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A Survey of Broken Rotor Bar Fault Diagnostic Methods of Induction Motor

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Abstract **– Electrical machines, induction motors in particular, play a key role in domestic and industrial applications. They act as a work horse in almost every industry and are responsible for a big proportion of total generated electricity consumption worldwide. The faults in induction motors are degenerative in nature and can lead to a catastrophic situation if not diagnosed earlier. The failures can cause considerable financial loss in the form of unexpected downtime. Broken rotor bar is a very common and frequently occurring fault in most of industrial induction motors. To select a better, more accurate and reliable fault diagnostic technique, this paper presents a comprehensive literature survey on the existing motor current signature analysis (MCSA) based fault diagnostic techniques. Different well-known MCSA based fault diagnostic techniques are summarized in the form of basic theories, considering complexity of their implementation, merits and demerits.**

Keywords **– Fault diagnosis; Induction motors; Rotors.**

I. Introduction

Induction motors are acting as a work horse in domestic and industrial applications because of their high power to weight ratio, rugged structure, low price, easy maintenance and reliability [1]. They play a significant role in about 80% of industries such as transportation, petroleum industries, mining industries, ship propulsion, aerospace, nuclear plants and many other [2].

Because of mechanically moving parts and rough industrial environment, induction machines are always vulnerable to faults. These faults are usually degenerative in nature, i.e. they tend to increase with time. Hence, it is very important to detect them at their early stages to avoid any catastrophic situations like shut down of the entire process [3]. In addition, detection of faults at the early stages gives a lot of advantages like reliability of operation, increased motor life and economic benefits [1]. When motor starts becoming faulty it tends to change some of its parameters, such as mechanical vibrations [4], [5], electromagnetic field distributions [6], [7], temperature [8], stator's current [9]–[11]. Since induction motors are proportionally among the biggest energy consumers worldwide, their proper maintenance and early fault diagnostics will increase efficiency as well. The bar charts in Fig. 1 show energy usage by induction motors in different sectors per hour downtime cost and comparison of rewinding versus recondition of motors as investigated by [12]. In this paper, the author analyzed a paperboard plan with 485 motors having two operating production lines with an average downtime cost of $6375 per hour and concluded that preventive maintenance program costs $73 900 per year and gives a total saving of $569 360 per year having a payback period of as short as 1.6 months. It is evident considering the figure that induction motors are a major consumer of total generated electricity and can lead to a major economic loss if faults are not timely diagnosed and repaired effectively.

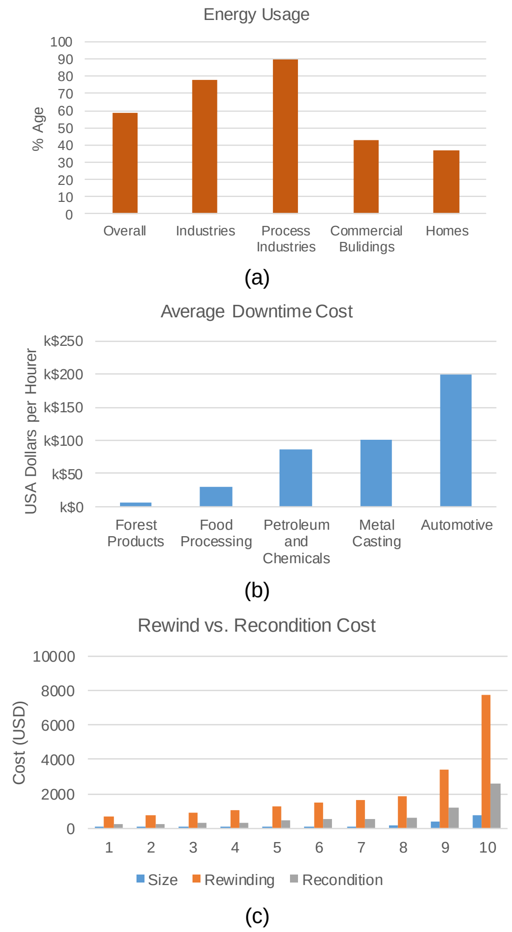

Fig. 1. Worldwide energy usage by electrical machines (a), an average loss due to failures (b) and a comparison of rewind vs. recondition cost (c).

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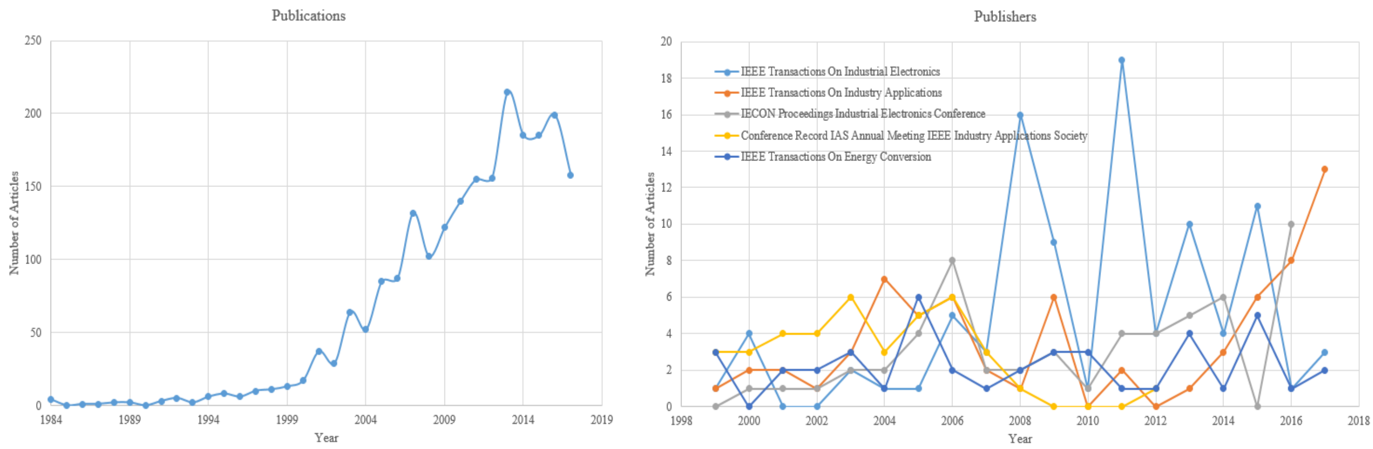

Fig. 2. Importance of fault diagnostics as reflected in the annual scientific research and publications.

It is also claimed in [12] that with preventive maintenance programs total motor rewinds reduced from 85 % to 20 % of the total motor repairs. A lot of research is being done on earlier fault diagnostics of induction motors with regard to the above-mentioned advantages. The graphs shown in Fig. 2 as taken from Scopus describe annual trends in scientific research published each year on fault diagnostics of induction machines.

II. Types of Faults and Diagnostic Techniques

A variety of faults found in literature can be divided mainly into three categories as shown in [13] and presented in Table I. Faults in electrical machines can be broadly divided into three categories: electrical, mechanical and external or environmental. Electrical faults are mainly associated with stator side and can be easily detected and controlled using some simple protective devices which can monitor the condition of supply voltage and loading conditions. Moreover, some flexible AC transmission systems (FACTS) device-based control of various parameters like voltage balancing, reactive power control can also be found in literature [14]. Mechanical faults make a big proportion of overall faults and they are degenerative in nature, i.e. they tend to increase with time. The early diagnosis of these faults is very important in order to avoid any catastrophic situations like shutdown of the entire industry or some portion of industry leading to a major economic loss [15]. These faults are difficult to detect at the early stages, but it is equally important. The main fault diagnosis technique found in literature is mainly associated with signal processing and pattern recognition using motor stator current signal or mechanical vibration signal.

In this paper, some commonly used techniques used for broken rotor bar fault diagnostic of induction machines are reviewed and comparison is done to consider advantages and drawbacks of each technique.

TABLE I
Categories of Most Common Faults, Types and Their Diagnostic Methods

Sr. No.	Category	Types	Location of the faults	Common diagnostic methods
1	Electrical	• Unbalanced supply voltage • Over or under voltage • Phase reversal • Inter-turn short circuit fault • Earth fault	Mainly stator	• Relays & Switches • MCSA
2	Mechanical	• Broken rotor bar • Broken end rings • Eccentricity fault • Bearing fault • Rotor winding failure	Mainly rotor	• Mechanical vibration detection • MCSA • Finite Element Analysis
3	Environmental	• Ambient temperature • External moisture • Vibrations due to bad foundation, etc.	Both	• Sensors and protective devices

A. Envelope Detection (Hilbert Transform)

Hilbert transform converts a real valued signal into a complex analytical signal. It can be used to find out the envelope of a signal, which is useful in many respects, e.g. in demodulation of an amplitude modulated (AM) signal. It can be considered as a filter which shifts phases of all frequency components of its input signal by $\pi/2$ radians. Implementation strategy of Hilbert transform to get current envelope is shown in Fig. 3.

Mathematically, it can be defined as the convolution of given signal with not integrable function $1/(\pi t)$, as follows,

$$H(t) = \frac{1}{\pi}\int_{-\infty}^{\infty} \frac{f(x)}{t-x}\,\mathrm{d}x. \quad (1)$$

The analytical signal can be obtained as,

$$A(t) = f(t) + \mathrm{j}h(t). \quad (2)$$

This can be expressed in polar coordinates as,

$$A(t) = B(t)\mathrm{e}^{\mathrm{j}\varphi(t)} \quad (3)$$

where $B(t)$ – envelope of analytical signal and φ – phase of analytical signal.

As discussed earlier, the harmonics produced by broken rotor bar (BRB) in stator current spectrum depends on slip. Under very low slip and no-load conditions the frequency of these harmonics becomes very close to the frequency of the fundamental component. This fact makes it very difficult to detect harmonics because of spectral leakage of fundamental one [16]. In other words, those harmonics are usually buried under the spectrum of the fundamental component.

This problem can be solved by using some filters to remove fundamental component. The filters commonly found in literature are notch filters [17], Hilbert transform [16], etc. Some techniques like Hanning window and Bartlett periodogram [18], shifting to DC level [19], quad demodulation [20], Park's vector [21], air gap torque and swing angle [22], [23], etc. have been proposed to avoid this problem. To overcome this problem some literature suggests a minimum percentage of load for experiment. Also, high frequency resolution is required for successful separation of sideband signals. The same kind of problem has also been reported in cases when load changes during the sampling time.

Speed changing devices such as gear boxes also give the same kind of side band frequencies which can be separated by taking a set of two motor current signature analysis (MCSA) tests at entirely different load references. [16] used a simple Hilbert transform to get analytical signal of stator current, found its envelope and by doing its spectral analysis proved that the main frequency component was successfully eliminated, and fault harmonics were clearly readable.

In [16], the number of samples required to get a minimum spectrum resolution of 0.01 was ($5 \cdot 10^5$) by using the formula $N = T_m f_s$. But [24] proposed a reduced stator current envelope taking only one sample per cycle rather than using high sampling frequencies to reduce aliasing effects in conventional Fourier analysis based techniques. In this paper, the authors used the points at $\theta(t) = 2k\pi\ (k = 0, 1, \ldots)$ of current envelope and found that the number of samples required was reduced to (4997) instead of ($5 \cdot 10^5$) giving similar results. They used a large industrial and a lab-based machine to validate the results and showed that the proposed method is able to segregate fault harmonics from the overall spectrum very efficiently. The authors also claimed that due to a smaller number of samples required, this technique can be easily implemented on simple available computational hardware like digital signal processor (DSP) or field-programmable gate array (FPGA).

In [25], the authors proposed that any fault, such as broken rotor bar, produces a series of harmonics having frequencies integral multiple of fundamental fault component frequency. These harmonics are distributed in the entire frequency spectrum as shown by the following equation for the broken rotor bar.

$$f_{\mathrm{asym}} = f_1 + 2ksf_1, k = \pm1, \pm2, \pm3, \ldots, \quad (4)$$

where, $f_{\mathrm{asym}} = f_1 \pm 2sf_1$ is fundamental harmonic component.

It is proposed that if fault current spectrum is taken by considering harmonic order k as an independent variable rather than frequency, the fault can be detected and analyzed more easily and will require less memory and computational power. In the proposed technique the authors took stator current, shifted it to rotor frame of reference, performed its spectrum analysis and rescaled it on harmonic order axis.

The authors also mentioned some drawbacks of this technique, for example, slip should be accurately measured, high frequency resolution is required, and some mechanical vibrations may damage the result.

Fast Fourier transform (FFT) based MCSA successfully gives fault pattern when machine is in the steady state condition but it has certain drawbacks in transient intervals [26]. Some methods like short term Fourier transform (STFT), wavelet transform (WT), Gabor transform (GT) can be regarded as extension of MCSA suitable for transient conditions.

However, the above-mentioned approaches give very complex time frequency patterns. These complex 3D patterns require a huge amount of hardware memory, computational power and trained staff to deal with. In [26], the authors proposed a simplification technique in which firstly they

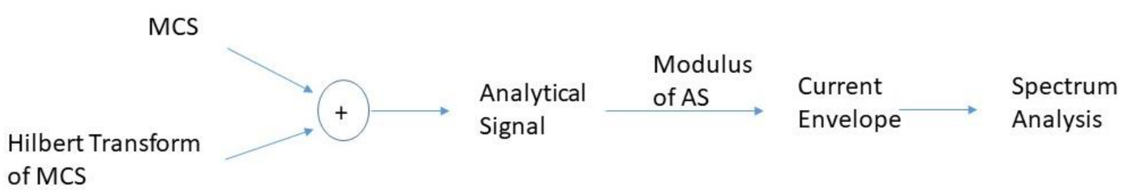

Fig. 3. Implementation strategy of Hilbert transform to get current envelope.

transformed stator current to rotor side and then obtained a re-scaled spectrogram using harmonic order tracking analysis.

B. Park's Vector Approach

Induction motor models are complex because of their mutual and varying inductances as a function of rotor position, also three circuits are required to represent a three-phase machine. This three-phase model can be transformed into an equivalent two-phase circuit as shown in figure with d_s-q_s as direct and quadrature axis of stator and d_r-q_r as direct and quadrature axis of rotor. Using this approach, the number of circuits and hence the number of equations is reduced but the problem of varying inductances still exists.

In 1920, R. H. Park proposed a technique to resolve this issue by transforming stator variables to a fictitious winding rotating with rotor at synchronous speed, hence made stator inductances static with respect to rotor. Afterward, some other transformations were also proposed, such as H. C. Stanely transformed rotor variables to a fictitious stationary winding, G. Krone transformed both rotor and stator windings to a fictitious winding rotating with rotating magnetic field.

Since then these transformed models have made a very significant contribution towards modeling [27], analysis [28], drives [29], fault diagnostics [30], [31] and design of various kinds of electrical machines.

Park's vector is a plot between d and q components of machine's rotor or stator currents, voltages or fluxes. For healthy machine, this plot is a perfect circle distributed uniformly across the center, but for faulty machines this pattern changes depending upon the severity of the fault. The modulus of Park's vector is known as extended Park's vector (EPV) in literature, it can be in continuous time [21] or discrete domain [32]. The analysis of this pattern opened new ways in fault diagnostics of induction and some other machines. This technique can be used for fault diagnostics of rotor faults [33], stator winding faults [21]–[34], winding faults in transformers [35], faults in motor drives [36], wind turbines [37], and power converters [38], etc.

TABLE II

DIFFERENT METHODS TO DETECT BROKEN ROTOR BARS IN INDUCTION MOTORS

Technique	**Group and assisting techniques**		**Speed estimation**	**Mathematical calculations**	**Memory required**	**References**	**Attributes**
Active and reactive currents	MCSA	FFT	No	Medium	Medium	[39]	Noninvasive, can segregate load vibration effects
Ant clustering	MCSA	Park's vector, FFT	No	Large	Large	[40]	Noninvasive, difficult to segregate different faults
Autoregressive method	MCSA	DTFT + Notch	No	Low	Low	[2]	Noninvasive, steady state current
Information entropy and fuzzy inference	MCSA	Fuzzy logic	No	Medium	Large	[41]	Noninvasive, requires steady state current
Homogeneity estimation	MCSA	FPGA	No	Low	Medium	[42]	Noninvasive, transient current, segregation of faults is difficult
Slot harmonics	MCSA	FFT	yes	Large	Large	[43]	Noninvasive, unbalanced power supply, speed ripples, segregation of different faults is difficult
Harmonic order tracking	MCSA	Gabor transform	yes	Low	Medium	[26]	Noninvasive, capable to segregate faults and nonstationary conditions
Envelope detection using Hilbert transform	MCSA	Hilbert transform	Yes	Low	Low	[16]	Noninvasive, steady state analysis, segregation of different faults is difficult, problem of varying load conditions
Reduced envelope	MCSA	Hilbert transform	Yes	Low	Low	[24]	Noninvasive, suitable for diagnostic on low slip, suitable to implement on DSP and FPGA kits, Segregation of different faults is difficult
Adoptive notch filter	MCSA	FFT	Yes	Low	Low	[17]	Noninvasive, suitable for diagnostic on low slip, difficult under varying load conditions, Segregation of different faults is difficult
Parameters estimation	MCSA	Analytical	Yes	High	High	[44], [45]	Noninvasive, can be more accurate, under steady state conditions, can be used to segregate faults
Pendulous oscillation	MCSA	Analytical	No	Medium	Low	[22], [23]	Noninvasive, suitable to implement under low slip conditions, under steady state conditions, can be used to segregate faults
Power spectral density	MCSA	STFT, wavelet	No	Medium	Medium	[46]	Noninvasive, suitable to implement under low slip conditions, cab be applied under varying load conditions, can be used to segregate faults, accurate sampling rate and selection of mother wavelet required

Technique	Group and assisting techniques		Speed estimation	Mathematical calculations	Memory required	References	Attributes
Spectrum synch technique	MCSA	Local band synch, central kurtosis analysis	Yes	Medium	Medium	[47]	Noninvasive, suitable to implement under low slip conditions, difficult to implement under varying load conditions, can be used to segregate faults
Zero sequence voltage	MCSA	Analytical	No	High	High	[3]	Noninvasive, suitable for constant load conditions, segregation of different faults is complicated
Wavelet transform	MCSA	Time frequency analysis		Medium	Medium	[48]	Noninvasive, sampling rate and selection of mother wavelet is important, can be used to segregate faults, can be used for varying load conditions

TABLE III
SOME VARIANTS OF PARK'S VECTOR APPROACH

Park's vector (MCSA)	Extended Park's vector	FFT, Gabor transform	No	Medium	Medium	[34], [49]	Noninvasive, suitable under nonstationary load conditions, high sampling rate required, problems of unbalanced power supply
	Double park's vector	FFT	No	Medium	Medium	[50]	Noninvasive, suitable to study various fault conditions, high sampling rate required.
	Reduced modulus of extended Park's vector	FFT	No	Low	Low	[32]	Sampling rate can be reduced, can be implemented on FPGA and DSP kits
	Multiplier Park's vector	FFT	No	Medium	Medium	[51]	Segregation of different faults is difficult

The drawback of conventional extended Park's vector analysis (EPVA) is that all three phase currents are required for its pattern development and FFT analysis. First, samples of all three phase currents are taken with high sampling rate to avoid aliasing and, second, a long acquisition time is required to improve resolution. This may lead to a huge amount of data for processing and analysis, hence making memory and computational power of hardware questionable [32].

In [21], a technique is proposed to reduce the data required for fault diagnosis. It is claimed and sounds good that if samples are taken of one phase only at points where other phases are zero, the results can be as good as for conventional techniques. The authors called this technique reduced Park's vector analysis (RPVA) and claimed that due to less data required for spectrum analysis it can be easily implemented on simple DSP and FPGA kits.

III. CONCLUSION

Conventional MCSA and Park's vector analysis techniques are suitable for fault diagnosis of induction machines operating under steady state conditions, because these techniques are mainly dependent on slip and require exact measurement of speed. [49] proposed a speed sensorless method for BRB fault diagnostic of wound rotor induction motor (WRIM). The authors used Park's vector of modulus of WRIM's rotor current [52] for time frequency (*t-f*) analysis and proposed a technique of rescaling frequency axis which makes its free from speed measurement, plots the same frequency spectrum and requires less memory and computational power. Based on above analysis and discussion the following conclusions can be made.

- MCSA is the biggest group of most common diagnostic techniques.
- It is easy to understand and implement.
- It requires less computational power.
- All techniques are directly or indirectly dependent on each other providing ample opportunities to exploit the benefits of each other.
- Mainly they rely on the presence of some specific faulty frequencies in the spectrum.
- These faulty frequencies can be misleading if there are some external factors such as bad power source;
- MCSA usually ensures a trade-off between simplicity of algorithm and accuracy of results.
- It becomes problematic if there is more than one fault in the same machine.
- The complexity level increases in case of inverter fed machines.
- It provides a very good platform for the implementation of more advanced techniques such as inverse problem theory, parameter estimation and intelligent techniques.

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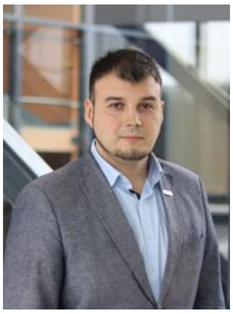

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