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Hilbert Transform, an Effective Replacement of Park's Vector Modulus for the Detection of Rotor Faults

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***Abstract*—The rotor-associated faults in electrical machines make the biggest most proportion of overall faults. Most of these faults particularly broken rotor bars, modulate all three phases of the stator in a symmetrical way. This fact makes Park's vector an effective tool to detect them at the incipient stage. As compared to other diagnostic algorithms, Park's vector is gaining more popularity for its noninvasive nature and comparatively simple mathematical model and a wide range of usage. In this paper, the broken rotor bars of a three-phase squirrel cage induction motor is detected using Park's vector modulus and Hilbert transform. It is shown that the Hilbert transform can be used to get the same kind of results as of Park's vector modulus but with a considerable decrease in data size required for analysis. The fault is first simulated using finite-element-based software for the study of its impact on various performance parameters and then Park's vector modulus and Hilbert transform are used to compare their required number of sensors and data size.**

Keywords—induction motors, fault diagnosis, signal processing, finite element analysis

I. Introduction

Electrical machines are the biggest producer of electricity worldwide in the form of induction and synchronous generators. As a load, they are also serving as a key element in modern day industrial, domestic and commercial applications. In the form of water pumps, ship propulsion, electric vehicles, cranes, locomotives, robots, and large industrial conveyer belt movers, they are consuming more than half of generated energy worldwide. They have a direct impact on the economy, safety, efficiency and reliability of operation. Out of various types of electrical to mechanical energy converters, the squirrel cage induction motors are being used extensively to exploit their benefits such as low cost, simple structure, easy maintenance, and good efficiency. Because of their duty hours and rough industrial environment, these machines always remain at the risk of faults. These faults can be electrical or mechanical, but mechanical faults such as damaged bearings, static and dynamic eccentricity, and broken rotor bars are more common. These faults increase in severity with time, for example, the damaged bearings can lead towards static or dynamic eccentricity, which can increase torsional vibrations. These vibrations can further start breaking the rotor end rings or bars embedded in rotor slots. Once the bar is broken, the magnetic field density will increase around it and as a result, the neighboring bars will come under magnetic stress tending them to break as well as a chain reaction. This fact makes their condition monitoring and fault diagnostic very important.

The diagnostic algorithms, which are simple, accurate, requiring less data, and able to detect a fault at the incipient stage are highly appreciated in literature. There is various kind of diagnostic techniques in literature such as electromagnetic field monitoring, noise, and vibration monitoring, acoustic noise measurement, temperature measurement, infrared detection, fuzzy logic, neural networks and motor current signature analysis (MCSA) and chemical analysis etc.

Out of all above-mentioned techniques, the MCSA is gaining more attraction because most of the associated algorithms need only line current or voltage, which can be measured very easily using simple clamp transformers. The second biggest advantage of MCSA is that it opens an entire domain of various signal-processing techniques where we can exploit their benefits and remove drawbacks by combining more than one techniques.

The most prominent signal processing technique is fast Fourier transform that makes the algorithm very convenient to detect specific frequency components caused by specific faults. The Fourier transform can have various drawbacks such as the resolution of the spectrum, spectral leakage, overlapping frequencies and a need for long measurement of a signal with good sampling rate. Various variants of Fourier transform to handle these problems can be found in literature such as discrete-time Fourier transform, short term Fourier transform along with various kind of filters. The problem becomes even more verse when the motor is inverter fed and the frequency spectrum contains many power electronics-based harmonics in it.

The Park's vector is the transformation of a three-phase system to orthogonal two-phase system and is a potential candidate for the condition monitoring of electrical machines. This technique was pioneered by A. J. M. Cardoso in [1]–[5] where he studied the various type of faults such as stator inter-tern short circuit, inverter related, eccentricity and extended Park's vector respectively. [6] used this technique to detect bearing inner and outer race damages. In [4] authors used it as an extended Park's vector for the detection of stator inter-turn short circuit faults . [3] used it for eccentricity fault detection of electrical machines. In [7] authors used Park's vector modulus to reduce the data size required for fault detection and called it reduced Park's vector modulus.

From the above-mentioned references, it is observable that Park's vector can be a potential candidate to reduce the need for complicated Fourier related tools. This is so because Park's vector modulus can detect the envelope of machine current carrying the broken rotor bars related fault information. The least number of sensors required in this case is three for three phases and then they can be transformed into two phases by using two-axis transformation. Since the broken rotor bar faults change all three phases symmetrically hence use of all three of them is exaggeratory. In this paper Hilbert, the transform is used to detect the broken rotor bar frequencies and envelope of the signal. Unlike Park's vector modulus, only one phase current is required reducing the number of sensors and computational power.

II. Theoretical Background

A. Park's Vector

Park's vector is a complex analytical representation of three phase currents into two phases proposed by R. H. Park in 1929 [8]. The transformation of abc phases to equivalent d-q phases reduces the number of equations and mutual inductances, making it a very popular tool in the field of electrical machines modeling [9], control [10] and diagnostics [11]. Cardoso et. al. as mentioned in previous references used Park's vector for studying various kind of faults in electrical machines for the first time in the 1990s. Park's space vector can be constructed by adding vectors to the corresponding single phases as:

$$\vec{\imath}_s(t) = \frac{2}{3}\left(\vec{\imath}_{as}(t) + a\vec{\imath}_{bs}(t) + a^2\vec{\imath}_{cs}(t)\right) \quad (1)$$

$$\vec{\imath}_s(t) = \frac{2}{3}\left(\vec{\imath}_{as}(t) + \left(-\frac{1}{2}+j\frac{\sqrt{3}}{2}\right)\vec{\imath}_{bs}(t) + \left(-\frac{1}{2}-j\frac{\sqrt{3}}{2}\right)\vec{\imath}_{cs}(t)\right) \quad (2)$$

$$\vec{\imath}_s(t) = \vec{\imath}_{ds}(t) + j\vec{\imath}_{qs}(t) \quad (3)$$

$$PVM_h = \sqrt{i_{ds}^2 + i_{qs}^2} = I_m \quad (4)$$

where $a = e^{\frac{j2\pi}{3}} = -\frac{1}{2} + j\frac{\sqrt{3}}{2}$,

$a^2 = e^{\frac{j4\pi}{3}} = -\frac{1}{2} - j\frac{\sqrt{3}}{2}$.

As proposed by [3], the modulus of Park's vector can be very useful to diagnose the faults. With the increase in the number of broken rotor bars, distortion in the modulus of Park's vector increases, as shown in Fig. 1.

B. Hilbert Transform

Hilbert transform converts a real-valued signal into a complex analytical signal. It can be used to find an envelope of a signal, which is useful in many ways, such as the demodulation of an amplitude modulated (AM) signal. It can be considered as a filter, which shifts the phases of all frequency components of its input signal by $-\pi/2$ radians. Mathematically, it can be defined as the convolution of a given signal with a nonintegrable function ($1/\pi t$) as follows.

$$H(t) = \frac{1}{\pi}\int_{-\infty}^{\infty}\frac{f(x)}{t-x}dx \quad (5)$$

In the form of convolution this transformation can be represented as:

$$h(t) = \mathcal{H}\{x(t)\} = x(t) * \frac{1}{\pi t} \quad (6)$$

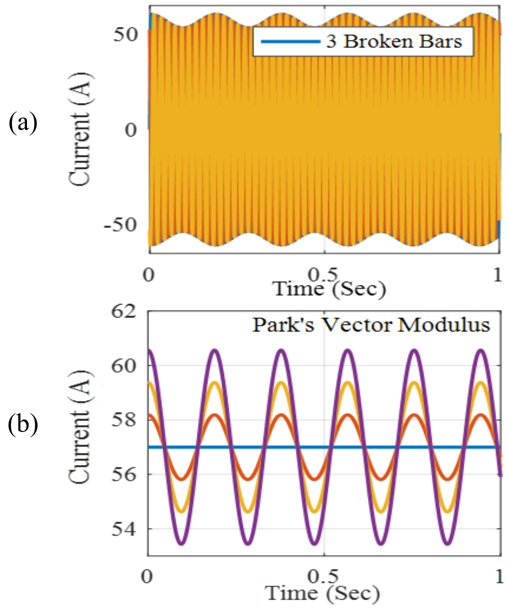

Fig. 1. (a) Motor current with three broken bars, (b) Park's vector modulus of healthy (blue), 1 (red), 2 (yellow) and 3 (purple) broken rotor bars motor.

The analytical function is the representation of the actual signal on the real axis and Hilbert transformed signal on the imaginary axis as shown by the following equation.

$$analytical\ function = x(t) + j\mathcal{H}\{x(t)\} \quad (7)$$

The absolute value of this function corresponds to the envelope of the signal.

III. Case Study

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 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. 2. It is evident that the flux density increases across 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. For accuracy, a good number of 5328 mesh elements are taken and simulation is done with a step size of 0.033 ms at rated load condition.

TABLE I. Motor Parameters

Parameter	Symbol	Value
Number of poles	P	4
Number of phases	φ	3
Connection	Y-Δ	Star
Stator slots	Ns	48; nonskewed
Rotor slots	Nr	40; nonskewed
Terminal voltage	V	333 V@50 Hz
Rated slip	S	0.0667
Rated power	Pr	18 kW@50 Hz

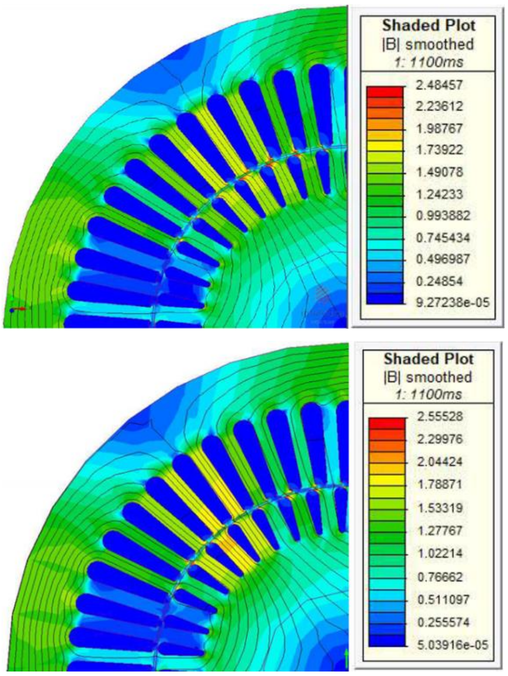

Fig. 2. Magnetic flux distribution in healthy (top) and faulty (bottom) motor.

IV. Simulation Results and Comparison

The simulated phase current of the motor is shown in Fig. 3, where the harmonics due to nonsinusoidal winding distribution are visible. The Fig. 4 is the Park's vector calculated from all three-phase currents. The width of the circle line is increasing with an increase in the number of broken bars. Due to the symmetrical change in all three phases, the Park's vector remains circular and the increase in the amplitude of the left-hand side (LHS) and right-hand side (RHS) frequency components, the width of circle line increases. The plot of Hilbert analytical function is shown in Fig. 5. The Hilbert circle shows the same behavior as Park's vector but it is constructed using only a single phase current.

Fig. 6 shows Park's vector modulus as current envelope in case of healthy, one and two broken rotor bars. In a healthy case, the PVM has less distortion and is not a constant line because of spatial harmonics. This distortion increases in an amplitude modulation manner with an increase in a number of broken bars. The Fig. 7 shows the envelope of the single-phase current carrying all potential information as in PVM, but the number of sensors and data required is one-third of as required in PVM.

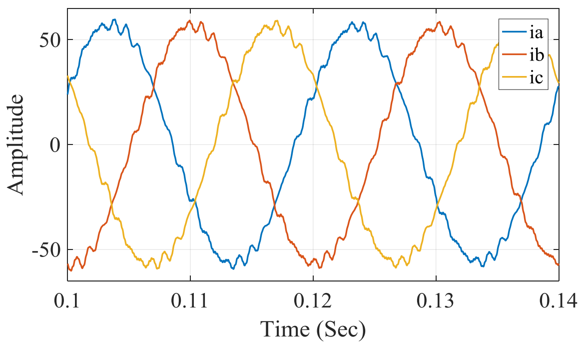

Fig. 3. Simulated line currents of the motor.

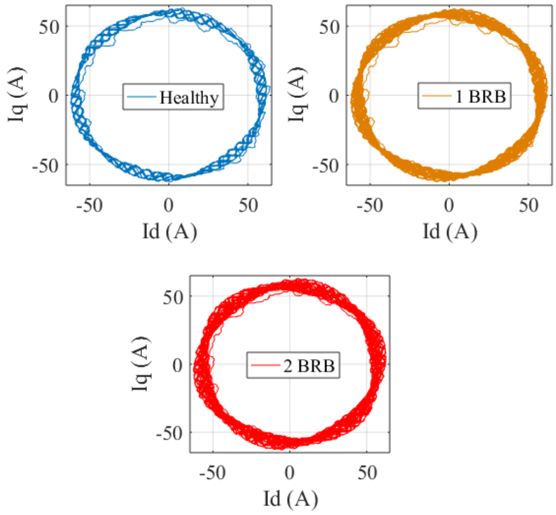

Fig. 4. Park's vector.

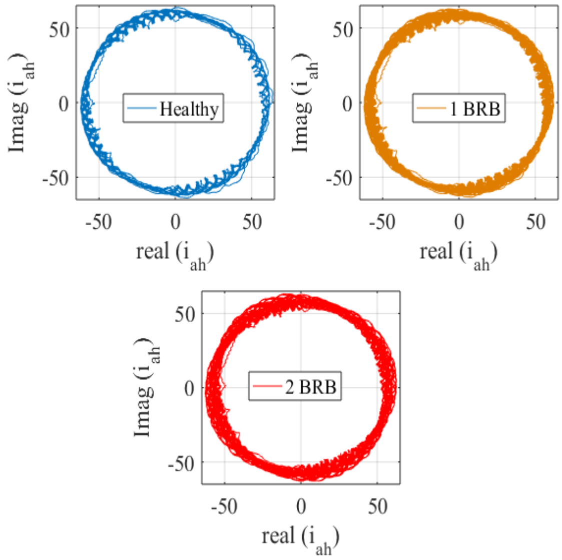

Fig. 5. Hilbert locus.

V. Conclusions

A complexity analysis of broken rotor bar fault diagnostic techniques, Park's vector modulus, and Hilbert transform are done in this paper. The finite element based simulation of three-phase squirrel cage induction motor in healthy and faulty conditions is done with a good amount of mesh elements and a very small step size of 0.033 ms for better accuracy. From the results, it is evident that both Park's vector and Hilbert analytical function make the same kind of circles with increasing width with an increase in a number of broken rotor bars. Moreover, the Park's vector modulus and the absolute value of Hilbert analytical function can be used for envelope detection of fault baring stator current. The Hilbert transform requires only one current signal measured with one current sensor resulting in a considerable data reduction and cost as compared to Park's vector modulus. This is true if the fault is symmetrically changing all three phases of the stator. Since the majority of rotor associated faults modulate stator current symmetrically, the Hilbert transform can be an effective replacement of Park's vector modulus.

TABLE II. THE COMPARISON OF PARK'S VECTOR MODULUS AND HILBERT TRANSFORM

Sr. No.	Technique	Data / Sensors Required	Attributes
1	Park's Vector Modulus	3 (all three phase currents)	Advantages: noninvasive, clever use can eliminate the need of FFT, can deal with unsymmetrical faults, can be used for envelope detection Disadvantages: data measurement of all phases is required, needs more memory
2	Hilbert Transform	1 (one phase current)	Advantages: noninvasive, clever use can eliminate the need of FFT, can be used for envelope detection, data measurement of a single phase is required, needs less memory as compared to PVM Disadvantages: difficult to deal with unsymmetrical faults

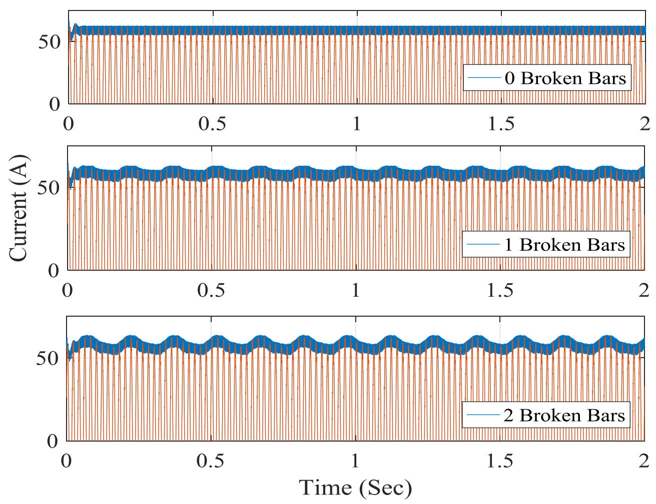

Fig. 6. Envelope detection using Park's vetor modulus.

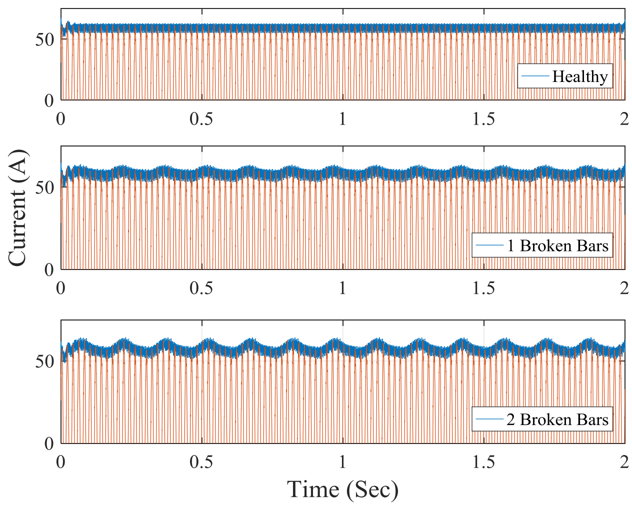

Fig. 7. Envelope detection using Hilbert transform.

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