SUPPLY VOLTAGE DISTORTION EFFECT ON OUTPUT VOLTAGE AND INPUT CURRENT OF THE AC CHOPPER FEEDING AN INDUCTION MOTOR

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Abstract

The purpose of the work was to investigate the effect of the supply voltage distortion on the main characteristics of the AC chopper, such as quality of the output voltage and the input current, and to conclude whether it is necessary to improve robustness of the system “AC chopper – Induction Motor” to a supply distortion. The research has been done by means of Fourier analysis for a generalized AC chopper with equal time-ratio control technique as the most widely used one. The presented results were verified by mathematical simulation in Mathcad and Matlab. The quality of the output voltage and the input current were assessed by their total harmonic distortion value (THD) and weighted THD value (WTHD). Input current analysis of the chopper feeding an induction motor was performed for a highly inductive load as it is a correct simplified model of the motor at the considered circumstances.

Introduction

AC chopper (Fig. 1) – a power electronic voltage converter based on fully controlled bi-directional semiconductor switches – is a promising direct voltage converter for supplying an induction motor in applications where motor operates with a cyclic load or underloaded for a long time at a constant speed. Besides improving energy efficiency of the induction motor it provides control and protection functions.

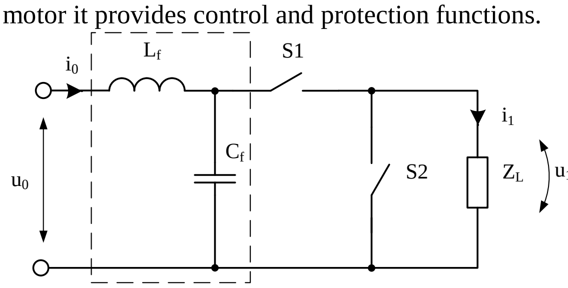

Fig 1. A power circuit of the single-phase AC chopper

The quality of the converter output voltage and its energy characteristics at various control techniques have been presented in many studies [e.g. 1]. However, the analysis has been done for purely sine input voltage, while in a real network the supply voltage can be distorted. It is especially typical for industrial networks where there are many powerful nonlinear energy consumers. Moreover, in some countries, including Russia, energy quality standards are not very strict and permit a relatively high supply voltage distortion [2].

Description

When the input voltage u_0 is purely sine, the output voltage of the converter u_1 (without output filter) comprises harmonics with frequencies (Fig. 2a)

$$\mathrm{f}(\mathrm{n}) = (n-1)\cdot f_{SW} \pm f_0$$

and magnitudes

$$\mathrm{U}_1(\mathrm{n}) = \mathrm{U}_0 \cdot \chi_1 \frac{\left|\sin((n-1)\cdot\pi\cdot\chi_1)\right|}{(n-1)\cdot\pi\cdot\chi_1},$$

where f_0 – the input (supply) voltage frequency;
$f_{SW} = q\cdot f_0$ – the chopper switching frequency, $q \in N$;
U_0 – the magnitude of input (supply) voltage;
$\chi_1 = t_1/T_{SW}$ – the control time-ratio; $n \in \mathrm{Z}$.

Normally for a powerful chopper $q = 20 \div 100$.

The total harmonic distortion of the output voltage

$$THD_{u_1}(\chi_1) = \sqrt{2\sum_{n=2}^{\infty}\left(\frac{\sin((n-1)\cdot\pi\cdot\chi_1)}{(n-1)\cdot\pi\cdot\chi_1}\right)^2}.$$

In this study the supply voltage is a sum of *m* low-frequency harmonics

$$u_0^d(t) = \sum_{k=1}^{m}\sqrt{2}U_{0(k)}\cos\left(2\pi\cdot k\cdot t - \psi_{0(k)}\right),$$

where *k* – the number of a harmonic, $k \in N$;
$U_{0(k)}$ – the magnitude of a harmonic *k*;
$\psi_{0(k)}$ – the phase of a harmonic *k*.

The THD of the distorted u_0

$$THD_{u_0} = \sqrt{\sum_{k=2}^{m}\mathrm{U}_{0(k)}^{\ 2}} \Big/ \mathrm{U}_{0(1)}.$$

When the switching frequency is at least twice higher than the highest frequency of the supply voltage harmonics (which is typical for real systems), there are 2*k* harmonics in the output voltage u_1 for each *n>1* with frequencies nearby the frequency $(n-1)\cdot f_{SW}$ (Fig. 2c)

$$f(n,k) = (n-1)\cdot f_{SW} \pm k\cdot f_0$$

and magnitudes

$$\mathrm{U}_1(n,k) = \mathrm{U}_{0(k)}\cdot\frac{\left|\sin((n-1)\cdot\pi\cdot\chi_1)\right|}{(n-1)\cdot\pi}.$$

For *n*=1 there are *k* harmonics of the supply voltage (including the fundamental harmonic) with magnitudes proportional to the time-ratio χ_1

$$\mathrm{U}_1(1,k) = \mathrm{U}_{0(k)}\cdot\chi_1.$$

The output voltage THD for such a case can be expressed in terms of the supply voltage THD

$\left(THD_{u_0}^{d}\right)$ and the THD of output voltage at zero supply distortion $\left(THD_{u_1}\right)$

$$THD_{u_1}^{d} = \sqrt{\left(THD_{u_0}^{d}\right)^2 + \left(1+\left(THD_{u_0}^{d}\right)^2\right)\cdot\left(THD_{u_1}\right)^2} = \sqrt{\left(THD_{u_1}\right)^2 + \left(1+\left(THD_{u_1}\right)^2\right)\cdot\left(THD_{u_0}^{d}\right)^2}\ .$$

Since the characteristics of an induction motor are more sensitive to low-frequency components of the feeding voltage it is important to consider the weighted THD value, where the magnitude of each harmonic is inversely proportional to its number. For AC chopper it is easy to show that

$$WTHD_{u_0} \approx WTHD_{u_1}\ .$$

As the load is highly inductive the magnitudes of high-frequency output current harmonics are fully attenuated by the load, while the magnitudes of low-frequency harmonics of the output current are inversely proportional to the corresponding voltage harmonics numbers. The spectrum of the output current contains *m* harmonics of the supply voltage (including the fundamental harmonic) with magnitudes

$$\mathrm{I}_1(1,k) \approx \mathrm{U}_1(1,k)/Z_L \cdot k^{-1}\ ,$$

where Z_L – the impedance of the load at the fundamental frequency.

Thus,

$$THD_{i_1} \approx WTHD_{u_0}\ .$$

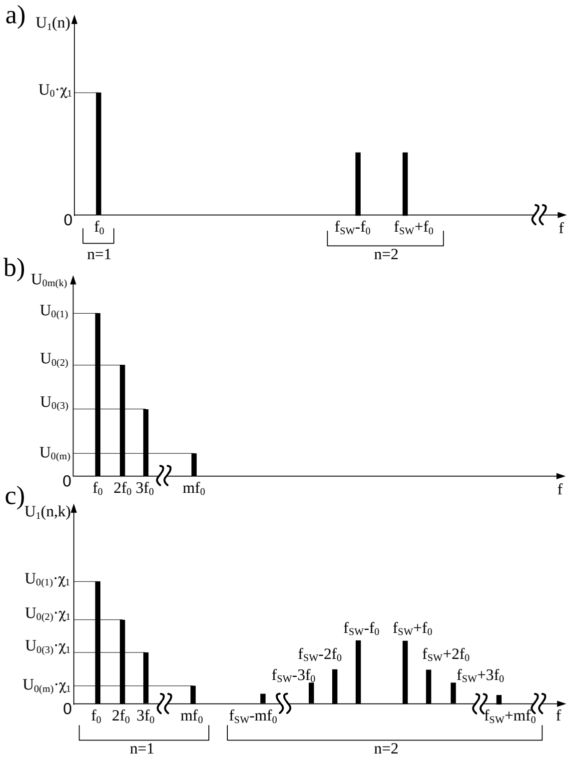

Fig. 2. Spectrum of: a) the output voltage of the chopper at zero supply distortion, b) the distorted supply voltage, c) the output voltage of the chopper at the distorted supply voltage

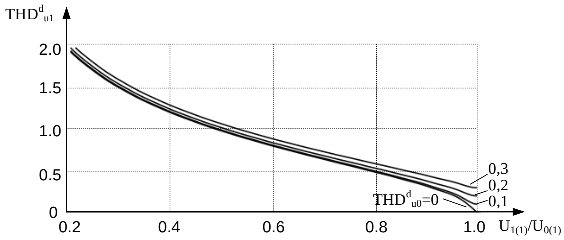

Fig. 3. The THD of the output voltage versus normalized magnitude of its fundamental harmonic at different supply voltage distortion values

In the considered voltage converter the input current is shaped from the output current by the same commutation function as the output voltage from the supply voltage, so the spectrum of the input current is similar to the spectrum of the output voltage, but the normalized magnitudes of higher harmonics are much smaller. Taking into consideration the fact, that high-frequency harmonics of the input current are filtered out by passive high-frequency low-pass filters, it has been shown that the THD of the input current is almost equal to the WTHD of the supply voltage

$$THD_{i_0} \approx WTHD_{u_0}\ .$$

For a three-phase system the derived relations are true if a distortion is symmetrical and the ratio $q/6$ is integer.

Results

1. The THD of the output voltage is nearly proportional to the THD of the supply voltage (Fig. 3).
2. The phase shift of supply voltage harmonics at $q > 2m$ does not affect magnitudes of output voltage harmonics.
3. For $THD_{u_0}^{d} = 0{,}012$ (12%), which is the maximum permitted value for Russian networks [2], the THD of the output voltage is only slightly higher than the THD of the output voltage at zero supply distortion.
4. The input current of the converter is less sensitive to the supply voltage distortion than the output voltage and with input high-frequency low-pass filters can be assumed purely sine.
5. The input low-frequency distortion goes directly through the chopper to the load and for operating at high supply distortion it is necessary to develop a special control technique of distortion compensation.

References

1. Arvindan A.N., Prashanthi S. Investigation for Power Quality in a PWM AC Controller Feeding a Three-Phase Three-Wire WYE Connected Load // IPEC–2010. – Singapore, 2010. – P. 648–653.
2. GOST R 54149–2010. [State Standard 54149–2010. Electrical energy. Electromagnetic compatibility of equipment. Rates of electrical energy quality in general purpose electrical supply systems]. Moscow, Standartinform, 2010. 16 p.