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A modified direct torque control with fault tolerance

Roberto Arnanz [a,]*, Luis J. Miguel [b], José R. Perán [b], Antonio Mendoza [a]

[a] CARTIF Foundation, Spain
[b] Universidad de Valladolid, Spain

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ABSTRACT

The use of inverters in induction motor control has reduced classical motor faults, such as broken rotor bars or windings short-circuit, besides improving control performance. The control becomes faster and more precise, reducing peaks in current and torque, so that the motor can have a softer operation. On the other hand, new elements are included in the system and it will be necessary to take into account their faults. These elements are sensors and power electronic devices that since a control point of view are the system sensors and actuators. Fault tolerance tries to maintain the system under control in case a fault appears in the system. If this is not possible, it takes the system to a safe operational point. In this paper a fault-tolerant control for induction motors is designed. Based on a direct torque control, new control strategies have been added in case current sensor and power switch faults are detected. The challenge is to overcome these faults without any physical redundancy of sensors or power switches as other authors propose. With the proposed control, it will be possible to guarantee the motor operation in the whole speed–torque range with one or none current sensors instead of the two usually used, though the performance will be slightly worsened. In case of inverter faults, the operation range will be restricted but the performance with respect to the fault situation is improved.

1. Introduction

One of the main objectives when a new design is being developed is reliability. System and process reliability are useful to avoid catastrophic consequences for operators or machines, reduce maintenance costs or improve product quality. The main idea of fault tolerance control is to design a controller that can guarantee the stability and maintain satisfactory performance, not only when all the elements of the control system are operative, but also when there is an erroneous behavior in any sensor or actuator as presented in Patton (1997). One of the main objectives in fault tolerance control is to apply appropriate control actions, to avoid incipient faults becoming critical.

The scheme of a fault-tolerant control is composed of the control and process level and the supervision level. The first level includes all the controllers, actuators and sensors. When a fault appears in any of these components, the behavior of the system changes and the purpose of the supervision level is to solve those problems. First supervision level can include physical elements, such as fuses in electrical equipment, to protect the system via the hardware. In addition, there is a monitorization of variables, which warns the operator if any of the variables has reached any limit. Above these two stages will be the real fault tolerance. Any wrong behavior is detected and analyzed in order to take the right action to make the plant work safely. This can be done by reconfiguration, fault adaptation, stopping, a maintenance operation or by modifying the control strategy. Fault tolerant control is a very complex issue that can be studied from several points of view. The bibliography in this research field is very extensive with a lot of different applications. Various state of the art papers can be found in Patton (1997) and Zhang and Jiang (2003).

During years, many solutions for control of electrical machines have focused on problems that could be considered to be in the field of fault-tolerant control. These are the cases of sensorless controls that can be used to overcome sensor faults (Menaa, Touhami, Ibtiouen, & Fadel, 2008; Vas, 1998), the use of observers to estimate real motor parameters that will allow a correct operation in case of degradation (Abbou, Mahmoudi, & Elbacha, 2007; Bose & Patel, 1998; Fang, Lin, & Wang, 2005; Holtz & Quan, 2002), or the case of robust and adaptive controls to deal with parameter changes (El Magri, Giri, A.A., & Chaoui, 2010; Oliveira, Araujo, & Dias, 2010). Most of them are passive fault-tolerant controls or adaptive schemes that can guarantee speed control when faults are present in the motor. A great number of proposals can be found in literature, and the previous cites are only presented as examples of these kind of solutions.

Related to specific fault tolerance control in electric motors, there are also some interesting previous works. In Patton and Lopez-Toribio (2000), the proposed solution is based on control and fault diagnosis theory. In it, a control with multiple models is

* Corresponding author. Tel.: +34 983546590.
E-mail addresses: robarn@cartif.es (R. Arnanz), luimig@dali.eis.uva.es (L.J. Miguel), peran@dali.eis.uva.es (J.R. Perán), amendozah@yahoo.es (A. Mendoza).

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designed, where the motor is linearized at different operating points depending on the speed and including fault situations. A fuzzy-logic system determines the combination of the models that must be used to obtain the required control actions. In Mendoza, de Miguel, Arnanz, Pacheco, and Peran (2003) an adaptive model with a fault tolerance capability is used. It is based on an extended Kalman filter used as observer, parameter estimator, and fault diagnosis system.

Related to sensor faults, in Lee and Ryu (2003) current and encoder faults are considered. The compensation for fault tolerant is based on an observer for the encoder. As three current sensors are considered, compensation of a fault in one of these sensors is not a critical problem and is solved considering $i_F=-i_1-i_2$, i_F being the faulty sensor and i_1 and i_2 the healthy ones.

Kastha and Bose (1994b) study faults in the converter and electric circuit of a motor, their effects, the protections needed, and present a classification to distinguish between critical and non-critical faults. The same author, in Kastha and Majumdar (2000), developed a fault-tolerant system for short-circuit and open circuit faults in IGBT. The new control allows the system to work as a single-phase system. To isolate the fault, there is an addition of six new switches. A configuration to control the motor using only three switches is presented in Welchko and Lipo (2001). To work properly, the motor has to be modified using double windings in each phase. In Correa, Jacobina, da Silva, and Lima (2001) three more topologies for IGBT fault are presented, in this case, to connect machine neutral to power converter. There are also two new topologies in Ribeiro, Jacobina, da Silva, and Lima (2004) with the objective of isolating the faulty phase. Both need power electronic devices to connect each phase to the continuous bus or to a new IGBT phase. The performance of two more fault-tolerant topologies is discussed in Mendes and Marques Cardoso (2006) showing that the results can be close to the normal operation ones. In Bolognani, Zordan, and Zigliotto (2000), there is also a redundant building of the inverter to isolate the faulty phase and substitute their switches. Although the motor used is a permanent magnet one, the strategy can be used in an induction motor. A comparison among several of these topologies is presented in Welchko, Lipo, Jahns, and Schulz (2004) where performances and costs are compared.

Attending control strategy, Elch-Heb and Hautier (1993) discuss modifications on a field-oriented control for two-phase operation where neutral point is connected to DC source voltage. Also Wallmark, Harnefors, and Carlson (2007) study the modification of the equations in sensorless field-weakening control for two-phase operation. For a direct torque control, Sun and He (2005) propose a modification of the switching table in case of inverter fault. This modification in control algorithm is combined with a modification in the topology of the inverter. Also Wang, He, and Ivonne (2008) use a DTC control and introduce a new flux observer and sliding mode control during fault situation. Using a V–f control, Kastha and Bose (1994a) propose the introduction of harmonics in the voltage source to compensate torque ripple in case of an IGBT fault. A novel strategy is presented in Caseiro, Mendes, and Cardoso (2009) where the rectifier control is used to obtain pre-fault voltage levels.

As can be seen, the vast majority of the proposals imply a physical redundancy or a modification of the topology. This leads to a bigger inverter and increased cost. To have fault tolerance using only a modified control structure could be an interesting alternative. In this paper it has been studied the possibility of maintaining motor control in case of sensor and actuators faults without using any additional components.

Section 2 gives a description of the direct torque control used in the no-fault situation. This control includes an energetic optimization trough the efficiency maximization. Section 3 presents the algorithms applied when sensor and actuator faults are detected. Finally Section 4 shows experimental results to evaluate the new controls performance for a real motor. It has been difficult to compare these results with previous works as solutions presented in the bibliography above are not equivalent in costs to the one exposed below.

2. Brief description of the control

Direct torque control (DTC) is a particular method of vectorial controls that aims to independently regulate flux and torque through an optimal selection of voltage vectors applied to the motor. This implies the absence of current regulation and PI controls inside the structure of the control. Attending to this criteria, a modified direct torque control has been designed for the no-fault situation. The modifications aim to solve the problems with the ripple and low speed operation that are often present in the classical DTC.

The equations used to calculate the control actions are (1) and (2), where the voltage vectors are obtained from different variables and parameters of the motor:

$$u_{sDref}(k)=R_s(k)\sqrt{|\bar{i}_s(k)|^2-\left(\frac{2}{3}\frac{1}{p}\frac{1}{|\overline{\psi}_s|_{ref}}t_{e_{ref}}\right)^2}+\frac{|\overline{\psi}_s|_{ref}\cos(\omega_s(k)T_c)-|\overline{\psi}_s(k)|}{T_c} \tag{1}$$

$$u_{sQref}(k)=\frac{2}{3}\frac{R_s(k)}{p}\frac{1}{|\overline{\psi}_s|_{ref}}t_{eref}+\frac{|\overline{\psi}_s|_{ref}\sin(\omega_s(k)T_c)}{T_c} \tag{2}$$

These equations are obtained from the electric model of the induction motor. So correct estimations of the non-measured variables that appear in (1) and (2) are needed. These are the stator flux space vector $|\overline{\psi}_s|$ and stator resistance R_s. The first one will be obtained using a second order filter that guarantees the correct estimation even at low frequencies, and R_s will be estimated with a neural network that is trained off-line with data from all operating points of the motor.

With this structure it is possible to control both the torque and flux of the motor. Torque control will be used to follow the speed reference that is selected by the user of the application. Flux reference adds one degree of freedom to the DTC that is used in this case to select different strategies of energetic control optimization such as reactive power minimization or efficiency maximization. A neural network is used to fix the flux reference in each of the cases. Fig. 1 shows the scheme of the designed control.

Parameters variation is one of the main problems to solve when the control is based on motor model. In this case R_s is the only parameter to estimate but torque and flux estimations will be affected by its value. Also the neural network that calculate flux reference depends on motor parameters. Both neural networks – R_s and flux reference – are trained offline with data of every operating point so they are simulating a static model of the motor. Neural networks have been chosen to model these variables because they allow to adjust the non-linear model of the motor by generalization of the acquired data. This is a property difficult to obtain using other methods of curve fitting, as for example a look-up table. Along next sections other neural networks are used to estimate different variables or motor properties that include an implicit model of the motor. In all cases they have been considered the best option to obtain a motor model from real data and to include it in control algorithm. The complexity of executing neural networks in real-time is not a critical issue as their evaluation only implies a few multiplications and sums.