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Fault diagnostic proposal for an induction motor using combined models of parity equations

Propuesta de diagnóstico de fallas para un motor de inducción utilizando modelos combinados de ecuaciones de paridad

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Abstract

This work consists of a combined technique of two residual arrays for additive and parametric detection faults in a three-phase induction motor based on parity equations applied through a hybrid model with stable state behavior in the DQ reference frame. The main idea of this technique is to approximate the nonlinear model of induction motor to the linear model of DC motor, during the synchronous reference frame, with the intention of generating a significant change in the residues obtained by the combinations of parity equations in presence of faults. On the other hand, a more simplified and reliable analysis is used in the detection of the fault. Final mathematical analysis can be validated using a reliable simulation environment that enables interaction with power electronics, motor control, data analysis, numerical calculation, and dynamic system model design such as the software of PSIM or MATLAB.

Diagnostic, Fault detection, Induction motor

Resumen

Este trabajo consiste en una técnica combinada de dos matrices residuales para la detección de fallas aditivas y fallas paramétricas en un motor de inducción trifásico basadas en ecuaciones de paridad aplicada a través de un modelo hibrido con comportamiento en estado estable en el marco de referencia DQ. La idea principal de esta técnica es aproximar el modelo no lineal del motor de inducción al modelo lineal del motor de CD durante el marco de referencia sincrónico, con la intención de generar un cambio significativo en los residuos obtenidos mediante las combinaciones de las ecuaciones de paridad obtenidas en presencia de fallas, por otro lado, se utiliza un análisis más simplificado y confiable para la detección de la falla. El análisis matemático final se podrá validar utilizando un entorno de simulación confiable que permite la interacción con la electrónica de potencia, control de motores, análisis de datos, calculo numéricos y diseño de modelos de sistemas dinámicos como lo es PSIM o Matlab.

Diagnóstico, Detección de fallas, Motor de inducción

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Introducción

The induction motor IM is well known as the labor force in the industry. It is and will continue to be widely used in a great variety of application due to a great variety of factors such as low costs, simple construction, robustness and reliability (Kosow, 1993) Unlike the DC motor, the IM can be utilized in volatile or aggressive environments since sparks and corrosion pose no trouble at all respectively, although the degree of reliability tends to diminish under extreme working environment conditions which are greatly magnified when the IM operates with a critical load, a situation which could be a risk for the safety of the personnel, the environment and economy. Its use varies in industrial processes, and it can be frequently seen integrated in many critical processes (Krishnan, 2001).One way to raise the degree of reliability is through maintenance programs and specific attention by means of constant monitoring of the motor, with the objective of detecting faults and avoiding errors in the process (Isermann T. H., 1996).

Generally, the most frequent IM faults are of mechanical nature, and these are related with the electrical operation of the motor, such as overheating and inter-turn short circuit in stator winding (Chen, 2012). A fault in the motor components cause a waste of resources, materials and time, in addition it may turn into a risk of damage to other elements of the process, not to mention the possible effects on the integrity of the staff that coexists with the equipment (Isermann R. , 1995). The most common basic faults in IM are rotor faults, stator faults, and bearing faults to name a few, the latter is the most recurrent and carries with it the eccentricity effect that consists of the misalignment of the axis of rotation with respect to the axis of the machine (Loparo, 2000).

The relevance of motors in industrial processes has prompted a fairly broad field of research in the diagnostic area (Benbouzid, 1999), (Bachir, 2001). Various studies have sought a way to increase the reliability of the object of study from preventive maintenance using criteria and methodologies for control and supervision (Krause, 2002). A starting point to begin any type of study inherent to IM is to understand their operation and the elements that comprise it.

Currently, two main fault detection and diagnosis methods are used in induction motors; one is the method based on signal analysis and the other is the method based on parameter estimation (Krause, 2002). The merit of the parameter estimation method is that it is easier to identify or isolate faults; if the necessary parameters can be estimated online, then fault detection and diagnosis can be easily achieved. The merit of the method based on signal analysis proposed by Schoen (Schoen, 1995) is that it can be easily used for fault detection, but it is difficult to use for the isolation of faults in IM. Current spectrum analysis has gained more prominence in its use in the last few decades due to its low cost in comparison with the other two methods above mentioned (Loparo, 2000), (Mohamed El, 2000).

Vibration analysis is the most widely studied technique to detect faults in IM (Nandi, 2002) due to its significant magnitudes and the immunity to external phenomena such as electromagnetic interference in sensors like accelerometers, although the problem is the very limited operating range.

Another technique based in the model is the use of parity equations (Bouattour, 2000), (Isermann T. H., 1996) which can be adequate for the detection of a wide variety of faults, but for calculating the residuals of the general parity equation it is necessary to first obtain an accurate mathematical model of the system (Chen, 2012). This is mostly performed on linear systems, where precise model is more easily available.

The most susceptible part to faults are bearings, stator winding, engine bar and the axis. Faults can be classified as follows *electrical faults, mechanical faults, and environmentally-related faults* (Kosow, 1993).

A simple way to detect faults is to compare the behavior of the process signals to the signals of the model in its ideal state. Any existing differences between the process and the model are detected through a residual series in such a way that residuals oversee detecting faults that may exist during the process. The parity equation method goes after the probability with the formulation of the model in state-spaces.

The proposal is to design and perform the physical modelling for the detection of faults in a three phase IM using a combination of the parity equations proposed in (Rodríguez, 2011) and (Chulines, 2018) and considering sensors to determine changes in the current, voltage and positioning in the IM. The residuals obtained through the parity equations will be implemented by using a test bank and the faults will be simulated through PSIM software.

In the Introduction section of this paper, it is highlighted the importance of IM in the industry, in addition to being the very core of the industry until today, it is also mentioned that there are techniques and methods for the detection of faults for preventive and corrective maintenance, to extend the lifetime of the IM. The current paper is developed based on one of the methods already described.

The Methodology section presents the IM modelling under the reference frame DQ, which describe the mechanical and electrical equations. The section continues to describe the residuals generation through the selected parity equations technique, as well as the operation thresholds in which these operate in fault-free conditions alongside the fault detection matrix for the DQ model. Next, it moves on to present the equations and residuals in the case of the stator model and the model combination is made to generate a combined detection table which gives as a result a better detection.

In the Conclusion section, considerations for the detection are presented as well as the references studied for this article.

Methodology

Fault diagnostic for the induction motor under the DQ reference frame

Usually, an IM is connected to an inverter to control the speed in various applications. However, there exists 'non-critical' applications in which it is only necessary to have a constant functioning in stationary state. In this sense, it is important to have a constant monitoring for a fault diagnostic in a synchronous IM.

Modelling of the induction motor under the DQ reference frame

The starting point for the analysis of the IM model under the synchronous reference frame is to initially deduce the transfer functions in the electrical and mechanical subsystem. For the electrical and mechanical pieces to be coupled, there exists a link between the current produced by torque and the induced magnetic force. This link is implicit in total current loop of IM and is independent from the mechanical part in the transfer function (Krishnan, 2001). The supposition for the deductions of the transfer functions applied to the IM is to consider constant the flux linkages in the rotor ψ_ry $p\psi_r = 0$.

Next, the stator equations are:

$$V_{qs} = (R_s + L_s\rho)i_{qs} + \omega_s L_s \rho i_{ds} + L_m \rho i_{qr} + \omega_s L_m i_{dr} \quad (1)$$

$$V_{ds} = (R_s + L_s\rho)i_{ds} - \omega_s L_s \rho i_{qs} + L_m \rho i_{dr} - \omega_s L_m i_{qr} \quad (2)$$

From these equations related to the rotor in the DQ axis from the flux linkages, the following equations in the stator currents are obtained.

$$i_{qr} = -\frac{L_m}{L_r} i_{qs} \quad (3)$$

$$i_{dr} = \frac{\psi_r}{L_r} - \frac{L_m}{L_r} i_{ds} \quad (4)$$

Substituting the rotor currents (3) and (4) in (1) and (2) the following expressions are obtained.

$$V_{qs} = (R_s + \sigma L_s \rho)i_{qs} + \sigma\omega_s L_s i_{ds} + \omega_s \frac{L_m}{L_r}\psi_r \quad (5)$$

$$V_{ds} = (R_s + \sigma L_s \rho)i_{ds} - \sigma\omega_s L_s i_{qs} + \frac{L_m}{L_r}\rho\psi_r \quad (6)$$

Where σ is the leakage coefficient and it is obtained when the flux component produced by the stator current is constant in steady state, so that the derivatives of the stator current in the *d* axis in the synchronous frame are:

$$i_f = i_{ds}$$

$$pi_{ds} = 0$$

ISSN: 2410-3454

June 2021, Vol.8 No.25 25-35

The total torque component produced by the stator current is the current in the q axis in the synchronous frame.

$$i_T = i_{qs}$$

It is also known that the rotor flux is given by:

$$\psi_r = L_m i_f$$

Substituting the values above in the stator voltage equation.

$$V_{qs} = (R_s + L_s\rho)i_T + \omega_s L_a i_f + \omega_s \frac{Lm^2}{L_r} i_f$$
$$= (R_s + L_s\rho)i_T + \omega_s L_a i_f \quad (7)$$

Where L_a is:

$$L_a = \sigma L_s = \left(L_s - \frac{Lm^2}{L_r}\right) \quad (8)$$

Now, the stator frequency is represented by:

$$\omega_{s1} = \frac{i_T}{i_f}\left(\frac{R_r}{L_r}\right)$$

$$\omega_s = \omega_r + \omega_{s1} = \omega_r + \frac{i_T}{i_f}\left(\frac{R_r}{L_r}\right) \quad (9)$$

The equation for the motor electrical part can be obtained substituting ω_s in (2).

$$V_{qs} = \left(R_s + \frac{R_r L_s}{Lr} + R_a\rho\right) i_T + \omega_r L_s i_f \quad (10)$$

When the torque is produced by the stator current it can be derived from the following equation.

$$I_T = \frac{V_{qs} - \omega_r L_s i_f}{R_s + \frac{R_r L_s}{L_r} + L_a\rho} = \frac{K_a}{1 + sT_a}\left(V_{qs} - \omega_r L_s i_f\right) \quad (11)$$

Where:

$$R_a = R_s + \frac{L_s}{L_r}R_r \qquad K_a = \frac{1}{R_a} \qquad T_a = \frac{L_a}{R_a}$$

For this section, the feedback voltage is converts to the torque current, then the electromagnetic torque is written:

$$\tau_e = K_f i_T \quad (12)$$

Where the torque constant is defined by

$$K_f = \frac{3}{2}\frac{P}{2}\frac{Lm^2}{L_r} i_f \quad (13)$$

Dynamic loads can be represented taking the electromagnetic torque and the load torque that is considered friction, in this particular case.

$$j\frac{d\omega_m}{dt} + B\omega_m = \tau_e - \tau_L = K_f i_T - B_l\omega_m \quad (14)$$

When in terms of the electric velocity of the rotor, it is derived from the multiplication of both sides by the pair of poles

$$j\frac{d\omega_r}{dt} + B\omega_r = \frac{P}{2}K_f i_T - B_l\omega_r \quad (15)$$

Next, the transfer function between velocity and produced torque.

$$\frac{\omega_r(s)}{I_T(s)} = \frac{K_a}{1 + sT_a} \quad (16)$$

Where

$$K_a = \frac{P}{2}\frac{K_f}{B_t}, \qquad B_t = B + B_l, \qquad T_a = \frac{J}{B_t}$$

Once the electrical and mechanical parts of the IM are solved from equations (7) and (8), the block diagram is obtained in the following drawn:

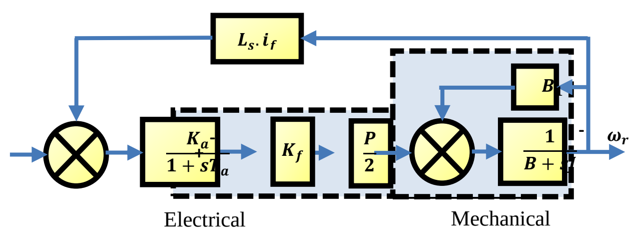

Figure 1 Block diagram of the IM model with rotor flux constant linkage
Source: R. Krishnan, Electric Motor Drives Modeling, Analysis and Control. Prentice Hall, 2001

This model is like the DC motor model shown in (Chan, 2006) and (Isermann T. H., 1996), the main difference is that this model takes V_{qs} as input parameter rather than the armature current I_A.

Residuals generation through parity equations

The present work makes use of a simple model of instantaneous computation in steady state mode which has little similarity to the DC motor (Krishnan, 2001) since the fault detection based on parity equations for this type of model is the availability to detect various parameters (Chan, 2006).

Based on known ways of theoretically modeling the structure of a linear mathematical model in continuous time without taking into account the perturbations (17) and (18), the representation of the state-space model obtained for the IM is shown in (19) and (20).

$$\dot{\mathbb{x}}(t) = \boldsymbol{A}\mathbb{x}(t)\mathbb{u}(t) \quad (17)$$

$$\mathbb{y}(t) = \boldsymbol{C}\mathbb{x}(t) \quad (18)$$

$$\begin{bmatrix} \dot{I_{qs}} \\ \dot{\omega_r} \end{bmatrix} = \begin{bmatrix} \frac{-R_a}{L_a} & \frac{-\psi}{L_a} \\ \frac{K_t N_p}{J} & \frac{-(B+B_1)}{J} \end{bmatrix} \begin{bmatrix} I_{qs} \\ \omega_r \end{bmatrix} + \begin{bmatrix} \frac{1}{L_a} & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} V_{qs} \\ 0 \end{bmatrix} \quad (19)$$

$$\mathbb{y}(t) = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} I_{qs} \\ \omega_r \end{bmatrix} \quad (20)$$

Where:

$$\psi = L_s I_{ds}, \qquad N_p = \frac{P}{2} \quad (21)$$

It should be taken into account that the structure obtained in (19) is similar to the DC motor model shown in (Chan, 2006) and (Isermann T. H., 1996) but it is not the same. An important difference is that the second input term $\dot{I_{qs}}$ in (19), the magnetic flux is defined as the relationship between the stator inductance and the stator current $\psi_s L$ of the D axis in the I_{ds} synchronous frames. Another important difference is that the first term of ω_r, the magnetic flux ψ, the motor model is defined as the ratio between the number of poles P, the magnetic inductance L_m, the rotor inductance L_r and the current flux producing component of the stator I_f.

One way to add redundancy in the equations in the instant t is introducing (17) in (18) with their respective derivatives as:

$$\boldsymbol{Y}(t) = \boldsymbol{T}\mathbb{x}(t) + \boldsymbol{QU}(t) \quad (22)$$

Where:

$$\begin{bmatrix} y(t) \\ \dot{y}(t) \\ \ddot{y}(t) \\ \vdots \\ y^q(t) \end{bmatrix} = \begin{bmatrix} \boldsymbol{C} \\ \boldsymbol{CA} \\ \boldsymbol{CA^2} \\ \vdots \\ \boldsymbol{CA^q} \end{bmatrix} \mathbb{x}(t) + \begin{bmatrix} 0 & 0 & 0 & \dots & 0 \\ \boldsymbol{CB} & 0 & 0 & \dots & 0 \\ \boldsymbol{CAB} & \boldsymbol{CB} & \boldsymbol{CB} & \dots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ \boldsymbol{CA^{q-1}B} & \boldsymbol{CA^{q-2}B} & \dots & \boldsymbol{CB} & \boldsymbol{0} \end{bmatrix} \begin{bmatrix} u(t) \\ \dot{u}(t) \\ \ddot{u}(t) \\ \vdots \\ u^q(t) \end{bmatrix}(t) \quad (23)$$

Now the residual vector based on the state-space model for continuous time is given in (24), which is deduced in (Isermann T. H., 1996) from the residual generation with parity equations for the MIMO process with transfer functions and polynomial error.

$$\boldsymbol{r}(t) = \boldsymbol{WY}(t) - \boldsymbol{WQU}(t) \quad (24)$$

An important condition to satisfy both the first and second terms of (24) is that the sum is equal to zero, then $\boldsymbol{W}T = 0$ (Isermann T. H., 1996), where $\boldsymbol{W}$ is called the null space of T and can be obtained by proposing as many zeros as possible in the rows, taking into account that the lines are linearly independent. In our case study the matrix W obtained by the induction motor is (25):

$$\boldsymbol{W} = \begin{bmatrix} R_a & \psi & L_a & 0 & 0 & 0 \\ -\alpha & \beta & 0 & J & 0 & 0 \\ \gamma & 0 & \delta & 0 & JL_a & 0 \\ 0 & \gamma & 0 & \delta & 0 & JL_a \end{bmatrix} \quad (25)$$

Where:

$$\alpha = K_t N_p, \qquad \beta = B + B_1 \quad (26)$$

$$\gamma = \psi\alpha + R_a\beta, \qquad \delta = L_a\beta + JR_a$$

By the assumption in the operation in healthy state the parameter does not change, $r(t) = 0$, then, a fault is detected when $r(t) \neq 0$. The residuals obtained by the MI are:

$$\begin{aligned} r_1(t) &= R_a I_{qs}(t) + \psi\omega_r(t) + L_a\dot{I_{qs}}(t) - V_{qs}t \\ r_2(t) &= -\alpha I_{qs}(t) + \beta\omega_r(t) + J\dot{\omega_r}(t) \\ r_3(t) &= \gamma I_{qs}(t) + (L_a\beta + JR_a)\dot{I_{qs}}(t) + \\ &\quad JL_a\ddot{I_{qs}}(t) - \beta V_{qs}t - J\dot{V_{qs}}(t) \end{aligned} \quad (27)$$

It must be taken into account that during the operation on steady-state the derivative of $x(t)$ is zero, and $V_{qs}t = V_{qs}$, therefore, the residual can be simplified, this is suitable when the type of fault is incipient; taking into account that it is the most common fault in electrical machines, then residual equations can be reduced in the following way:

$$\begin{aligned} r_4(t) &= \gamma\omega_r(t) + [L_a\beta + JR_a]\dot{\omega_r}(t) \\ &\quad + JL_a\ddot{\omega_r}(t) - \alpha V_{qs} \\ r_1(t) &= R_a I_{qs}(t) + \psi\omega_r(t) - V_{qs} \\ r_2(t) &= -\alpha I_{qs}(t) + \beta\omega_r(t) \\ r_3(t) &= \gamma I_{qs}(t) - \beta V_{qs} \\ r_4(t) &= \gamma\omega_r(t) - \alpha V_{qs} \end{aligned} \quad (28)$$

Likewise, like the D.C motor (Isermann, 1996), if an additive fault occurs, all the residuals except decoupling are diverted as shown in table 1. This is compatible to locate faults in the sensor and therefore this type of fault is easily detectable. When a parametric error occurs in R_s or R_r there is no considerable increase in $R3$, therefore, a null value can be considered to simplify the error detection matrix. In the other hand, a simple way to distinguish the fault is by using classic current detectors in the stator current, with limit values with an adequate tuning, considering the behavior in the Fig. 2.

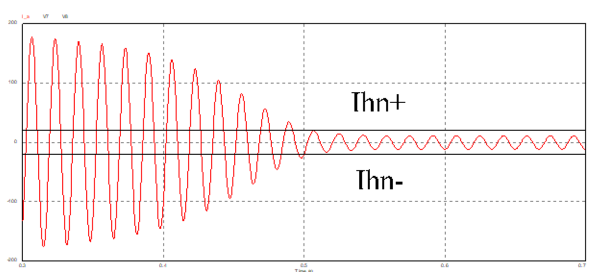

Figure 2 *Limit thresholds in IM nominal current.*
Source: Own design

The limit values of the thresholds are tuning by the "health condition" of the induction motor, the threshold is set close to the nominal current.

$$f_n = \begin{cases} 1 \rightarrow & I_n > Ih_{n+} \\ 1 \rightarrow & I_n < Ih_{n-} \\ 0 \rightarrow & Ih_{n-} > I_n > Ih_{n+} \end{cases}$$

Where:

n represents the phases a, b, or c.

f_n represents the faults in phases a, b, or c.

I_n is the current in phases a, b, or c.

$Ih_n +$ is the threshold of the current in phases a, b, or c.

$Ih_n -$ is the threshold of the current in phases a, b, or c.

Table 1 shows the parameters associated with the diagnosis of electrical faults in the induction motor model using the parity equations based on the DQ reference frame for their linearization. However, this information does not identify the damaged phase, associated with the electrical parameter.

Faults		R_1	R_2	R_3	R_4
parametrical	R_s	I	0	0	I
	R_r	I	0	0	I
	L_s	I	0	I	I
	L_r	I	I	I	I
	B	0	I	I	I
	B_l	0	I	I	I
Additi ve	i_{qs^e}	I	I	I	0
	ω_r	I	I	0	I
	V_{qs^e}	I	0	I	I

Table 1 Fault detection matrix on DQ reference frame
Source: Own design

Where "I" represents a significant change which can be positive or negative.

An easy way to validate the good performance of the fault detection technique proposed as the simplified IM model during steady state is through simulations software PSIM, which contains availability for parametric variation of the IM model (Rodríguez, 2011).

Since there is a relatively large change in the residual set obtained when an additive or incipient fault occurs, it is not necessary to use diagnostic methods to locate the fault, which simplifies the IM supervision, since the MI model is like the DC model, the analysis makes it possible to ensure the existence of a parity space, and therefore, obtain the advantages of fault detection for this type of system.

In order to interpret I_{qs} and a simple algebraic equation, The Park transform is sufficient to develop the mathematical algorithm for the fault detection system.

ISSN: 2410-3454

June 2021, Vol.8 No.25 25-35

The technique proposed by (Hernández López, junio 2011) considers that the V_{qs} value is equal to the RMS value of the stator voltage V_s. In this way, only the current and speed sensors are used.

Although this information does not identify the damaged phase associated with the electrical parameter, it tends to analyze the stator currents phase to accurately identify the damaged parameter (Chulines, 2018).

Parity in the three-phase induction motor model.

The state space representations from the electrical equations of the IM are:

$$\dot{x}(t) = Ax(t) + Bu(t) \quad (29)$$

$$y(t) = Cx(t) \quad (30)$$

$$\begin{bmatrix} \dot{I}_s \\ \dot{I}_r \end{bmatrix} \begin{bmatrix} -L_s^{-1}R_s & -L_s^{-1}\dot{M} \\ -L_r^{-1}\dot{M}^T & -L_r^{-1}R_r \end{bmatrix} \begin{bmatrix} I_s \\ I_r \end{bmatrix} \begin{bmatrix} L_s^{-1} & 0 \\ 0 & L_r^{-1} \end{bmatrix} \begin{bmatrix} V_s \\ V_r \end{bmatrix} + \begin{bmatrix} -L_s^{-1}M & 0 \\ 0 & -L_r^{-1}M^T \end{bmatrix} \begin{bmatrix} \dot{I}_r \\ \dot{I}_s \end{bmatrix} \quad (31)$$

In extended form

$$\dot{I}_s = -L_s^{-1}R_sI_s - L_s^{-1}\dot{M}I_r + L_s^{-1}V_s - L_s^{-1}M\dot{I}_r \quad (32)$$

$$\dot{I}_r = -L_r^{-1}\dot{M}^TI_s - L_r^{-1}R_rI_r + L_r^{-1}V_r - L_r^{-1}\dot{M}^T\dot{I}_s \quad (33)$$

Assuming only the behavior in steady state, it can be considered that $I_r = 0$, so the previous expressions are reduced to the following equations:

$$\dot{I}_s = -L_s^{-1}R_sI_s + L_s^{-1}V_s \quad (34)$$

$$0 = -L_s^{-1}\dot{M}^TI_s - L_r^{-1}M^T\dot{I}_s \quad (35)$$

Therefore, the equations affect the stator as follows:

$$\dot{x} = \dot{I}_s = \begin{bmatrix} \dot{I}_{sa} \\ \dot{I}_{sb} \\ \dot{I}_{sc} \end{bmatrix} \quad (36)$$

$$A = -[L_s]^{-1}[R_s] \quad (37)$$

$$B = [L_s]^{-1}$$

And the output of the system is $y = C_x$:

$$y = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \dot{I}_{sa} \\ \dot{I}_{sb} \\ \dot{I}_{sc} \end{bmatrix} \quad (38)$$

applying parity, a ω^T must be determined that satisfies the isolation of parameters of the equation

$$r(t) = \omega^TY(t) - \omega^TQ_uU(t)$$

$$[\omega_{i1}^T \quad \omega_{i2}^T \quad \omega_{i3}^T] \begin{bmatrix} C \\ CA \\ CA^2 \end{bmatrix} = 0 \quad (39)$$

To search for vectors that satisfy the desired structure, the following must be fulfilled:

$$\omega_{i1}^TC \quad \omega_{i2}^TCA \quad \omega_{i3}^TCA^2 = 0 \quad (40)$$

As the matrix C is equal to an identity in order to take physical measurements directly from the stator currents, then the equations of the residuals are as follows:

$$\omega_{i1}^TC = \omega_{i2}^TCA + \omega_{i3}^TCA^2 \quad (41)$$

$$\omega_{i2}^TC = \omega_{i1}^TC + \omega_{i3}^TCA^2 \quad (42)$$

$$\omega_{i3}^TCA^2 = \omega_{i1}^TC + \omega_{i2}^TC2 \quad (43)$$

To find each of the residuals, the ω^T of the equations was proposed to be insensitive to the changes in the associated parameters for each of the phases of the stator in the IM, the results of the behavior of the residuals for each of the stator phases can be seen in table 2.

Parametric faults	R_1	R_2	R_3
R_{sa}	I	0	0
R_{sb}	0	I	0
R_{sc}	0	0	I
L_{sa}	I	0	0
L_{sb}	0	I	0
L_{sc}	0	0	I

Table 2 Fault detection matrix limited to IM stator phases
Source: (Chulines, 2018)

For the diagnosis of the DQ model, as it is like the electrical model of the MI, it provides a system similar to DC motor. Once a W matrix is obtained, it is possible to determine the residuals and check its insulation flexibility.

Full fault detection

To carry out a more complete fault diagnosis for a particular object of study, it is important to correctly detect the symptoms that the system is possibly presenting.

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In this sense, after a detailed analysis of the IM fault detection system in (Rodríguez, 2011) and (Chulines, 2018) both techniques can be combined to be more accurate about the type of fault in the system therefore improving the life cycle of the motor.

As mentioned before, the combination of these two techniques complements each other since in (Rodríguez, 2011) faults have a 50 % margin of error in the DQ model in which the faults of the margin of error were parametric, (Chulines, 2018) does the same to determine the faults, but in each phase of stator currents and thus complement the detection of parametric faults in the MI of this combined system, resulting in a more complete detection system.

Table 3 shows the residuals obtained through the parity equations based on DQ model. In this matrix the failures in R_s and L_s are highlighted because the damaging phase cannot be identified. In this sense, table 4 shown the residues corresponding to the damaged phases related to the failures of R_s and L_s obtained through the parity equations based on stator model. So, the system provides us with better detection, and it is known exactly the damaged phase, giving the opportunity to apply preventive or corrective maintenance post-fault.

DQ model					
Faults		r_1	r_2	r_3	r_4
Parametric	R_s	I	0	0	I
	R_r	I	0	0	I
	L_s	I	0	I	I
	L_r	I	I	I	I
	B	0	I	I	I
	B_l	0	I	I	I
Additive	i_{qs}^e	I	I	I	0
	ω_r	I	I	0	I
	V_{qs}^e	I	0	I	I

Table 3 Fault detection matrix with parity equations witch DQ models.
Source: Own design

Stator model				
Faults	r_1	r_2	r_3	Insolation Faults
R_s	I	0	0	R_{sa}
	0	I	0	R_{sb}
	0	0	I	R_{sc}
	I	I	0	R_{sa}, R_{sb}
	I	0	I	R_{sa}, R_{sc}
	0	I	I	R_{sb}, R_{sc}
	I	I	I	R_{sa}, R_{sb}, R_{sc}
L_s	I	0	0	L_{sa}
	0	I	0	L_{sb}
	0	0	I	L_{sc}
	I	I	0	L_{sa}, L_{sb}
	I	0	I	L_{sa}, L_{sc}
	0	I	I	L_{sb}, L_{sc}
	I	I	I	L_{sa}, L_{sb}, L_{sc}

Table 4 Fault detection matrix with parity equations with stator models bases on faults in R_s and L_s
Source: Own design

The result presented in table 3, clearly show that detection is now capable of identifying the damaged phase unlike the model based on the DQ reference frame. In addition, the residuals obtained through the stator model add additional symptoms which enhance the detection of other parameters such as current and voltage in each of the IM phases. So, now you can have simultaneous multiple fault detection of R_s and L_s as shown in table 4.

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Conclusions

Since the induction motor model can be matched with the DC motor model, the analysis makes it possible to ensure the existence of the parity space and, therefore, obtain the advantages of the fault detection for this type of system. In this way, it is convenient to heuristically consider a diagnostic dead time from the beginning and fixed current thresholds, according to the stabilization time and from the input nominal current respectively. By adding a pair of fixed thresholds to the residual of stator and using table 3, it is possible to detect the parametric and additive faults, as well as the insolation of each of the affected phases for L_s and R_s respectively.

June 2021, Vol.8 No.25 25-35

The Park transform and simple algebraic equations it is enough to develop the mathematical algorithm of proposed detection system which can be easily implemented in any digital processor since the operators are addition, subtraction, and multiplication. This combined detection system is the most feasible option due to its short response time and at the same time the system can be improved for greater precision in the future.

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