Three-phase power factor corrector with direct power control and power supply of the unbalanced industrial network

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Abstract. Nowadays three-phase power factor correctors (PFC) became widely used. This is dictated by strict requirements of the international electrical technical commission standards to harmonic composition of current supplied by three-phase industrial network. New schematic technical version of three-phase PFC having direct power control and improved efficiency factor is presented. Mathematical description of power component and control system taking in account its functioning depending upon asymmetrical three-phase input voltage was fulfilled. The electrical processes in the presented PFC was analysed by means of computer simulation. The obtained results are of interest to the persons engaged in the development of electrical energy systems and complexes to which higher requirements in respect to power loss reduction and reliable functioning in case of three-phase asymmetrical industrial network are imposed.

1 Introduction

Nowadays the need for three-phase power factor correctors (PFC) is dictated by the requirements of international electrical technical commission standards (IEC 60028) concerning harmonic composition of current consumed in the view of the fact that electrical energy systems and complexes are connected to power distribution three-phase supply network. Besides decreasing the share of higher harmonics in current consumed, it should be noted that PFC application enables decreasing of active current as compared with none-controllable converters of alternating current into direct current.

Modern state of the component's base, namely: power semiconductor elements, passive elements, microprocessor technique, as well as control laws improvement, creates prerequisites for development of the existing PFC schemes to that having higher energetic and dynamic features.

2 Three-phase PFC with improved efficiency factor

Synthesis of the new scheme decision [1, 2] was carried out by means of analysis of the existing three-phase PFC [3-7] and finding out classification signs. This scheme is presented in figure 1, where E_a , E_b , E_c are the EMF of input voltage, $R_{L1}...R_{L6}$ are the active resistances of input power chokes $L1...L6$, R is the PFC load.

The presented PFC is a combination of three-phase rectifiers and six step-up converters. It functions in the following way. At time intervals when input phase E_a is positive, the power transistor VT1 opens and current

flows through the circuit «+» $E_a - L1 - VD1 - VT1 -$ «-» E_a . As a result, the current of power choke $L1$ increases. Then output capacitor $C1$ discharges at the load R . Shut down of the power transistor VT1 results in current flow through the circuit «+» $E_{L1} - VD7 - C1 - E_a -$ «-» E_{L1} . This leads to a decrease in the current in choke $L1$ and at the same time to charging of converters of output capacitor $C1$.

At time intervals where input phase E_a is of negative value, the power transistor VT2 opens and current flows through the circuit «+» $E_a - VT2 - VD2 - L6 -$ «-» E_a . As a result, current through power choke $L6$ grows and output capacitor $C2$ discharges through load R . Shutting down the power transistor VT2 results in current flow through the circuit: «+» $E_{L1} - VD7 - C1 - E_a -$ «-» E_{L1} . This leads to a decrease in the current in choke $L6$ and at the same time to charging of converters of output capacitor $C2$.

During the processes described above the value and phase of the consumed current corresponds to the same indices of the phase A voltage. Such coincidence is achieved by an ability to use power transistors VT1, VT2 commutation algorithm, which was specially developed for the PFC under consideration. Processes in other phases are analogous.

The distinctive feature of the proposed three-phase PFC is that the following conditions are fulfilled. Current in power diodes $VD1...VD6$ flows during relatively short time period, namely when corresponding transistors VT1...VT6 are in open state. Due to this, power losses in diodes $VD1...VD6$ are reduced and this potentially results in increased efficiency factor of the presented PFC.

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Fig. 1. The power circuit of the presented PFC.

3 Mathematical description of the developed PFC

Mathematical description of the proposed three-phase PFC was developed using the method of switching functions [8, 9]. Switching functions of the transistors are introduced as follows:

$$d_{VTi} = \begin{cases} 0, & \text{when } VTi \text{ is turned off} \\ 1, & \text{when } VTi \text{ is turned on} \end{cases}, \quad (1)$$

where $i = 1 \dots 6$ are the numbers of power transistors VT1...VT6.

After this, an equation system for the presented three-phase PFC was composed according to the Kirchhoff's rules. In this case vector of variable values of the power circuit includes phase current i_a, i_b, i_c , output voltage U_{DC} and difference of output capacitors voltages ΔU_{DC} . Equation system was composed in matrix form. It has the following form:

$$M\dot{x} + Jx + Rx = u, \quad (2)$$

where $x = (i_a \ i_b \ i_c \ U_{DC} \ \Delta U_{DC})^T$ is vector of variable values of the state;

$$M = \begin{pmatrix} L & 0 & 0 & 0 & 0 \\ 0 & L & 0 & 0 & 0 \\ 0 & 0 & L & 0 & 0 \\ 0 & 0 & 0 & -C & 0 \\ 0 & 0 & 0 & 0 & -C \end{pmatrix} \quad \text{is the matrix of}$$

switching functions;

$$J = \begin{pmatrix} 0 & 0 & 0 & \frac{1}{2}(1-d_a) & 0 \\ 0 & 0 & 0 & \frac{1}{2}(1-d_c) & 0 \\ 0 & 0 & 0 & \frac{1}{2}(1-d_c) & 0 \\ (1-d_a) & (1-d_b) & (1-d_c) & 0 & 0 \\ (1-d_a \operatorname{sgn}(i_a)) & (1-d_b \operatorname{sgn}(i_b)) & (1-d_c \operatorname{sgn}(i_c)) & 0 & 0 \end{pmatrix} \quad \text{is}$$

the matrix of coefficients of $\dot{x}$;

$$R = \begin{pmatrix} R_L & 0 & 0 & 0 & 0 \\ 0 & R_L & 0 & 0 & 0 \\ 0 & 0 & R_L & 0 & 0 \\ 0 & 0 & 0 & -\frac{2}{R} & 0 \\ 0 & 0 & 0 & 0 & 0 \end{pmatrix} \quad \text{is the matrix of the}$$

coefficients of x ;

$u = (u_a \ u_b \ u_c \ 0 \ 0)^T$ is the vector of the equation free member.

There are many ways to provide control of three-phase PFC. Methods of immediate network current curve shaping [8-10] and direct power control [11-15] are the most widely used. Here we have chosen the method of direct power control. It is based on the Clark and Park-Gorev transformations of vectors.

Vector transformations mentioned here contain three variables in its general view. Two of them correspond to three-phase currents or voltages projections at fixed or revolving co-ordinate axis accordingly. The third variables (phase currents and zero voltages components) are equal to the phase currents or voltages composition. Under such conditions this vector transformations result in decreasing the mathematical model by one. The resulting mathematical model will have the only one solution only in case when phase currents and zero voltage components will be equal to zero.

Nevertheless, analysis of asymmetrical three-phase PFC modes requires taking into account the zero sequence current. The assumption concerning dependence of the zero sequence current was made. This assumption permitted to place zero sequence current into vector of the equation free member.

The Park-Gorev three-phase transform of analogous topology but without joining the neutral lead to the middle point of the output capacitors is given in [15]. Joining the neutral lead to the middle point of output capacitors gives addition term « $i_a + i_b + i_c$ » in equation for node «N» (see figure1).

Taking into account this factor, we developed a three-phase mathematical model for the presented three-phase PFC in dq0 coordinate system. After multiplication by u_d , active power is $p = 1.5u_d i_d$ and reactive power is $q = 1.5u_d i_q$, and we obtain the following mathematical model:

$$M_{dq} \dot{x}_{dq} + J_{dq} x_{dq} + R_{dq} x_{dq} = u_{dq}, \quad (3)$$

$$\text{where } M = \begin{pmatrix} \frac{2}{3}L & 0 & 0 & 0 \\ 0 & \frac{2}{3}L & 0 & 0 \\ 0 & 0 & Cu_d & 0 \\ 0 & 0 & 0 & Cu_d \end{pmatrix}; \quad J =$$

$$\begin{pmatrix} 0 & \frac{2}{3}L\omega & \frac{1}{2}d_d u_d & 0 \\ -\frac{2}{3}L\omega & 0 & \frac{1}{2}d_q u_d & 0 \\ -d_d & -d_q & 0 & 0 \\ -\frac{4}{3\pi}d_0 & 0 & 0 & 0 \end{pmatrix};$$

$$R = \begin{pmatrix} \frac{2}{3}R_L & 0 & 0 & 0 \\ 0 & \frac{2}{3}R_L & 0 & 0 \\ 0 & 0 & -2\frac{u_d}{R} & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix};$$

$$x = (p \ q \ u_{DC} \ \Delta u_{DC})^T;$$

$$u = (u_d^2 \ u_d u_q \ 0 \ u_d i_0)^T.$$

The vector of final expression is given as:

$$x^* = (p^* \ 0 \ U_{DC}^*)^T, \quad (4)$$

In [15], an expression was found, which connected p^* and U_{DC}^* :

$$p^* = \frac{3}{4} \frac{u_d^2}{R_L} - \sqrt{\left(\frac{3}{4} \frac{u_d^2}{R_L}\right)^2 - \frac{3}{2} \frac{u_d^2 u_{DC}^{*2}}{R_L R}}, \quad (5)$$

Error vector should be introduced into mathematical model in dq0-coordinate system:

$$M_{dq} x_{dq} + J_{dq} x_{dq} + R_{dq} x_{dq} - (R_{dq} + R_a)(x_{dq} - x^*) = u_{dq}, \quad (6)$$

$$\text{where } R_a = \begin{pmatrix} r_{a1} & 0 & 0 & 0 \\ 0 & r_{a2} & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & r_{a4} \end{pmatrix}$$

Vector of final expression (4) should be substituted into equation system (6). This gives expressions for switching functions d_d, d_q, d_0 .

$$\begin{cases} d_d = \frac{2}{u_d u_{DC}} \left(u_d^2 + r_{a1} (p - p^*) - \frac{2}{3} R_L p^* - \frac{2}{3} L \omega q \right) \\ d_q = \frac{2}{u_d u_{DC}} \left(q r_{a2} - \frac{2}{3} L \omega p \right) \\ d_0 = \frac{3\pi (r_{a4} \Delta u_{DC} + u_d i_0)}{4p} \end{cases}, \quad (7)$$

Expression (7) makes it possible to find out switching functions of power transistors VT1...VT6. Using the Park-Gorev method for inverse transformation signals corresponding to expression (7) we obtain reference signals which control power transistors VT1...VT6.

So, development of the control system using expressions (5) and (7) makes it possible to develop a control law which can provide instantaneous value of reactive power q supplied by net power, and at the same time voltage difference ΔU_{DC} of output capacitors near zero values.

4 Computer simulation of the proposed PFC

By implementation of the derived equations (5) and (7) in the Matlab-Simulink software, the computer model was developed which helps to simulate electrical processes of the proposed three-phase PFC. Simulation and analysis of the electrical processes are based on the conditions for the input phase voltage U , the output voltage U_{DC} , the load resistance R , the DC chock inductivity L , capacity C of the output capacitors, and the voltage unbalance factor K_U , that are shown in Table 1.

Fig. 2. Results of computer simulation.

Table 1. Computer simulation conditions

U, V	UDC, V	R, Ω	L, μHn	C, mF	KU, %
230	800	9.14	200	25	10

As an example, figure 2 shows the oscillograms of the input phase voltages u_a , u_b and u_c , the input phase currents i_a , i_b and i_c as well as the power supply reactive power q .

The curves presented in figure 2 clearly show that the proposed control system successfully provides coincidence in phase and in shape of phase currents and voltages when power supply is asymmetrical to the industrial frequency.

In Table 2 we listed the results of computer simulation for the total harmonic distortions K_{ia} , K_{ib} and K_{ic} of phase currents i_a , i_b and i_c for various phase voltage unbalance factors K_u , where K_i is the phase current unbalance factor; Q is the average rectified value of reactive power consumed from the three-phase network.

The analysis of electrical process showed that the total harmonic distortions of the power supply input current is not higher than 4% and the unbalance factor of phase currents is not higher than 8% when the unbalance factor of the input phase voltage is at the level of 6%.

Thus, the performed simulation proved that the proposed mathematical model of the presented three-phase PFC was designed correctly.

Table 2. Results of computer simulation.

K_u , %	K_{ia} , %	K_{ib} , %	K_{ic} , %	K_i , %	Q , kW
0	1.4	1.4	1.4	0.0	1.17
2	1.7	1.9	1.7	2.6	1.48
4	2.4	2.7	2.5	5.0	2.14
6	3.2	3.6	3.4	7.3	2.96
8	4.0	4.5	4.3	9.4	3.78
10	4.8	5.4	5.2	11.4	4.59

5 Conclusions

The presented concept of mathematical model for the proposed three-phase PFC supplied by the asymmetrical input phase voltage provides:

- Coincidence in phase and in shape of phase currents and voltages;
- Output voltage stabilization at a given level;
- Total harmonic distortions factor not higher than 5.5%, when the unbalance factor of the input phase voltage is at the level of 10%.

The obtained results could attract the developers of electrical-power systems and units who are challenging to develop systems with lower power losses and higher operational reliability in the conditions of asymmetrical input three-phase voltage.

References

1. D.A. Sorokin, S.I. Volskiy, Mathematical Model of Three-phase Power Corrector with Improved Efficiency, *Electrical Technology Russia*, **5**, 58-66 (2019)
2. D.A. Sorokin, S.I. Volskiy, *Three Phase Converter AC/DC with High Power Factor*, Patent of the Russian Federation, **N2018126502** (2018)
3. V.I. Meleshin, D.A. Ovchinnikov, *Control transistor inverters*, 411 (2011)
4. A.F. Souza, D.C. Pereira, F.L. Tofoli, *Comparison of Control Techniques Used in Power Factor Correction Rectifiers*, IEEE 13th Brazilian Power Electronics Conference and 1st Southern Power Electronic Conference, 1-6 (2015)
5. D.A. Sorokin, S.I. Volskiy, Comparative Analysis of Three-Phase PFC Rectifier, *Electronics and electrical equipment of transport (EET)*, **5**, 10-15 (2018)
6. L. Huber, Performance Comparison of Three-Step and Six-Step PWM in Average-Current-Controlled

- Three-Phase Six-Switch Boost PFC Rectifier, IEEE Transactions on Power Electronics, **31**, 7264-7272.
7. J.W. Kolar, T. Friedli, The Essence of Three-Phase PFC Rectifier Systems, IEEE Transactions on Power Electronics, **28(1)**, 176-198 (2013)
 8. L. Wang, H. Wu, W.H. Tang, Z.Y. Yu, W. Ma, *CCM-DCM Average Current Control for Both Continuous and Discontinuous Conduction Modes Boost PFC Converters*, 2017 IEEE Electrical Power and Energy Conference (EPEC), 1-6 (2017)
 9. X. Du, L. Zhou, H.M. Tai, Average Current Control of a Series-Type Single-Phase PFC With Hybrid Modulation, IEEE Transactions on Power Electronics, **26(9)**, 2381-2385 (2011)
 10. R. Etz, T. Patarau, D. Petreus, *Comparison between Digital Average Current Mode Control and Digital One Cycle Control for a Bridgeless PFC Boost Converter*, 2012 IEEE 18th International Symposium for Design and Technology in Electronic Packaging (SIITME), 211-215 (2012)
 11. H. Ma, Y. Xie, Z. Shi, Improved direct power control for Vienna-type rectifiers based on sliding mode control, IET Power Electronics, 1-8 (2015)
 12. H. Ma, Y. Xie, B. Sun, L. Mo, Modelling and Direct Power Control Method of Vienna Rectifiers Using the Sliding Mode Control Approach, Journal of Power Electronics, **15(1)**, 190 – 201 (2015)
 13. L. Yacoubi, K.A. Haddad, L.A. Dessaint, F. Fnaiech, Linear and Nonlinear Control Techniques for a Three-Phase Tree-level NPC Boost Rectifier, IEEE Transactions on Industrial Electronics, **53(6)**, 1908-1918 (2006)
 14. M. Yongqing, L. Zheng, S. Yanmin, Y. Ting, *Study on Mathematical Model and Lyapunov-Based Control for Three-Phase Four-Wire Three-Level NPC Voltage Source Rectifier*, IEEE ISIE 2005, 669- 674 (2005)
 15. Z. Dandan, W. Jiuhe, S. Dongjin, *Passivity Based Control of Three-Phase Three-Switch Vienna Rectifier*, ICMMITA 2015, 1127-1132 (2015)
 16. G. S. Zinoviev, *Power electronics*, 668 (2015)
 17. Yu.K. Rozanov, M.V. Rabchynski, A.A. Kvasnyuk, *Power electronics*, 632 (2007)
 18. D. Sorokin, S. Volskiy, Y. Skorokhod, *Development of the control system for three-phase power factor corrector*, PCIM2019, 1813-1819 (2019)