Improvement of the frequency converter’s equivalent circuit when calculating non-sinusoidal modes

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Abstract. The issues related to modeling a variable frequency drive are discussed in the article. The authors were faced with the task of determining the influence of the drive load on the parameters of its equivalent circuit. An unambiguous dependence of the drive load on the value of the current’s harmonic components is revealed. Namely, the smaller the load, the greater the value of the current’s higher harmonics. It has been established that disregarding drive loading can lead to a 19% error in modeling the frequency converter current consumption. It is shown that the results of the study can be extended to a wide range of drives in terms of power, since all calculations were performed in relative units.

1. Introduction

The rapid development of power semiconductor technology leads to an increase in the number of adjustable converters that rise production energy efficiency and labor productivity. Nowadays, the proportion of adjustable AC and DC drives is more than 75% [1-4]. Based on power semiconductor technology, frequency converters (FC) should be highlighted among all electric power consumers. The power of such devices can be up to several megawatts [5,6]. Besides increasing the efficiency of the process, FC can also be a source of high harmonics (HH) currents. The negative consequences of the high harmonic currents flow through cables and equipment are known [7,8].

For these reasons, modeling and calculation of non-sinusoidal modes in the presence of such distortion sources is a relevant task [9,10]. These modes can occur in renewable sources’ energy systems [11,12] when using uninterruptible power supplies, and when there are many sources of HH in the network in general. In this regard, there is an issue of the equipment’s representation in equivalent circuits with minimal error to simplify the modeling of complex power supply systems that include many such devices.

2. Modern model for non-sinusoidal modes calculations

Until now, the models used to assess the effect of HH are a combination of either current sources connected in parallel or voltage sources connected in series [13,14], as shown in figure 1. The equivalent circuit contains: I(1), I(5), etc. – HH current sources; U(1), U(5), etc. – HH voltage sources.

An electric drive with a 6-pulse uncontrolled converter is the most common now. For this type of load, the parameters of current sources are selected based on two principles:

- the harmonic number is determined by the expression 2n+1, where n=1,2,3…
- root-mean-square amplitude of HH current for 5th, 7th, 11th, 13th, 17th, 19th, 23rd and 25th harmonics are determined with respect to the amplitude of the first harmonic as 0.2; 0.14; 0.10; 0.07; 0.06; 0.053; 0.043 and 0.04
The above model does not take into account the influence of the drive load, which has a significant impact on determining the parameters of the equivalent circuit as will be shown below.

The aim of the research, which results of are given in the article, was to determine the parameters of the FC equivalent circuit depending on the drive load.

![Nonlinear load equivalent circuit for calculating non-sinusoidal modes.](image)

Figure 1. Nonlinear load equivalent circuit for calculating non-sinusoidal modes.

However, in reality, the structure of the converter also includes a DC link, which introduces additional distortion into the current shape. In this regard, the aim of the study is to determine the parameters of the equivalent circuit of the frequency converter depending on the drive load.

3. Laboratory installation

For the research, a test bench was used (figure 2), which included a 5.5 kW asynchronous motor (AM) and a 5 kW synchronous generator (SG) connected to the AM by motor clutch. The load of the 5.5 kW frequency converter (FC) was regulated by resistors connected to the SG. Details of the equipment parameters are given in table 1.

| Name of equipment | Equipment parameters |
|-------------------|----------------------|
| SG                | Power (kW): 4.8;     |
|                   | Rotation frequency (rpm): 3000; |
|                   | Voltage (V): 380;    |
|                   | Current (A): 8.      |
| AM                | Power (kW): 5.5;     |
|                   | Rotation frequency (rpm): 3000; |
|                   | Voltage (V): 380;    |
|                   | Current (A): 10.8;   |
|                   | Power factor: 0.88.  |
| oscillograph      | Number of channels - 4 |
|                   | Bandwidth, MHz - 40 |
|                   | Apparent power 15 kVA |
| FC                | Supplied voltage 380 ... 500 V - 15 ... 10% |
|                   | Power frequency 50 ... 60 Hz - 5 ... 5% |
|                   | Line current 21.9 A at 380 V, Isc = 22 kA |
|                   | Nominal switching frequency 4 kHz |
An oscilloscope was installed between the supply network and FC. One channel of the oscilloscope measured the magnitude and shape of the linear current using current clamps, and the other channel was used to measure the linear voltage.

4. Results and Discussion
As a result, current and voltage waveforms were obtained, as shown in figure 3. The load of FC was 11%, 28%, 49%, 65%, 81%, 95% of the nominal value during the experiments. The load was calculated relative to the line rated current of FC, which is 21.9A. The FC current waveform shows double peaks caused by the presence of an uncontrolled rectifier in the FC. However, the amplitudes of the peaks are almost equal to the amplitudes of the fundamental harmonic, which allows us to talk about the presence of a significant filtering capacity in the DC link of the FC.

Figure 3. Oscillograms of line current and voltage the input of the FC.

Mathematical processing of the obtained experimental data was performed in Matlab software. Using a program written by the authors, the spectra of the FC consumed current were obtained, presented in figure 4. The histogram excluded all harmonics, the proportion of which is less than 5% of the main
harmonic in all FC operating modes. The obtained histograms differ significantly from the classical model, for example, the 5th harmonic of the consumed FC current in all modes varies from 0.79-0.94 of the magnitude of the fundamental harmonic. However, the 5th harmonic of the FC current is 0.2 of the fundamental current in the classical model.

Figure 4. Spectra of higher harmonics of FC current.

Figure 5. Dependences of HH currents in pu on FC load.

To analyze the results, the dependence of the higher harmonics currents on the FC load was drawn up, shown in figure 5. The current harmonics were calculated relative to the fundamental current of the
FC (p.u.). The operating modes for most FC applications require its continuous loading from 35% to 100%, since otherwise the use of such a high power FC is economically inefficient. Therefore, it is advisable to consider precisely this interval of the FC operating mode when analyzing the behavior of harmonics.

In the considered FC loading interval, harmonics above 13th had a value of less than 10% of the fundamental one. This means that these current components slightly affect the distortion indicators and the current value, since the parameters under consideration are calculated based on the sum of the squares of the components. In contrast to them, HH from 5th to 13th, we call these harmonics significant, for any FC operating modes exceed 10% of the fundamental.

Also, the parameters of significant harmonics (1st, 5th, 7th, 11th, 13th) change by less than 5% of the average value in the range from 35% to 95% of the FC load. So, harmonic ratios remain almost constant. Therefore, to construct an FC equivalent circuit for calculating non-sinusoidal modes in a wide FC loading range, it is proposed to use the average values of HH currents relative to the fundamental one.

5. Conclusion
Based on the analysis of the presented dependencies, the following conclusions can be drawn:

– The application of the classical FC model for calculating non-sinusoidal modes has a significant error on HH currents, for example, for the 5th harmonic it ranges from 59% to 74% of the fundamental current depending on the FC operating mode;

– 5th, 7th, 11th and 13th harmonics are essential for application in the calculations of non-sinusoidal modes when constructing the FC equivalent circuit. Their value is higher than 10% of the fundamental current for any FC operating modes, in contrast to other HH currents;

– The following ratios are proposed for significant harmonics: for 5th harmonics – 0.85 of the fundamental current, for 7th harmonics – 0.7, for 11th harmonics – 0.39, for 13th harmonics – 0.24.

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