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Robust QFT-based control of DTC-speed loop of an induction motor under different load conditions ⋆

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Abstract: Electric AC drives in manufacturing processes are well known and extensively studied. Speed loops can be commonly constructed through a decoupling method like Direct Torque Control (DTC) or Field Oriented Control (FOC) and a PID controller, which lacks of robustness towards torque variations. In this work a robust speed controller is incorporated to a DTC; its robustness is applied to the settling time of the speed when the system is subjected to different load conditions, which vary from a low value to nearly its maximum. DTC-speed loop is linearly modeled through least squares identification method and its uncertainties are overcome through Quantitative Feedback Theory (QFT). Control objectives are achieved and simulated results are presented together with a traditional PI controller perspective.

Keywords: Robust control, induction machine, QFT, DTC, speed control

1. INTRODUCTION

Induction machines are widely used in industrial applications related to manufacturing and automation due to their evident benefits towards traditionally used DC motors. Its efficiency and low-maintenance requirements have made induction motor to be highly considered in many productive areas since the moment of its invention; however, it was until the early 1970's when the field oriented control (FOC) was invented by Blaschke (1972) that it became possible to effectively decouple machine's flux and torque, making its speed and payload to be individually addressed, providing an effective solution to face induction motor as traditionally DC motors have been faced.

Nowadays, complications related to motor's nature and control approaches have been reduced so new areas of improvement have quickly raised together with digital systems processing capabilities and power electronics improvements. Motor's performance is now subjected to new more ambitious criteria, making optimal, intelligent, and robust perspectives (among others) to flourish and provide good results.

One current issue related to modern research and development around electrical machinery is uncertainties consideration into motor's modeling and control due to perturbations, parameter variation and unconsidered dynamics as told by Liaw and Lin (1994). Many works has been presented in order to deal with aforementioned uncertainties; it is possible to classify the solution approaches into: model, as done by Liaw and Lin (1994) and Griva et al. (1997); observer like in the work of Iwasaki and Matusi (1993); identification as addressed by Yang and Fang (1994), or artificial intelligence based as done in Uddin et al. (2002), Wai (2007), and Liu et al. (2010). Besides all of them have a common objective, they are also specialized on a given uncertainty source so control objectives and uncertainties sources need to be first specified.

Most literature deal with sudden perturbations on load and control robustness towards parameter variation, normally due to abnormal or prolongated operating regimes. In this case, this work takes a different perspective by achieving similar rising times on motor's speed asymptotic control of an induction machine under a cascade speed-torque control based on direct torque control (DTC) for its whole load capabilities. Furthermore, adaptability like the one achieved in Yang and Fang (1994) is not desired but robustness, which is faced through a QFT perspective as in Lucas et al. (2000), so the linear boundary transfer functions are obtained by identification of the whole torque-flux control loop through least square non-parametric identification.

Simulated results are provided showing good performance, enabling a real application like public transportation, mixers, or automatic conveyors and elevators to be addressed without the need of complex controllers, on-line considerations, sensors, or observers.

2. DIRECT TORQUE CONTROL (DTC)

Coupled nature of induction motor makes impossible to control its torque and flux by clearly separated input variables as in the DC motor case. Both variables are dependent on input voltage, while the speed is subjected to the input frequency of the AC voltage being fed. DTC enables decoupling of flux and torque by identifying the effect of the voltage source inverter (VSI) combinations as voltage vectors in the d-q plane (Fig. 1), so depending on the actual calculated position of the flux vector, each

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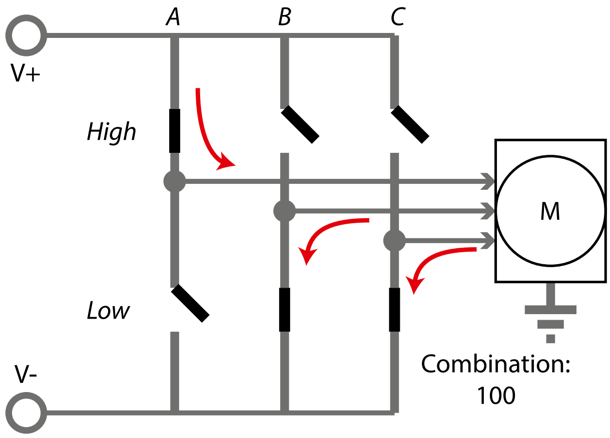

Fig. 1. VSI schematic representation

VSI combination would modify the flux and torque in a directed manner.

DTC first proposed by Takahashi and Noguchi (1986) provided a different way from FOC to achieve flux and torque decoupling through voltage and current sensors alone and a switching table subjected to hysteresis rules; this is, a whole simplification of the decoupling process became possible with good performance and fast response capabilities. After transforming voltages and currents onto the d-q plane through Clarke transform (1), torque and flux can be estimated through equations (2). A graphical approach to DTC is provided in Fig. 2 where the flux vector position is clearly dependent on the VSI semiconductors combinations (e.g. 101 represents the first and last branches of the VSI on the high position and the second on low position); in this way, the torque and flux can be increased, decreased, or remain unaltered depending on the error on both calculated quantities. Torque can be then increased by *pulling* the flux vector in the CCW direction while the flux itself by *pulling* it outwards the d-q plane.

$$\begin{bmatrix} X_q \\ X_d \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & -\frac{\sqrt{3}}{2} & \frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} X_a \\ X_b \\ X_c \end{bmatrix} \tag{1}$$

$$\psi_{dq} = \int (V_{dq} - Ri_{dq})\, dt \tag{2}$$
$$T = \psi_q i_d - \psi_d i_q$$

Depending on the error found on torque and flux, a voltage vector is selected through a decision table which is also aware of the zone in which the flux vector is, so the modification imposed by the VSI combination is consistent with the desired effect. The technique discussed so far shows the traditional DTC approach; however, different topologies have been proposed to improve its performance, e.g. integrating a commutation technique like space vector PWM (SVPWM) avoiding hysteresis band control or the decisions to be taken by a simple table, looking forward to achieve precise control over torque and flux.

Once torque control is achieved, it is possible to embed it within a speed loop, which will make the DTC torque input reference to be modified depending on the speed error calculated from the actual motor speed and the desired

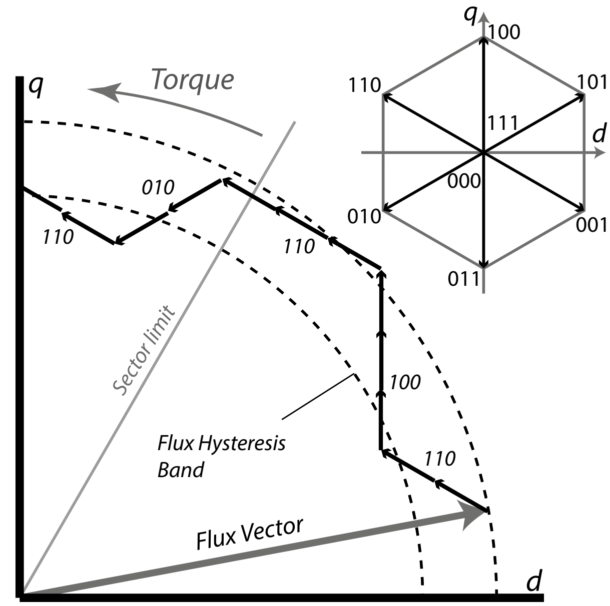

Fig. 2. DTC together with the VSI d-q graphical representations

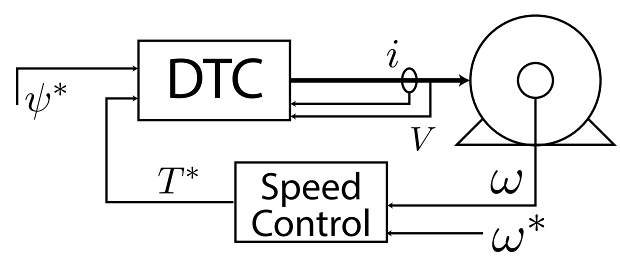

Fig. 3. Cascade speed-torque control loop

reference (Fig. 3). Nevertheless, the effect of each voltage vector delivered by the VSI on the motor is still non-linear, so modeling would not suffice if QFT is desired to be implemented. As a result, the torque control loop comprising the DTC and the machine itself can be considered together as a black box system and non-parametric identification could be performed in order to obtain linear approximated transfer functions for boundary conditions.

3. LEAST SQUARES NON-PARAMETRIC IDENTIFICATION

The following technique considers a black box system subjected to experimentation in such a way its inputs and outputs are known during a discrete time interval composed of H samples (Fig. 4); it can actually be compared to a generic linear regression technique where squared error is minimized. The discrete linear model to be fitted has the form of (3) where α_i and β_i are the function coefficients, d is a discrete delay on the input $u(k)$, $y(k)$ stands as the model's output, and the delay operator $q^{-a}\bullet(k) = \bullet(k-a)$ is used.

$$y(k) = \sum_{i=1}^{n} \alpha_i q^{-i} y(k) \tag{3}$$
$$+ q^{-d} \sum_{j=0}^{m} \beta_j q^{-j} u(k)$$