

# An Online Fault Detection Approach for Switched Reluctance Motors

A. De La Guerra \* L. Torres \*\*,\*\*\*\*  
V. A. Maldonado-Ruelas \*\*\*

\* *Facultad de Ingeniería, Universidad Nacional Autónoma de México,  
Coyoacán, Ciudad de México., México  
(ale\_delaguerra@comunidad.unam.mx)*

\*\* *Instituto de Ingeniería, Universidad Nacional Autónoma de México,  
Coyoacán, Ciudad de México, México (ltorreso@ingen.unam.mx)*

\*\*\* *Instituto Tecnológico de Aguascalientes, Aguascalientes,  
Aguascalientes., México, (vcko22@gmail.com)*

\*\*\*\* *Cátedras CONACYT*

---

**Abstract:** One of the major challenges to design a diagnosis system for Switched Reluctance (SR) motors with a High Grade Velocity (HGV) control is the detection of incipient faults before a significant damage is done. The principal goal of the HGV control is the precise tracking of a velocity reference by controlling the instantaneous torque and by minimizing the torque and velocity ripple. Problems arise when this type of controller compensates the faults, specifically those in the electrical subsystem, and as a consequence they are not detectable by only analyzing the controlled signal or the currents. To deal with these concerns, we designed an approach to detect and isolate faults in SR motors with a HGV control. The faults treated here are damages in the inverter circuit and stator windings breakdowns which are abrupt and incipient faults, respectively. The approach is based on an Extended Kalman Filter that estimates the currents of each phase from the position. Since currents are considered to be available, residuals can be constructed from them and their estimates. From the residuals, the detection of any fault can be achieved as well as the identification of the faulty phase.

---

## 1. INTRODUCTION

Switched Reluctance (SR) motors have inherent advantages such a simple structure with no windings in the rotor, fail safe because of its stator phase independence, low cost with no permanent magnets, and possible operation in high temperatures or in intense temperature variations (Ahn, 2011). SR motors are however, as all industrial processes, subjected to some undesirable stresses, which could provoke that some faults can result in failures. Researchers have studied a variety of motor-faults as winding faults, unbalanced stator and rotor, broken rotor bars, eccentricity, and bearing faults (Siddique et al., 2005).

In this paper the detection of stator faults is treated because of these two reasons:

- Approximately 30-40 % of motor's faults are in the stator because it is subjected to various stresses such as thermal, electrical, mechanical and environmental (Motor-Reliability-Working-Group, 1985; Siddique et al., 2005).
- There are only centralized multi-phase windings in the stator; so there are not electrical faults in the rotor. The electrical (stator phase) faults are classified as: inter-turn short circuit of a coil, inter-phase short circuit, one coil short circuit in a phase winding, open circuit of the coil, short circuit of the coils and open circuit of all the coil, which is equivalent to a lost phase (Hao and Chao, 2000).

There are different approaches to detect electric faults in SR motors. In Stephens (1991), it is made a comparison of different detection methods based on sensors (such as: an over-current detector, a current differential detector, a flux differential detector, a rate-of-rise detector among others) to define the best method in terms of how quickly the fault is detected in order to prevent further damages. In Ro et al. (2013), it is analyzed the current pattern based on a  $dq$  coordinate transformation to identify faults related to the driver. In Chen and Shao (2004), some operating indexes that relate the output power with the nominal current are defined to detect deviations from the normal operating conditions. The main drawbacks of these methods is that they must be designed for a particular motor, for example, in Ro et al. (2013) the  $dq$  transformation used is suitable only for four phase SR motors; while in Chen and Shao (2004) it is essential to know the nominal values of the current and the output power; whereas in Ruba et al. (2009) and Stephens (1991), it is necessary to include redundant windings or more sensors.

An alternative to these approaches is the design of an state observer to monitor the signals of interest as made for other electrical machines, e.g. for the Permanent Magnet motor (Foo et al., 2013) and for linear drives (Huang et al., 2012), where the generated residuals help to detect and isolate the electrical faults.

In short, this paper presents a fault diagnosis system for SR Motors with a HGV Control based on a state observer, an Extended Kalman Filter (EKF) in particular. Namely, the principal goal of the HGV control is the precise tracking of a velocity reference by minimizing the torque and velocity ripple. The available signals are, in general, the measured angular position, angular velocity and the stator phase currents. It must be emphasized that the fault method that we propose is suitable for faults occurring during continuous operation *i.e.*, under steady state operation, to avoid the rotor halt when the fault occurs during the transient.

The faults considered in this work are: (i) the loss of a stator phase current, caused by a fault in the inverter circuit or in the stator winding, and (ii) the break of one or various coils of a stator winding. The first one can be considered as an abrupt fault since exhibits sudden and unexpected changes in the motor dynamics, whereas the second one is an incipient fault, which indeed is more difficult to be detected.

The problem of detecting both kind of faults is that they can be compensated by the HGV control *i.e.*, SR motors possess the capability to continue operating despite faulted motor windings or inverter circuitry. Both the stator and inverter phase independence permit the SR motors to continue operating with one or more disabled phases (Stephens, 1991). And a consequence of this compensation is that the faults will not be detectable solely by analyzing the controlled signal *i.e.*, faults may not be detected before a major damage is done. Therefore, the condition of the motor should be monitored online in order to avoid unfortunate accidents. For the monitoring task, a Fault Detection (FD) system is required to detect the fault and the faulty stator phase.

The FD method proposed in this work is based on an Extended Kalman Filter that estimates the currents of each phase from the position. Since currents are considered to be available, residuals can be generated from them and their estimates. From the residuals, the detection of any fault can be achieved as well as the identification of the faulty phase.

This paper is organized as follows: Section 2 presents the model of the SR motor and the HGV controller, in Section 3 it is described the Fault detection algorithm, Section 4 presents the simulations test of the studied faults and the proposed method and Section 5 summarizes the results of this paper.

## 2. PRELIMINARIES

### 2.1 SR motor model

The SR motor, as shown in Fig. 1, has salient poles in both stator and rotor, where the number of stator poles is  $N_s$  while the number of rotor poles is  $N_r$ . Another important feature is that, only the stator has windings while the rotor is made solely of laminated steel (Miller, 2001).

The standard assumptions for the unsaturated SR motor are, (Krishnan, 2001)

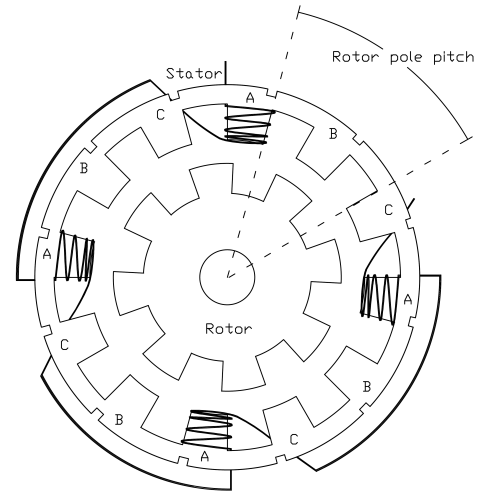


Figure 1. 12/8 Three phases SR motor

- (1) The mutual inductances are negligible *i.e.*, the stator phases are electrically and magnetically independent.
- (2) The winding inductance is defined as

$$L_{jj}(\theta) = l_0 - l_1 \cos \left( N_r \theta - (j-1) \frac{2\pi}{m} \right), \quad (1)$$

where  $j = 1, 2, 3, \dots, m$ , with  $m$  the number of stator phases,  $\theta \in \mathbb{R}$  is the angular rotor position and  $l_0 > l_1 > 0$  are the static winding coefficients.

- (3) The stator flux linkage  $\lambda_j$  is defined as

$$\lambda_j = L_{jj}(\theta) i_j, \quad (2)$$

where  $i_j$  is the stator current phase, with  $i_j$  lower than the saturation current.

Therefore, the mathematical model of a three phase SR motor *i.e.*,  $m = 3$ , is

$$\frac{d\mathbf{i}}{dt} = \mathbf{L}^{-1}(\theta) (\mathbf{u} - \omega \mathbf{C}(\theta) \mathbf{i} - \mathbf{R} \mathbf{i}) \quad (3a)$$

$$\dot{\theta} = \omega \quad (3b)$$

$$\dot{\omega} = \frac{1}{2J} \mathbf{i}^T \mathbf{C}(\theta) \mathbf{i} - \frac{d}{J} \omega - \frac{1}{J} \tau_L(t), \quad (3c)$$

where  $\mathbf{i} \in \mathbb{R}^3$  is the vector of stator currents,  $\mathbf{u} \in \mathbb{R}^3$  is the phase voltage input vector,  $\tau_L(t) \in \mathbb{R}$  is the load torque,  $\theta \in \mathbb{R}$  is the rotor angular position,  $\omega \in \mathbb{R}$  is the rotor angular velocity,  $\mathbf{R} \in \mathbb{R}_+^{3 \times 3}$  is the winding resistance matrix where the resistance per phase is denoted as  $r$ , while  $J \in \mathbb{R}_+$  is the rotor inertia and  $d \in \mathbb{R}_+$  is the friction coefficient,  $\mathbf{L}(\theta) \in \mathbb{R}^{3 \times 3}$  is a diagonal matrix whose elements are given by equation (1) and  $\mathbf{C}(\theta) \in \mathbb{R}^{3 \times 3}$  is a diagonal matrix whose elements are given by

$$C_{jj}(\theta) = N_r l_1 \sin \left( N_r \theta - (j-1) \frac{2\pi}{m} \right). \quad (4)$$

### 2.2 Cascade Control

In Espinosa-Pérez et al. (2004), a cascade speed Passivity Based Control (PBC) is proposed where, given the desired speed  $\omega_d$ , an external (mechanical) control loop calculates the corresponding desired torque as

$$\begin{aligned}\tau_d &= J\dot{\omega}_d - z + \tau_L \\ \dot{z} &= -az + be_\omega\end{aligned}\quad (5)$$

where  $e_\omega = \omega - \omega_d$ , which in turn is used to define the desired currents via the system inversion

$$i_d = \begin{cases} \sqrt{\frac{2m_j(\theta)\tau_d}{C_j(\theta)}} & \text{if } C_j(\theta) \neq 0 \\ 0 & \text{otherwise} \end{cases}, \quad (6)$$

where  $m_j(\theta)$  with  $j = 1, 2, \dots, m$ , are the torque sharing functions which defines the stator phases commutation and allows to minimize the torque/speed ripple. Based on these desired currents, an internal (electrical) control loop determines the stator phase voltage as

$$u = L(\theta)\frac{di_d}{dt} - \omega C(\theta)i_d - R i_d - K e_\omega \quad (7)$$

where  $\mathbf{K}$  is a diagonal matrix whose elements satisfy  $K_j = c|\omega|\mathbb{I}_3$  with  $c > N_r l_1$  and  $\mathbb{I}_3$  is the identity matrix. A simplified control system setup is shown in Fig. 2, where the cascade controller is implemented in a Computer interface, that receives the information of the measured states from a Data Acquisition card. While the electrical control law is implemented using PWM signals and an Electronic Converter, which is commonly an asymmetric bridge with two switches for stator phase (Krishnan, 2001).

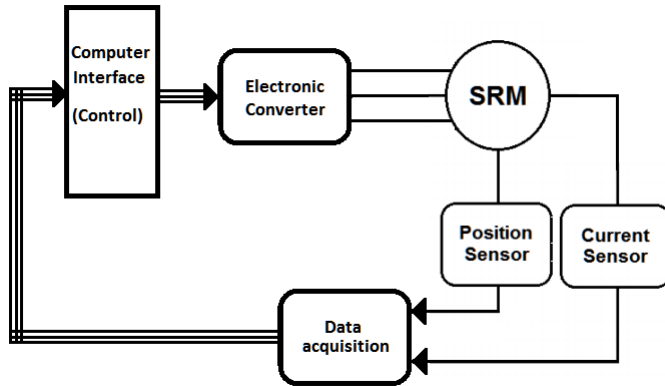


Figure 2. SR motor simplified control system

### 3. FAULT DETECTION APPROACH

For developing the FD scheme proposed in this article, we consider that angular position and stator currents are measurable. The idea of the scheme is then to design a state observer that permits the estimation of the state vector of system (3) solely from the position measurement, which means that the current estimates are independent from the real ones. Since currents are considered to be available, the following residuals can be then used to determine what phase is affected by the fault.

$$\begin{aligned}r_1(t) &= i_1(t) - \hat{i}_1(t) \\ r_2(t) &= i_2(t) - \hat{i}_2(t) \\ r_3(t) &= i_c(t) - \hat{i}_3(t)\end{aligned}\quad (8)$$

Where  $\hat{i}_1(t), \hat{i}_2(t), \hat{i}_3(t)$  are the estimated currents of each phase. In nominal conditions, i.e., when the motor is operating without faults, all the residuals will be zero

( $r_j = 0; \forall j = 1, 2, 3$ ). On the contrary, if a fault occurs in any phase, then all the residuals will be different to zero ( $r_j \neq 0; \forall j = 1, 2, 3$ ). Nevertheless, the residual corresponding to the affected phase will be negative. This logic is summarized in the signature matrix given in Table 1, where + and - mean positive and negative residuals respectively.

Phase	1	2	3
$r_1$	-	+	+
$r_2$	+	-	+
$r_3$	+	+	-

Table 1. Signature matrix.

To determine if a residual is positive or negative the residual mean can be used as index in operation offline, where the signal are processed out of line. On the other hand, in online operation a 'Flag' will be activated when the integral of the residual of one phase,  $I_{fj}$ , is below a threshold  $T_f$ , that is,

$$I_{fj} = \int_0^t (r_j - r_{fj}) d\sigma \quad r_{fj}(0) = 0 \quad (9)$$

where

$$\dot{r}_{fj} = -f_c r_{fj} + f_c r_j \quad (10)$$

with  $f_c$  a cut frequency which depends on the velocity reference value or equivalently the currents frequency. This is an integral moving in a time window, which means that unnecessary data storage is avoided during signal processing.

#### 3.1 Observer design

To estimate the state vector of model (3) including the stator currents, an Extended Kalman Filter was proposed because of the nonlinear nature of the SR motors. Other observer designs have been studied but their implementations have been unsuccessful mainly because of the highly nonlinear structure of the system. The following lines describe the EKF conception.

Consider that the SR motor model (3) can be represented by the following nonlinear representation:

$$\begin{aligned}\dot{x}(t) &= f(x(t), u(t)) \\ y(t) &= h(x(t))\end{aligned}\quad (11)$$

where  $x(t) \in \mathbb{R}^q$  is the state,  $u(t) \in \mathbb{R}^p$  the input and  $y(t) \in \mathbb{R}^m$  the output, an observer for (11), can then be designed as follows:

$$\dot{\hat{x}}(t) = f(\hat{x}(t), u(t)) + K(t)[y(t) - h(\hat{x}(t))] \quad (12)$$

where the state estimate is denoted by  $\hat{x}(t)$  and the observer gain  $K(t)$  is a time-varying matrix of  $q \times m$  dimension. To calculate this gain the following differential Ricatti equation matrix is considered, as in Gelb (1974):

$$\begin{aligned}\dot{\mathbf{P}}(t) &= (\mathbf{A}(t) + \alpha \mathbf{I})\mathbf{P}(t) + \mathbf{P}(t)(\mathbf{A}^T(t) + \alpha \mathbf{I}) \\ &\quad - \mathbf{P}(t)\mathbf{C}^T(t)\mathbf{W}^{-1}\mathbf{C}(t)\mathbf{P}(t) + \mathbf{Q}\end{aligned}\quad (13)$$

with

$$\mathbf{A}(t) = \frac{\partial f}{\partial x}(\hat{x}(t), u(t)), \mathbf{C}(t) = \frac{\partial h}{\partial x}(\hat{x}(t))$$

$$\mathbf{P}(0) = \mathbf{P}(0)^T > \mathbf{0}, \mathbf{Q} = \mathbf{Q}^T \geq \mathbf{0}, \mathbf{W} = \mathbf{W}^T > \mathbf{0}$$

and a positive real number  $\alpha > 0$  that provides a stability degree to the estimation. Namely, by means of this parameter, the estimation error is bounded and the estimation rate can be tuned. The proof of such statement can be found in Reif et al. (1998).

Finally, the observer gain is defined by

$$\mathbf{K}(t) = \mathbf{P}(t)\mathbf{C}^T(t)\mathbf{W}^{-1} \quad (14)$$

#### 4. SIMULATION TESTS

In this section some results of simulation tests are presented. Two cases of faults are treated: (i) an abrupt fault and (ii) an incipient fault, in order to show the functionality of the proposed FD method.

The simulations were made for a three phases SR motor with  $N_r = 8$  rotor poles, rotor inertia  $J = 0.001$  [Kgm<sup>2</sup>], viscous friction coefficient  $d = 0.001$  [Kgm<sup>2</sup>/s], winding resistance  $r = 1.7$  [ $\Omega$ ] per phase,  $l_0 = -0.0121$  [H] and  $l_1 = 0.0115$  [H] the coefficients of static winding inductance. The observer was tuned with the following parameters:  $\mathbf{Q} = \mathbf{I}$ ,  $\mathbf{P}(0) = \mathbf{I}$ ,  $\mathbf{W} = 1$  and  $\alpha = 0.8$ .

**No fault operation:** On one hand, in Fig. 3 it is shown the steady state operation without any fault in order to show that the 'Flag' is never activated. The velocity reference is  $50$  [rad/s] with no load torque. This figure shows the speed and the behavior of the currents together with their estimates, where  $i_{e1}, i_{e2}$  y  $i_{e3}$  denote the stator phase current estimates. On the other hand, Fig. 4 shows that the residuals are near to zero for the three phases.

**Case 1 (An abrupt fault):** This kind of fault occurs when a switch of the motor driver is damaged or when all the coils of a stator winding are open circuited. The effect of this fault is an open circuit, in other words, the complete phase is lost. This can be checked in Fig. 5 which shows the effects of an abrupt fault at  $t = 1.5$  [s] in the phase 2, at steady state operation with a velocity reference of  $50$  [rad/s] with no load torque. Notice that the current of phase 2 becomes zero after the fault occurrence. In this case the 'Flag' is activated after the residual integral is below the threshold  $T_f = -0.01$ . Fig. 6 shows the three phases residuals where is clear that the residual of phase 2 is negative.

**Case 2 (An incipient fault):** An example of this type of fault is a stator winding fault, that happens when one or more phase coils are lost. To simulate this fault, the resistance of the phase 3 was augmented 10%, this corresponds to 80 coils short circuit in a phase winding, given that there are 200 coils per pole and four poles per stator phase in the SR motor studied (Fenercoğlu and Kurt, 2008). The difficulty of detecting such a failure is that its effects are not easily noticeable in the measurements of velocity, position or current. Thus, to detect and identify incipient faults, it is necessary to process the available signals such that all the information about the fault can be extracted.

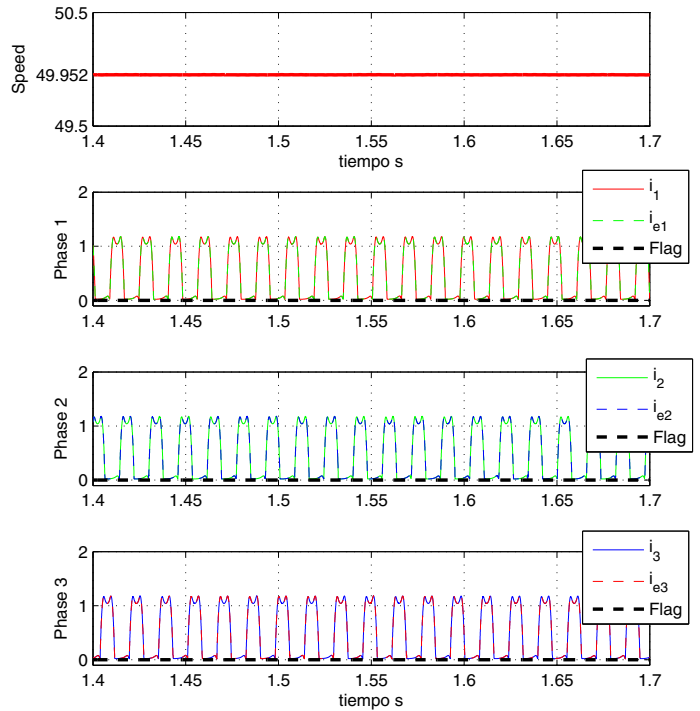


Figure 3. No fault operation: Speed and stator currents and their estimates, the 'Flag' is zero.

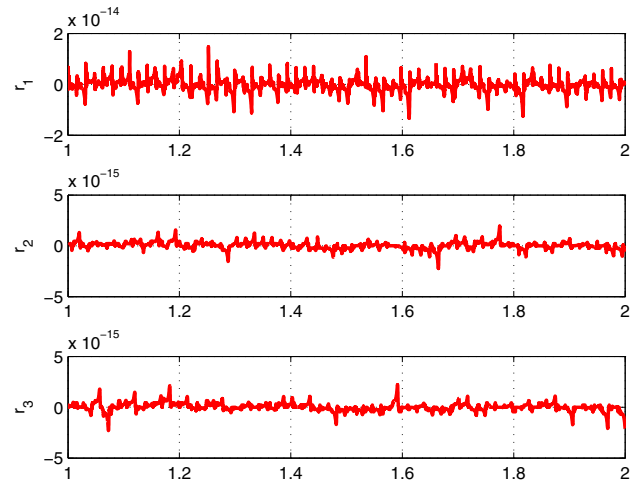


Figure 4. No fault operation: Residuals behavior.

Fig. 7 shows the three phase currents when a winding of any phase is damaged. The symptom of this fault is a resistance augmentation. The fault was simulated to occur at  $t_f = 1.5$  [s] in phase 3, at steady state operation with a velocity reference of  $50$  [rad/s] with no load torque. Notice in Fig. 7 that it is not evident to detect a fault directly from the currents times series or from the velocity. In this case the 'Flag' is activated after the residual integral is below the threshold  $T_f = -0.01$ .

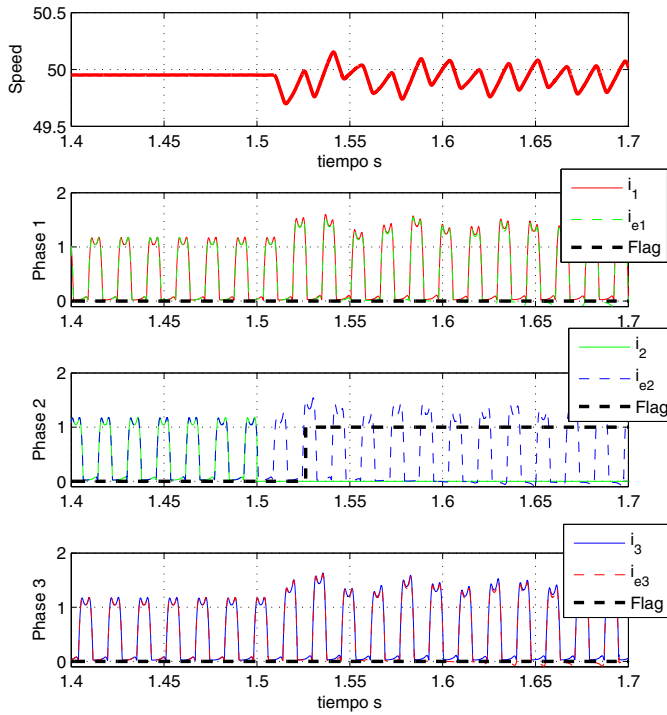


Figure 5. Case 1: Speed and stator currents and their estimates, the 'Flag' is different from zero for Phase 2.

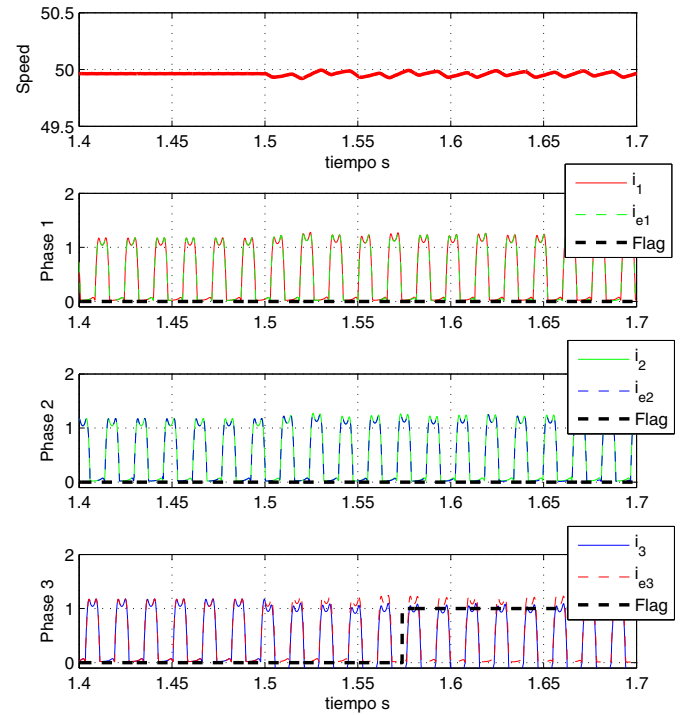


Figure 7. Case 2: Speed and stator currents and their estimates, the 'Flag' is different from zero for Phase 3.

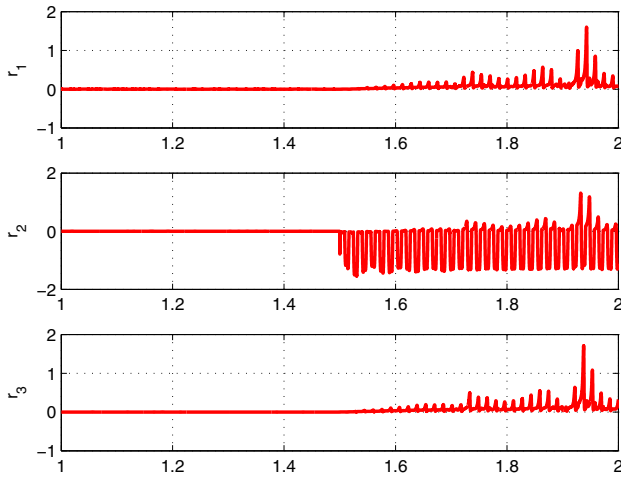


Figure 6. Case 1: Residuals behavior.

Moreover, as can be seen in Fig. 8, all residuals are zero before the fault occurs and all the three change after the fault occurrence. However, the mean of the residual  $r_3$  is negative and, according to the signature matrix in Table 1, this fact indicates a damage in the corresponding phase.

#### 4.1 Discussion

About the simulations presented above, it must be said that in this case it was used the same threshold for

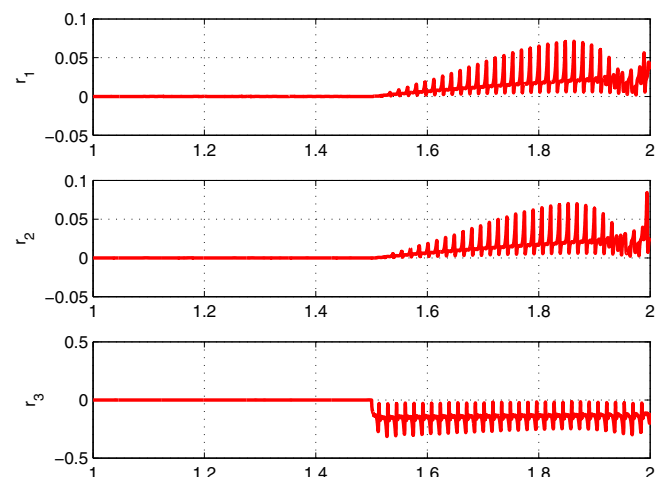


Figure 8. Case 2: Residuals behavior.

both faults, however, the value of  $T_f$  may be different depending on the fault as discussed in Marques et al. (2014). Therefore, the different value of  $T_f$  and the distinct behavior of the residuals shown in Fig. 6 and Fig. 8 may be a help to isolate the faults studied here.

It must be emphasized that the value of  $T_f$  in a real scenario will depend heavily on the noise measurement and the operation condition of the motor, that is, it must be defined experimentally.

## 5. CONCLUDING THOUGHTS

This paper presents a fault detection method for SR motors based on an EKF, where the estimates are obtained using solely angular position measurements. This method is able to detect both abrupt and incipient faults by evaluating the signal of the residuals means in offline operation and the value of the integral of the residuals in online operation. This algorithm together with a PBC velocity control forms a fault tolerant system thanks to the inherent properties of SR motors.

The main advantages of the method proposed here can be summarized as follows: it is independent of the number of stator phases or rotor poles, it does not need the exact knowledge of model parameters or state nominal values, it is not necessary to add more sensors or circuitry what makes it easy to integrate to any similar HGV control system.

The future work includes the isolation of the studied faults, the definition of the threshold for the abrupt and incipient faults and the experimental evaluation of the proposed scheme, where noise measurement must be considered.

## 6. ACKNOWLEDGES

A. De La Guerra would like to thank Instituto de Ingeniería UNAM for the financial support given during the realization of this work. V. Maldonado-Ruelas would like to thank CONACYT-Becas Mixtas for the scholarship given during his stage at Instituto de Ingeniería UNAM.

## REFERENCES

- Ahn, J.W. (2011). *Switched reluctance motor*. INTECH Open Access Publisher.
- Chen, H. and Shao, Z. (2004). Fault tolerant control for switched reluctance machine system. In *Industrial Electronics Society, 2004. IECON 2004. 30th Annual Conference of IEEE*, volume 3, 2526–2529. IEEE.
- Espinosa-Pérez, G., Maya-Ortiz, P., Velasco-Villa, M., and Sira-Ramírez, H. (2004). Passivity-based control of Switched Reluctance Motors with nonlinear magnetics circuits. *IEEE Transaction in Control Systems Technology*, 12, 439–448.
- Fenercoğlu, A. and Kurt, Ü. (2008). Three dimensional magnetostatic analysis of a 3-phase, 12/8 pole 250 w switched reluctance motor used in a washing machine drive. In *ELECO'2008 Elektrik - Elektronik - Bilgisayar Muhendisli i Sempozyumu Ve Fuarı*.
- Foo, G.H.B., Zhang, X., and Vilathgamuwa, D.M. (2013). A sensor fault detection and isolation method in interior permanent-magnet synchronous motor drives based on an extended kalman filter. *IEEE Transactions on Industrial Electronics*, 60(8), 3485–3495.
- Gelb, A. (1974). *Applied optimal estimation*. MIT press.
- Hao, C. and Chao, Z. (2000). Analysis of electrical faults for switched reluctance motor driver. In *Intelligent Control and Automation, 2000. Proceedings of the 3rd World Congress on*, volume 1, 666–669. IEEE.
- Huang, S., Tan, K.K., and Lee, T.H. (2012). Fault diagnosis and fault-tolerant control in linear drives using the kalman filter. *IEEE Transactions on Industrial Electronics*, 59(11), 4285–4292.
- Krishnan, R. (2001). *Switched Reluctance Motor drives: modeling, simulation, analysis, design and applications*. Industrial Electronics series, CRC Press.
- Marques, J.F., Estima, J.O., Gameiro, N.S., and Cardoso, A.J.M. (2014). A new diagnostic technique for real-time diagnosis of power converter faults in switched reluctance motor drives. *IEEE Transactions on Industry Applications*, 50(3), 1854–1860.
- Miller, T. (2001). *Electronic Control of Switched Reluctance Machines*. Newnes Publishers, Oxford, UK.
- Motor-Reliability-Working-Group (1985). Report of large motor reliability survey of industrial and commercial installations, part ii. *IEEE Trans. Ind. Appl*, 21(4), 865–872.
- Reif, K., Sonnenmann, F., and Unbehauen, R. (1998). An ekb-based nonlinear observer with a prescribed degree of stability. *Automatica*, 34(9), 1119–1998.
- Ro, H.S., Kim, D.H., Jeong, H.G., and Lee, K.B. (2013). A fault diagnosis and tolerant method for switched reluctance motor drives. In *Energy Conversion Congress and Exposition (ECCE), 2013 IEEE*, 4294–4299. IEEE.
- Ruba, M., Oprea, C., and Szabó, L. (2009). Comparative study on switched reluctance machine based fault-tolerant electrical drive systems. In *Electric Machines and Drives Conference, 2009. IEMDC'09. IEEE International*, 987–992. IEEE.
- Siddique, A., Yadava, G., and Singh, B. (2005). A review of stator fault monitoring techniques of induction motors. *Energy conversion, iee transactions on*, 20(1), 106–114.
- Stephens, C.M. (1991). Fault detection and management system for fault-tolerant switched reluctance motor drives. *Industry Applications, IEEE Transactions on*, 27(6), 1098–1102.