Schematics and Characteristics of Multiphase Compensated Power Supply Systems Based on Four-Phase Converter Units

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Abstract. The schemes of three types of four-phase compensated converter units with the double frequency voltage on commutating condensers are considered. The ways of building multiphase compensated converted power supply systems based thereon are suggested. The basic characteristics of these systems are presented. The advantages of the suggested systems in comparison with the traditional ones are shown.

1. Introduction

Recently, national researchers have shown a certain interest in four-phase systems of the electrical energy transmission. Thus, [1] considers the possibilities of the electric energy transmission by means of high-voltage four-phase electric ac power transmissions. [2] justifies the expediency of applying the four-phase operating mode of power supply systems built with the help of Ch.F. Scott transformers for power supply systems of high-speed ac railways of Siberia. This paper develops the idea of creating multiphase power supply systems based on the proposed variants of four-phase converter units, which not only provide transmission, but also convert ac energy into dc energy. At the same time, the problems of normalizing the qualitative indicators of electrical energy in the supply mains are simultaneously solved. The reactive power is compensated by transferring the four-phase converter units into the operating mode with a single-stage artificial valve commutation.

2. Models and Results

![Figure 1](image)

Figure 1. A schematic diagram of the four-phase compensated unit: a - based on Scott transformers; b – based on a three-phase transformer with the division of one valve winding in half; c – based on a three-phase transformer using a scalene zigzag of the valve windings.
The schematic diagrams of these three converter units are shown in Figure 1.

A high efficiency of the reactive power compensation by the units in accordance with Figure 2 is provided by a double voltage frequency on the commutating capacitors of the units’ compensating devices [3,4]. Each of these compensated four-phase converter units, on the one hand, has an independent importance and can be used as dependent and autonomous rectifiers, inverters, direct frequency converters and static reactive power compensators. On the other hand, in case the units are used in groups, as it is noted above, in cases of their chain, parallel and combined connection, the problem of improving the electrical energy quality through the formation of multiphase conversion modes, for example, in power supply systems of electro-technological installations, can be successfully solved [5,6].

**Figure 2.** Time diagrams of voltage and current on commutating capacitors of the four-phase converter units at the instant valve commutation.

As an example, Figure 3 shows a schematic diagram of one of the possible variants of threefold four-phase symmetrical compensated rectifiers (SCR) with a chain connection of the units according to the scheme in Figure 1 b. Let us demonstrate that similar converters with respect to the supply network operate in a twelve-phase mode according to the potentials of the valve anodes determined by the vector diagrams in Figure 3 b.

**Figure 3.** A schematic diagram of a threefold four-phase SCR (a) and vector diagram of the potentials of the valve anodes (b).
The amplitude of the k-th harmonic of the gate current of the four-phase unit having the duration of \( \pi/2 \), in accordance with the Fourier transformation, is determined by the ratio:

\[
I_{Bmk} = \frac{2I_d}{\pi k} \sin k \frac{\pi}{2}, \quad (1)
\]

where \( I_d \) – average value of the unit’s rectified current.

It follows from (1) that there are no evenly even harmonics in the gate current. Besides, the operating principle of the four-phase units predetermines the symmetry of the three-phase network currents with respect to the abscissa axis. Therefore, the mains currents of the four-phase units also lack a constant component and all even harmonics, apart from the evenly even ones. The connection of the odd current harmonics, sent by the unit to the three-phase supply network \( i_{A(k)}i_{B(k)}i_{C(k)} \) with the harmonics of the four-phase system of gate currents \( i_1(k), i_2(k), i_3(k), i_4(k), \ldots \) can be presented as follows [1]:

\[
\begin{align*}
  i_{A(k)} &= \frac{1}{2} \begin{pmatrix} 1 & 0 & -1 & 0 \\ -1 & \sqrt{3} & 1 & \sqrt{3} \\ 2 & 2 & 2 & 2 \\ 1 & \sqrt{3} & 1 & -\sqrt{3} \end{pmatrix} \begin{pmatrix} i_1(k) \\ i_2(k) \\ i_3(k) \\ i_4(k) \end{pmatrix} \\
  i_{B(k)} &= \begin{pmatrix} 1 & 0 & -1 & 0 \\ -1 & \sqrt{3} & 1 & \sqrt{3} \\ 2 & 2 & 2 & 2 \\ 1 & \sqrt{3} & 1 & -\sqrt{3} \end{pmatrix} \begin{pmatrix} i_1(k) \\ i_2(k) \\ i_3(k) \\ i_4(k) \end{pmatrix} \\
  i_{C(k)} &= \begin{pmatrix} 1 & 0 & -1 & 0 \\ -1 & \sqrt{3} & 1 & \sqrt{3} \\ 2 & 2 & 2 & 2 \\ 1 & \sqrt{3} & 1 & -\sqrt{3} \end{pmatrix} \begin{pmatrix} i_1(k) \\ i_2(k) \\ i_3(k) \\ i_4(k) \end{pmatrix}.
\end{align*}
\]

The analysis of the correlation (2) shows that the four-phase unit converts all the harmonics of the gate currents into the corresponding symmetrical three-phase harmonic systems in the power windings of the unit transformers. In particular, the gate currents harmonics multiple of three in the supply network do not form a zero order of the phase sequence but are transformed into symmetrical three-phase systems of a direct and reverse phase sequence [7-10].

In order to improve the quality of the electrical energy in the supply network by a transition to multiphase conversion modes, two ways can be used. The first way is illustrated in Figure 3 by the example of forming a twelve-phase SCR operating mode. It is realized by using one three-phase three-leg transformer with a common three-phase power winding. The second way, also by the example of a twelve-phase conversion mode, is realized by connecting three independent four-phase units to the power supply network by any of the circuits in Figure 1 with a 120 electrical degree shift in the connection to the mains, i.e. by one third of the mains voltage period. Both solutions lead to the fact that in the spectra of the resulting currents of the supply network, the harmonics, which are non-canonical for the twelve-phase conversion mode, are excluded, namely, harmonics 3,5,7,9, etc. In the spectra of currents and voltages of the supply network, only harmonics 1, 11, 13, 23, 25, etc. remain.

The operation of the threefold four-phase SCR in a symmetric twelve-phase mode allows us to use the general theory of converters with a single-step artificial commutation [3] to determine its characteristics, if to consider that the SCR corresponds to the circuit parameter \( \psi = \pi/4 \). For this purpose, the authors calculated and modeled the main characteristics of the threefold four-phase SCR. Several calculation results are shown in Figure 4: a - external characteristics of the threefold four-phase SCR; b – dependencies of the reactive power of the threefold four-phase SCR on the load current and the eigenfrequency of the valve commutation circuit; c – dependencies of the reactive power factor of the threefold four-phase SCR on the load current and the eigenfrequency of the valve commutation circuit. The authors took the relative value of the eigenfrequency of the valve commutation circuit of the rectifier unit as one of the parameters:
where $x_c$ and $x_k$ – phase capacity reactance of the units’ capacitor bank and equivalent inductive resistance of the supply network and the converter transformer reduced to the valve commutation contour and determined at the basic frequency. For the purpose of universality, the characteristics are built in relative quantities. The authors adopted the no-load run EMF in the load circuit, the amplitude of the steady-state value of the valve commutation current and their product as the base values of voltage, current and power. All the dependencies in Figure 4 have an appearance typical of the known compensated rectifiers. Value $\nu = 0$ corresponds to the uncompensated rectifier. With an increase in value $\nu$ (otherwise with a decrease in the capacity of the capacitors of the units’ compensating devices), the rigidity of the external characteristics increases, and the converter's consumption of the reactive power decreases. The solid curves on the given characteristics correspond to the converter’s consumption of the reactive power, and the dashed curves - to its generation into the supply network.

The closest by the nature of the electromagnetic processes to the above-discussed zero four-phase compensated units are the traditional six-phase compensated units, respectively, with a triple (ChPI scheme) and double (KPI scheme) voltage frequency on the capacitors. Using the example of a twelve-phase SCR version, let us note the advantages of the above-mentioned way of building multiphase compensated converters. To form a twelve-phase SCR version, two six-phase units are required with the wye and delta connection of the power windings, respectively. In this case, the variant using the units according to the scheme in Figure 5 cannot compete, for example, with the
variant according to the scheme in Figure 3.

![Diagram of the six-phase compensated unit with a triple frequency of voltage on the capacitors](image)

Figure 5. Schematic diagram of the six-phase compensated unit with a triple frequency of voltage on the capacitors (b)

In fact, one of the units with the wye connection of the power winding is essentially not operable because of the magnetic flux of the forced triple frequency magnetization on the core legs of the transformer. The latter is caused by the 60-degree duration of the gate current.

3. Conclusions

High-efficiency multiphase converter power supply systems of electro-technological installations can be built on the basis of compensated four-phase units.

The increased phase mode of the "p" converter can be implemented on the basis of using self-compensated four-phase units feeding the individual electric energy consumers according to the schemes in Figure 1 with unified independent magnetic systems and winding circuits of converter transformers. In this case, to implement the p-phase conversion mode, it is necessary to use \( n = p/4 \) converter units with a shift of the connection to the power supply network of one unit with respect to the other one by an angle equal to \( 2\pi/n = 8\pi/p \). For example, twelve-phase conversion mode \( p = 12 \) requires the use of three units with a shift in connection, equal to \( 2\pi/3 \). Twenty-four-phase mode \( p = 24 \) requires six units with a shift in connection, equal to \( \pi/3 \).

Multiphase power supply systems of powerful consumers based on compensated four-phase units can be built with a common converter transformer with a single three-phase magnetic system and valve windings creating a p-phase voltage system.

References

[1] D’yakov A F 2012 Ways to enhance the reliability of power supply in Russia Herald of the Russian Academy of Sciences 82(2) 90–101

[2] Vorfolomeyev G N, Evdokimov S A, Morozov P V, Sopov V I 2008 Application of Scott transformers on traction substations of electric railways Scientific problems of transport in Siberia and the Far East 6 273–276

[3] Baev AV, Volkov Yu K, Dolinin V P, Korneev V Ya 1969 Valve inverters with capacitors in
power circuits (Moscow: Energia)

[4] Khokhlov Yu I, Safonov V I, Lonzinger P V 2016 Electromagnetic processes in power transformers with vector control *Russian Electrical Engineering* **87**(3) 145–149

[5] Khokhlov Yu.I., Bashmakova N.Yu. 2009 Electromagnetic processes in the threefold four-phase thyristor compensated converter *Proceedings of the International Scientific and Technical Conference "Problems of Electrical Engineering, Power Engineering and Electro-technology"* (Togliatti: TSU) 2 296–301

[6] Usynin Y S, Shishkov A N, Sychev D A, Savosteenko N V and Khayatov E S 2015 Improving the energy efficiency of electric drives of reciprocating rolling mills *Russian Electrical Engineering* **86**(12) 709–711

[7] Hamad M S, Masoud M I, Finney S J, Williams B W 2008 Medium voltage series connected 12-pulse compensated current source controlled rectifier with a novel front end transformer configuration *IET Conference Publications* (538 CP) 27–32

[8] Serrano-Jiménez, D., Abrahamsson, L., Castaño-Solís, S., Sanz-Feito, J. Electrical railway power supply systems: Current situation and future trends *International Journal of Electrical Power and Energy Systems* **92** 181-192

[9] Kharlamova, N V, Khalyasmaa A I, Eroshenko S A 2017 Alternative power supply systems for remote industrial customers *Conference Series: Earth and Environmental Science* (Yurga technological Institute) **72**(1) 012027

[10] Pratap S B, Kajs J P, Walls W A, Weldon W F, Kitzmiller J R 1997 A Study of Operating Modes for Compulsator Based em Launcher Systems *IEEE Transactions on Magnetics* **33** 495–500