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EXPERIMENTAL ANALYSIS OF THE SUPPLY VOLTAGE QUALITY OF INDUCTION MOTORS WITH PWM CONVERTERS

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Abstract: *This paper presents an experimental analysis of the harmonic content of the supply voltage in induction motor electric drives. The drives are fed by voltage and frequency converters with autonomous voltage inverters with sinusoidal Pulse Width Modulation. For the purpose of analysis a laboratory stand is developed for measuring non-sinusoidal periodic signals. The stand consists of an induction motor, frequency converter, digital storage osciloscope and harmonics analyzer. The quantitative integral evaluations of non-sinusoidal periodic voltages are obtained based on the V/f=const and V=var; f=const control law. The analysis is carried out in Simulink environment by the fast Fourier transform Analysis Tool in SimPowerSystems Toolbox for Matlab. Conclusions are drawn about the supply voltage quality and the possible application of converters for the supply of induction motors in operation modes.*

Key words: *electromagnetic compatibility, induction motor electric drives, harmonic spectrum, fast Fourier transform*

1. Introduction

Presently induction motor electric drives based on non-linear semiconductor converters are widely used in various industrial areas. While offering enhanced opportunities for the control of technological processes, these drives also create problems. They generate current and voltage harmonics that can reduce the rated torque and efficiency, increase heating and magnetic noise of motors [1, 2]. For this reason, it is necessary to determine the supply voltage quality.

The induction motor drives use variable voltage converters (VVC) and variable frequency converters (VFC) with a DC link. Such converters have numerous capabilities regarding the forming of the output voltage and its harmonics toward high carrier frequencies due to the implementation of fast switching elements. One of the most commonly used methods for modulating the VFC output voltage is through Pulse Width Modulation (PWM).

The aim of this paper is to determine the supply voltage quality of induction motors fed by static frequency and voltage converters using PWM. For that purpose a laboratory stand of induction motor electric drive is developed and the voltage harmonic spectrum indicators of the PWM equipment are determined. The experimental analysis is carried out by the fast Fourier transform Analysis Tool in SimPowerSystems Toolbox for Matlab. On obtaining the quantitative indicators of the supply voltage quality, their impact on the electrical drive characteristics is evaluated.

The paper is organized as follows. Section 2 outlines the harmonic spectrum indicators of the supply voltage of the motor. Section 3 focuses on the mathematical analysis of the modulated periodic signals. The developed laboratory stand and research methodology are given in Section 4. In Section 5 the results from the experimental analysis are presented. Finally, conclusions are drawn in Section 6.

2. Harmonic spectrum indicators

The phase voltage of the motor in an induction motor (IM) electric drive controlled by a semiconductor converter is analysed. The latter is set to operate as frequency converter and voltage converter. To evaluate the IM periodic non-sinusoidal supply voltage, the following coefficients are used [3, 4]: total harmonic distortion coefficient (k_{THD}), coefficient of deformation (k_D), form coefficient (k_f) and weighted harmonic voltage factor (k_{HVF}).

In addition, the rms values of the stator phase voltage (U) and of its first harmonic (U_1) are also evaluated.

The above coefficients are determined by the formulae [5, 6]:

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$$k_{THD} = \frac{\sqrt{\sum_{\nu=2}^{\infty} U_\nu^2}}{U_1}; \; k_{HVF} = \frac{\sqrt{\sum_{\nu=5}^{\infty} \frac{U_\nu^2}{\nu}}}{U_1}. \quad (1)$$

$$k_D = \frac{U_1}{U}; \; k_f = \frac{U}{U_{AV}}. \quad (2)$$

All odd harmonics not multiple of 3 are included in k_{HVF} in (1).

It should be taken into account that for induction motors, fed by sinusoidal voltage with harmonic components, the standard determines the ability for loading within the range from 1 to 0.7 of the rated power with k_{HVF} varying from 0.030 to 0.115 [7]. Implementation of static PWM converters increases the steel losses by about 12% [5]. The total increase in the motor losses is by another 3%, 0.5% of wich is in the stator coil, 2% in the rotor coil and 0.5% are additional losses. This leads to a decrease in efficiency of the general-purpose motors by about 0.7% (95.3%-94.6%) at rated speed and load for 3kHz modulation signal.

3. Mathematical analysis of modulated periodic signals

The output voltage formed by the PWM is given by [8, 9]:

$$u_a = 0{,}5 m U_d \sin(\omega t + \psi) + F(M\omega_c \pm N\omega). \quad (3)$$

Here m is the index of modulation; $\omega=2\pi f$ is the angular frequency of the modulated signal; ψ is its phase angle; $\omega_c=2\pi f_c$ is the carrier angular frequency; U_d is the rectified voltage by the DC-link unit and the residual function $F(M\omega_c \pm N\omega)$ equals the sum of all high-frequency harmonics.

Expression (3) contains harmonics that depend on the carrier frequency. They are concentrated around the multiples of M (both even and odd) of the carrier frequency. As shown in Table 1, the sum M+N is a positive odd integer.

The most commonly used techniques for evaluating the measured signals include Fast Fourier Transform (FFT) and specialized software.

Table 1. Harmonic spectrum of sinusoidal PWM voltage

N(M)		M		
Odd M	Even M	1	2	....
0	±1	$1\omega_c$	$2\omega_c \pm 1\omega$	.....
±2	±3	$1\omega_c \pm 2\omega$	$2\omega_c \pm 3\omega$	.....
±4	±5	$1\omega_c \pm 4\omega$	$2\omega_c \pm 5\omega$	.....
±6	±7	$1\omega_c \pm 6\omega$	$2\omega_c \pm 7\omega$	.....
±8	±9	$1\omega_c \pm 8\omega$	$2\omega_c \pm 9\omega$	.....
......	......	.....	.....	.....

4. Laboratory stand and research methodology

Based on the analysis, a laboratory stand of induction motor electric drive is developed. It consists of a static AC to DC converter capable of working as VFC and VVC, digital oscilloscope and personal computer. The stand is shown in Fig. 1. Here UR stands for uncontrolled rectifier and C_F for DC-link capacitor. The rms value of the supply voltage is U=220 V and the frequency is f=50 Hz.

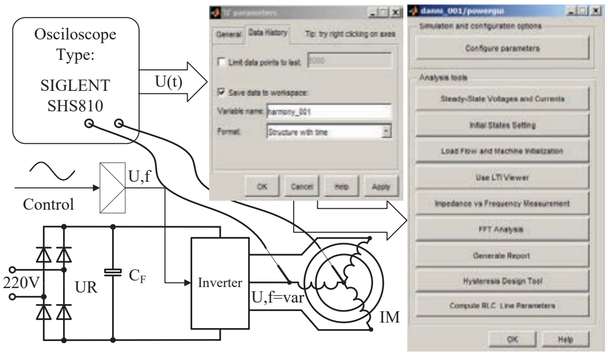

Fig. 1. *Schematic of the laboratory stand*

A full wave bridge rectifier and DC-link are used. The power inverter operates with sinusoidal PWM and carrier frequency f_c=5(2.5) kHz. The DC voltage maximum value is $V_{DC}=220\sqrt{2}$ V. The induction motor model has the folowing rated parameters: active power P_r=180 W; speed n_r=1366 rpm; line voltage V_r=380 V; frequency f_r=50 Hz; number of pole pairs z_p=2; efficiency η=64 % and power factor $\cos\varphi$=0.64.

The T-shaped equivalent circuit parameters are: stator resistance R_s=55.8 Ω; stator leakage reactance L_s=0.089 H; rotor resistance R_r=46.6 Ω; rotor leakage reactance L_r=0.157 H and magnetizing reactance L_m=1.367 H.

The FFT Analysis Tool from the SimPowerSystems ToolBox in Simulink uses Structure with Time format for the measured values of the voltage V(t). The values are stored in the Workspace. The discretization time t_k is between 2μs and 20μs depending on the modulated signal frequency. The induction motor operates at no-load. The supply voltage is varied based on the V/f=const control law for the VFC mode and V=var; f=50 Hz=const for the VVC mode. A Siglent 1810 digital oscilloscope with 2GB memory is used.

5. Results from the experimental analysis

Fig. 2 shows the induction motor phase voltage at 30 Hz when supplied by VFC. The values of the first 33 harmonics are also displayed as a percentage of the first hamonic peak value (V_{1max}). Here V_{1max}=124.2 V and k_{THD}=91.22 %.

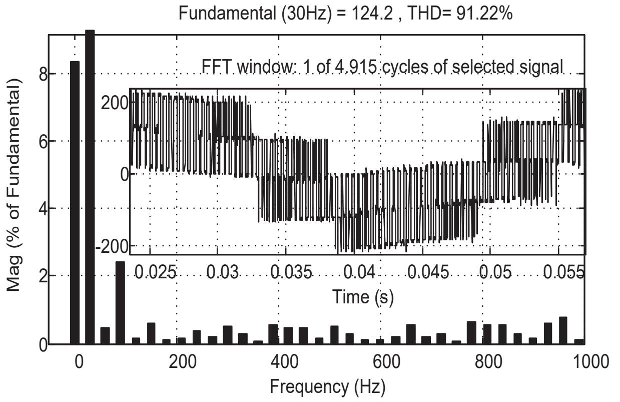

Fig. 2. *VFC output voltage form and values of the first 33 voltage harmonics at f_c=2500 Hz, f=30 Hz*

The shape of the motor phase voltage at 50 Hz, minimum voltage amplitude V_{1max} = 27.83 V and VVC converter mode is shown in Fig. 3. The values of the first 20 harmonics expressed as a percentage of the first harmonic peak value are also displayed. Here k_{THD} = 266.45%.

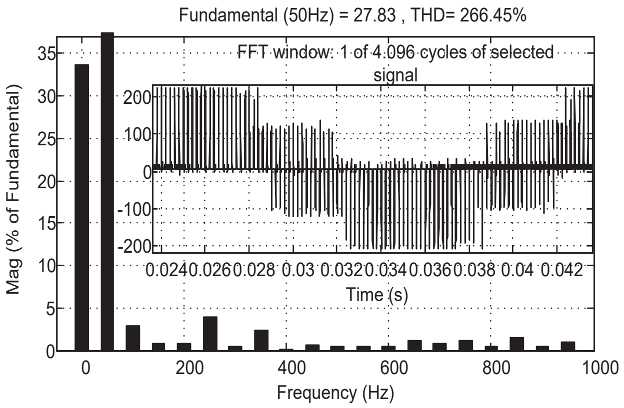

Fig. 3. *VVC output voltage shape and values of the first 20 voltage harmonics at f_c=2500 Hz, f=50 Hz*

The phase voltage harmonic spectrum at 30 Hz and VFC mode is shown in Fig. 4. The analysis is carried out up to f_{max}=15 kHz. It can be seen that that harmonics tend to group around the multiples of M of the carrier frequency.

The phase voltage harmonic spectrum at 50 Hz, V_{1max}= 27.92 V and VVC mode is shown in Fig. 5. The analysis is also carried out up to f_{max}=15 kHz. There is again grouping of harmonics around the carrier frequency multiples of M.

To determine the quantitative indicators by means of formulae (1) to (2), a set of experiments is carried out. Six modulated frequencies (10, 20, 30, 40, 50 and 100 Hz) are analyzed for the VFC mode. Tables 2 and 3 show the obtained results for the harmonics spectrum indicators of the voltage when the motor follows the V/f=const control law.

Five voltages (20, 48, 77, 106 and 133 V) at f=50 Hz and two carrier frequencies (2.5 kHz and 5 kHz) are analyzed for the VVC mode. Tables 4 and 5 show the obtained results for the harmonic spectrum indicators of the voltage at no-load.

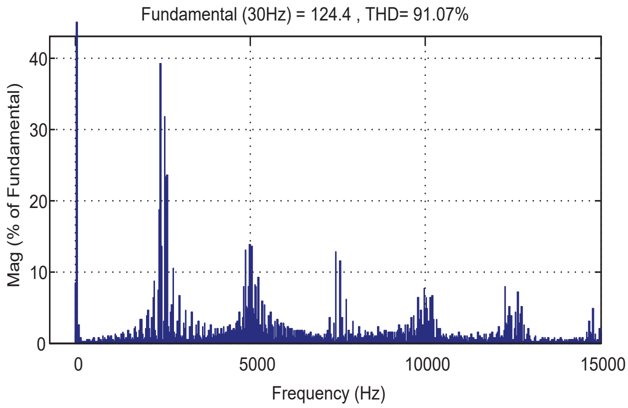

Fig. 4. *VFC output voltage harmonic spectrum at f_c=2500 Hz, f=30 Hz*

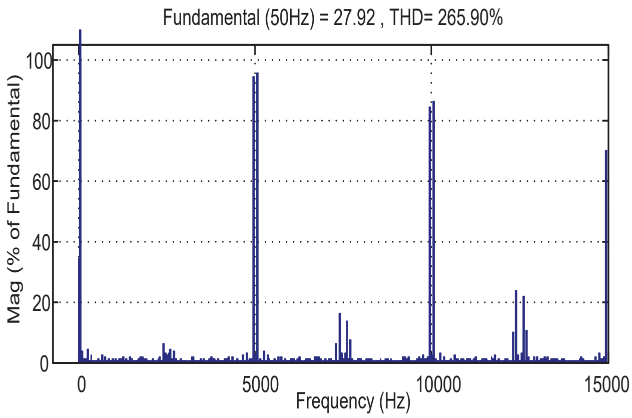

Fig. 5. *VVC output voltage harmonic spectrum at f_c=2500 Hz, f=50 Hz*

Table 2. VFC output voltage harmonic spectrum indicators at f_c=2500 Hz, no-load

f [Hz]	U [V]	U_1 [V]	k_f	k_{THD}	k_d	t_k [μs]
10	71	30	1.92	2.11	0.43	20
20	96	58	1.51	1.33	0.60	8
30	118	88	1.32	0.91	0.74	8
40	139	118	1.19	0.62	0.85	8
50	150	136	1.12	0.46	0.91	8
100	153	140	1.11	0.45	0.91	8

Table 3. VFC output voltage harmonic spectrum indicators at f_c=5000 Hz, no-load

f [Hz]	U [V]	U_1 [V]	k_f	k_{THD}	k_d	t_k [μs]
10	73	30	1.97	2.18	0.42	20
20	96	58	1.51	1.33	0.60	8
30	118	88	1.32	0.91	0.74	8
40	139	118	1.19	0.62	0.85	4
50	150	136	1.12	0.46	0.91	4
100	153	139	1.13	0.46	0.91	2

Table 4. VVC output voltage harmonic spectrum indicators at f_c=5000 Hz, no-load

f [Hz]	U [V]	U_1 [V]	k_f	k_{THD}	k_d	t_k [μs]
50	57	20	2.08	2.66	0.35	4
50	87	48	1.62	1.50	0.55	4
50	112	77	1.44	1.05	0.69	4
50	133	106	1.25	0.74	0.80	4
50	148	133	1.18	0.49	0.90	4

Table 5. VVC output voltage harmonic spectrum indicators at f_c=2500 Hz, no-load

f [Hz]	U [V]	U_1 [V]	k_f	k_{THD}	k_d	t_k [μs]
50	57	20	2.08	2.66	0.35	4
50	88	49	1.62	1.50	0.55	4
50	111	77	1.44	1.03	0.70	4
50	133	106	1.25	0.74	0.80	4
50	148	133	1.18	0.49	0.90	4

Tables 6 and 7 present the k_{HVF} values, calculated from the experimental data. The first value takes into account all harmonics with magnitude greater than 5% of the main harmonic. The second value is obtained by (1). Table 6 is for VFC at two carrier frequencies. Table 7 presents the k_{HVF} values for the VVC at one carrier frequency.

Table 6. Weighted k_{HVF} coefficient for the VFC converter

f_c [kHz]	f [Hz]					
	10	20	30	40	50	100
	k_{HVF} [%]					
2.5	4.9 8.5	6.9 10.0	5.4 8.5	4.4 6.4	3.7 8.0	5.1 7.6
5	4.3 15.9	4.6 7.4	4.3 6.1	0.8 4.5	2.5 4.1	3.1 5.3

Table 7. Weighted k_{HVF} coefficient for the VVC converter

f_c [kHz]	U_1 [V]				
	20	48	77	106	133
	k_{HVF} [%]				
2.5	11.5 17.1	5.5 17.5	9.0 12.3	5.6 8.5	3.8 5.8

6. Conclusion

This paper evaluates the supply voltage quality and its impact on induction motors, fed by static frequency and voltage converters using PWM. A series of experiments are conducted on a specially developed laboratory stand. The voltage from the converters is examined by FFT-analyser in SimPowerSystems Toolbox of Simulink.

Based on the results, it can be concluded, that harmonics tend to group around the multiples of M of the carrier frequency for both the VFC and VVC mode. Despite shifting of the harmonics towards high carrier frequencies, the weighted harmonic voltage factor exceeds the limit, set by the Standard IEC 60034-1. To improve the quality of the supply voltage, sinusoidal filters can be implemented on converters outputs.

The obtained results show that the total harmonics distortion coefficient and the distortion coefficient do not significantly vary with the carrier frequency, but strongly depend on the voltage. The values of k_{THD}, however, are well above the limit, recommended by the IEEE Std 519-1992.

The developed laboratory stand and the experiments carried out can be used as a foundation for future research of other types of modulation.

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