

Linear Quadratic Robust Control of Synchronous Reluctance Motor [†]

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[†] Presented at the Sustainable Mobility and Transportation Symposium 2024, Győr, Hungary, 14–16 October 2024.

Abstract: Synchronous reluctance motors (SynRMs) play a key role in modern vehicles as they do not require permanent magnets and sliding brushes, reducing maintenance requirements and increasing reliability. My research focused on the development of robust torque control for SynRM. In the simulations, I compared the linear quadratic (LQ) controller with the conventional proportional–integral (PI) controller. To apply the LQ control method, I converted the nonlinear motor model into a linear one. We expect the results of this research to show that the LQ controller provides faster and more robust performance than the PI controller. LQ control can provide faster response times and a more stable operation, which are particularly important under dynamic vehicle operating conditions. Although LQ control is more computationally intensive and takes longer to fine tune, the results show that it results in a better and more stable control system. Such benefits are significant in dynamic vehicle operating conditions where fast and reliable torque control is essential. Overall, it can be concluded that advanced control techniques such as LQ can contribute to increasing the efficiency and performance of synchronous reluctance motors in the automotive industry, thus contributing to the development of sustainable and reliable vehicles.

Keywords: synrm; LQ control; robust control



Citation: Bányai, D.G.; Németh, Z. Linear Quadratic Robust Control of Synchronous Reluctance Motor. *Eng. Proc.* **2024**, *79*, 3. <https://doi.org/10.3390/engproc2024079003>

Academic Editors: András Lajos Nagy, Boglárka Eisinger Balassa, László Lendvai and Szabolcs Kocsis-Szürke

Published: 28 October 2024



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1. Introduction

Electromobility has been increasingly gaining ground recently. In this article, a mathematical description is presented for the development of new types of controllers. The great advantage of a motor with these types of controllers is that it does not contain rare earth metals, making its production cheaper.

The motor will be tested with two controllers, PI (proportional integrator) and LQ (linear quadratic) [1]. Although more advanced controllers can be found in the literature [2–4], simpler controllers are not addressed [5]. There are many reference calculation methods in the literature [6,7], but constant i_d control has been implemented in this study. In the following study, a motor model [8] was linearized for the LQ control method.

The obtained controllers were tested with noisy current measurements and parameter detuning during the simulations.

2. Model Formulations

In this Section, the motor formulas and the SynRM reference calculation method will be discussed.

2.1. Motor Formulations

The well-known [8,9] synchronous motor model could be used in this research because it is identical to the SynRM. In the simulation, the d-q coordinate system was used for an easier formulation. The operation of a SynRM can be described using the following equations:

$$v_d = R_s i_d + L_d \frac{di_d}{dt} - N\omega i_q L_q, \quad (1)$$

$$v_q = R_s i_q + L_q \frac{di_q}{dt} - N\omega i_d L_d, \quad (2)$$

$$T = \frac{3}{2} N (i_q i_d L_d - i_d i_q L_q), \quad (3)$$

$$J \frac{d\omega}{dt} = T - T_l - B_m. \quad (4)$$

In the formulas, the currents in the d and q directions are denoted by i , the voltages by v , and the inductance by L . The omega represents the rotational speed, T the motor torque, T_l the load torque, J the inertia, B_m the friction coefficient, R_s the phase resistance of the motor winding, and N denotes the pole pair.

The speed equation will not be used because, in torque control mode, the torque value at the operating point needs to be investigated, which can be simulated at a constant speed. Therefore, a constant speed is used for the simulation.

2.2. SynRM Reference Formulations

Reference calculations have to be used because proceeding without them is not possible. In this article, the constant i_d reference calculator method is used. First, we have to calculate $\Psi_{smaxref}$ (maximum stator flux reference), which is used in the i_{dref} equation. In the equations, T_{eref} denotes the reference torque. The formulations used can be seen below:

$$\Psi_{smaxref} = \sqrt{\frac{4|T_{ref}|L_d L_q}{3p(L_d - L_q)}}, \quad (5)$$

$$i_{dref} = \frac{\Psi_{smaxref}}{\sqrt{2}L_d}, \quad (6)$$

$$i_{qref} = \frac{2T_{eref}}{3p(L_d - L_q)i_{dref}}. \quad (7)$$

The simulations were run in MATLAB and Simulink. MATLAB was used to initialize the SynRM parameters and calculate the PI and LQ parameters. The obtained parameters were used in Simulink, where the SynRM model and torque controller were run.

3. Torque Controller Desing

In the next Section, the design of and formulas for the PI and LQ controllers, which are needed for controlling the SynRM, are presented.

3.1. PI Controller Desing

The well-known bode-based PI controller design method cannot be used due to the nonlinearity of the system. Therefore, the pole placement method has been applied [10]. The SynRm PI controller's I value and d-q direction formulation are as follows:

$$i_q = \frac{R_s}{L_q} P_q, \quad (8)$$

$$i_d = \frac{R_s}{L_d} P_d. \quad (9)$$

The “Try and Error” method has been used to find the P (Proportional) value because there no exact solution in this case.

3.2. Lq Controller Desing

The LQ controller design is an interesting topic because there are a lot of methods for this [11]. First of all, I used the MATLAB integrated LQ controller planner. To find the Q and R matrices I used the “fmincon” command. The “fmincon” command requires an error value to find the best Q and R values. The error value in these cases is the difference between the reference torque and motor torque.

To use the LQ for our SynRM motor, the model must be linearized. The linearization was performed as follows [12] and the linearized mathematical description of the motor can be seen below:

$$\frac{di_d}{dt} = \frac{R_s}{L_d} i_d + \frac{\tilde{\omega} L_q N}{L_d} i_q + \frac{L_q \tilde{i}_q N}{L_d} \omega, \quad (10)$$

$$\frac{di_q}{dt} = \frac{\tilde{\omega} L_d N}{L_q} i_d - \frac{R_s}{L_q} i_q + \frac{L_d \tilde{i}_d N}{L_q} \omega, \quad (11)$$

$$\frac{d\omega}{dt} = \frac{\frac{3}{2} N (L_d - L_q) i_q}{J} i_d + \frac{\frac{3}{2} N (L_d - L_q) \tilde{i}_d}{J} i_q - \frac{B_m}{J} \omega \quad (12)$$

In Equations (10)–(12), the values of current and rotational speed taken at the operating point are denoted with a tilde. The linearization must be performed at an operating point, which in this case was the motor’s nominal speed and torque.

4. Simulation Results

During the simulations, the controllers were tested with varying directions and magnitudes of load. The load was increased from 0 Nm to 17.5 Nm, with an increment of 2.5 Nm, ensuring that the given load was applied in both directions at 1 s intervals. The motor parameters used in the simulation can be seen in Table 1.

Table 1. SynRM Parameters.

SynRM Parameters	Value	Unit
Stator 1-phase Resistance	0.57367	Ω
Pole pairs	2	
Rated Torque	17.5	Nm
Rated Speed	3000	rotation/min
Rated Voltage	380	V
Rated Current	13.4	A
Inductance L_d	0.07628	H
Inductance L_q	0.03856	H
Rotor Inertia	0.00351	kg·m ²
Friction Coefficient	0.004	Nm·s/rad

In the first case, the performance of the “LQ” and “PI” controllers was examined with correct parameters without noise. Figure 1 clearly shows that the “LQ” reaches the reference torque much faster and without overshoot compared to the “PI” controller.

In the next step, noise was added to the current feedback in the motor model. The noise corresponds to the measurement accuracy of the current sensor used for this measurement range in everyday applications, which is 100 mA.

The result obtained in the case of noisy current feedback can be seen in Figure 2. During the examination, the noise did not cause an additional overshoot in the LQ or PI controllers. However, it can be stated that the noise has a more intense effect on the system with the LQ controller, which can be seen perfectly in the voltage signals in Figure 2.

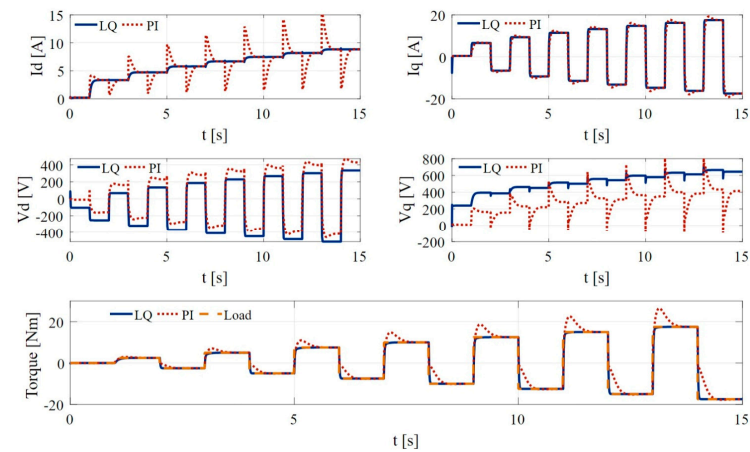


Figure 1. Operation of LQ and PI controllers in the ideal case.

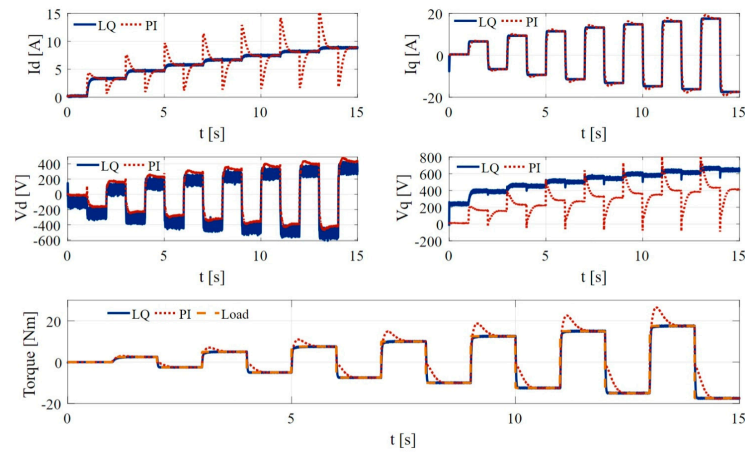


Figure 2. Operation of LQ and PI controller with noisy current feedback.

In the following case (Figure 3), the inductance value was varied by plus 10% in the simulation, as in reality, this value is not constant but frequency dependent. It can clearly be seen in this Figure that the detuning of the inductive parameter causes an offset in both the LQ and PI controllers.

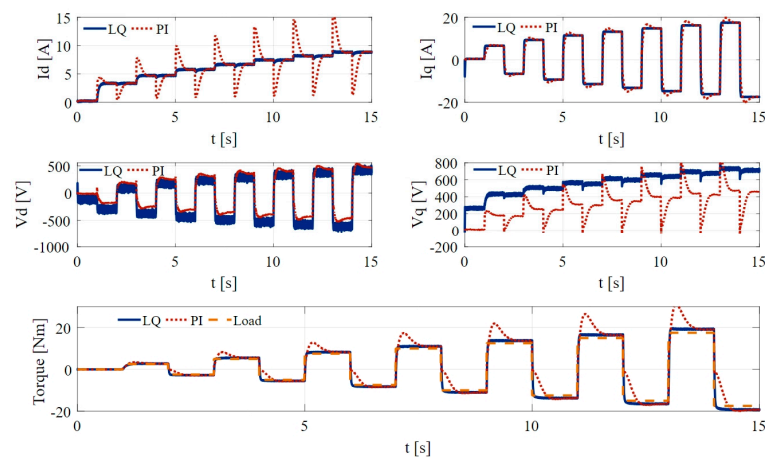


Figure 3. Operation of LQ and PI controllers in 110% L_q and L_d .

Finally, the response of the controllers when the resistance was changed was examined (Figure 4). The resistance value was increased by 61%, as this value is reached at 180 °C, which is the maximum for winding insulation in industrial applications.

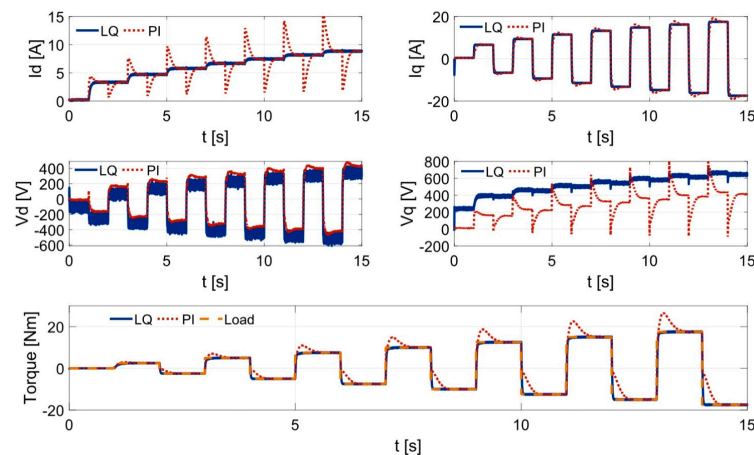


Figure 4. Operation of LQ and PI controller in plus 61% resistance.

There is no significant difference in the output torque compared to the ideal case. However, it can be seen in this Figure that the change in resistance has a more pronounced effect on the voltage signals in the LQ controller.

5. Conclusions

Overall, it can be stated that, in this case, the PI controller is more robust against noise. However, in the LQ controller, the effect of noise is constant, which can be improved. According to the results, it can be stated that LQ can be improved by applying some kind of filter or observer to the control system, such as a low-pass filter or a Kalman filter.

Our plan for future research is to improve the tuning of the controllers' parameters. For the LQ controller, a design method that results in a more robust controller, such as the H-infinity method, will be applied.

Author Contributions: Conceptualization, D.G.B. and Z.N.; methodology, D.G.B.; software, D.G.B.; validation, D.G.B.; formal analysis, D.G.B.; investigation, D.G.B.; resources, D.G.B.; writing—original draft preparation, D.G.B.; writing—review and editing, D.G.B. and Z.N.; visualization, D.G.B.; and supervision, Z.N. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data for this study are available upon request from the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

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