A Comparative Study between Linear and Non-linear Control Methodologies for Induction Motor Control

Muhammet HAŞİMİ, Onur AKBATI

Department of Electrical and Electronics Engineering

Yildiz Technical University

Istanbul, Turkey

muhammethasimi92@gmail.com, oakbatı@yildiz.edu.tr

Abstract

Induction motor is one of the most common motors in industrial applications because of its advantages related to its durability and low cost compared to other motors. In order to design a drive system for the induction motor, either scalar or vector methods are used. The vector control has a high dynamic performance in terms of response time and overcoming external disturbances. In this paper, a comparative study was presented between two control methods for regulating motor speed based on the vector control concept. The paper focuses on the importance of regulating both components of the magnetic flux vector, in order to avoid the magnetic saturation that can occur when the system parameters change. The simulation results in Matlab-Simulink show that the backstepping controller has a robust performance compared to the PI regulator, where it achieves lower settling time and greater ability in overcoming external disturbances despite the change of system parameters. Both control systems were tested for the presence of a change in values of the stator and rotor resistances, the simulation results show that a magnetic saturation has occurred in the machine in order to use PI regulator, but for the backstepping controller, this problem has been eliminated.

Key words:

Induction motor, magnetic saturation, PID, Backstepping, FOC.

Introduction

Induction motors are classified as the most widely-used motors due to their reliability, low cost, and rigidity compared to other types of electric motors [Ebrahim et al., 2010; Nasir Uddin et al., 2002 Chen, and Zhang, 2015.]. Despite that, induction motors were not commonly used in the past due to the difficulty of controlling their speed, Rather, DC motors were relied upon for ease of controlling their speed. However, developments in electronic converters technologies effectively contributed to an increase in reliance on induction motors, until they became the most widely used in the world Industry [Chen, and Zhang, 2015; Diyoke and Okeke, 2016.].

In order to control the speed of the induction motor, various methods have been developed. The method of changing the frequency and voltage (V/F) is the simplest method [Karthik and Chelliah, 2016; Peña and Díaz, 2016.], the more complex methods are Vector control methods, but these methods have high dynamic performance, so we rely in this article on Vector control to design the control unit [Ebrahim et al., 2010; Chen, and Zhang, 2015; Diyoke and Okeke, 2016.].

In order to design the control system, it is possible to rely on traditional regulators (PID) because they are simpler and easier to implement [Chen, and Zhang, 2015.

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], but the performance of the control system ,in this case, will be bad in terms of response speed and the system's ability to overcome external disturbances and change system parameters [Nasir Uddin et al., 2002; Chen, and Zhang, 2015.], so advanced control systems such as the linear quadratic controller [Ebrahim et al., 2010; Swargiary et al., 2015.], sliding mode controller [Liu and Hao, 2006; Benchaib et al., 1999.], backstepping controllers are relied upon [Tan et al., 2003; Trabelsi, et al., 2012.], It can also rely on intelligent and expert control systems to design the control system [Fu and Li, 2015; Kar et al., 2011; Kwan and Lewis, 2000; Bhushan et al., 2011.].

In our research, we will apply linear and non-linear control systems, but what distinguishes this research is conducting a test of the proposed control systems for the presence of a change in the parameters of the system, and studying the impact of this on the presence of magnetic saturation in the motor, and clarifying the importance of regulating each of the two components of the Magnetic flux vector in a general reference d-q frame

Dynamic Model of the Induction Motor:

The mathematical model of a three-phase induction motor that uses two components of a rotor flux vector and two components of a stator current vector as state variables, is given in a general reference d-q frame $(\omega_k = \omega_s)$, as follows [Chen, and Zhang, 2015; Trabelsi, et al., 2012; FEREKA et al., 2018]:

$$\dot{i}_{sd} = -a_5 i_{sd} + \omega_k i_{sq} + a_3 \Phi_{rd} + a_4 \omega \Phi_{rq} + b v_{sd} \qquad (1-1)$$

$$\dot{i}_{sq} = -\omega_k i_{sd} - a_5 i_{sq} - a_4 \omega \Phi_{rd} + a_{3rq} + b v_{sq} \qquad (1-2)$$

$$\dot{\Phi}_{rd} = a_2 i_{sd} - a_1 \Phi_{rd} + \omega_r \Phi_{rq} \qquad (1-3)$$

$$\dot{\Phi}_{rq} = a_2 i_{sq} - \omega_r \Phi_{rd} - a_1 \Phi_{rq} \qquad (1-4)$$

$$\dot{\omega} = (p/J)(G\Phi_{rd} i_{sq} - G\Phi_{rq} i_{sd} - T_d) - (f/J)\omega \qquad (1-5)"$$

Where: $a_1 = R_r / L_r, a_2 = L_m R / L_r, a_3 = L_m R_r / (\sigma L_s L_r^2), a_4 = L_m / (\sigma L_s L_r)$, $a_5 = (L_r^2 R_s + L_m^2 R_r)/(\sigma L_s L_r^2), b = 1/(\sigma L_s), G = P L_m / L_r, \sigma = 1 - L_m^2 / (L_s L_r)$ Where: ω_k reference $\omega = P\Omega, \omega_r = \omega_k - \omega$ frame speed. ω_s : Synchronous speed. ω :Rotor electric angular speed, Ω : Rotor mechanical angular speed, v_{sq}, v_{sd} : stator voltage components, i_{sq}, i_{sd} : stator current components. Φ_{rq}, Φ_{rd} : Rotor Flux components. P: the number of pole pairs, L_m : magnetizing inductance, L_s : stator inductance, L_r : rotor inductance,

J: rotor inertia, f: friction coefficient T_d : load torque

Vector Control of Induction Motor:

The dynamic model of an induction motor is a highly non-linear model, so it is difficult to control its speed, To facilitate the design of the control system, Vector control is used, which is the most common technique for controlling the speed of an induction motor**,** The vector control has greatly improved the dynamic performance of the induction motor [1 Ebrahim et al., 2010; Nasir Uddin et al., 2002; Karthik and Chelliah, 2016].

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The main objective of vector control is to obtain a linear relationship to the electromagnetic torque, as is the case in DC motors with independent excitation, and thus achieve the possibility of decoupling control of flux and torque [Ebrahim et al., 2010; Karthik and Chelliah, 2016; Liu and Hao, 2006.].

In the d-q reference frame (Fig.1),

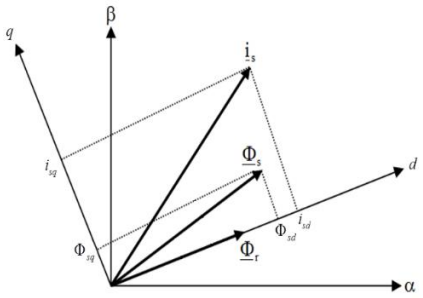

Figure 1: Orientation of the rotor flux vector toward the axis d

The d axis is attached with the rotor flux vector, the q axis component of rotor flux is always equal to zero [Nasir Uddin et al., 2002; Chen, and Zhang, 2015; Liu and Hao, 2006.]:

$$\underline{\Phi}_r = \Phi_{rd} \qquad (1-6)$$

$$\Phi_{rq} = 0, \qquad (1-7)$$

The components of the rotor flux vector in a general reference (α, β) frame ($\omega_k = 0$), are calculated as follows:

$$\Phi_{r\alpha} = (L_r/L_m)(\Phi_{s\alpha} - \sigma L_s i_{s\alpha}) \qquad (1\text{-}8)$$

$$\Phi_{r\beta} = (L_r/L_m)(\Phi_{s\beta} - \sigma L_s i_{s\beta}) \qquad (1\text{-}9)$$

Where:

$$\Phi_{s\alpha} = \int (v_{s\alpha} - i_{s\alpha} R_s) \qquad (1\text{-}10)$$

$$\Phi_{s\beta} = \int (v_{s\beta} - i_{s\alpha} R_s) \qquad (1\text{-}11)$$

Where:

$i_{s\alpha}$, $i_{s\beta}$, $\Phi_{s\alpha}$, $\Phi_{s\beta}$: stator current components, stator flux components respectively, in a general reference (α, β) frame.

To obtain the two components of the rotor flux vector in a general reference (d, q) frame, the Clack transformations are applied as follows [Peña and Díaz, 2016.]:

$$\begin{bmatrix} \Phi_{rd} \\ \Phi_{rq} \end{bmatrix} = \begin{bmatrix} \cos(\theta_s) & \sin(\theta_s) \\ -\sin(\theta_s) & \cos(\theta_s) \end{bmatrix} \begin{bmatrix} \Phi^s_{r\alpha} \\ \Phi^s_{r\beta} \end{bmatrix} \qquad (1\text{-}12)$$

Control system design

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The control system consists of two control loops. In the inner loop, the currents are regulated using hysteresis regulators in order to obtain the pulses to be applied to the inverter feeding the motor. Therefore, the current regulating loop can be equivalent to a first-order transfer function with a gain factor equal to one.

In the outer control loop, the flux and speed will be regulated using three different control methodologies:

1- PI controllers, 2- LQI controllers, 3- Backstepping controllers

PI controllers:

PID controllers are the easiest and simplest types of controllers, and the most commonly used in electrical machine driving systems such as motors, generators, and control systems, but they have some disadvantages such as their sensitivity to changing system parameters, Also, the dynamic model of the system must be approximated to a linear model in order to implement these controls **[**Nasir Uddin et al., 2002**;** Chen, and Zhang, 2015**;** Peña and Díaz, 2016.**].**

Controlling of the rotor flux component Φ_{rd} using PI controller:

Ignoring the internal disturbances in equation (1-3), it becomes as follows:

$$\dot{\Phi}_{rd} = a_2 i_{sd} - a_1 \Phi_{rd} \tag{2-1}$$

Applying the Laplace transforms, and taking into account the current regulating loop, it is possible to draw a block diagram to obtain the transfer function between i_{sd-ref} and Φ_{rd} as in Fig.2.

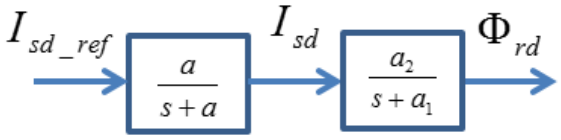

Figure 2: the block diagram of an induction motor on d-axis

Controlling of the electric speed using PI controller:

Likewise, by ignoring the internal and external disturbances in equation (1-5), it becomes as follows:

$$\dot{\omega} = (p/J)(G\Phi_{rd}^{*} i_{sq}) - (f/J)\omega \tag{2-2}$$

Applying the Laplace transforms, and taking into account the current regulating loop, it is possible to draw a block diagram to obtain the transfer function between i_{sq_ref} and ω as shown in Fig.3. Where: $\Phi_{rd}^{*} = 0.945$.

Figure 3: the block diagram of an induction motor on q-axis

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Deduce a value of ω_r :

In order to obtain ω_r , based on the relationships (1-6)-(1-8), relationship (4) can be fixed to be as follows [Nasir Uddin et al., 2002; Trabelsi, et al., 2012.]:

$$\omega_r = i_{sq} a_2 / \Phi^*_{rd} \tag{2-3}$$

The block diagram of the control system using PI is shown in Fig.4.

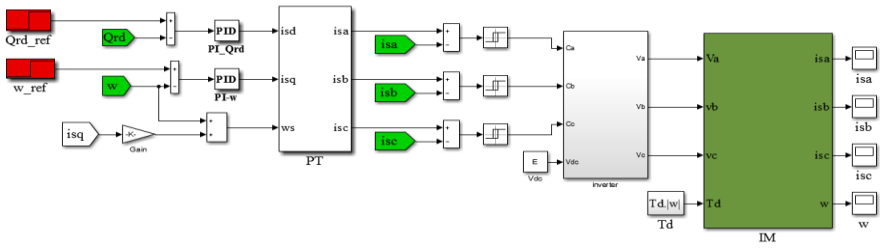

Figure 4: the block diagram of the control system using PI controllers

The Backsteeping controller:

The controller design method based on backstepping was first proposed by Koditschek in 1987. [You et al., 2011.]The common back-step design methodology is one of the commonly used control methods in non-linear control systems. The main idea of this technique is to design control loops iteratively by assuming that some state variables are "virtual controls" and each control loop gives a reference to the inner loop until the desired control signal is reached. [Li and Khajepour, 2004.The control signal for each control loop is determined by a condition on Lyapunov for stability, which states that the Lyapunov function must be defined positively and its derivative must be defined negatively [You et al., 2011; Nikdel et al., 2016.]

Controlling of the rotor flux component Φ_{rd} using Backsteeping controller:

Let's assume:

$$e_1 = \Phi_{rd-ref} - \Phi_{rd} \tag{3-1}$$

By deriving the previous relationship and after substituting the relationship (1-4) we find:

$$\dot{e}_1 = -a_2 i_{sd} + a_1 \Phi_{rd} - \omega_r \Phi_{rq} \tag{3-2}$$

We now suppose the z1 function as follows:

$$z_1 = \gamma_1 e_1 + \int \gamma_2 e_1 dt \tag{3-3}$$

By deriving the previous function, we find:

$$\dot{z}_1 = \gamma_1 \dot{e}_1 + \gamma_2 e_1 \tag{3-4}$$

By substituting the relationship (4-2), we get:

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$$\dot{z}_1 = -\gamma_1 a_2 i_{sd} + \gamma_1 a_1 \Phi_{rd} - \gamma_1 \omega_r \Phi_{rq} + \gamma_2 e_1 \tag{3-5}$$

We now suppose the Lyapunov function according to the following formula:

$$v_1 = 0.5 z_1^{\,2} \tag{3-6}$$

By derivation of the Lyapunov function, and by substituting the relation (4-4), we find:

$$\dot{v}_1 = -z_1 \gamma_1 a_2 i_{sd} + z_1 \gamma_1 a_1 \Phi_{rd} - z_1 \gamma_1 \omega_r \Phi_{rq} + z_1 \gamma_2 e_1 \tag{3-7}$$

We add and subtract $k_1 z_1^{\,2}$, so we find:

$$\dot{v}_1 = -k_1 z_1^{\,2} + z(-\gamma_1 a_2 i_{sd} + \gamma_1 a_1 \Phi_{rd} - \gamma_1 \omega_r \Phi_{rq} + \gamma_2 e_1 + k_1 z_1) \tag{3-8}$$

The derivative of the Lyapunov function must be a negative identifier, so we find:

$$i_{sd\,ref} = (\gamma_1 a_1 \Phi_{rd} - \gamma_1 \omega_r \Phi_{rq} + \gamma_2 e_1 + k_1 z_1)/(\gamma_1 a_2) \tag{3-9}$$

Controlling of the electric speed using Backstepping controller:

Let's assume:

$$e_2 = \omega_{ref} - \omega \tag{3-10}$$

By deriving the previous relationship and after substituting the relationship (1-4) and ignoring Td, we find:

$$\dot{e}_2 = -PGi_{sq}\Phi_{rd}/J + PGi_{sd}\Phi_{rq}/J + f\omega/J \tag{3-11}$$

We now suppose the function z2 according to the following formula:

$$z_2 = \gamma_3 e_2 + \int \gamma_4 e_2 dt \tag{3-12}$$

By deriving the previous function, we find:

$$\dot{z}_2 = \gamma_3 \dot{e}_2 + \gamma_4 e_2 \tag{3-13}$$

By substituting the relationship (4-11), we find:

$$\dot{z}_2 = -\gamma_3 PGi_{sq}\Phi_{rd}/J + \gamma_3 PGi_{sd}\Phi_{rq}/J + \gamma_3 f\omega/J + \gamma_4 e_2 \tag{3-14}$$

We now suppose the Lyapunov function according to the following formula:

$$v_2 = 0.5 z_2^{\,2} \tag{3-15}$$

By derivation of the Lyapunov function, and by substituting the relation (4-14), we find:

$$\dot{v}_2 = -z_2 \gamma_3 PGi_{sq}\Phi_{rd}/J + z_2 \gamma_3 PGi_{sd}\Phi_{rq}/J + z_2 \gamma_3 f\omega/J + z_2 \gamma_4 e_2 \tag{3-16}$$

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We add and subtract $k_2 z_2^{\ 2}$, so we find:

$$\dot{v}_2 = -k_2 z_2^{\ 2} + z(-\gamma_3 PGi_{sq}\Phi_{rd} / J + \gamma_3 PGi_{sd}\Phi_{rq} / J + \gamma_3 f\omega / J + \gamma_4 e_2 + k_2 z_2) \quad (3\text{-}17)$$

The derivative of the Lyapunov function must be a negative identifier, so we find:

$$i_{sq\,ref} = (\gamma_3 PGi_{sd}\Phi_{rq} / J + \gamma_3 f\omega / J + \gamma_4 e_2 + k_2 z_2) / (\gamma_3 PG\Phi_{rd} / J) \quad (3\text{-}18)$$

Controlling of the rotor flux component Φ_{rq} using Backstepping controller:

Let's assume:

$$e_3 = \Phi_{rq-ref} - \Phi_{rq} \quad (3\text{-}19)$$

By deriving the previous relationship and after substituting the relationship (1-4), we find:

$$\dot{e}_3 = -a_2 i_{sq} + \omega_r \Phi_{rd} + a_1 \Phi_{rq} \quad (3\text{-}20)$$

We now suppose the z3 function as follows:

$$z_3 = \gamma_5 e_3 + \int \gamma_6 e_3 dt \quad (3\text{-}21)$$

By deriving the previous function, we find:

$$\dot{z}_3 = \gamma_5 \dot{e}_3 + \gamma_6 e_3 \quad (3\text{-}22)$$

By substituting the relationship (4-20), we find:

$$\dot{z}_3 = -\gamma_5 a_2 i_{sq} + \gamma_5 \omega_r \Phi_{rd} + \gamma_5 a_1 \Phi_{rq} + \gamma_6 e_3 \quad (3\text{-}23)$$

We now suppose the Lyapunov function according to the following formula:

$$v_3 = 0.5 z_3^{\ 2} \quad (3\text{-}24)$$

By derivation of the Lyapunov function, and by substituting the relation (4-23), we find:

$$\dot{v}_3 = -z_3 \gamma_5 a_2 i_{sq} + z_3 \gamma_5 \omega_r \Phi_{rd} + z_3 \gamma_5 a_1 \Phi_{rq} + z_3 \gamma_6 e_3 \quad (3\text{-}25)$$

We add and subtract $k_3 z_3^{\ 2}$, so we find:

$$\dot{v}_1 = -k_3 z_3^{\ 2} + z_3(-\gamma_5 a_2 i_{sq} + \gamma_5 \omega_r \Phi_{rd} + \gamma_5 a_1 \Phi_{rq} + \gamma_6 e_3 + k_3 z_3) \quad (3\text{-}26)$$

The derivative of the Lyapunov function must be a negative identifier, so we find:

$$\omega_r = (\gamma_5 a_2 i_{sq} - \gamma_5 a_1 \Phi_{rq} - \gamma_6 e_3 - k_3 z_3) / (\gamma_5 \Phi_{rd}) \quad (3\text{-}27)$$

The block diagram of the control system using Backstepping controllers is shown in Fig.5.

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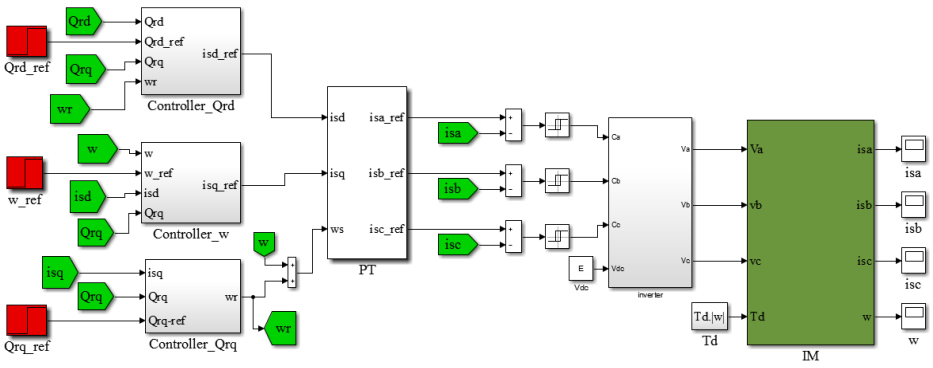

Figure 5: the block diagram of the control system using Backstepping controllers

Simulation results:

The speed is regulated at 250rad/sec, the rotor flux component on d-axis is regulated at 0.945wb, while the rotor flux component on q-axis must be equal to zero, the load torque is applied at the moment 1sec.

Fig.6 shows the response time for speed regulation, the settling time is the same for both control systems (ts=0.15 sec), Static error is equal to zero for backstepping controller, while we note that it is equal to 0.02% for regulator pi.

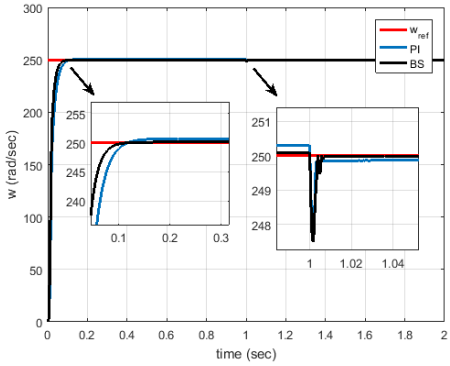

Figure 6: Response time for speed regulation

Fig.7 shows the response time for component Qrd regulation, the settling time is 0.05 sec for backstepping controller, while it equal to 0.2 sec for regulator pi. Static error is equal to zero for both control systems.
Fig.8 shows the response time for component Qrq regulation, the settling time is 0.01 sec for backstepping controller, while it equal to 0.2 sec for regulator pi. Static error is equal to zero for both control systems.

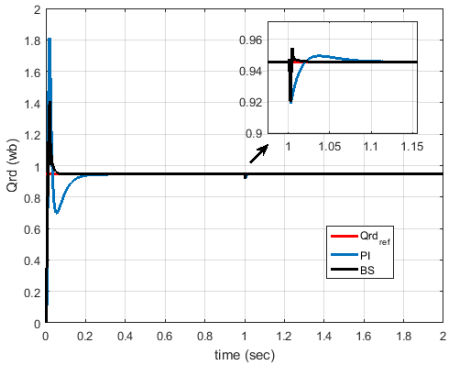

Figure 7:Response time for Qrd regulation

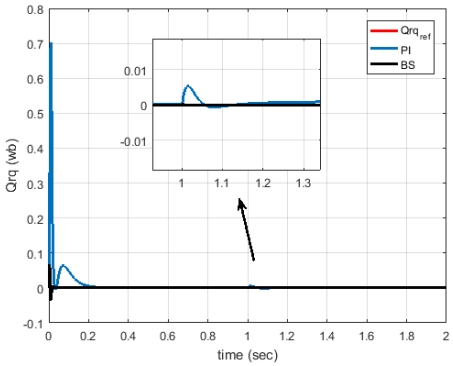

Figure 8 :Response time for Qrq regulation

From the two figures Fig.7 and Fig.8, it is clear that for regulate both components of the rotor flux vector,

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the Backstepping controller, achieves a higher response speed and greater ability in overcoming the external disturbances represented by the load torque.

The performance of both control systems was tested for the presence of a change in both the stator resistance (Rs=1.3*Rsn) and the rotor resistance (Rr=1.5*Rrn), Fig.9 shows the response time for speed regulation, as it is clear that the performance of the control systems did not change, (ts=0.15 sec, ess=0-0.02%).

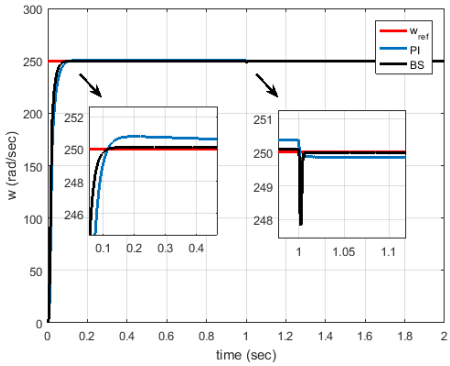

Figure 9: Response time for speed regulation

Fig.10 shows the response time for component Qrd regulation, the settling time is 0.05 sec for backstepping controller, while it equal to 0.2 sec for pi regulator. Static error is equal to zero for both control systems. Fig.8 shows the response time for component Qrq regulation, we notice that for the pi regulator, the static error equals 0.03 wb before applying the load torque and increases to 0.42 wb after applying the load torque, this causes a magnetic saturation to occur in the machine, resulting in an increase in magnetic losses, a decrease in efficiency and an increase in the thermal heating of the machine., while for a backstepping controller, we notice that the static error is equal to zero, which contributes to the absence of magnetic saturation in the machine.

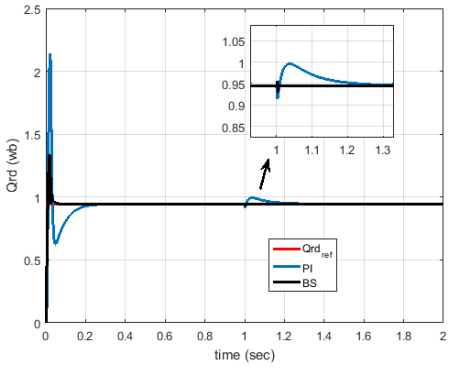

Figure 10: Response time for Qrd regulation

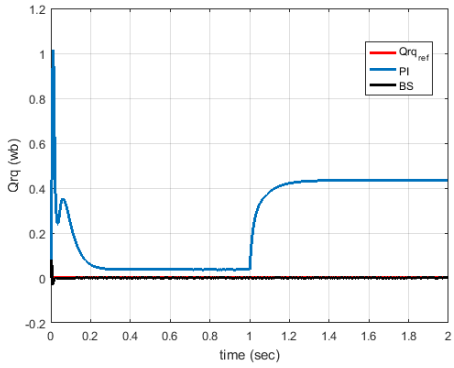

Figure 11: Response time for Qrq regulation

Conclusion:

In this research, a comparative study was presented between tow control methods for regulating the motor speed based on the concept of vector control. The results of the paper indicate the importance of regulating the both components of the rotor flux vector, in order to avoid the occurrence of magnetic saturation in the machine when there is a change in the values of the stator and rotor resistances.

The simulation results showed the superiority of the Backstepping controller compared to the PI in terms of response time characteristics (settling time and static error) and overcoming external disturbances.

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The use of the backstepping controller has clearly contributed to avoiding the problem of magnetic saturation and improving the dynamic performance of the induction motor.

References

Ebrahim, O,S., Salem M.F., and Jain P.K and Badr M.A, Application of linear quadratic regulator theory to the stator field-oriented control of induction motors, *IET Electric Power Applications*, Vol. 4, Iss. 8, pp. 637–646, 2010.

Nasir Uddin, M., Radwan, S., and Azizur Rahman, M., Performances of Fuzzy-Logic-Based Indirect Vector Control for Induction Motor Drive, *IEEE TRANSACTIONS ON INDUSTRY APPLICATIONS, VOL*. 38, NO. 5, SEPTEMBER/OCTOBER, 2002.

Chen, M., Zhang, W., H2Optimal Speed Regulator for Vector Controlled Induction Motor Drives, *27th Chinese Control and Decision Conference (CCDC)*, 2015.

Diyoke, G.C., Okeke, C., and Aniagwu, U., Different Methods of Speed Control of Three-Phase Asynchronous Motor, *American Journal of Electrical and Electronic Engineering*, Vol. 4, No. 2, 62-68Vol. 4, No. 2, 62-68, 2016.

Karthik, D., and Chelliah, T.R., Analysis of Scalar and Vector Control Based Efficiency-Optimized Induction Motors Subjected to Inverter and Sensor Faults, *International Conference on Advanced Communication Control and Computing Technologies*, ISBN No.978-1-4673-9545-8, 2016.

Peña, T.M., and Díaz, E.V., Implementation of V/f scalar control for speed regulation of a three-phase induction motor, *IEEE*, 2016.

Swargiary, M. Dey, J., and Saha, T.K., Optimal Speed Control of Induction Motor Based on Linear Quadratic Regulator Theory, *IEEE INDICON*, 2015.

Liu, P., and Hao, L., Vector Control-Based Speed Sensorless Control of Induction Motors Using Sliding-Mode Controller, *Proceedings of the 6th World Congress on Intelligent Control and Automation*, June 21 - 23, Dalian, China, , 2006

Benchaib, A., Rachid, A., Audrezet, E., and Tadjine, M., Real-Time Sliding-Mode Observer and Control of an Induction Motor, *IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS*, VOL. 46, NO. 1, FEBRUARY, 1999.

Trabelsi, R., Khedher, A., Mimounic, M.F., and M'sahli, F., Backstepping control for an induction motor using an adaptive sliding rotor-flux observer, *Electric Power Systems Research*, 2012.

Tan, Y., Chang, J., and Tan, H., Adaptive Backstepping Control and Friction Compensation for AC Servo With Inertia and Load Uncertainties, *IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS*, VOL. 50, NO. 5, OCTOBER, 2003.

Fu, X., and Li, S., A Novel Neural Network Vector Control Technique for Induction Motor Drive, *IEEE TRANSACTIONS ON ENERGY CONVERSION*, 2015.

Kar, B. N., Mohanty, K.B., and Singh, M., Indirect Vector Control of Induction Motor Using Fuzzy Logic Controller, *IEEE*, 2011.

Kwan, C.M., and Lewis, F.L., Robust Backstepping Control of Induction Motors Using Neural Networks, *IEEE TRANSACTIONS ON NEURAL NETWORKS*, VOL. 11, NO. 5, 2000.

Bhushan, B., Singh, M., and Prakash, P., Performance Analysis of Field Oriented Induction Motor using Fuzzy PI and Fuzzy Logic based Model Reference Adaptive Control, *International Journal of Computer Applications*, (0975 – 8887) Volume 17– No.4, March, 2011.

FEREKA, D., ZERIKAT, M., and BELAIDI, A., MRAS Sensorless Speed Control of an Induction Motor Drive based on Fuzzy Sliding Mode Control, *Proceedings of the 7th International Conference on Systems and Control, Universitat Politècnica de València, Spain*, 2018.

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Molavi, R., and Khaburi, D.A., Optimal Control Strategies for Speed Control of Permanent-Magnet Synchronous Motor Drives, *International Journal of Computer, Electrical, Automation, Control and Information Engineering*, Vol:2, No:8, 2008.

Araar, O., and Aouf, N., Full Linear Control of a Quadrotor UAV,LQ vs H_∞, *UKACC International Conference on Control 9th - 11th July, Loughborough, U.K*, 2014.

You, X., Chen, W., Yu, S., and Wu, X., Dynamic Control of a 3-DOF Cable-Driven Robot Based on Backstepping Technique, *IEEE- the National Natural Science Foundation of China under Grant* No. 50875011 and No. 50975017, 2011.

Li, G., and Khajepour, A., Robust control of a hydraulically driven flexible arm using Backstepping technique, *Journal of Sound and Vibration* 280 (2005) 759–775, 2004.

Nikdel, N., Badamchizadeh, M.A., Azimirad, V., and Nazari, M.A., Adaptive Backstepping control for an n-degree of freedom robotic manipulator based on combined state augmentation, *Robotics and Computer-Integrated Manufacturing*, 44 (2017) 129–143, 2016.

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