Analysis of the harmonic composition of the rectified voltage at the asymmetry of the secondary system of windings with different turns in converter

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Abstract. The use of integrated transformer converters of the number of phases, in which the EMF phase system at the input of bridges is formed by the geometric addition of the EMF components of individual windings, expands the scope of application of DC voltage sources with ripple frequency. With the symmetry of the transformer converter of the number of phases included in the valve bridges, each ripple of the rectified voltage of the integrated rectifier contains \( m \) ripples of exactly the same amplitude and duration, containing the corresponding composition of harmonics. However, when designing such integrated rectifiers, there is a problem of ensuring an acceptable level of symmetry of the multiphase EMF system. This is due to the inability to implement the required ratios between the numbers of turns due to their discreteness. This paper presents studies of the analysis of harmonics of rectified voltage with an asymmetry formed by a secondary system of multi-turn windings for an eight-pulse rectification scheme.

1. Introduction

Constant voltage sources with multiple ripple frequencies are a complex of power transformers and semiconductor valve circuits. Usually, for them, the increase in the number of phases is achieved by using integrated transformer converters of the number of phases. In which the phase system of EMF at the input of bridges is formed due to the geometric addition of the EMF components for individual windings [1 – 3].

Under ideal conditions, each ripple of the rectified voltage of a multi-pulse rectifier is part of the sum of the sinusoids of the corresponding EMF (voltages) of the valves, windings of a transformer converter of the number of phases. During one period of the supply voltage curve, \( m \) exactly identical pulsations are observed in the rectified voltage curve which contains the corresponding order of harmonics in the rectified voltage curve.

However, when designing such integrated transformer converters, there is usually a problem of ensuring an acceptable level of symmetry of a multiphase EMF system, which is due to the technological complexity and implementation of the required ratios between the numbers of turns due to their discreteness.

Therefore, in practice, it is allowed to reduce or increase the winding turns by exactly one integer, which relative to the calculated value of the output voltage can be an error of up to several per cent of the required number of turns.
Modern achievements in the field of construction of transformers and Converter technology allow creating integrated multipulse rectifier units that meet the currently increased requirements of electromagnetic compatibility between different consumers of electric energy and the network feeder. Current rectification, which is performed using rectifier valves, is closely related to commutation processes. The widespread use and dissemination of these sources requires precise consideration of the factors that determine them. In particular, it is important to consider the degree of influence of the structural asymmetry of the phase number transformer on the overlap angle and on the rectified voltage in the commutation zone [1–3].

2. Materials and methods

The operation of the transformer Converter, which is included in the valve group, has its own characteristics, due to the number of combinations included in the General sequential chain of windings with different turns and with a different number of turns from the calculated value. Moreover, for the formation of the same value of the phase-amplitude of the voltage at the input of the gate bridges throughout the supply network, a different number of windings is involved in the operation of the Converter. This is determined by the design feature of the circuit and its output voltage pulse. The resulting phase voltage asymmetry, which is formed by the secondary system of the converter windings, will affect the quality of the rectified voltage. In this case, the nature of the ongoing processes differs significantly from the case of symmetry. This is due to the influence of commutation processes that occur in each gate bridge. This is due to the difference in the amplitude values of the phase EMF and their initial phases at the input of the bridges. The degree of mutual influence that leads to disturbances in the operation of the Converter and an increase in the voltage ripple coefficient at the output of the rectifier depends on the magnitude of the resulting asymmetry.

Changes in electromagnetic processes caused by the mutual influence of bridges lead to changes in the angles of the beginning of commutation and the shape of the rectified voltage and the level of its harmonics.

Determining the harmonic composition is reduced to finding the harmonic composition of the modified form of the rectified voltage curves of gate multipulse converters, which are made according to the scheme of transformer orthogonal sources of phase-shifted EMF variables. The voltage harmonics at the output of the circuit are found through their cosine and sine components according to the formula [4, 5]

\[ U_{km} = \sqrt{a_{km}^2 + b_{km}^2}, \]  

where \( k \) – the order of the harmonic which equal to the ratio of its frequency to the frequency of the main harmonic of the supply voltage; \( a_{km} \) and \( b_{km} \) – amplitudes of the cosine and sine components of the \( k \) – the harmonic; \( U_{km} \) – amplitude value \( k \) – the harmonics of the voltage at the output of the rectifier.

The components of the harmonics of the total rectified voltage of circuit a and b can be found by summing the corresponding harmonics, which are introduced by an alternating group of different-winding gate windings. This is determined by the Fourier transform of the rectified voltage curves at the output of the bridges

\[ a_{km} = \frac{2}{T} \int_{0}^{T} f(t) \cos(k \omega t) dt, \]  

\[ b_{km} = \frac{2}{T} \int_{0}^{T} f(t) \sin(k \omega t) dt. \]

The given formulas (1) and (2) are convenient in their structure to use for a certain type of symmetry of the output voltage curves. This allows getting analytical relations available for calculation without resorting to numerical methods. For systematizing these curves, the concept of
symmetry of four genera (for even function, odd function) is introduced in [4]. However, the considered types of symmetry do not cover the entire variety of existing functions, which are a sequence of a series of identical curves.

Due to the resulting asymmetry, the steady-state process of the studied schemes is described through periodic piecewise sinusoidal functions, the period of which is divided into a finite number of sections of the sinusoidal change.

Obtaining formulas for calculating harmonics using conventional integral methods in each case requires quite large operations.

Such functions can only be calculated using numerical integration methods.

In particular, it is advisable to calculate the Fourier coefficients using the following general formulas

\[
a_{km} = \frac{2}{T} \sum_{n=0}^{m} \int_{0}^{T} f(t) \cos km \omega dt,
\]

\[
b_{km} = \sum_{n=0}^{m} \int_{0}^{T} f(t) \sin km \omega dt,
\]

where \( n \) – the corresponding section of the piecewise sinusoidal function.

The summation extends over all intervals of piecewise sinusoidal functions over the period \( T = 2\pi \).

Formulas (4) and (5) are valid for any starting point of the periodic function. The choice of the reference point only affects on the numerical values of the coordinates of the transition points from one sinusoidal section to another. Thus, there are no restrictions on the duration of the analyzed functions.

Expressions that associate harmonics with the values of piecewise sinusoidal functions are, although volumetric but simple enough and convenient for numerical analysis and obtaining the values of harmonics through the specified parameters of circuit modes.

Thus, it is most appropriate to use the method of numerical integration of equations of the form (4) and (5) as the basis for solving the problem.

3. Analysis of theoretical results by simulation

The calculation was performed using the expression (1) on the example of the 8-pulse rectification scheme [1, 6].

Obtaining linear harmonics spectra of the output voltage was performed with full symmetry of orthogonal phase-shifted sources of variable EMF (\( \alpha = 0, \beta = 90^\circ \)) to exclude their influence.

The scheme for two different degrees of asymmetry, which is formed by a secondary system of different-winding turns, was studied. The main results of these studies in the form of linear harmonics spectra of the output voltage are shown in Figures 1, (a-f).

Figures 1 (a-c) presents the results of a study of the worst-case probability distribution, in which the greatest difference between the minimum and maximum values of the rectified voltage was observed.

Figures 1 (d-f) presents the results of the study when discretization fractional turns to an integer using the rounding rule with excess and a disadvantage [4].

The research also took into account the value of the output voltage due to the established difference between the turns relative to the unit winding \( \frac{U}{U^{(1)}} = 1,0, \frac{U}{U^{(1)}} = 0,5, \frac{U}{U^{(1)}} = 0,166 \), which corresponds to the number of turns: \( w = 150; 75; 25 \).

Note that for \( w = 25 \) in comparison with \( w = 150 \) (Fig. 1 a, c), the discretization of different turns of windings to an integer has a great influence on the spectral composition of the output voltage.
Also from Figure 1, and it follows that in the worst case the amplitudes of the harmonics formed by the winding asymmetry, even at a very low output voltage, are at the level of 2% of the voltage amplitude of the unit winding (Fig. 1c).

![Harmonics Spectra](image)

**Figure 1.** Linear harmonics spectra of the output voltage in the case of coil asymmetry with 8-pulse rectification: a, b, c – the worst case of the probability distribution of the discretization turns; d, e, f – when sampling turns according to the rules of rounding to an integer

### 4. Conclusion
For higher voltages, the harmonic level does not exceed 0.2...0.4% of the voltage amplitude of the unit winding.

When discretization fractional turns of windings to an integer by the rounding rule (Figures 1, d-f) the level of output harmonics, which are due to the coil asymmetry, was significantly lower.

When the output voltage of the converter is comparable to the linear input voltage of the transformer conversion system, the harmonic amplitude does not exceed 0.2% of the unit winding voltage.
With a more accurate analysis, the calculation can be performed using the above method, which may be convenient for comparative analysis of circuits with different versions of the turn numbers of the valve windings, their connection schemes, and other features. For all these differences, calculations will be performed using the same approach.

References
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