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Robust Strategy for position Control of Permanent Magnet Synchronous Motor Used for robot systems

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Abstract: In this paper we present a robust control Strategy for design a position control system for the three-phase synchronous motor with permanent magnets PMSM, It is known that the dynamic model of this Motor is a non-linear model, Our approach use the exact coupled model of PMS motor, and produces robust state feedback control law called Robust Parametric Quadratic RPQ control strategy. This approach needs to reformulate the coupled model of PMSM in (d,q) reference frame as Affine/Polytopic state space model. The RPQ approach produces a linear law which only require the solution of a set of Riccati based LMI technique at the vertex of convex space off-line. It achieves robust stability of the realistic PMSM model, and guarantees fast response.

Keywords: PMSM, robust control, parameters, feedback parameters, design, position control.

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1 Introduction

Permanent magnet synchronous motors - PMSM are commonly used in small and middle power range motion control applications because of their reliability, excellent dynamics, large overload and compact structure [T. Glinka, July 2008], [M. Lech, and T. Tarczewski,2011], [R. Molavi, and A. Avood, 2008]. The speed control of the PMSM is most often realized in a classical cascade structure with PI controllers [D. Janiszewski,2010]. Sliding mode control [L. Shihua, and L. Zhigang, 2009], [S. M. Fazeli, H. A. Zarchi, J. Soltani, H. Ping,2008] and nonlinear control based on neural networks and fuzzy logic [T. Pajchrowski, K. Zawirski,2009] can be used in cascade structure to ensure robustness of the drive. Classical structure is also used in sensorless control of the PMSM [D. Janiszewski,2010]. Additional signals from observers are also applied to improve control precision [X. Yue, C. M. Vilathgamuwa and K.-J. Tseng,2005].

State feedback control can be an alternative for a typical cascade structure [K.-H. Kim and M.-J. Youn,2002]. State feedback speed control of the PMSM requires an internal input model to eliminate a steady state speed error caused by step reference speed command as well as load torque variations. Due to the coupled, non-linear model of the PMS Motor, the use of the linear control theory to design a state feedback position controller is not obvious. To accomplish this task, we have to modify the coupled, non-linear (bilinear) model of PMS motor to a linear uncertain form or Affine Parameter Based Model as well known in robust control theory.

2 Representation of the three-phase synchronous motor in a two-dimensional coordinate system:

For a two-dimensional coordinate system d, q as shown in Fig. 1,

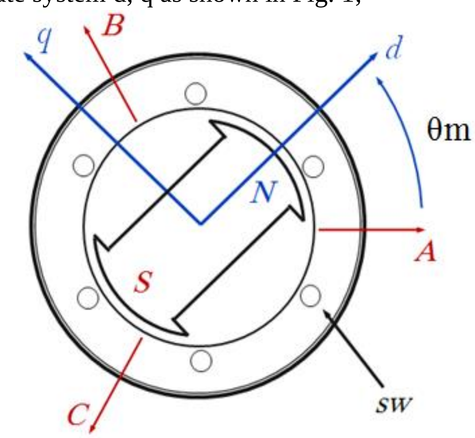

Figure 1: 3-Phase Stator, Rotor winding and Two-Axes Equivalent (d, q) Reference Frame

The equations representing the Motor are given as follows [Asslan M , Joukhadar A, Fares B,2018]:

$$\frac{di_{sd}}{dt} = \frac{-R_s i_{sd} + p\omega_m L_{sq} i_{sq} + V_{sd}}{L_{sd}} \quad (1)$$

$$\frac{di_{sq}}{dt} = \frac{-R_s i_{sq} - p\omega_m L_{sd} i_{sd} - p\varphi_m \omega_m + V_{sq}}{L_{sq}} \quad (2)$$

$$\frac{d\omega_m}{dt} = \frac{(1.5p\varphi_m i_{sq} - f\omega_m - T_d)}{J_m} \quad (3)$$

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$$\frac{dpos}{dt} = \omega_m \qquad (4)$$

3 Vector Control Definition:

The (PMS) motors are typically used for high-efficiency motor drives. High-performance motor control is characterized by smooth rotation over the entire speed range of the motor, full torque control at zero speed, and fast acceleration and deceleration. To achieve such control, vector control techniques are used for PMS motors. The vector control techniques are usually also referred to as field-oriented control (FOC). The basic idea of the vector control algorithm is to decompose a stator current into a magnetic field-generating part and a torque generating part. Both components can be controlled separately after decomposition. Then, the structure of the vector control controller is almost the same as a separately excited DC motor, which simplifies the control of a motor.

The electro-magnetic torque of PMSM is generated by an interaction of two magnetic fields (one on the stator and one on the rotor). The stator magnetic field is represented by the magnetic flux/stator current. The magnetic field of the rotor is represented by the magnetic flux of permanent magnets that is constant, except for the field weakening operation. We can imagine those two magnetic fields as two bar magnets, as we know a force, which tries to attract/repel those magnets, is maximal, when they are perpendicular to each other. It means that we want to control stator current in such a way that creates a stator vector vertical to rotor magnets. As the rotor spins, we must update the stator currents to keep the stator flux vector at 90 degrees to rotor magnets at all times. Fig. (2) show (d, q) reference frame. The “d” axis refers to the “direct” axis of the rotor flux. The “q” axis is the axis of motor torque along which the stator current must be developed. [Asslan M , Joukhadar A, Fares B,2018]. Figure 2 illustrates the stator current vector in this case.

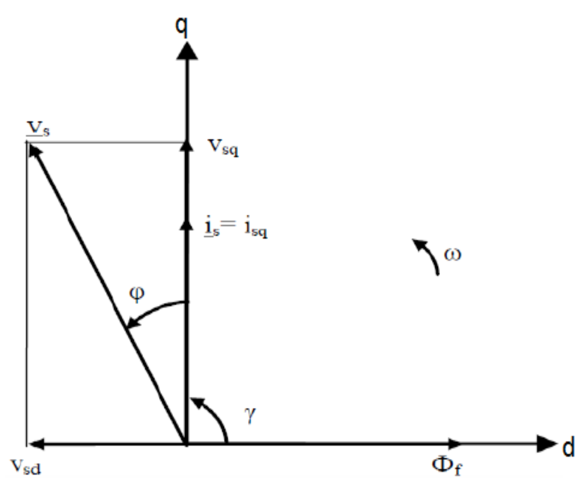

Figure 2: The components of the stator current vector in Two-Axes Equivalent (d, q) Reference Frame in order to generate maximum torque.

4 Definition of the interconnected system (Affine / polytypic):
For constant values δ_i that are within the domain $[\delta_i^s\ \delta_i^l]$ where δ_i^l is the maximum value, and δ_i^s is the minimum value, then the vector of the parameters $\delta = (\delta_1, \ldots, \delta_l)$ takes values within a convex space as shown in Figure 4-1. The number of vertices of the convex space is n, Where $n = 2^l$, These vertices can be represented as follows: $(\prod_1, \prod_2, \ldots, \prod_n)$
If the function S (δ) is directly related to the parameter δ, thus several systems are formed $S(\prod_1), \ldots S(\prod_n)$, The values indicated by the Systems $S(\prod_i)$, i = 1,2, . . ., n, are formulated according to the polytypic formula at each vertex of the space as in the following equation:

$$\dot{x} = A^i x + Bu \tag{5}$$

The matrix of parameters of the system A at a vertex i can be defined as follows:

$$A^i = \bar{A} + \sum_{j=1}^{l} A_j\ \delta_j^{(i)} \tag{6}$$

$\delta_j^{(i)}$:uncertainty parameter Value (j) At a vertex i from the space C whose axes are δ_j
$\bar{A}$: System matrix not containing the uncertainty parameters.
A_j: System matrix containing uncertainty parameter (j).
l: Number of uncertainty parameters.
B: Input matrix.
U: Input vector of the system.

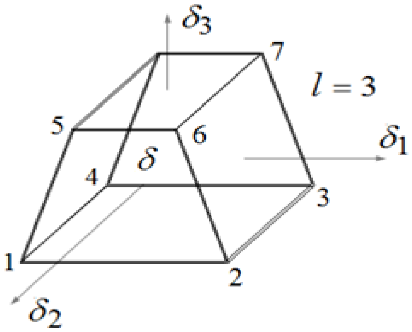

Figure 3: Convex space (C)

System $S(\prod_i)$ at each space vertex (i) is described as a linear system that does not change with time LTI, it represents a model with direct correlation with parameters for constant values of parameters (δ_i) at each vertex (i) of the space (C)[Asslan M , Joukhadar A, Fares B,2018][Al-Asaad A , Naassani A, Fares B,2018].

5 Control law according to control methodology RPQI:
The RPQI control methodology aims to find a linear control law that achieves the following:
- Ensure strong stability of the state space.
- Reduce as much as possible the cost index given according to the following relationship:

$$J = ||x||_Q^2 + ||u||_R^2 \quad (7)$$

Where:

Q: weighting matrix of state variable vector, a positive known matrix.

R: weighting matrix of input vector, a positive known matrix.

We can find the feedback gain vector after solving the following set of inequalities:

$$\Gamma^{(i)}(P_c, k_c) = \frac{Q + k_c' R k_c + (A^{(i)} + B k_c)' P_c + P_c (A^{(i)} + B k_c)}{2} < 0 \quad (8)$$

Where the last relationship must be fulfilled at all vertices of the space, that is:

$$\Gamma^{(i)}(P, k_c) \prec O, i = 1,2,\ldots,2^l \quad (9)$$

Where:

k_c: feedback gain vector.

P_c :A positive known matrix called a modification matrix (Covariance)

5.1 Model (Affine / polytypic) of the three-phase synchronous motor with permanent magnets:

In order to convert the previous nonlinear uncertainty system into an Affine / Polytypic system, it is for nonlinear correlation terms such as ($\omega_m i_{sd}$, $\omega_m i_{sq}$), We replace the first part ω_m with (δ_1) and keep the second part as a state variable.

On the other hand, in order to take into account that the resistance of the stator coil is variable, it is represented as an uncertainty parameter and therefore the term that contains it is replaced by (δ_2). Thus, the equations representing the Motor are as follows:

$$\frac{di_{sd}}{dt} = \frac{-\delta_2 i_{sd} + p\delta_1 L_{sq} i_{sq} + V_{sd}}{L_{sd}} \quad (10)$$

$$\frac{di_{sq}}{dt} = \frac{-\delta_2 i_{sq} - p\delta_1 L_{sd} i_{sd} - p\varphi_m \omega_m + V_{sq}}{L_{sq}} \quad (11)$$

$$\frac{d\omega_m}{dt} = \frac{(1.5 p\varphi_m i_q - f\omega_m - T_d)}{J_m} \quad (12)$$

$$\frac{dpos}{dt} = \omega_m \quad (13)$$

In order to cancel the static error, an integral term is added, to represent the integrity of the error. Generally, the system to be controlled include a position regulation, and a regulation of the stator current component along d axis at a reference value of zero.

We add the following two equations to the dynamic model of the Motor:

$$\dot{\zeta}_{pos} = pos_{ref} - pos \quad (14)$$

$$\dot{\zeta}_{i_{sd}} = i_{sd-ref} - i_{sd} \quad (15)$$

Where:

pos_{ref}: Desired position.

pos : Real position.

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i_{sd-ref} :Reference value of the stator current component along d axis, where is zero.

i_{sd} :Measured value of the stator current component along d axis.

Thus, the three-phase synchronous motor model with permanent magnets is as follows:

$$\frac{d}{dt}\begin{bmatrix} i_{sd} \\ i_{sq} \\ \omega_m \\ pos \\ \zeta_{pos} \\ \zeta_{i_{sd}} \end{bmatrix} = \begin{bmatrix} -\delta_2 / L_{sd} & p\delta_1 & 0 & 0 & 0 & 0 \\ -p\delta_1 & -\delta_2 / L_{sq} & -p\phi_m / L_{sq} & 0 & 0 & 0 \\ 0 & 1.5 p\phi_m / J_m & -f / J_m & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & -1 & 0 & 0 \\ -1 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}\begin{bmatrix} i_{sd} \\ i_{sq} \\ \omega_m \\ pos \\ \zeta_{pos} \\ \zeta_{i_{sd}} \end{bmatrix} + \begin{bmatrix} 1/L_{sd} & 0 \\ 0 & 1/L_{sq} \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix}\begin{bmatrix} V_{sd} \\ V_{sq} \end{bmatrix}$$

Figure 4 illustrates the system diagram of a closed loop RPQI controller in the MATLAB / Simulink environment, followed by Figure 5 showing the internal structure of the controller.

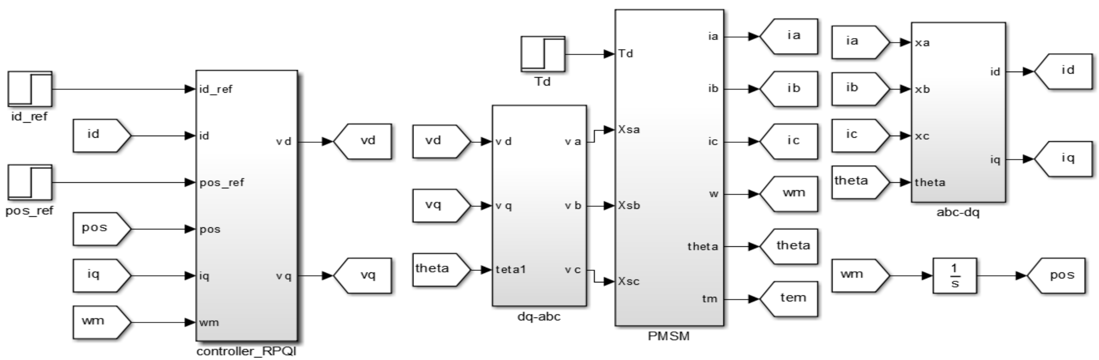

Figure 4: System diagram of the closed loop RPQI controller in MATLAB / Simulink environment.

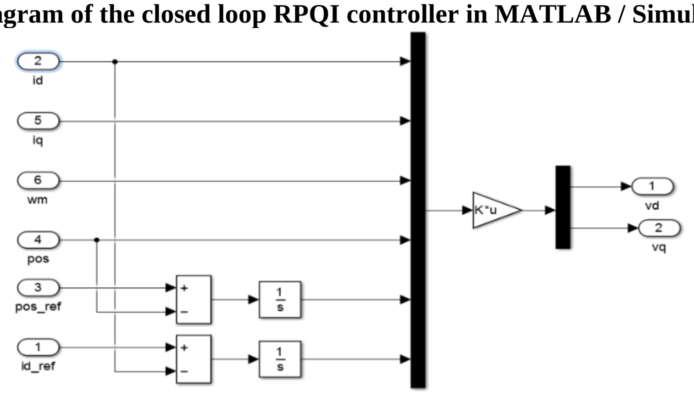

Figure 5 illustrates the internal structure of the RPQI controller

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Figure 6 illustrates the closed-loop system diagram of PID organizations in the MATLAB / Simulink environment.

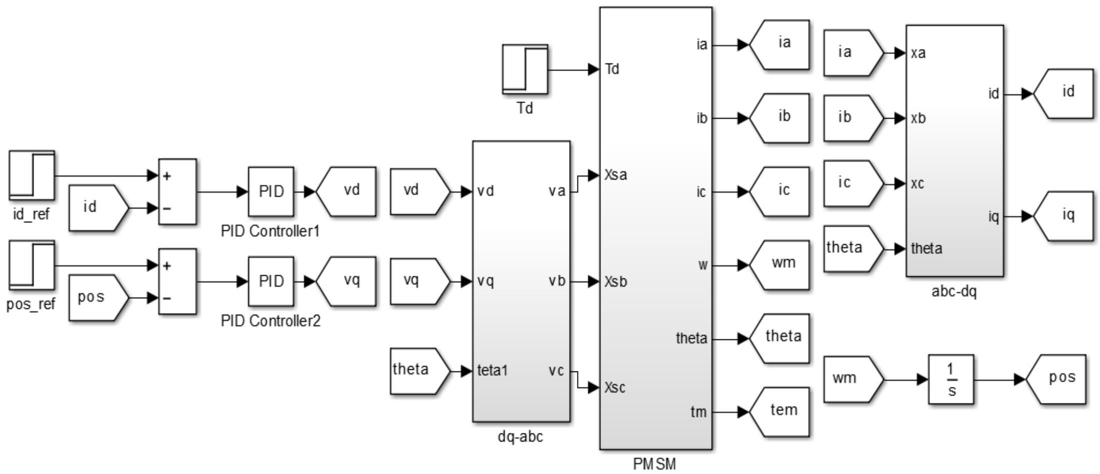

Figure 6: Closed-loop system diagram of PID organizations in MATLAB / Simulink environment

5.2 Simulation results for speed control of permanent magnet synchronous motor:
Figure 7 shows the system response for position regulation at 1rad for loading at 3sec.

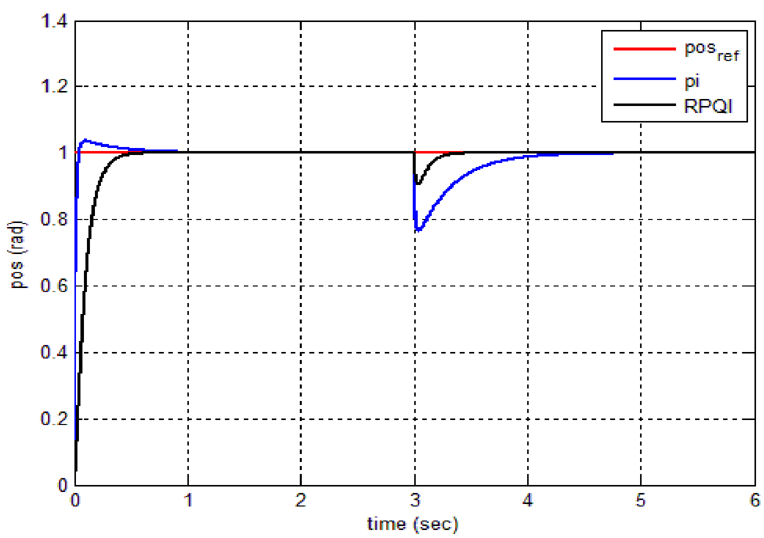

Figure 7: System response for position regulation at 1rad for loading at 3sec moment.

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From Figure 7, the RPQI methodology outweighs the classical regulators in terms of the speed of response, as well as the speed of overcoming external disturbances. Also, to validate the robustness of the proposed control system, the value of stator resistance was doubled, the response of the system is illustrated in Figure (8):

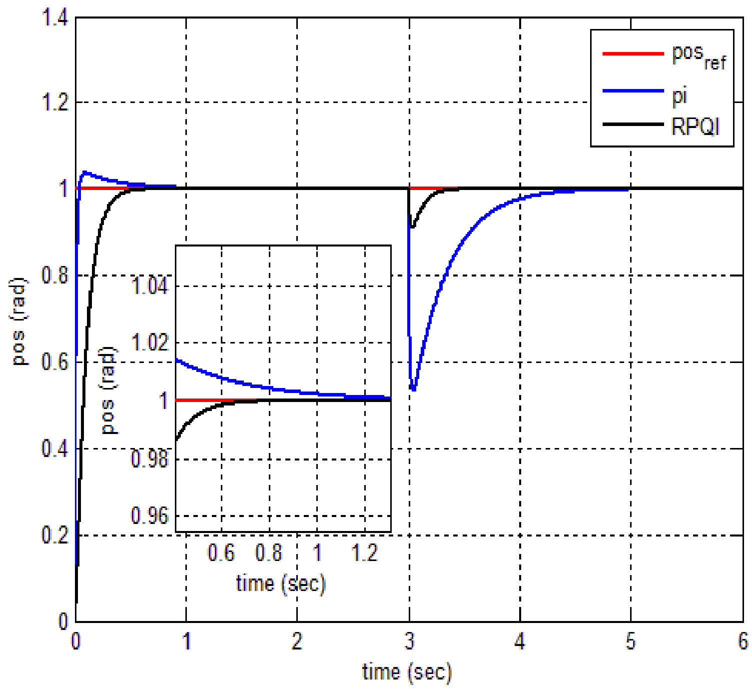

Figure 8: System response to position regulation at 1rad, and change the value of stator resistance to double value.

From the previous figure, the RPQI control method clearly outperforms the traditional regulators, because the system performance of the traditional regulators is heavily affected when loading occurs, and the RPQI controller achieves less latency without exceeding target.
With regard to regulation the current vector component isd at zero, the response of the system after changing the value of stator resistance to double value is illustrated in Figure (9):

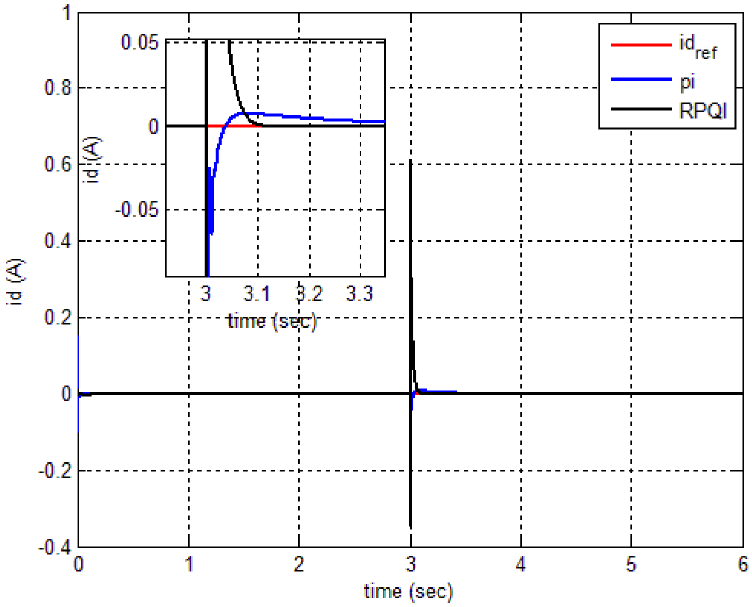

Figure 9: System response to current regulation isd at 0A and change the value of stator resistance to double value.

We also note the superiority of the proposed methodology in terms of the robustness of the system in overcoming external disturbances and achieving greater system stability.

6 Conclusion:

In this paper, a robust position control methodology was introduced for the PMS Motor, The proposed methodology is based on the conversion of the nonlinear system of the motor to a uncertain linear system, and then calculate the feedback constants that contribute to the proposed cost minimization as well as the system's robust stability despite changing system parameters, It also gives the system greater ability to overcoming external disturbances.

The simulated results in the MATLAB / Simulink environment demonstrated the robustness of the proposed methodology performance and its superiority over the traditional PID regulators in terms of the response time and external disturbances overcoming,

Pointing out that the simulation was done for the non-linear system of the motor, and the performance of the proposed methodology against changing parameters was tested by changing the value of stator resistance to double value.

The proposed methodology showed robust performance and maintained system stability.

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