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Rotor Fault Diagnostic of Inverter Fed Induction Motor Using Frequency Analysis

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Abstract – Condition monitoring of electrical machines is essential in industrial operations for improving workplace safety and ensuring reliable and economical exploitation of the machines. Motor current signature analysis (MCSA) monitoring technique is gaining heightened popularity due to the simplicity of its algorithms and the least number of sensors required. In this paper, the harmonic spectrum of industrial inverter fed induction motor is investigated for the detection of broken rotor bars. To improve the legibility of the spectrum, the fundamental component is attenuated using infinite impulse response (IIR) filter because of its good transition band, less passband ripples and low order. The results are first taken from finite element method (FEM) based simulation, where the motor is fed with pure sinusoidal current and only faulty and spatial frequencies are investigated and used as a benchmark. The practical results are based on the measurements taken from the laboratory setup, where the motor under investigation is fed through an industrial inverter working under scalar control mode. The data acquisition is done with a good sampling rate of 100 kHz for better resolution.

Index Terms—Fast Fourier transform, fault diagnosis, harmonic analysis, induction motors.

I. INTRODUCTION

INDUCTION motors are playing a vital role in our domestic and industrial life. Since the second industrial revolution, their presence can be witnessed everywhere in the form of generators such as doubly fed induction generators and in the form of electrical to mechanical energy converters such as in electrical vehicles, ship propulsion, fans and pumps, etc. As a load, they are responsible of consuming about 60% of total generated energy worldwide [1]. This fact makes their control, efficiency and health, to have a direct impact on reliability of operation and economy.

Although three phase induction motors are acting as the workhorse for industry, researchers are working on multiphase motors to exploit their advantages, such as high efficiency, reduced torque ripples high power density and reliability, etc. Their versatile structures, power ratings, different nature of applications, reliability and safety of both operation and machine itself, increases the need of inverters as

an input source [2]. These inverters are purposely designed to control the motor according to the load requirements and responsible to convert standard grid AC-to-AC supply with the desired number of phases, amplitudes and frequencies. While working as a closed loop control system, these drives can better control machine ranging from simple scalar (v/f , v/f^2 , $v/\sqrt{f}$) to complex vector control, such as field-oriented control (FOC), direct torque control (DTC), model predictive control (MPC) and sliding mode observers (SMO), etc.

Although these drives improve the safety and reliability of operation, they also inject many harmonics into the motor. The amplitude and frequency of these harmonics depend on the modulation technique and the switching frequency of the solid-state switches of the inverter, making a tradeoff between efficiency and amplitude of low order harmonics. The increase in modulation frequency increases the inverter losses but attenuates low order harmonics. The low order harmonics are dangerous in the sense that they produce more torsional oscillations, pulsating torques and consequent deformations such as damaged shaft and broken rotor bars. For the sake of efficiency, the maximum switching frequency in the range of less than 1 kHz for a maximum stator frequency of 50 or 60 Hz is reported in [3][4][5][6]. For high speed motors having modulation frequencies in the range of 167-1500 Hz, the switching frequencies in the range of few kilo hertz (up to 16 kHz) can be found in [7][8].

The researchers are trying to reduce the required switching frequency and switching losses with different control strategies, such as [9], [10] used discontinuous pulse width modulation (DPWM) which reduces the switching frequency (f_{sw}) up to two-third of f_{sw} of continuous PWM strategies, sine-triangle PWM based DPWM can be found in [11]. The authors in [12], [13] used space vector based DPWM and modified DPWM can be found in [14], while space vector based synchronized DPWM is presented in [3].

In the field of fault diagnostics, the most common approach to detect the nature and severity of the fault is through the detection of faulty frequency components in the frequency spectrum of the stator current, etc. This detection is simple in case of grid fed machines, as there are only few frequency components based on grid supply and motor itself, which are easy to segregate. However, in case of inverter fed machines, there is always a mess of frequency components, making a challenging task for diagnostic algorithms to detect frequencies of interest. These inverter fed frequencies sometimes cannot be defined using some specific rule, such as in case of inverters, being controlled by stochastic control

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algorithms and working in a feedback control manner, making frequencies dependent on load. Also, in case of low switching to fundamental frequency ratio of the inverter, the low order faulty frequencies are highly likely to be buried under the frequencies coming from the inverter side. Moreover, as most of the drives work in closed loop control system, the influence of drive controller on harmonics is inevitable.

In this paper the frequency spectrum of an industrial inverter fed three phase induction motor is investigated and broken rotor bar components are tried to recover using infinite impulse response (IIR), band stop filters. The fundamental component being the strongest frequency is first attenuated to improve the legibility of the spectrum and then the rest of frequencies are studied on the linear scale. This paper is the extension of [15], where the spectrum of a grid fed motor was investigated under healthy and broken rotor bar conditions. The motor harmonics are studied using finite element-based simulation and used as a benchmark for the comparison with actual spectrum.

II. HARMONICS DESCRIPTION

A. Slots and Broken Rotor Bars

The harmonics in line current of the motor are due to three factors: 1) the harmonics coming from supply side, 2) the harmonics generated by the motor itself and 3) the harmonics produced by faults in the motor. The motor generated harmonics are called rotor slot harmonics (RSH) or principal slot harmonics (PSH). These harmonics are present due to the non-sinusoidal nature of the stator and the rotor winding functions and continuous change in air gap due to their slot permeance. This change in the air gap changes all stator and rotor self and mutual inductances, as shown by the modified winding function formula:

$$L_{ij}(\theta) = \mu_0 r l \int_0^{2\pi} P(\varphi, \theta) N_i(\varphi, \theta) N_j(\varphi, \theta) d\theta \quad (1)$$

where r is the average radius of the air gap, l is the effective length of the stator core, P is the inverse air gap distribution, N_i and N_j are the winding functions of i th and j th phase of the motor.

The power of PSHs depends upon the saturation of the core, which changes the effective air gap, skewing of stator and the rotor slots, which tend to reduce them. Moreover, machine asymmetries and unbalanced power supplies can also produce some of them. The RSHs or PSHs can be described by following analytical expression as in [16].

$$f_{sh} = \left[(kn_{br} \pm n_d) \left(\frac{1-s}{p} \right) \pm v \right] \quad (2)$$

where n_{br} are the number of rotor slots, n_d is for the dynamic eccentricity, s is the slip, p is the number of the fundamental pole pairs and v is the order of slot time harmonics. The first two harmonics are the most powerful components as compared to the rest of them and can be used for sensor less speed estimation if n_{br} and p are known.

It is well known that each kind of fault modulates the motor line current with some specific frequencies, which can be

detected for fault diagnostics. Deformations in the rotor, such as the broken end rings, broken rotor bars or high resistance connections can be detected by the following frequencies in the spectrum:

$$f_{BR} = f_s \pm 2ksf_s, \quad k = 1, 2, 3, \dots \quad (3)$$

where f_s is the supply frequency, s is the slip of the machine and k is the order of harmonics. These harmonics decrease in amplitude and increase in frequency as their order increases in the spectrum. The first two harmonics at $(f_{lsb} = f_s - 2sf_s)$ and $(f_{usb} = f_s + 2sf_s)$ are called the upper side band (USB) and the lower side band (LSB) respectively. The LSB is emerging due to broken rotor bars, while USB is present due to the subsequent oscillations in the speed. The fundamental fault frequencies are more powerful components than the rest of the fault harmonics and are highly likely to be buried under the supply frequency due to its spectral leakage, if the resolution of FFT is not appropriate, particularly under the low slip conditions.

B. Inverter Supply

The presence of inverters in the drive systems cannot be neglected in modern day industries. Along with various advantages, such as precision, accuracy and safety of operation, inverters bring various drawbacks, such as increase in cost, torque ripples, switching losses, increase in iron losses, radiated electromagnetic field interference [17], acoustic noise and high frequency harmonics, for which most of machines are not designed. Moreover, as it is previously mentioned that there is a tradeoff between power of low order harmonics and efficiency as switching frequency increases. Out of various control strategies of inverter switches, pulse width modulation (PWM) is the most common because of its simplicity and many types as well as having different advantages. For example, authors in [18] used random PWM (RPWM) to reduce the acoustic noise in motor drive systems. Authors of [19] have used four different PWM modes to investigate the iron losses of a salient stator permanent magnet machine. The authors in [20] used minimum torque ripple PWM technique with reduced switching frequency for medium voltage motor drive systems, while [21] tested an induction motor for its efficiency, powered from three different PWM drive systems. The radiated electromagnetic field interference due to the switching frequency in PWM motor drives is investigated in [17].

The output line and phase voltage measured from ABB industrial drive system with a sampling rate of 100 kHz is shown in Fig. 1.

C. Motor's Behavior as a Filter

Since the inverter fed motors are subjected to many high frequency components, it is important to discuss its frequency magnitude response. Using equivalent circuit model, the per phase transfer function of the three phase induction motor can be approximated as:

$$\frac{i_{as}}{v_{as}} = \frac{1}{\sqrt{(R_s + \frac{R_r}{s})^2 + \omega_e^2 (L_{ls} + L_{lr})^2}} \quad (3)$$

Fig. 1. Inverter's output line and phase voltage respectively.

Fig. 2. Motor's current gain magnitude response.

where i_{as} , v_{as} , R_s , R_r , ω_e , L_{ls} and L_{lr} are the motor phase current, voltage, stator per phase resistance, rotor's equivalent per phase resistance, synchronous speed, stator's and rotor's leakage inductances respectively.

The natural frequency response is shown in Fig. 2 from where the low pass nature of the induction motor is evident. Hence, for fault diagnostic, the low frequency components are very important and the performance of machine will improve when low order harmonics are less powerful, because the high frequency components will be attenuated by the motor itself.

D. Fourier Transform and its Resolution

Fourier transform has proven its importance in almost every field of engineering and is the tool to understand the nature of a signal. It was invented as Fourier series, responsible to convert a single time domain signal to n time domain sinusoids, having different amplitudes and frequencies. However, the need of the analysis of aperiodic and non-stationary signals led us towards its variants such as continuous time Fourier transform (CTFT), discrete time

Fourier transform (DTFT) and short time Fourier transform (STFT), etc. The fast Fourier transform (FFT) is an efficient algorithm to solve DFT represented by the following formula:

$$X_n = \sum_{k=0}^{N-1} x_n e^{-i2\pi kn/N}, \quad k = 0, 1, 2, \dots, (N-1) \quad (4)$$

where x_n is the discrete sampled signal and N is the number of samples, which should be a number in power of 2, i.e. $N = 2^x$.

The frequency resolution is very important for signal analysis, particularly in case of inverter fed machines, where there are a number of frequencies and it is important to segregate fault frequencies. It is the difference between two adjacent frequency bins and can be described by the following equation [22].

$$t_{sig} = t_s \times N = N/f_s \quad (5)$$

$$df = 1/t_{sig} = f_s/N = BW/SL \quad (6)$$

$$SL = N/2 \quad (7)$$

where, t_{sig} is the measurement or acquisition time of the signal, t_s and f_s are representing the sampling frequency, N is the total number of data samples, BW is the bandwidth, df is the frequency resolution or frequency difference between two adjacent frequency bins and SL is the total number of spectral lines. It is obvious that the frequency resolution depends upon the length of measured signal, also called acquisition or frame time of the signal. Since the measured signal is of finite duration, the frequency resolution can also be improved by a technique called zero padding or spectral interpolation. In this technique, the length of the signal is artificially increased by adding zeros before and after it.

E. Infinite Impulse Response Filters

Filters have many applications in data acquisition and analysis. They can be used to remove or amplify certain frequency components, anti-aliasing, noise reduction and offset removal, etc. They can be broadly classified into two types, called the finite impulse response (FIR) and the infinite impulse response (IIR) filters. Unlike FIR, IIR filters use some of their outputs as inputs, making them recursive functions. This fact reduces their computational time, filter order and accuracy, as compared to the corresponding FIR filters. However, their closed loop nature makes them more unstable than the FIR filters. In this paper, a low order IIR filter is tuned to attenuate the fundamental component, which is more powerful as compared to the rest of the harmonics. This attenuation increases the legibility of the spectrum on linear scale and makes the faulty frequencies easily detectable.

III. CASE STUDY

The modeling, simulation and analysis is always been very important for design, control and diagnostics of electrical machines. The most common types of modeling found in literature are analytical and numerical such as finite element

TABLE I
MOTOR SPECIFICATIONS

Sr. No.	Parameter	Symbol	Value
1	Rated speed	N_r	1400 rpm@50 Hz
2	Rated power	P_r	18 kW@50 Hz
3	Connection	Y, Δ	Star (Y)
4	Power factor	$\cos\phi$	0.860
5	Number of poles	P	4
6	Number of rotor bars	N_{rb}	40
7	Number of stator slots	N_s	48

method (FEM) based models. Out of these techniques, FEM based models give good approximation of actual systems but at the cost of complexity and long computational time.

The FEM-based simulation of a three-phase induction motor, with the parameters shown in Table I, is performed under healthy, one, and two broken rotor bar conditions. Since the simulation is performed using 2D field analysis, the ignored end windings are compensated by adding additional resistances and inductances in series with coils. The per phase stator coils are series and parallel connections of copper strands, making the current density uniformly distributed. The simulation is performed at rated load under constant speed. The flux distribution under healthy and two broken rotor bar conditions is shown in Fig. 3. It is evident that the flux density increases across the broken bars, putting the adjacent bars under increased magnetic stress. The increase in the current of the neighboring bars makes the machine vulnerable to break more bars in time, if the fault is not timely diagnosed and repaired. The obtained results can be used as a benchmark to differentiate between harmonics due to motor itself (slot harmonics), due to a fault, such as broken rotor bars, and due to inverter. In Fig. 4, simulated three phase currents for the healthy case and frequency spectra for the healthy and the broken rotor bars is presented. The attenuation of the fundamental component with the help of IIR filter improves the legibility of the spectrum and makes the segregation of various harmonics easy. The simulation is performed for two seconds with 5328 mesh elements at stator and rotor temperatures of 120°C and 140°C respectively.

Fig. 3. Motor's flux distribution under healthy and broken rotor bar conditions.

The detailed description of these specific harmonics can be found in [15], where the harmonic spectrum analysis is done for a grid fed induction motor with broken rotor bars.

Fig. 4. Simulated stator currents and corresponding frequency spectrum for healthy, one, and two broken rotor bars respectively from top to bottom.

IV. PRACTICAL SETUP

The measurement setup consists of two same type motors with the parameters shown in Table 1. One machine is under investigation and the other one is acting as the load. Both machines are mounted on the same mechanical base and coupled through their shafts as shown in Fig. 5(a). Both machines are fed through the inverters to improve the controllability of the loading motor and investigate the harmonic spectrum of the machine under investigation. The stator currents and voltages are measured using the Dewetron transient recorder. The sampling frequency of the measured signals is 100000 samples per second and the measurement time is 70 seconds, giving a very good resolution of the frequency spectrum. Fig. 5(b) shows the block diagram of the test setup. The ABB industrial frequency converters is used in scalar control mode, preferable for the smaller size motors. Moreover, the modulation scheme is simple sinusoidal pulse width modulation (SPWM), as it can directly control the inverter output voltage and output frequency according to the sine functions. The modulation frequency is in the range from 2 kHz to 16 kHz and can be tuned manually for selected models.

(a)

(b)

Fig. 5. (a) Hardware setup, (b) block diagram.

It is important to know that the motor under investigation is working under scalar control mode, because in DTC the faulty frequencies are highly likely to be attenuated by the drive controller.

V. RESULTS AND DISCUSSION

Fig. 6 shows a few cycles of the inverter fed phase voltage with the corresponding frequency spectrum up to 400 Hz and 25 kHz respectively. The fundamental component is effectively attenuated with the second order IIR filter with stopband attenuation of 45 dB and sampling frequency of 100 kHz.

In Fig. 7, the experimental results are presented. The topmost graph is representing the actual three phase currents drawn by motor from the inverter, which are much smoother than their corresponding supply voltages, because of the motor filtering effects. In the rest of graphs, the spectrum for healthy, one, two and three broken rotor bars are shown. The elimination of 50 Hz component by proper tuning of IIR bandstop filter makes faulty frequencies discoverable even when only one out of 48 rotor bars is broken. The motor under this test is working under rated load conditions and the total harmonic distortion is calculated before attenuation of the fundamental component.

Fig. 6. Inverter's generated phase voltage and corresponding frequency spectrum up to 400 Hz and 25 kHz respectively with attenuated fundamental component.

VI. CONCLUSIONS

The MCSA is the most common technique used for the fault diagnostics of induction motors, because of its simplicity and noninvasive nature. As an extension of [15], in this paper harmonic spectrum of an inverter fed induction motor for the healthy and broken rotor bar cases using signals from the simulation and experiments is studied.

FEM-based simulations reveal that the rotor bars next to the broken one come under more magnetic and thermal stresses making them vulnerable to break, increasing the severity of the fault with the passage of time. Hence, it is very important for diagnostic algorithm to be able to detect fault at incipient stage. The accurate attenuation of the fundamental component can improve the legibility of spectrum for detection of the frequencies representing broken rotor bars.

The use of the IIR filter for the attenuation of the fundamental component reduces its spectral leakage considerably. This filter has a good transition band and makes less impact on the upper and lower sidebands of the broken rotor bar frequencies. Less passband ripples reduces the impact of filter on frequency spectrum. Moreover, the low order IIR filters can give more accurate results as compared to the correspondent finite response (FIR) filters.

Fig. 7. Measured phase currents and corresponding frequency spectra for health, one, two and three broken rotor bars respectively.

Since the most powerful component is filtered out, it improves the legibility of the spectrum even at the linear scale. From the simulation results, the broken rotor bar and high frequency slot harmonics are easily readable on the same graph. In case of the experimental setup, since the load motor is supplied from an inverter, the slip of the test motor is carefully controlled to investigate the location of the fault frequencies.

The proposed filter works good to attenuate the 50 Hz component without having major impact of sideband frequencies emerging because of broken rotor bars. The frequencies of interest are clearly detectable, even when one out of 48 bars is broken. The method gives promising results for scalar control, but in case of DTC, some extra care is needed to avoid the impact of the drive controller on these frequencies.

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