary coordinate system plane (α, β) the OVT inverter generates a sequence of three voltage vectors: V_{OVT-}, V_{OVT}, V_{OVT+}, assigned to the k-th sector of the plane (α, β). The order of generation is describing in in Equation (1):

$$\begin{aligned} \boldsymbol{V_{OVT-}} &= \boldsymbol{V_{AIk\oplus 3}} + \boldsymbol{V_{MIk}} \\ \boldsymbol{V_{OVT}} &= \boldsymbol{V_{MIk}} \\ \boldsymbol{V_{OVT+}} &= \boldsymbol{V_{AIk}} + \boldsymbol{V_{MIk}} \end{aligned} \quad (1)$$

Figure 4 shows a summary of the control vectors for the main and auxiliary inverters. Along with the vectors, the theoretical waveforms of the phase-to-phase voltages for each inverter are shown. In the basic configuration, the main inverter is connected to the load in a star configuration, while the auxiliary inverter is connected by use of a transformer working in delta-star configuration. Figure 4 shows that the vectors of the auxiliary inverter are generated three times frequently 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).

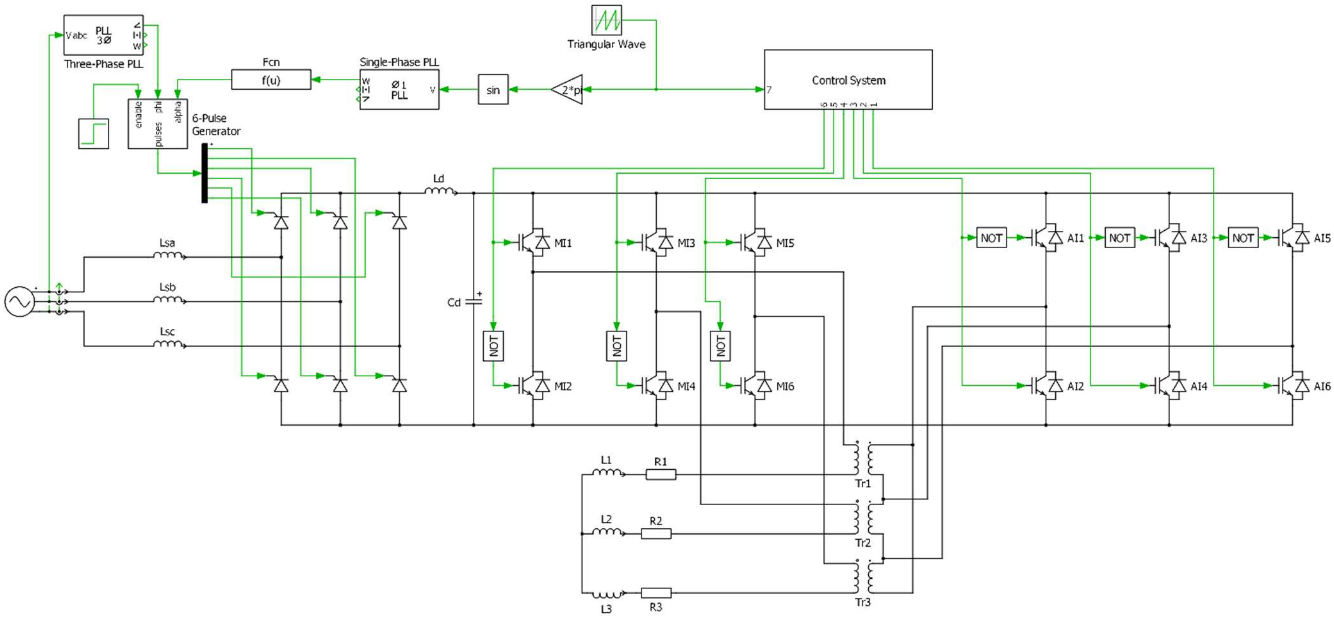


Fig. 5. The complete converter diagram under simulation tests.

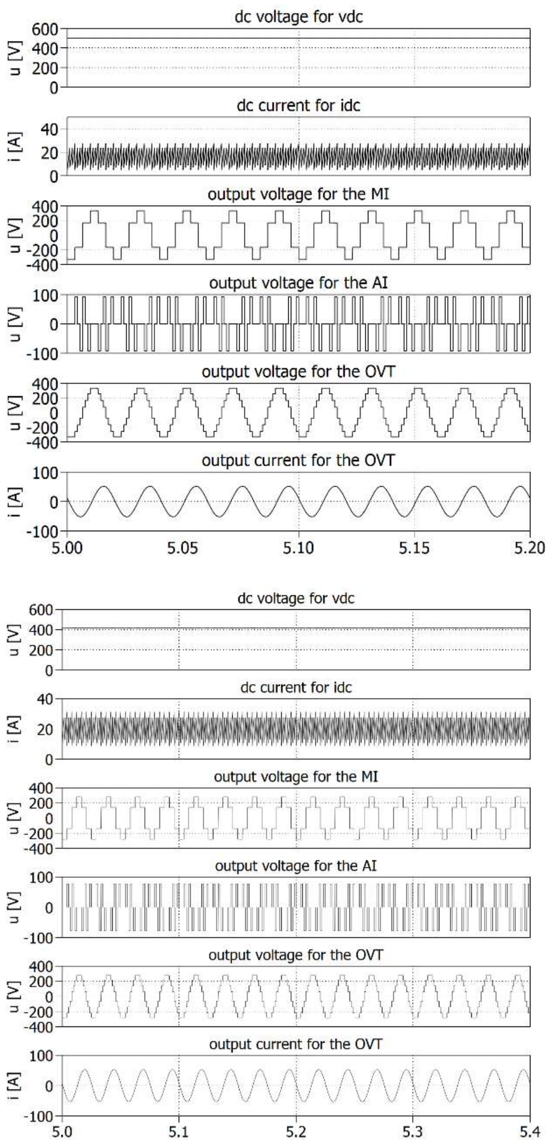
3. Simulation model and operation principle

Scalar control algorithm u/f = constant applied to the OVT inverter needs an additional converter who works as a rectifier providing the DC voltage to supply the OVT. The PWM control method is not used in OVT inverters because the idea of their operation is based on the assumption that the MI is switched possibly infrequently. The whole strategy of control is created on cyclical switching of defined vector sequences according to the rule presented in Figure 4. The auxiliary inverter AI is controlled synchronously to the MI and it acts as an active filter of the MI output voltage. Both inverters are DC voltage supplied, so it is easy to control the output voltage frequency and it’s impossible to adjust the output voltage level. In order to achieve this property a thyristor controlled rectifier has been used. Therefore the output average voltage of the rectifier depends on the control angle. An additional gamma filter, built from L_D and C_D elements, is connected to the rectifier output. The complete converter diagram is presented in Figure 5.

Realization of the u/f characteristic has need of a specialized control system. Its goal is to synchronize both MI and AI inverters according to the set output voltage frequency. At the same time it has to synchronize the thyristor rectifier’s operation. The block denoted as ***6-pulse generator*** obtains mains synchronous signals to the input ***phi*** from the PLL (phase locked loop) block. The ***alpha*** input of the block acquires calculated thyristor phase angles according to the function set into the block ***Fcn***.

4. Results of simulation tests

Figure 6 shows the preliminary results of the OVT control operation. The results demonstrate the OVT ability to generate voltage waveforms in a large scale of frequency. Three resulting examples taken for 50, 40 and 30 Hz illustrate suitable DC, AI, MI and OVT voltages and currents. The variable DC voltage source makes it possible to realize the control characteristic u/f = constant .



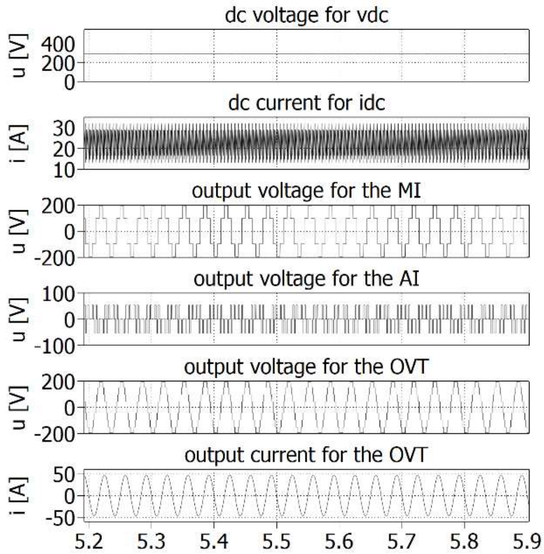


Fig. 6. Voltage and current waveforms received during simulation tests – set frequency 50, 40 and 30 Hz.

The results prove the evident ability of the OVT inverter to control the voltage level of available waveforms. All voltage and current waveforms save the same identical stepped character. However the most important consequence concerns to the rising length of subsequent pulses of the AI inverter for lower frequencies. The difficulty is related to the transfer of long pulses and such an operation requires special means and operations.
The next Figure 7 presents the OVT operation in case of urgent change of the set frequency: 30 to 50 Hz..

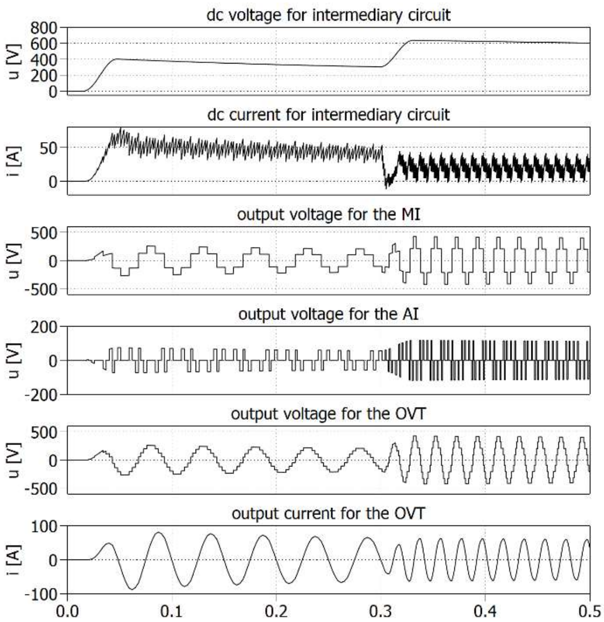


Fig. 7. Waveforms showing the voltages and currents for the OVT inverter during the frequency change from 30 Hz to 50 Hz.

Figures 8 and 9 show the spectra of the subsequent voltage and current waveforms: Figure 8 Figure 7 shows the spectra for the frequency of 20 Hz, and Figure 8 shows the spectra for the frequency of 50 Hz. In simulation studies, u/f was adopted at level 8.

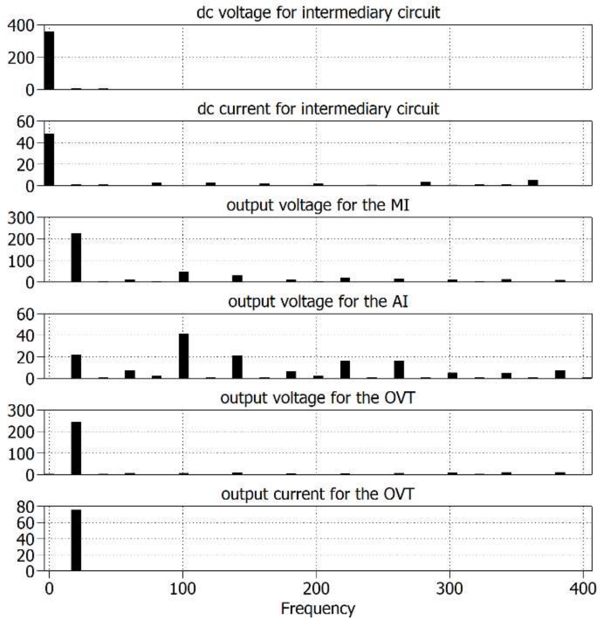


Fig.8. Spectrum for voltage and current waveforms with a frequency of 20 Hz.

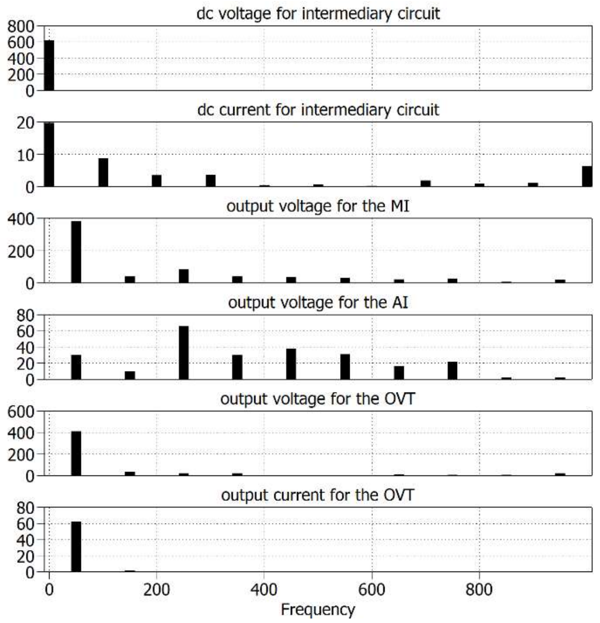


Fig.9. Spectrum for voltage and current waveforms with a frequency of 50 Hz.

In addition to simulation tests with RL load, simulation tests were performed with an induction motor as the load. The parameters of the induction motor used in the tests are listed in the table 1.

Table I. - Induction motor parameters

Parameters	VALUE
Pn [VA]	4000
Vn [Vrms]	400
fn [Hz]	50
Rs [ohm]	1.405
LIs]H]	0.005839
Rr' [ohm]	1.395
LIr' [H]	0.005839
Lm [H]	0.1722
J [kg m^2]	0.0131
F [N.m.s]	0.002985

p	2

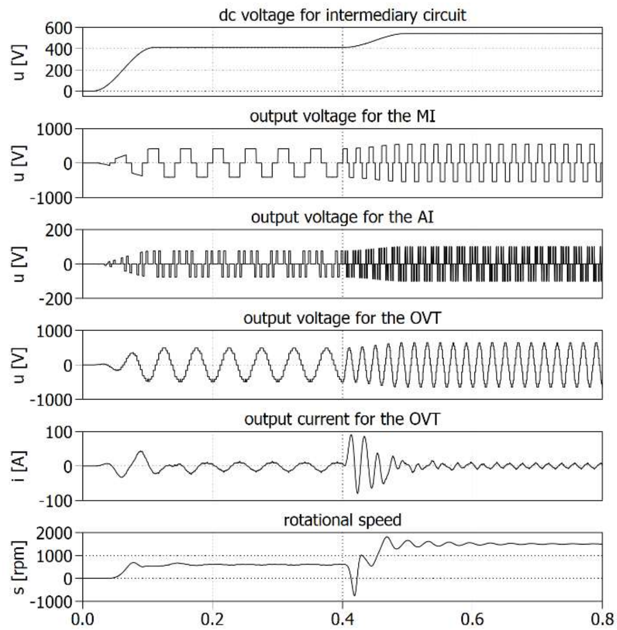


Fig.10. Voltage, current and speed waveforms for an orthogonal inverter feeding a 4 kW induction motor.

Figure 10 presents an example of simulation results for a 4 kW induction motor, which was powered by an orthogonal inverter, which implements a scalar voltage/frequency algorithm together with a thyristor rectifier. In the simulation presented here, the engine speed was varied from 600 rpm to 1,500 rpm.

Conclusions

The presented OVT inverter is suitable for the operation of an effective DC/AC conversion process. The total power of the OVT inverter may be very high, so is the power of the MI but the power of the AI inverter remains relatively low. Resulting in power losses of the complete OVT inverter as well as both MI and AI inverters are very low. The main inverter MI is switched only six times in one period of the voltage fundamental harmonic and power losses of the AI, equating to approximately just 5% ÷ 7% of the MI losses. Therefore, the control circuit of the complete OVT inverter can operate in the simplest way. The simulation results prove that the OVT inverter is able to control at the same time the output voltage frequency and amplitude but it requires a controlled source of the DC voltage. The OVT output voltage essential parameters may be a function of the DC voltage level and the control circuitry permits easy defining a selection of voltage/frequency characteristics. The voltage and current THD factors meet the limit values of the EN: 50160 standard.

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