A New Way to Control a Static Synchronous Series Compensator Using the Parameters of an Electric Arc Furnace Equivalent Circuit

Alexei M. Evseev
Automation and computer science faculty
Lipetsk State Technical University
Lipetsk, Russia
ORCID: 0000-0003-0687-7383

Sergey S. Titov
LLC "Research and Development enterprise System 48"
Lipetsk, Russia
ORCID: 0000-0002-4567-7328

***Abstract*—In this study, a new method for controlling a static synchronous series compensator is proposed, which consists in using data on the parameters of the equivalent circuit of the electric arc furnace. In this case, the compensator is used to improve the energy efficiency and electromagnetic compatibility of a particular unit. A relationship was established between the control parameter - the primary voltage of the compensator and the current consumed by the technological plant. Data on the technological plant and the process can be presented for a given relationship in the form of nonlinear resistance and reactance. The installation of a series compensator controlled in this way makes it possible to regulate the unit current consumption without additional current injection. In the course of mathematical modeling of the process using the established dependence, it was found that the proposed solution allows for full or adjustable compensation of reactive power, filtering of current harmonics and excluding the impact of supply voltage distortions on the progress of the technological process.**

Keywords—electric arc furnace, flexible AC transmission systems, static synchronous series compensator, reactive power compensation, harmonic distortion filtering, distortion of supply voltage, energy efficiency, electromagnetic compatibility

I. Introduction

One of the most topical issues in electrometallurgy today is the problem of high energy losses and low electromagnetic compatibility of energy-intensive technological equipment. This increases the cost of manufactured or processed products, and thereby reduces the rate of innovative development of the industry. At the same time, if for installations powered by electronic rectifiers or frequency converters this problem can be solved in most cases at the software level, then for systems operating without an electronic converter, which includes an AC electric arc furnace (EAF), the development of hardware systems is necessary. Various researchers carried out a wide analysis of harmonic distortions of current and voltage [1-3], changes in power factor [4], as well as other indicators of the quality of electricity consumed by EAF [5] in various configurations of plants and their operating modes.

There are solutions for the development of flexible AC transmission systems (FACTS) to improve the energy efficiency of EAFs, such as the static variable compensator (SVC) [6], the static synchronous compensator (STATCOM) [7] and the unified power flow controller (UPFC) [8]. However, in the case of SVC and STATCOM, harmonic components and other voltage quality indicators are not corrected, which affect both the amount of energy losses and the progress of the technological process. The UPFC, which injects both current and voltage, is a versatile means of compensating for any electrical distortion, however, it has large dimensions in comparison with the STATCOM or static synchronous series compensator (SSSC). In addition, at the software level, most FACTS use algorithms for calculating compensation actions based on the current and calculated instantaneous values of phase currents without taking into account the parameters of the technological process [9, 10], which may cause undercompensation of distortions or affect its progress.

Due to the fact that at the moment there are studies confirming the possibility of determining the parameters of the electric equivalent circuit EAF [11-13], it becomes possible to direct determine of compensating influences using FACTS. The solution described below consists in the introduction of an additional regulated source of emf, the role of which will be played by the SSSC, into the EAF supply circuit. The emf value of this source is supposed to be controlled based on the requirements of the technological process, specifically - the instantaneous value of the arc current and the parameters of the equivalent circuit EAF. Thus, current injection to compensate for distorted harmonic currents will be replaced by voltage injection. The objectives of the study are to establish the relationship between the voltage introduced into the AC line and the specified instantaneous arc current EAF, as well as to check its validity by mathematical modeling.

II. Energy Flow Control Principle

To accomplish this task, it is first of all necessary to determine the initial data, namely, the parameters of the equivalent circuit of the system under study, as well as the relationship between them. The hardware component of the SSSC power section consists of a three-phase transformer, the secondary windings of which are connected oppositely to each phase of the supply network, and the primary windings are connected to a star and connected to the output of the voltage inverter. For simplicity of description of the equivalent circuit, let us assume that the phase voltages of the power source, phase resistances of the secondary winding of the transformer SSSC and EAF are symmetrical, and we will also proceed to a single-line diagram of electrical circuits. Imagine the supply network as a voltage source U_s, the complex nonlinear resistance of the plant $Z_{load} = R_{load} + jX_{load}$, while its active R_{load} and reactive X_{load} components do not take into account the resistance of the supply lines, as well as other circuit elements. In this case, it is assumed that the SSSC is connected at the electrical connection point of the EAF. The secondary winding circuit of the SSSC transformer will be presented in the form of a regulated source of emf E_2 connected according to the supply network and complex resistance of the secondary winding $Z_2 = R_2 + jX_2$. The current flowing through the circuit is I_2. The described equivalent circuit of the system under study is shown in Fig. 1.

The expected results of the system operation are regulation or minimization of the reactive component of the consumed power, reduction of harmonic components of phase currents, stabilization of the EAF power supply in case of unbalance, fails or harmonic distortions of voltage in the supply lines. To ensure the regulation of the reactive power EAF, which consists in adjusting the angle φ_2 between the vectors U_s and I_2, it is necessary E_2 to introduce, as shown in Fig. 2 a, b. For further control of the E_2, it is required to establish a functional relationship between the phase current (secondary current of the SSSC transformer) and the primary voltage of the SSSC transformer. The ratios required for this are the balance equations of the primary and secondary windings voltages of the SSSC transformer are determined by the ratios given below. When describing the connections in this system, we will use the parameters and variables of the EAF circuit, reduced to the primary winding of the transformer.

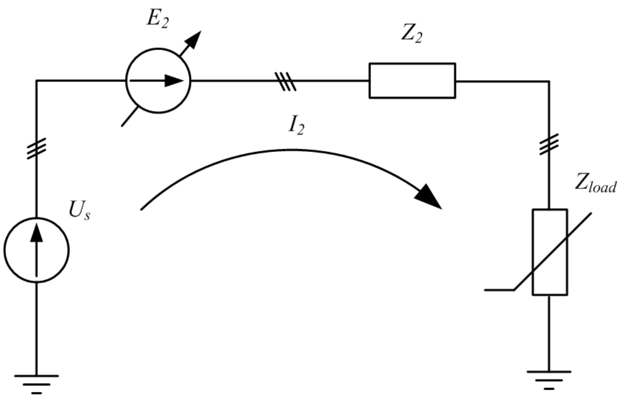

Fig. 1. Electrical equivalent circuit of the system under research

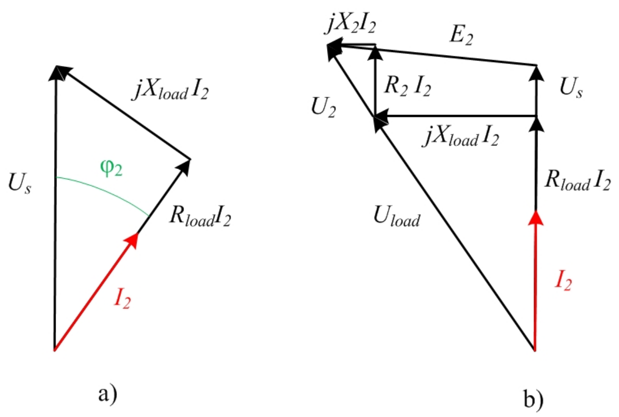

Fig. 2. Vector diagrams of currents and voltages: a – EAF, b – EAF with reative power compensation by SSSC

Equation of balance of voltages of the primary winding:

$$U_1 = R_1 I_1 + jX_1 I_1 - E_1, \quad (1)$$

where U_1 is the voltage of the primary winding of the transformer, I_1 is the current of the primary winding of the transformer, R_1 is the resistance of the primary winding of the transformer, X_1 is the reactance of the primary winding of the transformer.

In accordance with the vector diagram in Fig. 2b, the reduced emf of the secondary winding is defined as

$$E_2' = I_2' R_2' + jX_2' I_2' + U_{load}' - U_s k \quad (2)$$

and

$$E_2' = E_1 = E_2 k, \quad (3)$$

where E_1 is the emf of the primary winding, k is the transformation ratio, $U_{load}' = U_{load} k = I_2'(R_{load}' + jX_{load}')$ is the referred to the primary side voltage drop across the load (voltage at the EAF input), $I_2' = I_2 / k$ is the referred to the primary side current of the secondary winding, $R_2' = R_2 k^2$ is the referred to the primary side active resistance of the secondary winding of the transformer, $X_2' = X_2 k^2$ is the referred to the primary side reactance of the secondary winding of the transformer, $R_{load}' = R_{load} k^2$ is the referred to the primary side active resistance of the load , $X_{load}' = X_{load} k^2$ is the referred to the primary side reactance of the load.

III. Determination of the Control Voltage as a Function of the EAF Parameters

Substituting into (1) A from (3) and B from (2) we obtain:

$$U_1 = R_1 I_1 + jX_1 I_1 - R_2' I_2' - jX_2' I_2' - U_{load}' + U_S k. \quad (4)$$

For the convenience of further transformations, we will pass from the referred values:

$$U_1 = R_1 I_1 + jX_1 I_1 - R_2 I_2 k^2 \frac{1}{k} - jX_2 I_2 k^2 \frac{1}{k} - \\ -I_2(R_{load} + jX_{load})k^2 \frac{1}{k} + U_S k, \quad (5)$$

$$U_1 = I_1(R_1 + jX_1) - I_2 k((R_2 + R_{load}) + \\ + j(X_2 + X_{load})) + U_S k. \quad (6)$$

The primary current of the transformer is also determined by the ratio

$$I_1 + I_2' = I_1 + I_2 \frac{1}{k} = I_0, \quad (7)$$

where I_0 is the no-load current of the transformer.

Since the voltage U_1 changes during the active filter operation, I_0 is also changes. To determine the dependence of the no-load current on the voltage amplitude of the primary winding of the transformer, a series of experiments was carried out to measure the no-load current with a ТСП-10 / 0.7 transformer.

From a series of the no-load tests a dependence $I_0 = f(U_1)$ was established, presented in the exponential form of a complex number for the convenience of further transformations:

$$I_0 = U_1 \frac{2.1975}{311.1278} e^{j(1.4549)}. \quad (8)$$

We also transform the representation of the complex vector of the secondary current:

$$I_2 = I_{2amp} \cdot e^{j(\omega t+\varphi_2)}, \quad (9)$$

where I_{2amp} is the amplitude of the transformer secondary winding current (EAF current), ω is the pulsatance, φ_2 is the phase shift of the transformer secondary winding current (EAF current),

Substituting (8) and (9) into (7) we obtain:

$$I_1 = U_1 \frac{2.1975}{311.1278} e^{j(1.4549)} - \frac{1}{k} I_{2amp} \cdot e^{j(\omega t+\varphi_2)}. \quad (10)$$

For further transformations, we also translate the complex resistances in expression (6) into exponential form:

$$R_1 + jX_1 = \sqrt{R_1^2 + X_1^2}\, e^{j(\arctan(\frac{X_1}{R_1}))}, \quad (11)$$

$$(R_2 + R_{load}) + j(X_2 + X_{load}) = \\ = \sqrt{(R_2 + R_{load})^2 + (X_2 + X_{load})^2}\, e^{j(\arctan(\frac{X_2+X_{load}}{R_2+R_{load}}))}. \quad (12)$$

Substituting (11) and (12) into (6) we obtain:

$$U_1 = I_1 \sqrt{R_1^2 + X_1^2}\, e^{j(\arctan(\frac{X_1}{R_1}))} - \\ -I_{2amp} k \sqrt{\begin{matrix}(R_2 + R_{load})^2 + \\ +(X_2 + X_{load})^2\end{matrix}} \cdot e^{j\left(\begin{matrix}\omega t+\varphi_2+ \\ +\arctan(\frac{X_2+X_{load}}{R_2+R_{load}})\end{matrix}\right)} + \\ +U_S k. \quad (13)$$

Substituting (10) into (13) we obtain:

$$U_1 = U_1 \frac{2.1975}{311.1278} e^{j(1.4549)} \sqrt{R_1^2 + X_1^2}\, e^{j(\arctan(\frac{X_1}{R_1}))} - \\ -I_{2amp} \frac{1}{k} \sqrt{R_1^2 + X_1^2}\, e^{j(\omega t+\varphi_2+\arctan(\frac{X_1}{R_1}))} - \\ -I_{2amp} k \sqrt{\begin{matrix}(R_2 + R_{load})^2 + \\ +(X_2 + X_{load})^2\end{matrix}} \cdot e^{j\left(\begin{matrix}\omega t+\varphi_2+ \\ +\arctan(\frac{X_2+X_{load}}{R_2+R_{load}})\end{matrix}\right)} + \\ +U_S k \quad (14)$$

Expressing U_1 from (14) we get:

$$U_1 = \left(\begin{matrix} I_{2amp} \frac{1}{k} \sqrt{R_1^2 + X_1^2}\, e^{j(\omega t+\varphi_2+\arctan(\frac{X_1}{R_1}))} + \\ +I_{2amp} k \sqrt{\begin{matrix}(R_2 + R_{load})^2 + \\ +(X_2 + X_{load})^2\end{matrix}} \cdot e^{j\left(\begin{matrix}\omega t+\varphi_2+ \\ +\arctan(\frac{X_2+X_{load}}{R_2+R_{load}})\end{matrix}\right)} - \\ -U_S k \end{matrix}\right) / \\ / \left(\frac{2.1975}{311.1278} \sqrt{R_1^2 + X_1^2}\, e^{j(\arctan(\frac{X_1}{R_1})+1.4549)} - 1\right) \quad (15)$$

The resulting function allows you to determine the required instantaneous voltage values of the primary winding of the transformer U_1 for each of the phases, depending on the set values of the amplitude I_{2amp} and phase shift of the current φ_2, based on the measured instantaneous values of the mains voltage φ_2 and the known parameters of the transformer. When changing the load parameters, which is, the equivalent circuit EAF, is possible enter data on the process progress into the function.

IV. Math Modeling

The adequacy of the calculations was verified by simulation in the MATLAB Simulink software package using the Sim Power Systems library. Fig. 3 shows a model of the power section of the system under study, consisting of an SSSC inverter, connected to the phase windings of a three-phase transformer T , an inverter current source, switching capacitors C_1, C_2, C_3 at the output of the inverter, three-phase voltage sources U_{SA}, U_{SB}, U_{SC} a load, which represented by RL chains (R_{load}, L_{load}) in each phase, and measurement elements of the mains voltage v_{2A}, v_{2B}, v_{2C}, voltage on the primary windings of transformers v_{1A}, v_{1B}, v_{1C}, load current i_{2A}, i_{2B}, i_{2C}, current I_d and voltage U_d in the DC link of the SSSC inverter.

The SSSC is controlled by the transmission of switching pulses through the IGBT $g_1 - g_6$ gate channels, which come from the block of hysteresis regulators, shown in Fig. 4. The block works as follows: the regulators receive the signal difference between the measured values of the voltage of the primary windings of the transformer and the set values U_{1A}, U_{1B}, U_{1C}. After the hysteresis block, in the event of a significant excess or decrease in the actual voltage value, a switching combination is selected and transferred to the inverter keys for switching the required circuit. In addition, this unit has a built-in open circuit protection algorithm, which is an emergency mode of operation of the inverter.

The calculation of the references instantaneous voltages of the primary windings of the transformer is carried out in accordance with (2.15). All initial parameters of the equivalent circuit of the SSSC transformer were calculated according to the passport data of the ТСП-10/0.7 transformer. The EAF parameters, namely: resistance R_{load} and inductance L_{load} in the simulation are set at 30 Ohm and 50 mH, respectively.

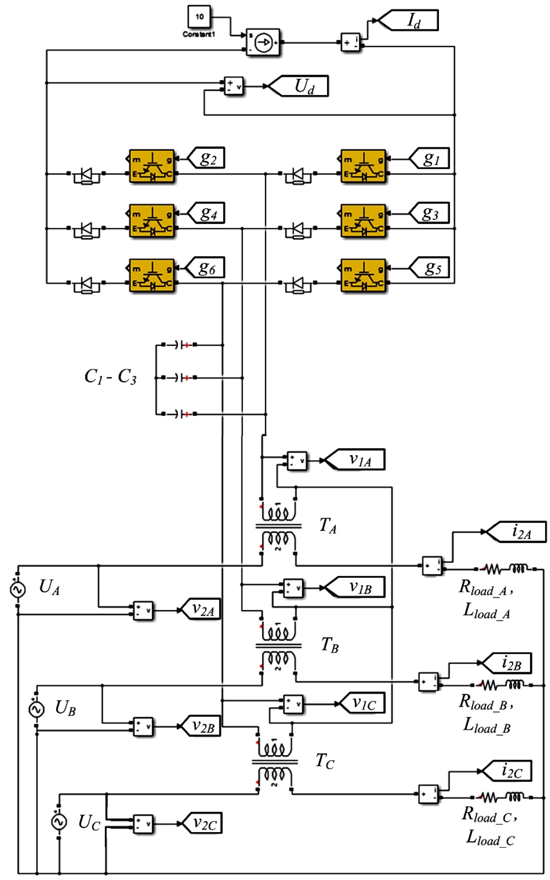

Fig. 3. The Simulink-model of the power section of the system under study

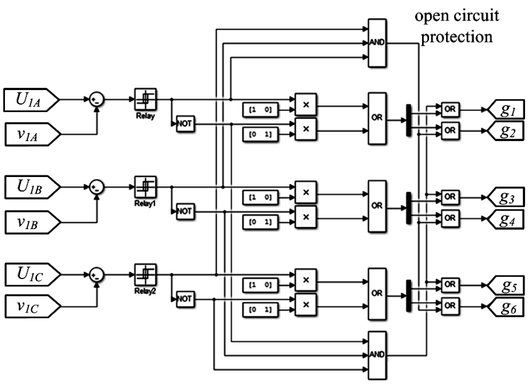

Fig. 4. The Simulink-model of the block of hysteresis regulators

During the experiment of reactive power compensation, the phase shift is set to zero, the amplitude of the load current is 5 A. In this case, full compensation of reactive power occurs, which can be observed in Fig. 5, which shows the phase shifts between the load current and phase A voltage in a system without SSSC and with it, as well as in Fig. 6, which shows the levels of active and reactive power consumption in phase A before and with the SSSC. It can be seen from the graphs in Fig. 6 that the phase active power with the filter is higher than in the system without it, while the phase reactive power is completely absent. At the same time, the phase apparent power of the systems did not change and amounted to 419 W. To assess the capabilities of the algorithm in the problems of filtering harmonics, an experiment was carried out with a change in the harmonic composition of the supply voltage by seeing additional power supplies with a frequencies of 150 Hz and 250 Hz and a voltage level of 10% and 5% of the voltage level of the fundamental harmonic, respectively. The total harmonic distortions of the current consumed by the load in this case was 7.44%, which is reflected in Fig. 7 a and 7 b. Installing the SSSC with an algorithm for restoring the sinusoidal shape of the consumed current allows reducing the level of harmonic distortions of the current consumed in this experiment to 0.49 %, which is reflected in Fig. 7c and 7g.

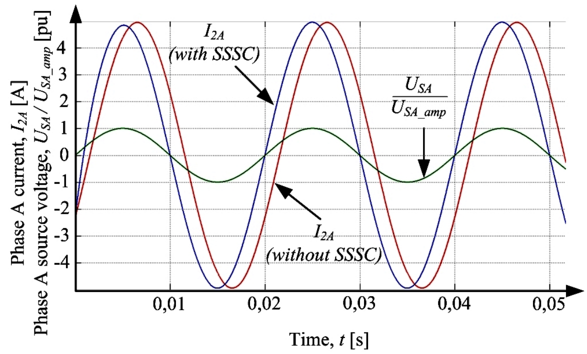

Fig. 5. Phase A load currents and voltage graphs befor and after installation of SSSC

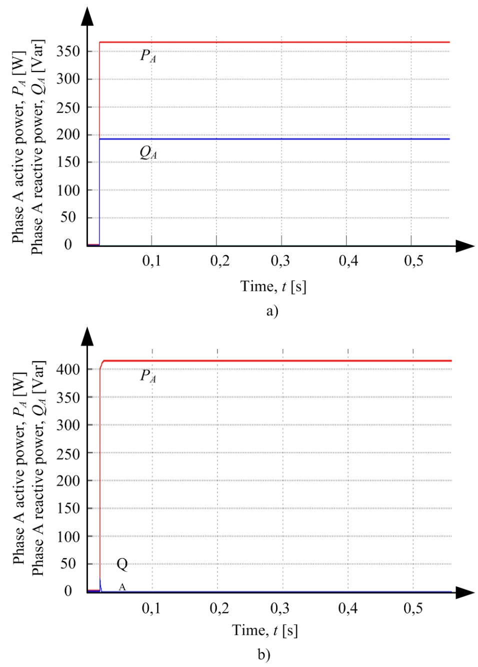

Fig. 6. Phase A active and reactive power: a – befor SSSC installation, b – after SSSC installation

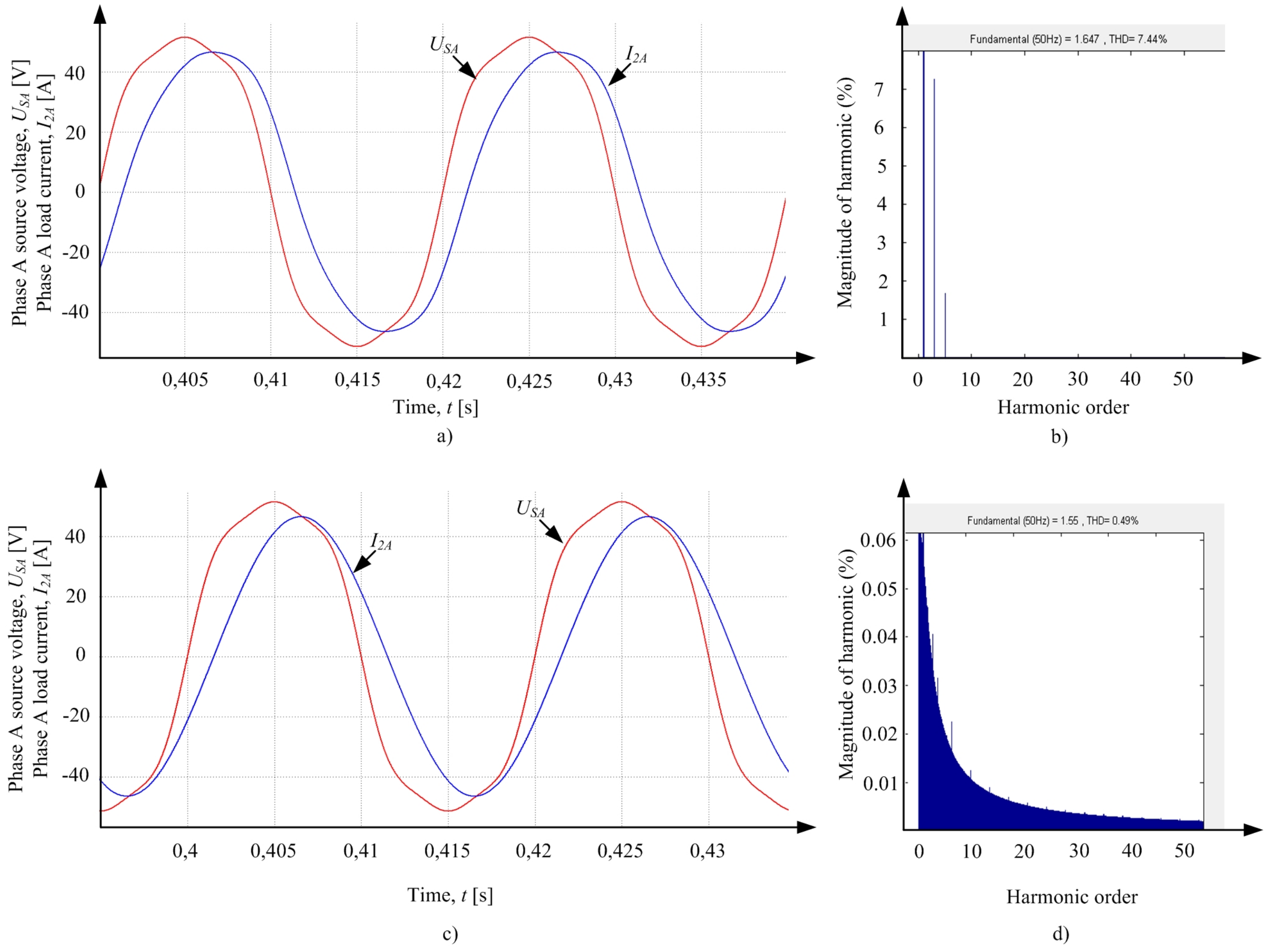

Fig. 7. Harmonic filtering by SSSC: a – graphs of phase A source voltage and current befor SSSC installation, b - spectral analysis of phase A current befor SSSC installation, c – graphs of phase A source voltage and current after SSSC installation, d - spectral analysis of phase A current after SSSC installation.

V. CONCLUSION

The originality of the proposed energy-efficient method of energy flow control based on SSSC lies in the use of the load model as the initial data for regulating the flows, whereas in the existing solutions [14-16] the measured values of the alternating voltage at the filter connection point are used. The proposed solution, in contrast to the classical ones, is primarily used not for correcting the shape of the supply voltage (compensation of voltage harmonics, eliminating unbalance), but for the formation of the consumed alternating current, regardless of the quality of the supply voltage.

Simulation has confirmed the functionability of the SSSC control system using the relationships obtained during the study. Thus, the results obtained allow us to conclude that the established ratios:

1. Allows controlling the SSSC for correcting the power factor of the plant. It should be borne in mind that the installed power of the SSSC must be higher than the level of the compensated power.

2. Allows controlling the SSSC, excluding current harmonic distortion. In this case, the installed power of the SSSC can be significantly reduced to the values of the filtered harmonic distortion power.

3. Allows controlling the SSSC, excluding the influence of harmonic distortions, unbalances, faults and other distortions of the mains voltage.

4. Allows to adjust the supply voltage and current consumption at the same time solely due to voltage injection, without additional current injection, as is the case when using UPFC.

In the course of further research, it is proposed to consider in more detail the performance of the SSSC with the proposed control method at the rated power of the EAF in various modes of its operation.

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