

Measurement and Evaluation of Electromagnetic Noise

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Abstract – This paper deals with measurement and evaluation of electromagnetic noise generated by induction electric motor fed by inverter controlled by PWM. It suggests and describes possible method of evaluation the electromagnetic noise which can be used in real-time applications.

Keywords–electromagnetic noise, induction motor, inverter, PWM, noise measurement, Goertzel algorithm

I. INTRODUCTION

One of the negative phenomena associated with operation of electric drives is their noise. During their operation, electric machines generate mechanical noise (bearings, gears), ventilation noise (air-cooling of the machine) and electromagnetic noise.

The main source of electromagnetic noise is inside the motor. Since the motor is in motion and is fed by time-variable current, this causes time-variable electromagnetic forces. Between the rotor and the stator there are tangential forces (which make the torque) and radial forces (which deform the stator). This deformations and oscillations are radiated to the environment.

Electromagnetic noise is affected by magnetic circuit design (teeth, slots) and by current waveform from the power supply. A large part of electric drives are fed from inverter usually controlled by Pulse Width Modulation (PWM). In this case, switching frequency of the inverter affects the electromagnetic noise considerably. A motor controlled by PWM can be identified by a „whistling“ sound. In some cases, this sound can be disturbing and unhealthy for exposed persons.

II. PWM FREQUENCY SPECTRUM

A. Voltage spectrum

We are considering electric drive consisting of 3-phase induction motor fed by an inverter controlled by PWM. In this case, PWM is modulated by a harmonic signal with desired stator frequency (f_s). The carrier signal of the PWM is symmetrical and its frequency is equal to the switching frequency of the inverter (f_{PWM}). The output PWM signal contains frequencies derived from the stator frequency and switching frequency, as shown in Table I. This frequencies also appear in the output voltage of the inverter.

Some of these frequencies appear in all 3 phases with the same amplitude and phase, so they are eliminated in the spectrum of line voltage and phase voltage of the motor. Frequencies contained in the motor phase voltage are summarized in Table II. Frequency spectrum of both inverter output voltage and motor line voltage is shown in Fig. 1.

TABLE I. SPECTRUM OF INVERTER OUTPUT VOLTAGE

f_{PWM}		$3 f_{PWM}$		$5 f_{PWM}$	...
	$2 f_{PWM} \pm f_s$		$4 f_{PWM} \pm f_s$		...
$f_{PWM} \pm 2 f_s$		$3 f_{PWM} \pm 2 f_s$		$5 f_{PWM} \pm 2 f_s$	...
	$2 f_{PWM} \pm 3 f_s$		$4 f_{PWM} \pm 3 f_s$		...
$f_{PWM} \pm 4 f_s$		$3 f_{PWM} \pm 4 f_s$		$5 f_{PWM} \pm 4 f_s$	...
	$2 f_{PWM} \pm 5 f_s$		$4 f_{PWM} \pm 5 f_s$		...
...

TABLE II. SPECTRUM OF MOTOR LINE VOLTAGE

f_{PWM}		$3 f_{PWM}$		$5 f_{PWM}$	...
	$2 f_{PWM} \pm f_s$		$4 f_{PWM} \pm f_s$		...
$f_{PWM} \pm 2 f_s$		$3 f_{PWM} \pm 2 f_s$		$5 f_{PWM} \pm 2 f_s$	...
	$2 f_{PWM} \pm 3 f_s$		$4 f_{PWM} \pm 3 f_s$		...
$f_{PWM} \pm 4 f_s$		$3 f_{PWM} \pm 4 f_s$		$5 f_{PWM} \pm 4 f_s$	...
	$2 f_{PWM} \pm 5 f_s$		$4 f_{PWM} \pm 5 f_s$		...
$f_{PWM} \pm 6 f_s$		$3 f_{PWM} \pm 6 f_s$		$5 f_{PWM} \pm 6 f_s$	...
...

B. Current and Noise Spectrum

The T-equivalent scheme of the induction motor is shown in Fig. 2. If we know the feeding voltage and electrical parameters of the motor, we can determine the currents (i_1, i_{2l}, i_m) and fluxes (Ψ_S, Ψ, Ψ_R). While current spectrum contains the same frequencies as the spectrum of phase voltage of the motor, the magnetic flux Ψ is almost harmonic due to large parallel magnetization inductance L_m .

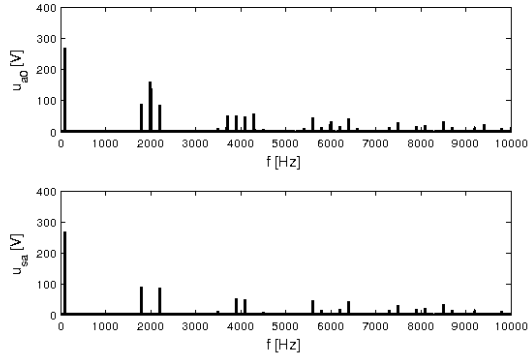


Figure 1. Frequency spectrum of inverter output voltage and motor line voltage

If rotor flux Ψ_R and stator current I_I are considered as space vectors, the torque of the machine is proportional to their cross product:

$$M = k_m (\Psi_R \times I_I) \quad (\text{equation 1})$$

where k_m is a constant. It means that relation between forces inside the machine and the feeding voltage (or current) is non-linear. Generally, frequencies which may appear in the forces and also in the noise are given by this formula:

$$f_X = f_{PWM} \pm f_s \quad (\text{equation 2})$$

When we want to evaluate the electromagnetic noise, these are the frequencies we have to focus on.

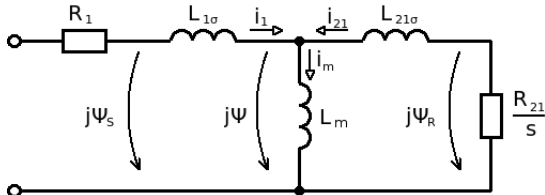


Figure 2. Equivalent scheme of induction motor

III. NOISE MEASUREMENT

The generation and propagation of the electromagnetic noise is very complicated and complex phenomena and is dependent on many factors (parameters of concrete motor, environment). For this reason we must employ measurement to obtain precise results.

For measuring the noise we use a microphone and simple preamplifier. This preamplifier includes phantom power supply for the microphone, amplifier with THAT 1510 integrated circuit and fourth-order anti-aliasing filter. The preamplifier can be connected to an oscilloscope or Digital Signal Processor, which controls the electric drive. The circuit diagram of the preamplifier is shown in Fig. 3.

There are several methods of measuring and evaluation of the noise. The simplest method is to measure a sequence of noise, load it to the computer and apply the Fast Fourier Transform. This method is suitable for off-line measurement and it gives us complete spectrum of the noise including mechanical and other noises. Since longer sequences lead up to

more precise measurement, recording of every sequence means large number of samples to be stored in memory.

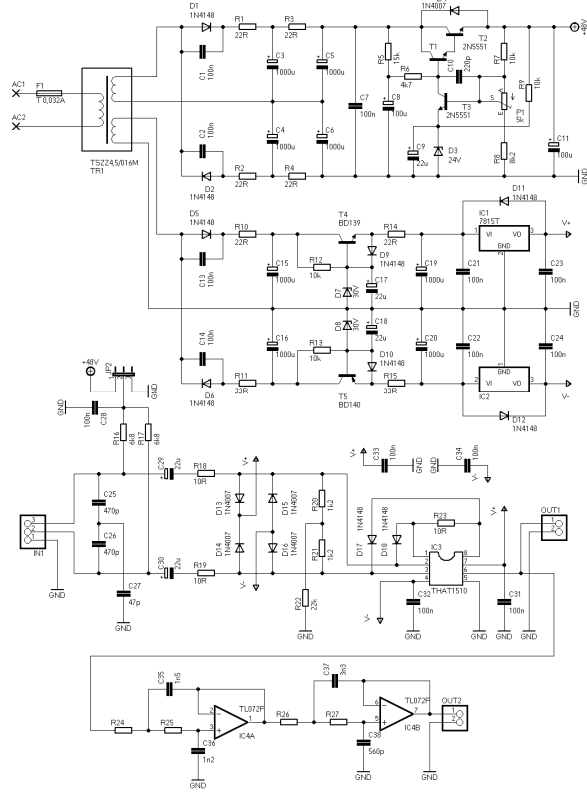


Figure 3. Microphone preamplifier

For this reason it can be advantageous to use methods, which demand less data to be stored. As we have mentioned, the electromagnetic noise (which we are focused on) contains frequencies, which are determined by modulation frequency and carrier frequency of the PWM. It means that we do not need to compute complete spectrum by FFT but only individual frequencies.

Amplitude of a single frequency can be obtained by DFT. Definition of DFT is:

$$Y(n) = \sum_{k=0}^{N-1} y(k) e^{-j2\pi k \frac{n}{N}} \quad (\text{equation 3})$$

If we want the result of DFT not to depend on the number of samples N , we need to modify the formula:

$$Y(n) = \frac{2}{N} \sum_{k=0}^{N-1} y(k) e^{-j2\pi k \frac{n}{N}} \quad (\text{equation 4})$$

We can also replace the discrete frequency k with „real“ frequency f :

$$k = fT \quad (\text{equation 5})$$

where f is frequency in Hertz and T is length of the sequence in seconds. So the final formula is:

$$Y(n) = \frac{2}{N} \sum_{k=0}^{N-1} y(k) e^{-j2\pi f T \frac{n}{N}} \quad (\text{equation 6})$$

Theoretically, frequency f can be any real frequency (it means that k is not an integer), but this leads to very imprecise results. Since we need to measure any frequency regardless of the length of sequence T , using the Goertzel algorithm is more suitable.

The Goertzel algorithm uses digital filter with two stages. The first stage calculate the intermediate sequence $s(n)$ using the input sequence $x(n)$:

$$s(n) = x(n) + 2 \cos(2\pi f) s(n-1) - s(n-2) \quad (\text{equation 7})$$

where f is the detected frequency in cycles per sample. Second stage generates the output sequence $y(n)$:

$$y(n) = s(n) - e^{-j2\pi f} s(n-1) \quad (\text{equation 8})$$

Since the first stage uses last three samples of input signal and second stage uses only last two samples of the intermediate signal, it is not needed to storage the whole sequences. In every step (getting sample from measurement) we need to update the state of the first stage of the filter (equation 7). After getting the last sample we compute the output (equation 8).

While the first stage uses only real numbers, the second stage generates complex numbers. Using the real-valued arithmetic means that we need to separate the real part and imaginary part of the output:

$$y(N) = c_r s(N-1) - s(N-2) + j c_i s(N-1) \quad (\text{equation 9})$$

where c_r and c_i are coefficients defined as:

$$c_r = \cos\left(2\pi \frac{K}{N}\right) \quad (\text{equation 10})$$

$$c_i = \sin\left(2\pi \frac{K}{N}\right) \quad (\text{equation 11})$$

K is an integer which restricts possible frequencies:

$$K = fN \quad (\text{equation 12})$$

$$K \in \{0, 1, 2, \dots, N-1\} \quad (\text{equation 13})$$

When we need to detect a frequency, which does not meet the condition given by the equation 12, we can modify the coefficients:

$$c_r = \cos(2\pi f) \quad (\text{equation 14})$$

$$c_i = \sin(2\pi f) \quad (\text{equation 15})$$

This means that K is not integer and this fact affects the accuracy of the calculation. But if the measured sequence much longer than period of the detected frequency, the error is acceptable.

For practical application it is useful to normalize the frequency and amplitude to "real" units. Equation for the first stage:

$$s(n) = x(n) + 2 \cos\left(2\pi \frac{fT}{N}\right) s(n-1) - s(n-2) \quad (\text{equation 16})$$

where f is frequency in Hertz, T is length of measurement in seconds and N is number of samples. Equation for the second stage:

$$y(N) = \frac{2}{N} [c_r s(N-1) - s(N-2) + j c_i s(N-1)] \quad (\text{equation 17})$$

Coefficients:

$$c_r = \cos\left(2\pi \frac{fT}{N}\right) \quad (\text{equation 18})$$

$$c_i = \sin\left(2\pi \frac{fT}{N}\right) \quad (\text{equation 19})$$

These equations can be directly used in Digital Signal Processor or in computer for off-line evaluation of the measurement. Block diagram of control and measuring system is shown in Fig. 4.

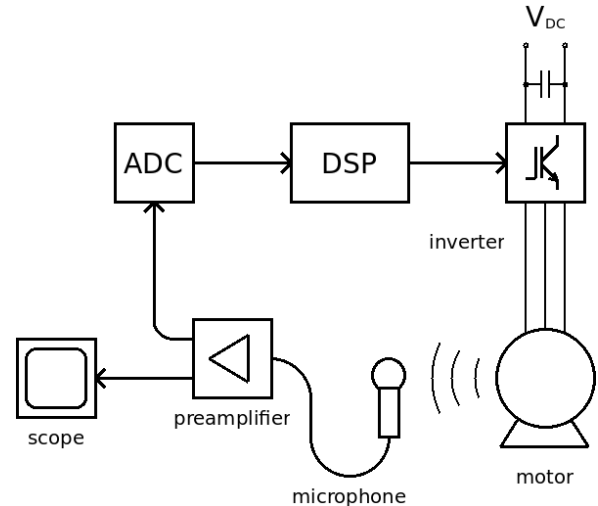


Figure 4. Control and Measuring system

An example of offline measurement noise frequency spectrum obtained by FFT is shown in Fig. 5. A detail of frequency spectrum with use of Goertzel algorithm is shown in Fig. 6. For overall evaluation of the electromagnetic noise we can calculate energy of all measured frequencies (see equation 2) which is proportional to:

$$E \sim \sum_{a=1}^A \sum_{b=-B}^B y(a f_{PWM} + b f_s)^2 \quad (\text{equation 20})$$

Theoretically the number of measured frequencies should be infinite, but with increasing indexes a and b , the amplitudes are converging to zero.

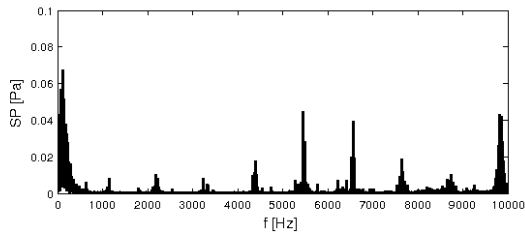


Figure 5. Noise frequency spectrum

The level of electromagnetic noise does not depend on the control only but also on motor and environment parameters, which can vary in time. To decrease the noise we need to respect the frequency response of the motor and the environment and avoid resonant frequencies. To achieve this, the control system can change the switching frequency and measure how the energy of measured frequencies changed. After testing few switching frequencies the system can choose one which makes the lowest noise.

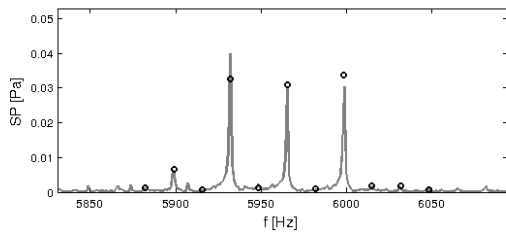


Figure 6. Frequency spectrum and Goertzel algorithm

IV. CONCLUSION

The suggested method for electromagnetic noise evaluation was tested off-line on measured data to compare the results with FFT. This method seems to be suitable for using in Digital Signal Processor. Up to now the measurement was carried out on electric drive in steady state (constant rpm and load). In real operation we will need to deal with variable conditions of the electric drive. However, this method can be easily employed to control electric drives which operates in steady state often enough to make the measurement.

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