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Investigation into effect of mixed air gap eccentricity on dq components of currents in induction motor

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***Abstract*- dq components of currents are extensively used in the controller applications of industrial drives as they are dc quantities. In this paper, it is shown that these components will no longer remain as dc quantities, if they are extracted from the induction motor suffering from mixed air gap eccentricity. A dynamic model of an induction motor suffering from mixed air gap eccentricity is developed and simulated to show the presence of eccentricity characteristic harmonics in dq components of the stator currents in synchronous reference frame. In this paper, it is also shown that the frequency analysis of dq currents helps in the detection of air gap non uniformity in the machine. The results obtained by modeling and simulation are also validated experimentally.**

Index Terms— Data acquisition system. dq currents, eccentricity, induction motor

I. INTRODUCTION

Separately excited dc motor controller design is simple whereas complex controller is required in ac induction motor drives which require a coordinated control of stator current magnitudes, frequencies and their phases. In dc drives, field flux and torque can be controlled independently. Vector control made the ac drives to function similar to dc drives in which torque and flux can be controlled independently. Hence ac drives find applications in high performance drives.

dq components of stator currents in synchronous reference frame are dc signals. Hence they are ideal for use as control variables and processing these signals also will be simple. In this paper, investigations are carried out to see the impact of presence of mixed air gap eccentricity in the machine on these signals. When machine suffers from both static and dynamic air gap (mixed) eccentricity, stator currents will contain eccentricity characteristic harmonics as described by (1) [1].

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$f_e = \left| f_1 \pm k f_r \right|$ for k = 1,2,3, ….. where

$$f_r = f_1 (1 - s) / p = N_r/60 \tag{1}$$

where f_e is the eccentricity related frequency component present in the machine in Hz, f_r is the rotor frequency in Hz, s=slip, p=number of pole pairs, N_r=rotor speed.

These harmonics may give rise to high frequency harmonics as defined by (2) [1].

$$f_e=f_1[(kR\pm n_d) (1-s)/p) \pm v] \tag{2}$$

where n_d=0, in case of static eccentricity and n_d=1,2,3……., in case of dynamic eccentricity. (n_d is known as eccentric order), *R* is the number of rotor slots, f_1 is the fundamental frequency, *s* is the slip, *p* is the number of pole pairs, *k* is any integer, and *v* is the stator harmonics that are present in the power supply driving the motor (v=±1,±3,±5). But it is reported in the literature that (2) is valid only for those machines which have definite relationship between rotor bars and stator slots [1].

If the air gap non uniformity is not detected at the earliest in the machine, it may result in the increase of unbalanced magnetic pull on the rotor resulting in the rub between rotor and stator. Hence it is necessary to monitor the health of the machine continuously. Motor Current Signature Analysis (MCSA) and vibration monitoring are the most popular methods used to detect eccentricity fault in the machine [2]. Recently other parameters such as instantaneous power, instantaneous power factor etc are also used for mixed eccentricity fault detection [3,4]. In this paper, it is illustrated that dq components of stator currents is one such parameter which can be used for mixed eccentricity fault detection.

In this paper, it is shown that the presence of these harmonics in stator currents in eccentric induction motor produces harmonics 'mf_r' where m=1,2,3…in the dq components of currents in synchronous reference frame. Section II, present the modeling and simulation results. The results obtained in Section II, are validated by experiments and are discussed in Section III. In Section III, it is also shown that these parameters can be used to characterize the air gap eccentricity fault in the machine. Conclusions based on the results obtained in section II and III are presented in Section IV.

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II. MODELING AND SIMULATION

A dynamic model of induction motor is developed using multiple coupled circuit approach [5,6]. Inductances are calculated using 2 Dimensional Modified Winding Function Theory (2D-MWFT) [7,8,9]. Model is developed for a 3 hp machine whose machine details are given in Appendix. The mixed eccentricity condition is incorporated into the model by defining the air gap function as in (3) [7,8]. Permeance P along the axial length of the rotor (z) is given by

$$P(\varphi(z,\theta_r) = p_0(z) + p_1(z)\cos(\varphi - \rho(z)) + p_2(2\varphi - 2\rho(z)) \quad (3)$$

$$\delta(z) = \sqrt{\delta_s^2(z) + \delta_d^2(z) + 2\delta_s(z)\delta_d(z)\cos(\theta_r)}$$

$$p_0(z) = 1/g_0$$

$$p_1(z) = 2\,(1/(g_0\sqrt{1-\delta^2(z)}))(1-\sqrt{1-\delta^2(z)}\,/\,\delta(z))$$

$$p_2(z) = 2\,(1/(g_0\sqrt{1-\delta^2(z)}))(1-\sqrt{1-\delta^2(z)}\,/\,\delta(z))^2$$

where θ_r is the rotor position angle (rad), ϕ is the rotor ircumferential angle (rad), z is the point along the axial length of rotor (m), δ_s is the degree of static eccentricity
δ_d is the degree of dynamic eccentricity

The model is simulated for the mixed air gap condition of 10% dynamic eccentricity (DE) and 20% static eccentricity (SE). The machine model is simulated for constant full load condition. The model is simulated for a fixed step size of 0.00005 secs using Runge- Kutta 4 method. Using (4,5), the dq components of currents are obtained in synchronous reference frame [10].

$$i_q = 2/3[\cos(\omega_s t)\, i_a + \cos(\omega_s t - 2\pi/3)\, i_b + \cos(\omega_s t + 2\pi/3)\, i_c \quad (4)$$

$$i_d = 2/3[\sin(\omega_s t)\, i_a + \sin(\omega_s t - 2\pi/3)\, i_b + \sin(\omega_s t + 2\pi/3)\, i_c \quad (5)$$

where i_q is the q axis component of stator current (A), i_d is the d axis component of stator currents (A), ω_s is the stator supply angular frequency (rad/sec).

20000 data samples from dq current signals are obtained at 20 kHz and filtered using a low pass FIR filter at 1000 Hz. Power Spectral Density (PSD) is applied on these samples to extract the air gap eccentricity related harmonic components. The frequency resolution is assumed to be 1 Hz. The dq current spectra should contain at least frequency components 'mf_r' for m=1,2,3 with all other higher harmonic components being ignored.

The dq current spectra obtained for the healthy and mixed eccentricity conditions are shown in Figures 1-2. From Figures 1-2, it is observed that both i_q and i_d current spectra contain eccentricity characteristic harmonic components f_r, $2f_r$, $3f_r$ so on, in general 'mf_r' frequency components, where m=1,2,3…..,in case of a machine suffering from mixed air gap eccentricity.

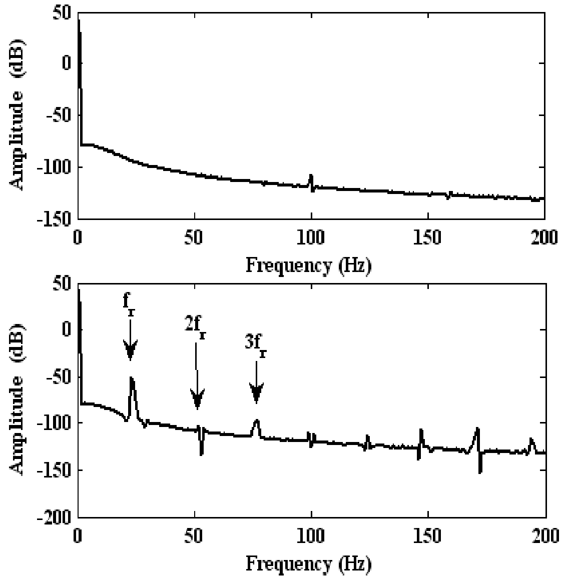

Fig1 i_q current spectra of healthy machine (above), eccentric machine with δ_s=0.2 and δ_d=0.1 (below). (under full load)

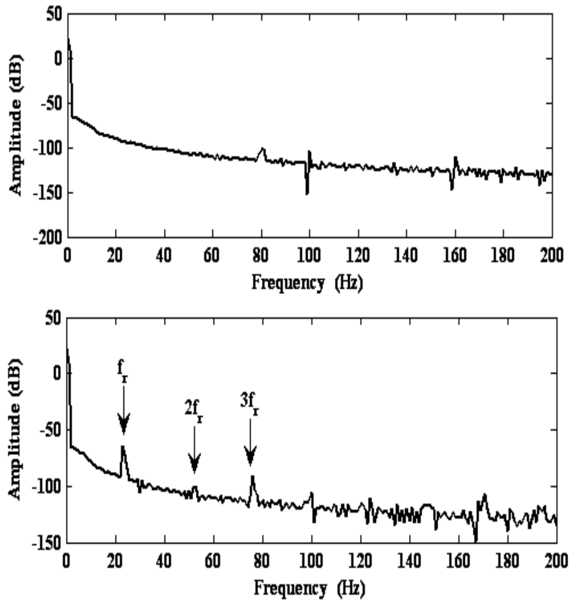

Fig2 i_d current spectra of healthy machine (above), eccentric machine with δ_s=0.2 and δ_d=0.1 (below). (under full load)

Variation of the amplitude of eccentricity characteristic components in the stator current with variation of eccentricity level in the machine is reported in [11]. The variation in the amplitude of 'f_r' component in the 'i_q' and 'i_d' current spectra, with static eccentricity in the machine maintained at 20% and dynamic eccentricity being varied is as shown in Table 1

TABLE 1
ECCENTRICITY RELATED FREQUENCY COMPONENT f_r AND ITS AMPLITUDE IN i_q AND i_d

Dynamic Eccentricity index	i_q		i_d	
	f_r (Hz)	Amplitude (dB)	f_r (Hz)	Amplitude (dB)
0.05	24	-80.13	76	-74.91
0.1	24	-73.63	76	-68.91
0.15	24	-70.77	76	-64.63
0.2	24	-67.88	76	-61.62
0.25	24	-63.91	76	-58.70
0.3	24	-57.92	76	-56.23

From the Table 1, it is concluded that the amplitude of eccentricity related harmonic component increases with the increase in the degree of air gap eccentricity in the machine. Hence they can be used as an index to detect the severity of mixed eccentricity fault in the machine.

III. EXPERIMENTAL RESULTS

3 hp induction motor is modified so that static air gap eccentricity can be varied axially as well as tangentially. It suffers from inherent dynamic eccentricity. The machine is modified according to the diagram shown in Figure3. Fan is removed for convenience. Two plates with bores on it are placed on either side of the shaft with the help of which it is possible to create uniform eccentricity along the length of rotor as well as inclined eccentricity in the machine. The fabricated machine side view and top view are shown in Figure 4. The machine has 4% static eccentricity and inherent dynamic eccentricity. To measure the static eccentricity, vernier caliper of least count 10 micron is used.

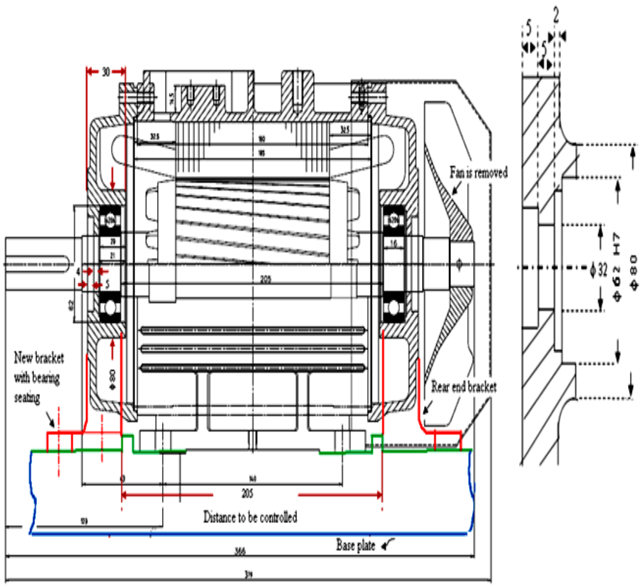

Fig3 Modified machine to vary static air gap eccentricity

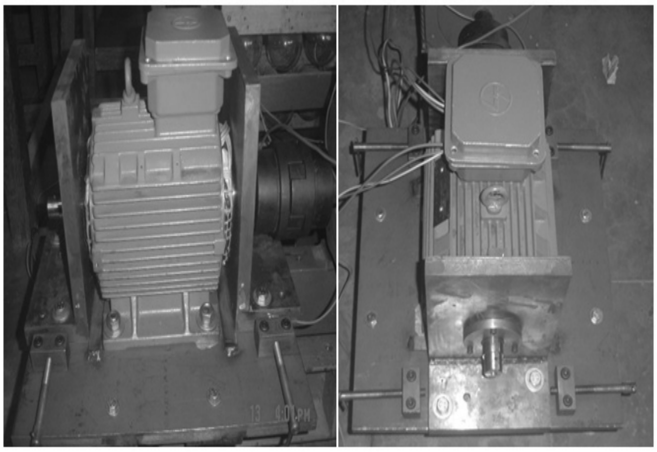

Fig4 Modified machine (a) side view (b) top view

Data Acquisition System (DAS)

In the DAS assembled, the stator phase currents are sensed by a set of three Hall Effect Current Transducers and are converted into equivalent voltages in SCXI 1338. Both current and voltage signals are conditioned in SCXI 1125 and then they are processed in PC through Data Acquisition Card. 6024-E. The SCXI-1125 provides two filtering stage with an overall response of a four pole Butterworth filter. There is a provision to control the cutoff frequency of the filter through software by choosing 4 Hz or 10 kHz provided in DAQ assistant. The chosen cut off frequency is 10 kHz.

20000 samples of three phase currents and three phase voltages at sampling frequency of 20 kHz are collected and stored as .lvm files using LabVIEW® software. Data samples are obtained for no load, 85% load and full load conditions of the motor.

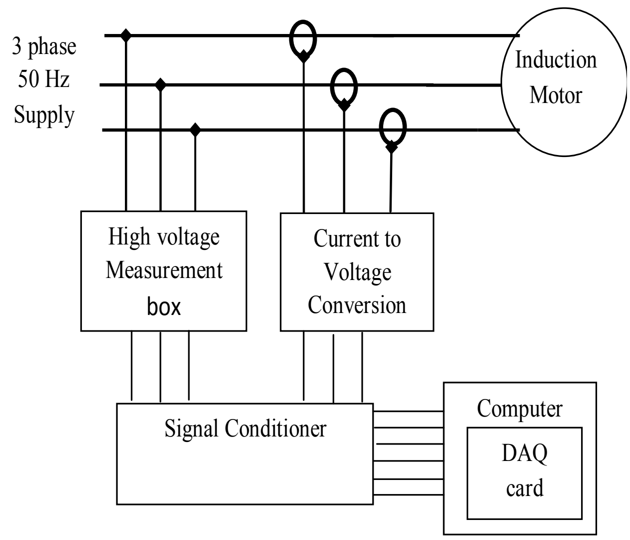

Fig5 Data Acquisition System (DAS)

Analysis of results

dq components of currents in synchronous reference frame are obtained from extracted current data samples of both healthy machine and mixed air gap eccentric machine. Power Spectral Density Analysis is performed on the stator phase A current and dq components of current to extract the eccentricity related harmonic components of mixed air gap eccentricity. As only the lower frequency components around the fundamental are considered for air gap eccentricity fault detection, further the data samples are filtered using a low pass FIR filter of 1000Hz.

Figure6 shows the stator current spectra obtained from PSD analysis of stator current data samples. From the stator phase A current spectra, it is observed that air gap mixed eccentricity related side band frequency components (f_l-f_r) (26.03 Hz), f_l (50 Hz),(f_l+f_r) (73.91 Hz), (f_l+2f_r) (99.45 Hz) are present. In general, ($f_l \pm kf_r$) for k=0,1,2……are present in the current spectra.

The machine speed is found to be 1438rpm at full load. Hence f_r=23.97 Hz. Table 2-4 gives the comparison between theoretical and experimental values of eccentricity related harmonic components found in the stator phase current. From the Tables 2-4, it is inferred that theoretically obtained air gap eccentric related side band frequency components at (f_l-f_r) and (f_l+f_r) in stator phase current especially at full load condition of the motor match with those of experimental values.

Figures 7-10 shows the q component of current, its spectra, d component of current and its spectra respectively

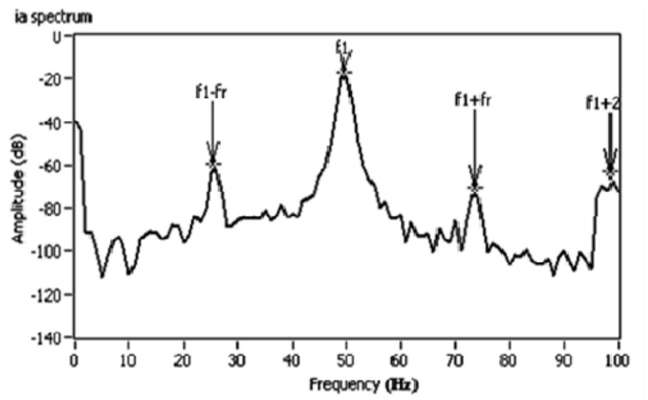

Fig 6 i_a current spectra

TABLE 2
ECCENTRICITY RELATED CHARACTERISTIC COMPONENTS IN CURRENT SPECTRA FOR MACHINE- NO LOAD CONDITION

Characteristic frequency components	No load	
	Theoretical	Experimental
f_l-2f_r (Hz)	0.21	0.35
f_l-f_r (Hz)	**25.07**	**24.98**
f_l (Hz)	**49.93**	**49.97**
f_l+f_r (Hz)	**74.79**	**74.95**
f_l+2f_r (Hz)	99.65	99.58

TABLE 3
ECCENTRICITY RELATED CHARACTERISTIC COMPONENTS IN CURRENT SPECTRA FOR MACHINE- 85% LOAD CONDITION

Characteristic frequency components	85% load	
	Theoretical	Experimental
f_l-2f_r (Hz)	1.57	0.7
f_l-f_r (Hz)	**25.68**	**25.69**
f_l (Hz)	**49.79**	**49.63**
f_l+f_r (Hz)	**73.9**	**73.90**
f_l+2f_r (Hz)	98.01	99.23

TABLE 4
ECCENTRICITY RELATED CHARACTERISTIC COMPONENTS IN CURRENT SPECTRA FOR MACHINE -FULL LOAD CONDITION

Characteristic frequency components	Full load	
	Theoretical	Experimental
f_l-2f_r (Hz)	2.05	0.7
f_l-f_r (Hz)	**26.02**	**26.04**
f_l (Hz)	**49.99**	**49.97**
f_l+f_r (Hz)	**73.96**	**73.9**
f_l+2f_r (Hz)	97.93	99.23

From the Figures 7-10, it is concluded that dq components of current will no longer remain as dc signals under mixed eccentricity conditions. The eccentricity characteristic harmonics are also present in these signals.

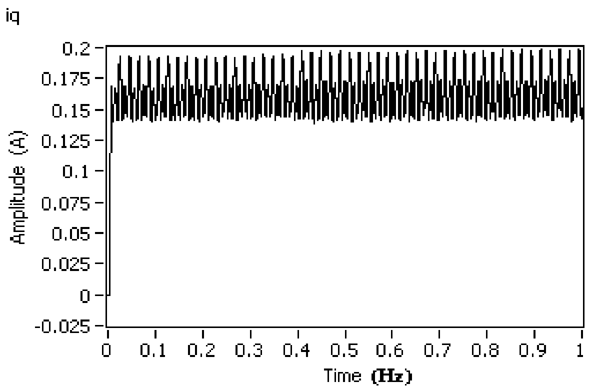

Fig 7 i_q component of current

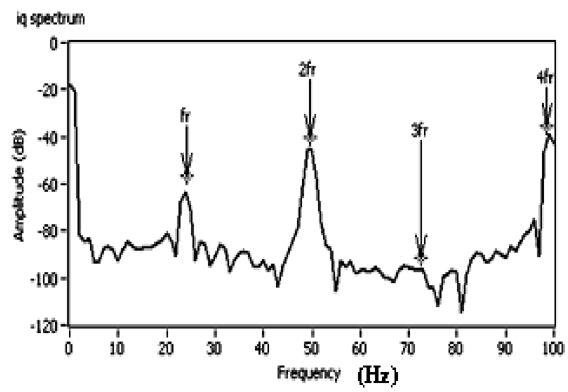

Fig 8 i_q current spectra

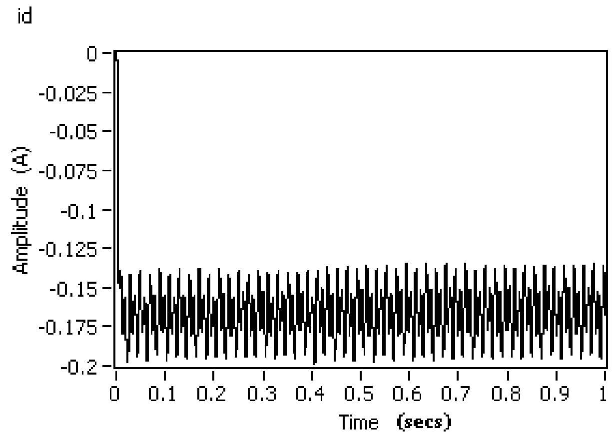

Fig 9 i_d component of current

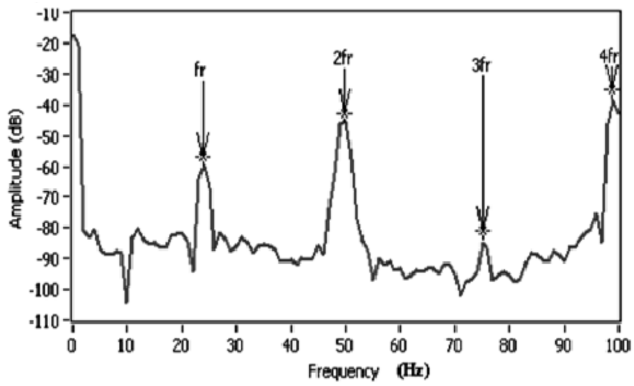

Fig10 i_d current spectra

Considering only lower frequency harmonics defined by (1) in current spectra, there should be 'mf_r' air gap eccentricity related harmonic components in i_q and i_d current spectra.

Tables 5-7 lists these eccentricity related frequency components in these currents and gives the comparison between the theoretically calculated values with those of experimental for the machine under no load, 85% load and full load conditions respectively.

From Tables 5-7, it is concluded that the rotor frequency components f_r found in the i_q and i_d current spectrum can be used to predict the presence of air gap eccentricity in the machine. Hence it can be used as an index to detect mixed air gap eccentricity in the machine.

TABLE 5

ECCENTRICITY RELATED CHARACTERISTIC COMPONENTS IN i_q AND i_d CURRENT SPECTRA FOR NO LOAD CONDITION

Characteristic frequency components	No load		
	Theoretical	Experimental	
		i_q	i_d
f_r (Hz)	**24.86**	**25**	**25**
$2f_r$ (Hz)	49.72	50	50
$3f_r$ (Hz)	74.58	75	75

TABLE 6

ECCENTRICITY RELATED CHARACTERISTIC COMPONENTS IN i_q AND i_d CURRENT SPECTRA FOR 85% LOAD CONDITION

Characteristic frequency components	85% load		
	Theoretical	Experimental	
		i_q	i_d
f_r (Hz)	**24.11**	**24.21**	**24.21**
$2f_r$ (Hz)	48.22	50	50
$3f_r$ (Hz)	72.33	75.52	75.52

TABLE 7

ECCENTRICITY RELATED CHARACTERISTIC COMPONENTS IN i_q AND i_d CURRENT SPECTRA FOR FULL LOAD CONDITION

Characteristic frequency components	Full load		
	Theoretical	Experimental	
		i_q	i_d
f_r (Hz)	**23.97**	**23.95**	**23.95**
$2f_r$ (Hz)	47.94	50	50
$3f_r$ (Hz)	71.91	76.05	76.05

It is also observed that as the degree of eccentricity increases, the amplitude of these harmonics will increase. Since these harmonics superimpose with the dc value, higher bandwidth for the computational circuits to processing these signals in the controller circuit is desired.

IV. CONCLUSION

In this paper, it is shown that, in an induction motor suffering from mixed eccentricity faults, dq components of stator currents will no longer remain as dc signals in synchronous reference frame. By both modeling and simulation and experimental results, it is pointed out that dq components of stator currents have dc component superimposed with eccentricity related harmonic frequency components 'mf_r' where m=1,2,3….. Hence the bandwidth of the computational circuits required to process these signals must be wider. As these dq components of current are used as control variables in induction motor controllers, just performing frequency analysis on these signals can reveal the presence of air gap eccentricity in the machine. The rotor rotational frequency 'f_r' in the dq current spectra can be used to characterize the mixed eccentricity fault in the machine and its amplitude can give information regarding the severity of the fault in the machine.

APPENDIX

Machine data:2.2 kW,3 hp,400/415V,50Hz,3φAC,1500rpm,4 pole squirrel cage induction motor.
Number of stator slots =24, Number of rotor bars =30, Length of stacks =120mm, Effective air gap =0.35mm, Number of turns/phase =400, Stator resistance =7.6Ω, Mean radius of air gap=89.65mm, Stator leakage inductance =38.43mH, Rotor bar resistance=0.00376Ω, Rotor bar leakage inductance =44.52μH, Rotor end ring segment resistance =0.0012 mΩ, Rotor end ring segment inductance =1.24μH, Rotor inertia =0.024 kg-m^2

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