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Milad Akrami, Ehsan Jamshidpour, Serge Pierfederici, Vincent Frick. Comparison of Flatness-based Control and Field-Oriented Control for PMSMs in Automotive Water Pump Application. 23rd International Conference on Environment and Electrical Engineering (EEEIC 2023), Jun 2023, Madrid, Spain. pp.1-6, 10.1109/EEEIC/ICPSEurope57605.2023.10194821 . hal-04137313

HAL Id: hal-04137313

<https://hal.univ-lorraine.fr/hal-04137313v1>

Submitted on 22 Jun 2023

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Comparison of Flatness-based Control and Field-Oriented Control for PMSMs in Automotive Water Pump Application

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Abstract—With electric vehicles (EVs) becoming more and more prevalent as a reaction to climate change, efficient methods of temperature regulation are becoming necessary. Electric motors are preferred in EVs over mechanical cooler pumps and flow-regulating valves found in conventional vehicles. There are many industries that use permanent magnet synchronous motors (PMSMs) due to their high power density, high torque-to-weight ratios, simplicity, and ease of maintenance. This paper provides an overview of PMSM control research in automotive water pumps. Due to the nonlinearity of the PMSM system and its effects on multiple operating points, flatness-based control is discussed as a potential solution to overcome the limitations of field-oriented control (FOC) with proportional-integral-derivative (PID) regulators. An analysis of robustness is conducted to compare PI-based FOC with flatness-based control, and simulations are used to show the results.

Index Terms—Flatness-based control, Field-oriented control, Robustness analysis, Water Pump, Electric vehicle (EV)

I. INTRODUCTION

Global warming and climate change concerns have led to an increase in the use of electric vehicles (EVs) and hybrid electric vehicles (HEVs) instead of conventional vehicles powered by internal combustion engines. However, regardless of the type of vehicle, efficient cooling systems are crucial. Engine temperature is regulated by mechanical pumps and valves in conventional vehicles, but in EVs, advanced techniques are required. Compared to traditional methods, electric motors provide faster cooling, consume less energy, and are easier to maintain [1], [2]. Electric motors are also suitable for EV applications with multiple cooling circuits due to the high number of components requiring heat control, such as the engine, batteries, and power electronic converters [3], [4].

For many years, induction motors have been used for both residential and industrial water pump applications. The reasons for their use are mainly the low cost, low maintenance, and simplicity of control. From the energy consumption point of view, the induction motor is not ideal as a long-term solution due to its low efficiency. PMSMs, on the other hand, offer much higher efficiency in a smaller design for the same load requirements. Thanks to their high power density, high torque per weight ratio, and simple structure, PMSMs have been widely used in the aerospace, industrial control, and EV industries [5]–[7].

Most of the motors used in the current automotive water pump industry are PMSMs and Brushless Direct Current (BLDC) motors. An optimized design of a BLDC motor for water pump application in EVs is introduced in [8] that offers an equilibrium between the cost, performance and lifetime.

In [9], the process of designing and analyzing electrical machines, specifically PMSMs for automotive applications, was presented. The authors have provided a summary of the two main approaches used for designing electrical machines, analytical design and computer-aided design (CAD). Moreover, the article provided a brief overview of the main steps in the design process. In [10], the authors demonstrate that for electrical pumps with high pressures and low flows, axial flux motors can be a good alternative to classical radial flux motors. It is possible to reduce friction on the bearing by using the motor's asymmetrical axial force, attain levitation and therefore increase the pump's efficiency and life span by using that structure.

FOC method is used traditionally for speed and torque regulation in PMSM drives. The PID control scheme has proven to be one of the most popular solutions because of its ease of tuning and straightforward implementation [11]. Although PID control is a widely used control method, its

fixed gain characteristics pose challenges to its application in EV systems where operating scenarios are constantly changing. This is particularly true in applications where automotive water pumps operate dynamically within the EV system. Fuzzy logic controller (FLC) has been proposed due to having wide operating ranges. In contrast to the PID controller, which has a large overshoot value, the FLC is able to minimize overshoot, despite having a faster performance [11], [12].

Observer-based methods are essential for motor control when a position sensor is not available, allowing for the implementation of sensorless control and optimal efficiency. These methods rely on an observer to estimate the rotor's speed and position. Several techniques have been proposed for achieving this, including the Extended Kalman filter (EKF) [13], model reference adaptive system (MRAS) method [14], high-frequency signal injection (HFSI) [15], sliding-mode observer (SMO) [16], [17], and flux observer [18].

In the automotive industry, implementing cost-effective sensorless control with optimal efficiency is a challenge due to noise on the motor side's feedback signal. When a position sensor is not available to detect the motor's position and speed, feedback signal noise can cause ripples in torque, motor stoppage, or cogging, resulting in high torque ripples. Hence, several studies have been performed to optimize the motor design to maintain a balance between low cost and high efficiency with minimal torque ripples [8].

A linear approximation is required when designing controller parameters using linear methods, which are determined by the system's operating point. Model-based nonlinear control strategies have been used to address the nonlinear nature of PMSM drive systems [19]. A differential flatness theory was originally proposed by Fliess et al. [20]. It is possible to estimate a flat output directly from its derivatives by using differential flatness without integrating differential equations. Compared to the FOC method, the flatness-based method of PMSM control offers several advantages [21]:

- The flatness-based strategy can be implemented without regulators when all parameters are known, enabling open-loop control.
- Despite model errors and external disturbances, the flatness-based strategy can achieve high dynamic performances.
- Trajectory planning outperforms cascaded linear controllers in both transient and disturbed conditions.
- The performance of the flatness-based strategy is consistently competitive with conventional FOC approaches, as demonstrated in [22].

This paper compares FOC control and flatness-based control of PMSM for water pump applications. The paper is organized as follows: section II discusses the working principle of FOC control with cascaded PI-based regulators. Following this, a flatness-based control scheme for PMSM motors will be described and presented. Section III examines the robustness of the two control methods against motor parameter variation. In section IV, the results of simulations are presented to

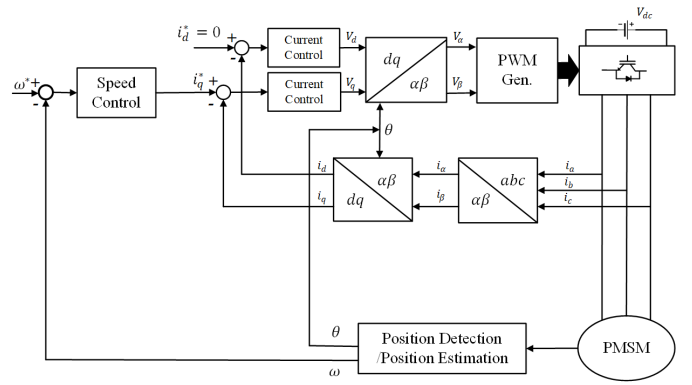


Fig. 1. FOC schematic of the PMSM.

compare these methods under different scenarios. Conclusion is given in Section V.

II. CONTROL METHODS

A. FOC control

FOC is a well-known method for controlling PMSM speed and torque by adjusting the stator current using PI controllers. The FOC method is similar to a separate-excited DC motor since the motor current is transformed using Concordia and Park transformations from a three-phase frame to the dq frame. The stator current is divided into two parts as a result: the d-axis current aligns with the rotor's magnetic field; the q-axis current runs perpendicularly to it. Motor speed and torque control can be achieved by regulating d-axis and q-axis currents through PI controllers as depicted in Fig. 1.

When cascade control is used, two controllers operate independently on inner and outer loops. Control of slower and less dynamic variables is performed by the outer loop, while control of faster and more dynamic variables is performed by the inner loop. In a PMSM control system, the outer loop controls motor speed, while the inner loop controls stator current. Following is a cascade control scheme that can be used to control PMSM motor speed using FOC:

- A current controller controls the d- and q-axis currents of the PMSM motor during the inner loop control. In the current controller, the outer loop controller provides references for d- and q-axis currents and compares those with the actual motor currents. In order to maintain the d- and q-axis currents at their desired levels, the current controller adjusts the voltage applied to the motor.
- An outer loop control uses a speed controller to control the speed of a PMSM motor. Speed controller receives speed reference and compare it to actual motor speed provided by measurement sensors or estimation methods.

B. Flatness-based control

As previously discussed, the PMSM model is utilized for flatness control. The unsaturated PMSM is regulated through Concordia and Park transformations, which leads to model described in (1).

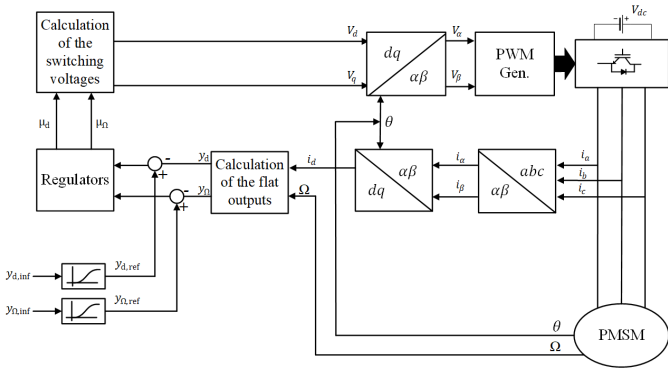


Fig. 2. Flatness-based control schematic of the PMSM.

$$\begin{cases} V_d = R_s i_d + L_d \frac{di_d}{dt} - p\Omega L_q i_q \\ V_q = R_s i_q + L_q \frac{di_q}{dt} + p\Omega L_d i_d + p\psi_f \Omega \\ J \frac{d\Omega}{dt} = p[\psi_f + (L_d - L_q)i_d]i_q - f\Omega - T_L. \end{cases} \quad (1)$$

In a motor, direct and quadrature currents are indicated by i_d and i_q , respectively. ψ_f refers to constant magnet flux, while L_d and L_q refer to the d-axis inductance and q-axis inductance, respectively. p represents the number of pole pairs and Ω is the mechanical angular frequency. T_L represents the load torque, f is the friction coefficient, and J represents the moment of inertia of the rotor. Inverters and PMSMs have losses that are accounted for by R_s , a simplified resistance.

The chosen flat outputs are the motor current in the d-axis (i_d) and the mechanical speed of the PMSM (Ω).

$$\begin{cases} y_d = i_d \\ y_\Omega = \Omega. \end{cases} \quad (2)$$

It is possible to express the state variables as a function of the flat outputs and their derivatives as illustrated in (3):

$$i_q = \frac{1}{p[\psi_f + (L_d - L_q)y_d]} (J\dot{y}_\Omega + f y_\Omega + T_L) = h_{i_q}(y_d, \dot{y}_\Omega, y_\Omega) \quad (3)$$

(2) and (3) can be used to express the switching voltages for the PMSM (V_d and V_q) as a function of the flat outputs and their derivatives. Thus, PMSM drive can be controlled by the flatness-based control method as the PMSM system is flat.

As mentioned in the previous section and illustrated in Fig. 2, according to the proposed flatness-based control architecture, two state variables (i_d and Ω) are directly controlled while the q-axis current (i_q) is indirectly controlled.

It is necessary to define two new variables in order to implement regulators for differential flatness-based control. Each of them represents one of the two maximum derivative order components in V_d and V_q equations.

$$\begin{cases} \mu_d = \dot{y}_d \\ \mu_\Omega = \ddot{y}_\Omega. \end{cases} \quad (4)$$

Using input/output linearization, regulators are designed in accordance with the following laws:

$$\begin{cases} y_{d,ref} - \mu_d + k_{d1} \cdot (y_{d,ref} - y_d) + k_{d2} \cdot \int (y_{d,ref} - y_d) d\tau = 0 \\ y_{\Omega,ref} - \mu_\Omega + k_{\Omega1} \cdot (y_{\Omega,ref} - y_\Omega) + k_{\Omega2} \cdot (y_{\Omega,ref} - y_\Omega) + k_{\Omega3} \cdot \int (y_{\Omega,ref} - y_\Omega) d\tau = 0. \end{cases} \quad (5)$$

Integral terms provide a robust rejection of both static error and parameter uncertainties. Regulation parameters are determined based on (6).

$$\begin{cases} k_{\Omega1} = 3\zeta_\Omega \omega_\Omega \\ k_{\Omega2} = \omega_\Omega^2 + 2\zeta_\Omega^2 \omega_\Omega^2 \\ k_{\Omega3} = \zeta_\Omega \omega_\Omega^3 \end{cases} \quad \begin{cases} k_{d1} = 2\zeta_d \omega_d \\ k_{d2} = \omega_d^2 \end{cases} \quad (6)$$

where ω_Ω , ω_d , and ζ_Ω , ζ_d are the cutoff pulsations and the damping coefficients, respectively.

III. ROBUSTNESS ANALYSIS

The closed-loop model of the system is used to analyze the robustness of control methods against variations in motor parameters. Considering the d- and q-axis currents of the motor and its mechanical speed as state variables of the system, the PMSM state-space equations in open-loop system are described in (1). The following subsections will present the state-space representation of the closed-loop system for FOC and flatness-based control methods of PMSM.

A. FOC method

As a result of the cascade control system, each PI regulator adds one extra state variable to the closed-loop model. It is therefore necessary to take into account the state variables given in (7).

$$\begin{cases} \dot{x}_{id} = k_{ic}(i_{d,ref} - i_d) \\ \dot{x}_{iq} = k_{ic}(i_{q,ref} - i_q) \\ \dot{x}_\Omega = k_{i_\Omega}(\Omega_{ref} - \Omega), \end{cases} \quad (7)$$

where k_{ic} and k_{i_Ω} are integral coefficients in current and speed regulator respectively.

The nonlinear closed loop state-space presentation of the system for FOC control is described in (8) by calculating the V_d and V_q variables based on the state variables of the system and substituting in (1).

$$\dot{X}_{FOC} = A(X_{FOC}) \cdot X_{FOC} + B_{FOC} \cdot U_{FOC}. \quad (8)$$

Where $X_{FOC} = [i_d, i_q, \Omega, x_{id}, x_{iq}, x_\Omega]^T$ is the matrix of state variables and $U_{FOC} = [i_{d,ref}, \Omega_{ref}, T_L]^T$ is the matrix of the system inputs. By linearizing the state-space equations of the system around the equilibrium point for the nominal operating point of the system, the Jacobian matrix of the system, $J_{FOC} \in R^{6 \times 6}$, can be computed.

TABLE I. PMSM parameters

Nominal speed	3000 rpm
Number of poles	8
Battery voltage	12 V
Motor equivalent resistance	66.7 mΩ
Motor series inductance	40 μH
Motor inertia	45.5e-6 kg.m ²

B. Flatness-based control method

For flatness-based control, each regulator adds one state variable to the state-space representation of the closed-loop system. Therefore, it is necessary to consider the state variables in (9).

$$\begin{cases} \dot{x}_{id} = i_{d,ref} - i_d \\ \dot{x}_{\Omega} = \Omega_{ref} - \Omega. \end{cases} \quad (9)$$

For flatness-based control, the nonlinear state-space presentation of the system is found in (10), by calculating the V_d , V_q , and $\dot{\Omega}$ based on the state variables of the system and substituting into (1).

$$\dot{X}_{Flatness} = A(X_{Flatness}) \cdot X_{Flatness} + B_{Flatness} \cdot U_{Flatness}. \quad (10)$$

Where $X_{Flatness} = [i_d, i_q, \Omega, x_{id}, x_{\Omega}]^T$ is the matrix of state variables and $U_{Flatness} = [i_{d,ref}, i_{d,ref}, \Omega_{ref}, \Omega_{ref}, \Omega_{ref}, \Omega_{ref}, \dot{i}_{d,ref} \cdot \Omega_{ref}, \Omega_{ref}^2, \Omega_{ref} \cdot \Omega_{ref}, T_L]^T$ is the matrix of the system inputs. It is possible to compute the Jacobian matrix of the system, $J_{Flatness} \in R^{5 \times 5}$, using the state-space equations of the system around their equilibrium points for the nominal operating point of the system.

C. Comparison

Robustness of the control methods against motor parameters variation is investigated based on the eigenvalues of the Jacobian matrix of FOC and flatness-based control for different values of motor parameter.

As the nonlinear term of model equation is related to the motor inductance, Fig. 3 shows the eigenvalues of the J_{FOC} for different values of motor inductance from $0.5 L_{nom}$ to $12 L_{nom}$. This diagram shows that the closed-loop system will become unstable if the motor's inductance exceeds a certain value.

Fig. 4 shows the $J_{Flatness}$ eigenvalues for different motor inductance from $0.5 L_{nom}$ to $7 L_{nom}$. The flatness-based method is a model-based method with only one control loop, which makes it less robust than FOC with cascaded structure against parameter variations. The method is, however, robust to parameter variation in industrial applications. It is possible to improve the robustness of flatness-based control methods by using observers to estimate model parameters more accurately.

IV. SIMULATION RESULTS

The FOC and flatness-based control techniques for PMSM using the parameters outlined in Table I were simulated using Matlab Simulink.

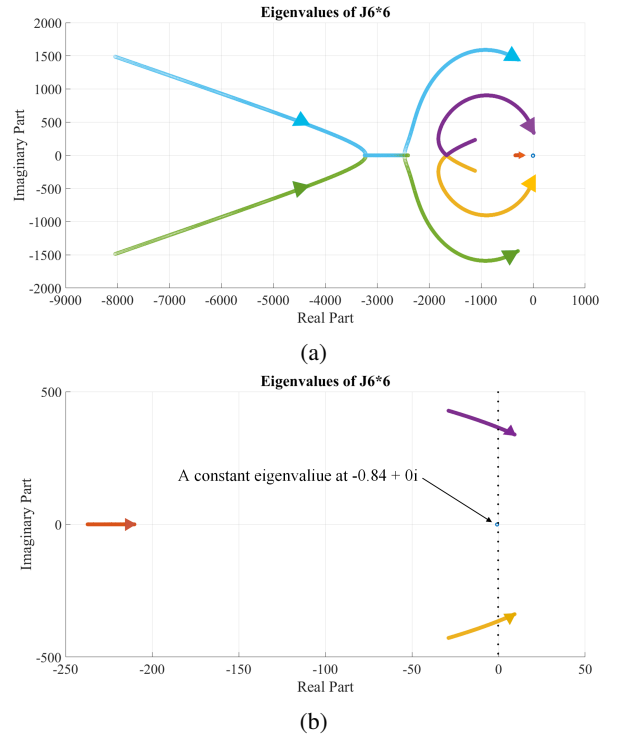


Fig. 3. (a) Eigenvalues of J_{FOC} for different motor inductance from $0.5 L_{nom}$ to $12 L_{nom}$. (b) Zoom on the eigenvalues that make the system unstable.

The switching frequency of the inverter is 10 kHz. Considering that the bandwidth of the inner loop (current control loop) should be at least 10 times higher than the bandwidth of the outer loop (speed control loop) for tuning FOC regulators, the response time of current control and speed control is considered to be 1 ms and 10 ms, respectively. Fig. 5 shows motor speed under two different events of changing the speed reference and changing the load torque for three different cases (with accurate parameters, with inaccurate motor inductance $L = 3 L_{nom}$, and with inaccurate motor resistance $R = 3 R_{nom}$).

At $t = 1$ s, the motor reference speed changes to 3000 rpm, and at $t = 2$ s, the load torque changes to 0.26 N.m. As it was discussed in the last section, this cascaded control method is robust for this range of variation in motor parameters. The results are very similar for all these three cases. However, the dynamic of system against disturbances, change in load torque and change of operating points is not very fast as is depicted in Fig. 5 (a).

In this flatness-based control system, there is only one loop, therefore ω_n is at least 10 times smaller than the switching frequency, 600 rad/s in the simulation studies. The trajectory function is defined as follows:

$$y_{ref} = \frac{1}{\frac{1}{\omega_f^2} s^2 + \frac{2\zeta_f}{\omega_f} s + 1} y_{inf} \quad (11)$$

to ensure the flatness conditions for the system. Fig. 6 shows

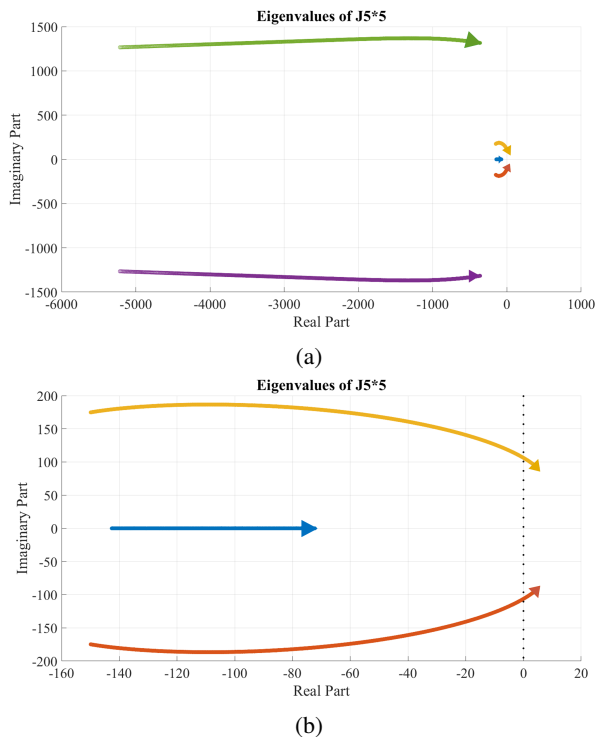


Fig. 4. (a) Eigenvalues of $J_{Flatness}$ for different motor inducance from $0.5 L_{nom}$ to $7 L_{nom}$. (b) Zoom on the eigenvalues that make the system unstable.

simulation results for a similar scenario to FOC. As one of the advantages of the flatness-based control method, the output of the trajectory planning block closely follows the motor speed even when model parameters are inaccurate. The system dynamics are also faster with flatness-based control than with the FOC method, as shown in Fig. 6 (c) compared with Fig. 5 (c).

As a result of the simulations, it is shown that flatness-based control exhibits better dynamic response, especially with respect to variation of load torque and disturbances.

V. CONCLUSION

An overview of PMSMs' usage in automotive water pump applications was presented. The paper discussed various control methods, their advantages, and their drawbacks. A comparison has been made between flatness-based control and FOC since the latter is the most widely used, whereas few studies have been conducted on the drive of PMSMs by flatness-based control. While PI-based controls are more robust against motor parameter variations, flatness-based controls with integral terms in regulators have acceptable robustness for industrial pumps. In addition to this, it is important to note that flatness-based control can also be modified for saturated PMSMs if the motor operates in saturated mode, which changes the parameters and the model of the system.

It has been demonstrated that flatness-based control, using only one loop, controls the motor speed with a faster time

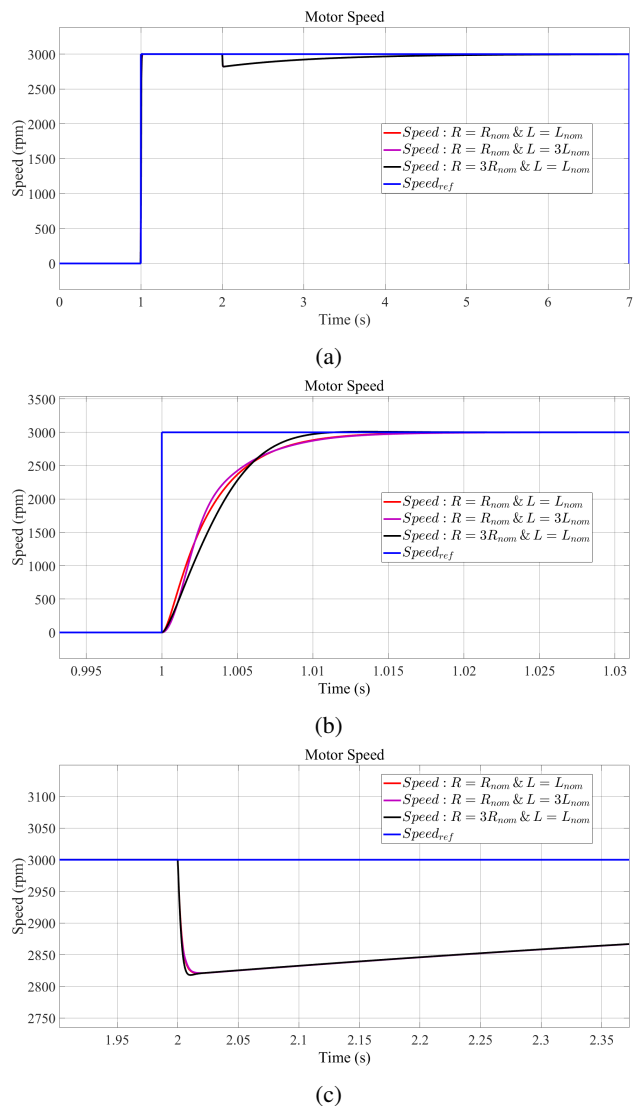


Fig. 5. (a) Motor speed with FOC method. (b) Comparison of motor performance under change of speed reference considering motor parameter variation. (c) Comparison of motor performance under change of load torque considering motor parameter variation.

response, especially when there are disturbances and changes in load torque. Using flatness-based control with only one loop has the disadvantage of sacrificing motor current protection. This will be discussed in future work, and a solution will be proposed and verified on a testbench.

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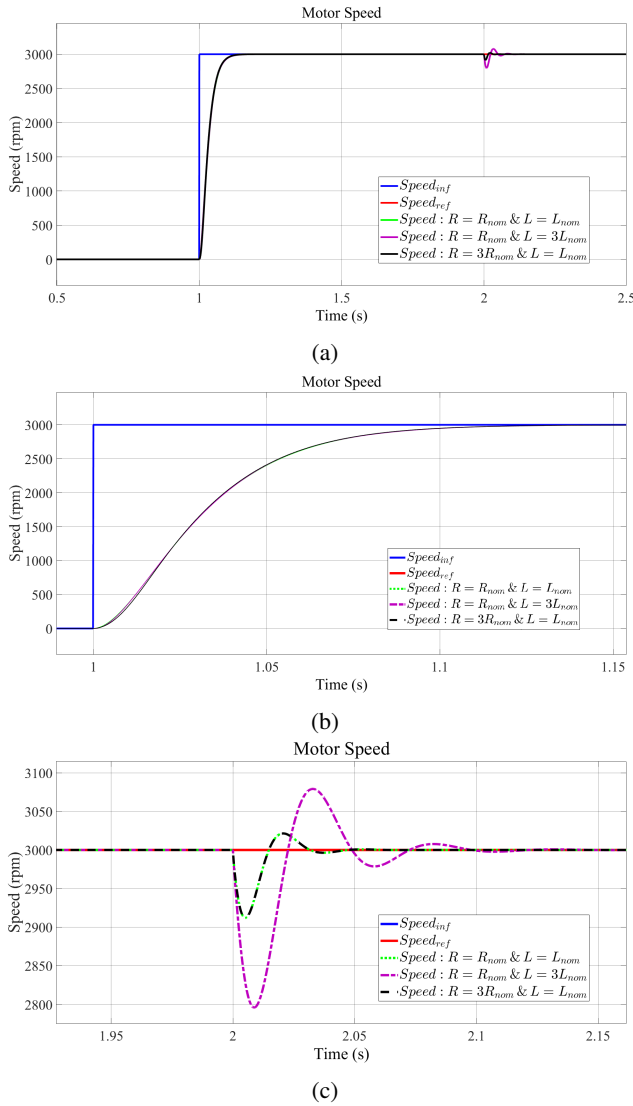


Fig. 6. (a) Motor speed with flatness-based control method. (b) Comparison of motor performance under change of speed reference considering motor parameter variation. (c) Comparison of motor performance under change of load torque considering motor parameter variation.

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