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The use of induction motor line current harmonics in drive system applications: A survey

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SUMMARY

The line current spectrum of an induction motor normally contains a variety of harmonics of different magnitudes and frequencies from a variety of different sources. Signal processing techniques are used to extract the useful information contained in the line current harmonics. In this paper several different applications of induction motor line current spectrum are reviewed. First, the origin and the producing mechanism of the line current harmonics and the factors which affect these harmonics are explained. Then the applications of these harmonics from sensorless speed control to condition monitoring are explained.

***Key words**: Line current spectrum, airgap field, condition monitoring, speed prediction.*

1. INTRODUCTION

In recent years, harmonics embedded in the stator line current of induction motors which arise from the current carrying winding conductors in slots, the slotting of the stator and rotor surfaces, the magnetic saturation of the iron and the eccentricity of the stator and rotor have found several applications. In particular, harmonics produced by the rotation of the slotted rotor, in particular the rotor slot harmonics RSH, contain useful information. They indicate the motor speed and rotor eccentricity by their frequency and amplitude. Thus they find application as a diagnostic tool for machine health monitoring, for sensorless speed detection and for sensorless vector control. Slot harmonics also have disadvantages and are associated with stray load loss, noise, vibration and cogging torques.

2. PREDICTION OF HARMONIC CURRENTS

It is important to be able to predict accurately the signal levels that would be present for a particular design of machine from design data. This will assist the drive system designer to know how to design or to select machines to optimise signal levels. It will also assist in determining the severity of potential faults in machine health monitoring. The prediction of frequency and especially of the amplitude of the speed dependent harmonics is complicated even before considering the whole line current spectrum. In particular the steady-state, airgap, flux-density distribution as a function of time and space is required, since this is used directly to determine the induced emfs and currents in the windings. The airgap field results from the interactions of the airgap, mmf and permeance variations.

The interactions between the airgap mmf and effective airgap permeance in induction machines has traditionally been expressed in terms of their harmonic series expansions and their product used to determine the harmonic content of the airgap field. However, the complex nature of these interactions, the multiplicity of terms and the difficulties of keeping track of amplitude and phase of each of the possible components has meant that usually only frequency information is extracted from the analysis. Where amplitude information is evaluated, the normal procedure is to use only what are perceived to be the key components.

An alternative approach, which has found favour more recently, is the complete solution of the electromagnetic field equations as a repeated part of a time stepping numerical solution of the differential equations defining the line currents in terms of applied line voltages. The electromagnetic field is normally solved by finite element techniques and winding inductances are evaluated including saturation effects and skew. This technique automatically keeps track of all of the interactions of mmf and permeance but losses the direct link between cause and effect which can be traced in the mmf permeance series approach. Generally however amplitude prediction for slot harmonics is improved. The technique has the disadvantage of being exceptionally computationally intensive. This can be a problem in relating cause, in terms of machine design changes, to effect, in terms of changes to harmonic signal levels. This is because repeated analysis may be required for several small changes in order to establish the link.

3. SPACE AND TIME HARMONIC SOURCES

The source of harmonic components in an induction machine line current waveform can be divided into two main areas: the space harmonic components and the time harmonic components. Space harmonics are produced by sinusoidal currents received from the supply. They result when the stator windings do not possess perfect distribution. If the voltage supplied to a poly-phase induction motor contains harmonics, the airgap flux may have components that rotate at speeds other than corresponding to fundamental frequency. These induce fundamental voltages. The non-linear effect of saturation can produce harmonics of different pole number rotating in synchronism with the fundamental flux. The very simplest machine models for obtaining information about flux densities inside induction motors, such as those described in Say [1], include saturation as a standard distribution by assuming the presence of at least a third harmonic. This results in zero sequence, third harmonic voltages being induced which circulate currents in delta connected machines or produce star point voltages in star connected machines.

The line current spectrum may also contain harmonics at a frequency determined by supply voltage harmonics. The time harmonic voltages present in the mains supply are usually small in proportion to the fundamental voltage. The reactance of the motor to time harmonics is high. Consequently the amplitudes of the time harmonic currents are small. Conners et al. [2] are among many authors who discuss and analyze the effects of supplying induction motors from a solid state adjustable frequency controller which results in the input voltage being far from sinusoidal.

Even when the voltage input to an induction motor is sinusoidal, the line current will not normally be sinusoidal. When saturation is absent, the motor line current will still contain a number of harmonics of varying amplitudes and frequencies from a variety of different sources. The two main sources of these harmonics are mmf variations and permeance variations. Each of these sources has a number of causes and produces a number of different harmonics. Some of the line current harmonics are illustrated in Figure 1 [3]. The prediction of an induction motor line current spectra can be found in Ref. [4].

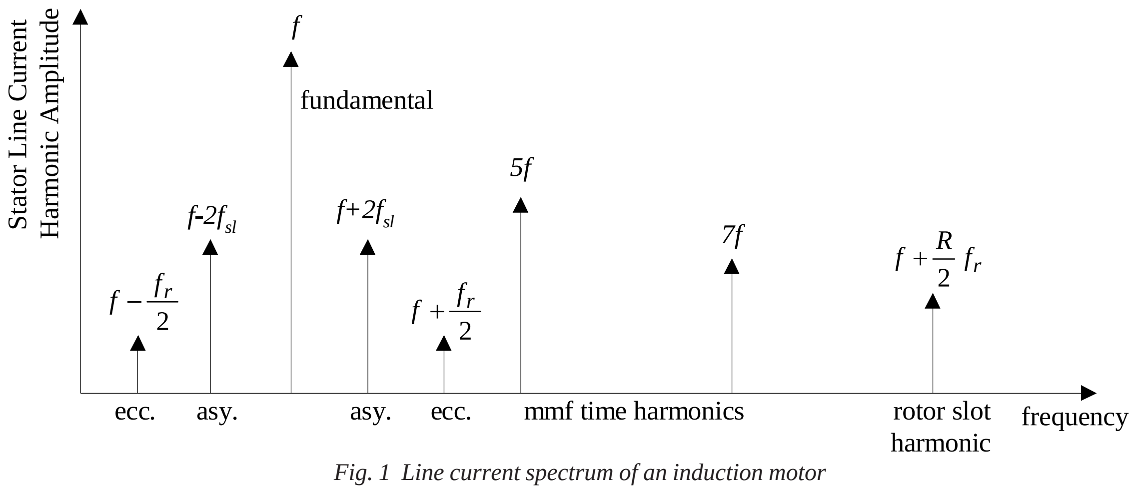

Fig. 1 Line current spectrum of an induction motor

3.1 The airgap field

Since all the harmonics are associated with variations in the physical airgap of the machine, the airgap flux density is modulated and stator currents are generated at predictable frequencies related to electrical supply, motor rotational speed and source of the harmonics. The prediction of the complete harmonic components in the line current spectrum of an induction motor requires an accurate description of the distribution of the flux density around the motor and its variation both in space and time.

3.2 Factors influencing airgap field

The basis of operation for the three phase electric machine is for the stator winding to produce a continuously rotating magnetic field in the air gap. This rotating field induces currents in the rotor conductors. Hence a torque is generated which causes the rotor to rotate.

Normally the performance of an induction machine is analyzed in text books in terms of main and leakage fluxes, assuming the machine is balanced both electrically, magnetically and mechanically, with both space distributed and time varying quantities of fundamental sinusoidal distribution. However, the second order aspects of performance such as parasitic torques [5], stray losses [6] and magnetic noise [7, 8] which are of importance in design depend on the harmonic content of the airgap flux distribution.

3.2.1 Saturation of magnetic steel

Digital computers spurred the development of numerical techniques to accomplish air gap flux prediction including saturation with a high degree of precision. Lee [9] developed a method based on an iterative procedure to ensure that the airgap flux harmonic content was consistent with the applied voltage. He assumed a sinusoidal flux density variation in the core but allowed the teeth to saturate. Chalmers and Dodgson [10] extended this method to include core saturation. They used only the fundamental component of the mmf in the airgap to determine the saturation effect. In order to simplify the problem the rotor currents were neglected giving results for the no-load condition. Finite element application to induction machines was introduced by Tindal and Lees [11] and since then there has been a burgeoning application of the method to solve problems both statically, for one or more rotor positions and dynamically for a moving rotor. All of these approaches have been essentially 2D. The complete 3D solution to induction motor problems involving axial flux and eddy current effects has yet to be applied in practice.

3.2.2 Windings

The magnetic flux is dependent upon the winding arrangement of both rotor and stator. Windings are normally arranged to minimize as far as practical the low order space harmonics associated with the division of the winding into blocks of slots, referred to by Alger [12] as Phase Belts, which are associated with the three phase windings. Most poly-phase, single speed, induction machine windings are either single or double layer with uniform numbers of conductors in each slot to simplify the winding. A variety of end winding connections results in different names for the same winding from the point of view of mmf. The differences between them are in the length of a mean turn and hence winding resistance and overhang reactance. The common, non-uniform distribution of current carrying conductors within the slots along the airgap surface causes mmf waves to be stepped and produces further space harmonics. These cannot be influenced by winding distribution.

3.2.3 Slot openings

The slotted nature of the airgap boundary also influences the flux harmonics that are developed in particular the slot harmonic fields. This is so because the low order harmonic mmfs produced act across an airgap the permeance of which varies with the relative positions of stator and rotor teeth. The amplitude of the flux density variations caused by the slot opening vary with the ratio of the width of the slot opening to the radial length of the airgap. They also vary with the slot pitch in machines where the airgap length is not small in comparison to that pitch. This however is not the case in induction motors which are essentially short airgap machines. The effects of slot openings can be reduced, particularly at no load through the use of closed or semi-closed slots or magnetic slot wedges. Closed rotor slots are common in induction machines. The effect of slot closure on induction machine behavior is discussed in Ref. [13]. This can be significant making leakage reactance a function of winding current.

3.2.4 Slot combinations

Slot permeance variations are normally evaluated for the stator and rotor independently assuming no slotting on the other airgap surface. The combination of stator and rotor slotting causes interaction between their slot permeance waves. The choice of stator-rotor slot combination is an important matter influencing the resulting magnetic flux distribution. In addition to cogging, synchronous crawling and other harmonic torque effects, there are several aspects of performance, such as magnetic noise and vibration which are influenced by the slot combination [14].

It has been found that a motor with a good starting characteristics could crawl at low speed or not start at all if the number of slots are changed by one or two [15]. This was a result of synchronous and asynchronous harmonic torque's being produced due to the presence of harmonic fields in the airgap resulting from slot permeance and slot mmf interactions. Binns et al. [16, 17] used conformal transformation to solve for the flux distribution in a motor in doubly slotted machines. In these studies, the influence of slot combinations on the flux pulsation in and the force pulsation on induction motor teeth on load were analyzed. For a given stator slot number, the airgap field was evaluated for different rotor slot numbers. Their conclusions extended the rules concerning the choice of good slot combination. However, the analysis was still simplistic in that key effects for saturation and eccentricity were not considered. The rules for choice of a good slot combination were still only comprehensive in eliminating most if not all combinations dependent upon pole number.

3.3 Slot harmonic components

The regular variations in mmf and permeance due to slotting produce harmonic components called tooth or slot harmonics. Spatially, these occur at harmonic orders set by the spacing between adjacent slots and are given by:

$$v_k = k\frac{N}{P} \pm 1 \tag{1}$$

where v_k is the order of harmonic component, N is the number of slots, P is the number of pole pairs and k is an integer. $k=1$ yields the lowest frequency slot harmonics which are the most troublesome ones. For almost as long as engineers have been designing electric machines, they have attempted to suppress these slot harmonics so that the magnetic field is as close to sinusoidal as possible.

This goal is impossible to achieve, but the use may be made of the side effects of slot harmonics as measured from the machines voltage or current spectra in terms of sensorless speed detection or for diagnostic purposes.

4. THE APPLICATIONS OF LINE CURRENT SPECTRAL ANALYSIS

4.1 Sensorless control of induction motors

A speed sensor is always required for closed-loop speed control. However the speed sensor affects the drive cost, reliability and noise immunity. Especially in the case of the induction machine, speed sensors can undermine the ruggedness and simplicity of the drive. Furthermore in many industrial applications it is either not possible or undesirable to use a mechanical sensor for speed or position measurement. This leads to the concept of speed sensorless control where a varying motor quantity is a speed sensor.

Recently, the elimination of the speed sensor has been an important research area in variable speed drives. Different speed prediction methods have been proposed for induction machines [18-23]. These different techniques for obtaining the speed information of an induction motor without using a speed sensor, utilize the electrical quantities driving the motor or the electrical quantities resulting from the motor operation, such as airgap flux, stator flux and rotor flux. Additionally, the measurement of the slot harmonic frequencies can be used to provide information to assist in tuning these models.

4.2 Speed prediction using terminal quantities

From the beginning of the 70's a large number of different schemes based on simplified motor models have been proposed to calculate the speed of induction motors from measured electrical terminal quantities, i.e. voltages and currents. These approaches are alternatives to, or may be used in conjunction with, speed detection using line current harmonics. They perform signal processing operations on the measured terminal quantities to derive an analog signal which is proportional to the slip of the motor.

In 1975 Abondanti et al. [24] used the induction motor terminal quantities to design an analog slip calculator for computing the slip frequency. The slip frequency is the difference between the stator frequency and the electrical frequency corresponding to the rotor speed. He used the equivalent circuit of the induction motor and its governing equations, which relate torque to the slip angular frequency through the rotor resistance. This type of model is prone to errors due to differences between the actual machine parameters and those in the model. Most common problems appear at low inverter output frequencies where the stator resistance, which is a function of machine winding temperature, becomes dominant in the equations. At higher frequencies, similar errors in the rotor resistance and thus rotor time constant cause speed errors. Problems with the correct determination of the magnetizing inductance can cause errors in the motor flux level and result in loss of vector control.

There have been many papers providing improved methods of sensorless control [25], and for self commissioning [26], or adaptive control [27-29], which attempt to address the problems of sensored and sensorless vector control. The problem is obviously much simpler with a speed signal and hence the interest in sensorless vector control using rotor slot harmonics.

4.3 Speed determination using rotor slot harmonics

Ishida et al. [30] presented a new method for speed determination in 1979. They used the rotor slot harmonic voltages to calculate the slip frequency of an inverter fed induction motor. Green [31] used the rotating wave approach to measure the rotor speed of an asynchronous motor which involves the detection of the rotor induced harmonics in the phase currents. He demonstrated that an induced current harmonic due to the rotor dynamic eccentricity can be extracted from the phase current. The frequency of this component is related to the rotor speed while its bandwidth is related to the supply frequency. In 1992, Ferrah et al. [32] presented a novel approach for the speed measurement using rotor slot harmonics. The approach was based on the spectral analysis of a line stator current, of an inverter-fed squirrel-cage induction motor, using the fast Fourier transform. The system is able to perform over a wide range of speeds down to *2 Hz* under loaded and unloaded conditions.

In an induction motor the slots on the stator and rotor surface produce a regular variation of the radial airgap permeance. The variation of permeance bounded by a smooth stator and a slotted rotor rotating at angular velocity ω_r is given by:

$$\Lambda(\theta,t) = \Lambda_0 + \sum_i \Lambda_i \cos\left[i\frac{R}{p}(p\theta - \omega_r t)\right] \qquad (2)$$

where the coefficient Λ_0 is the average permeance, R is the number of rotor slots and p is the number of pole pairs. This permeance wave interacts with the fundamental component of the airgap mmf:

$$F(\theta,t) = F_1 \cos(p\theta - \omega t) \qquad (3)$$

where F_1 is the amplitude of the mmf which is a function of the stator current and mechanical structure of the induction machine. The flux density distribution, $B(\theta,t)$ is given as the product of the permeance $\Lambda(\theta,t)$ and the mmf $F(\theta,t)$. The result of the multiplication is a ripple which varies both in space and time according to following equation:

$$B(\theta,t) = B_0 \cos(p\theta - \omega t)\left[1 + B_1 \cos\frac{R}{p}(p\theta - \omega_r t)\right] \qquad (4)$$

A graphical representation of the ripple is shown in Figure 2. This ripple is mathematically equivalent to two oppositely travelling waves which induce corresponding current harmonics in the stator winding. The frequencies of these harmonics are defined by:

$$\omega_{sh} = \omega_0 \pm \frac{R}{p}\omega_r \qquad (5)$$

which is dependent on rotor speed.

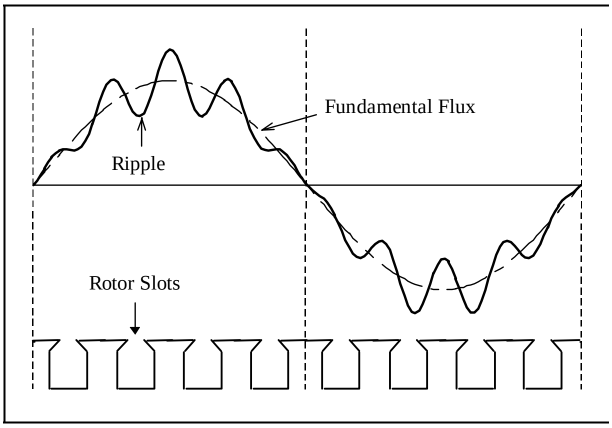

Fig. 2 Variation of airgap flux of induction motor

Therefore stator currents contain speed dependent harmonics and the speed of the motor can be extracted from the stator line current spectrum. The Figure 3 shows a typical line current spectrum on no load for a *415 V*, 3 phase, 4 pole, squirrel cage induction motor with 48 stator slots and 56 rotor slots. The two principle, speed dependent, slot harmonic frequencies *f1* and *f2* are shown. Normally one slot harmonic has a pole number which is harmonically a multiple of three and so induces no voltage or current in the supply.

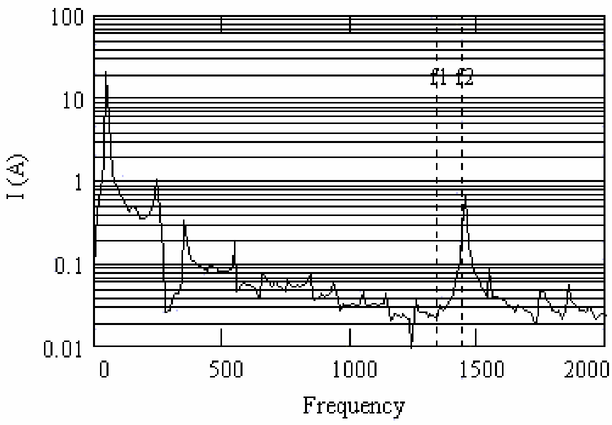

Fig. 3 Spectrum of an induction motor line current showing the rotor slot harmonics

The speed is estimated by the decomposition of the stator current signal into its spectral components to determine the speed dependent slot harmonic frequency, f_{sh} and the motor fundamental frequency, f_0. The rotor speed in rpm is calculated by the following equation:

$$n = \frac{60}{R}\left(f_0 \pm f_{sh}\right) \qquad (6)$$

The block diagram of a speed detector used in field oriented control similar to that given in Ref. [33], is shown in Figure 4. The technique is based on the Fast Fourier Transform (FFT) to obtain the spectrum of the induction motor line current. A spectral analysis of one phase current is performed using a FFT method to detect the rotor slot harmonic frequency.

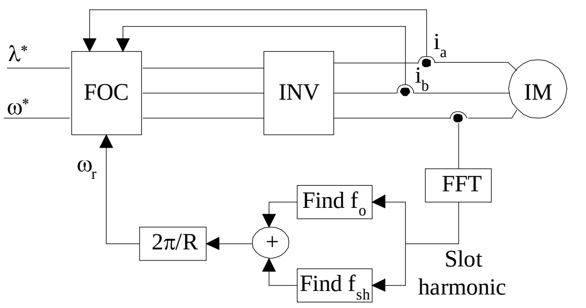

Fig. 4 Sensorless speed detection using FFT

Once the frequency of such a harmonic is detected the rotor speed is derived by Eq. (6). Much work has been carried out to enhance the speed and reliability of the extracted RSH employing digital signal processing techniques [34-37].

4.4 Fault detection and condition monitoring of induction motors

Among the different diagnostic techniques, the spectral components present in the machine variables allow the identification of several fault conditions. In particular, the input current spectrum and flux density spectrum are widely considered in the diagnostic systems applied to the induction machines.

The faults in induction motors affect either the airgap permeance caused by such factors as rotor unbalance, rotor and stator slots or airgap mmf caused by broken rotor bars and non-sinusoidal winding distribution. Variations in either of these quantities affect distribution of the airgap flux of the motor giving rise to detectable changes in the stator current spectrum.

Fault conditions in induction machines such as eccentric airgaps and broken rotor bars result in harmonics in the stator current of the motor which can be used to monitor the health of the machine. The ability to monitor the condition of an electrical machine has been a concern of industry for many years. Improved industrial monitoring techniques have produced a number of studies [38-40] on the detection of rotor faults in induction machines. Several of these investigations have proposed schemes that monitor the spectrum of a single phase of the stator current for frequency components associated with both airgap eccentricities and broken rotor bars.

4.4.1 Detection of broken rotor bars

The principle on which the method depends is that a fault associated with rotor and stator windings alters the normal airgap flux waveform, causing quantities that are functions of airgap flux also to change.

Damage to the rotor bars of an induction motor causes an electrical unbalance in the rotor circuit. The resulting unbalanced slip frequency rotor currents produce a negative sequence flux in the airgap that rotates backwards with respect to the rotor movement at *sn*, where *s* is the slip and *n* is the synchronous speed, or *2sn* relative to the rotating stator flux. This produces induced currents in the stator windings with frequencies ($1\pm2s$)f, where f is the supply frequency, that is, sideband components separated from the fundamental by $\pm2s$ are produced [41]. Figure 5 shows the line current spectrum of an induction motor with electrical unbalance in the rotor circuit. The figure is zoomed for clear view of the ($1\pm2s$)f components.

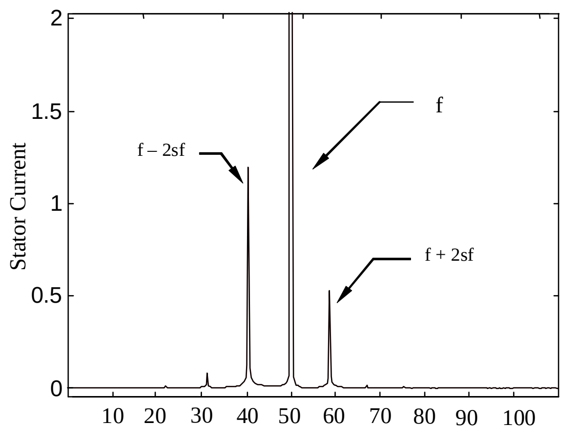

Fig. 5 Stator current spectrum showing the ($1\pm2s$)f frequencies

The amplitudes of these components give an indication of the extent of the damage to the rotor [42]. These components may even be present in a new motor due to manufacturing defects.

Therefore broken rotor bars in a squirrel-cage induction motor may be detected by examining the frequency spectrum of the stator current for the existence of twice slip frequency modulation side-bands around the supply frequency. Unfortunately there is always some electrical imbalance in induction motor rotors and a healthy rotor will produce some sidebands. The production of the reverse rotating magnetic field by an unbalanced rotor is a special case of the rotor reacting to an impressed field to produce other rotating fields and stator frequencies other than those normally expected.

4.4.2 Detection of rotor eccentricity

In many machines the magnitude of the slot harmonic component is influenced by the degree of rotor static eccentricity [43]. Dynamic eccentricity may also introduce new pole frequencies of slot harmonic existing alongside the traditional terms. Monitoring of these levels on a routine basis enables changes in eccentricity to be detected and action to be taken if required. Figure 6 shows the effect of different level of static eccentricity on slot harmonic current of a *30 kw* induction machine [44].

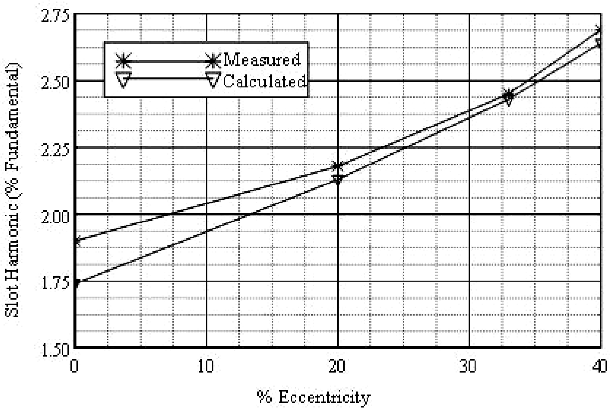

Fig. 6 Magnitude of slot harmonic with different levels of eccentricity

It is clear from this figure that the harmonic levels increase with increasing eccentricity. Monitoring of these levels on a routine basis enables changes in eccentricity to be detected and action to be taken if required.

5. CONCLUSION

In this paper the spectral components embedded in the line current of induction motors, their sources, factors affecting the magnitude and frequency of these harmonics and different application areas have been discussed. The spectral components include speed dependent harmonics including those which do not obey the classical rules with regard to their frequency and arise from additional interactions of saturation, eccentricity and stator space harmonics with the traditional slotting components. The magnitude and frequency of these spectral components of line current can be used for sensorless speed detection. The information is also of use in machine health monitoring.

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KORIŠTENJE HARMONIKA LINIJSKE STRUJE INDUKCIJSKOG MOTORA U PRIMJENAMA NA POGONSKI SUSTAV: PREGLED

SAŽETAK

Spektar linijske struje indukcijskog motora normalno sadrži niz harmonika različitih veličina i frekvencija iz različitih izvora. Koriste se tehnike obrade signala da bi se izdvojile korisne informacije koje se nalaze u harmonikama linijske struje. Ovaj rad iznosi nekoliko različitih primjena spektra linijske struje u indukcijskom motoru. Najprije se objašnjava porijeklo i mehanizam nastajanja harmonika linijske struje kao i faktori koji utječu na harmonike. Zatim su objašnjene primjene ovih harmonika iz kontrole bezsenzorske brzine vrtnje da bi uvjetovali promatranje.

***Ključne riječi**: spektar linijske struje, zračni prostor, uvjeti promatranja, predviđanje brzine.*