Investigation of Analog And Spase-Vector Pulse-Width Modulation In Three-Phase Current Source Rectifiers

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***Abstract*—The article presents a investigation of three-phase current source rectifiers. A space-vector modulation algorithm for an current source rectifier is presented. The analog sinusoidal pulse-width modulation algorithm for a three-phase current rectifier has been proposed. In the Matlab/Simulink program, a model of an currentsource rectifier was developed. The processes of rectification and recuperation when applying the proposed modulation algorithm were studied. The features of the spectrum of higher harmonics of the input current are determined. It is shown that in the rectification and energy generation modes in the three-phase network, the current source rectifier implements a sinusoidal current form with a power factor greater than 0.99.**

Keywords—voltage source rectifier, current source rectifier, PWM, spase-vector for CRV, analog sine PWM for CSR.

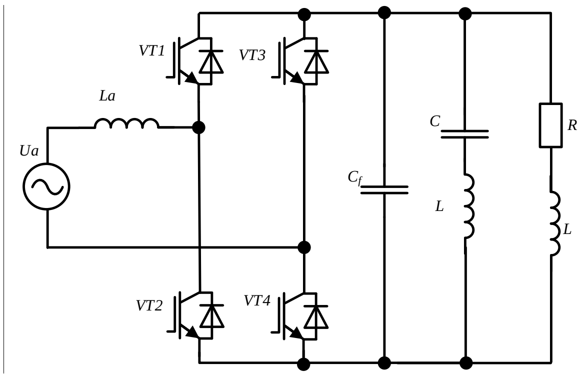
I. INTRODUCTION

Active four-quadrant rectifiers with power factor correction have a number of advantages over diode and thyristor rectifiers: the ability to form a sinusoidal input current, the ability to adjust the power factor and operate in the power factor mode close to unity, the possibility of bidirectional transmission of electrical energy [1, 2]. Active four-quadrant rectifiers are quite promising converters that can be used in many possible applications:

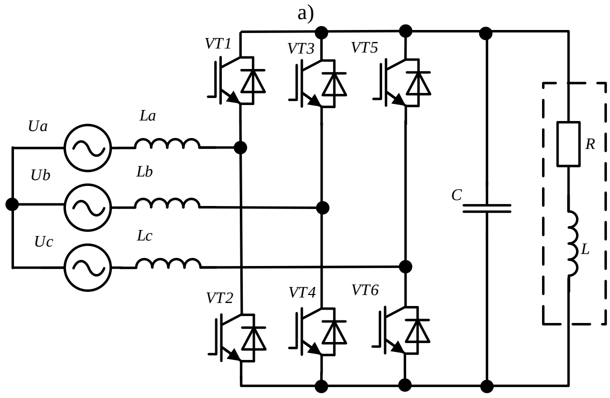
- converters in solar and wind energy generation systems in general industrial electrical networks [3, 4];
- converters for autonomous power supply systems [5, 6];
- converters in electric vehicle charging systems [7, 8];
- power active filters and power factor correction systems [9, 10].
- frequency converters and electric drive systems [11, 12, 13].

In most of the above applications, circuits based on thyristor rectifiers or voltage source rectifiers (VSR) are used.

Schemes of single-phase and three-phase voltage source rectifiers are shown in Fig. 1



a)



b)

Fig. 1. Voltage source rectifiers: a) single-phaseVSR: b) three-phase VSR

At the same time, voltage source rectifiers have their own characteristics and limitations. In particular, voltage sourse rectifiers are step-up (boost) converters and for implementation of input current sine form and power factor correction mode, the VSRs output voltage must be higher than the amplitude value of the input voltage of converter.

Therefore, it`s possible to regulate converters output voltage only in the direction of its increasing. This is a significant limitation of their use, for example, for systems of generating electricity from solar panels or lithium-ion batteries, the voltage of which varies. In the case when their voltage is below the voltage of the line voltage of the network, the mode of forming a sinusoidal current is impossible.

For applications when the voltage in DC link must be lower and the voltage regulation must be in the direction of its decrease, it is advisable to use the scheme of current sourse rectifiers (CSR) [14, 15, 16].

Schemes of a single-phase and three-phase current source rectifiers are presented in Fig. 2.

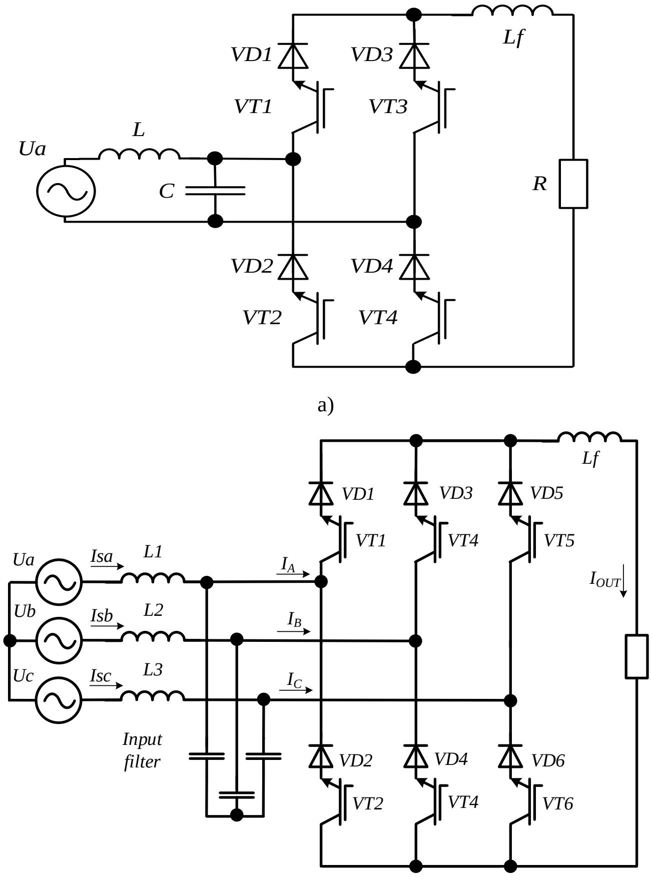


Fig. 2. Current source rectifiers: a) single-phase CSR: b) three-phase CSR

The realized energy efficiency parameters and level of emission of higher current harmonics and reactive power depend both on the parameters of the converter filter and on the implemented control system and modulation algorithm.

II. CURRENT SOURCE RECTIFIER CONTROL SYSTEMS

As in the voltage source rectifier, in the current source rectifier the control systems can be quite different, depending on the different types of regulators used. However, in principle, there space-vector or analog sinusoidal width pulse modulation can be applied [17, 18].

A. CSR Space-vector PWM

A feature of space-vector pulse-width modulation of an current source rectifier is the need for simultaneous switching of two power transistors. Thus, the base vectors in the vector PWM for the current source rectifier have fundamentally different switching states of the power transistors of the converter.

Let's consider the possible switching states of the current source rectifier and the corresponding values and corresponding values of the current in the phases.

TABLE I. POSSIBLE SWITCHING STATES OF THE CURRENT SOURCE RECTIFIER

Vector	**On switches**	I_A	I_B	I_C
1	VT1; VT6	Idc	0	- Idc
2	VT3; VT6	0	Idc	- Idc
3	VT3; VT2	- Idc	Idc	0
4	VT5; VT2	- Idc	0	Idc
5	VT5; VT4	0	- Idc	Idc
6	VT1; VT4	Idc	- Idc	0
0	VT1; VT6 VT1; VT6 VT1; VT6	0	0	0

The switching states of the power switches correspond to Fig. 2, b.

A feature of the space-vector modulation of the current source rectifier is that the basic vectors form not the voltage value, but the AC current value I_A, I_B, I_C.

Base vectors and their switching states for an current source rectifier are shown in Fig. 3.

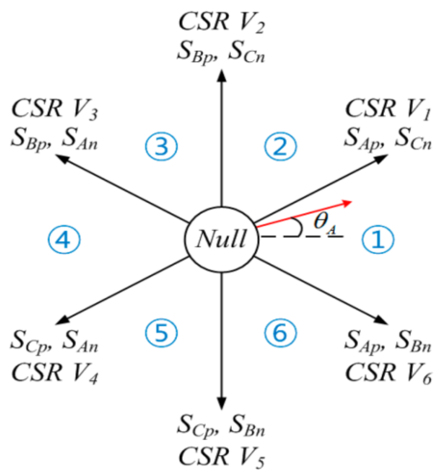


Fig. 3. Basic vectors and їx states stations for CSR

In general, algorithms for calculating the duration of vectors for the formation of PWM for an current source rectifier are the same as for an voltage source rectifier.

Vector sinusoidal pulse width modulation is optimal when implementing a microprocessor control system. At the same time, its implementation on FPGA is complicated and almost impossible.

B. Analog sine *pulse-width modulation* for CRS

Analog pulse-width modulation is advisable when creating an analog control system on separate golic microcircuits or FPGA [19].

Classic three-phase sinusoidal PWM, which is used in voltage source rectifiers, is presented in Fig. 4.

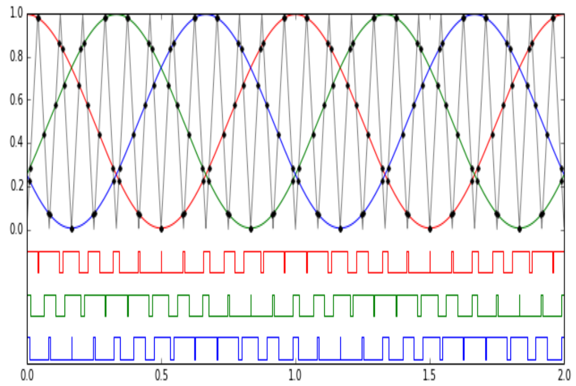


Fig. 4. Three-phase sinusoidal PWM in VSR VSI

As can be seen from Fig. 4, with a classic three-phase sinusoidal PWM, there are switching states when three power transistors of the converter are turned on at the same time. Thus, it is impossible to use the sinusoidal modulation algorithm from voltage source rectifiers in current source rectifiers. More precisely, when using it, the converter will not work in the power factor correction mode.

Thus, it is necessary to create an algorithm of analog sinusoidal modulation in which only two transistors will be open at each moment.

Analog sinusoidal pulse-width modulation for an current source rectifier, built on logic elements, which can be implemented on a FPGA, is presented in Fig. 5

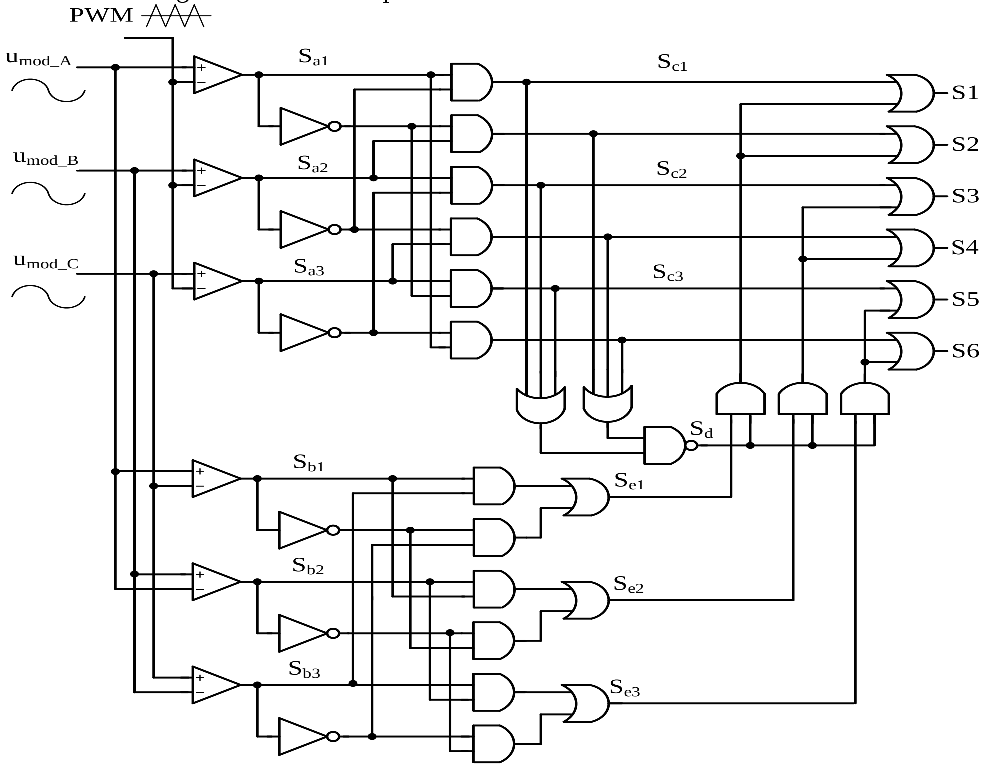


Fig. 5. Logical scheme of analog sinusoidal pulse width modulation for three-phase current-source rectifier

In analog sinusoidal pulse width modulation for an current source rectifier, as well as for analog and vector modulation of an voltage source rectifier, three sinusoids are used as input modulating signals.

Transient processes in the proposed analog algorithm sinusoidal pulse width modulation for an current source rectifier is presented in Fig. 6.

The presented pulse width modulation algorithm has significant features:

- the input current of the I_A bridge has a frequency that is doubled relative to the pulse width modulation frequency;
- There is a phase shift φ_A between the shape of the modulating sinusoidal signal UmodA and the input current of the rectifier bridge I_A.

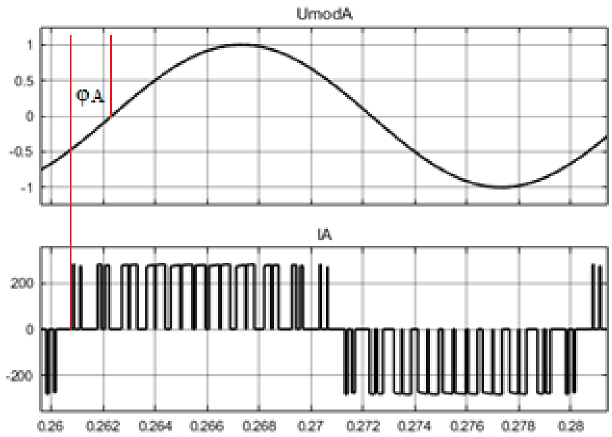


Fig. 6. modulating sinusoidal signal UmodA and the input current of the rectifier bridge IA

Intermediate signals in the modulation algorithm Sa, Sb, Sc, Se, Sd, S1 that presented in Fig. 7 and correspond to the ones in Fig. 5.

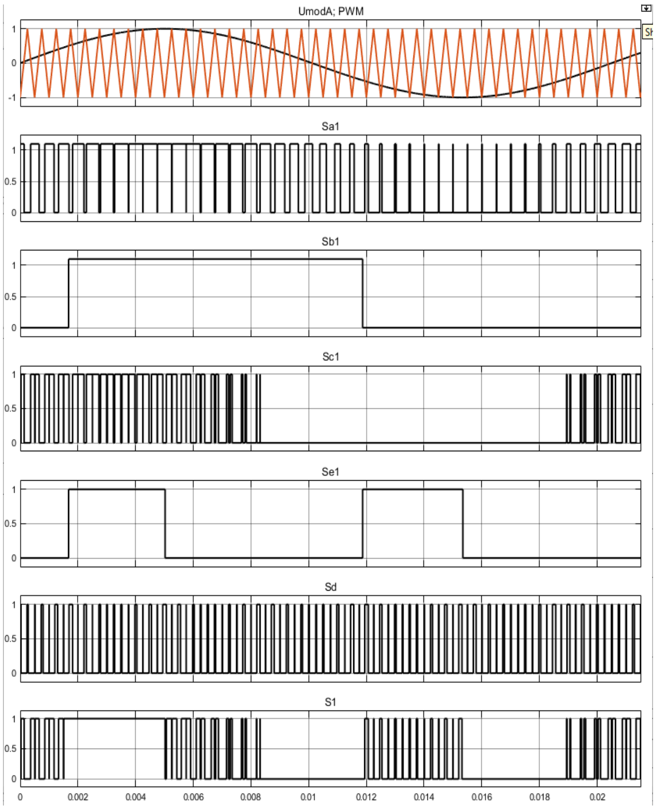


Fig. 7. Transient processes in the proposed analog algorithm sinusoidal pulse width modulation

The output current of the CSR is adjusted by adjusting the amplitude of the modulating sinusoidal signals U_{modA}, U_{modB}, U_{modC}.

The presented modulation algorithm can be applied both for the implementation of the rectification algorithm of the current source rectifier and for the implementation of the recuperation process.

To implement the recovery mode in the control system, it is necessary to supply input modulating signals UmodA, UmodB, UmodC in antiphase to the input voltage of the rectifier.

III. Computer Simulation of Three-Phase Current Source Rectifier

A matlab model will be developed to study the energy indicators of the CSR during the implementation of the proposed control system. The developed CSR model in the Matlab software is shown in Fig. 8.

In the Table 2 shows the parameters current source rectifier Matlab model.

TABLE II. CSR Matlab Model Parameters

Parameter	Value
Input voltage	3*380 V, AC
The inductance of the input filter	1 mH
Input filter capacity	500 uF
PWM frequency	2000 Hz
The inductance of the output filter	2 mH
Load resistance	1,4 Ohm
Constant voltage in the DC link in recovery mode	400 V

On the developed model, the processes of rectification and recuperation (electricity generation from the direct current link to the three-phase electric network.

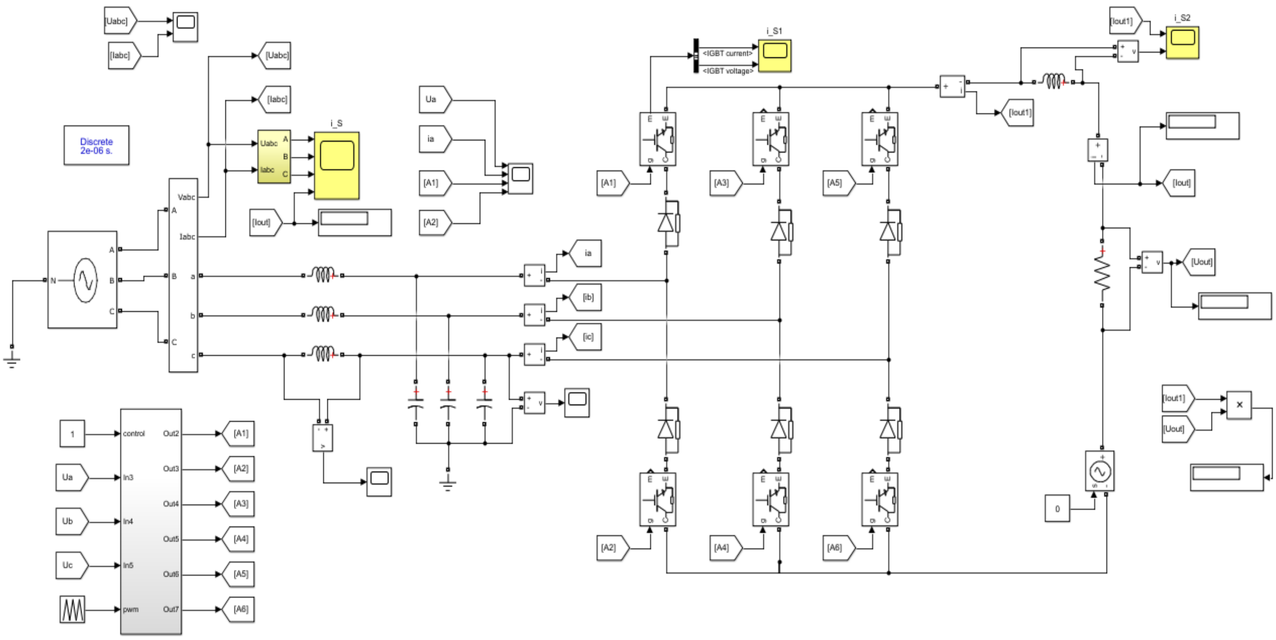


Fig. 8. Matlab model of a solar panel with a step-down pulse converter

In the developed simulation Matlab model, Analog sinusoidal pulse-width modulation is applied for the current source rectifier, which is shown in Fig. 5, which confirms its operability and determines the efficiency of forming a sinusoidal phase current in the rectification and recovery modes.

To compensate for the phase shift φA between the shape of the modulating sinusoidal signal UmodA and the input current of the rectifier bridge IA, an adaptive phase compensation algorithm φA has been developed, which is formed according to the phase of the input voltage Ua and the phase of the input current Isa.

Transient processes of input voltage, input current in three phases, and output current when starting an current source rectifier in the rectifier operating modes are presented in Fig. 9.

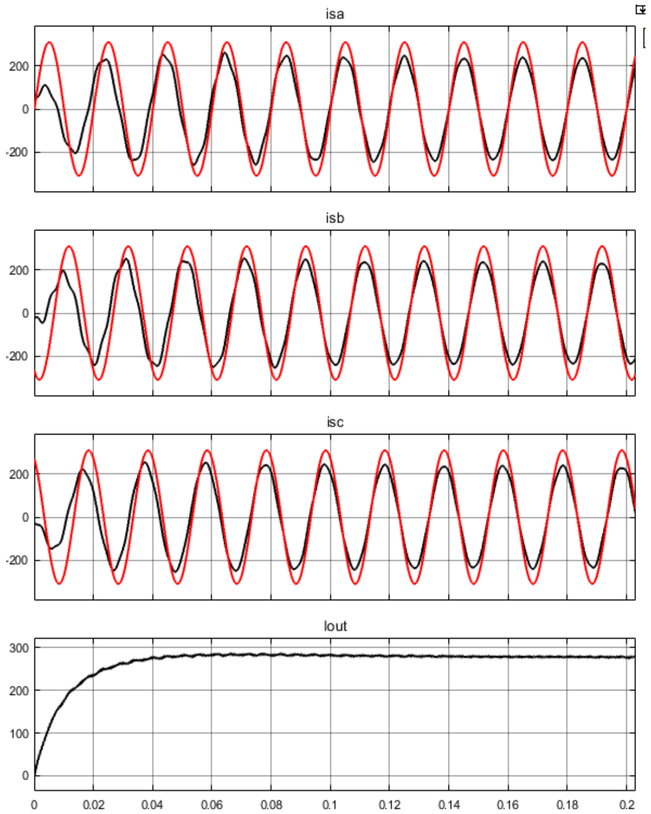


Fig. 9. Transient processes of input voltage, input current in three phases and output current when starting the converter in the rectification mode

As can be seen from Fig. 9, a significant advantage of the current source rectifier in comparison with the voltage source rectifier is the absence of shock starting current in the input network, which is due to the novelty of a sufficiently large capacity in VSI.

The harmonic composition of the input current of the current source rectifier is shown in Fig. 10.

As can be seen from Fig. 10, the coefficient of harmonic distortion of the input current of the current source rectifier is 2.55%, which is a fairly high quality indicator.

It was determined that an essential feature of the spectrum of higher harmonics of the input current of the current source rectifier is the practical absence of higher harmonics at the pulse width modulation frequency. However, higher harmonics with a frequency twice the PWM frequency are present in the input current spectrum. In addition, the spectrum of the input current is characterized by a small amount of content of low-frequency higher harmonics.

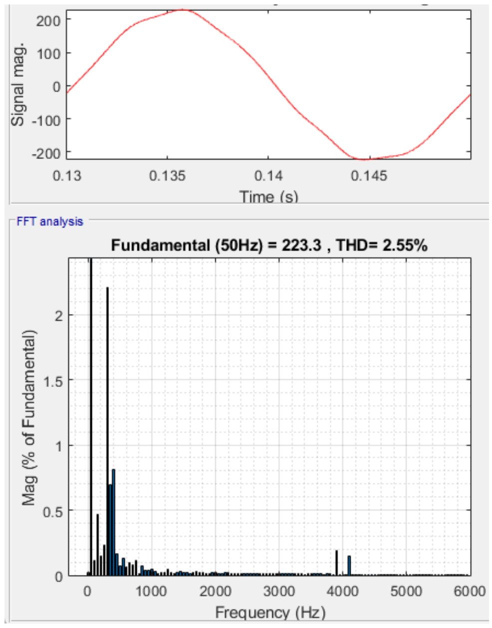


Fig. 10. The form and harmonic composition of the input current of the current source rectifier

If there is an voltage or power source in the direct current link, which can be a block of solar panels or block of lithium ion batteries, and others, the current source rectifier makes it possible to implement the process of energy recovery from the link of constant voltage to the three-phase electrical network.

Transient processes of input voltage, input current in three phases, and output current when starting an CSR in energy generation modes to a three-phase electrical network are presented in Fig. 11.

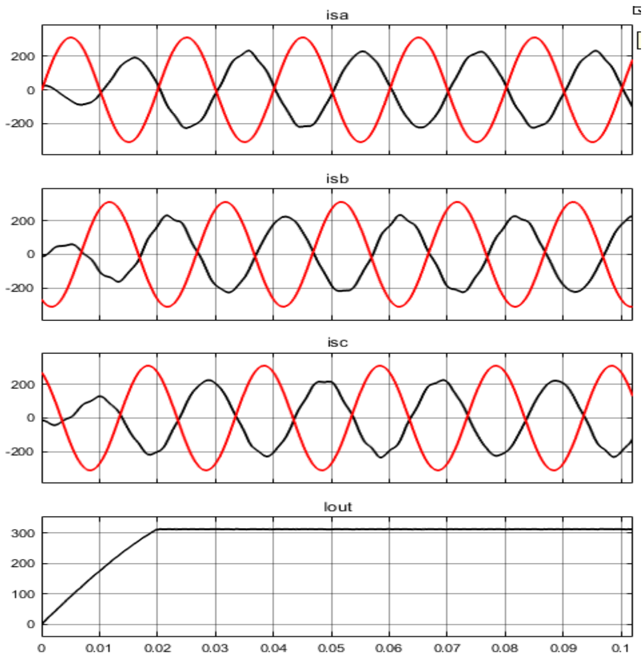


Fig. 11. Transient processes of input voltage, input current in three phases and output current when starting the converter in recovery mode

Thus, it can be seen that in the rectification and recovery modes, the current source rectifier realizes high quality indicators of electrical energy with a current shape close to a sinusoid and a power factor close to unity.

CONCLUTIONS

The article shows that in some applications current source rectifiers have a number of advantages over voltage source rectifiers. The possible states of the power transistors of the current source rectifier and the features of the space-vector modulation algorithm are considered. The algorithm and scheme of analog sinusoidal pulse width modulation are presented. It is determined that the input current of the I_A bridge has a frequency that is doubled relative to the pulse width modulation frequency. Also its determined that there is a phase shift φ_A between the shape of the modulating sinusoidal signal UmodA and the input current of the rectifier bridge I_A. To compensate for the phase shift φA between the shape of the modulating sinusoidal signal UmodA and the input current of the rectifier bridge IA, an adaptive phase compensation algorithm φA has been developed, which is formed according to the phase of the input voltage Ua and the phase of the input current Isa.

A matlab model of an current source rectifier with a proposed modulation algorithm was developed. The rectification and recovery processes of the current source rectifier are simulated on the model. Transient processes, the harmonic spectrum of the input current, and the power factor were investigated.

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