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The “Engineer” publishes the most significant results of scientific and applied research carried out in universities of transport profile, as well as other higher educational institutions, research institutes, and centers of the Republic of Uzbekistan and foreign countries.

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Single-phase to six-phase voltage converter

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Abstract: This paper presents a novel circuit for converting a single-phase power supply into a stabilized six-phase voltage system. The proposed converter is based on a three-limb transformer with six secondary windings connected in a hexagonal configuration and two primary windings connected in series opposition. Each primary winding is shunted by a capacitor, forming two ferroresonant circuits that ensure voltage stabilization and precise phase shifting.
Key features of the design include:

- **Simplified construction** – Reduced number of windings and optimized connection scheme.
- **Improved conversion quality** – Stabilized output voltages and maintained phase shifts (60° between adjacent phases).
- **High efficiency** – Use of an amorphous alloy core minimizes losses and reduces overall size.

The converter operates by exciting ferroresonant oscillations in the primary circuits, which saturate the outer transformer limbs while keeping the middle limb (with double cross-section) unsaturated. This ensures stable magnetic fluxes (Φ_1, Φ_2, and their sum Φ_3), inducing balanced six-phase voltages in the secondary windings. By adjusting the capacitive reactance, a 120° phase shift between Φ_1 and Φ_2 is achieved, resulting in a symmetrical six-phase output.
Potential applications include:

- Household appliances (enabling three-phase motor operation from single-phase supply).
- Industrial and transportation systems (where single-phase input is preferred).
- Power electronics and automation devices requiring multi-phase voltage.

The proposed design offers a cost-effective and reliable solution for generating high-quality six-phase power from a standard single-phase source.
Keywords: phase converter, six-phase system, ferroresonant circuit, voltage stabilization, amorphous core

1. Introduction

A circuit for converting a single-phase voltage system into a multiphase system, specifically a six-phase system, is considered. Such converters can be applied in household appliances, where their use combines the advantages of three-phase electric motors with frequency control and the availability of only a single-phase network. In particular, the use of such devices eliminates voltage dips caused by the starting currents of asynchronous motors. These converters are also used in electrified transport systems, such as shop floor, mining, and mainline transportation, where a single-phase voltage system is preferable due to the reduced number of conductors. Additionally, they are employed in protection and automation devices for power transmission lines [1,2].

2. Research methodology

In the stabilized single-phase to six-phase voltage converter under consideration (Fig. 1), which includes a three-core transformer with six secondary windings connected in opposition and arranged in pairs on each core, and two primary windings located on the outer cores with terminals for network connection, the three-core transformer is designed with a doubled cross-section for the middle core.

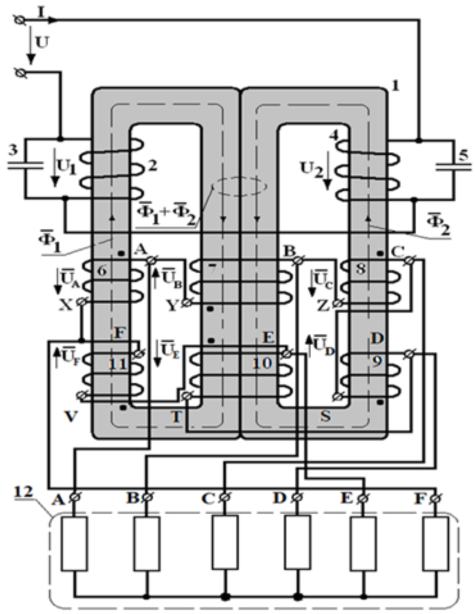

Fig. 1. Stabilized single-phase to six-phase voltage converter

The secondary windings are connected in a hexagonal configuration, while the primary windings are connected in a series-opposed arrangement and are shunted by capacitors, forming two ferroresonant circuits. This design simplifies the device by reducing the number of windings and simplifying their connection scheme while also improving

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conversion quality by stabilizing the voltage in the artificially generated phases and maintaining the required phase shifts. The use of a magnetically soft amorphous material as the transformer core enhances the efficiency of the converter and reduces its overall size [3,4].

The proposed stabilized phase number converter (Fig. 1) consists of a three-core transformer 1 of the core-shell system, where the middle core is designed with double the cross-sectional area compared to the outer cores. It includes two primary windings 2 and 3, connected in a series-opposed configuration and placed on the outer cores of the magnetic core. The winding 2, shunted by capacitor 4, forms the first ferroresonant oscillatory circuit, serving as the stabilizing element, while winding 3, shunted by capacitor 5, forms the second ferroresonant oscillatory circuit, acting as the stabilized ballast element. The secondary windings 6, 7, 8, 9, 10, and 11, where A, B, C, D, E, F are the start points of the phase windings, and X, Y, Z, S, T, V are the end points of the phase windings, located on the outer and middle cores of the magnetic core and connected in a hexagonal configuration, are used to generate an artificial six-phase voltage system that powers the load 12. The stabilized phase number converter operates as follows. When alternating input voltage U is applied to the device, ferroresonant oscillations are excited in the first and second ferroresonant circuits, formed by winding 2 and capacitor 4, and winding 3 and capacitor 5, respectively. The magnetic fluxes Φ1 and Φ2, induced by currents in windings 2 and 4, saturate the outer cores of transformer 1. Their magnitude remains almost unchanged, which results in the stabilization of voltages U1 and U2 across windings 2 and 4. Due to the opposing connection of windings 2 and 4, the magnetic flux in the middle core of the magnetic core, equal to the sum of the stable fluxes Φ1 and Φ2, is also stabilized, despite the fact that saturation does not occur in the middle core due to its doubled cross-sectional area.

The magnetic fluxes of the left and right cores Φ1 and Φ2, as well as the magnetic flux of the middle core, equal to the sum of Φ1 and Φ2, induce voltages UA, UB, UC, UD, UE, UF in the corresponding secondary windings 6, 7, 8, 9, 10, 11. The stability of these voltages is ensured by the minimal variation of the magnetic fluxes *Φ1* and *Φ2* when the outer magnetic cores of transformer 1 reach saturation. The phase shifts between the magnetic fluxes *Φ1* and *Φ2* allow for the generation of an artificial six-phase voltage system, including phase voltages U_A, U_B, U_C, U_D, U_E, U_F, or line voltages U_{AB}, U_{BC}, U_{CD}, U_{DE}, U_{EF}, U_{FA}, which power the six-phase load 9. The connection of the secondary windings 6, 7, 8, 9, 10, 11 in a hexagonal configuration improves the harmonic composition of the phase and line voltages of the artificial phases by eliminating higher harmonics that are multiples of three.

Figure 2 shows the vector diagrams of the magnetic fluxes $\bar{\Phi}_1$ and $\bar{\Phi}_2$ in the magnetic core rods, the phase voltages $\bar{U}_A, \bar{U}_B$ $\bar{U}_C, \bar{U}_D, \bar{U}_E, \bar{U}_F$, and the line voltages $\bar{U}_{AB}, \bar{U}_{BC}, \bar{U}_{CD}$ $\bar{U}_{DE}, \bar{U}_{EF}, \bar{U}_{FA}$ of the secondary windings, explaining the process of artificial phase conversion.

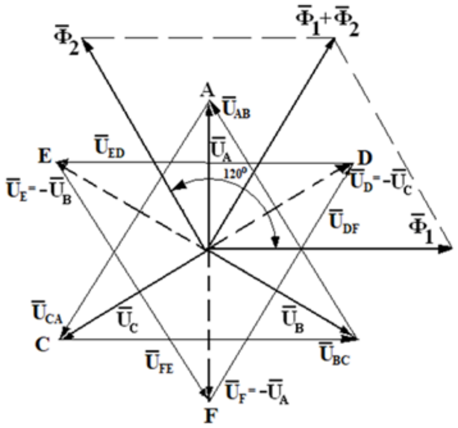

Fig. 2. Vector diagrams of the phase number converter

When autopraramétric oscillations are excited in the first (winding 2 and capacitor 3) and second (winding 4 and capacitor 5) ferroresonant circuits, the phase shift between the magnetic flux vectors $\bar{\Phi}_1$ and $\bar{\Phi}_2$ in the outer rods of the magnetic core can theoretically range from 90° to 180°. By varying the capacitance of capacitor 5 and thereby adjusting the capacitive reactance of the second oscillatory circuit, it is possible to achieve a phase shift of 120°. In this case, the magnitude of the magnetic flux vector in the central core $\bar{\Phi}_3$, which is equal to the sum of the vectors $\bar{\Phi}_1$+$\bar{\Phi}_2$, will be the same as the magnitudes of the vectors $\bar{\Phi}_1$ and $\bar{\Phi}_2$. Consequently, the amplitudes of the phase voltages $\bar{U}_A, \bar{U}_B$,$\bar{U}_C, \bar{U}_D, \bar{U}_E, \bar{U}_F$, induced by these magnetic fluxes in the secondary windings 6, 7, 8, 9, 10, and 11, as well as the amplitudes of the line voltages $\bar{U}_{AB}, \bar{U}_{BC}$,$\bar{U}_{CD}$, $\bar{U}_{DE}$,$\bar{U}_{EF}$ and $\bar{U}_{FA}$, will also be equal. The beginnings of the windings, marked with dots in Fig. 3, should be on the same side for the windings of the outer cores (6, 11 and 8, 9), while for the winding of the central core (7 and 10), they should be on the opposite side. As a result, the voltage vectors of winding 7 and$\bar{U}_E$ winding 10 are rotated by 180°, which ensures the required phase shift of 60° between the secondary voltage vectors $\bar{U}_A, \bar{U}_B$ $\bar{U}_C, \bar{U}_D, \bar{U}_E, \bar{U}_F$.

3. Conclusion

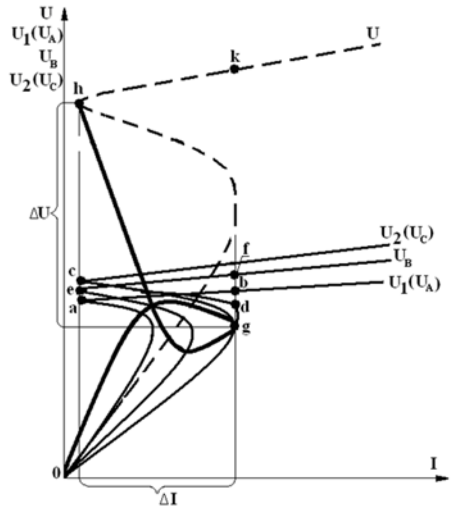

Fig. 3. Volt-ampere characteristics of the phase number converter

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Fig. 3 shows the volt-ampere characteristics of the components of the phase number converter, illustrating the principle of stabilization of phase and line voltages of the artificial phases. The curve U represents the overall volt-ampere characteristic of the entire circuit, $U=f(I)$. The curve $U_1(U_A)$ represents the volt-ampere characteristic of the first ferroresonant circuit, $U_1=f(I)$, or, considering the transformation ratio, the volt-ampere characteristic of phases A and F, i.e., $U_A=f(I)$ and $U_F=f(I)$. The curve $U_2(U_C)$ represents the volt-ampere characteristic of the second ferroresonant circuit, $U_2=f(I)$, or, considering the transformation ratio, the volt-ampere characteristic of phases C and D, i.e., $U_C=f(I)$ and $U_D=f(I)$. The curve U_B represents the volt-ampere characteristic of phases B and E, i.e., $U_B=f(I)$ and $U_E=f(I)$. When an alternating input voltage U, whose value is within the range ΔU (or when the supply current I varies within the range ΔI), is applied to the device, ferroresonant autoparametric oscillations occur in the first and second ferroresonant circuits. These oscillations are characterized by energy exchange not only within the circuits but also between them. This ensures the stability of the device's operation, where the first ferroresonant circuit operates inductively with a lower resonance voltage (segment a − b of the curve $U_1(U_A)$), and the second ferroresonant circuit operates capacitively with a higher resonance voltage (segment c − d of the curve $U_2(U_C)$). For any operating mode of the circuit, the expression for voltage vectors is valid $\bar{U} = \bar{U}_1 + \bar{U}_2$. Considering that the voltages U1 and U2 of the first and second ferroresonant circuits, operating in inductive and capacitive modes respectively, are nearly in antiphase, the volt-ampere characteristic of the entire circuit is determined not as the arithmetic sum of the voltages U_1 and U_2 across the circuits (dashed curve U on segment 0 – h – k), but as the vector difference between the voltage U_1 in the inductive segment and U_2 in the capacitive segment (bold curve U on segment 0 – g – h – k). From the graphs, it is evident that in the zone of ferroresonant autoparametric oscillations (segment g – h of curve U), when the supply voltage changes within ΔU, the voltages $U_1(U_A)$ (segment a – b) and $U_2(U_C)$ (segment c − d) vary insignificantly. Meanwhile, the phase voltage U_B, equal to the vector sum of U_A and U_C with the opposite sign (segment e − f of curve UB), remains virtually unchanged. Thus, the device is simplified by reducing the number of windings, while the conversion quality is improved through the stabilization of voltages in the artificially generated phases.

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