DOI: 10.31897/PMI.2019.2.229

UDC 621.314.6

APPLICATION OF AN ACTIVE RECTIFIER USED TO MITIGATE CURRENTS DISTORTION IN 6-10 KV DISTRIBUTION GRIDS

Juan Manuel MUNOZ-GUIJOSA[1], **Sergei B. KRYLTCOV**[2], **Sergei V. SOLOVEV**[2]
[1] *Polytechnic University of Madrid, Madrid, Spain*
[2] *Saint-Petersburg Mining University, Saint-Petersburg, Russia*

The paper addresses issues of using the active rectifier in partially loaded variable frequency drive as active filter in the conditions of non-sinusoidal current and voltage disturbances caused by the presence of high-power non-linear load in the grid. The topology of transformless three-level converter for 6-10 kV suitable for proposed solution has been presented and its mathematical model has been de-rived. Based on the model, the direct power control algorithm with ability to compensate non-linear currents has been designed. The investigation of active rectifier efficiency was performed depending on the relation between linear and non-linear load currents of the grid node, as well as on active power load of the active rectifier. Efficiency analysis was based on the developed computer model of the grid node with connected non-linear load simultaneously with the variable frequency drive with active rectifier.

***Key words*:** active Rectifier; active Filtering; harmonic disturbance; Direct Power Control

***How to cite this article*:** J.M.Munoz-Guijosa, S.B.Kryltcov, S.V.Solovev. Application of an Active Rectifier Used to Mitigate Currents Distortion in 6-10 kV Distribution Grids. Journal of Mining Institute. 2019. Vol. 236, p. 229-238. DOI: 10.31897/PMI.2019.2.229

Introduction. Variable frequency drives (VFD) have become a popular solution in nearly all fields of industry [7]. While development of VFD allowed to achieve effective operation of different industrial processes, it also introduced power quality problems in distribution grids, mainly associated with high-order harmonics injected in grid voltage and current by VFDs.

Traditionally the most widespread topology of VFDs was a 2-level VFD inverter with diode rectifier. This solution became the most popular as a cheapest topology providing control of the motor, while allowing to maintain near-constant DC-link voltage in a non-controlled way. However, peculiarities of diode bridge operation lead to injection of 5-th and 7-th harmonics with amplitudes up to 20 % in consumed current spectrum, that in turn, in different grid conditions may cause voltage disturbances in different grid nodes [5].

To deal with this problem, a concept of VFD with four quadrants operational inverter, called active rectifier (AR) or active front-end (AFE), when performing additional functions was introduced [2]. The VFD with AR was able to consume near-sinusoidal currents from the grid while maintaining unity power at the VFD input. At the same time, the AR topology was the same as one of the flexible AC transmission systems (FACTS) device – shunt compensator D-STATCOM, which provides following functions to increase grid power quality: reactive power compensation, voltage stabilization, compensation of harmonic and asymmetry disturbances of grid voltage waveform, active filtering [9].

The possibility to use AR as a compensation device became a subject of the great interest recently. However, the AR may maintain such functions only if it is not fully loaded with active power supplied to the inverter side of VFD. There are several VFD applications with operational conditions that lead to partial load of AR on a regular basis. The study presents one of the cases: the VFD of a main mine fan, which consumed active power increases with the mining process and reaches its nominal value only at the end of fan lifetime [6]. Consumed active power by the fan VFD depends on the cubed air flow, and at the beginning of the fan lifetime usually equals only to 20 % of its power rating. The rest of AR capabilities in such cases may be utilized to improve the grid power quality.

DOI: 10.31897/PMI.2019.2.229

As present mines still contain numbers of non-linear loads based on diode rectifier, the presented study considers case of using the AR to mitigate current harmonic distortion, caused by traditional VFD operation. To maintain such functions special control algorithm is required. There are two basic control system topologies for the AR, both came from similar algorithms used to control motor inverters: voltage oriented control (VOC) and direct power control (DPC). VOC is an analogue of well-known field-oriented control systems for motor inverters [8]. It is based on calculations of active and reactive current components in rotational reference frame, synchronized with grid voltage vector [12]. VOC system contains outer control loops of DC-link voltage and reactive power, which provide reference for active and reactive currents to inner loop used to produce modulating voltages for pulse-width modulation (PWM) block. Every loop contains 2 PID controllers to reduce feedback error that leads to tuning problems for such systems.

DPC, in contrast, provides great simplicity due to direct power calculations according to the instantaneous power theory and its control with hysteresis regulators in inner loop that provide high dynamics and absence of necessity for fine tuning. The main drawback of DPC algorithm is variable switching frequency, which leads to increased high-order harmonics injection in consumed currents and provides additional complexity to input filter design.

While DPC due to its dynamics is the most suitable algorithm for active filters, its drawbacks become a severe problem especially in megawatts rated application, causing noticeable losses and degrading of grid power quality. To eliminate this problem, several authors propose DPC improvements in recent papers, which consider achieving constant switching frequency of hysteresis controllers [10], replacement of hysteresis controllers by direct [14] or predictive [4] calculations of voltage references that further applied to the input of space-vector modulation block. Therefore, modified DPC becomes a viable solution as control algorithm for AR operating as AF.

The study considers issues and performance analysis of AR application for mitigating harmonic distortion of grid currents, cause by the presence of high power non-linear load. The 3-level neutral-clamped inverter topology is proposed for the application and based on the given mathematical model of converter, the DPC algorithm with currents filtration is derived.

The model and control systems are implemented in MATLAB/Simulink, and analysis of AR efficiency is preformed depending on the active load of AR.

Grid topology. The use of AR for non-sinusoidal currents filtering is considered on the example of a mine node with radial power supply scheme, which is shown in the Fig.1. The mine power is supplied by 70 km overhead line 110 kV connected to the main grid, which is considered as an ideal voltage source. All mine loads are connected to the bus of the step-down transformer 110/6 kV that is considered as point of common coupling further (PCC). The initial distribution network has two considered load types: linear distributed load connected to the PCC via the step-down transformers 6/0.4 kV and cable lines with length of 12 km, and non-linear load considered as VFD of a power rating equal to 2 MW with non-controlled 2-level rectifier connected to PCC via 10 km cable line and step-down transformer 6/0.4 kV. The further mine development led to appearance of another mine shaft, where the ventilation fan has to be placed. As a presence of non-linear load negatively affects grid currents and voltages, the VFD with AR was chosen to be placed to the new shaft, where AR can most of its lifetime implement filtering functions.

The currents waveform absorbed by the mine node depends on the ratio between the non-linear and linear loads. The non-sinusoidal currents in the considered grid are mainly consumed by the 2-level VFD with diode rectifier. The AR in such case is supposed to suppress mainly 5-th and 7-th harmonics, however it is also important, that AR also injects higher order harmonics, related to the IGBT switching.

DOI: 10.31897/PMI.2019.2.229

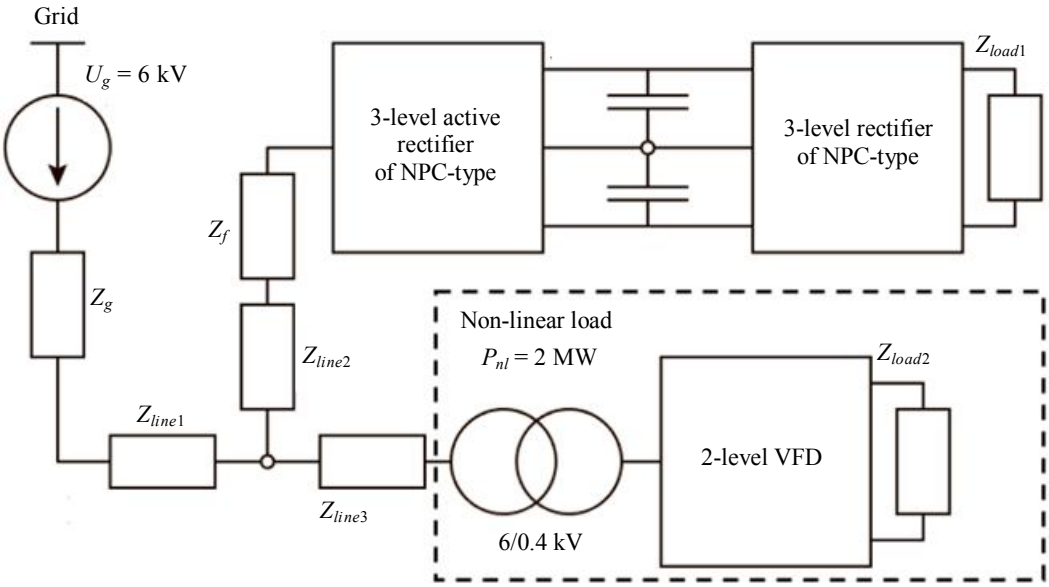


Fig.1. Structure of the investigated grid node topology

The grid currents and voltages harmonic content is regulated according to the IEEE 519. The total voltage harmonic distortion for 1-69 kV class of grids shouldn't exceed 5 %, while harmonic content for any particular voltage harmonic shouldn't exceed 3 % of the fundamental. The currents harmonic content is regulated according to its ration between short-circuit value at PCC and maximum load current. The PCC considered as second bus of transformer, and calculated $I_{scr}/I_l = 74$, that brings the grid to 50-100 kV class.

Active rectifier mathematical model. The paper considers AR closely connected to the node with non-linear load, which in general allows to consider AR as AF with variable power rating.

Three-level topology of the VFD becomes a viable solution in 6-10 kV distribution networks thanks to development of semiconductor devices. In comparison with two-level topology, three-level VFD allows to: connect load of several MWs directly to the grid; distribute load between power switches that leads to decreased switching losses; increase of number of output voltage levels leads to decrease of harmonic distortion caused by switching, which becomes severe problem on MW rates of VFD due to exponentially increased losses on the input filter [3].

At the same time 3-NPC topology remains relatively simple and cheap to implement in comparison with other multilevel topologies. However, the disadvantage of multilevel inverter is the unbalanced voltage in DC-link, which requires advanced control algorithms [11].

Structure of 3-NPC AR in VFD is shown in the Fig.2.

Its model can be described as follows:

$$\begin{bmatrix} u_{ga} \\ u_{gb} \\ u_{gc} \end{bmatrix} = R_f \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + L_f \frac{d}{dt} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} u_{ARa} \\ u_{ARb} \\ u_{ARc} \end{bmatrix}, \quad (1)$$

where u_g – phase-to-ground voltages at the PCC; i – phase currents; R_f, L_f – resistance and inductance of input filter; u_{AR} – output inverter voltages, which are calculated as follows:

$$\begin{bmatrix} u_{ARa} \\ u_{ARb} \\ u_{ARc} \end{bmatrix} = u_{dc} \begin{bmatrix} S_a \\ S_b \\ S_c \end{bmatrix}; \quad (2)$$

DOI: 10.31897/PMI.2019.2.229

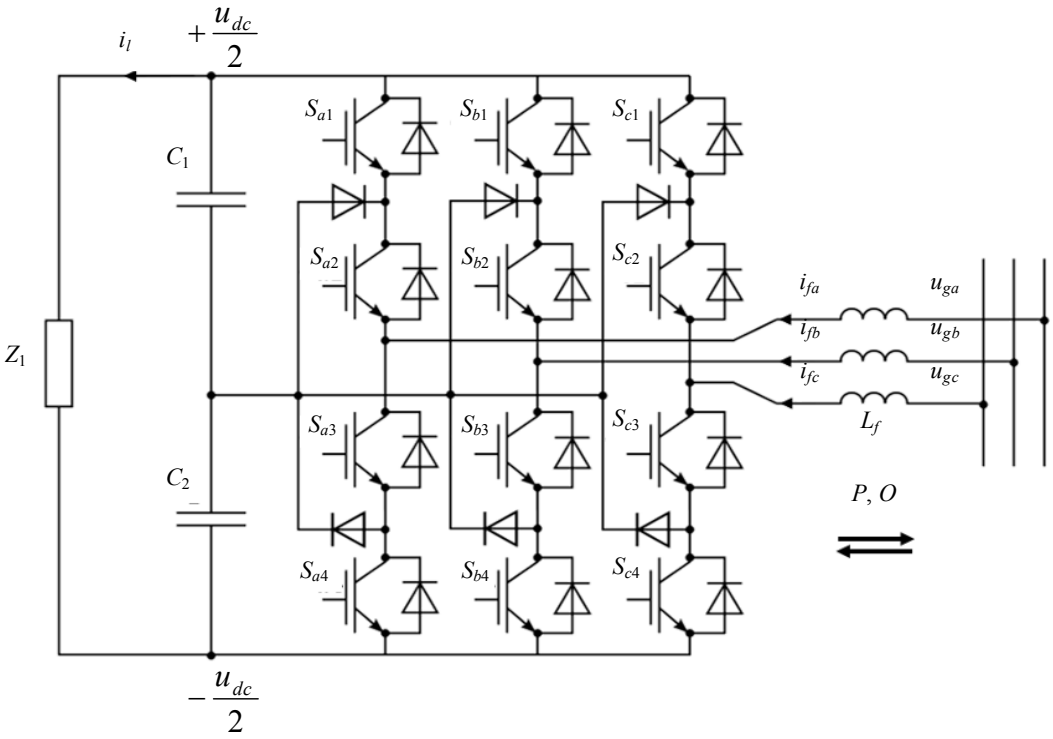


Fig.2. Structure of the 3-level NPC active rectifier

where u_{dc} – DC-link voltage; S – switching states, which in 3-level NPC may become next functions P, O, N, in each phase of inverter depending on the Table (u_{pn} is a phase-to-neutral voltage).

DC-link power balance equations are written as follows:

$$C_{dc}\frac{du_{dc}}{dt} = S_a i_a + S_b i_b + S_c i_c - i_1, \tag{3}$$

where C_{dc} – capacitance of each DC-link capacitor; i_1 – load current.

Active rectifier control system. The DPC control algorithm is used to control AR in presented solution. Structure of the proposed AR control system is shown in the Fig.3. The control system contains following blocks: 1 – calculation of the instantaneous power on the grid side; 2 – fundamental harmonic extraction of the grid currents and voltages; 3 – calculation of the angle of the grid voltage vector; 4 – determination of the sector of the grid voltage vector; 5 – calculation of the instantaneous power of the load harmonics; 6 – DC-link voltage control circuit; 7 – saturation for the AR output apparent power; 8 – hysteresis controllers; 9 – switching table with DC-link voltage balancing.

All calculations in the DPC systems are maintained in stationary two-phase plane, transform to which from the abc-frame is obtained by Clarke transform equations:

Switching states of the 3-level NPC inverter

State	S_1	S_2	S_3	S_4	u_{pn}
P	1	1	0	0	$u_{dc}/2$
O	0	1	1	0	0
N	0	0	1	1	$-u_{dc}/2$

$$\begin{bmatrix} u_\alpha \\ u_\beta \\ u_0 \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \begin{bmatrix} u_a \\ u_b \\ u_c \end{bmatrix}. \tag{4}$$

DOI: 10.31897/PMI.2019.2.229

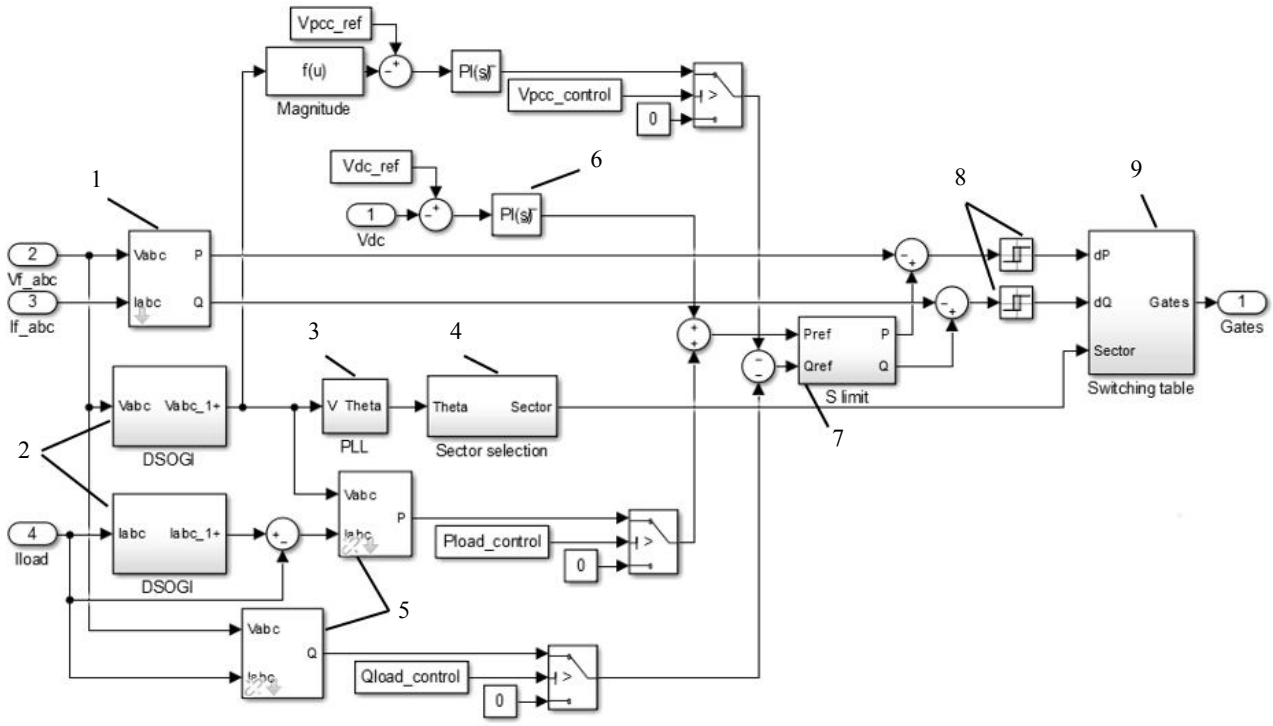


Fig.3. Proposed structure of the Active Rectifier control system

DPC system is built according to the instantaneous power theory. Instantaneous active and reactive powers therefore are calculated as follows:

$$p = u_\alpha i_\alpha + u_\beta i_\beta;$$
$$p = u_\alpha i_\beta + u_\beta i_\alpha. \quad (5)$$

The equation (3) is useful for balanced and sinusoidal voltage and currents. Otherwise the calculated powers will be also distorted.

In such case power can be written as a sum of average $\overline{p}$, $\overline{q}$ and oscillating components $\widetilde{p}, \widetilde{q}$:

$$p = \overline{p} + \widetilde{p};$$
$$p = \overline{q} + \widetilde{q}. \quad (6)$$

Assuming that AR consumes near sinusoidal active currents from the grid, power balance for the grid node shown in the Figure 1 is written in terms of pq-components as follows:

$$p_g = \overline{p}_{nl} + \widetilde{p}_{nl} + p_{AR};$$
$$q_g = q_{nl}. \quad (7)$$

To achieve grid node sinusoidal power consuming, the p_g should have no oscillating power components. To enhance grid power quality, the reactive power exchange of the grid and grid node should be also reduced to zero. Therefore, active filtering functions of the AR are obtained when it compensates oscillation caused by the diode rectifier $\widetilde{p}_{nl}$ and full reactive power of the grid node q_g.

AR should provide constant level of the DC-link voltage by absorbing active power from the grid, that is achieved by PI-control law

DOI: 10.31897/PMI.2019.2.229

$$p^*_{DC} = u_{DC} k_{pl} (U^*_{DC} - u_{DC}) . \quad (8)$$

Power references for the AR control system to provide active filtering therefore become:

$$p^*_{AR} = u_{DC} k_{pl} (U^*_{DC} - u_{DC}) - \tilde{p}_{ni}; \quad q^*_{AR} = q_{nl} . \quad (9)$$

The $\tilde{p}_{nl}$ component is calculated according to (7):

$$\tilde{p}_{nl} = p_{nl} - \bar{p}_{nl} . \quad (10)$$

The average power $\bar{p}_{nl}$ usually obtained by filtering the oscillations of $\tilde{p}_{nl}$ from the oscillating component of p_{nl} value. Low-pass Butterworth filter was used in presented work for that purpose [13]. To maintain following obtained reference signals, the AR switches are controlled by the switching table, which is also used to balance DC-link capacitors voltages, similarly to as it was done in the paper [1, 14].

Simulation. The waveforms and spectrum of currents, consumed by the grid node before connecting the VFD with AR to the node are shown in the Fig.4. It can be seen that currents waveform is far from sinusoidal, which is caused by presence of 5-th and 7-th harmonic components, injected by diode rectifier. THD_i in this case equals to 16.11 %, which in turn leads to voltage distortions: THD_u = 7.29 % that is not acceptable level according to IEEE 519 (<5 % is allowed for such applications).

Simultaneous work of 2 drives without harmonic compensation. The next simulation case considers connected VFD with AR operating to consume only active sinusoidal currents from grid. The grid current waveform and spectrum was obtained for AR loaded with active power at 80 % of

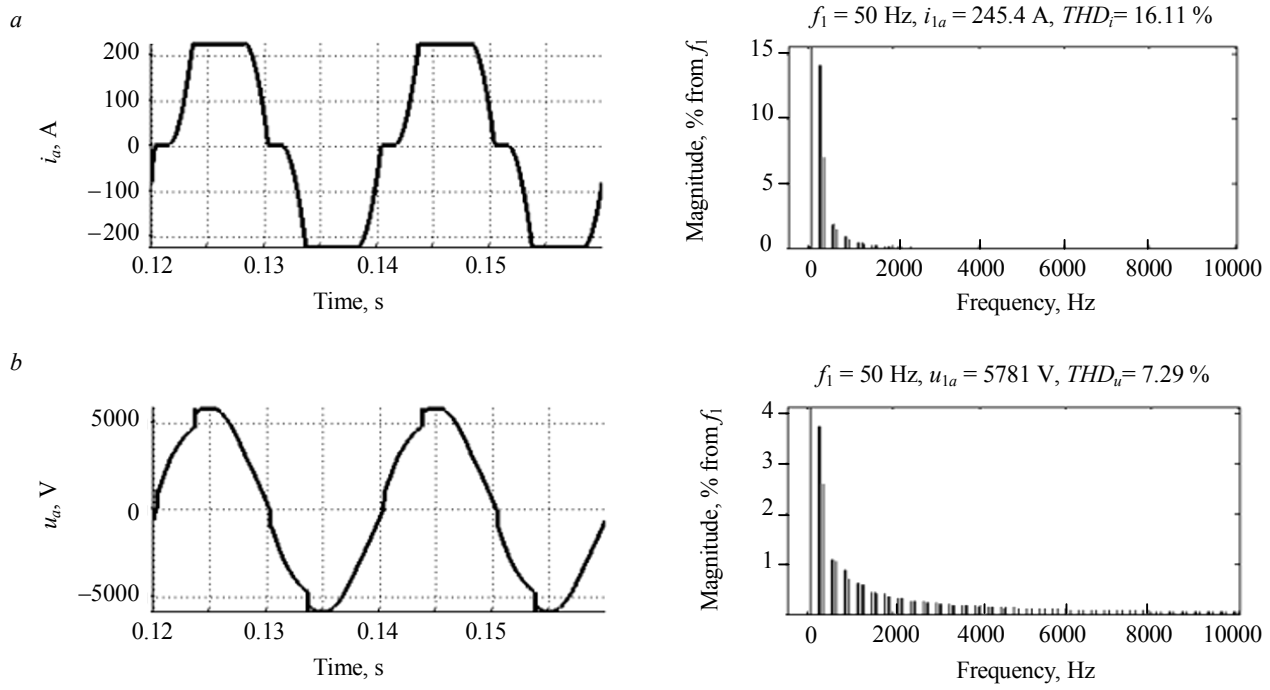


Fig.4. Waveforms and spectrums of the grid node input before the VFD with AR placement (*a* – currents [A]; *b* – voltages [V])

DOI: 10.31897/PMI.2019.2.229

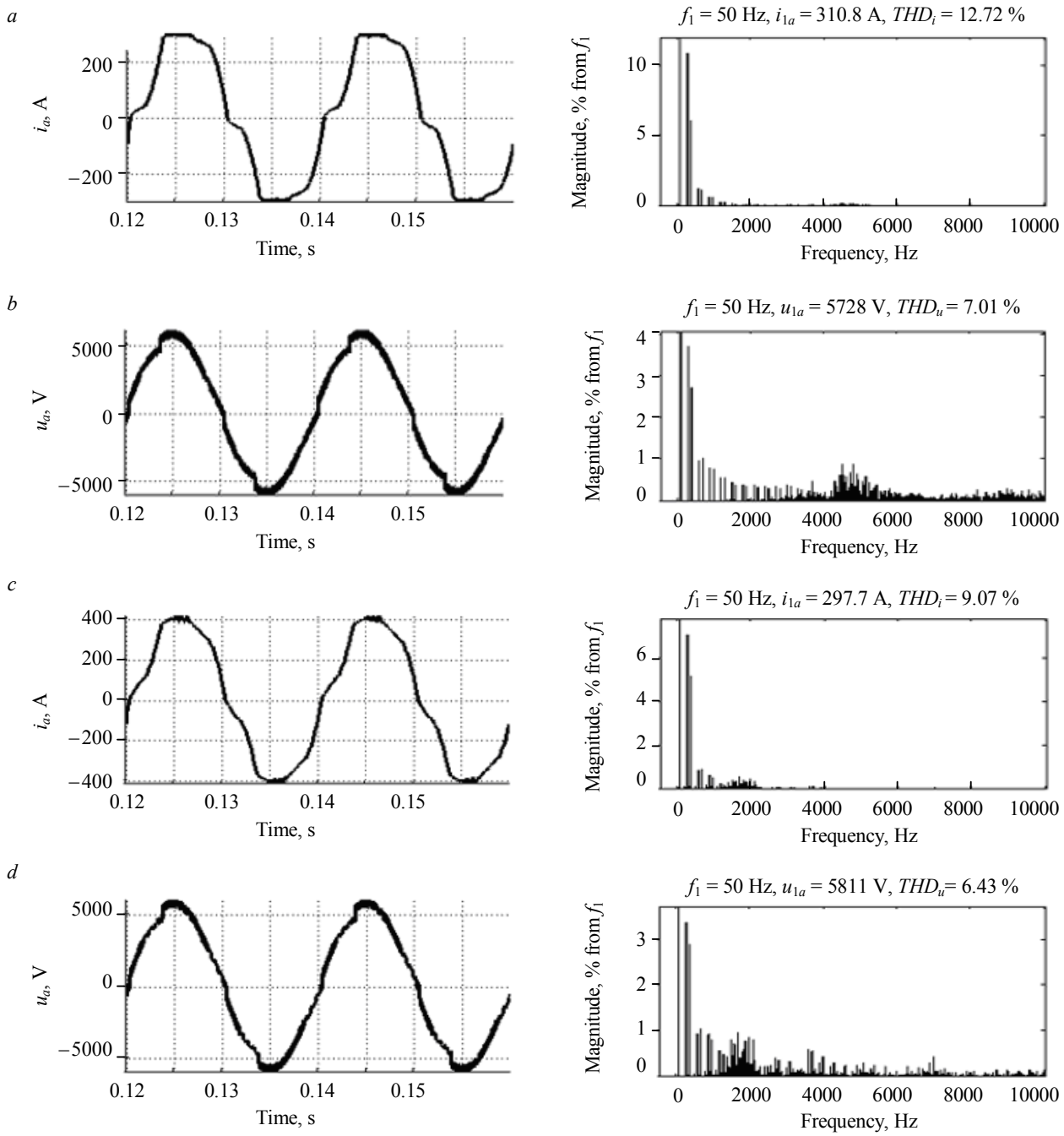


Fig.5. Waveforms and spectrums of the grid node input with connected VFD with AR loaded by 30 % (*a* – currents [A]; *b* – voltages [V]) and AR loaded by 80 % (*c* – currents [A]; *d* – voltages [V]). Active filtering function is disabled

rated (Fig.5, *a*, *b*) and 30 % (Fig.5, *c*, *d*). It can be seen from the figures that connecting of VFD with AR to the grid node improves the waveform of consumed currents: THD_i = 9.07 % in case of 80 % loaded AR; however, when AR is loaded with active currents only for 30 %, currents waveform is more distorted: THD_i = 12.72 %. This is explained by the fact that as AR consumes nearly sinusoidal currents, the magnitude of the fundamental component increases – from 245A before placing the VFD with AR to 310A for 30 % loaded and 412A for 80 % loaded AR.

It also should be noticed that currents spectrum contains higher harmonics caused by high switching frequency of AR IGBTs, however their magnitude is much smaller than magnitudes of 5-th and 7-th harmonics, injected by the diode rectifier.

DOI: 10.31897/PMI.2019.2.229

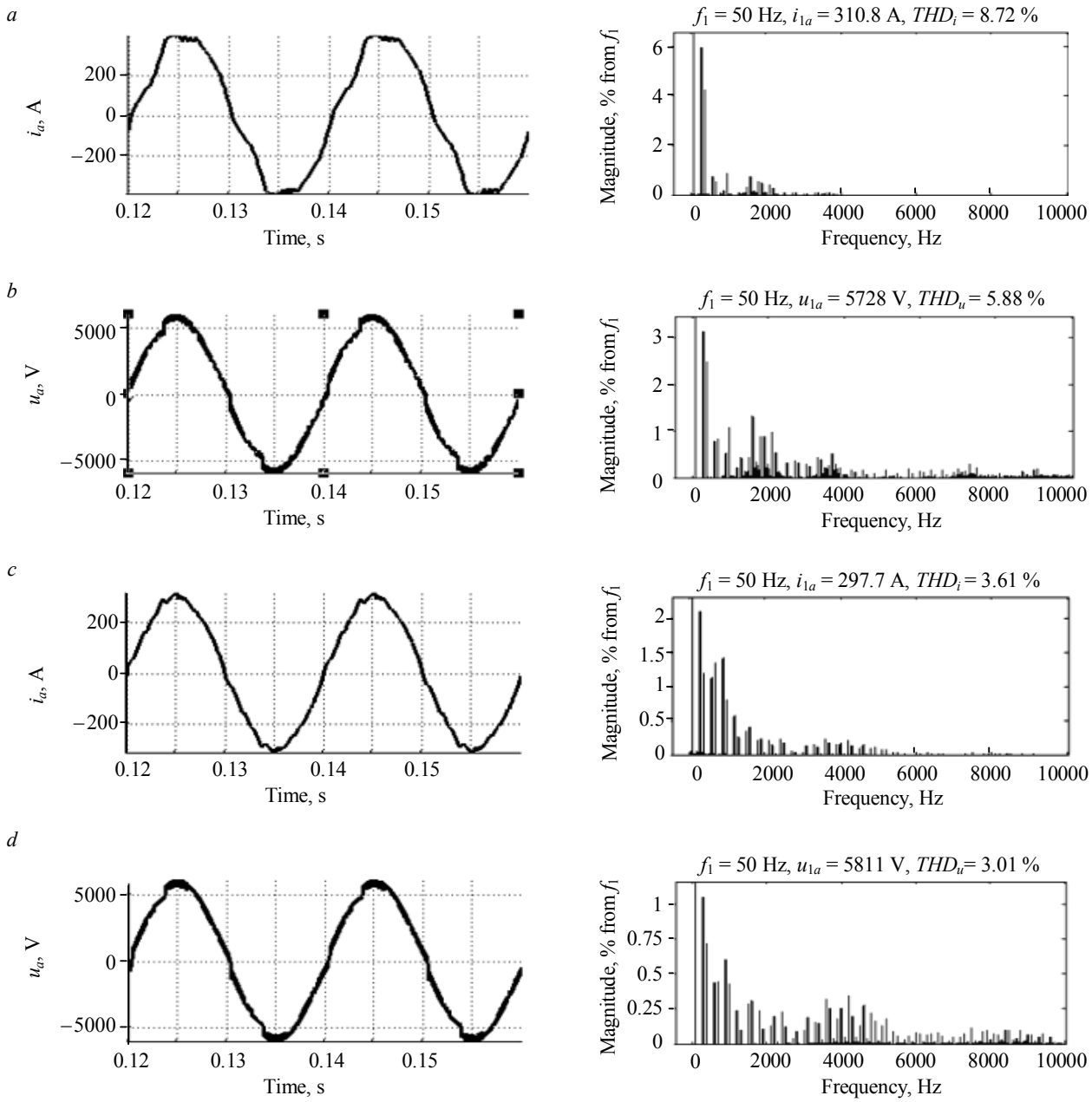


Fig.6. Waveforms and spectrums of the grid node input with connected VFD with AR loaded by 80 % (*a* – currents [A]; *b* – voltages [V]) and AR loaded by 30 % (*c* – currents [A]; *d* – voltages [V]). Active filtering function is enabled

Simultaneous work of both drives with harmonic compensation. The Fig.6 shows results of simulation for AR with active filtering function enabled. Two cases of AR load were considered. In the case of AR loaded at 80 % the THD_i = 8.72 %, which is achieved by the use of available 20 % of AR rated power to filter currents distortion. Magnitude of fundamental harmonic component equals to the case with no active filtering function, while magnitudes of 5 and 7-th harmonics decrease from 8 and 6 to 4 and 3 %, which shows effectiveness of active filter algorithm. Decrease of AR active load to 30 % leads to further improvement of THD_i to 3 %, while 5 and 7 harmonics decrease to 1 % value.

Active filtering performance. As it was indicated in particular simulations, the active filtering function of AR allows to greatly reduce currents distortion. However, the filtering effectiveness hardly depends on the amount of available current to perform this function and accordingly on the AR active current load. To investigate that dependency, the series of simulation with different

DOI: 10.31897/PMI.2019.2.229

percentage of AR load by active current was performed. The results of simulation are shown in the Fig.7.

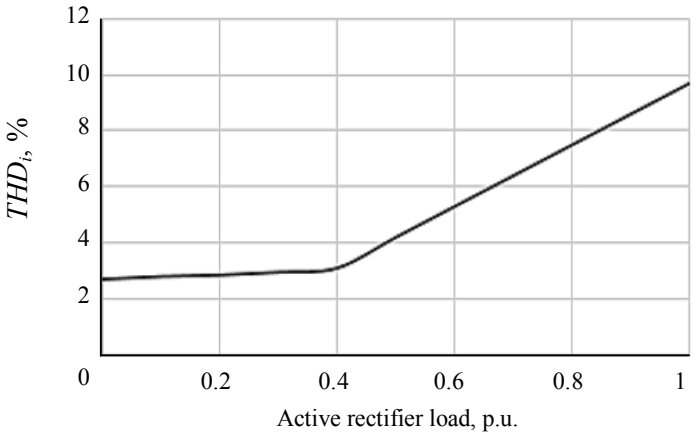


Fig.7. The efficiency of grid current harmonics mitigation by use of AR depending on its load by active power

Conclusion. The paper considered application of the AR in VFD for reducing currents harmonic distortion caused by the presence of non-linear load. The case was considered on the example of 6 kV mine grid node. The model of AR was built according to three-level NPC topology, which allows to achieve EMC standards in medium voltage distribution grids. The DPC system with filtering of fundamental current component was used to maintain active filtering functions for AR. To investigate effectiveness of the presented solution, the simulation model of the grid node with presence of the non-linear load of 2 MW and VFD with AR of 1.5 MW power rating, were built in the MATLAB/Simulink software.

The simulation results have shown that before connecting the VFD with AR, grid node consumes highly distorted currents that in turn leads to voltage waveform distortion. Connection of VFD with AR to the grid node allows to reduce *THD* to half even without filtering function, which is caused by increase of fundamental current component magnitude depending on the AR active current load – higher load percentage leads to higher fundamental component magnitude and lower *THD*. Performing a filtering function, AR is able to significantly reduce *THD* of current by use of free current to compensate high-order harmonics.

Based on the simulation results, the active filtering efficiency was plotted depending on the active current load of AR. The dependency has shown the effectiveness of using AR as active filter in applications, where the AR is not always fully loaded.

REFERENCE

1. Frolov V.Ya., Zhiliglotov R.I. Development of sensorless vector control system for permanent magnet synchronous motor in Matlab Simulink. *Zapiski Gornogo instituta*. 2018. Vol. 229, p. 92-97. DOI: 10.25515/PMI.2018.1.92 (in Russian).

2. Abdelli Y., Machmoum M., Coulibaly P. A three-phase PWM rectifier with active filtering function. Power System Technology. Proceedings. International Conference. 2002. Vol. 1, p. 485-490.

3. Pena-Alzola R., Liserre M., Blaabjerg F., Sebastián R., Dannehl J., Fuchs F.W. Analysis of the passive damping losses in LCL-filter-based grid converters. IEEE Transactions on Power Electronics. 2013. Vol. 28. Iss. 6, p. 2642-2646.

4. Bouafia A., Gaubert J.P., Krim F. Predictive direct power control of three-phase pulsewidth modulation (PWM) rectifier using space-vector modulation (SVM). IEEE Transactions on Power Electronics. 2010. Vol. 25. Iss. 1, p. 228-236.

5. Pisică I., Lipan L., Postolache P., Toader C., Comănescu G., Daşu D.C. Electric Power Quality Monitoring and Analysis at a Tri-Generation Plant under Development. The 11th WSEAS International Conference on mathematical methods and computational techniques in electrical engineering (MMACTEE'10). 2010, p. 654-879.

6. Fisk W.J., De Almeida A.T. Sensor-based demand-controlled ventilation: a review. Energy and buildings. 1998. Vol. 29. Iss. 1, p. 35-45.

7. Keskar P.Y. Specification of variable frequency drive systems to meet the new IEEE 519 standard. IEEE Transactions on Industry Applications. 1996. Vol. 32. Iss. 2, p. 393-402.

8. Kubota H., Matsuse K. Speed sensorless field-oriented control of induction motor with rotor resistance adaptation. IEEE Transactions on Industry Applications. 1994. Vol. 30. Iss. 5, p. 1219-1224.

9. Lawrence T. Demand-controlled ventilation and sustainability. ASHRAE Journal. 2004. Vol. 46. Iss. 12, p.117-121.

10. Liu S.Y., Mendes V.F., Silva S.R. Analysis of direct power control strategies applied to doubly fed induction generator. Proceeding XI Brazilian Power Electronics Conference (COBEP). 2011, p. 949-954.

DOI: *10.31897/PMI.2019.2.229*

11. Marchesoni M., Tenca P. Diode-clamped multilevel converters: a practicable way to balance DC-link voltages. IEEE Transactions on Industrial Electronics. 2002. Vol. 49. Iss. 4, p. 752-765.

12. Sanjuan S.L. Voltage oriented control of three-phase boost PWM converters: design, simulation and implementation of a 3-phase boost battery charger. Master of Science Thesis in Electric Power Engineering. Göteborg: Chalmers University of Technology, 2010, p. 114.

13. Selesnick I.W., Burrus C.S. Generalized digital Butterworth filter design. IEEE Transactions on Signal Processing. 1998. Vol. 46. Iss. 6, p. 1688-1694.

14. Zhang Y., Xie W., Zhang Y. Deadbeat direct power control of three-phase pulse-width modulation rectifiers. IET Power Electronics. 2014. Vol. 7. Iss. 6, p. 1340-1346.

***Authors*: Juan Manuel Munoz-Guijosa,** *PhD*, *Professor*, *jmguijosa@etsii.upm.es* (*Polytechnic University of Madrid*, *Madrid*, *Spain*), **Sergei B. Kryltcov,** *Assistant Lekturer*, *kryltcov@outlook.com* (*Saint-Petersburg Mining University*, *Saint-Petersburg*, *Russia*), **Sergei V. Solovev,** *Candidate of Engineering Sciences*, *Assistant Lekturer*, *forsakenfour@gmail.com* (*Saint-Petersburg Mining University*, *Saint-Petersburg*, *Russia*).

The paper was received on 21 January, 2019.
The paper was accepted for publication on 6 March, 2019.