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Off-grid system using a converter with multiple DC inputs and three-phase, multi-level AC output

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Abstract. This paper describes the possibility of interfacing a three-phase voltage converter with a configurable DC input and a multi-level AC output with an on-grid system. The described converter uses magnetically coupled reactors. The multilevel output voltage of the converter is characterized by a favorable value of the THD coefficient. With the ability to configure DC inputs, the proposed converter allows easier integration of renewable energy installations, such as PV. A control strategy for the voltage inverter has been developed. Experimental studies of the basic converter design are presented. An analysis of the converter about cooperation with inverters is presented. The use of magnetically coupled reactors made it possible to use a magnetic system with lower power and dimensions.

Key words. voltage inverters; magnetically coupled reactors; converter; coupling; on-grid; isolated grid, PV.

1. Introduction

The changes in renewable energy sources are currently the main reasons driving development in power electronics, which are contributing to the emergence of circuit solutions geared toward the cooperation of different converters with each other and the conditioning of electricity [1]. The basic group of converters used in RES are voltage inverters [2-4].

The paper [5] provides a comprehensive overview of the different types of inverters currently used in various applications and variants of power systems. Generally, a traditional voltage-fed inverter is used, where two voltage levels can be generated [6]. For other applications, especially those requiring high power conversion (e.g., on-shore power supply systems), multi-level inverters (MLIs) are used [7,8]. MLI circuits are desirable for various applications due to intrinsic benefits, for example, low switching voltages, low DV/DT ratio on switches, reliability, lower cost, reduced complexity, improved THD, and exceptional performance when used in applications [9,10].

Traditional bilevel inverters are still very popular in low-power systems [5]. Various modulation schemes are available and are used to build control strategies for inverter operations [11,12]. A significant proportion of the modulators used for inverters are based on pulse width modulation (PWM) modifications. Modulations using PWM mainly increase the switching losses of the electronic keys used in inverters [12–15].

As mentioned earlier, using multi-level inverters and appropriate control strategies allows for multiple levels of output voltages. Multi-level voltage is usually associated with lower THD and better power quality [16]. As it has been shown, obtaining such a voltage requires the use of complex inverter structures and complicated control strategies based on a large number of electronic key switches [17].

This paper describes a converter that uses magnetically coupled reactors connected like a TDS circuit and inverters with a simple control strategy to provide multiple interfaces to low-power systems (such as photovoltaic panels) [18]. The proposed system also has the property of producing a three-phase and multi-level voltage system with the right control strategy.

The converter with multiple inputs DC and outputs in the form of a three-phase system AC requires the analysis of systems that allow for the integration of multiple inverters in one system. For this purpose, systems based on transformers, multi-winding transformers, and systems using magnetically coupled reactors were compared [19–24]. The works [19,24] describe special multi-winding transformers that enable the conversion from three phases to five phases. Transformers of this type were mainly built to power multi-phase drives, e.g., five-phase. In these works, they were not combined with inverters. The works [19–22] indicate various structures of multi-winding transformers and their advantages/ disadvantages. The largest advantage of this type of transformer is galvanic separation and conversion from a certain number of phases to another number of phases. The disadvantage of this type of transformer is the high cost in relation to the power. Another disadvantage of this type of transformer is its size. However, in [23], it is pointed out that it is still smaller than in the case of traditional transformers, especially if a multi-winding transformer is compared to an appropriate number of single-phase transformers. Magnetically coupled reactors have favorable properties when it comes to the relationship between size, weight, and power. Due to their simplified construction, their dimensions are much smaller than typical transformers or multi-winding transformers. However, ensuring the possibility of

conversion from several phases to several other phases is possible by appropriately connecting reactors. The works [24,25] thoroughly analyzed the properties of reactors that can be used in power electronic systems or for connecting them with other systems.
According to the author, it is important to connect inverters to the public power system so that this process is effective and ensures the conditioning of electricity, the result of which is maintaining high quality. Using magnetically coupled reactors and inverter control allows for obtaining multilevel output voltage waveforms characterized by a low content of higher harmonics [18].
The described converter is based on passive magnetically coupled reactors. The mentioned advantages make the converter much easier to use and more damage-resistant. The used topology to connect magnetically coupled reactors reduces their number. Reducing the number of magnetic elements in power electronic devices is currently a desirable measure due to material costs and the tendency to minimize the dimensions of devices. The connection of the magnetically coupled reactors (MCRs) used is called TDSλ (three-phase coupled reactors in the lambda connection variant) and is described in more detail in [26]. A significant advantage of the TDSλ system is that its weight and size are significantly smaller for the same power compared to a transformer that would be designed for that power. On the other hand, a significant disadvantage of the TDSλ system is the lack of galvanic separation that transformers or multi-winding transformers have.
However, the most important advantage of the described solution is that by selecting the appropriate number of turns for the adopted topology of connecting reactors at the output of the structure, one obtains—with simple control of inverters—three-phase multi-level waveforms, which translates into a very low THD content (Total Harmonic Distortion) for output voltages and currents [26].

2. Converter structure and analysis

The system using magnetically coupled reactors of the TDSλ type was used to build 12-, 18-, or 36-plus rectifiers as stable voltage sources for multi-level inverters in the papers [29–31]. The TDSλ structure is optimal in terms of the number of magnetic elements used. It is characterized by high efficiency (above 90%) and its main parameter dependent on the load is the overall power [26].
The three-phase coupled reactors, thanks to its appropriate design, block certain higher harmonics (of the orders of 5, 7, 11, 13, 17, 19, etc.) and also transform two three-phase systems with a given mutual phase shift into one three-phase system.
The reactors (MCR) are composed of three separate magnetic cores with an appropriately selected number of turns (Nx, Ny, Nz) (Fig. 1 - orange frame). Thanks to the appropriately selected number of reactors windings, their output results in two three-phase and symmetrical voltage systems shifted in phase by an angle of $\pi/6$, but the mutual phase shift can be modified by changing the number of windings in a wide range. This possibility was used in the construction of multi-pole rectifiers, i.e., 18-, 24-, or 36-plus rectifiers [26].
In the case under consideration, these windings were selected in the following ratio: 3.72:1:2.72. For the developed converter, first, the gears that will ensure the aforementioned shift in vectors were calculated. Then, for the assumed power, the number of windings was selected to not lead the core to saturation. For this number of windings, the self and mutual inductances were calculated. Further simulation studies and tests were performed for the following number of windings: 279:75:204, which corresponds to the design of the TDSλ system for 2 kW of power.
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 MCRi, where i is the reactor number with indexes from 1 to 3.

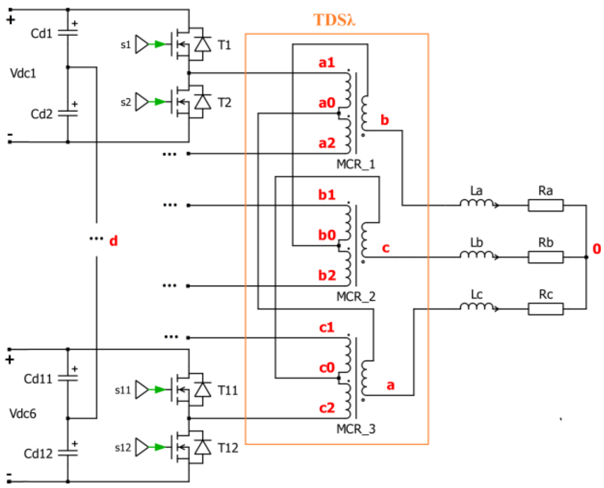


Fig. 1. The main topology of a converter in a system with six single-phase inverters.

The characteristic points of the converter system are marked in the diagram presented in Figure 1. 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.
Figure 2 shows example signals controlling electronic keys for inverters responsible for generating voltage on the reactor marked MCR1 in the considered version of the converter. The control signals (marked s1…12) are phase-shifted by $2\pi/3$ and $4\pi/3$ to ensure compatibility with the three-phase power system.

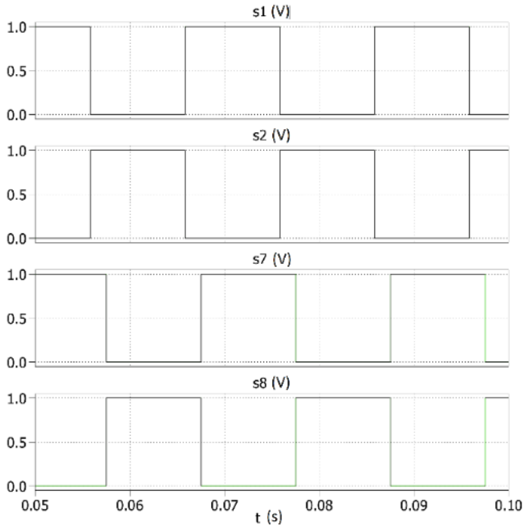
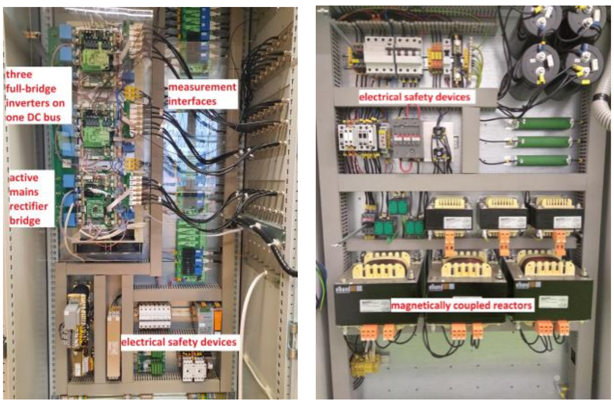


Fig. 2. Examples of signals controlling the inverters connected to the MCR1 reactors

Simplifications are made for the analysis. In the converter system with single-phase inverters, it is assumed that the supply voltages of the inverters are the same and meet the condition: Vdc1 = Vdc2 = … = Vdc6 = Vdc. To keep the analysis readable and transparent, we focus on the cooperation of the inverters with the first MCR1 reactor and the influence of the system on the “a” phase. In selected stages of the analysis, there also have to be references to other characteristic points of the converter. By making the aforementioned assumptions, the analysis allows for taking into account the operation of the system presented in Figure 1.

3. Experymental research

The main concept of the converter was verified in the experimental research. For this study, a three-phase power supply with a voltage of 3 × 400 V and a frequency of 50 Hz was used, which, in the DC circuit, allowed for obtaining a voltage of 560 V. The load consisted of three resistors with a value of 3 × 50 Ω and a three-phase reactor with a value of 3 × 50 mH.



(a) **(b)**

Fig. 3. The photo of magnetically coupled reactors in the TDSλ system (a) and the six-phase inverter (b)

A test stand was adapted for the experiment, using a six-phase inverter on a single DC bus and magnetically coupled reactors in a TDSλ arrangement. The simplification results from the limited capabilities of the current laboratory station. A photograph of the inverters and magnetically coupled reactors is shown in Figure 3. The oscillogram shown in Figure 4 shows the waveforms of output voltages and currents for two phases.

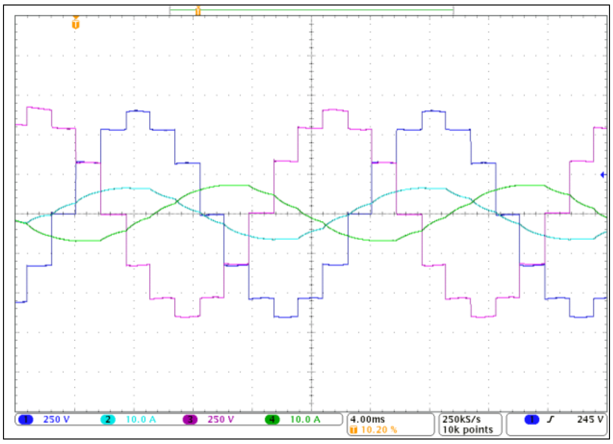


Fig. 4. The oscillograms with the voltage (u_{ba}, u_{cb}) and current (i_a, i_c) waveforms for two phases

4. Topology of the off-grid and control algorithm

Figure 5 shows a topology of the off-grid system with various inverters and control algorithm that were connected to a distributed PV system.
The presented topology of the off-grid system is based on a system with TDSλ magnetically coupled reactors. The TDSλ system is an interface to which you can connect various inverters, the number of which depends on the inverter type. Figure 5 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. 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 voltages asymmetry in the TDSλ system.
The article presents the results of simulation tests for the case where the load is inductive and resistive. The system does not use a passive network filter. The off-grid system with a network filter will be the subject of another analysis.
The control algorithm is presented in Figure 5 in the form of a block diagram. The algorithm uses typical Clark and Park transformations.
Based on the phase voltages and currents recorded on the load, the dq components are calculated. They are used to generate a PWM signal at the modulator input. The modulator developed for the system generates control signals by the diagram shown in Figure 2 and connects them with the PWM signal, which enables control of the effective value of the output voltage.
The modulator is also prepared to cooperate with the power system. The frequency of output voltages and currents depends on the frequency of the system named in the diagram: Triangular Wave Generator (twg).

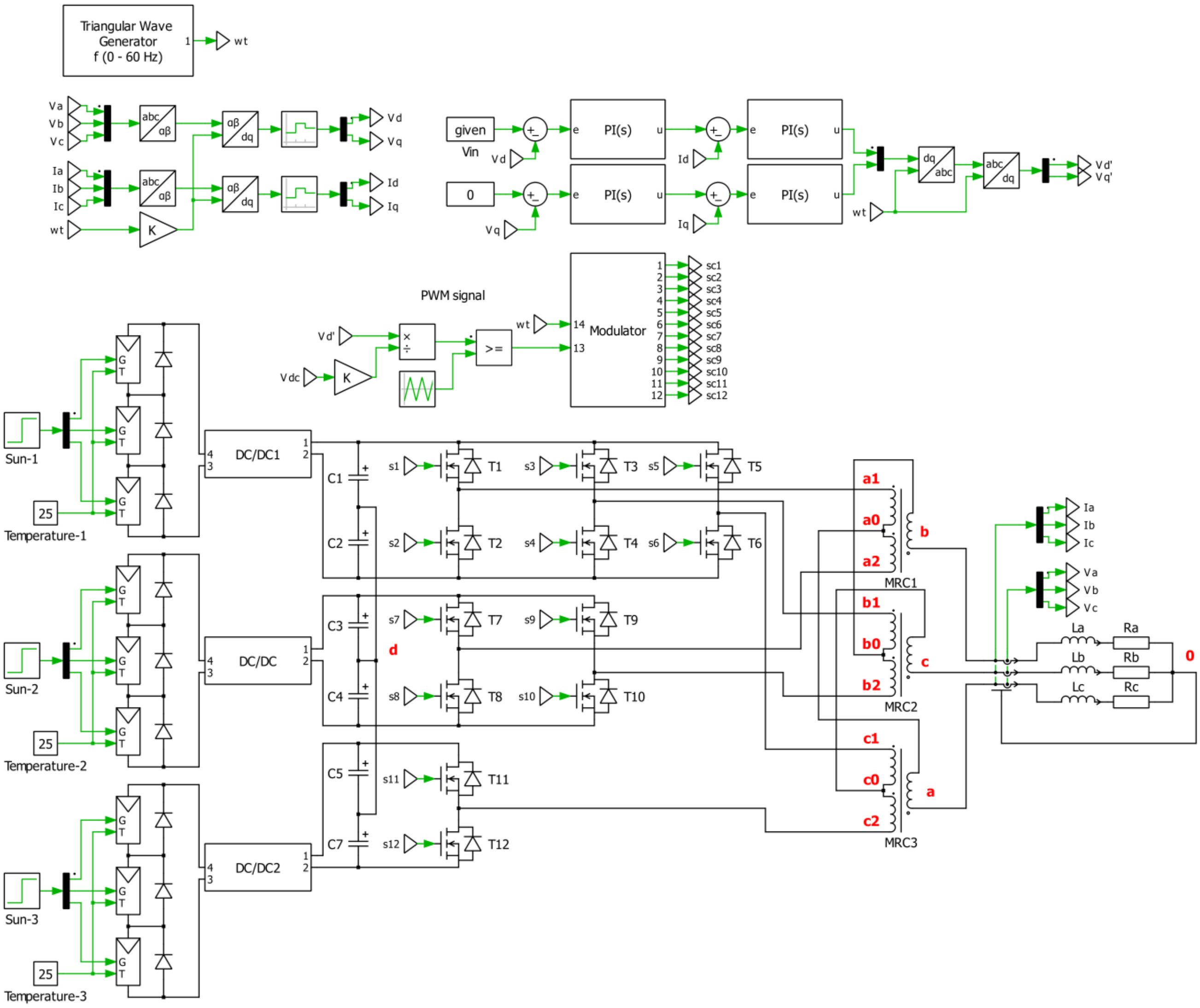


Fig. 5. Topology of the off-grid system with various inverters and control algorithm.

5. Simulation research

This chapter presents the results of simulation tests performed in the PLECS program. The DC supply voltage of 400 V was assumed at the input of the inverters. The load was resistive-inductive ($R_{a,b,c}$ and $L_{a,b,c}$). The simulations were performed at a PWM signal modulation frequency of 5 kHz.

Figures 6 and 7 show voltage and current waveforms along with their amplitude spectra for the case in which the fill factor for PWM modulation was equal to 1. With these settings, the output currents reach their maximum value.

Figure 8 shows example signals s1, s2, s3 i s4 from a modulator with PWM modulation with a frequency of 5 kHz. However, Figures 6 and 7 present voltage and current waveforms along with their amplitude spectra for the case in which the duty cycle for PWM modulation was equal to 0.5.

Table I. - RMS and THD for output voltages and currents.

PWM (%)	RMS_{Ub} (V)	THD_{Ub} (%)	RMS_{Ib} (A)	THD_{Ib} (%)
100	189.61	15.14 %	8.94	3.38
50	133.72	101.7%	4.47	4.63

Table I shows a list of selected parameters (RMS and THD) of output voltages and currents in phase b.

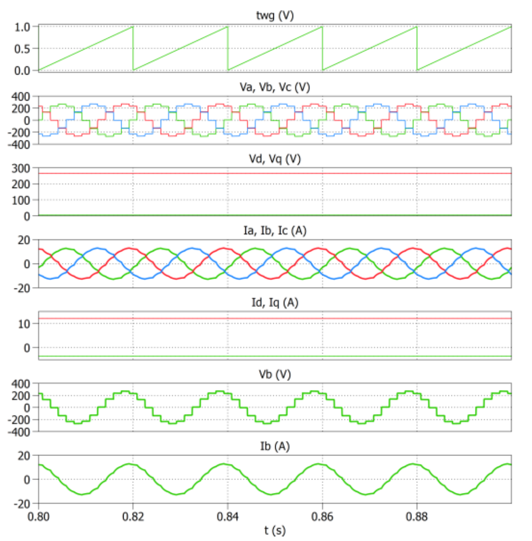


Fig. 6. Selected voltage and current waveforms along with the synchronizing signal and dq values - PWM filling factor equals 1.

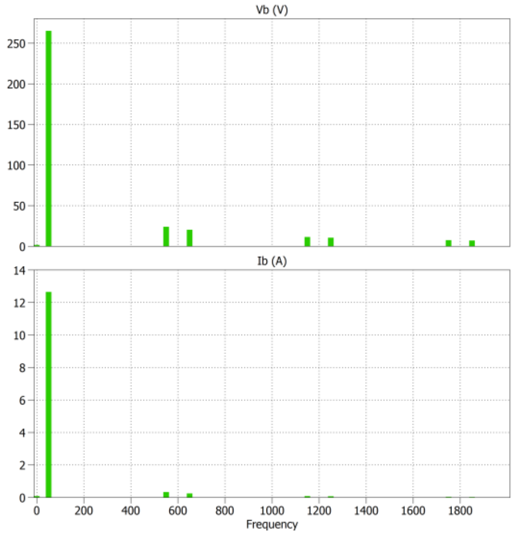


Fig. 7. Amplitude spectrum of the output voltage and current from Figure 6.

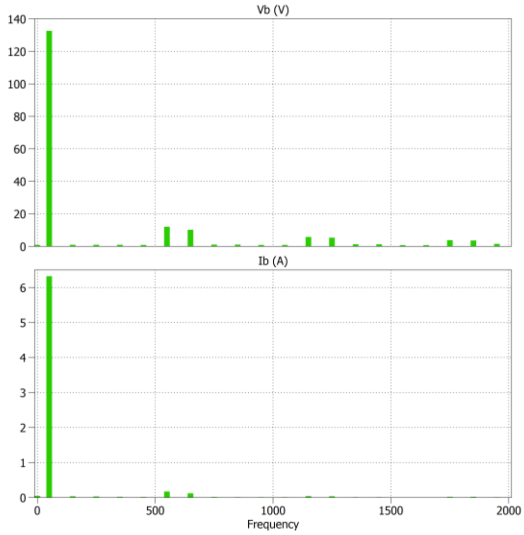


Fig. 10. Amplitude spectrum of the output voltage and current from Figure 9.

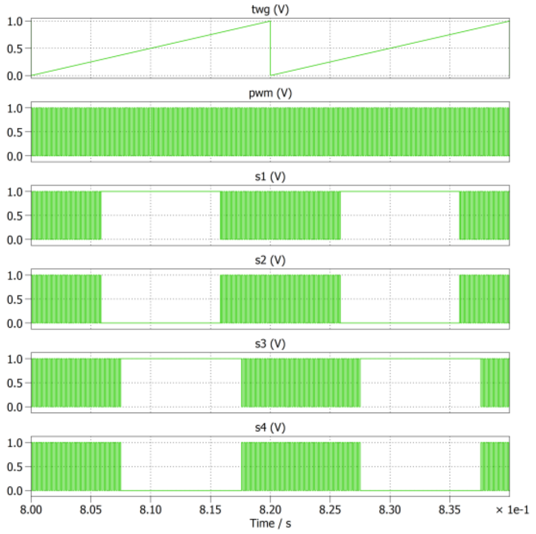


Fig. 8. Modulator - control signals with PWM modulation.

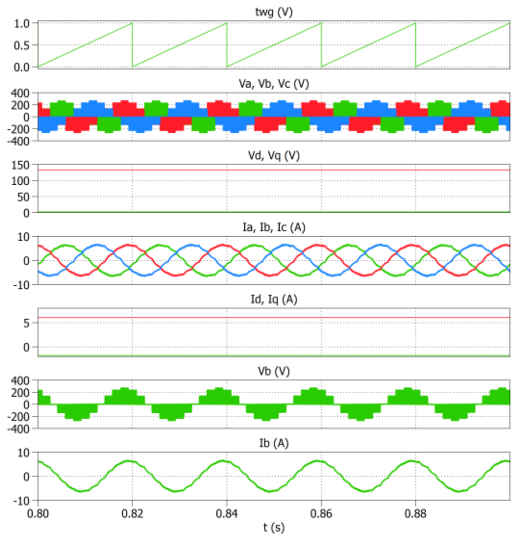


Fig. 9. Selected voltage and current waveforms along with the synchronizing signal and dq values - PWM filling factor equals 0.5.

6. Conclusion

The presented off-grid system enables the integration of various voltage inverters with coupled reactors and the conversion of direct voltages to a three-phase system. The proposed system seems to be an interesting solution that largely solves the problem of energy conditioning and ensures a multi-level nature of output voltages. The TDSλ system using magnetically coupled is passive, which does not require additional power supply and makes it less susceptible to damage [35].

The presented concept of an off-grid system with various inverters is characterized by high flexibility, as it can be used both in simple cases with six single-phase half-bridge inverters and in other configurations, without major changes to the structure itself. The capacitive dividers used in the converter also ensure the elimination of the direct current component in the power supply circuit.

The proposed structure of an off-grid system based on magnetically coupled reactors and inverters requires further research. The experimental tests carried out confirmed some of the obtained simulation results and created the possibility of further expansion of the control system in terms of cooperation with the power grid.

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