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Influence of load and operating parameters on efficiency of three-level voltage source inverter with soft-switching technique

Wpływ parametrów odbiornika i parametrów pracy na sprawność trójpoziomowego falownika napięcia z łagodnym przełączaniem tranzystorów

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Abstract: The first part of the article briefly describes the soft-switching of transistors in a three-phase three-level voltage source inverter. The main part of this article is devoted to discussing the influence of load and operating parameters on the efficiency of this inverter. The efficiency of the inverter with soft-switching of transistors is compared with the efficiency of the voltage source inverter with hard-switching technique. The influence of the switching frequency on the inverter efficiency is also discussed. The efficiency is estimated for a load with a rated power of 100 kW and 1 MW.

Keywords: efficiency, soft-switching; switching losses; three-level voltage source inverter

Streszczenie: W pierwszej części artykułu krótko omówiono miękkie przełączanie tranzystorów w trójfazowym, trójpoziomowym falowniku napięcia. Główna część artykułu poświęcona jest omówieniu wpływu parametrów odbiornika na sprawność falownika. Sprawność falownika z miękkim przełączaniem tranzystorów jest porównywana ze sprawnością falownika z techniką twardego przełączania. Omówiono również wpływ częstotliwości przełączania na sprawność falownika. Sprawność jest szacowana dla obciążenia o mocy znamionowej 100 kW i 1 MW.

Słowa kluczowe: sprawność, miękkie przełączanie, straty przełączania, trójpoziomowy falownik napięcia

Introduction

Three-phase three-level voltage source inverters (3LVSIs) are usually employed in industrial and traction drive systems with medium- and high-power induction motors. The 3LVSI can operate with lower switching frequency in comparison to two-level voltage source inverters providing the same coefficient of the total harmonic distortion (THD). Each phase contains four Insulated-gate bipolar transistors (IGBTs) (Fig. 1) [1–3]. Additional diodes make it possible to obtain the zero voltage value at the inverter output relative to the neutral point of the voltage source, consisting of two voltage sources with the same U_{DC} value.

The IGBTs of the 3LVSI are most often controlled by the pulse width modulation method, which differs significantly from the modulation used in two-level inverters. In the control system of the 3LVSI, the sinusoidal control waveform with a set frequency and amplitude is compared with two sawtooth waveforms with a frequency that is many times higher, where one of the carrier waveforms has values not lower than zero and the other not higher than zero. As a result of comparing these waveforms, signals controlling the operation of transistors S11 and S14 of the first phase of the 3LVSI are obtained. Transistor S12 is controlled by a signal that is the negation of the control signal of transistor S14, and transistor S13 receives a control

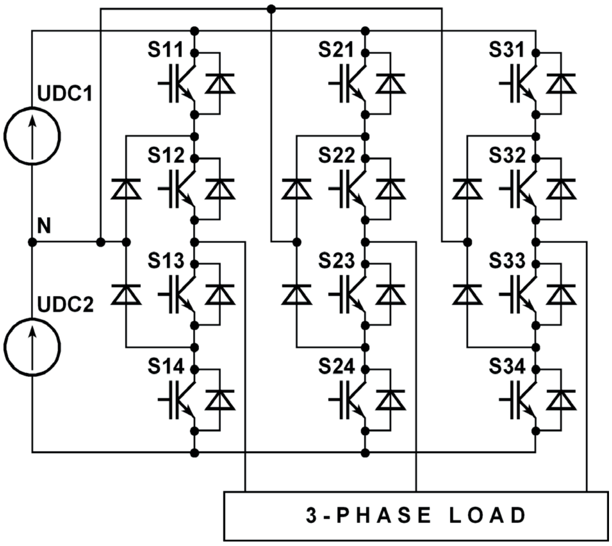

Fig. 1. Three-level voltage source inverter

signal that is the negation of the control signal of transistor S11.

The efficiency of typical power electronic converters is found in the range of about 96 percent for low rated power systems and is close to 99 percent for the highest power converters. However, that even with such high efficiency, research is still being carried out to reduce losses, especially in multilevel voltage source inverters in medium- and high-power systems. Power losses in inverters are caused primarily by losses in transistors and diodes in their conduction states and during switching processes. Reducing losses by even one percent can lead to "recovering" several dozen or even several hundred kilowatts of power, depending on the rated power of the inverter.

The users of voltage source inverters do not have possibilities to reduce the conduction losses. However, the switching losses can be reduced by using soft-switching systems. These systems have additional circuits containing, among others, capacitors connected in parallel to the main transistors [4–6]. In case of disturbances, one of the main transistor may be turned on at a non-zero voltage of the capacitor which is connected in parallel with this transistor; as a result the transistor current may reach an unacceptable value. In other existing solutions of the soft-switching, transistors are connected in series with additional inductors. When a given transistor is turned off at a non-zero current of the inductor, then an overvoltage appears, which is usually dangerous to this transistor.

Unlike these systems, in the described solution capacitors are not connected in parallel to the main transistors, and inductors are not connected in series with auxiliary transistors. This leads to an improvement in the operational reliability of inverters with the soft-switching systems

Proposed Soft-Switching System in 3LVSI

The structure of one phase of the 3LVSI with the proposed soft-switching system is shown in Figure 2 [7–9]. Capacitors C11–C14 are applied to decrease the steepness of the voltage increase in the main transistors S11–S14 during their turn-off processes. The use of inductors L11–L14 is intended to reduce the rate of the current rise of these transistors during their turn-on processes.

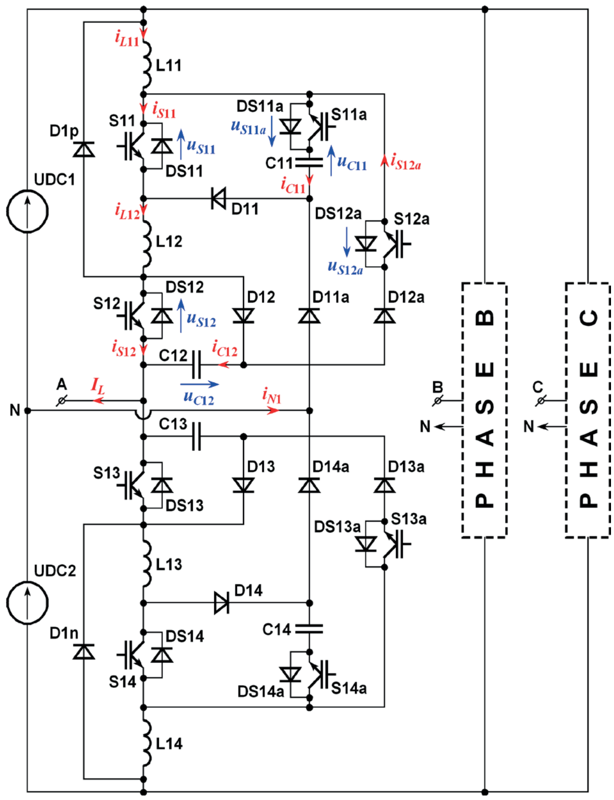

Fig. 2. One phase of the 3LVSI with the soft-switching technique: A, B, C – load terminals; N – neutral point

Simplified waveforms when transistor S11 (and dependent on it S13) is switched are shown in Figure 3. Figure 4 presents waveforms in the case when S12 is switched, where S11 is in a non-conduction state.

The 3LVSI was supplied by two DC voltage sources with the maximum voltage of 60 V each, and the permissible supply current was 12 A. Due to its prototype nature, the laboratory inverter was built using components with significantly higher current and voltage ratings than those indicated above. In the laboratory inverter IGBTs type G4PH50KD were applied, with rated current and voltage of 24 A and 1200 V ($U_{CE(ON)}$ = 2.77 V, I_{rrm} = 8.3 A), respectively, and fast diodes type DSEI30-12A with the rated current of 30 A. All transistors were protected against overvoltage using appropriately selected varistors. The operation of the laboratory 3LVSI with the soft-switching tech-

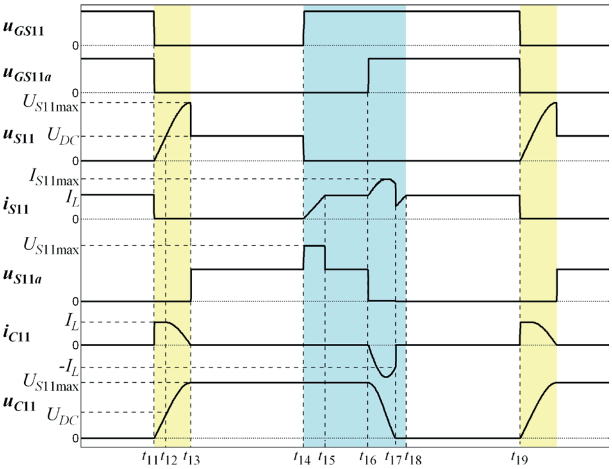

Fig. 3. Simplified waveforms when S11 is switched: u_{GS11}, u_{GS11a} – control signals of transistors S11 and S11a, respectively; u_{S11}, i_{S11} – voltage and current of transistor S11, respectively; u_{S11a} – voltage of transistor S11a; i_{C11}, u_{C11} – current and voltage of capacitor C11, respectively, yellow and blue colors – processes related to soft turning off and soft turning on of transistor S11, respectively

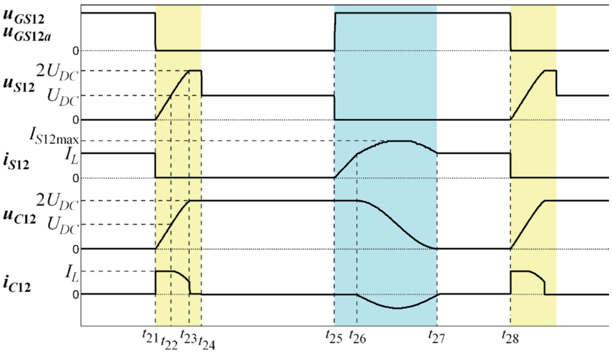

Fig. 4. Simplified waveforms when S12 is switched ON/OFF: u_{GS12}, u_{GS12a} – control signals of transistors S12 and S12a, respectively; u_{S12}, i_{S12} – voltage and current of transistor S12, respectively; u_{C12} i_{C12} – voltage and current of capacitor C12, respectively, yellow color – processes related to soft turning-off of transistor S12, blue color – processes related to soft turning-on of transistor S12

nique and the selection of elements are described in detail in [8, 9].

The control signals of the auxiliary transistors were dependent on the operating states of the main transistors, unlike in existing soft-switching systems. The auxiliary transistors S11a, S14a were turned on with a slight time delay relative to the turn-on moments of the corresponding main transistors. The auxiliary transistors S12a, S13a were turned on simultaneously with corresponding main transistors S12, S13. All auxiliary transistors were turned off when the corresponding capacitors were completely discharged. Figures 5 and 6 show the selected current and voltage waveforms in the prototype there-phase 3LVSI ($C_{11} = C_{14} = 1$ µF, $L_{11} = L_{14} = 120$ µH, $L_{12} = L_{13} = 300$ µH).

Figure 7 shows waveforms of the phase voltage u_p and phase current i_p measured at the switching frequency of 3000 Hz in the case when the 3LVSI with soft-switching technique supplied a squirrel cage induction motor.

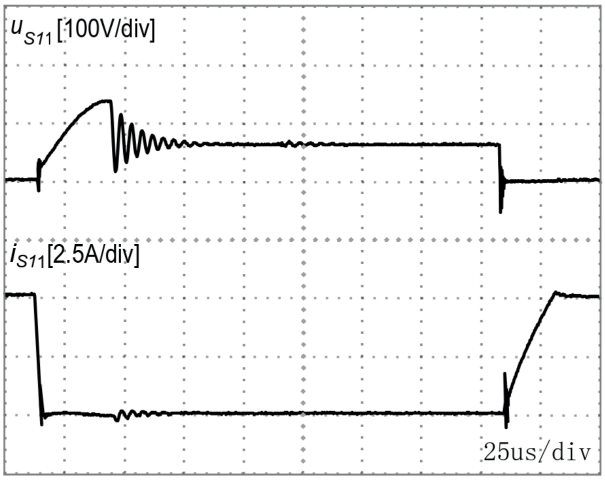

Fig. 5. Waveforms during turn-off and turn-on processes of transistor S11

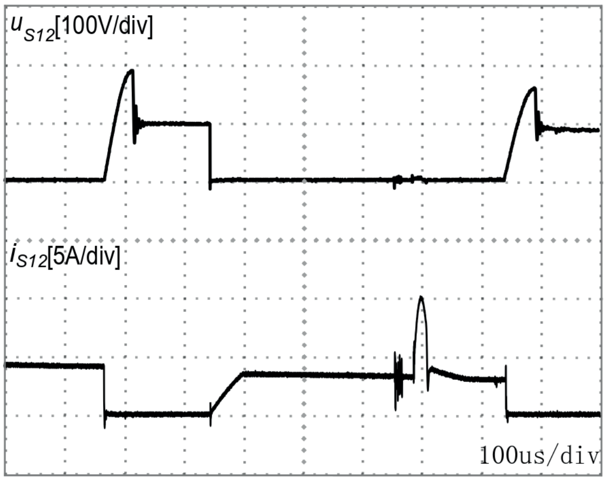

Fig. 6. Waveforms during turn-off and turn-on processes of transistor S12

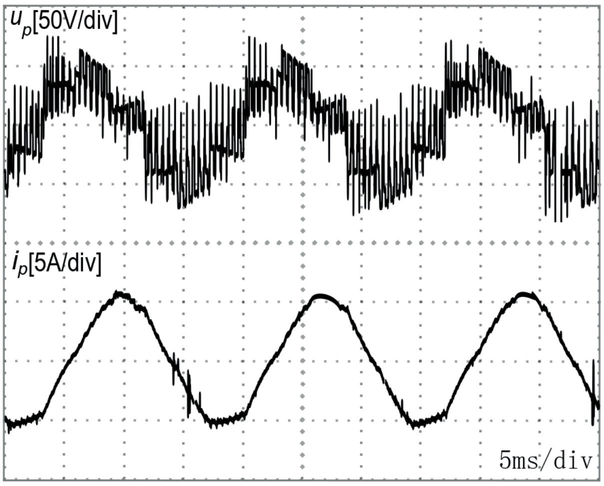

Fig. 7. Waveforms of the phase voltage u_p and phase current i_p measured at the switching frequency of 3000 Hz in the case when the 3LVSI with soft-switching technique supplied a squirrel cage induction motor, voltage source 2 x 50 V

Results of laboratory research confirmed that the switching processes of all transistors of the 3LVSI have a soft character. This significantly reduces the switching power losses despite the occurrence of power losses in the additional diodes and inductors of the described soft-switching system.

The parallel connections of capacitors with the main transistors and series connections of inductors with auxiliary transistors do not exist in the presented 3LVSI with the soft-switching technique. Therefore, the discharges of the capacitors through the main transistors and the sudden interruption of the inductor currents are not possible.

The purpose of constructing the prototype 3LVSI was to check the correct operation of this inverter with the proposed soft-switching system. Due to the prototype nature of the 3LVSI, its efficiency was not estimated, because these inverters are used in systems with a rated power of at least several hundred kW.

Influence of load parameters on inverter efficiency

The efficiency of the 3LVSI was determined according to the well-known relationship:

$$\eta = \frac{P_L}{P_L + \Delta P} \tag{1}$$

where:
P_L – active power delivered to the load,
ΔP – power losses in the 3LVSI.

The total losses in 3LVSI are the sum of the conduction and switching losses of inverter transistors and conduction and turn-off losses of all diodes and losses occurring in inductors.

The efficiency of the 3LVSI with the soft-switching technique was determined using the PLECS software. Estimation of the power losses is based on thermal considerations concerning individual transistors and diodes. In the PLECS software, the current and voltage waveforms during switching processes are primarily a function of the current-voltage conditions before and after switching processes, as well as the component temperature. Since the paper does not refer to issues related to the temperature of transistors, the idealized heat sink was selected assuming the operation temperature oscillates around 125°C.

The thermal model of the FZ750R65KE3 transistor was used to analyze the 1 MW inverter. During the numerical analysis, values of the Total Harmonic Distortion (THD) of the phase currents were also estimated, both for the inverter with hard- switching technique and for the proposed soft-switching system. The analyses were performed for the switching frequencies of 2 kHz, 4 kHz and 6 kHz and for $k = 2.0$ (Table 1); k denotes the multiple of the maximum voltage on the main transistors relative to the voltage U_{DC} [8, 9].

Table 1. Values of THD of 3LVSI with hard- and soft-switching technique

Switching frequency [kHz]	3LVSI with hard-switching technique	3LVSI with soft-switching technique
2	0.55	0.58
4	0.37	0.40
6	0.33	0.37

The efficiency was estimated for a load with the rated power of 100 kW and 1 MW. Calculations were performed for two switching frequencies and two power factors. It was assumed that the 100 kW inverter was made based on SiC MOSFETs, and the 1 MW inverter was based on IGBTs. Figures 8 and 9 show efficiencies as a function of the load power for two switching frequencies. The power losses in the 3LVSI with the soft-switching technique depend on the coefficient k [8, 9].

For the 100 kW 3LVSI with the soft-switching system (at $k = 2.0$), built on SiC MOSFETs (Fig. 8a), the efficiency gain relative to the 3LVSI with the hard-switching technique is about 1.5 % for both assumed power factors. However, the efficiency of the 1 MW 3LVSI based on IGBTs (Fig. 8b) is about 4 % higher than the efficiency of the 3LVSI with the hard-switching of transistors. It should be noted that SiC-MOSFETs have much shorter switching times compared to IGBTs, which significantly affects the slight increase in efficiency of the 3LVSI using transistors based on the silicon carbide technology.

Influence of switching frequency on inverter efficiency

The switching frequency has a significant impact on the power losses occurring in 3LVSIs. On the one hand, the switching frequency should be relatively low to reduce the switching losses; on the other hand, it should be as high as possible due to the need to limit the content of higher harmonics in the load current. Figure 9 shows the dependence of the efficiency η on the switching frequency f for the rated load power P_N and for half the rated load power $0.5P_N$.

In the 100 kW inverter with the hard-switching technique, based of SiC-MOSFETs (Fig. 9a), the efficiency decreases as a function of the switching frequency, while for the inverter with the soft-switching system at rated load power, the efficiency increases up to a switching frequency of about 25 kHz.

A similar case occurs in the 1 MW inverter, based on IGBTs (Fig. 9b). In the 3LVSI with the hard-switch-

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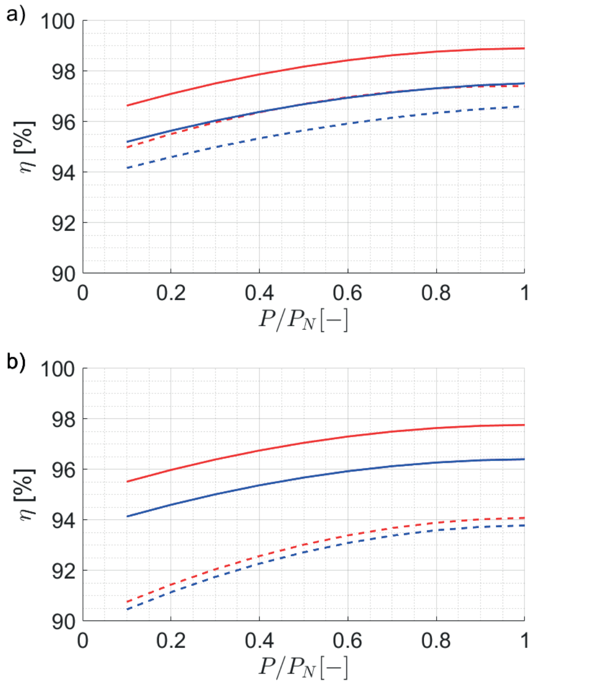

Fig. 8. Efficiencies η as function of the rated load power: a) 100 kW, b) 1 MW: continuous lines – inverter with soft-switching technique; dashed lines – inverter with the hard-switching technique; red lines – power factor 1.0, blue lines – power factor 0.5; switching frequency 20 kHz and 2 kHz, respectively, k = 2.0, where k is the multiple of the maximum voltage on the main transistors relative to the DC voltage

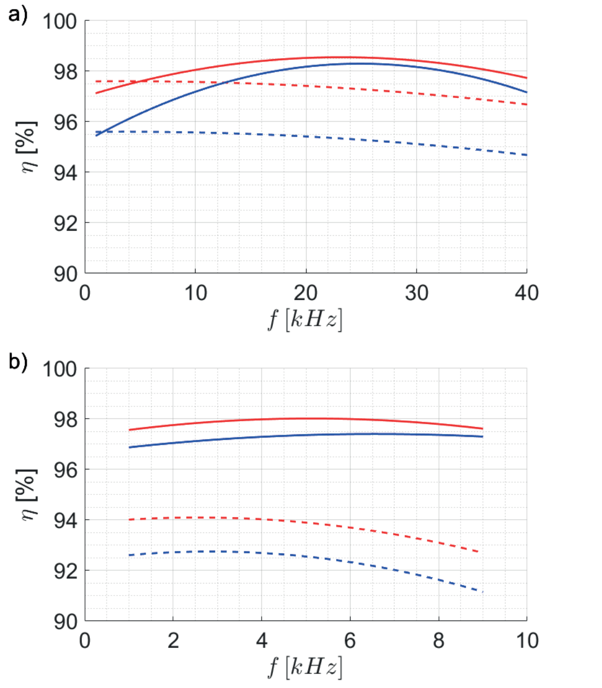

Fig. 9. Efficiencies η as function of the switching frequency for rated load power: a) 100 kW, b) 1 MW: continuous lines – 3LVSI with soft-switching technique; dashed lines – 3LVSI with the hard-switching technique; red lines – load power 1.0 P_N, blue lines – load power 0.5 P_N; switching frequency 20 kHz and 2 kHz, respectively, k = 2.0

ing system, the efficiency gradually decreases with the increasing switching frequency.

Dependence of inverter efficiency on maximum transistor voltage

The switching losses can be significantly reduced if the maximum voltage across the main transistors during the turn-off process equals to twice or more with respect to the value U_{DC} of the voltage source. The dependence of the inverter efficiency on the coefficient k is shown in Figure 10 for two values of the load power. Analysis was carried out for coefficient k in the range 1.5 to 2.5.

The efficiency of the 100 kW 3LVSI changes from 98% to 99.4%, while, the efficiency of the 1 MW 3LVSI increased from 96.7 % at k = 1.5 to 98.3 % at k = 2.5. Notably that the increase in efficiency is significant already at k = 1.5.

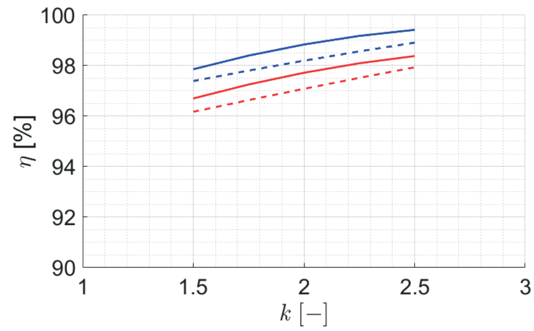

Fig. 10. Efficiencies η as function of the coefficient k: continuous lines – load power 100 kW and 1 MW, respectively; dashed lines –load power 50 kW and 500 kW, respectively; red lines – 1 MW 3LVSI, blue lines – 100 kW 3LVSI; switching frequency 20 kHz and 2 kHz, respectively, *cosφ* = 1.0

Conclusions

The use of the soft-switching technique in voltage source inverters results in increased efficiency for both assumed rated powers. However, the efficiency gain for the 100 kW inverter is relatively low. Therefore, application of the soft-switching technique in the inverters with such rated power is not recommended, especially since the inverters in this case are based on SiC-MOSFETs, and are designed as two-level inverters.

A significant increase in efficiency is achieved for voltage source inverters with a rated power of at least 1 MW, which are based on IGBTs. In three-level voltage source inverters operating with the described soft-switching technique, the coefficient k should be 2.0; however, a significant increase in the efficiency is visible in the range of 1.5 to 2.0. Notably that the efficiency of the VSI depends significantly on the load parameters, i.e. the power delivered to the load and the power factor of the load.

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