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Off-grid system with configurable inverters, magnetically coupled chokes and LC low-pass filter

Działanie systemu off-grid z konfigurowalnymi przekształtnikami, magnetycznie sprzężonymi dławikami i dolnoprzepustowym filtrem LC

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Abstract. The paper presents the operation of a three-phase voltage converter with configurable DC inputs and multilevel AC output, which has been adapted to cooperate with photovoltaic systems. The developed converter uses a magnetically coupled choke system, which allows conversion from a 3-phase system to a 6-phase system or vice versa and shows filtering properties, which can be improved by adding capacitances in parallel and using inductances resulting from the choke system. The chokes and capacitances form a low-pass LC filter. This possibility has been demonstrated in simulation studies.

Keywords: inverter, magnetically coupled chokes, PV, photovoltaics, composite converter

Streszczenie. W artykule przedstawiono działanie trójfazowego przekształtnika napięcia z konfigurowalnymi wejściami DC i wielopoziomowym wyjściem AC, który przystosowano do współpracy z systemami fotowoltaicznymi. Opracowany przekształtnik wykorzystuje system dławików sprzężonych magnetycznie, który umożliwia konwersję z układu 3-fazowego na 6-fazowy lub odwrotnie i wykazuje właściwości filtracyjne, które można poprawić przez dodanie równolegle pojemności i wykorzystanie indukcyjności wynikających z systemu dławików. Dławiki i pojemności tworzą dolnoprzepustowy filtr LC. Możliwość taka została wykazana w badaniach symulacyjnych.

Słowa kluczowe: falownik, dławiki sprzężone magnetycznie, PV, fotowoltaika, przekształtnik złożony

Introduction

Rapid development in renewable energy technologies significantly impacts power electronics, stimulating the emergence of advanced converter solutions [1,2]. Integration and efficient conditioning of energy from renewable sources into power systems is a critical challenge [2,3]. Voltage inverters dominate the key power electronic components extensively utilized in renewable energy systems (RES) [4].

Traditional two-level voltage-fed inverters remain widely used in low-power systems due to simplicity [4,5], whereas multi-level inverters (MLIs) have become essential in higher-power applications [6,7]. MLIs offer several advantages over conventional designs, including lower switching voltage stresses, reduced dV/dt, increased reliability, decreased complexity, and improved total harmonic distortion (THD) [8,9].

Despite these benefits, existing multi-level inverter systems frequently involve complex structures and intricate control strategies, often requiring numerous electronic switches and additional filtering components [10–12]. Consequently, research into simpler, more robust configurations with fewer components remains highly relevant.

This paper proposes a new converter configuration that leverages magnetically coupled reactors arranged in a TDSλ topology (Three-phase Delta-Star Lambda), enabling simple yet effective interfacing of multiple DC inputs, such as photovoltaic arrays, with multi-level AC outputs suitable for off-grid systems. Magnetically coupled chokes provide significant benefits, including reduced dimensions, weight, and costs compared to traditional and multi-winding transformers [13–16].

The work describes the possibility of controlling a similar system using a more or less complex modulation method. The results obtained are promising [17,18].

The study's main objective is to validate the proposed converter structure through experimental and simulation analyses, emphasizing its performance in renewable energy integration and power quality improvement. The results demonstrate the effectiveness of the proposed configuration, highlighting its potential application in off-grid renewable energy installations. In particular, the focus is on the filtering properties of the magnetically coupled choke systems and the LC low-pass filter system they create after adding additional capacitance.

Converter Structure and Analysis

The proposed converter architecture integrates six single-phase half-bridge inverters with a passive magnetic coupling network configured in TDSλ topology. This arrangement facilitates the transformation of multiple DC inputs into a three-phase, multi-level AC output, making it particularly suitable for off-grid renewable energy applications.

Figure 1 shows the basic converter circuit. In this version, six single-phase half-bridge inverters are connected to the TDSλ system, where there are two inverters for each reactor MCR_i (Magnetically Coupled Reactors), where *i* is the reactor number with indexes from 1 to 3.

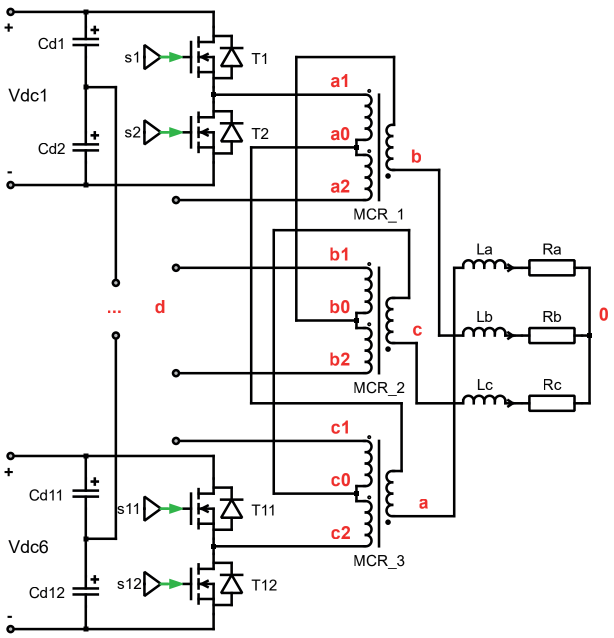

Fig. 1. The main topology of a converter in a system with six single-phase inverters [19]

The characteristic points of the converter system are marked in the diagram presented in Figure 1 [19]. These points were used in the converter analysis to determine voltages important for the operation of the system: d– the star point of the capacitive voltage divider; a1, a2, b1, b2, c1, and c2 – the inputs of the TDSλ system; a, b, and c–the outputs of the TDSλ circuit, which also correspond to the phases; and 0 – the reference point for the load circuit. Characteristic points in the diagram (Figure 1) are additionally highlighted in red. A description of the analysis is included later in the article.

An important element in the diagram is the capacitive voltage divider (created by capacitors marked Cd1 = Cd2 = … = Cd12), which creates a common star point for all voltages in the intermediate circuits of single-phase inverters. The purpose of the capacitive divider is to create a connection for the alternating-current components in the power supply circuit while eliminating the direct components.

Central to the converter's design, there are three magnetically coupled reactors (MCRs), each comprising two windings: a primary winding connected to the inverter output and a secondary winding arranged in a delta-star configuration. This setup enables the synthesis of two sets of three-phase voltages with a specific phase shift, effectively creating a multi-level voltage waveform at the output. The magnetic coupling not only aids in phase shifting but also contributes to harmonic attenuation, reducing the Total Harmonic Distortion (THD) in the output voltage.

The MCRs are designed with specific turn ratios to achieve the desired phase shift and voltage levels. For instance, in a prototype designed for a 15 kW power rating, the windings were configured with 108 turns on the primary side (N_z), 29 turns on the secondary side (N_y), and 79 turns on the tertiary side (N_x), resulting in a turn ratio of approximately 2.72:1:3.72. This configuration ensures a phase shift of $\pi/12$ between the output voltage vectors, which is critical for generating a 12-pulse waveform with reduced harmonic content.

A capacitive voltage divider is employed to stabilize the neutral point and eliminate the DC component from the output voltage. This configuration ensures that the AC output remains centered around zero volts, which is crucial for the proper functioning of connected loads and for maintaining power quality standards.

Each inverter operates independently, generating square-wave voltages that, when combined through the magnetic coupling network, result in a multi-level staircase waveform approximating a sinusoidal shape. This method simplifies the control scheme and reduces the computational burden on the control hardware.

The converter's design offers several benefits:

- Reduced Component Count: By utilizing magnetically coupled reactors instead of traditional transformers, the system achieves a more compact and lightweight design.
- Enhanced Power Quality: The multi-level output waveform exhibits lower THD, improving compatibility with sensitive loads.
- Scalability: The modular nature of the converter allows for easy scaling to accommodate different power levels and system requirements.

Prototype testing and simulation studies have demonstrated the converter's effectiveness in delivering high-quality power output. Measurements indicate a significant reduction in THD and confirm the system's ability to efficiently integrate multiple DC sources.

In summary, the proposed converter architecture, with its innovative use of magnetically coupled chokes and simplified control strategy, presents a viable solution for off-grid renewable energy systems requiring high-quality, multi-level AC power output [19].

Experimental research

The main concept of the converter was validated through experimental research. In this study, a three-phase power supply with a voltage of 3 × 400 V and a frequency of 50 Hz was utilized, resulting in a DC voltage of 560 V in the converter's DC circuit. The load configuration comprised three resistors, each rated at 50 Ω, and a three-phase reactor with an inductance of 50 mH per phase. This setup facilitated the assessment of the converter's performance under controlled conditions, providing insights into its operational characteristics and efficiency. A test stand was prepared for the experimental verification of the converter concept. The setup utilized a six-phase inverter connected to a single DC bus, interfaced with magnetically coupled reactors configured in the TDSλ topology. This configuration was chosen to align with the current capabilities of the laboratory infrastructure.

Figure 2 presents a photograph of the assembled inverters and the magnetically coupled reactors. Figure 3 displays an oscillogram illustrating the output voltage and current waveforms for two of the three phases, providing insight into the converter›s operational performance.

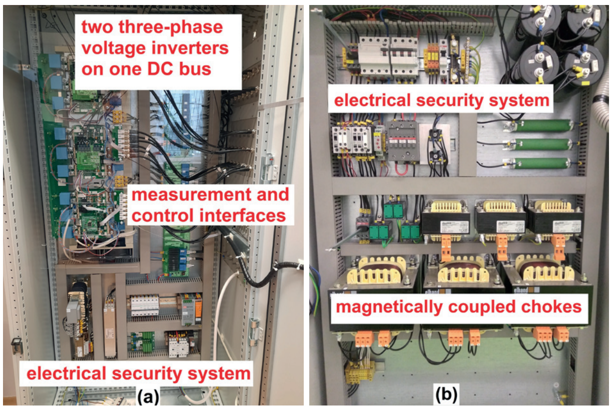

Fig. 2. The photo of the six-phase inverter (a) and magnetically coupled reactors in the TDSλ system (b)

For further analysis conducted in the form of simulation studies, it was necessary to measure the actual inductances of the used magnetically coupled chokes. A laboratory impedance bridge was used in the measurements. The following inductance values were obtained as a result of the measurements, i.e. Lx = 31.1 mH, Ly = 4.5 mH, Ly = 62 mH. The choke with the number of turns Ny, which is treated as a secondary winding for the considered system, will have the greatest influence on the filtration properties of the TDS system. It is also a choke directly connected to the load of the off-grid system.

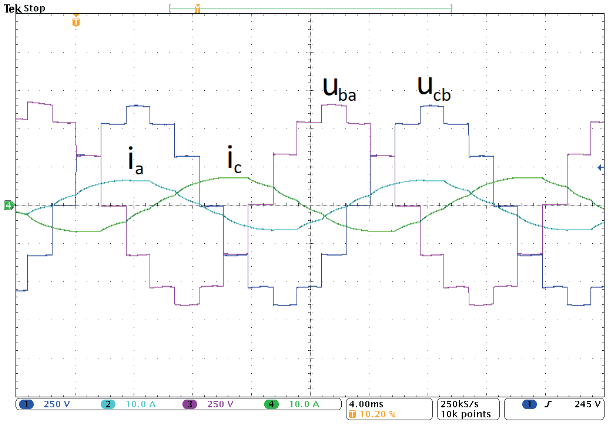

Fig. 3. The oscillograms with the voltage and current waveforms for two phases

Simulation studies

Figure 4 shows a topology of the off-grid system with various inverters and a control algorithm that were connected to a distributed PV (photovoltaic) system. The presented topology of the off-grid system is based on a system with TDSλ magnetically coupled chokes. The TDSλ system is an interface to which you can connect various inverters, the number of which depends on the inverter type. Figure 4 shows the connection of three different types of inverters. In the final version of the system, it is best to use inverters of the same type, e.g. two 3-phase inverters, or three single-phase full-bridge inverters, or six single-phase half-bridge inverters. The system also uses DC/DC converters to increase the voltage, e.g. DAB (Dual Active Bridge). Their purpose is to adjust the voltage from the PV to the voltage level supplying the inverters. The voltages from PV, after matching, should be the same to prevent voltage asymmetry in the TDSλ system. This paper presents the results of simulation studies for the case where the load is resistive (Ra = Rb = Rc = 20 Ω) in order to better indicate the filtering properties that the choke system in the TDSλ circuit does or does not exhibit.

Simulation studies were performed in the PLECS program. In the simulation studies, currents and volt-

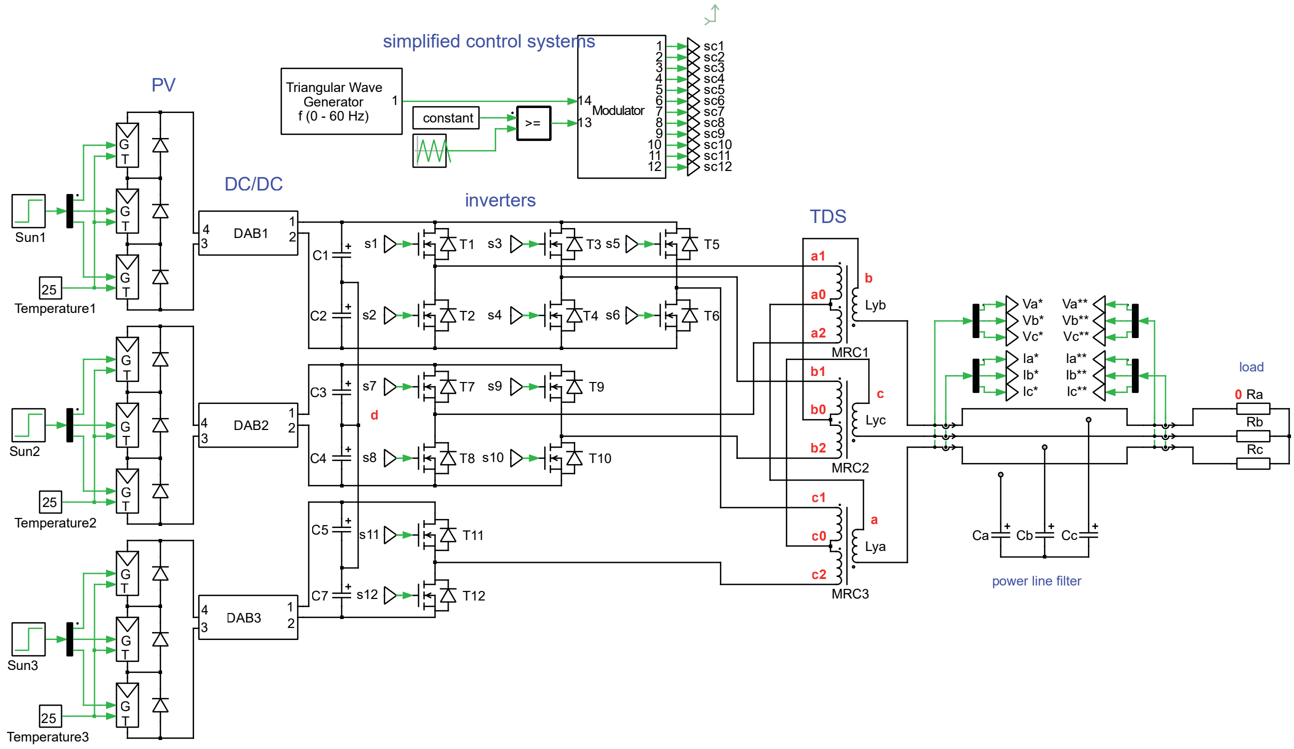

Fig. 4. The off-grid system model used in the simulation studies, along with a description of the most important blocks

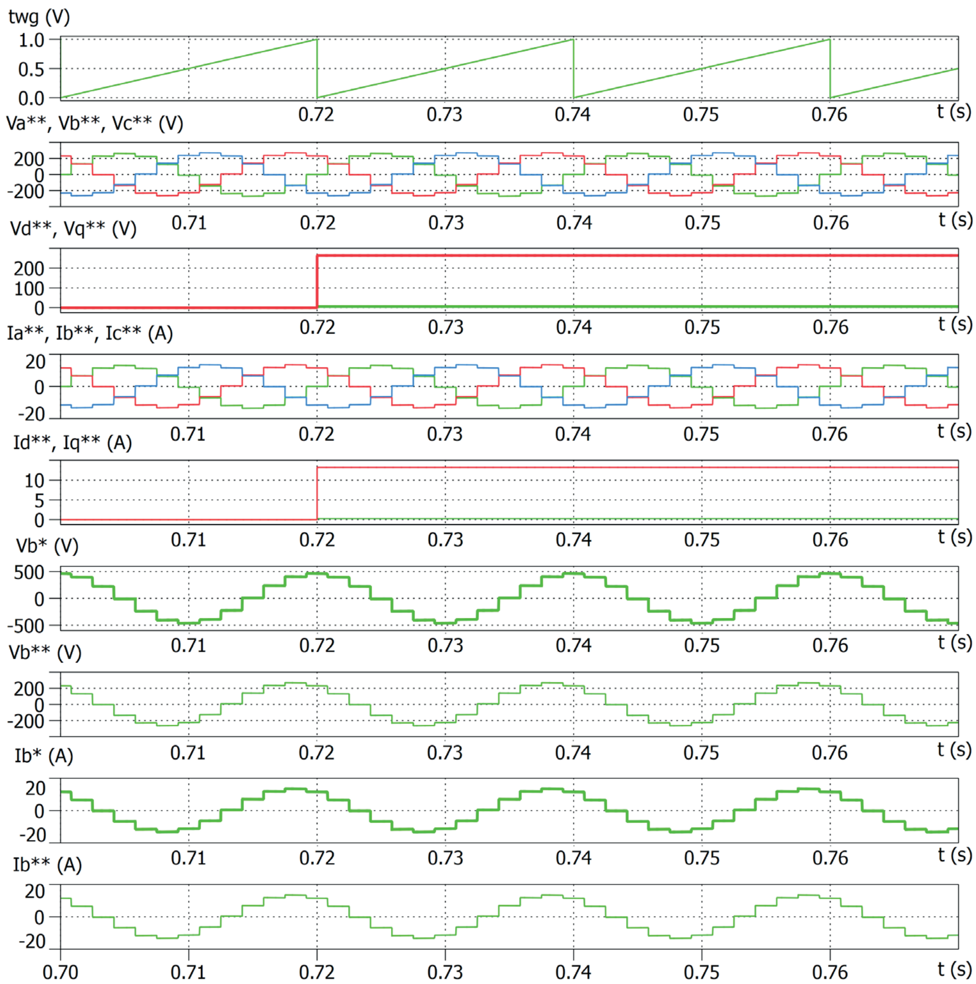

Fig. 5. Waveforms of selected voltages and currents without the use of additional capacitances and $THD_{Vb**} = THD_{Ib**} = 15.2\%$

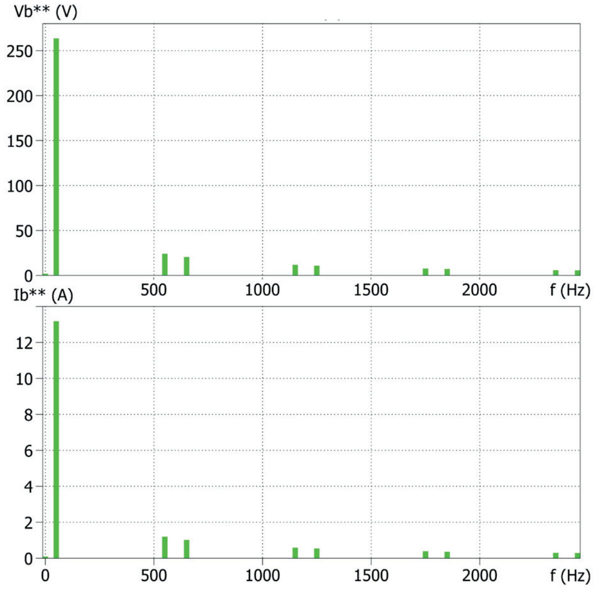

Fig. 6. Output voltage and current spectra with 49 harmonics from Figure 5

ages were recorded at the output of the TDSλ system and before the load $R_{a,\,b,\,c}$. The voltages and currents recorded at the output of the TDSλ system were indexed $V_{a,\,b,\,c}{}^{*}$ and $I_{a,\,b,\,c}{}^{*}$ and before the load: $V_{a,\,b,\,c}{}^{**}$ and $I_{a,\,b,\,c}{}^{**}$.

For the purpose of testing the filtering properties of the TDS system and parallel connected capacitors, a simplified control system for the inverter unit was used (Figure 4).

Figure 6 shows the voltage and current waveforms recorded between the choke system and the load. These results are consistent with the experimental results shown in Figure 3.

This shape of voltages results from the properties of the control system and TDSλ chokes. The use of chokes alone allows for obtaining $THD_{u,\,i} = 15\%$ for output voltages and currents, which is already a good result.

Figure 6 shows the spectrum of output voltages and currents. The choke system filters higher harmon-

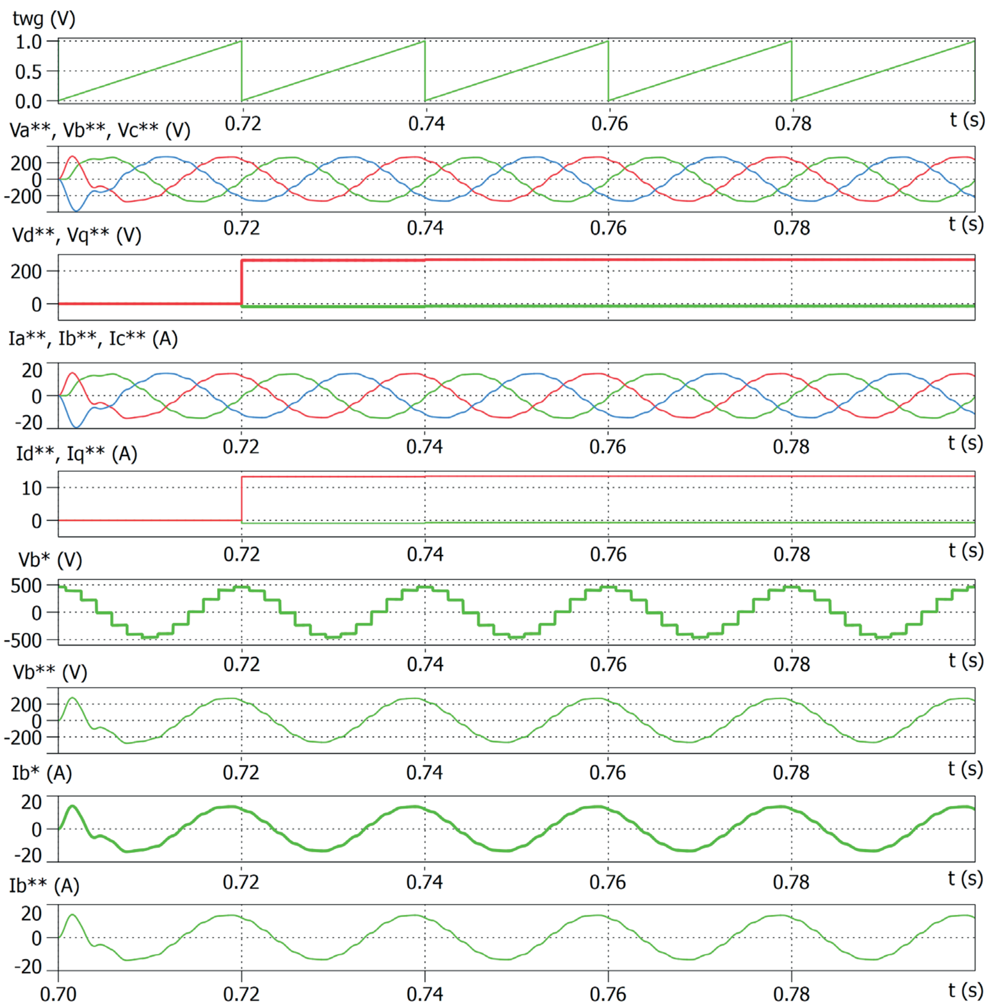

Fig. 7. Waveforms of selected voltages and currents with the use of additional capacitances and $THD_{Vb**} = THD_{Ib**} = 2.6\%$

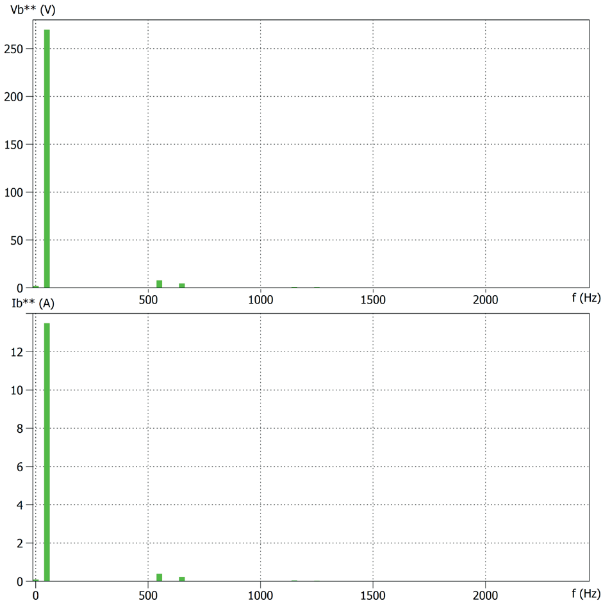

Fig. 8. Output voltage and current spectra with 49 harmonics from Figure 7

ics, but harmonics with numbers 11 and 13 and their multiples still remain. Their values are significant and constitute about 11%.

Figure 4 shows schematically the possibility of adding capacitance $C_{a,b,c}$, which in combination with the inductance of the chokes seen from the load side and marked $L_{ya,b,c}$ creates a low-pass LC filter.

The inductance $L_{ya,b,c}$ can be estimated by measurement, e.g. with an impedance bridge and in the considered case it amounted to $L_{ya,b,c} = 4.5$ mH. However, the selection of capacitance requires the use of a different procedure. For the needs of a short analysis, a typical formula for an LC filter was used, in the form given by formula (1), where fc is the filter cut-off frequency.

$$f_c = \frac{1}{2\cdot\pi\cdot\sqrt[2]{L\cdot C}} \tag{1}$$

After transforming formula (1) for C, it can be used to estimate the capacitance $C_{a,\,b,\,c}$ of the network filter. Assuming f_c = 11h (11th harmonic), the value $C_{a,b,c}$ = 18.6 pF was obtained, and for fc = 11h/2, $C_{a,b,c}$ = 90.1 pF was obtained, for which value the simulation study was performed.

The simulation results are presented in Figures 7 and 8 confirming the good filtration properties of the LC filter.

Conclusion

The article demonstrates, without complicated analyses, that magnetically coupled chokes with parallel connected capacitances create a low-pass LC filter. The filter parameters can be easily estimated based on the analysis of the current and voltage spectra and a simple design formula. The operation of the system with PWM or other modulations requires further analysis. The research presented in the article will be used to build an on-grid.

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