The Moving Average Filter of Stator Current as Alarm for Overload of Induction Motor

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Abstract—In this paper, the method of detecting the overload of the induction motors (IMs) by applying moving average filter of the stator current in the time domain, was suggested. This method can be analyzed as the part of the analysis of the motor current signature analysis (MCSA). The stator current is analysed as the signal and it is divided into regular intervals – windows, within moving average filter applied. The minimum length of the moving window is determined by the sampling frequency detector, as well as the frequency of the stator current. The better resolution of peaks in moving average filter, can be achieved by the greater length of moving window. This is particularly important in areas of variable torque induction motor. This opens the possibility of detecting finer changes in the value of the stator current. It is shown that within the time window of changes in load of IMs, the signal of stator current becomes non-stationary. Otherwise, it is stationary. The changes of stationarity of the signal could be the alarm of overload of induction motor. The advantage of this method is improved response time of detector due to changes in the stator current. Software solution of proposed method is relatively simple: time series of the stator current is mapped according to the action of the moving average filter in different time series, suitable for use in real-time.

Index Terms—Induction Motor, Stator current, Signal analysis.

I. INTRODUCTION

Electric motors are now widespread and irreplaceable in various industries and production activities. Among them, the most used motors are induction motors because of properties such as robustness, reliability and durability. Therefore, special attention is paid to their maintenance and development of many techniques for timely detection of their failure. The most common failures of the IMs are bearing damage, shaft bending, stress and overload current, voltage and power underload, overload due to external mechanical torque and overheating of the stator windings. Studies show that IM failures can be classified as follows: bearing failure ~ 40%, stator failures ~ 38%, rotor failures ~ 10% and 12% of other faults [1]. All control techniques of IMs can be divided into two categories: classical or traditional techniques and techniques based on the use of computers and microprocessors. The traditional technique involves the use of various mechanical and electrical components (relays, timers, contactors, ...), which increase the number of dynamic components of the system and reduce its efficiency. On the other hand, modern solutions based on the use of computers and microprocessors, include the conversion of analog

signals into digital signals, so that ultimately the PC software decides whether to stop the engine [2], [3]. The disadvantage of these methods is that it increases the price of the cost compared to the classical technique. Control of the stator current of IMs is practically realized by the thermal relay and a microprocessor-based relay [4]. This type of relay stator winding temperature is usually determined by the thermal model of the first order. Thermal models of higher order are more accurate, but the implementation is more complicated [5], [6]. Motor Current Signature Analysis (MCSA) is analysis technique of IMs current, which considered as a signals. This method can detect some various types of damages of the motor and its overload [7], [8]. This method is based on Fourier transformation (FFT) of stator current. The appearance of multiple peaks in the power spectra of the stator current, can be an indicator of bearing damage, broken rods or motor overload. Properties of the peaks are determined by the type of damage output [9]. The main disadvantages of FFT is the fact that it is applicable only to stationary signals, and that this method gives only the distribution of power in the frequency domain, but not in the time domain. This problem is solved in the signal analysis by introducing Wavelet transformation [10], [11]. In the core of this method is the solving convolution integral at the each point of the signal. Convolution integral is solved by applying various, so-called, "mother wavelets" and their successors at the different frequencies. The solutions of convolution integral (details) represent desired distribution in the frequency and time domain. However, the problem of stationarity of signal still persists. In biosignal analysis, this problem is solved by dividing the signal in the stationary segments. Determination of the boundaries of these segments (change point detection - CPD), is not simple and it is associated with the introduction of a series of parameters, dependent on the type of signal. This further complicates the problem and especially its technical solution.

In this paper a simple solution of this problem is suggested and it is based on moving average filter of stator current. Namely, when an overload of IMs occurs, the stator current becomes non-stationary. In these points, changes within a moving sliding window of average values are much more pronounced than the original stator current. These changes occur before the signal of stator current reaches its maximum, indicating the possibility of shortening the response time of the detector.

II. MATERIAL AND METHODS

A. The mathematical model of the induction motor

In a theoretical experiment in this paper, the influence of a variable load torque on the stator current of squirrel-cage induction motor was analysed. The following assumptions were taken into account: a uniform air gap, balanced rotor and stator windings, saturation and parameter changes are ignored. The standard system of differential equation has been solved [12], [13]:

$$\begin{aligned}\frac{d\Psi_{qs}}{dt} &= \omega_b \left[V_{qs} - \left(\frac{\omega_e}{\omega_b} \right) \Psi_{ds} - \left(\frac{R_s}{X_{ls}} \right) (\Psi_{mq} - \Psi_{qs}) \right] \\ \frac{d\Psi_{ds}}{dt} &= \omega_b \left[V_{ds} - \left(\frac{\omega_e}{\omega_b} \right) \Psi_{qs} - \left(\frac{R_s}{X_{ls}} \right) (\Psi_{md} - \Psi_{ms}) \right] \\ \frac{d\Psi_{qr}}{dt} &= \omega_b \left[V_{qr} - \left(\frac{\omega_e - \omega_r}{\omega_b} \right) - \left(\frac{R_r}{X_{lr}} \right) (\Psi_{md} - \Psi_{dr}) \right] \\ \frac{d\Psi_{dr}}{dt} &= \omega_b \left[V_{dr} - \left(\frac{\omega_e - \omega_r}{\omega_b} \right) - \left(\frac{R_r}{X_{lr}} \right) (\Psi_{md} - \Psi_{dr}) \right] \\ \frac{d\omega_b}{dt} &= \frac{p}{2J} [T_e - T_l]\end{aligned}\quad (1)$$

where are T_e , T_l , electromagnetic and mechanical load torque, p is the number of poles, and J is the moment of inertia of the motor axis. Corresponding fluxes in the two-dimensional Q, D system are given as:

$$\begin{aligned}\Psi_{mq} &= X_{ml} \left[\frac{\Psi_{qs}}{X_{ls}} + \frac{\Psi_{qr}}{X_{lr}} \right] \\ \Psi_{md} &= X_{ml} \left[\frac{\Psi_{ds}}{X_{ls}} + \frac{\Psi_{dr}}{X_{lr}} \right].\end{aligned}\quad (2)$$

The corresponding equations linking fluxes with currents are:

$$\begin{aligned}i_{qs} &= \frac{1}{X_{ls}} [\psi_{qs} - \psi_{mq}] \\ i_{qr} &= \frac{1}{X_{lr}} [\psi_{qr} - \psi_{mq}] \\ i_{ds} &= \frac{1}{X_{ls}} [\psi_{ds} - \psi_{md}] \\ i_{dr} &= \frac{1}{X_{lr}} [\psi_{dr} - \psi_{md}]\end{aligned}\quad (3)$$

Electromagnetic torque T_e and the quantity are described by expressions:

$$\begin{aligned}T_e &= \frac{3p}{4J\omega_b} [\Psi_{ds} i_{qs} - \Psi_{qs} i_{ds}] \\ X_{ml} &= \frac{1}{\frac{1}{X_m} + \frac{1}{X_{ls}} + \frac{1}{X_{lr}}}\end{aligned}\quad (4)$$

The correlation between the currents i_d , i_q in two dimensional system, current stator and rotor currents i_α , i_β and line currents i_a , i_b , i_c are given as:

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \begin{bmatrix} \cos \theta & -\sin \theta \\ \sin \theta & \cos \theta \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix}$$

$$\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \frac{2}{3} \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \\ \frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix}\quad (5)$$

$$\theta = \omega_e t$$

In this numerical simulation three-phase balanced system was used:

$$\begin{aligned}V_a &= \sqrt{2} V_{rms} \sin(\omega t) \\ V_b &= \sqrt{2} V_{rms} \sin\left(\omega t - \frac{2\pi}{3}\right)\end{aligned}\quad (6)$$

$$V_c = \sqrt{2} V_{rms} \sin\left(\omega t + \frac{2\pi}{3}\right)$$

where: $V_a = V_b = V_c = 400 \text{ V}$, $f = 50 \text{ Hz}$. The properties of the IMs: $P = 4 \text{ kW}$, $L_s = L_r = 5,84 \text{ mH}$, $L_m = 172,2 \text{ mH}$, $L_{sm} = L_{rm} = 166,36 \text{ mH}$, $n_r = 1430 \frac{\text{ob}}{\text{min}}$, $J = 0,0131 \frac{\text{kg}}{\text{m}^2}$, $p = 2$. Mechanical torque of external load is controlled as follows:

$$T_L = \begin{cases} 0; & 0 < t \leq 1 \text{ s}; \\ 50 \text{ Nm}; & 1 \text{ s} < t \leq 2 \text{ s}; \\ 120 \text{ Nm}; & 2 \text{ s} < t \leq 3 \text{ s}. \end{cases}\quad (7)$$

Iteration simulation step was $\Delta t = 10^{-5} \text{ s}$, while the total duration was $t = 3 \text{ s}$. In the next section, the algorithm of moving average filter was proposed as a solution for detecting a variable load torque of IMs.

B. Algorithm of moving average filter

The stator current is analysed as a time series and its changes are determined as follows:

1. Select the length of the time window. Let the sampling frequency of detector f_s and frequency of stator current f . Then, the length of sliding window should be:

$$L = \frac{T}{T_s} = \frac{f_s}{f}\quad (8)$$

In the case of stationary signal, $L = \text{const}$. This condition is fulfilled in normal working conditions of IMs, when stator current has its nominal values. At the points of changes of loads of IMs, the frequency f of signal (stator current) changes and signal becomes non-stationary. That leads to variable length of time windows, $L \neq \text{const}$ and sharp peaks in spectra of moving average filter occur. The linear relation between f , L does not hold anymore and it is very difficult to find analytical expression of that relation. After numerical experimentations, the optimum length of time sliding window was found. It was 4000 samples or 0,04 s. Within this window, changes in load of IMs had most pronounced peaks in moving average filter values.

2. Divide signal into overlapping sliding windows of length of L , centered in index i and find average

value:

$$y_i = \frac{1}{L} \sum_{k=i-\frac{L}{2}}^{i+\frac{L}{2}} x_k \quad (9)$$

For use in real-time it can be easily shown that following recurrent formula holds:

$$y_{i+1} = y_i + \frac{1}{L} \cdot \left(x_{i+1+\frac{L}{2}} - x_{i-\frac{L}{2}} \right) \quad (10)$$

3. Set threshold of determining of peaks in response of moving average filter. Since, the signal of stator current is a harmonic function: $x \sim x_0 \sin \omega t$, from equation (9) follows that new signal y_i has the properties of harmonic function. From equation (10) it follows:

$$y_{i+1} - y_i = \frac{1}{L} \cdot \left(x_{i+1+\frac{L}{2}} - x_{i-\frac{L}{2}} \right) \leq \frac{2\Delta x_{kr}}{L} = 2y_{kr} \quad (11)$$

where x_{kr}, y_{kr} represents the critical values of overload of IMs. Since the threshold of overload is usually 125% of stator current under maximum overload, from (10) it follows: $2y_{kr} = 2 \cdot 1,25y_{max} = 2,5y_{max}$. The selected threshold was: $2,9y_{max}$, within $T = 50 \text{ Nm}$, so the points y_i above and below threshold are expected. The benefit of this approach is that violation of threshold starts before the signal of stator current reaches its values characteristic for overloads of IMs.

III. RESULTS AND DISCUSSION

The value of torque of the load, at which the engine speed drops to zero was $T = 120 \text{ Nm}$. In Fig. 1a the stator current is shown, with corresponding changes in load of IMs, marked by dashed lines. The response of moving average filter of the signal in time domain is shown in Fig. 1b. The changes in load of IMs are emphasized as a peak in this response. In Fig. 2 these changes are zoomed, for load of $T = 50 \text{ Nm}$, Fig. 2a (signal), Fig. 2c (filter) and for overload of $T = 120 \text{ Nm}$, Fig. 2b (signal) and Fig. 2d (filter). It can be clearly seen that the trip below the threshold in Fig. 2d (dashed line, denoted by t_{avg}) prior to the onset values of the stator current of overload of IMs (dashed line, t_{det}). This phenomenon allows earlier detection of changes in load of IMs. The signal can be considered as stationary if its central tendency (mean, median and standard deviation) is constant in time [14], [15]. Another important indicator of its stationarity is autocorrelation function. If it slowly drops to zero the signal can be regarded as stationary, otherwise, it is non-stationary [16]. Also, violation of stationarity signal during changing of motor load can be visually observed on the basis of zero crossings in signal y . This suggests that in the frequency spectrum of the stator current additional peaks may occur. This is consistent with the results of the research of signature of overload in the stator current [17]. On the other hand, there is (Fig. 1a) constant distance between the zeroes of the rotor current in steady conditions of IMs. In contrast, this distance is not constant under non-steady conditions (time before pull-up

Fig. 1. The stator current of the induction motor at varying engine load of $T_L = 0 - 120 \text{ Nm}$; (a) the signal of the stator current i_s ; (b) the signal of the moving average filter i_{av} .

Fig. 2. Stator currents during changes of the load of IMs, $T_L = 0 - 50 \text{ Nm}$ (a) and $T_L = 50 \text{ Nm} - 120 \text{ Nm}$ (b) as well corresponding moving average filters for $T_L = 0 - 50 \text{ Nm}$ (c) and for $T_L = 50 \text{ Nm} - 120 \text{ Nm}$ (d).

torque). This points to the fact that the signal in that part, non-stationary. That part was not considered in this work. The moment of occurrence of the critical load is determined on the basis of the above mentioned algorithm. According to the equation (7) the critical change in load of IMs occurs at the time $t = 2 \text{ s}$, while in spectra of moving average filter appeared, $\Delta t = \frac{L}{2} = 0.02 \text{ s}$ earlier. The next logical question is whether this method can distinguish between failures and overload of induction motor. In a wide literature electrical and mechanical failures, as well as overloads of IMs are described and they leave characteristic signatures of the stator current [18], [8]. In the power spectrum characteristic peak occurs at the center frequency ($f_e = 60 \text{ Hz}$, in our case) and accompanying peaks around it. Most of these methods are based on the application of Fourier transform, which is not applicable in the cases of non-stationary signals. In the analysis of the biosignals, this problem is solved by detecting the change point in the stationarity of the signal (CPD). For this purpose, numerous methods have been proposed [19], [20]. The essence of these methods is the detection of the change points of stationarity of a signal, whereupon the FFT to the thus defined stationary intervals of signal is applied. Determination of the CPD could be achieved with filter of moving average value, as well as with the wavelet filter [21]. There is the question of technical implementation of detector

based on the method proposed in this work. The proposed filter can be used in conjunction with superfast solid state relays, whose typical response time is of order $\sim 100 \mu s$. On the other hand, the fastest time of classical thermal relay is 5s and the proposed filter can not be used in this case. Trip time of the relays is determined on the basis of the thermal curves, which depend on type of IMs and its vendor [22]. Another possible solution is counting zeroes of stator current. There are various technical solutions for this, mainly based on comparators and optocouplers [23], [24]. The focus is on the theoretical analysis of the proposed method, so we will not go into hardware details.

IV. CONCLUSION

In this article the method of determining of overload of IM was analysing, by applying moving average filter to the stator current. It is shown that in case of the overload of IM, the signal of stator current becomes non-stationary. This method is free of shortcomings of spectral analysis current in terms of signal stationarity. It is simple in terms of software implementation. It is necessary to analyse the application of this method in cases of various defects of IMs. This is left for future work.

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