Abstract—In this paper, a comprehensive definition of eccentricity fault in cage induction motor is introduced, and instantaneous power is considered as eccentricity-fault index. In addition to the line current, the stator line voltage influences the instantaneous power of the motor; therefore, harmonics of this power can be employed as a fault-diagnosis index when the motor is supplied by a closed-loop control method. It is theoretically shown that the frequencies of harmonics of the instantaneous power due to mixed eccentricity fault are the same for the mains-fed and open/closed-loop drive-connected motors, although the number of factors affecting the amplitudes of the harmonics is relatively large when closed-loop drive connected. A flexible test rig is described, which was established to carry out various measurements on the eccentric motor with different eccentricity degrees, under different supply and control methods, varying load, and variable speeds. The experimental results indicate that the amplitudes of the dominant instantaneous-power harmonics depend on the degrees of mixed-eccentricity static and dynamic components, although these amplitudes are influenced by the supply methods, load level, and speed of the motor.

Index Terms—Affecting factors, cage induction motor, experimental investigation, instantaneous-power harmonics, mixed-eccentricity index.

I. INTRODUCTION

ECCENTRICITY is one of the major and common faults occurring in electrical motors including squirrel-cage induction motors (SCIMs), so it requires a special attention. If this fault is not diagnosed and not removed in the initial stages, the rotor may rub against the stator, and the fault damages the motor [1]. This has been the reason for wide research in eccentricity-fault diagnosis of induction motor in the past two decades [2]–[19]. A more complete list of references can be found in [1] and [20].

There are three longitudinal axes in an SCIM including the following: rotor symmetrical axis ($A_r$), stator symmetrical axis ($A_s$), and rotor rotational axis ($A_w$). These three axes coincide with each other in an ideal healthy SCIM. Any deviation of the axes causes the eccentricity fault to occur. Fig. 1 shows the stator and rotor cross sections in a general (mixed) eccentricity condition. As seen, all three mentioned axes have been separated from each other. We have denoted the mixed-eccentricity degree by $\rho$, its static component by $\rho_s$, and its dynamic component by $\rho_d$, such that $\rho_{g0}$ is the distance from $A_s$ to $A_r$, $\rho_s g_0$ is the distance from $A_s$ to $A_w$, and $\rho_d g_0$ is the distance from $A_r$ to $A_w$, where $g_0$ is the normal air-gap length of the healthy SCIM. Moreover, $\theta$ is the rotor angular position, $\varphi_s$ is the angle at which $A_w$ is separated from $A_s$, and $\varphi_m$ is the angle of minimum air-gap position introduced due to eccentricity. All three angles are measured from a horizontal reference beginning from $A_w$. Generally, $\rho_s$, $\rho_d$, and $\varphi_s$ are constants, and $\rho$ and $\varphi_m$ are functions of them and of $\theta$. These functions are

$$\rho(t) = \sqrt{\rho_s^2 + \rho_d^2 + 2 \rho_s \rho_d \cos[\theta(t) - \varphi_s]}$$  \hspace{1cm} (1)

$$\varphi_m(t) = \varphi_s + \tan^{-1} \left( \frac{\rho_d \sin[\theta(t) - \varphi_s]}{\rho_s + \rho_d \cos[\theta(t) - \varphi_s]} \right)$$  \hspace{1cm} (2)

In (1) and (2), if $\rho_d = 0$, then $\rho = \rho_s$, and $\varphi_m$ becomes a constant angle equal to $\varphi_s$; the resultant eccentricity is called static. In addition, if $\rho_s = 0$, then $\rho = \rho_d$, and $\varphi_m = \theta$ meaning that the minimum air-gap angle rotates by the rotor with the same speed; this results in a so-called dynamic eccentricity. In practice, full coincidence of the axes is so difficult, and there are some deviations depending on the manufacturing process even in a new motor; this is called the inherent eccentricity of the

Fig. 1. Stator and rotor cross sections in a mixed-eccentricity condition.
motor [1]. Due to the inherent static- and dynamic-eccentricity components, generally mixed eccentricity takes place in real SCIMs.

As results of past research, where some of which are merely based on experimental investigations [2], [5], [7], [15], several indexes have been introduced to diagnose eccentricity in SCIMs under different conditions [1], [21]. When a fault index does not change considerably by changing factors other than the degree of fault, it may be used in a conventional fault-diagnosis technique to indicate the fault occurrence and its degree. To establish a conventional fault-diagnosis technique, the following are usually done:

1) selecting a proper fault index;
2) determining some reference values for the selected index;
3) determining the index-measurement technique;
4) measuring the index and comparing it with the reference values and concluding the fault occurrence.

On the other hand, when an index changes considerably by changing other factors, a fault-diagnosis technique based on artificial intelligence (AI) such as artificial neural networks (ANN) would be useful [9].

The most well known indexes for eccentricity faults in SCIMs are the amplitudes of high- and low-frequency harmonics of the stator line current. The precise frequencies of these harmonics are, respectively, as follows [1]:

\[ f_{\text{high}} = f_1 \left( \frac{kR \pm n_d}{P} \right) \pm \nu \]  
\[ f_{\text{low}} = |f_1 \pm kf_r| \]  

where \( f_1 \) is the fundamental frequency of the supply voltage, \( f_r \) is the rotor-rotation frequency in revolutions per second, \( R \) is the number of rotor bars, \( s \) is the slip, \( P \) is the number of pole pairs, \( \nu \) is the supply-current-harmonic order, \( n_d \) is the eccentricity order, and \( k \) is a non-zero positive integer number. Some factors as well as the type and degree of eccentricity affect the index harmonic amplitudes [21]. Supplying an SCIM with inverter and the application of speed, current, torque, and flux controllers in a closed-loop control strategy are among these factors [2]–[4], [9]–[11]. By experiments on an eccentric SCIM, Cruz et al. verified that a direct-torque control (DTC) strategy can change the amplitudes of the low-frequency current harmonics in different manners [2]. Bangura and DeMerdash studied the effects of pulsewidth-modulation-inverter excitation on the current and torque spectra of the eccentric SCIM using a so-called coupled finite element-state-space method [3]. A more detailed study on the subject was carried out by Huang et al. [4], [9]–[11]. Under closed-loop field-oriented control of SCIM, they verified that the stator line-voltage harmonics must be considered as well as its current harmonics to diagnose eccentricity faults correctly. Then they introduced ANN to meet their proposition. Moreover, they introduced a technique for eliminating load-oscillation effects from the diagnosis technique. According to the Huang et al. studies, it is recommendable to consider the stator line-voltage harmonics as well as its line-current harmonics when diagnosing eccentricity faults in SCIMs under closed-loop control strategies.

Some harmonics in the spectrum of various power components, such as instantaneous power [21]–[24] and modulus of complex apparent power [25], are among the mixed eccentricity-fault indexes. While these components are recognized for mains-fed SCIMs, they may be good indexes when supplying SCIM under closed-loop control strategies because they are determined from stator line voltages as well as stator line currents. Having this motivation, the main goal of this paper is to study the performance of harmonic components of instantaneous power as eccentricity-fault indexes for SCIMs under closed-loop DTC-based drive connection. To reach this goal, a flexible test rig was arranged and a lot of experimental data were collected. Then, the frequencies of the harmonic components produced in the spectrum of instantaneous power due to mixed eccentricity were determined theoretically and then proved by experiments. More dominant harmonic components were determined, and their performance by varying load level and speed reference was studied, when supplying an industrial SCIM by an industrial closed-loop DTC-based drive system. For comparison purposes, similar studies were carried out on the mains-fed and open-loop drive-connected SCIM.

In this paper, we have considered an instantaneous partial power, which is the product of an instantaneous line voltage and an instantaneous line current. However, if it can be proved that any other component of instantaneous power have more exact and complete information about eccentricity, the study can be repeated based on it easily. Details of the test rig and its components are given in the next two sections. Determining the frequencies of the instantaneous-power harmonics due to mixed eccentricity and selecting more dominant ones is the subject of Section IV. Variations of the normalized amplitudes of the dominant harmonics by varying the load level and rotor speed are studied in the last two sections. These studies indicate a considerable dependence of the relevant harmonic components to supply method, load level, and speed. Therefore, as previously mentioned, they can be used in an AI-based technique to diagnose mixed-eccentricity faults of SCIMs.

**II. Test Rig**

A general plan of the prepared test rig is shown in Fig. 2. This system can be used to sample two line currents \( I_a \) and \( I_b \), two line voltages \( V_{ab} \) and \( V_{bc} \), and speed signals. If necessary, it can be arranged to sample third line current \( I_c \) and voltage \( V_{ca} \), too. The main components of the test rig, as indicated by numbers on the plan, are as follows:

1) Three-phase 11-kW SCIM (see Table I for details).
2) DC generator coupled to the SCIM to provide its adjustable load.
3) Tachogenerator coupled to the shaft of the dc generator as angular-speed sensor.
4) Mechanical coupling between SCIM and dc generator.
5) Variable-resistor bank as a variable load of the generator; the load of the generator and, consequently, the induction motor can be adjusted by varying this resistance and/or regulating the excitation current of the generator by relevant variable resistor.
III. MAKING SCIM ECCENTRIC TEMPORARILY

So far, various methods have been used to create different types of eccentricity in SCIMs [5]–[18]. Some of the methods are invasive, i.e., they change the normal structure of the motor [8]–[14], while some of them are permanent, and it is impossible to return to a healthy condition easily or one cannot change the eccentricity degree at all [6], [17]. Moreover, some methods are capable of producing only static type of eccentricity [5], [7], [15], [18].

In this paper, a method has been adopted without the aforementioned drawbacks. It means that it is not invasive or permanent, does not require precise measuring equipment in the test rig, and it is capable of producing all types of eccentricity with variable degrees. Therefore, when doing the tests, the type and degree of the eccentricity can be changed, and then, the motor can be returned to the healthy condition. At this end, ball bearing number 6011 was chosen to replace instead of the motor’s original ball bearings numbered 6309 [31]. The inner diameter of the new ball bearing is 10 mm larger, and its outer diameter is 10 mm smaller than the corresponding diameters of the original ball bearing. By this replacement, empty rooms are created between the rotor shaft and the ball bearings and also between the ball bearings and their housings. These rooms can be filled by coaxial and/or eccentric rings with different degrees in order to obtain different types of eccentricities with different degrees temporarily and noninvasively. Therefore, we have the following.

1) Fixing coaxial rings on both ends, between the ball bearings and rotor shaft and eccentric rings between the ball bearings and their housings, creates static eccentricity. The degree of static eccentricity varies by varying the eccentricity of the latter rings.

2) Fixing eccentric rings on both ends, between the ball bearings and rotor shaft and coaxial rings between the ball bearings and their housings, creates dynamic eccentricity. The degree of dynamic eccentricity varies by varying the eccentricity of the former rings.

3) Fixing eccentric rings on both ends, between the ball bearings and rotor shaft and eccentric rings between the ball bearings and their housings creates mixed eccentricity. The degree of mixed eccentricity varies by varying the eccentricity of the former and/or latter rings.

In all experiments, \( \varphi_s \) was taken to be \(-90^\circ\), i.e., the static eccentricity was taken downward. At the end of the tests, the original ball bearings can be replaced to return the motor to its healthy condition. Fig. 3 shows a photograph of samples of the built rings with the original and new ball bearings. Table II shows the overall dimensions of the ball bearings and the built rings. The rings were built to be fully fixed on their positions. However, special bolts or screws were also prepared on the rings to ensure their nonslip mode.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal Power</td>
<td>11</td>
<td>kW</td>
</tr>
<tr>
<td>Nominal Voltage</td>
<td>380</td>
<td>V</td>
</tr>
<tr>
<td>Nominal Frequency</td>
<td>50</td>
<td>Hz</td>
</tr>
<tr>
<td>Connection</td>
<td>( \Delta )</td>
<td>-</td>
</tr>
<tr>
<td>Number of Poles</td>
<td>4</td>
<td>-</td>
</tr>
<tr>
<td>Rotor Slots Number</td>
<td>28</td>
<td>-</td>
</tr>
<tr>
<td>Air gap Length</td>
<td>0.435</td>
<td>mm</td>
</tr>
<tr>
<td>Inertia</td>
<td>0.0625</td>
<td>kg·m(^2)</td>
</tr>
</tbody>
</table>

In all experiments, the eccentricity was taken downward. At the end of the tests, the original ball bearings can be replaced to return the motor to its healthy condition. Fig. 3 shows a photograph of samples of the built rings with the original and new ball bearings. Table II shows the overall dimensions of the ball bearings and the built rings. The rings were built to be fully fixed on their positions. However, special bolts or screws were also prepared on the rings to ensure their nonslip mode.
IV. INSTANTANEOUS-POWER HARMONICS DUE TO MIXED ECCENTRICITY FAULT

Assume an SCIM supplied by a system of balanced three-phase voltage, where the voltage between two stator terminals is \( u_L \), and the current entering one of these terminals is \( i_L \). Thus, the instantaneous partial power is

\[
p(t) = u_L \cdot i_L. \tag{5}
\]

The mains-fed and open-loop drive-connected modes of supply, neglecting all harmonic components excluding low-frequency ones created by mixed eccentricity \([4]\), the \( u_L \) and \( i_L \) waveforms are as follows:

\[
u_L = \sqrt{2}U_1 \cos(2\pi f_1 t) \tag{6}
\]

\[i_L = \sqrt{2}I_1 \cos(2\pi f_1 t - \varphi_L) + \sqrt{2} \sum_{k=1}^{\infty} \left\{ I_{pk} \cos[2\pi (f_1 + k f_r) t - \varphi_{ipk}] + I_{nk} \cos[2\pi (f_1 - k f_r) t - \varphi_{ink}] \right\} \tag{7}
\]

where time origin \((t = 0)\) was defined such that the initial angle of \( u_L \) is zero, \( U_1 \) and \( I_1 \) are the rms values of the fundamental components of \( u_L \) and \( i_L \), respectively. \( \varphi_L \) is phase angle of the fundamental component of \( i_L \) with respect to the fundamental component of \( u_L \). \( I_{pk} \) and \( I_{nk} \) are rms values of the current harmonics at \( f_1 + k f_r \) and \( f_1 - k f_r \), respectively, and \( \varphi_{ipk} \) and \( \varphi_{ink} \) are their initial angles. \( k \), \( f_1 \), and \( f_r \) are as defined in \((4)\).

Substituting \((6)\) and \((7)\) into \((5)\), one can obtain

\[
p(t) = U_1 \cdot I_1 \cos(4\pi f_1 t - \varphi_L) + \cos \varphi_L + \sum_{k=1}^{\infty} \left\{ U_1 \cdot I_{pk} \cos[2\pi (2f_1 + k f_r) t - \varphi_{ipk}] + \cos[2\pi k f_r t - \varphi_{ipk}] \right\} + U_1 \cdot I_{nk} \cos[2\pi (2f_1 - k f_r) t - \varphi_{ink}] + \cos[2\pi k f_r + \varphi_{ink}] \right\} \tag{8}
\]

As seen, due to the fundamental harmonics of \( u_L \) and \( i_L \), the instantaneous power contains a dc and an ac component at \( 2f_1 \). Moreover, due to the fundamental harmonic of \( u_L \) and the mixed eccentricity-related harmonics of \( i_L \), the instantaneous power contains many other harmonics at \( 2f_1 \pm k f_r \), \( 2f_1 \mp k f_r \), and \( k f_r \). Since \( I_{pk} \) and \( I_{nk} \) have higher values when \( k = 1 \), it is expected that the corresponding harmonics of the instantaneous power have higher amplitudes. Ignoring \( I_{pk} \) and \( I_{nk} \) for \( k > 1 \), \((8)\) becomes

\[
p(t) = U_1 \cdot I_1 \cos(4\pi f_1 t - \varphi_L) + \cos \varphi_L + U_1 \cdot I_{p1} \cos[2\pi (2f_1 + f_r) t - \varphi_{ip1}] + U_1 \cdot I_{n1} \cos[2\pi (2f_1 - f_r) t - \varphi_{ink1}] + U_1 \cdot I_{p1} \cos(2\pi f_r t - \varphi_{ip1}) + I_{n1} \cos[2\pi f_r t + \varphi_{ink1}] \tag{9}
\]

With constant \( U_1 \), the amplitude of \( 2f_1 + f_r \) component only depends on \( I_{p1} \) and that of \( 2f_1 - f_r \) component only depends on \( I_{n1} \), but the amplitude of \( f_r \) component depends on \( I_{p1} \) and \( I_{n1} \) as well as on \( \varphi_{ip1} \) and \( \varphi_{ink1} \). Because of the one by one modulation of the voltage and current harmonics, it is obvious that considering all probable harmonic components of \( u_L \) and \( i_L \) may cause no change in the earlier conclusion.

In the closed-loop drive-connected mode of supply, it is expected that \( u_L \) contains the same mixed eccentricity-related harmonics \([9]-[11]\)

\[
u_L = \sqrt{2}U_1 \cos(2\pi f_1 t) + \sqrt{2} \sum_{k=1}^{\infty} \left\{ U_{pk} \cos[2\pi (f_1 + k f_r) t - \varphi_{upk}] + U_{nk} \cos[2\pi (f_1 - k f_r) t - \varphi_{unk}] \right\} \tag{10}
\]

where other harmonic components are ignored again. \( U_{pk} \) and \( U_{nk} \) are rms values of voltage harmonics at \( f_1 + k f_r \) and \( f_1 - k f_r \), respectively, and \( \varphi_{upk} \) and \( \varphi_{unk} \) are their initial angles. Putting \((10)\) together with \((7)\) in \((5)\), a sum of sinusoidal functions, like \((8)\), could be obtained. Considering little amplitudes of nonfundamental voltage and current harmonics, compared with their corresponding fundamental amplitudes,
many of the sinusoidal terms can be reasonably ignored because their amplitudes are product of amplitudes of nonfundamental voltage and current harmonics. Therefore, what remains is equivalent to the following equation:

\[
p(t) = \left[ \sqrt{2} U_1 \cos(2\pi f_1 t) \right] i_L + \left[ \sqrt{2} I_1 \cos(2\pi f_1 t - \varphi_L) \right] u_L - \sqrt{2} U_1 \cos(2\pi f_1 t) \right]
\]

where \(i_L\) and \(u_L\) must be replaced from (7) and (10), respectively. It is easy to recognize that (11) has the same harmonic components as (8). Thus, the harmonic components at \(2f_1\) respectively. It is easy to recognize that (11) has the same harmonic components as (8). Thus, the harmonic components at \(2f_1 + kf_r, 2f_1 - kf_r\), and \(kf_r\) will also be present in instantaneous power, with a closed-loop drive connection of SCIM. Ignoring \(I_{pk}, I_{nk}, U_{pk},\) and \(U_{nk}\) for \(k > 1\), (11) can be rewritten in details as follows:

\[
p(t) = U_1 \cdot I_1 \left[ \cos(4\pi f_1 t - \varphi_L) + \cos \varphi_L \right] + U_1 \cdot I_{p1} \left[ \cos \left( 2\pi (2f_1 + f_r) t - \varphi_{ip1} \right) \right] + U_1 \cdot I_{n1} \left[ \cos \left( 2\pi (2f_1 - f_r) t - \varphi_{in1} \right) \right] + U_n \cdot I_1 \left[ \cos \left( 2\pi (2f_1 - f_r) t - \varphi_L - \varphi_{un1} \right) \right] + U_L \left[ \cos \left( 2\pi f_r t + \varphi_L + \varphi_{un1} \right) \right].
\]

By comparing (12) and (9), it is clear that under closed-loop control of SCIM, the amplitude of \(2f_1 + f_r\) component depends not only on \(I_{p1}\) but also on \(I_1, U_{p1}, \varphi_{ip1}, \varphi_{up1},\) and \(\varphi_L\). Similarly, the amplitude of \(2f_1 - f_r\) component depends not only on \(I_{n1}\) but also on \(I_1, U_{n1}, \varphi_{in1}, \varphi_{un1},\) and \(\varphi_L\). In addition, \(I_1, U_{p1}, U_{n1}, \varphi_{up1}, \varphi_{un1},\) and \(\varphi_L\) must be added to the list of factors affecting the amplitude of the \(f_r\) component. It is known that closed-loop control can cause \(I_{p1}\) and \(I_{n1}\) to be decreased and \(U_{p1}\) and \(U_{n1}\) to appear and increase [9]-[11]. However, the overall changes on the amplitudes of the instantaneous-power harmonics depend on \(I_1\) and the relative values of the various phase angles as well. \(I_1\) depends on the SCIM load level. In addition, \(\varphi_L\) is related to the power factor of the SCIM, which depends on its load level. Therefore, it is expected that the closed-loop control increases the dependence of the amplitudes of the instantaneous-power harmonics to the load level.

We used \(u_{ab}\) as \(u_L\) and \(i_a\) as \(i_L\) when computing the instantaneous power. Fig. 4 shows the normalized spectra of the instantaneous power obtained by the experiments in three modes of supply. In this figure and all subsequent figures (except Fig. 5), normalization is against the amplitude of \(2f_1\) component. Eccentricity-related harmonic components were indicated on the spectra. As seen, the instantaneous-power spectrum in the mains-fed mode of supply has many of such harmonics, while with \(k = 1\), the resultant harmonics \((f_r, 2f_1 - f_r, 2f_1 + f_r)\) have higher normalized amplitudes. In the drive-connected modes, \(2f_1\) is below 100 Hz. This is due to the attempt to maintain the nominal speed under fractional load. Moreover, as seen in the drive-connected modes, only the high-amplitude harmonics are visible and the others are buried in noise. This is because the noise level is higher due to switching operation of the power-electronic devices of the drive. Table III gives the exact amplitudes of the three harmonics in the spectra. As seen, in the open-loop CV/f mode, the harmonic components at \(f_r\) and \(2f_1 - f_r\) have been amplified but that in \(2f_1 + f_r\) weakened below noise level (compared with mains-fed mode). As shown in Fig. 5, this is due to the amplifying effect of the CV/f mode on the \(I_{n1}\) and its weakening effect on the \(I_{p1}\). Thus, open-loop control strategies may also alter mixed eccentricity-related harmonic amplitudes in the line current, the reason of which is unclear yet. Table III also indicates a little and a large amplification of the \(f_r\) and \(2f_1 + f_r\) components, respectively, in closed-loop DTC mode. As mentioned before, multiple factors may contribute in the change of harmonic amplitudes in this mode.
TABLE III

<table>
<thead>
<tr>
<th>Supply mode</th>
<th>$f_r$ (dB)</th>
<th>$2f_1 - f_r$ (dB)</th>
<th>$2f_1 + f_r$ (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mains-fed</td>
<td>-38.8</td>
<td>-34.6</td>
<td>-39.5</td>
</tr>
<tr>
<td>Open-loop CV/f</td>
<td>-30.8</td>
<td>-29.5</td>
<td>Below noise</td>
</tr>
<tr>
<td>Closed-loop DTC</td>
<td>-37</td>
<td>-34.4</td>
<td>-32.7</td>
</tr>
</tbody>
</table>

Fig. 6. Variations of normalized amplitudes of harmonics $f_r$, $2f_1 - f_r$, and $2f_1 + f_r$ of instantaneous power versus varying load (slip) at rated speed and two mixed eccentricity cases: (1) (---) $\rho_s = 0.230$, $\rho_d = 0.380$ and (2) (---) $\rho_s = 0.115$, $\rho_d = 0.380$—mains-fed motor.

V. INFLUENCE OF VARYING LOAD ON INSTANTANEOUS-POWER HARMONICS

To extend the results to larger and smaller SCIMs, it is common to study the normalized amplitudes of eccentricity-related line-current harmonics. For the same reason, we consider the normalized amplitudes of the instantaneous-power harmonic components at $f_r$, $2f_1 - f_r$, and $2f_1 + f_r$, versus $2f_1$ amplitude and study the influence of varying load on them in this section using experimental data.

A. Mains-Fed SCIM

Figs. 6 and 7 show the variations of the normalized amplitudes of the proposed harmonic components versus varying load (slip) in four different eccentricity cases. The static-eccentricity component is dominant in Fig. 6, and, conversely, the dynamic eccentricity is dominant in Fig. 7. Except for harmonic $f_r$ in some eccentricity cases, other components are decreased by increasing load. This is mainly due to increasing the $2f_1$ power component which was used to normalize the amplitudes. Different behavior of the $f_r$ component may be due to its dependence on $\varphi_{ip1}$ and $\varphi_{in1}$ (see (9]). Reduction of the degree of static component of the mixed eccentricity leads to a decrease of the harmonic components (except one test point for $f_r$ harmonic in Fig. 7 that may be due to an experiment error). This reduction in normalized amplitude of harmonic $2f_1 + f_r$ is almost independent of the load. The same is valid for $2f_1 - f_r$, when the static-eccentricity component is dominant (Fig. 6), but it decreases more deeply on the low slips when the dynamic eccentricity is dominant (Fig. 7). It seems that in this supply mode, the harmonic component at $2f_1 + f_r$ is the most appropriate index for mixed-eccentricity-fault diagnosis.

B. Open-Loop Drive-Connected SCIM

In this mode of supply, the SCIM is controlled using CV/f technique in an open-loop manner. As seen previously, in such conditions, harmonic $2f_1 + f_r$ may not be visible in the instantaneous-power spectrum. Therefore, in this section, the influence of the varying load upon the normalized amplitudes of the two remaining harmonics will be studied. Figs. 8 and 9 show the variations of the normalized amplitudes of these harmonics by varying load (slip). The corresponding curves in the mains-fed mode are also given. The degrees of static and dynamic components of the mixed eccentricity are different in these figures. It is clear that the performance of the drive in this control technique increases the normalized amplitude of harmonic $f_r$ by more than 10 dB in most loads over two eccentricity cases. In addition, the normalized amplitude of
harmonic \(2f_1 - f_r\) in most loads increases by more than 5 dB. Thus, the aforementioned mode of supply can considerably increase the amplitudes of harmonics at \(f_r\) and \(2f_1 - f_r\), which is due to an increase of \(I_{n1}\), as indicated in Section IV.

C. Closed-Loop Drive-Connected SCIM

Amplitudes of the instantaneous-power harmonics also change when a DTC closed-loop control is applied to the SCIM. A typical result has been shown in Fig. 10. The relevant curves for \(f_r\) and \(2f_1 - f_r\) harmonics indicate that the closed-loop DTC method has no considerable effect on the amplitudes of these harmonics at around 1% slip. However, in both cases, by increasing the slip above 1% and also, in the case of \(2f_1 - f_r\), by decreasing the slip below 1%, a considerable reduction on the normalized amplitudes occurs compared with that of the mains-fed cases. Curves relevant to harmonic \(2f_1 + f_r\) also show that the DTC method has no effect on the amplitude of this harmonic at no load or low loads. However, higher loads lead to a considerable increase of the normalized amplitude of this harmonic. As predicted in Section IV, it is clear that the dependence of the harmonic amplitudes to the load level has been increased by the proposed closed-loop control strategy.

the mentioned speed reduction has no effect on the normalized amplitude of harmonic \(2f_1 - f_r\) over low loads, while it causes a considerable reduction on the harmonic over high loads (about 10 dB).

VI. INFLUENCE OF REFERENCE SPEED ON INSTANTANEOUS-POWER HARMONICS

In the case of a drive-connected motor, the speed can be changed considerably as well as the load. Therefore, its effect upon the values of the fault indexes must be determined. This is done for harmonics of the instantaneous power using the test results in this section.

A. Open-Loop Drive-Connected SCIM

Fig. 11 shows the effect of the change of reference speed on the normalized amplitudes of the two harmonics \(f_r\) and \(2f_1 - f_r\), at different loads, when the motor is supplied by the drive with CV/f control method. As seen, a 45% reduction on the speed causes no considerable change on the normalized amplitude of harmonic \(f_r\) over high loads, while it causes a considerable rise (about 8 dB) on it over low loads. Conversely,
Fig. 12. Variations of normalized amplitudes of harmonics \( f_r \), \( 2f_1 - f_r \), and \( 2f_1 + f_r \) of instantaneous power versus load (slip) at mixed eccentricity (\( \rho_s = 0.402 \) and \( \rho_d = 0.254) \) when SCIM supplied by a DTC controlled drive at (---) rated speed and (---) at 55% of rated speed.

VII. Conclusion

Theoretical study proved by experiments in this paper has illustrated that the same three major harmonic components will be present in instantaneous power of mixed eccentric SCIM, when the motor is supplied by the mains or open/closed-loop drive, although the number of factors affecting the amplitudes of the harmonics are relatively large when it is supplied by the closed-loop drive. Theoretical study has also indicated that the closed-loop drive may increase the dependence of the harmonic amplitudes to the load level, which was proved by experiments. Experimental study has illustrated a direct relationship between the harmonic normalized amplitudes and degree of mixed eccentricity over a wide range of load level. Open-loop CV/f control strategy amplifies the normalized amplitudes of two lower harmonics, while it reduces that of the third higher harmonic. Closed-loop DTC strategy have a rather opposite effects on the different harmonic components. Changing speed reference may affect normalized amplitudes of the harmonics considerably in both control strategies. Thus, the normalized amplitudes of the instantaneous-power harmonics are under the influence of different factors as well as the eccentricity degree, which are the following: the motor supply type (with drive or with no drive), control type (open loop or closed loop), load level, and speed. Therefore, using these harmonics in a fault-diagnosis technique based on AI may provide an efficient fault-diagnosis system. Obviously, all factors affecting these harmonics must be considered as inputs to the system.

REFERENCES


[31] [Online]. Available: www.bearing-king.co.uk/metric-deep-grooveball-bearings/

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