Multilevel Convertors for Distributed Power Generation Systems with DC Voltage Sources

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Abstract

The paper is related to the problem of generating the high quality AC voltage waveforms in distributed power generating systems with DC voltage sources like photo-voltaic farms and fuel cells. A novel approach to the synthesis of AC voltage waveforms, applying chosen analytical methods like Fourier transform, Haar wavelets transform and orthogonal vectors method, is discussed. The simulation and experimental results for the proposed complex convertor's structures are presented in the paper.

Key words

Distributed power generation, multilevel convertor, amplitude modulation, waveform synthesis.

1. Introduction

There are two categories of renewable energy sources used in distributed power generation systems. AC sources like wind farms, where the power is transferred on the mechanical rotation basis, can use classical electrical machines to generate demanded 50 Hz sinusoidal voltage waveforms. In static DC sources like photo-voltaic farms and fuel cells the obtained DC power should be converted to AC using power electronics convertors. The quality of generated waveforms, especially **THD** (***Total Harmonic Distortion*** factor) should comply with the appropriate standards. Commonly for this purpose the two level **VSI**s (***Voltage Source Inverter***) controlled using **PWM** (***Pulse Width Modulation***) method are used. This method has well known disadvantages related to high frequency switching like power losses in switching elements and necessity of using special filters for high frequency components in the output voltages. These disadvantages can be reduced using multilevel convertors and amplitude modulation method.

The presented proposal deals with the topology and control strategy of multilevel convertors. Three different methods for synthesis of the output waveforms applying Fourier transform, wavelet transform and orthogonal space vectors method are discussed. The comparison of the results obtained using different methods as well as the impact of the used method on multilevel convertor's topology are also in the paper.

2. Fourier series waveforms synthesis

Given is function φ(x):

$$\varphi(x) = \begin{cases} 1 & \textit{for} \quad 0 \le x < \alpha, \\ 0 & \textit{for} \quad \textit{other} \quad x \end{cases} \qquad \alpha \neq 0$$

The scaling function $\varphi_n(x)$ is defined as following:

$$\varphi_n(x) = \varphi(x - n\alpha) \quad \textit{for} \quad n = \ldots,-2,-1,0,1,2,\ldots$$

Scaling function represents square pulse of unitary amplitude and duration α, The pulse position on x axis depends on parameter *n*. Some examples of the scaling functions are presented in Fig.1.

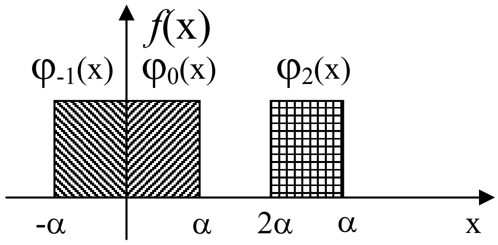

Fig. 1. Examples of the scaling functions: $\varphi_0(x) = \varphi(x)$, $\varphi_{-1}(x)$ and $\varphi_2(x)$

The transform of the function to generalized Fourier series based on the set of scaling functions (φ_n):

$$f(x) = \sum_{n=0}^{\infty} c_n \varphi_n(x)$$

where $$c_n = \frac{(f, \varphi_n)}{\|\varphi\|^2} = \frac{\int_a^b f(x)\varphi_n(x)dx}{\alpha}$$

Practically approximation consists in summation of finite number N of terms of the series. The accuracy of the approximation of the function *f(x)* in integral *<a,b>*, depends on parameter *α*. In power electronics applications the most important criterion of approximation accuracy of sinusoidal waveform is **THD**. An example of approximation of *f*(x)=sinx function for N=6 is presented in Fig. 2.

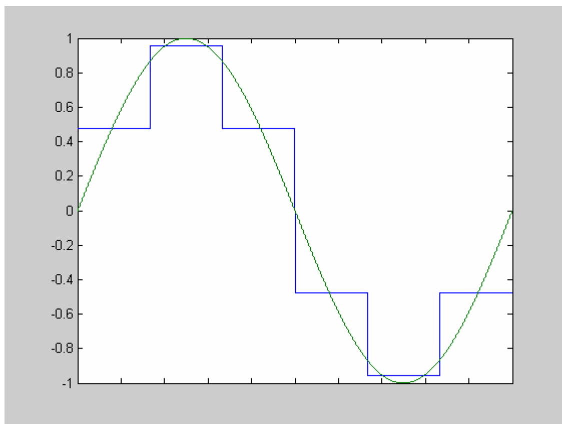

Fig. 2. The Fourier approximation of *f*(x)=sinx function for N=6

In Fig. 3 the spectrum analysis of this waveform is presented.

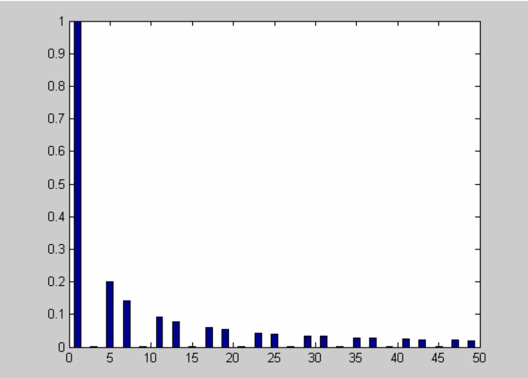

Fig. 3. The spectrum analysis of the waveform from Fig. 2. THD=31.09 %

The approximation of the same function for N=12 is presented in Fig. 4.

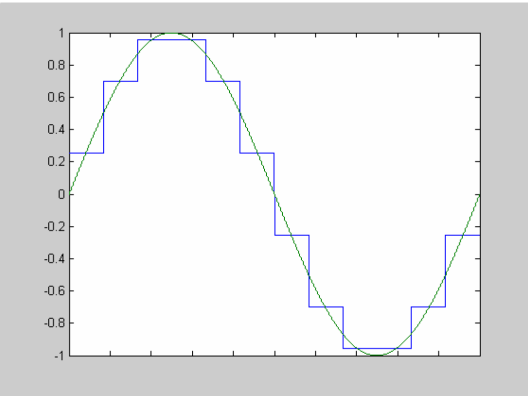

Fig. 4. The Fourier approximation of $f(x)=\sin x$ function for N=12

In Fig. 5 the spectrum analysis of this waveform is presented.

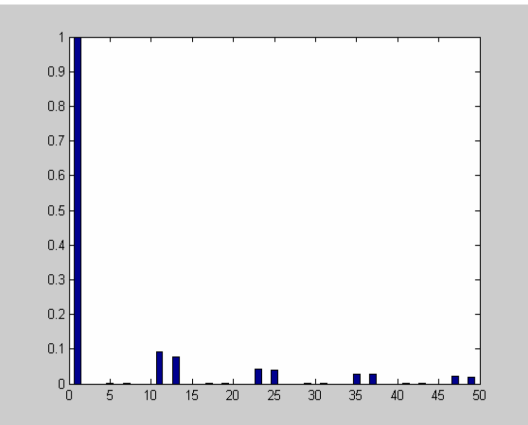

Fig. 5. The spectrum analysis of the waveform from Fig. 4. THD=15.23 %

The results of Fourier approximation for consequent N are collected in Tab.1.

Tab.1. Fourier approximation for different N.

F_N	α	$N_{\lvert F_N \rvert}$	*THD*
$F_{N=2}$	π	*1*	*48,37 %*
$F_{N=6}$	$\pi/3$	*2*	*31,09 %*
$F_{N=12}$	$\pi/6$	*3*	*15,23 %*
$F_{N=16}$	$\pi/8$	*4*	*11,41 %*
$F_{N=24}$	$\pi/12$	*6*	*7,63 %*

The parameter $N_{\lvert F_N \rvert}$ denotes the number of demanded independent supply voltage sources.

3. Wavelet waveforms synthesis

The wavelets is a term for mathematical functions, which allow the analysis of signals in different time scale and with different resolution. Thanks to this adjustable „scope of the view" the wavelets can be used to distinguish and analyse small and big details of the investigated process as well. Especially they are useful in analyse of discontinuous processes or processes with step level changing. The wavelets application are in many not directly related areas like seismology, video analysis, quantum mechanics or electronic. The term „wavelets" is the direct translation of french term *„ondelettes"* or *„petites ondes"*, which means „little waves".

Till now the wavelets have been used mainly for analysis of processes or signals based on decomposition of the elements of the processes. The following considerations will prove that wavelets can be also useful in composition of the power electronics signals and structures.

For this purpose the Haar wavelets have been adopted. The fundamental Haar wavelet $\psi(t)=\psi_{00}(t)$ can be constructed transforming the following scaling function $\varphi(t)$:

$$\varphi(t)=\begin{Bmatrix} 1 & \text{for} & 0\le t<1, \\ 0 & \text{for} & \text{other} \quad t \end{Bmatrix}$$

The composition of two consecutive scaling functions $\varphi(2t)$ and $\varphi(2t-1)$:

$$\varphi(2t)=\begin{Bmatrix} 1 & \text{for} & 0\le t<0{,}5), \\ 0 & \text{for} & \text{other} \quad t \end{Bmatrix}$$

$$\varphi(2t-1)=\begin{Bmatrix} 1 & \text{for} & 0{,}5\le t<1), \\ 0 & \text{for} & \text{other} \quad t \end{Bmatrix}$$

creates the Haar wavelet: $\psi(t)=\varphi(2t)-\varphi(2t-1)$

which can be described as following:

$$\psi(t)=\begin{Bmatrix} 1 & \text{for} & 0\le t<\frac{1}{2}, \\ -1 & \text{for} & \frac{1}{2}\le t<1, \\ 0 & \text{for} & \text{other} \quad t \end{Bmatrix}$$

The scaling functions and the fundamental Haar wavelet are presented in Fig. 6.

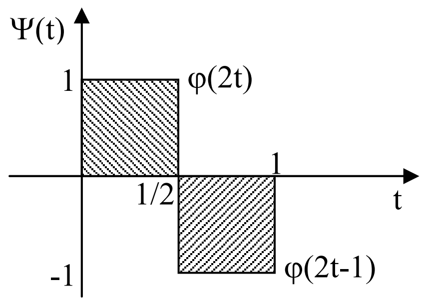

Fig. 6. The scaling functions $\varphi(2t)$ and $\varphi(2t-1)$ and the fundamental Haar wavelet $\psi(t)=\psi_{00}(t)$

By introducing two parameters: m – scale factor and n – displacement factor the generalised Haar transform is obtained:

$$\psi_{mn}(t) = \frac{1}{\sqrt{2^m}} \psi\left(2^{-m} t - n\right) \, for \; m, n = \ldots, -2, -1, 0, 1, 2, \ldots$$

The scale factor $\boldsymbol{m}$ – settles the width and amplitude of the wavelet, and the displacement factor $\boldsymbol{n}$ – settles the wavelet position on time axis.

The fundamental Haar wavelet corresponds to the factors: $m=0$ and $n=0$ and can be denoted as $\psi(t) = \psi_{00}(t)$.

Some examples of wavelets ($\psi_{10}(t)$ and $\psi_{12}(t)$) are presented in Fig. 7.

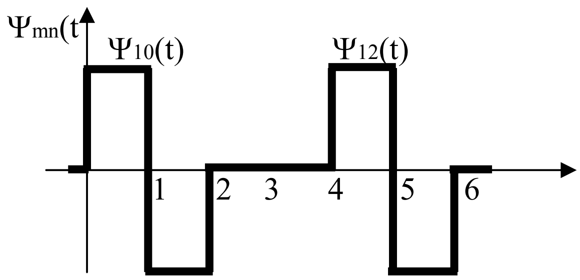

Fig. 7. Examples of the wavelets: $\psi_{10}(t)$ and $\psi_{12}(t)$

The Haar wavelet form is similar to the form of the voltage or current pulse that can be obtained using simple one-phase inverter. The displacement and width of the wavelet can be freely controlled. Thanks to these properties it is possible to apply wavelets in power electronics i.e. to form the output waveforms of multilevel convertors.

For the one-phase power electronics purpose the scaling function $\varphi(x)$ is defined in interval $x \in <0, 2\pi)$:

$$\varphi(x) = \begin{Bmatrix} 1 & for & 0 \le x < 2\pi, \\ 0 & for & other \quad x \end{Bmatrix}$$

The fundamental proposed wavelet is defined like the Haar one: $\psi(x) = \varphi(2x) - \varphi[2(x-\pi)]$

and can be expressed as following:

$$\psi(x) = \begin{Bmatrix} 1 & for & 0 \le x < \pi, \\ -1 & for & \pi \le x < 2\pi, \\ 0 & for & other \quad x \end{Bmatrix}$$

The wavelet transform is defined as follows:

$$\psi_{mn}(x) = \psi\left[2^{-m}\left(x - n2^{m+1}\pi\right)\right] for \; m, n = \ldots, -2, -1, 0, 1, 2, \ldots$$

where $2^m 2\pi = 2^{m+1}\pi$ is a wavelet carrier.

The x axis position is defined as n-times $2^{m+1}\pi$ displacement. The m factor scales not the wavelet amplitude but the carrier. All the wavelets $\psi_{mn}(x)$ are orthogonal in interval $x \in <0, 2\pi)$. For the wavelets of different m and equal n the integral:

$$\int_0^{2\pi} \psi_{m_k n}(x)\psi_{m_l n}(x) dx = 0 \quad for \quad k \ne l$$

because each wavelet with smaller carrier is contained in interval, in which the wavelet of bigger carrier is constant.

Let the approximation function $f_\psi(x)$ in interval $x \in <0, 2\pi)$ be a combination of wavelets with $m = -3, -2, -1, 0$. It can be denoted as a sum:

$$f_\psi(x) = \sum_{m=-3}^{m=0} \sum_{n=0}^{2^{-m}-1} a_{mn}\psi_{mn}(x) = \sum_{m=-3}^{m=0} \sum_{n=0}^{2^{-m}-1} f_{mn}(x)$$

where the functions $f_{mn}(x)$ are component wavelets of amplitude and phase defined by the factors a_{mn}:

$$a_{mn} = \frac{1}{N_m} \int_0^{2\pi} \sin(x)\psi_{mn}(x) dx$$

The function $f(x)$=sinx approximated using wavelets $f_{00}(x)$, $f_{-20}(x)$, $f_{-21}(x)$, $f_{-22}(x)$ and $f_{-23}(x)$ is presented in Fig. 8.

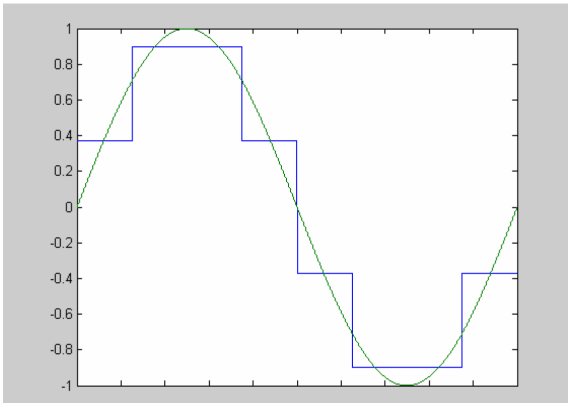

Fig. 8. The approximation of $f(x)$=sinx using wavelets $f_{00}(x)$, $f_{-20}(x)$, $f_{-21}(x)$, $f_{-22}(x)$ and $f_{-23}(x)$

The spectrum analysis of this approximated waveform is presented in Fig.9.

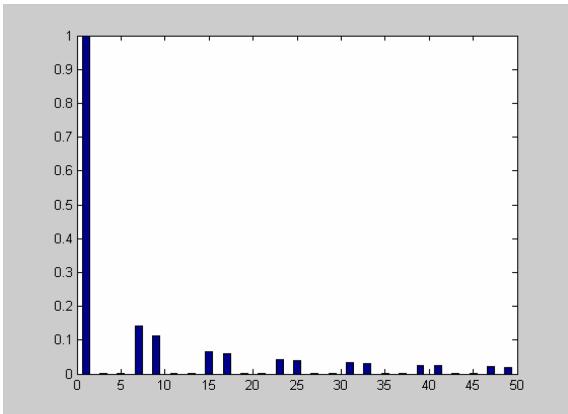

Fig. 9. The spectrum analysis of the waveform from Fig. 8. THD=23.06 %

The function $f(x)$=sinx approximated using wavelets $f_{00}(x)$, $f_{-2n}(x)$ and chosen wavelets $f_{-3n}(x)$ is presented in Fig. 10.

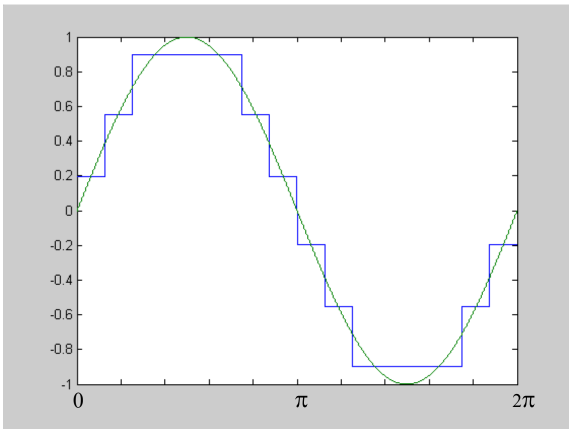

Fig. 10. The approximation of f(x)=sinx using wavelets f_{00}(x), f_{-2n}(x) and chosen wavelets f_{-3n}(x)

The spectrum analysis of this approximated waveform is presented in Fig.11.

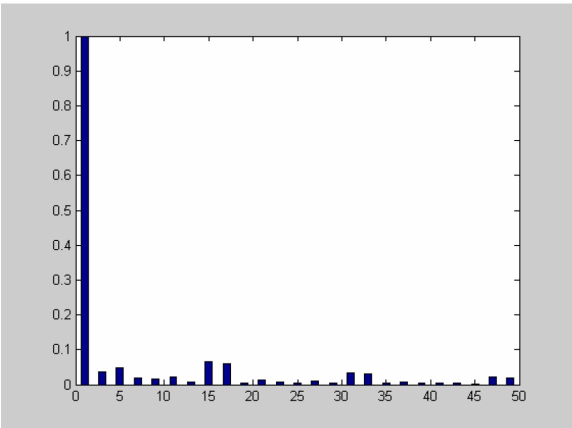

Fig. 11. The spectrum analysis of the waveform from Fig. 10. THD=13.70 %

The results of wavelet approximation for consequent N are collected in Tab.2.

Tab.2. Wavelet approximation for different N.

f_{ψ_k}	*α*	$N_{\lvert f_{\psi_k} \rvert}$	*THD*
f_{ψ_0}	***π***	***1***	***48,37%***
f_{ψ_1}	***π/4***	***2***	***23,60%***
f_{ψ_2}	***π/6***	***3***	***13,70%***
f_{ψ_3}	***π/8***	***4***	***11,44%***

The comparison between Tab. 1 and Tab. 2 shows that the for the same number of independent voltage sources the **THD** factor varies depending on the used transforming method.

4. Recurrence Orthogonal Vectors synthesis

The **OVT** convertor consists of two standard inverters: a main inverter (**MI**) and an auxiliary inverter (**AI**), connected together with the help of a summing node (S) which can be set up in a number of ways. The **MI** generates $\underline{V}_{Mk}$ space vectors while the **AI** generates space vectors $\underline{V}_{Ak}$, orthogonal to the **MI** vectors. The idea of the **OVT** convertor control is outlined in Fig. 12.

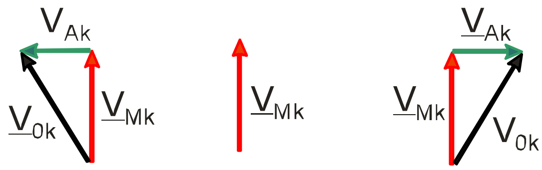

Fig. 12. The idea of the OVT convertor.

The **OVT** convertor generates 18 output voltage space vectors of similar length. The maximal value of the fundamental reaches 430 V and the **THD** ratio of the output voltage slightly exceeds 10,52 %.

The **OVT** convertor has been verified during laboratory tests in the **AC Drives and Control Laboratory** of the **Electrotechnical Institute** in Gdansk.

The idea of the **OVT** convertor has the property of recurrence. It is possible to duplicate the used mechanism of vector formation, and by adding a next **OVT** inverter (of adequately reduced power) it is possible to significantly improve the output voltage of the convertor.

The convertor (called **RECOVT**) consists of a main inverter (**MI**) and few auxiliary inverters: **AI1** to **Ain**, which are connected together with the help of a summing node **SN**. The sequence of nine voltage vectors generated by two stage **RECOVT** is presented in Fig. 13.

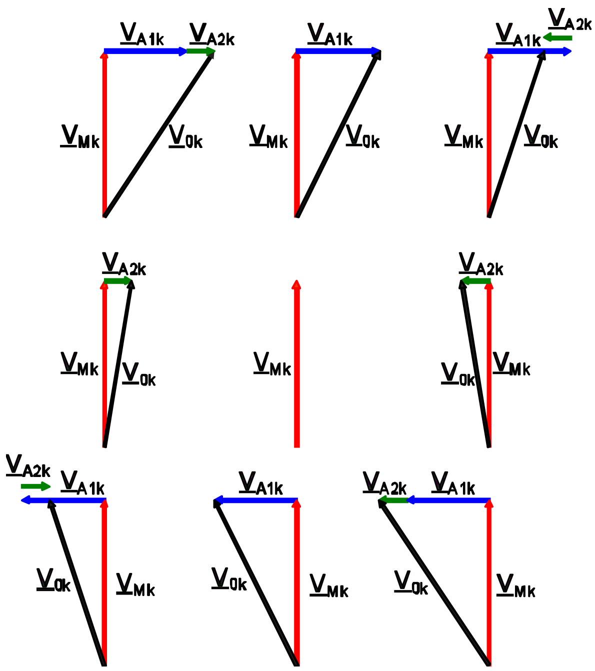

Fig. 13. The voltage vectors generated by two stage **RECOVT** convertor.

This convertor is able to generate 54 output voltage space vectors of the similar length. The **THD** ratio of the phase voltage does not exceed 5 %. The results obtained during laboratory tests of this convertor are presented in Fig. 14.

The complex convertor, built of i.e. four simple inverters, generates excellent output phase voltage with very low harmonic level.

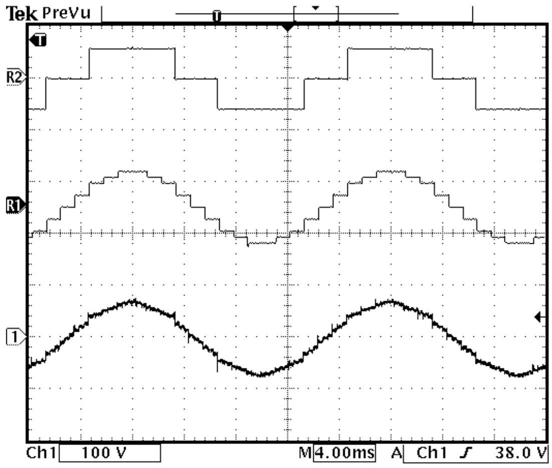

Fig. 14. The laboratory results for two stage **RECOVT** convertor

5. Topology considerations

The topology of multilevel convertor is dependent on the method used for its output waveform synthesis.

When the additive amplitude level modulation is used (i.e. **RECOVT** convertor) with Volage Source Inverters (**VSI**) as the building blocks the additional summing node is necessary. The summing node is realised in the form of the appropriate transformer.

The topology of two stage **RECOVT** convertor with summing node is presented in Fig. 15.

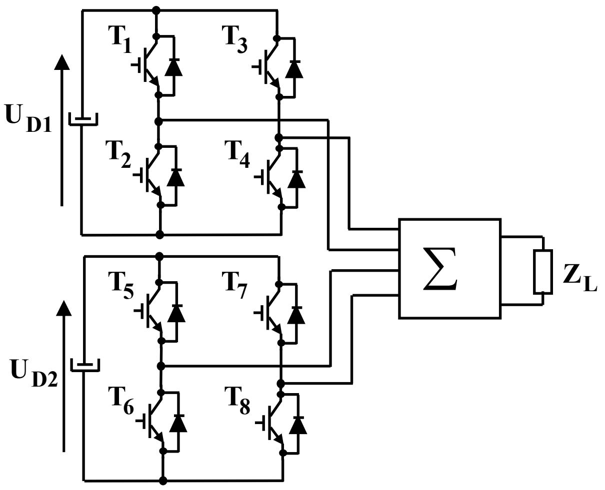

Fig. 15. The topology of two stage **RECOVT** convertor with summing node

The summing node in the form of transformer is a significant disadvantage of this circuit. Changing the building blocks or the control method it is possible to create the requested waveforms without the summing node.

When Current Source Inverters (**CSI**) are used as the building blocks of the multilevel convertor, the direct coupling without the summing node is possible independently of the synthesis method. The topology of multilevel convertor based on **CSI**s is presented in Fig. 16.

If the control method is based on independent voltage vectors distributed in time domain (synthesis based on Fourier or wavelet transform), the outputs of the inverters realizing different levels can be connected directly to the load. An example of this kind of coupling is presented in Fig. 17.

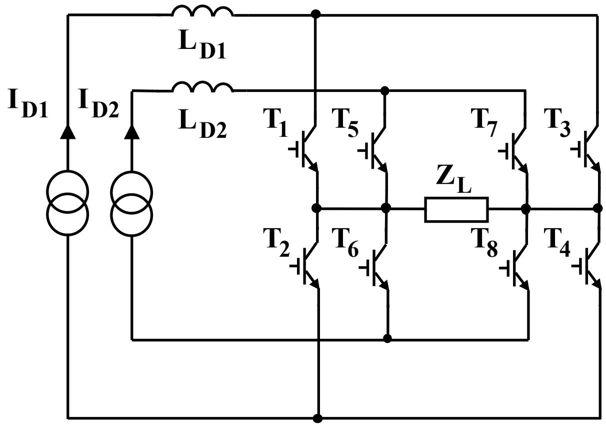

Fig. 16. The topology for direct coupled one-phase multilevel convertor with Current Source Inverters

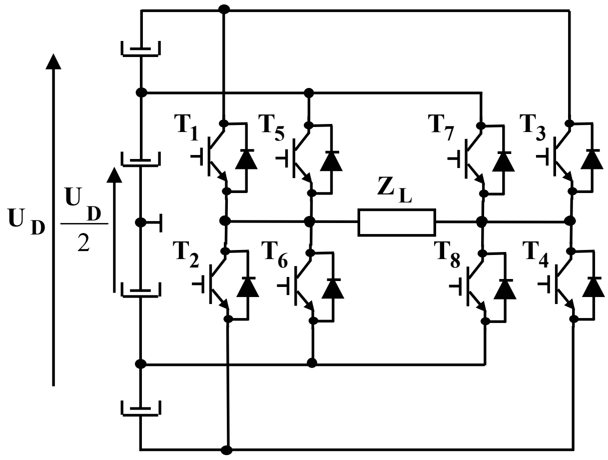

Fig. 17. The topology for direct coupled one-phase multilevel convertor

A simplified topology with only four switches is presented in Fig. 18.

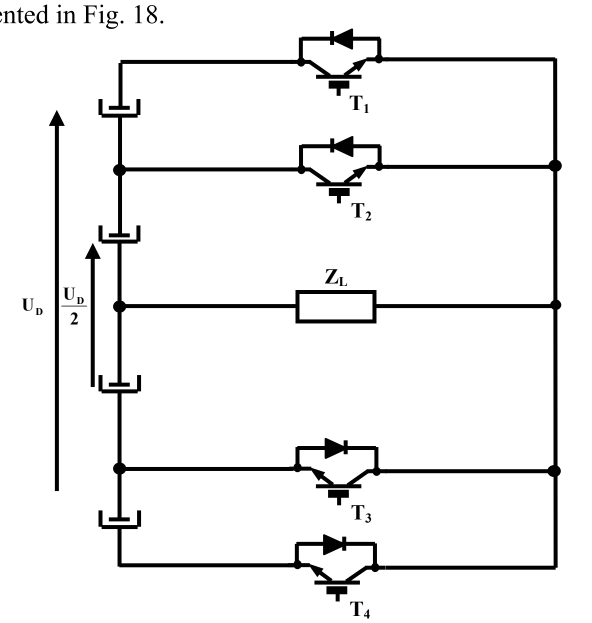

Fig. 18. The simplified topology for direct coupled one-phase multilevel convertor

5. Conclusions

The described methods for waveforms synthesis can be useful in designing convertors with low level of output harmonic distortion. Choosing the proper control method and topology of convertor it is possible to obtain the desired harmonic distortion level.

The proposed control methods for multilevel convertors have the following advantages:

- low harmonic content of the output voltage,
- low switching frequency of all inverters,
- low switching losses, related to switching frequency,
- relatively low power rating of AI inverters,
- relatively simple topology,
- simple convertor control circuit.

The possible application area belongs mainly to higher power convertors especially in distributed power generation systems with DC sources like photovoltaic or fuel cells with discrete voltage levels. In the sources of this kind there is an easy way to group cells to obtain the desired voltage levels for the multilevel convertor. This new solution becomes an attractive alternative to a traditional output filtering technique utilizing passive components.

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