About Direct Start of Induction Motor with Two-Stage Reactive Power Compensation as a Part of the Auxiliary Drive of Electric Locomotive

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Abstract: The auxiliary electric drive of electric locomotives is often built on the basis of three-phase induction motors. In a number of auxiliary drive circuits, direct starting of motors is practiced, which is accompanied by significant starting currents. This imposes increased requirements on the installed power of the supply converter. A method for reducing starting and operating currents through the use of three-phase capacitor banks is considered. The simulation results are presented.

Key-Words: induction motor, reactive power compensation, direct start, compressor, autonomous voltage inverter, capacitor, computer simulation

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1 Introduction

The power supply circuit of three-phase induction motors (IM) for auxiliary needs of an electric locomotive from electromechanical phase splitters (Arno converters) or capacitive phase splitters provides for direct-on-line start-up of both motor-fans and air motor-compressors (MC) [1-5].

Also, the direct start of auxiliary electric drives is provided by the static phase splitter based on IGBT proposed in [6], and based on GTO proposed in [7].

The modern ideology of building auxiliary static converters (ASC) of electric locomotives provides for the presence of several parallel channels [8, 9]. The basis of the channel is a frequency converter based on an autonomous voltage inverter (AVI). One of the reasons for the multi-channel ASC is the presence of loads of different nature on board the electric locomotive. For example, frequency regulation of the speed of rotation of IM driving fans, depending on temperature or current of traction motors, provides significant energy savings [10]. The MC operates at a constant speed, has a significant starting torque (especially with a piston compressor [11, 12]), which may be aggravated in cold operating conditions. To simplify the ASC control system, it is permissible to connect the MC to an unregulated channel with a fixed output frequency and voltage, i.e. direct-on-line start of MC.

2 Problem Formulation

Direct-on-line start of IM is associated with significant starting currents, multiples of the nominal value. Starting currents are consumed from the phase splitter or from ASC. The installed power of these devices should be able to withstand IM start-ups, including protracted ones (at low voltage in the overhead wire, at low ambient temperature). The IM current, especially during start-up, contains a significant reactive (inductive) component, the compensation of which would make it possible to facilitate the operation of the supply converter, to reduce its installed power.

3 Problem Solution

One of the relatively simple ways to compensate for the reactive component of the IM current is to install three-phase capacitor banks in the power circuit. The amount of reactive power to be compensated is different in the starting and rated modes, therefore, either compensation should be applied only in the starting mode, or two-stage compensation, changing the value of the connected capacitance depending on the operating mode.

Let the IM, which drives the MC, receive power from an unregulated channel of the ASC, the schematic diagram of the power part of which is shown in Fig. 1. In Fig. 1 the diodes connected in opposite parallel to the IGBT are not conventionally shown as part of the AVI.

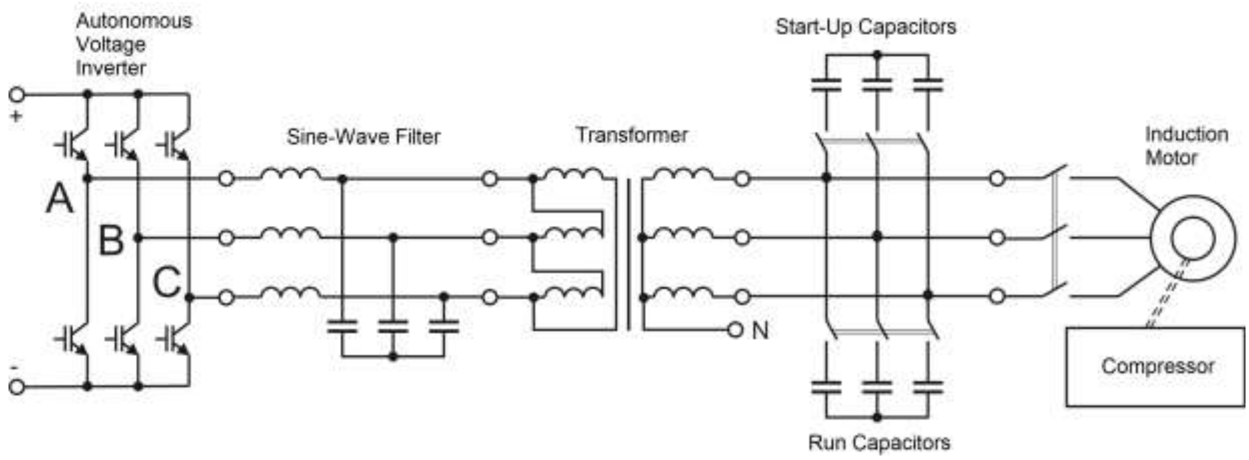

Figure 1 - Schematic diagram of the power part of the unregulated ASC channel

Table. Comparison of calculated and experimental characteristics of the nominal mode of operation of 4-pole IM NVA-55

Phase-to-phase voltage RMS (V)	Stator phase current RMS (A)	Active power consumed (kW)	Power on the shaft (kW)	Electrical power losses in stator winding (W)	Electrical power losses in rotor winding (W)	Iron power losses (W)	Efficiency (%)	Power factor (p.u.)	Rotor speed (rotation per minute)	Torque on the shaft (Nm)
Test results										
379	116	62.2	55.8	1930	2310	1600	89.7	0.817	1441.5	369.8
Simulation results obtained by means of OrCAD										
380	113	58.9	55.0	1635	2229	1531	93.4	0.792	1442.4	364.4

The structure of the ASC includes a two-level AVI with hard switching, a sine-wave filter, a three-phase transformer. The IM is connected to the secondary winding of the transformer. In parallel with the secondary winding of the transformer two three-phase capacitor banks are connected, which provide the process of direct-on-line starting of the IM with two stages of reactive power compensation. In our case, the sine-wave filter capacitors with a capacity of 450 μF per phase are connected according to the "wye" circuit, the sine-wave filter inductances are 2 mH per phase, the transformer windings have a Δ/Y connection scheme (neutral is connected to the secondary winding to be able to connect single-phase loads), the capacitors in each three-phase battery (start-up capacitors and run capacitors) are connected in a star configuration. In the further calculation and in computer simulation, the parameters of the NVA-55 type IM were used, the characteristics of which for the rated mode are presented in the Table.

The capacity of the phase of the run capacitors is calculated by the equation [13, 14]:

$$C_{ph\ run} = \frac{P_{ph\ rated}}{2\pi \cdot f \cdot V_{ph\ rated}^2} (\mathrm{tg}\varphi_{ini} - \mathrm{tg}\varphi_{des}), \quad (1)$$

where ($\mathrm{tg}\varphi_{ini} - \mathrm{tg}\varphi_{des}$) - the conversion factor; $\mathrm{tg}\varphi_{ini} = 0.75$ - initial value corresponds to the value of the power factor $\cos\varphi = 0.8$; $\mathrm{tg}\varphi_{des} = 0$ - the desired value corresponds to the value of the power factor $\cos\varphi = 1.0$);

$P_{ph\ rated} = 21000$ W - the accepted value of the active power consumed by one phase of IM NVA-55 at rated mode;

$V_{ph\ rated} = 220$ V - RMS value of the rated phase voltage;

$f = 50$ Hz - the frequency of the fundamental (1st) harmonic of the supply voltage.

$$C_{ph\ run} = \frac{21000}{2\pi \cdot 50 \cdot 220^2} 0.75 = 1000\ \mu\text{F}.$$

Equation (1) can be written in another way:

$$C_{ph\ run} = \frac{1}{2\pi f V_{ph\ rated}^2} (Q_{ph\ rated\ ini} - Q_{ph\ rated\ des}), \quad (2)$$

where $Q_{ph\ rated\ ini}$ and $Q_{ph\ rated\ des}$ the initial and desired values of reactive power.

When combining compensating capacitors according to the “delta” scheme, the equation (1) can be written as follows:

$$C_{ph\ run} = \frac{P_{ph\ rated}}{2\pi \cdot f \cdot V_{ph-ph\ rated}^2} (\text{tg}\varphi_{ini} - \text{tg}\varphi_{des}), \quad (3)$$

where $V_{ph\text{-}ph\ rated}$ - RMS value of the rated phase-to-phase voltage.

The value of the per-phase capacity of the start-up capacitors is selected according to the criterion for minimizing the current through the phase of the secondary winding of the transformer in the process of starting-up of IM and in our case amounted to 7000 μF per phase. From the formula (2) we can calculate that when both stages of capacitors are turned on (8000 μF per phase total), compensated reactive power of the phase is about 122 kVAr. The time of shutdown of the start-up capacitors (point t_1 in Fig. 2) is selected so that the current in the phase of the secondary winding of the transformer is less than the current of the phase of IM during the entire launch time.

Using OrCAD [15, 16], the computer model was compiled that simulates the operation of the circuit presented in Fig. 1. Mathematical models of three-phase IM and transformer are described in [1, 17, 18]. Information about sine-wave filter simulation is presented in [19].

In Fig. 2 designation Mcconst means reactive load torque of a constant magnitude. Designation Mcstart means the part of the load torque exists at low speeds of the shaft. Designation Mc0 is the instant load torque value without taking into account it’s dependence on the angle of rotation. But the designation Mc is the instant load torque value which takes into account its dependence on the angle of rotation of the piston compressor mechanism (simplified) [2]. In Fig. 2 designation n2 is the rotor speed of IM (rotation per minute); Fi2 is the angle of rotation of rotor of IM or compressor mechanism (radian). The dependence of the load torque of piston compressor on the angle of rotation is described in more detail, for example, in [11, 12].

The simulation results for the direct start of IM NVA-55, which drive the piston compressor of double compression, with two-stage compensation of reactive power are shown in Figs 3-6. Fig. 3 shows the acceleration process of IM. The beginning of the acceleration process is presented in Fig. 4.

In Fig. 3 and in Fig. 4 indicated: 1 - the rotor speed of IM; 2 - load torque on the shaft of IM; 3 - phase current of the IM stator; 4 - phase current of the secondary winding of the transformer; 5 - phase voltage of IM.

The steady-state mode at the end of the starting process is shown in Fig. 5, the accompanying graphs of the phase-to-phase voltages on terminals of sine-wave filter are shown in Fig. 6.

The simulation results indicate the effectiveness of the use of capacitive compensation of reactive power during direct start and in the steady-state mode of operation of the IM, including in the case of power from the ASC of an electric locomotive. In the steady-state mode, the fundamental harmonic of the current of the secondary winding of the transformer is about 38 % of the fundamental harmonic of the IM current; during acceleration of IM, this share is approximately 65 - 70 %.

It should be noted that in our computing experiment in the IM steady-state mode, the most pronounced 5th temporary harmonic of the current of the secondary winding of the transformer is 10% of the fundamental. In the spectrum of the phase of IM, the 5th harmonic is 4% of the fundamental. In this regard, it must be borne in mind that the parameters of the sine-wave filter have a significant impact on the harmonic composition of the currents and voltages of the auxiliary electric drive.

For example, a decrease in the sine-wave filter inductance to 0.85 mH per phase would be quite acceptable in the absence of reactive power compensation in the capacitors. But in the presence of reactive power compensation significant distortions of the shape of curves of currents and voltages are occurred in case of 0.85 mH: so, in the steady-state mode of IM, the 5th harmonic of the current of the secondary winding of the transformer will be already 147% of the fundamental. For the phase of IM, the similar ratio will be 60%.

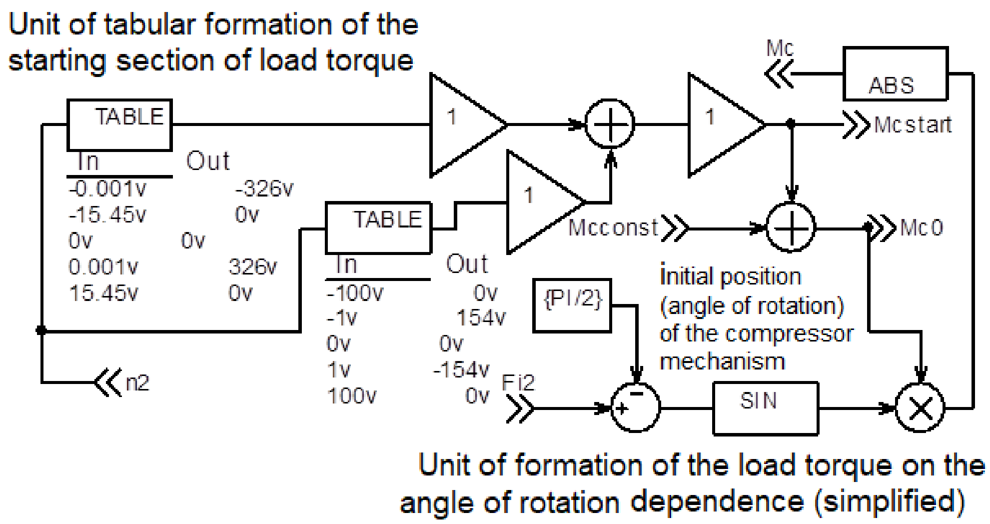

Figure 2 - Piston type compressor load simulation segment of the start-up computer model of the IM type NVA-55

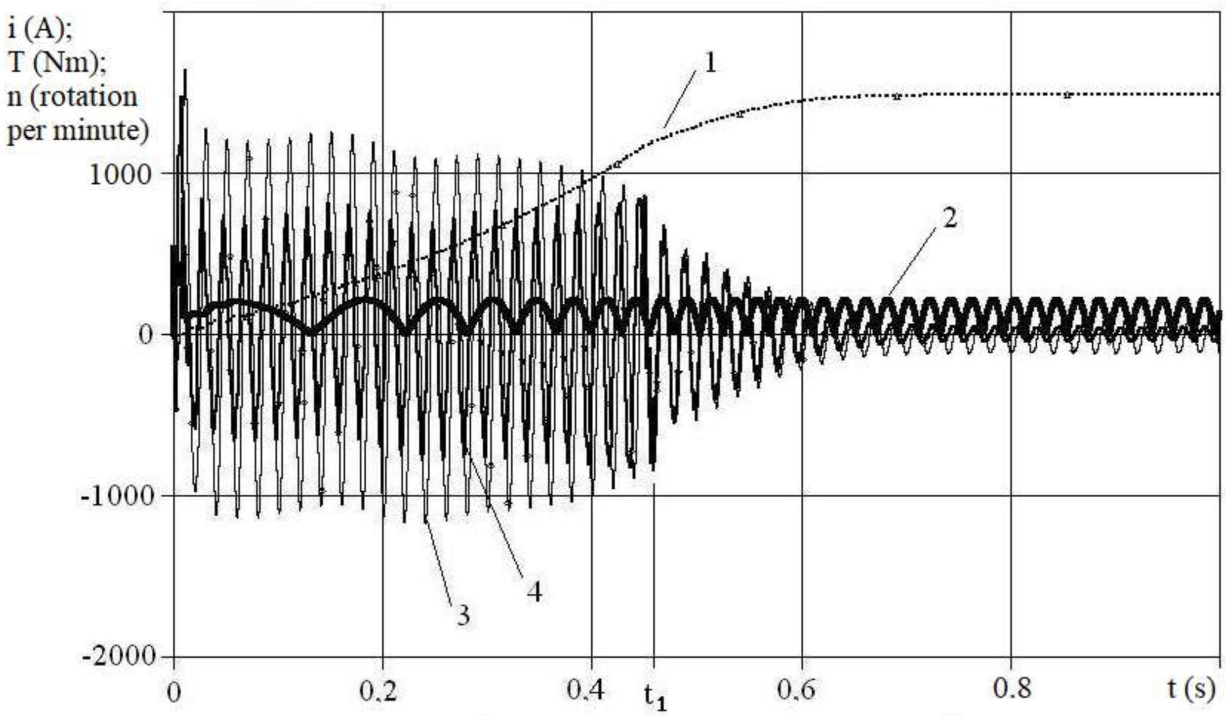

Figure 3 - Process of acceleration of IM. t_1 - moment of time to turn off the starting step of the capacity

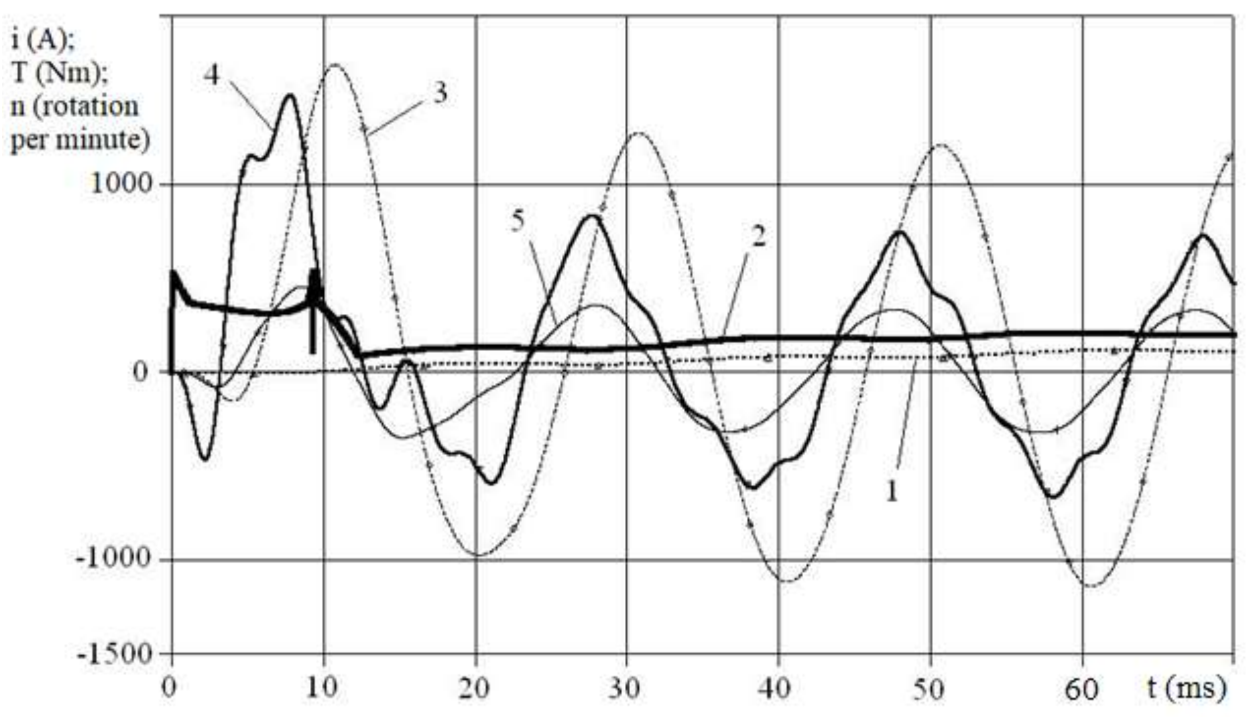

Figure 4 - Initial section of the acceleration process of IM

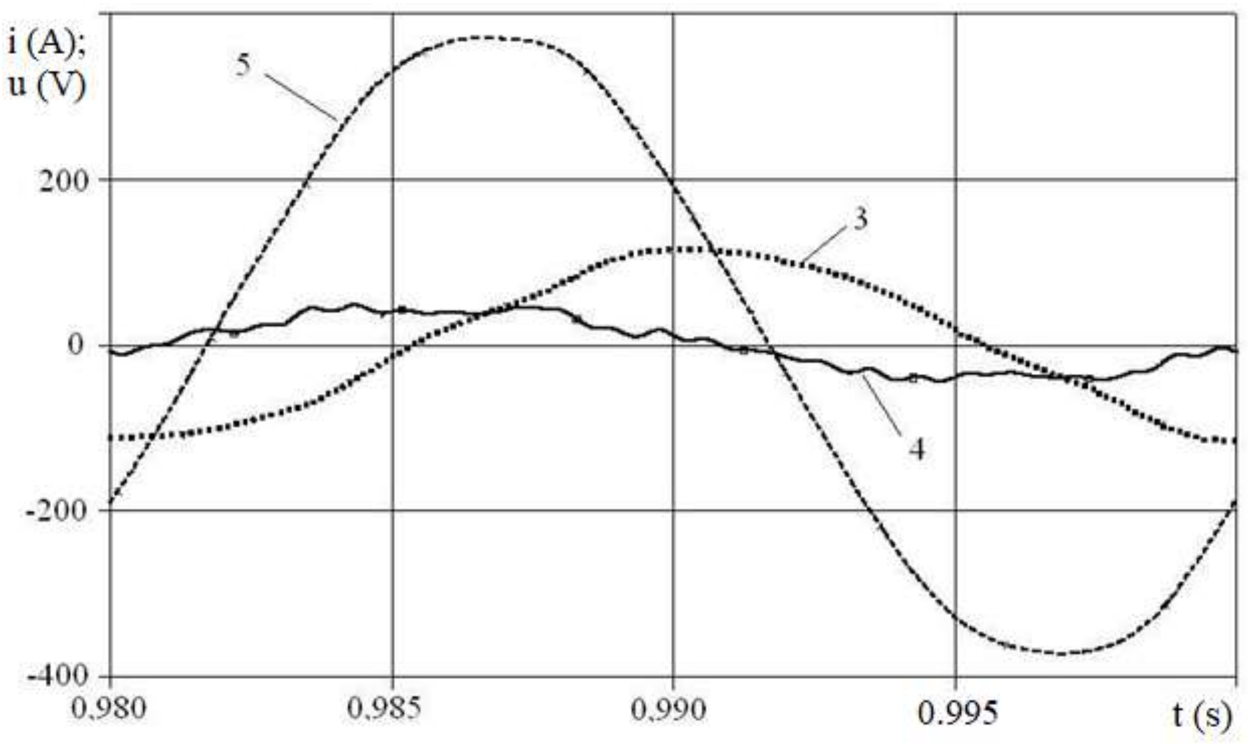

Figure 5 - Steady-state mode of IM at the end of the start-up process

From Fig. 6 it is clear that the current of the secondary winding of the transformer has a phase shift somewhat advantageous with respect to the phase of IM. We can see the overcompensation of a reactive power of IM, the capacity of the run capacitors is somewhat overstated. This happened because the power of MC is below the rated power of the NVA-55, while the capacity calculation of the run capacitors is made for the rated mode.

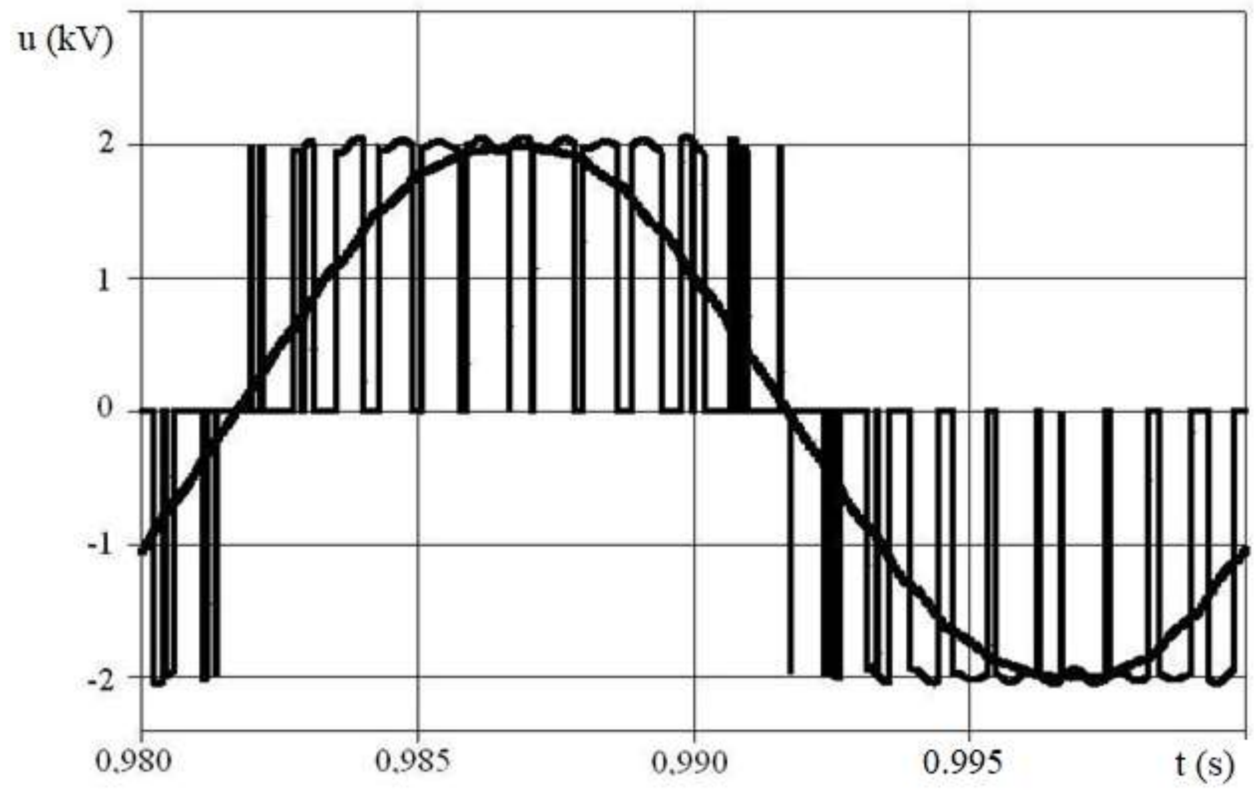

Figure 6 - Phase-to-phase voltage at the input (pulses) and at the output (sine wave) of the sine-wave filter

4 Conclusion

Through computer simulation, it is shown that in the ASC on board of electric locomotive it is possible to use an unregulated channel to power the motor-compressor during its direct starts and further operation. At the same time, the system of two-stage reactive power compensation with capacitor banks makes it possible to effectively reduce the amount of current consumed by the induction motor from ASC.

References:

[1] Pustovetov M., *'Induction Electrical Machine Simulation at Three-Phase Stator Reference Frame: Approach and Results', Applied Electromechanical Devices and Machines for Electric Mobility Solutions*, IntechOpen, 2020. DOI: 10.5772/intechopen.88906.

[2] Pustovetov M., Shukhmin K., Goolak S., Matijošius J., Kravchenko K., *Induction Motor Computer Models in Three-Phase Stator Reference Frames: A Technical Handbook*, Bentham Science Publishers Pte. Ltd. Singapore, 2023. DOI: 10.2174/97898151243091230101

[3] Arunodai C. Use of Arno converter and motor generator set to convert a single-phase AC supply to a three-phase AC for controlling the speed of a three-phase induction motor by using a three-phase to three-phase cycloconverter. *International Journal of Electrical Engineering & Technology*, Vol.7, No.2, 2016, pp. 19-28. http://iaeme.com/Home/issue/IJEET?Volume=7&Issue=2

[4] Dhunna G.S., Dhingra A., Kumar N., "Performance analysis of static versus ARNO converter in Rail AC locomotives," *2008 IEEE Canada Electric Power Conference*,

Vancouver, BC, Canada, 2008, pp. 1-5, DOI: 10.1109/EPC.2008.4763314

[5] Chaudhari M.A., Chaudhari S.M., *Modern Electric Traction.. Second Edition*, Nirali Prakashan, Pune, 2018.

[6] Litovchenko V.V., Nevinskii A.V., Sidorova N.N., Phase splitter for auxiliary machines in alternating-current locomotives, *Russian Electrical Engineering*, Vol.83, 2012, pp. 676–680. DOI:10.3103/S1068371212120085

[7] Kumar N.V.V.R., Rajgopal P.V., Saxena S.N., Mondal S.K., Muni B.P., Vithal J.V.R., "A new GTO-based single-phase to three-phase static converter for loco auxiliaries," *Proceedings of International Conference on Power Electronics, Drives and Energy Systems for Industrial Growth*, New Delhi, India, 1996, pp. 713-719 vol.2, DOI: 10.1109/PEDES.1996.535867.

[8] Ilonciak J., Struharnansky L., Kuchtaa J., Modular concept of auxiliary converters for diesel electric Locomotives. TRANSCOM 2017: International scientific conference on sustainable, modern and safe transport, *Procedia Engineering*, Vol.192, 2017, pp. 359–364.

[9] Marogy B.Y.M., "Specification of static auxiliary converters for rolling stock," *IEE Colloquium on Auxiliary Power Supplies for Rolling Stock*, London, UK, 1992, pp. 1/1-1/4.

[10] Usmonov S., Frequency-Controlled Asynchronous Electric Drive with Extreme Control for Fan Load, *International Journal of Advanced Research in Science, Engineering and Technology*, Vol.4, No.10, 2017, pp. 4633-4642.

[11] Yanagisawa T., Shimizu T., Horioka T, "A Study on Starting Characteristics of a Rolling Piston Type Rotary Compressor," *International Compressor Engineering Conference.* Paper 572. 1986. https://docs.lib.purdue.edu/icec/572

[12] Chernyi S.G., Erofeev P., Novak B., Emelianov V. Investigation of the Mechanical and Electromechanical Starting Characteristics of an Asynchronous Electric Drive of a Two-Piston Marine Compressor, *J. Mar. Sci. Eng.*, Vol.9, No.2, 2021, p. 207. DOI:10.3390/jmse9020207

[13] Wang Y., Saad W., Sarwat A.I., Hong C.S., "Reactive Power Compensation Game Under Prospect-Theoretic Framing Effects," *in IEEE Transactions on Smart Grid*, Vol. 9, No. 5, pp. 4181-4193, 2018, DOI: 10.1109/TSG.2017.2652846

[14] Thang Trung Nguyen, Kim Hung Le, Tan Minh Phan, Minh Quan Duong, An Effective Reactive Power Compensation Method and a Modern Metaheuristic Algorithm for Loss Reduction in Distribution Power Networks, *Complexity*, Vol. 2021, 2021. DOI:10.1155/2021/8346738

[15] Keown J, *OrCAD PSpice and Circuit Analysis, 4th edition*, Prentice Hall, 2000.

[16] Rashid M.H., *SPICE for Power Electronics and Electric Power, 3rd edition*, Boca Raton, USA: CRC Press, 2012.

[17] Pustovetov M., A universal mathematical model of a three-phase transformer with a single magnetic core, *Russian Electrical Engineering*, Vol.86, No.2, 2015, pp. 98-101.

[18] Pustovetov M., Loaded by RL-Branch EMC Filter on the Output of the Inverter Transfer Function Taking into Account Resistances and Electric Transformer's Transfer Function Derivation, *Journal of Engineering Research and Sciences*, Vol.1, No.5, 2022, pp. 102-108.

[19] Pustovetov M., Determining the Parameters of the Sine-Wave Filter. Factors Affecting Filtration Quality, *Journal of Engineering Research and Sciences*, Vol.1, No.4, 2022, pp. 127-136.

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Conflict of Interest

The author has no conflicts of interest to declare that are relevant to the content of this article.