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Restorer as a cascade inverter controlled by use of Haar wavelet transform

Kompensator napięcia jako kaskadowy falownik sterowany za pomocą transformacji falkowej Haara

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Abstract. The paper presents a three-phase cascaded voltage compensator designed as a multilevel cascaded inverter integrated with an energy storage system and a dedicated control scheme. The proposed system protects isolated power networks, such as those used in industrial applications, against short-duration interruptions, voltage sags, and dips. Two control strategies for the inverter are discussed. The first employs pulse-width modulation (PWM), while the second utilizes the Haar wavelet transform. The selected experimental and simulation results are provided.

Keywords: supercapacitor, voltage dips and sags, PWM, Haar wavelets, multilevel inverter

Streszczenie. W artykule przedstawiono trójfazowy kaskadowy kompensator napięcia, który został zbudowany jako wielopoziomowy kaskadowy falownik wyposażony w magazyn energii elektrycznej wraz z układem sterowania. Opisany model systemu może chronić izolowaną sieć, na przykład wykorzystywaną do celów przemysłowych, przed krótkotrwałymi przerwami, spadkami i zapadami napięcia. Zwrócono uwagę na dwie metody sterowania falownika. W pierwszej z nich zastosowano modulację szerokości impulsów (PWM), a w drugiej wykorzystano transformację falkową Haara. Zamieszczono także wybrane wyniki badań eksperymentalnych i symulacyjnych.

Słowa kluczowe: superkondensator, zapady i zaniki napięcia, PWM, falka Haara, falownik wielopoziomowy

Introduction

The low efficiency of the electrical grid results in significant energy losses and poor power quality, largely due to imperfect energy flows. Approximately 90% of grid disturbances are caused by voltage sags and short interruptions lasting less than one second. These events can lead to considerable losses in manufacturing and disrupt information systems. Improving grid efficiency requires optimized energy flows and effective compensation of voltage disturbances, achievable through deploying power electronics-based energy flow controllers. Such controllers must be implemented as fast, multilevel, high-precision inverters integrated with efficient energy storage, such as high-voltage, high-power stacked supercapacitors with aqueous electrolytes [1,2]. Prismatic supercapacitors with organic electrolytes are less suitable.

The work [3] describes a cascaded inverter topology controlled using the Haar wavelet transform and attaining low THD (total harmonic distortion). Various modulation schemes support inverter control strategies [4] which many of them are based on pulse-width modulation (PWM). However PWM method of control increases switching losses [5].

Assumed the grid's sensitivity to disturbances, it becomes essential to protect critical loads against outages. Traditionally, UPS systems with chemical batteries have been used; although compensators offer an alternative for short disturbances. A three-phase voltage restorer built with a cascaded multilevel inverter and a supercapacitor energy storage is presented in [6]. This topology offers advantages over conventional two-level inverters especially in waveform quality. Improvements to sag detection mechanisms are discussed in [7].

Compensators can be classified as a type of dynamic voltage restorers (DVR). DVRs based solely on supercapacitors (EDLCs) require minimal maintenance, unlike battery-based systems, but commonly introduce losses via series transformers [8]. Transformerless DVR designs have been proposed [9–11].

The compensator discussed in this paper is based on a cascaded multilevel inverter. Two inverter control methods are analyzed: PWM control and control using the Haar wavelet transform to generate a stepped approximation of a sine wave [12]. The anticipated performance suggests the compensator can fully regenerate voltage regardless of sag depth. Structures and methods improving sine wave approximation and THD minimization in multilevel inverters are addressed in [13].

Construction of the laboratory model

The first three-phase compensator laboratory model was built as a stand-alone and integrated device and tested in the Electrotechnical Institute Laboratory as part of the special research project COST/255/2009. The compensator consisted of three independent one-phase multilevel cascaded inverters and an energy store based on high voltage stacked supercapacitor-type EDLCs.

Each single-phase compensator is formed as a cascaded multilevel inverter built from two H-bridge units, which are independently supplied. This allows the utilization of semiconductor switches with lower rated voltage to receive output voltage waveforms of higher amplitudes. Another advantage concerns the number of possible voltage steps in the output waveform.

To realize the compensation process or active filtering, it is possible to use a transformerless connection between the compensator device and the power grid voltage [9]. A simplified diagram of a suitable single-phase circuit is shown in Fig. 1.

Energy exchange between the network and the supercapacitor provides the cascade inverter consisting of two H-bridge inverters connected in series and supplied by two DC/DC intermediary circuit converters

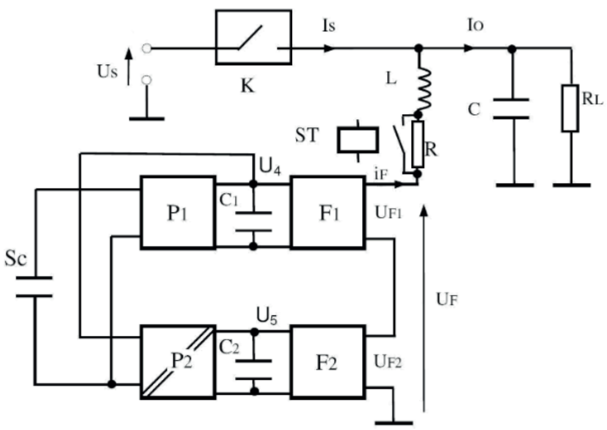

Fig. 1. The simplified block diagram of one phase of the three-phase voltage outage compensator

(P1 and P2) shown in Fig.1. The load consists of three phase impedances Z = RL + jωL connected to phase outputs L1, L2, L3 (Fig. 2). Symbols L and RL denote the parameters of the load. The switch K is usually closed, allowing energy flow from the mains to the load and the compensator. It must be disconnected at the specific instant of voltage interruption or dip when the compensator supplies power-sensitive loads.

Experimental tests were undertaken on a more complicated compensator circuit, a block diagram of which is shown in Fig. 2. The compensator has been developed by adding two DC/DC converters. Their task is to maintain a standardized and controlled voltage level supplying the particular H-bridges of the compensator. Additionally, two capacitors, C1 and C2, were connected.

The compensator consists of three identical phase inverters. Each inverter is connected in parallel to the appropriate phase of the protected network and operates independently. The digital controller assures the proper work of the system consisting of network, load, and compensator.

Every phase of the compensator is equipped with one block of supercapacitors, creating an energy store. To supply each H-bridge separately, a high-frequency transformer was used. The main energy storage in each phase is accomplished using a high-voltage supercapacitor Sc 2 F/300 V, manufactured by ECOND. The energy storage capacity of this component is approximately 90 kJ.

The adopted compensator topology requires the use of mutually isolated power converters (blocks P1 and P2) and inverter bridges (F1 and F2), forming an asymmetrical multilevel inverter operating as an inverter or rectifier and charging the supercapacitor Sc energy storage. The converters were constructed using electro-insulated IGBT Mitsubishi modules IPM 200 A/1200 V. Every module contains two transistors with diodes and gate circuits. For the cores of the inductive components: transformers and reactors, an amorphous magnetic material with high saturation induction (type 2605SA1, Metglas) in the form of a slot-shaped CC was chosen. As an AC switch K, a thyristor electro-insulated module with a rated current of 125 A (Crydom) is used.

The converters F1 and F2 are connected to the grid through an LC filter circuit and the resistor for precharging electrolytic capacitors C1 and C2 to establish intermediate constant voltages of U4 and U5, which can be bypassed by the switch.

The three-phase energy storage facility is located in a separate compartment and connected to the compensator by a cable line.

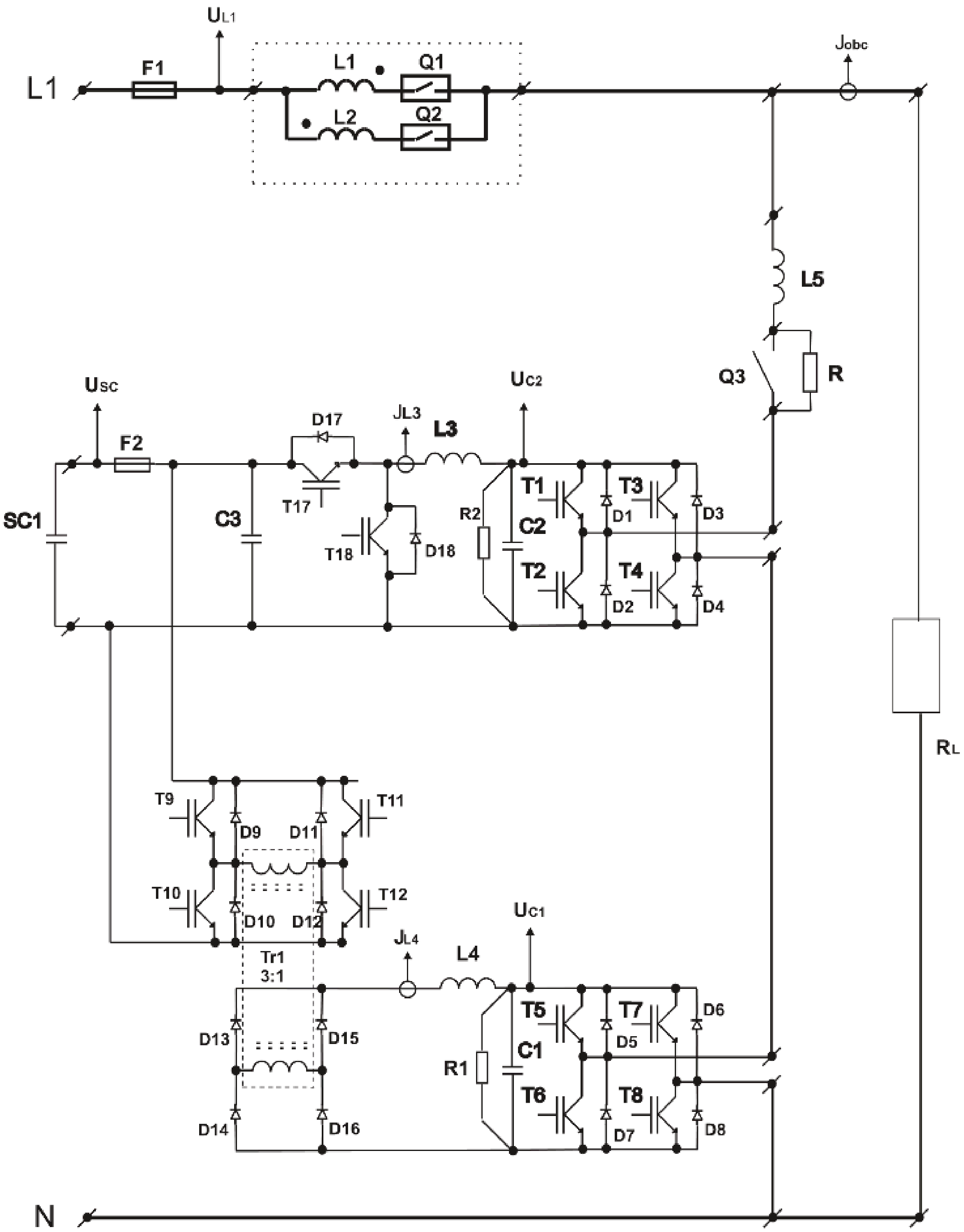

Fig. 2. The simplified block diagram of one phase of the three-phase voltage outages compensator

Description of the Compensator Algorithm

The operation of the compensator requires the realization of multiple concurrent real-time control tasks. To solve the complexity of these issues, a finite-state machine (called a finite automaton) was created in the controller of the compensator [3]. Six basic states of operation were distinguished in the control algorithm: **STOP** – off – no mains power; **CHARGE C2** – the device is powered and supply voltage (Us) is normal. Capacitor C_2 is charged to the voltage $U_5 = 0.33A_1$, where A_1 is the first harmonic amplitude of the mains voltage; **CHARGE C1** – the device is powered and supply voltage (Us) is normal. Capacitor C_1 is charged to the voltage $U_4 = 0.8A_1$; **WAIT** – standby – waiting for dip or voltage outage; **CHARGE Sc** – charging the supercapacitor Sc in a given compensator phase. The charger raises and maintains the level of the supercapacitor voltage at $U_{sc} = U_{p2} = 300$ V; **INVERTER** – based on the energy stored in the supercapacitor Sc, the phase voltage is generated using the cascade inverter. The device enters this state after the identification of a voltage dip or power failure.

Experimental Results

An example of a step waveform of a cascade inverter is shown in the oscillogram (Fig. 3).The referenced waveform of the voltage is denoted u_{ref}, while the phase voltage is u_{out}. The control error is denoted d_u and determines the difference between the network and stepped voltage: $d_u = u_{ref} - u_{out}$. The phase-to-phase voltage of the cascade converter is also presented as the waveform E. The presented voltages u_{ref}, u_{out} on the oscillogram (Fig. 3) were normalized against the supply voltage E.

The next figure shows the voltage waveforms, illustrating the operation of the compensator in response to grid voltage disturbances.

The most important question of such voltage restorers, as presented above the compensator, is concerning the rapidity of the compensator's reaction in response to grid voltage disturbances such as voltage dips and interruptions (Fig.4). The oscillograms in Figure 4 show the system's response to voltage collapses. The sine-shaped voltage is the voltage coming from the power grid, and the system generates the stepped voltage when a voltage collapse is detected. When the grid voltage is detected again, the system shuts down.

The possible fastest switching from the network to the supply voltage of the supercapacitor energy storage as well as back switching after restoration of the network voltage, is the key characteristic of the compensatory system and strongly depends on the key applied. The slight deformation of the obtained voltage around zero crossing points is caused by the properties of the thyristor switching at low voltages.

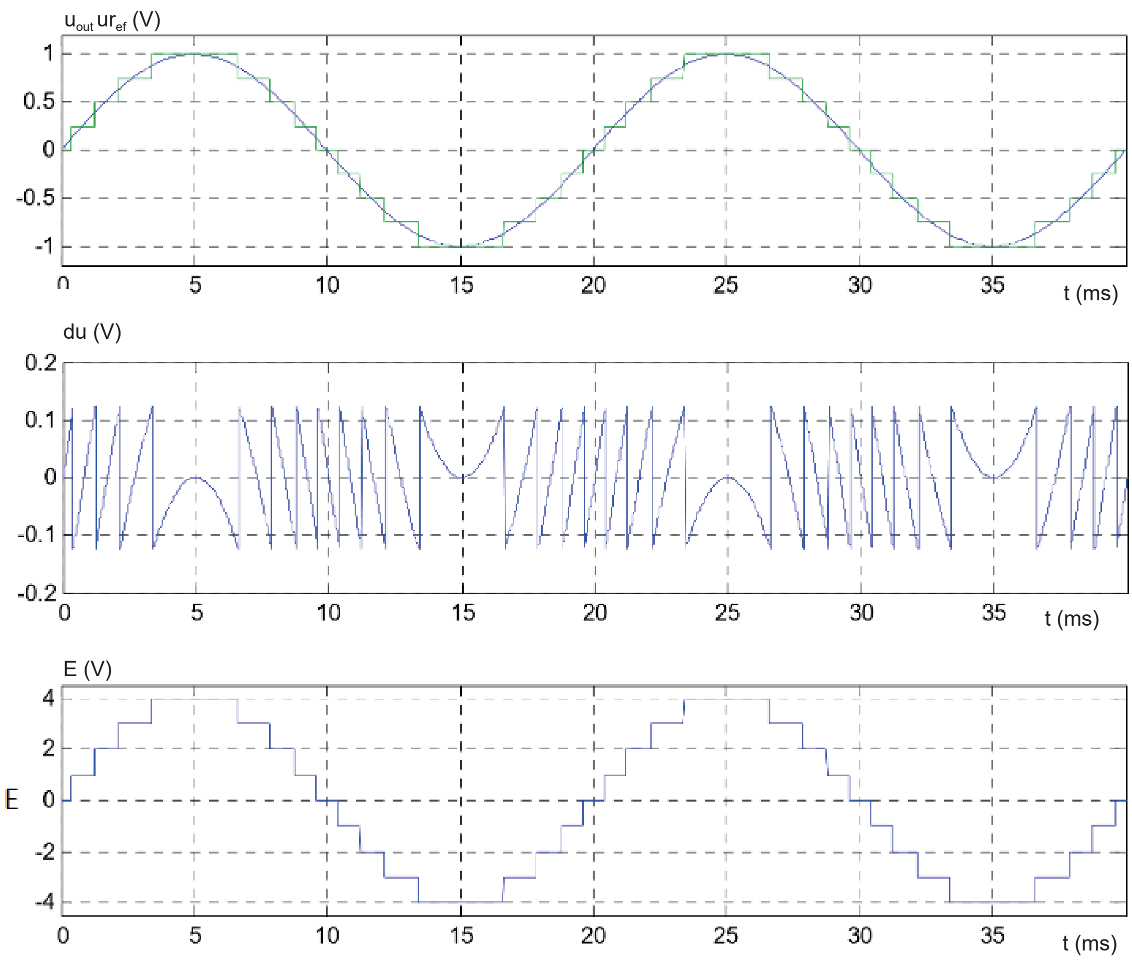

Fig. 3. The referenced and output voltage – u_{ref}, u_{out}, the control error – d_u, and the phase-to-phase voltage – E

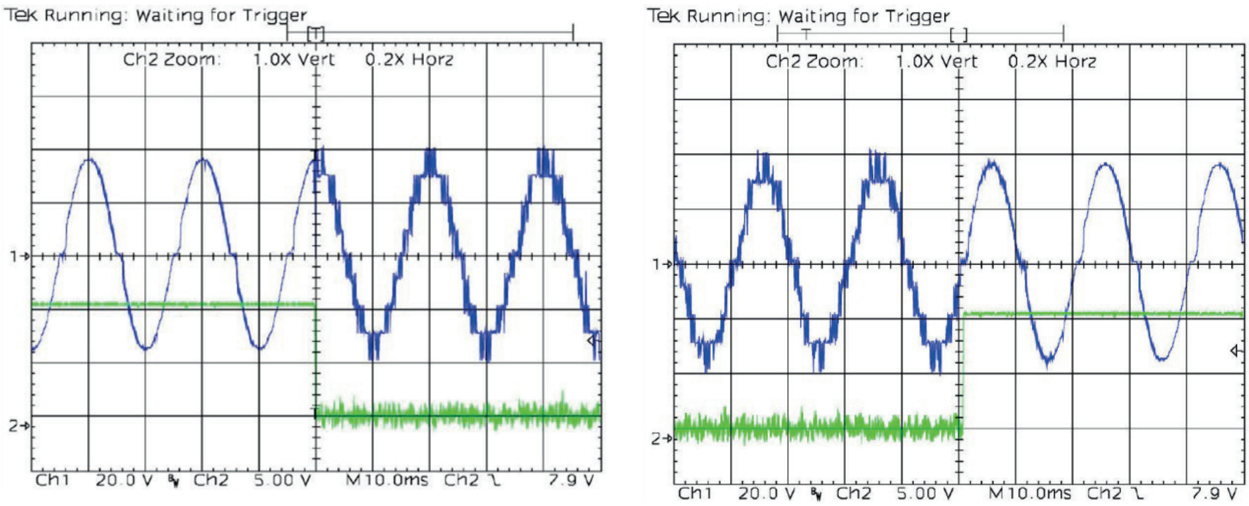

Fig. 4. Laboratory test waveforms showing the start (a) and the end (b) of voltage generation by the cascaded inverter

Model of the Compensatory Cascaded Inverter Controlled by the Use of the Haar Wavelets

The Haar wavelet form is similar to the form of the voltage or current pulse that can be obtained using a simple one-phase inverter i.e. H-bridge cell. The displacement and width of the wavelet can be freely created and controlled. Thanks to these properties it is possible to apply wavelets in power electronics e.g. to form the output stepped waveforms of multilevel converters [14].

The wavelet determines one period of the rectangular wave and is the mother function, introducing a family of wavelets:

(1) $$\psi_{min}(x)\ \psi(2^{-m}x - 2\ \pi n) \text{ for m, n} = \\ = \ldots, -2, -1, 0, 1, 2, \ldots$$

The wavelet scale is done as $2^m 2\pi$, and its displacement on the x-axis is determined as n-times $2^{m+1}\pi$. A m factor scales not only the wavelet but also the amplitude. The scaling function and a few wavelets have been presented in Fig. 5. All wavelets $\psi_{mn}(x)$ are orthogonal in the interval $x \in <0,2\pi)$.

The proposed method, based on wavelet transform, is very suitable for cascade converters even though it demands independent voltage sources. In each phase of the complex converter, the component inverters are supplied from two independent voltage sources: U_{D1} and U_{D2}.

Simulation tests were carried out in the PLECS program and the RT Box device, which enables HIL (hardware in the loop) simulations. In simulation tests, the cooperation of the proposed inverter with a resistive-inductive load was checked.

Simulation Results

In the simulation studies, the operation of the cascade inverter was compared in the case where the control signals were uniform (they formed equal steps) and in the case where the control signals were calculated from the Haar wavelet. The simulations were performed in the PLECS program. The main frequency was 50 Hz, and the load consisted of resistance and inductance, with the value R = 10 Ω and L = 30 mH. Figure 6 shows the results for the step approximation, and Figure 7 for the Haar wavelet approximation.

Table 1 shows the summary of the output voltage and current parameters.

Table 1. Output voltage and current parameters

Control type	RMS u_{out}	RMS i_{out}	THD u_{out}	THD i_{out}
uniform (steps)	300.9 (V)	20.9 (A)	32 (%)	7.63 (%)
Haar wavelet	344.3 (V)	24.43 (A)	23 (%)	3.57 (%)

Conclusions

The model of the compensator presented in this paper permits the compensation of dips and short-term interruptions in a three-phase four-wire grid. The device consists of three one-phase cascade multilevel voltage converters. The high-voltage stacked supercapacitors are used as energy storage of the compensator, and the supercapacitors do not need any service.

It is possible and advantageous to use compensators based on supercapacitors to protect sensitive processes in the public sector or industry. The compensators in question can react against interruptions or voltage dips in supply networks, as well as they can suppress disturbances in networks with disruptive

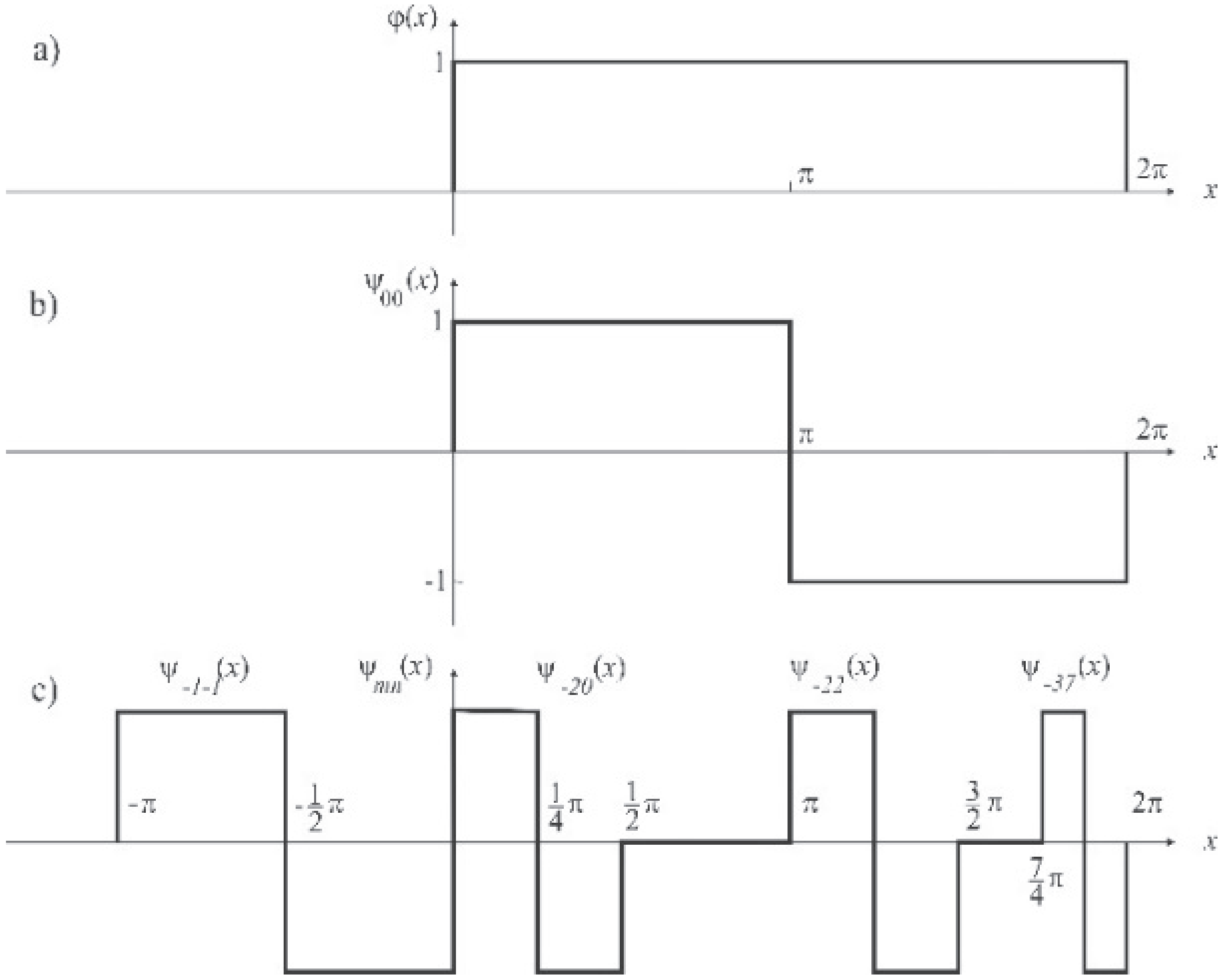

Fig. 5. The scaling function φ (x) and wavelets ψ_{mn} (x): a) scaling function φ(x), b) fundamental wavelet ψ_{00} (x), c) wavelets y_{-1-1} (x), y_{-20} (x), y_{-22} (x), y_{-37} (x)

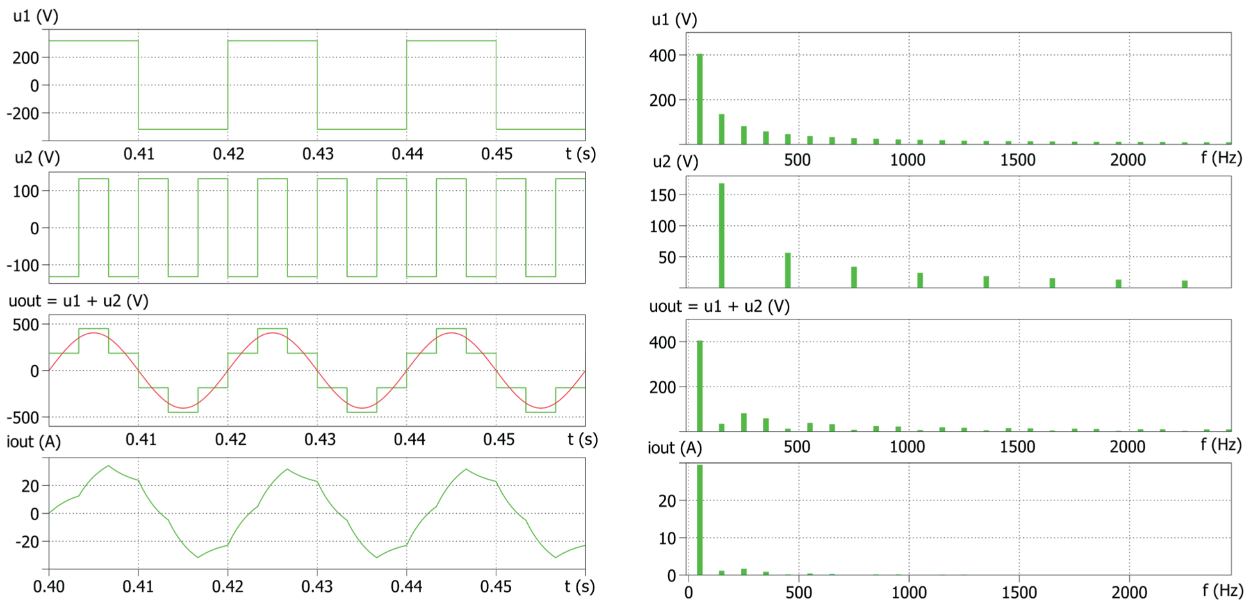

Fig. 6. Voltage and current waveforms for controlling uniform signals (a) and their spectra (b)

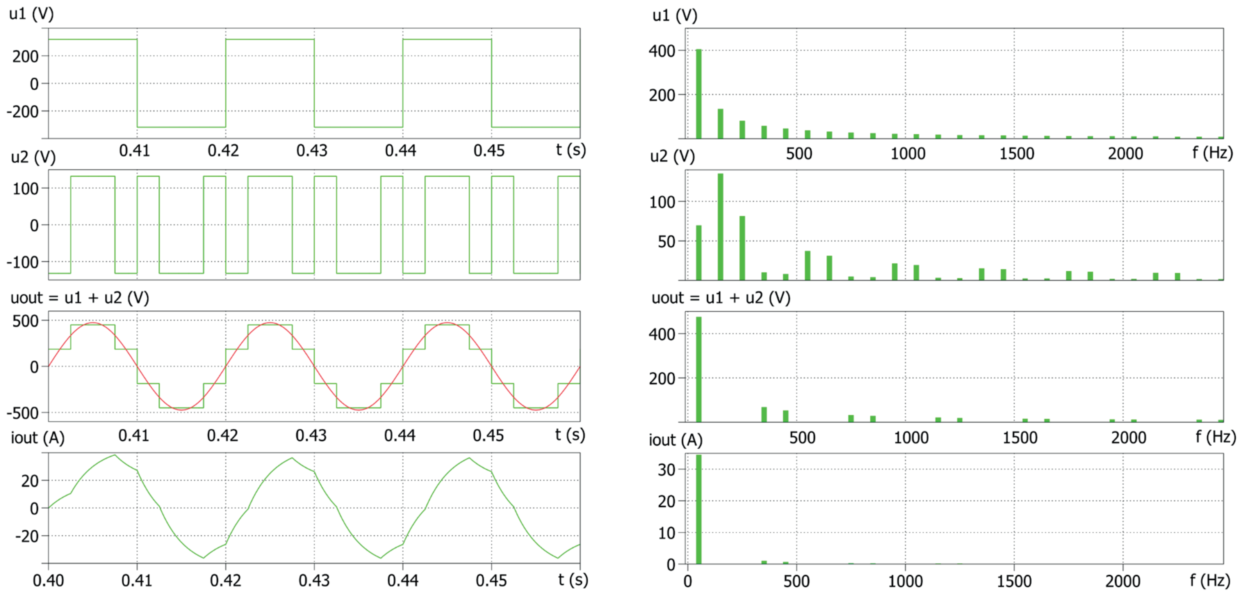

Fig. 7. Voltage and current waveforms for controlling Haar wavelet signals (a) and their spectra (b)

sources. The different supply voltages needed to energize successive steps of the cascaded inverter are easily available in small photovoltaic farms.

The control method based on Haar wavelets is extremely suitable for higher power converters, thanks to a limited number of switching states in comparison to the PWM method.

Simulation studies have shown that the use of signals calculated from the Haar wavelet to control a cascade inverter consisting of two H-bridges (two inverter levels) allows for obtaining better parameters of the output voltage and current spectrum. A similar situation applies to THD and RMS for voltages and currents at the same values of resistance and inductance in the load. Expanding the cascade inverter with additional inverters would result in further improvement of the considered parameters.

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