Efficiency Estimation of Hybrid Electrotechnical Complex for Non-Sinusoidal Signals Level Correction in Autonomous Power Supply Systems for Oil Fields

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Abstract. Actuality of highest harmonics hybrid compensation in currents and voltages was gained to improve efficiency of oil fields power supply equipment. A positive effect is achieved due to implementation of active and passive filters in centralized and autonomous power supply systems with high percentage of non-linear loads. There was an observed structure of the hybrid electrotechnical complex based on a parallel active filter and two passive filters that were set for elimination of the 5th and 7th current harmonics that were generated by non-linear load represented as a power converter. This scheme was adapted for the use with a frequency-controlled electric drive due to adjustment of the parallel filter DC link and non-linear load of the frequency converter. There were developed mathematical and computer simulation models of the observed hybrid electrotechnical complex with the common DC link for the conditions of autonomous power supply at the oil field object. The control system of the autonomous electrotechnical complex hybrid part was develop. It contains phase converters and a dead space width disposal variable of relay controllers during generation of control pulses. Analyses of non-sinusoidal level adjustment efficiency of voltage and current signals were conducted after simulation of the hybrid electrotechnical complex. The calculations of technical-and-economic indices and efficiency usage were performed taking into account implementation of the hybrid electrotechnical complex into industrial power supply systems. The obtained results prove that the developed hybrid electrotechnical complex with the common DC link for the autonomous power supply of oil fields in the DG networks is efficient, reliable and can be installed in the existing power supply systems.

1. Introduction
Non-sinusoidal operational modes of centralized and autonomous power networks imply the efficiency and operation modes of power electrical equipment installed in technological complexes, digital systems of relays protection, control, phone, and TV networks negatively [1]. As a result, during connection of non-linear loads to the power network, high levels of current and voltage harmonics occur, which influence leads to the significant economic losses that determine mainly worsening of energy indicators, power networks robustness reduction and shortening of the main power equipment life cycle [1].

During this problem analysis, it is necessary to answer the following main questions: assessment of power sources and other linear loads of electromagnetic compatibility during harmonics generation, harmonics influence on the power sources and appearing economic damage, analysis of perspective
technical means and solutions for correctness of non-sinusoidal current and voltage waves [2].

Almost at all industrial factories, a frequency-controlled electric drive is the main source of harmonic disturbances. It is commonly used in electromechanical complexes together with pumps, coolers, water sewages, and other technological units like contact welding machines, arc furnaces of metallurgical plants [2].

The rate of influence of current harmonics on the different types of power equipment displays itself differently and depends on voltage or current magnitude specter, power source characteristics, connected linear or non-linear load, and other reasons [3]. During substantiation of implementation of technical solution for non-sinusoidal waves’ correction, an engineer must always analyze all these factors and their possible consequences. In addition, application permissions of such technical solutions and quantity specifications of the allowed values for harmonics compensation are mainly made according to the expert analysis, national or international standardizing documentation. The above-mentioned standards and solutions take into account properties of power networks, linear and non-linear loads [4]. This is fair for both centralized and decentralized autonomous power systems with distributed generation (DG).

2. Materials and methods

However, taking into account conditions that there are no centralized power systems, or they are placed at a very distant point from the end user, changes in power supply scheme should be made. According to the stability criteria of the technological process, functioning equipment of the mining complex and other industry branches receives power supply from autonomous power systems with DG. Alternative power sources like photovoltaics, wind turbines, etc. are widely implemented in such systems. That is why under conditions that there are no centralized power supply, diesel power stations and microturbines become the main power source for the mining complex equipment. These units operate very often using associated petroleum gas as the main fuel. That is why the harmonics disturbances’ problem gains important actuality considering a big impedance value of power source and connected growth of sin wave voltage signal distortion in the power network [5].

Existing hybrid structures for harmonics disturbances’ compensation features as different combinations of Active and Passive Power Filters (APFs and PPFs) [6]. However, PPFs are mainly used for compensation of one or two characteristic harmonics (5th, 7th or 13th), because their magnitudes prevail in the consumed current specter by the non-linear load. APFs of series and bypass types (SAPF and BAPF) that are implemented in such structures are used for the efficiency increase of voltage or current harmonics compensation [7, 8]. At the same time, mass-dimensional characteristics of APFs may be decreased, because this is the most expensive part in the complex. This happens due to presence of PPFs, which increase technical and economic indices in hybrid structures [7, 8].

Some existing APFs for current harmonics compensation contain a Common DC Link (CDCL). They are widely implemented in Variable-Frequency Electric Drive (VFED) structures and their efficiency is scientifically validated and proved [9, 10]. However, use of CDCL for BAPFs connection significantly decreases its value due to the presence of one capacitive storage element [9, 10]. In addition, it is reasonable to use the same BAPF in the structure of the developed Hybrid Electrotechnical Complex (HETC). Its block scheme is shown in Fig. 1 and contains the following references: a diode rectifier (DR), a reservoir capacitor (RC), an autonomous inverter (AI), a frequency converter (FC), a hybrid electrotechnical complex (HETC), a BAPF inverter (BAPFI), a BAPF automatic control system (BAPF-ACS), a BAPF DC link reactor (BAPF-DCLR), high-frequency RC PPF (RC-PPF).
It is well known that centralized power systems have a well-studied and researched correction level of efficiency of non-sinusoidal signals, performed with hybrid structures, based on conventional BAPFs [11]. Based on this fact, it is necessary to conduct an efficiency analysis of HETC with CDCL functionality as part of the autonomous power supply system in the structure of the petroleum development plant.

This plant has an autonomous power supply system with a diesel-driven generator set as the power source that is connected to the single frequency-controlled electric drive of the axial pump submersible motor used for the petroleum development. The obtained modelling result will be true for the group of controlled electric drives connected to the common autonomous power source (petroleum development clusters of wells located far away from the centralized power supply system).

Fig. 2 shows a block scheme of the autonomous power supply system with a frequency controlled electric drive as the main power user and non-linear load for the conditions of petroleum development.

Figure 2 contains the following references: a combustion engine (CE), a synchronous generator (G), a diesel generator (DG), a cage induction motor (M), electric drive automatic control system (ED ACS).

The frequency controlled electric drive operates as non-linear load, based on the cage induction motor and vector control system as the most common in the industry electric drive type.

Figure 3 contains a computer model of the autonomous power supply system with a frequency-controlled electric drive and with a vector control system made in Matlab/Simulink software.

Modelling results contain oscillography charts and spectral recordings of voltages and currents at the diesel-driven genset output (Fig. 4 and Fig. 5). In addition, there were calculated current and
voltage THDs in the system, which do not correspond to the standardizing documentation (GOST 32144-2013) and international standards for power quality regulations.

An average value of voltage THD (THDu) in the 0.38 kV network measured during a 10-minute time interval must not exceed a 12% value during 100% of the time interval in one week. These requirements are written in GOST 32144-2013. This standard also defines values for the 5th and 7th harmonics components ($k_u(5)$ and $k_u(7)$ respectively), averaged in a 10-minute time interval, must not exceed 6% and 5% values respectively. GOST 32144-2013 allows increasing these values 1.5 times (up to 9% and 7.5%) during 100% of the time interval in one week [12].
According to the current spectral analysis, consumed from the main power supply network, it is obvious that characteristic harmonics prevail (5th, 7th, 11th, 13th). However, some non-typical harmonics and subharmonics are also present in the diagram [13].

Figure 6 shows a block scheme of the autonomous power supply system with non-linear load in the form of the frequency-controlled electric drive along with the developed HETC with CDCL that serves as the technical solution for harmonics compensation.

The developed HETC has a lot of advantages and outstanding features. The BAPF included in it has a control system, based on phase converters abc/αβ with an option to control relay controllers’ dead space zone width. These controllers operate as a part of the control pulses driver for invertor power IGBT switches [14]. This control scheme allows regulating current and voltage harmonics compensation levels of the APF depending on the existing tasks and needs. For example, this can be useful when full or partial distortion compensation is required up to the certain level. In addition, developed HETC has no need for preliminary charge of the accumulative capacitor [15]. Besides APF (BAPF), the developed HETC contains additionally high-frequency RC-PPF in order to increase operating efficiency of the BAPF in the autonomous power supply systems schemes with big power source impedance value [16].

Figure 7 contains a Matlab-Simulink model of the autonomous power supply system with non-linear load and developed HETC with CDCL.
Figure 7. A Matlab-Simulink model of the autonomous power supply system with non-linear load and developed HETC with CDCL

Figures 8 and 9 contain scope charts and spectral charts of the voltage and current signals from the power supply network. They were obtained after installation of developed HEPC in the power supply network.

Figure 8. Voltage and current scope charts with the connected HETC

Figure 9. Voltage and current waveforms’ spectral charts with the connected HEPC for evaluation of power quality

Table 1 contains data about voltage and current THDs (THDu and THDi respectively) and data about harmonics order: (kU(5), kU(7) for the voltage harmonics and (ki(5), ki(7) for the current harmonics).
**Table 1.** Data about voltage and current THDs (THDu and THDi respectively) and data about harmonics order: (kU(5), kU(7) for the voltage harmonics and (ki(5), ki(7) for the current harmonics)

|                      | THDi, % | ki(5),% | ki(7),% | THDu, % | ki(5),% | ki(7),% |
|----------------------|---------|---------|---------|---------|---------|---------|
| GOST 32144-2013 value | -       | -       | -       | 12      | 6       | 5       |
| HETC is OFF          | 22.99   | 21.32   | 11.41   | 16.09   | 13.85   | 8.75    |
| HETC is ON           | 0.43    | 0.13    | 0.02    | 1.43    | 0.08    | 0.02    |

Spectral charts analysis results demonstrate that the power quality level after current and voltage harmonics compensation coincides with GOST 32144-2013 requirements.

Figure 10 contains diagrams that show behavior of THDu and THDi versus the dead space zone of the current relay controllers of the pulse driver obtained after modelling. These charts allow setting correctly current relay regulators according to the set value of current and voltage harmonics corresponding to compensation results. This approach also fulfills a correct switching mode of power IGBT switches in the APF’s inverter [17, 18].

**Figure 10.** THDu and THDi versus dead space zone of the current relay controllers of the pulse driver

Hence, cost advantages of the developed HETC can be analyzed and described. Main economic benefits are achieved due to increase of the network’s power factor and a reduction of diesel fuel consumption. Taking into account the diesel fuel consumption rate before and after HETC connection, 12.47% economy was obtained during connection of 108 kW nominal load.

**3. Conclusion**

Proposed HETC provides a significant reduction of current and voltage harmonics. At the same time, current THD reduces from 22.99% to the 0.43% and voltage THD reduces from 16.09% to the 1.43%. In addition, it covers and compensates almost all reactive power consumed from the power network to the level of the power factor value that is close to one. This option gives a good possibility for optimal control of power flows in autonomous electrotechnical complexes.

The developed HETC with CDCL is an effective technical solution for correction of non-sinusoidal current and voltage waveform and can be successfully implemented in decentralized DG power systems with autonomous generators at the well clusters of petroleum development plants.

**References**

[1] Belsky A A, Skamyin A N and Iakovleva E V 2016 Configuration of a standalone hybrid wind diesel photoelectric unit for guaranteed power supply for mineral resource industry facilities *Int.*
[2] Araujo-Vargas I, Salas-Duarte S, Ramirez-Hernandez J, Del-Muro-Cuellar B and Rivera M 2015 Predictive current control of a four-wire, active power filter for an unbalanced utility load of metro railway IEEE Int. Symp. on Pred. Contr. of Electr. Dr. and Pow. Electr. (PRECEDE) 1 79-84

[3] Abramovich B N and Sychev Yu A 2016 The evaluation of hybrid active filter efficiency Int. Conf. on Actual Problems of Electron Devices Engineering, APEDE 2016 2 7879064

[4] Jimenez F R, Salamanca J M and Cardenas P F 2014 Modeling and circuitual analysis of a Single Phase Shunt Active Power Filter IEEE 5th Colomb. Works. Circ. and Syst. (CWCAS) 1 1-10

[5] Abramovich B N, Sychev Yu A, Ustinov D A and Shkljarskiy A Ya 2014 Reducing The Risk Of Fires In Conveyor Transport Oil Ind. 8 110-112

[6] Monroy-Morales J L, Campos-Gaona D, Hernández-Ángeles M, Peña-Alzola R and Guardado-Zavala J L 2017 An Active Power Filter Based on a Three-Level Inverter and 3D-SVPWM for Selective Harmonic and Reactive Compensation Energies 297(10) 1-23

[7] Liu Q, Peng L, Kang Y, Tang S, Wu D and Qi Y 2014 A novel design and optimization method of an LCL filter for a shunt active power filter IEEE Trans. on Ind. Electr. 61(8) 4000-4010

[8] Pedra J 2008 On the Determination of Induction Motor Parameters From Manufacturer Data for Electromagnetic Transient Programs IEEE Trans. on Pow. Sys. 23(4) 1709-17188

[9] Abramovich B N and Sychev Yu A 2016 Maintenance problems of PWM-inverters in power networks with distributed generation Int. J. of Appl. Eng. Res. 11(4) 2640-2645

[10] Stephane C, Mboving A and Hanzelka Z 2016 Application of C-type filter to DC adjustable speed drive Electr. Pow. Qual. and Supply Reliab. (PQ) 1 91-96

[11] Borisov P, Poliakov N and Strzelecki R 2016 Size and mass minimization of capacitor bank in a power converter DC line of DC drive with closed loop control system with PWM and current limitation IX Int. Conf. on Pow. Dr. Syst. (ICPDS) 1 1-5

[12] Kuznetsov P A and Stepanov O A 2016 Combined system for electric power consumers protection against emergency states Aerospace MAI J. 4(23) 145-154

[13] Kuznetsov P A and Stepanov O A 2017 Reactive power compensation automated systems application to prevent blackouts Aerospace MAI J. 2(24) 157-163

[14] Kozyaruk A 2016 Energy efficient electromechanical systems of mining and transport machines Journal of Mining Institute 218(2) 261-269

[15] Rozanov Y K, Lepanov M G, Kiselev M G 2014 Multifunctional controller based on a power electronic converter. Russian Electrical Engineering 85, 8 527-535

[16] Tenti P, Costabeber A, Caldognetto T, Mattavelli P 2013 Cooperative control of smart micro-grids based on conservative power commands. Przeglad Elektrotechniczny 89 32-40

[17] Pronin M V, Vorontsov A G, Kalachikov P N, Emelyanov A P 2004 Electric drives and systems with electrical machines and semiconductor converters (modeling, calculation, application). (St. Petersburg, Power Machines Electrosila)

[18] Pronin M V, Vorontsov A G 2005 Active filtration of voltages and network currents in installations with high-voltage thyristor converters. Mining equipment and electromechanics 5 41