Detection of Eccentricity Fault in Closed-Loop Induction Motor Drive using Wavelet Transform

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***Abstract*--The present paper examines eccentricity fault detection for a variable speed induction motor (IM) using an indirect field oriented control (IFOC) based inverter (PWM) for speed and stator current regulation. Although the induction machine is well known to be robust, it is subject to certain constraints due to operating conditions. Hence, detection of faults inherent to the machine is essential for improving reliability, security and avoiding unwanted or even catastrophic failures. In this work, we propose to use the Discrete Wavelet Transform (DWT) with different approaches for the diagnosis of induction machine to detect faults and identify their severity. The obtained results show that the considered methods can effectively diagnose and detect mixed eccentricity faults.**

***Index Terms*--Diagnostic, modeling, Induction Motor, IFOC, Mixed Eccentricity, Discrete Wavelet Transform.**

1. INTRODUCTION

Induction motors are also known as the asynchronous motors and they are the most used electric drive in industrial applications. (IM) are wide spread electromechanical conversion systems for high-dynamic performance applications. Now it covers most of the transformation needs of electrical energy to mechanical energy. Since it has the advantage of being robust, simple and low cost. However, the fault diagnosis of such machines has become an essential and necessary task to get a will functioning of a more secured production chain for most industrial applications. Also, the production lines must be provided with effective protection systems since any failure can cause hardware damage and / or body. To avoid such problems, many researchers are still working to develop various dynamic models for analysis and fault diagnosis purpose of the induction motor. They have developed many types of software whose main objective is to prevent users from risks that could possibly happen in a particular point of the system. There are many studies on eccentricity faults in line connected induction motors, but there are fewer studies on inverter driven induction motors. The supply voltage in line-connected motor has a sinusoidal waveform. On the other hand, the closed-loop harmonic components through controllers in control loops affect the machine parameters (voltage and current) and try to make them equal to the command values. The impact of faults on controlled variables weakens and faults detection may be difficult. On the whole, characteristics of control loops should be considered in an appropriate fault detection method. The work we developed through this contribution relates to a fault detection method of mixed eccentricity in a three-phase variable speed induction motor using an indirect field oriented control powered by a voltage inverter (PWM) [1], [2]. We present in this paper a method for detecting and isolating defects of eccentricity. The proposed method uses frequency analysis of stator phase current based on Discrete Wavelet transform (DWT) [3]. Its multi resolution analysis and good time localization are used to detect electrical and mechanical failure in an induction machine, we use Daubechies 44 (db44) as mother wavelet function for the analysis of the mixed eccentricity [4].

2. INDUCTION MOTOR MATHEMATICAL MODEL

The proposed model is based on an approximation of coupled circuits where the magnetic current in each mesh of the rotor cage is an independent variable as shown in Fig.1.

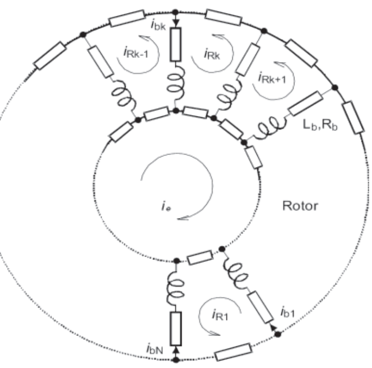

Fig.1. Equivalent Rotor mesh circuit

This approach offers a compromise in terms of model accuracy and computation time. In addition to that, this type of model can take into account a number of electromagnetic faults such as broken bars and eccentricity faults. By using extended Park transformation in the (d, q) frame, we obtain the mathematical model of the induction motor [2], [3], [5] which takes into account the failure of the rotor and can be written as:

$$[L]\frac{d[I]}{dt}=[V]-[R][I] \tag{1}$$

$$[I]=[I_{ds} \quad I_{qs} \quad I_{dr} \quad I_{qr}]^T$$

$$[V]=[V_{ds} \quad V_{qs} \quad V_{dr}=0 \quad V_{qr}=0]^T$$

$$[L]=\begin{bmatrix} L_{sc} & 0 & \frac{-N_r}{2}M_{sr} & 0 & 0 \\ 0 & L_{sc} & 0 & \frac{-N_r}{2}M_{sr} & 0 \\ \frac{-3}{2}M_{sr} & 0 & L_{rc} & 0 & 0 \\ 0 & \frac{-3}{2}M_{sr} & 0 & L_{rc} & 0 \\ 0 & 0 & 0 & 0 & L_e \end{bmatrix} \tag{2}$$

where

L_{sc} : is the total inductancegiven by the expression with

$$L_{sc}=\frac{6.\mu_0.N_s{}^2.r.l}{e.\pi.p^2}+L_s \tag{3}$$

e: air gap of the machine, L_s : leakage inductances, r: mean radius of the machine, l : length of the machine and μ_0 :air permeability.

$$[R]=\begin{bmatrix} R_s & -\omega.L_{sc} & 0 & \frac{-N_r}{2}.\omega.M_{sr} & 0 \\ \omega.L_{sc} & R_s & \frac{-N_r}{2}.\omega.M_{sr} & 0 & 0 \\ 0 & 0 & R_r & 0 & 0 \\ 0 & 0 & 0 & R_r & 0 \\ 0 & 0 & 0 & 0 & R_e \end{bmatrix} \tag{4}$$

$$R_r=L_{rp}+\frac{2L_e}{N_r}+2R_b(1-\cos(a)) \tag{5}$$

$$L_{rc}=L_{rp}-M_{rr}+\frac{2L_e}{N_r}+2L_e(1-\cos(a)) \tag{6}$$

After applying the extended Park transformation on the expression of electromagnetic torque, the mechanical part is ultimately determined by the relationship obtained below:

$$\frac{d\omega}{dt}=\frac{1}{J}(T_e-T_r-f_v.\omega) \tag{7}$$

$$T_e=\frac{3}{2}.p.N_r.M_{sr}.(I_{ds}.I_{qr}-I_{qs}.I_{dr}) \tag{8}$$

Where p: is pole number, N_r: number of rotor bar, M_{sr}: Mutual inductance.

3. INDIRECT FIELD ORIENTED CONTROL

The principle of control by (FOC) field oriented control [6] applied to an asynchronous motor is based on the decoupling between the current components used for generating magnetizing flux and torque. The decoupling allows the induction motor to be controlled as a simple DC machine with separate excitation [7]. The field oriented control implies the translation of coordinates from the fixed reference stator frame to the rotating synchronous frame. This implies that the i_{ds} component of the stator current would be aligned with the rotor field and the i_{qs} component would be perpendicular to i_{ds} as shown in Fig.2.This translation makes possible the decoupling of the stator current into two components, which are responsible for the magnetizing flux and the torque generation. However, calculation of the rotor flux is carried out by two different ways. If it is measured directly by using sensors, it is called direct Field Oriented Control (DFOC). If measurement is calculated from slip of dynamic model of induction motor, it is called indirect Field Oriented Control (IFOC) [8], [9]. The IFOC technique has simple implementation and it is more reliable what makes it widely used in industry. The IFOC is based on a number of assumptions, more precisely: $\varphi_{rq}=0$; $V_{rd}=0$and$V_{rq}=0$.

The advantage of using a reference related to the rotating field frame is to have constant magnitudes. It's then easier to make the regulation, by acting on the i_{ds} and i_{qs} variables. The magnitudes φ_r and T_e are ordered separately. This results in:

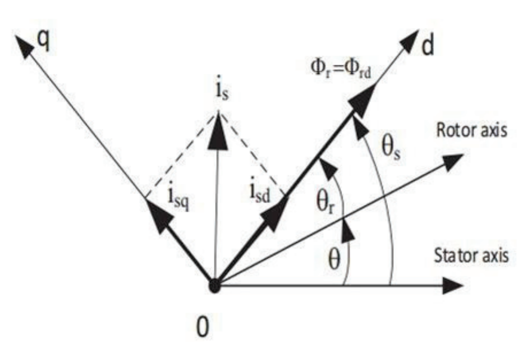

Fig. 2. Stator current space vector and its component

$$\begin{cases} \dfrac{d\varphi_r}{dt} = \dfrac{M_{sr}.i_{ds} - \varphi_r}{T_r}; \ \omega_{sl} = \dfrac{M_{sr}.i_{qs}}{T_r.\varphi_r} \\ T_e = \dfrac{p.M_{sr}.i_{qs}.\varphi_r}{L_r} = K.i_{qs} \end{cases} \quad (9)$$

Where ω_{sl}: is a slip frequency.
Hence, the analogy with DC machine performance is clearly established, by keeping the flux constant. The electric torque is found proportional to the i_{qs} component, and the flux φ_r and i_{ds} component of current can be related through the first-order linear transfer function where T_r is a rotor time constant.

4. ECCENTRICITY FAULT MODEL

Eccentricity fault is more related with internal faults of the machine; it appears when there is an unequal air gap between rotor and stator. Three kinds of eccentricity can be considered: static eccentricity (SE) [1], dynamic eccentricity (DE) [11] and mixed eccentricity (ME), [10]. In the first static eccentricity, the air gap becomes irregular, therefore in this case the minimum air gap location appears at a specific fixed position. Its function varies in a sinusoidal manner with the angular position of the stator. Dynamic eccentricity exists when axis of rotation coincides with axis of stator but not with axis of rotor, the minimum air gap location then changes with the rotor's angular position and revolves with it. For the mixed eccentricity(ME), the two defects(SE)and (DE)are present at the same times and axis of rotation is different from both axis of stator and rotor. In this work, we chose to study mixed eccentricity fault. The expression of the air gap that reflects this type of defect is expressed by the following equation:

$$e(\theta_s, \theta_r) = e + \varepsilon_s \cos(\theta_s) + \varepsilon_d \cos(\theta_s - \theta_r) \quad (10)$$

with
e: air gap of the machine;
$\varepsilon_s = a_1.e$: is the percentage of static eccentricity;
$\varepsilon_d = a_2.e$: is the percentage of dynamic eccentricity.

5. FAULTS DETECTION METHODS

A. Wavelet Transform

This transform is an extension of a given waveform in a space which is defined by a set of orthonormal or orthogonal functions. The wavelet *Ψ (t)* is as its name suggests the localized waveform [12], which satisfies some conditions and defined as:

$$\psi_{s,\tau}(t) = \frac{1}{\sqrt{s}}\psi\left(\frac{t-\tau}{s}\right) \quad (11)$$

The parameter τ indicates the translation in time, and the parameter s is a scale parameter. The translation and the expansions transform the signal into another timescale. The representation form with smaller scales corresponding to the high frequency components [13].
In the case of discrete wavelet transform, the expansion and translation parameters s, τ are limited only to discrete values leading to the following expression:

$$\psi_{s,\tau}(t) = \frac{1}{\sqrt{s_0^j}}\psi\left(\frac{t - k\tau_0 s_0^j}{s_0^j}\right) \quad (12)$$

Where, the whole numbers s and τ control respectively the wavelets expansion and translation. For practical reasons, the simplest and most efficient discretization comes by choosing $s_0 = 2$ and $\tau_o = 1$:

$$\psi_{s,\tau}(t) = \frac{1}{\sqrt{2^j}}\psi\left(\frac{t - k2^j}{2^j}\right) = 2^{\frac{-j}{2}}\ \psi\ 2^{-j}t - k \quad (13)$$

Obviously, different mother wavelets generate different classes of wavelets, and hence the behaviour of the decomposed signal can be quite different.

B. Wavelet Energy

The fault diagnosis is based on observation and comparison between levels decomposition that contain default information. When mixed eccentricity fault appears in an asynchronous machine, the stator current signal, contain information included in each frequency band which is resulting from the decomposition of wavelet packet. The energy value associated to each level or each node of decomposition is defined by [12], [13]:

$$E_j = \sum_{k=1}^{n} D^2{}_{j,k}(n) \quad (14)$$

where
j is the level of detail,
D_{jk} is the detail signal at level j and n is the total number of samples of the signal.

The energy values of decomposition levels contain necessary diagnostic information. The plot of these values can be used to diagnose faults in the squirrel cage induction motor and it can also identify the degree and the severity of the fault. Before the calculation of the wavelet energy, the number of the decomposition levels must be well defined by the following relationship [13], [14]:

$$N = \text{int}\left[\frac{log\left(f_e / f_s\right)}{log\left(2\right)}\right] + 2 \quad (15)$$

With f_s: frequency of the fundamental, f_e: frequency of sampling.

6. Simulation and Interpretation

The static and dynamic performances of IFOC are evaluated using the Software Matlab/Simulink. The machine parameters are mentioned in the appendix below.

a. Results for healthy machine

Figs. 3(a-c) shows the speed, the stator currents and the electromagnetic torque under healthy conditions of the machine. The test of control is realised with an inversion of the speed from +20rad/s to -20rad/s at time t=1.5s. This change of the direction of rotation proceeds with application of load torque equal to 3.5N.m at time t=0.6s. The speed settling time is about 0.2s and the steady state error is very small.

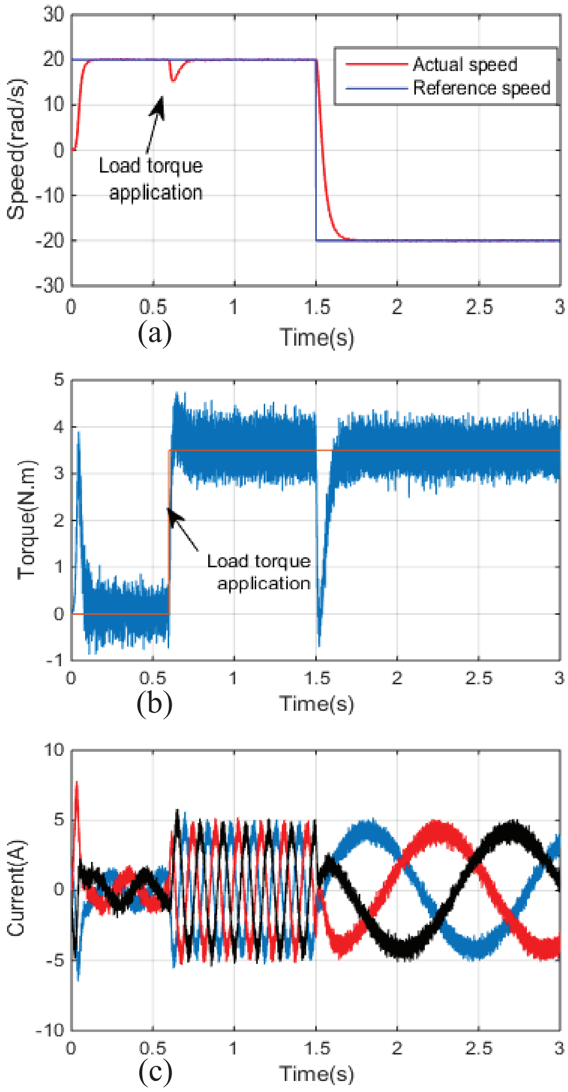

Fig. 3. Healthy condition of the motor: (a) Rotor speed, (b) Stator currents, (c) Electromagnetic torque.

b. Results for machine with mixed eccentricity fault

In Figs. 4(a-c) we applied mixed eccentricity fault ME=10% (SE=10% and DE=10%) at start-up of motor. We note the apparition of oscillations. They are very visible considering the healthy case and are due to the impact of eccentricity defect. In Fig. 4(a) we observe that speed always remains stable and follows the reference with small oscillations. These results show that the indirect vector command applied to the asynchronous machine presents an interesting performance.

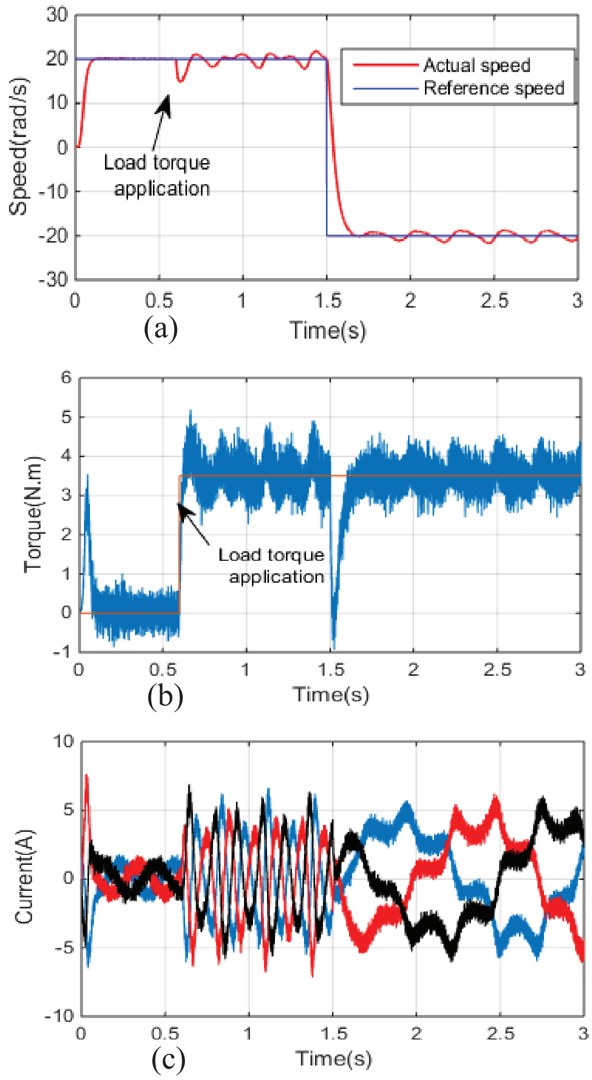

Fig. 4. Faulty motor with mixed eccentricity fault (ME 10%): (a) Rotor speed, (b) Stator current, (c) Electromagnetic torque.

c. DWT analysis

The decomposition in multi levels of the stator current is carried out using the mother wavelet Daubechies44 (db44). The level of decomposition necessary is calculated with the relationship [15]:

TABLE 1
Frequency bands of approximation and details

Levels	Frequency bands approximation	Frequency bands Details
7	0-39.0625	39.0625-78.125
8	0-19.531	19.531-39.0625
9	0-9.76	9.76_-19.531
10	0-4.88	4.88-9.76
11	0-2.44	2.44-4.88
12	0-1.22	1.22-2.44

$$N = \text{int}\left[\frac{log\left(10^4/7\right)}{log\left(2\right)}\right] + 2 = 12\ levels \qquad (16)$$

With f_s: frequency of the fundamental, f_e: frequency of sampling. In our simulation, f_s=7 Hz and f_e =10 kHz. One can calculate the number of appropriate decompositions that is equal to 12 levels; the Table1 indicates the different frequency bands of approximation and details [16], [17].

Fig. 5 shows the DWT analysis of the stator current signal given in Fig. 3(a), Fig. 4(a) (original signal) and d12, d11, and d10 are the detail signals obtained by mother wavelet db44 at level 12, in the case of healthy condition and faulty case.

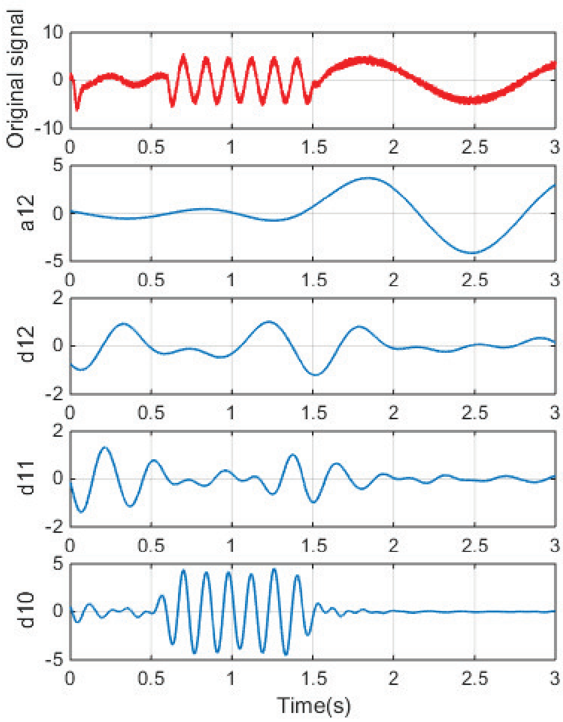

Fig. 5. DWT analysis of current for the healthy machine

A comparison between Fig. 5, and Fig 6 when we applied a load torque at t=0.6s and then we changed direction of rotation at t=1.5s, shows that in the d10 and d12 levels signal, there is no much change but there is an important variation in the d11 level signal, which contains low band frequency, caused by harmonic of the eccentricity fault. The fault frequency components of the eccentricity defect are based on expressions **(18)**:

$$f_{ecc} = f_s\left(1 \pm k\left(\frac{1-s}{p}\right)\right) \qquad (17)$$

with

f_{ecc} :eccentricity fault frequency, f_s :fundamental frequency, $k = 0, 1, 2,\ldots n$:constant and s :is motor slip.

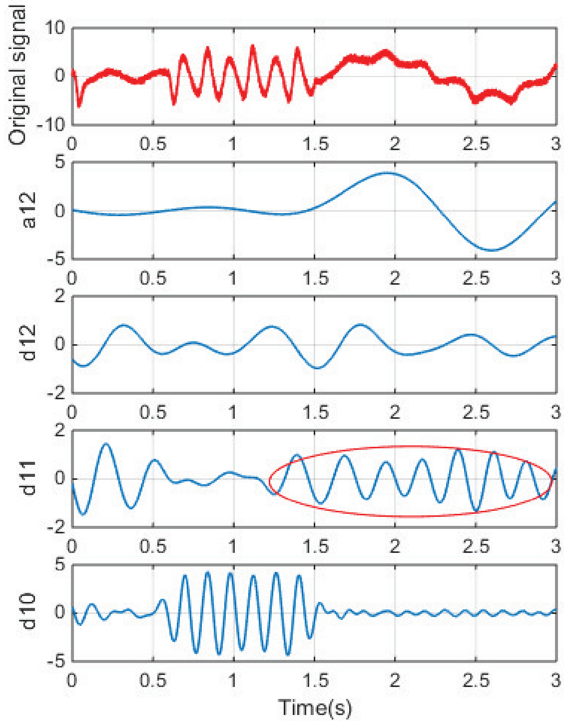

Fig. 6. DWT analysis of current for faulty machine under (ME 10%)

Fig. 7 shows the variation of the energy in the frequency bands of decomposition of multi wavelet-levels in the case of a healthy machine and with three degrees of mixed eccentricity defects: (ME 5%, ME 10%, ME 20%) [6], [11]. The stored energy in each level of decomposition, confirms the observed increase in the signals of detail and approximation especially in the level 10 (see TAB1). This is corresponding to the band of neighborhood and below of the fundamental f_s=7HZ. The effect of the mixed eccentricity default is clearly manifested by the energy stored in the level 10. The increase differs according to the severity of default: the energy in the healthy case is 14.5%, in the case of (ME 5%) the energy is 15.8%, in the case of (ME 10%) the accumulated energy is 18%, and for the case of (ME 20%) the stored energy in the level 10 is in a remarkable way 22.7%. We can see that the difference between the healthy and the faulty case is very clear, and the increase of energy differs according to the severity of default.

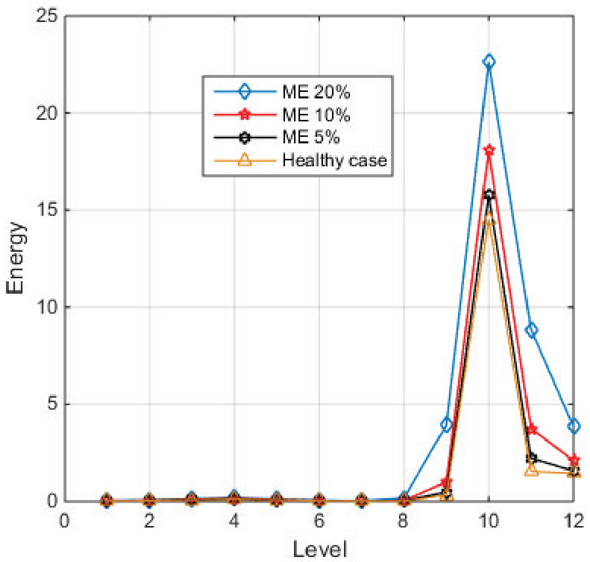

Fig. 7. Energy calculation from stator current for healthy and faulty cases

7. CONCLUSION

The aim of this work is the use of DWT in the diagnosis of indirect field oriented control (IFOC) based asynchronous machine. From the obtained results, it has been shown that, using the proposed approach and the energies of the high-level DWT decomposition, the mixed eccentricity faults could be easily detected, even for the case of non-stationary operating conditions (variable speed and load torque) of the motor. Moreover, and despite of closed loop control, it has been noticed that the employed technique is very effective in detection of fault and its severity.

APPENDIX

The machine parameters are:

Pn=1.1Kw, U=220/380V, In=4.5/2.6A, Ωn=2850tr/mn,
Rs=7.58Ω, Rr=6.3Ω, Rb= 0.15 mΩ, Re= 0.15 mΩ,
Lb=0.1 μH, Le= 0.1 μH, Lsf= 26.5mH, Msr= 46.42 mH,
Ns= 160, Nr=16, L=65mm, e= 2.5 mm,
J= 0.0054 kg.m2 et P= 1.

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