Robust Decoupling Vector Control of Interior Permanent Magnet Synchronous Motor Used in Electric Vehicles with Reduced Parameter Mismatch Impacts

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Abstract: Interior permanent magnet synchronous motor (IPMSM) drives have been widely employed in sustainable transport such as electric vehicles (EV). However, the traditional vector control (VC) strategies cannot achieve optimal control due to the intrinsic property of the IPMSMs, which is strong coupling. To solve the issue, this paper proposes an improved decoupling VC strategy to improve the steady-state performance of the IPMSMs with reduced parameter mismatch impacts. First, a deviation decoupling strategy is developed, and meanwhile, the parameters that influence the decoupling method are clearly illustrated. This enriches the theory concerning decoupling control and lays the ground for the development of effective solutions to the parameter mismatch issue. Second, the Luenberger observer theory is discussed, based on which the reason why the Luenberger inductance observers are not widely employed is explained for the first time. Third, with the aid of intermediate variables, which are the disturbances caused by the mismatched inductances, a new inductance identification method based on the Luenberger observer is proposed. Finally, the simulation and experimental results prove that the proposed decoupling methods, as well as the parameter identification method, are effective.

Keywords: interior permanent magnet synchronous motor; decoupling control; electric vehicles; parameter mismatch; Luenberger observer; sustainable transportation

1. Introduction

For the sake of sustainability, environmental friendliness, energy conservation, etc., electric vehicles (EV) have become one of the most crucial forms of transportation at present [1,2]. In addition, because the EVs have the typical advantages of easy driving, reduced noise, low maintenance, high safety, and low cost, an increasing number of drivers are obsessed with them [3–5]. As the key component of an EV, the traction system plays a dominant role in improving the response speed, stable operation, and working efficiency of the vehicle, and so, it has attracted much attention from both manufacturers and scholars [6]. Considering that interior permanent magnet synchronous motors (IPMSM) have the advantages of high torque density, high energy efficiency, and strong controllability, they are widely adopted in the application of EV traction [7–10], and the typical vehicle products include the Tesla Model 3, the Porsche Taycan, the Toyota Prius, etc.

In practice, EVs place great demand on the performance of the IPMSM drives. Specifically, when a car starts and overtakes, the motor should show high dynamics, but when the car works in a cruise control state, the motor is required to rotate stably at a certain speed [11]. On this basis, high-performance control strategies which have both good dynamics and steady-state performance are highly desired. The commonly used IPMSM control methods include vector control (VC) and direct torque control (DTC) [12,13]. Traditional VC has both speed and current regulation loops, endowing the motor with satisfying steady-state performance. However, as for the DTC, it discards the speed control loop and directly regulates the output torque of the motor by converting acceleration/deceleration...
signals from drivers to torque reference. In comparison with the DTC, the VC is characterized by better steady-state performance, but it does not significantly sacrifice the dynamics once the parameters of the PI regulators are well-designed; it is therefore deserving of much more investigation [14].

Based on the automatic control principle, the reasons why the traditional VC does not have dynamics as good as those of the DTC (but has better steady-state performance) include the fact that the dual-loop structure, with at least three PI regulators incorporated, lowers the bandwidth of the system [15]. Low bandwidth brings about larger delay but can reject the impacts of high-frequency noises and disturbances. There are two practical challenges when designing a high-performance VC strategy. First, it is necessary to tune the parameters of the speed and current PI regulators approximately [16]. Nevertheless, the IPMSM is well known for its nonlinear properties. In this case, the system cannot be described as a standard transform function, making it difficult to obtain the optimal parameters of the PI regulators. Second, due to the intrinsic property of the IPMSMs, that is, strong coupling, the $d$- and $q$-axis currents are not controlled by the corresponding manipulated voltages. Instead, they are interactively influenced, resulting in static errors and declined dynamics [16]. From the perspectives of these two aspects, decoupling strategies that can linearize the system and remove the coupling effect are highly desired practically [17]. However, the decoupling strategies are usually parameter-dependent, leading to the fact that once mismatched parameters are utilized, static current errors will occur, degrading the steady-state performance remarkably. Hence, it is valuable to develop effective strategies to solve the parameter mismatch issue for the decoupling techniques.

To reduce parameter mismatch impacts on the decoupling VC strategies, two kinds of solutions would be useful: online parameter identification and disturbance rejection [18–28].

1. **Online parameter identification**: The common online parameter identification strategies can be categorized as the model reference adaptive system (MRAS) [18], the recursive least square (RLS) method [19], the extended Kalman filter (EKF) [20], state observers [21], and the artificial intelligence (AI) method [22,23]. In terms of these techniques, because the state-observer-based ones are easy to implement and understand, they are attracting increasing attention now. For instance, a series of sliding mode (SM) observers are proposed in [24] to detect the stator inductances, and [25] develops a reduced-order observer to estimate the time constant.

2. **Disturbance rejection**: In [26–28], the current errors caused by parameter mismatch are regarded as disturbances. By the use of observers and disturbance regulators, the disturbances can be observed first and then compensated through feedback compensation. Comparatively speaking, the first method is a direct solution to the parameter mismatch problem, while the latter is a non-direct strategy with a more complicated structure. Overall, the online parameter identification methods based on state observers deserve in-depth investigation, but they are seldom focused on in the field of the decoupling control of IPMSMs.

The Luenberger observer is a method proposed by Luenberger, Kalman, and Bucy which was originally targeted at improving the control rate of a system [29]. It has the advantages of fast response speed, relatively high robustness against external disturbances, and strong capacity for handling nonlinearity; therefore, it has been widely employed for state estimation [30–32]. For example, in [30], the PMSM rotor speed and position are detected by a nonlinear Luenberger observer. However, it needs to be mentioned that the previous studies mostly utilized the Luenberger observers to identify the state variables (e.g., position, speed, etc.) of the motor but few focus on parameter (e.g., inductance, resistance, etc.) identification. So far, no studies exactly point out this issue and explain why this happens or mention developing effective Luenberger parameter observers.

This paper presents an improved decoupling VC method to enhance the performance (especially the steady-state performance) of IPMSMs used in EVs. To reduce parameter mismatch impacts on the decoupling VC strategy, a novel inductance identification technique based on the Luenberger disturbance observer is innovatively proposed. The main contributions and novelties can be summarized as follows:
(1) A deviation decoupling scheme is designed to linearize and decouple the IPMSM model, with the parameter mismatch impacts on its current performance analyzed. This reveals the parameters that influence the control performance of the decoupling VC and addresses the necessity of employing effective parameter identification strategies to solve the issue. Undoubtedly, the theories concerning decoupling control can be enriched through this study.

(2) Targeting the parameters that are prone to become mismatched and have severe impacts on the control performance, a parameter identification method based on the Luenberger disturbance observer is proposed, with its stability analyzed. It needs to be mentioned that this observer-based online parameter identification method treats the disturbances caused by the mismatched parameters as intermediate variables. It is achieved by discovering the relationship between the parameters and the disturbances, which has seldom been investigated before.

(3) The reason why the Luenberger observers are not broadly used for parameter identification is explained after introducing the basic theory concerning the observer in this paper for the first time.

The structure of the rest of the paper is as follows. Section 2 presents the deviation decoupling strategy and the impacts of the parameter mismatch on it. In Section 3, the parameter identification method based on the Luenberger disturbance observer is designed. The simulation and experimental results are given in Section 4. Section 5 is the conclusion.

2. Analysis of Deviation Decoupling VC Strategy

The structure of the deviation decoupling VC strategy is illustrated in Figure 1. Compared to the conventional VC in [12], one main difference is reflected in the decoupling part. This part mainly introduces the design method of the decoupling strategy first, and then, the impacts of the parameter mismatch on the decoupling VC are discussed clearly.

![Figure 1. Structure of the deviation decoupling VC strategy.](image)

**Figure 1. Structure of the deviation decoupling VC strategy.**

2.1. Deviation Decoupling VC Strategy

The electrical properties of the IPMSM in Figure 1 can be described by the following differential equations in the rotating coordinate frame (d, q-axis), where the iron saturation, eddy current, and hysteresis loss are ignored [33]:

\[
\begin{align*}
\frac{di_d}{dt} &= -\frac{R_d}{L_d} i_d + \frac{1}{L_d} p \omega_m i_q + \frac{u_d}{L_d} \\
\frac{di_q}{dt} &= -\frac{1}{L_q} p \omega_m i_d - \frac{R_q}{L_q} i_q + \frac{u_q}{L_q} \psi_f
\end{align*}
\]

(1)

where \(i_d, i_q\) are stator \(dq\)-axis currents; \(u_d, u_q\) are \(dq\)-axis control voltages; \(L_d, L_q\) are real \(dq\)-axis inductances; \(R_d\) is real stator winding resistance; \(\omega_m\) represents rotor speed; \(p\) is the number of pole pairs; \(\psi_f\) is real flux linkage generated by permanent magnets; and \(t\) is time. For the sake of intuitiveness, Figure 2a depicts the s-domain model of the motor with the current regulation process considered, where \(G_1\) and \(G_2\) are the \(d\)- and \(q\)-axis automatic
current regulators (ACR), respectively, and \( s \) is the \( s \)-domain symbol. It can be noted that the \( d \)-axis current is not only related to the \( d \)-axis variables but also to the \( q \)-axis current, and this applies to the \( q \)-axis current as well. This is the so-called coupling. In practice, \( u_d \) and \( u_q \) cannot control the \( d \)- and \( q \)-axis currents independently. Concretely, when regulating the \( d \)-axis current using an ACR, \( i_d \) would influence \( u_d \) and further \( i_d \), but when \( i_d \) is regulated, \( u_q \) and \( i_q \) will be influenced simultaneously. This results in a longer settling time and static current errors, and even worse, the system stability is inclined to decline. To improve motor control performance, it is significant to develop effective decoupling techniques.

As shown in Figure 2b, a deviation coupling method with three modules \( G_3, G_4 \), and \( G_5 \) is adopted for decoupling. Concerning the decoupling strategy, three aspects should be addressed. First, considering that the decoupling component is implemented in the digital processor, which will be combined with the original IPMSM model into the decoupled one, the delay effect of the inverter needs to be ignored, and it is equivalent to a scaling module. Second, \( G_3 \) is incorporated into the \( q \)-axis property to eliminate the impacts of motional back electromotive force (EMF); so, it can be described as:

\[
G_5 = p\omega_m\psi_f
\]

(2)

Third, the purpose of using \( G_3 \) and \( G_4 \) is to convert the original machine model to the form of (3).

\[
\begin{align*}
&u_d' = \frac{1}{L_d + R_d} i_d \\
&u_q' = \frac{1}{L_q + R_q} i_q
\end{align*}
\]

(3)

where \( u_d' \) and \( u_q' \) are the manipulated voltages after decoupling. The main challenge of the proposed decoupling method is how to design \( G_3 \) and \( G_4 \).

**Figure 2.** Diagram of \( s \)-domain IPMSM model with current regulation process considered: (a) before decoupling; (b) after decoupling.

In Figure 2b, \( u_d \) and \( u_q \) can be represented by:

\[
\begin{align*}
&u_d = G_1 (i_{d,ref} - i_d) + G_4 (i_{q,ref} - i_q) \\
&u_q = G_2 (i_{q,ref} - i_q) + G_3 (i_{d,ref} - i_d) + p\omega_m\psi_f
\end{align*}
\]

(4)

Substitute (4) into (1), and it can be further derived that:

\[
\begin{align*}
&u_d' + G_4 (i_{q,ref} - i_q) + p\omega_m L_d i_q = L_d \frac{di_d}{dt} + i_d R_s \\
&u_q' + G_3 (i_{d,ref} - i_d) - p\omega_m L_q i_d = L_q \frac{di_q}{dt} + i_q R_s
\end{align*}
\]

(5)
Then, to make (5) consistent with (3), \(G_3\) and \(G_4\) should satisfy the following condition:

\[
\begin{align*}
G_4(i_{q, \text{ref}} - i_q) + p\omega_m L_q i_q &= 0 \\
G_3(i_{d, \text{ref}} - i_d) - p\omega_m L_d i_d &= 0
\end{align*}
\]

By using (6), the IPMSM can be decoupled completely in the \(d\), \(q\)-axis reference frame; the manipulated voltages \(u_d'\) and \(u_q'\) generated by the \(d\)- and \(q\)-axis ACRs, respectively, can regulate the corresponding currents independently. In theory, this contributes to improving both the dynamics and the stability of the VC strategy [34].

### 2.2. Parameter Mismatch Impacts on Decoupling VC Strategy

Based on the above analysis, the decoupling strategy is directly related to \(L_d\), \(L_q\), and \(\psi_f\). In practice, these parameters are measured by using offline methods [35]. However, different parameter values might be obtained once the test instruments and tester are changed; so, it is possible that the offline parameters would mismatch with the real ones.

Denote the measured \(d\)-axis inductance, \(q\)-axis inductance, and flux linkage as \(L_{d,m}\), \(L_{q,m}\), and \(\psi_{f,m}\), respectively. Then, when using the proposed decoupling strategy, \(u_d\) and \(u_q\) in Figure 2b are:

\[
\begin{align*}
u_d &= u_d' - p\omega_m L_{q,m} i_q \\
u_q &= u_q' + p\omega_m L_{d,m} i_d + p\omega_m \psi_{f,m}
\end{align*}
\]

When substituting (7) into (1), the machine model after decoupling is:

\[
\begin{align*}
u_d' &= L_d \frac{di_d}{dt} + i_d R_s + p(L_{q,m} - L_q)\omega_m i_q \\
u_q' &= L_q \frac{di_q}{dt} + i_q R_s - p(L_{d,m} - L_d)\omega_m i_d - p(\psi_{f,m} - \psi_f)\omega_m
\end{align*}
\]

By comparing (8) with (3), the goal of decoupling cannot be achieved once the parameter mismatch issue occurs, degrading the system performance. To discuss the parameter mismatch impacts on the steady-state performance (static errors), simplify (8) as:

\[
\begin{align*}
u_d' &= i_d R_s + p(L_{q,m} - L_q)\omega_m i_q \\
u_q' &= i_q R_s - p(L_{d,m} - L_d)\omega_m i_d - p(\psi_{f,m} - \psi_f)\omega_m
\end{align*}
\]

Then, \(i_d\) and \(i_q\) can be obtained by solving the equations in (9):

\[
\begin{align*}
i_d &= \frac{R_s i_d' - p^2(L_{q,m} - L_q)(\psi_{f,m} - \psi_f)\omega_m^2 - p(L_{q,m} - L_q)\omega_m u_q'}{R_s^2 + p^2(L_{q,m} - L_q)(L_{d,m} - L_d)\omega_m^2} \\
i_q &= \frac{R_s i_q' + R_s p(\psi_{f,m} - \psi_f) + p(L_{d,m} - L_d)\omega_m u_d'}{R_s^2 + p^2(L_{q,m} - L_q)(L_{d,m} - L_d)\omega_m^2}
\end{align*}
\]

The static current errors \(\Delta i_d\) and \(\Delta i_q\) corresponding to certain \(u_d'\) and \(u_q'\) can be calculated by:

\[
\begin{align*}
\Delta i_d &= \frac{R_s i_d' - p^2(L_{q,m} - L_q)(\psi_{f,m} - \psi_f)\omega_m^2 - p(L_{q,m} - L_q)\omega_m u_q'}{R_s^2 + p^2(L_{q,m} - L_q)(L_{d,m} - L_d)\omega_m^2} - \frac{u_q'}{R_s} \\
\Delta i_q &= \frac{R_s i_q' + R_s p(\psi_{f,m} - \psi_f) + p(L_{d,m} - L_d)\omega_m u_d'}{R_s^2 + p^2(L_{q,m} - L_q)(L_{d,m} - L_d)\omega_m^2} - \frac{u_d'}{R_s}
\end{align*}
\]

For the sake of intuitiveness, taking an IPMSM prototype, of which the real parameters are shown in Table 1 as an example, Figure 3 illustrates the relationship between the static current errors and the measured parameters (at the rated speed) when the manipulated voltages satisfy the following extreme conditions:

\[
u_d' = 1, u_q' = 0.9U_{dc}
\]
where $U_{dc}$ is the bus voltage. From Figure 3, three interesting phenomena can be found. First, as shown in Figure 3a, when only the $d$-axis inductance mismatches, the magnitudes of the static $d$-axis current errors increase linearly as the inductance deviations increase, but the $q$-axis current errors remain zero. Figure 3b shows the similar phenomenon. Second, because the given $d$-axis manipulated voltage is much lower than the $q$-axis one, the static error magnitudes in Figure 3b are much smaller in comparison with those in Figure 3c. This represents the fact that when the voltage is higher, the parameter mismatch impacts become clearer. Third, when only the flux linkage mismatches, both the $d$- and $q$-axis current errors stand at low positions. In particular, the $d$-axis one is zero. This means that the flux linkage mismatch has weak impacts on the control performance. Overall, the $d$- and $q$-axis inductances have more severe impacts on the proposed decoupling control method; so, they need to be detected online.

### Table 1. Interior permanent magnet synchronous motor (IPMSM) parameters.

| Variable        | Description       | Value  | Unit |
|-----------------|-------------------|--------|------|
| $U_{dc}$        | bus voltage       | 334    | V    |
| $L_d$           | real $d$-axis inductance | 1.2 | mH |
| $L_q$           | real $q$-axis inductance | 2.4 | mH |
| $R_s$           | real resistance   | 0.18   | Ω    |
| $P$             | number of pole pairs | 3 | - |
| $\psi_f$       | PM flux           | 0.078  | Wb   |
| $\omega_{rated}$ | rated speed     | 300    | rad/s |
| $i_{rated}$    | rated current    | 10     | A    |

![Figure 3](image-url)

**Figure 3.** Relationship between the static current errors and the measured parameter values: (a) static errors versus $L_{d,m}$; (b) static errors versus $L_{q,m}$; (c) static errors versus $\psi_{f,m}$; (d) static errors versus $L_{d,m}$ and $L_{q,m}$ simultaneously.

### 3. Proposed Luenberger Disturbance Observer-Based Inductance Identification

As explained in Section 2, inductance mismatch has remarkable impacts on the steady-state performance of the proposed deviation decoupling VC strategy. To solve the issue, this part develops a Luenberger disturbance observer-based inductance identification method to estimate the real-time parameter values after briefly introducing the basic theory concerning the Luenberger observer and the reason why the Luenberger inductance observers are not available.
3.1. Introduction of Luenberger Observer Theory

The Luenberger observer is a model-based method, and usually, the state space model of a system is a prerequisite for constructing the observer. It regards the errors between the observed and the measured state variables as the feedback. When the observer becomes stable, the feedback errors are expected to reach zero, ensuring that the observed state variables can equal the real values. It deserves to be mentioned that when the feedback errors become zero, the variables that need to be detected can be obtained.

When designing a Luenberger observer, two stages should be included. First, select the measured states and the to-be-detected states as the global variables, and construct a standard system, which is described as:

\[
\begin{aligned}
\frac{dx}{dt} &= Ax + Bu + D \\
y &= Cx
\end{aligned}
\]  

where \( x \) represents the global variables, and \( y \) is the output state variables of the system. \( A, B, C, \) and \( D \) are the coefficient matrixes. \( u \) is the manipulated variable. Second, based on the feedback control theory, use a feedback matrix \( H \) to introduce the feedback errors between the observed and real states into the state space equations, and the Luenberger observer can be constructed as:

\[
\begin{aligned}
\frac{dx^*}{dt} &= Ax^* + Bu + D + H(y^* - y) \\
y^* &= Cx^*
\end{aligned}
\]  

where \( x^* \) is the observed states, and \( y^* \) is the observed output state variables. Finally, as long as \( H \) can be designed appropriately, making \( y^* = y \), (14) will show the same properties as the real system. Then, the variable/parameter values obtained from the observer will equal the real ones.

Based on the abovementioned theory concerning the Luenberger observer, if directly constructing inductance observers, apart from \( i_d \) and \( i_q, L_d \) and \( L_q \) should be selected as the global variables, namely \( x = [i_d, i_q, L_d, L_q]^T \). However, from the machine model (1), it can be noticed that the \( d \)-axis and \( q \)-axis inductance information is contained in the same terms, \( L_d \omega_m i_q / L_d \) and \( L_q \omega_m i_d / L_q \), leading to the fact that a standard system in the form of (13) cannot be established. This is the reason why there are no Luenberger inductance observers now. Therefore, in order to use the Luenberger observer theory to detect the inductances, intermediate variables must be employed. In this paper, a disturbance observer-based inductance identification strategy (disturbances are treated as the intermediate variables) is developed and is detailed in Section 3.2.

3.2. Inductance Identification Based on Luenberger Disturbance Observer

3.2.1. Relationship between Inductances and Disturbances

If the inductance mismatch issue appears, the real \( d \)- and \( q \)-axis inductances \( L_d, L_q \) can be described as:

\[
\begin{aligned}
L_d &= L_{d,m} + \Delta L_d \\
L_q &= L_{q,m} + \Delta L_q
\end{aligned}
\]  

where \( \Delta L_d \) and \( \Delta L_q \) are the \( d \)- and \( q \)-axis inductance errors, respectively. Substitute (15) into (1), and it can be derived that:

\[
\begin{aligned}
\frac{di_d}{dt} &= -\frac{R_s}{L_{d,m}}i_d + \frac{L_{q,m}}{L_{d,m}} p\omega_m i_q + \frac{u_d}{L_{d,m}} + \frac{\Delta L_d}{L_{d,m}} p\omega_m i_q - \frac{\Delta L_d}{L_{d,m}} \frac{di_d}{dt} \\
\frac{di_q}{dt} &= -\frac{L_{d,m}}{L_{q,m}} p\omega_m i_d - \frac{R_s}{L_{q,m}}i_q + \frac{u_q}{L_{q,m}} - \frac{\Delta L_q}{L_{q,m}} p\omega_m i_d - \frac{\Delta L_q}{L_{q,m}} \frac{di_q}{dt}
\end{aligned}
\]  

where \( \omega \) is the angular velocity.
Denote the \( d \)- and \( q \)-axis disturbances \((f_d, f_q)\) caused by inductance mismatch as:

\[
\begin{align*}
    f_d & = \frac{\Delta L_d}{L_d} p \omega_m i_d - \frac{\Delta L_q}{L_q} p \omega_m i_q \\
    f_q & = -\frac{\Delta L_d}{L_d} p \omega_m i_d - \frac{\Delta L_q}{L_q} p \omega_m i_q
\end{align*}
\]  

(17)

It needs to be mentioned that \( f_d \) and \( f_q \) are the disturbances when using the measured inductances to establish the machine model. Considering that our purpose is to identify the inductances under the stable states, (17) can be further simplified as:

\[
\begin{align*}
    f_d & = \frac{\Delta L_d}{L_d} p \omega_m i_d \\
    f_q & = -\frac{\Delta L_d}{L_d} p \omega_m i_d
\end{align*}
\]  

(18)

Equation (17) shows that when the motor rotates stably, there are certain relationship between the inductance errors and the disturbances. Practically, as long as the disturbances can be observed by a Luenberger observer, \( \Delta L_d \) and \( \Delta L_q \) can be calculated by using (18). Then, the relationship between the real-time \( d \)- and \( q \)-axis inductions and the disturbances can be obtained as:

\[
\begin{align*}
    L_d & = L_{d,m} - \frac{L_{q,m} f_d}{p \omega_m i_q} \\
    L_q & = L_{q,m} + \frac{L_{d,m} f_d}{p \omega_m i_d}
\end{align*}
\]  

(19)

3.2.2. Luenberger Disturbance Observer

Based on (19), it is feasible to calculate the real-time inductances once the disturbances are obtained at first. Now, the prerequisite of inductance identification becomes disturbance estimation. This part presents the Luenberger disturbance observer design process, after which the inductance identification technique is developed.

(a) Design of observer

First, to observe the \( d \)- and \( q \)-axis disturbances, \( i_d, i_q, f_d, \) and \( f_q \) need to be selected as global variables and \( x = [i_d, i_q, f_d, f_q]^T \). Meanwhile, define the output state variables of the system as \( y = [i_d, i_q, f_d, f_q]^T \) and \( u = [i_d, i_q, 0, 0]^T \). Then, assume that the change rate of \( f_d \) and \( f_q \) is small enough to be ignored [36], and when constructing the standard system in the form of (13), the coefficient matrixes are as follows:

\[
A = \begin{bmatrix}
-\frac{R_s}{L_{d,m}} & \frac{L_{q,m}}{L_{d,m}} p \omega_m & 1 & 0 \\
0 & -\frac{R_s}{L_{q,m}} & 0 & 1 \\
0 & 0 & 0 & 1 \\
0 & 0 & 0 & 0
\end{bmatrix}, \quad B = \begin{bmatrix}
\frac{1}{L_{d,m}} & 0 & 0 & 0 \\
0 & \frac{1}{L_{q,m}} & 0 & 0 \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0
\end{bmatrix}, \quad C = \begin{bmatrix}
1 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 \\
0 & 0 & 1 & 0 \\
0 & 0 & 0 & 1
\end{bmatrix}, \quad D = \begin{bmatrix}
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0
\end{bmatrix}
\]  

(20)

Second, construct the Luenberger disturbance observer (see Figure 4) in the form of (14), in which the observed states are as follows:

\[
x^* = [i_d^*, i_q^*, f_d^*, f_q^*]^T, \quad y^* = [i_d^*, i_q^*, i_d^*, i_q^*]^T
\]

(21)

When the system reaches the equilibrium state, the estimated currents equal the real ones, that is, \( i_d^* = i_d \) and \( i_q^* = i_q \). At the moment, \( f_d^* \) and \( f_q^* \) represent the real disturbances. In terms of the feedback matrix \( H \), because there are four feedback variables, it can be defined as:

\[
H = \begin{bmatrix}
h_1 & 0 & 0 & 0 \\
0 & h_2 & 0 & 0 \\
0 & 0 & h_3 & 0 \\
0 & 0 & 0 & h_4
\end{bmatrix}
\]  

(22)

where \( h_1, h_2, h_3, \) and \( h_4 \) are constants that need to be adjusted to make the observer stable.
(b) Stability analysis

As shown in Figure 4, the proposed \( d \)- and \( q \)-axis disturbance observers are independent. Hence, stability analysis should be applied to them one by one. Considering that the stability analysis process is similar for both observers, this paper only takes the \( d \)-axis one as an example for analysis.

When it comes to the \( d \)-axis disturbance observer, the global variables are \( x = [i_{ld}, f_d]^T \), \( x^* = [i_{ld}^*, f_d^*]^T \), \( y = [i_{ld}, i_d]^T \), \( y^* = [i_{ld}^*, i_d^*]^T \), and \( u = [u_{ld}, 0]^T \). Then, the coefficient matrixes are:

\[
A = \begin{bmatrix}
-R_{s} & 1 \\
L_{d,m} & 0 \\
0 & 1
\end{bmatrix},
B = \begin{bmatrix}
\frac{1}{L_{d,m}} \\
0 \\
0
\end{bmatrix},
C = \begin{bmatrix}
1 & 0 \\
0 & 1
\end{bmatrix},
H = \begin{bmatrix}
h_1 & 0 \\
0 & h_3
\end{bmatrix}
\] (23)

According to the automatic control theory, to make a Luenberger observer stable the feedback coefficients need to be placed based on the expected poles [37]. Assuming that the expected poles of the observer are \( p_1 \) and \( p_2 \), the conditions that ensure the system to be stable are as follows:

\[
Eig(A - HC) = \{p_1, p_2\}
\] (24)

where \( Eig(\cdot) \) is the function to calculate the eigenvalues of a matrix. Denote \( E \) and \( \gamma \) as the identity matrix and the eigenvalue, respectively. \( \gamma E - (A - HC) \) can be derived as:

\[
\gamma I - (A - HC) = \begin{bmatrix}
\gamma + \frac{R_s}{L_{d,m}} + h_1 & -1 \\
h_3 & \gamma
\end{bmatrix}
\] (25)

Then, the determinant of (25) can be calculated by:

\[
\det(\gamma I - (A - HC)) = \gamma^2 + (\frac{R_s}{L_{d,m}} + h_1)\gamma + h_3
\] (26)

Considering that the expected determinants of (25) equal \( p_1 \) and \( p_2 \), it can be derived that:

\[
(\gamma - p_1)(\gamma - p_2) = \gamma^2 - (p_1 + p_2)\gamma + p_1p_2
\] (27)

By comparing (26) and (27), to make the observer stable the following conditions should be satisfied:

\[
h_1 = -(p_1 + p_2) - \frac{R_s}{L_{d,m}}, h_3 = p_1p_2
\] (28)

In practice, the feedback coefficients can be obtained by using (28). In addition, when the observer becomes stable the disturbances \( f_d^* \) (as well as \( f_q^* \)) can be directly calculated.
3.2.3. Inductance Calculation

After estimating the disturbances $f_d^*$ and $f_q^*$, substitute them into (19) and the $d$- and $q$-axis inductances can be calculated by:

$$
\begin{align*}
L_d^* &= L_{d,m} - \frac{L_{d,m} f_q^*}{\rho \omega_n i_d} \\
L_q^* &= L_{q,m} + \frac{L_{d,m} f_d^*}{\rho \omega_n i_q}
\end{align*}
$$

(29)

where $L_d^*$ and $L_q^*$ are the estimated $d$- and $q$-axis inductances, respectively. Furthermore, the estimated inductances can be applied to the decoupling component in Figure 1, improving the steady-state performance of the system.

4. Verification Results

To verify the proposed decoupling VC and inductance identification strategies, the simulation and experiments are conducted on a three-phase IPMSM, of which the parameters comply with Table 1. The simulation system that is consistent with Figure 1 is established in MATLAB/Simulink 2018b and is shown in Figure 5a, and the experimental test bench is shown in Figure 5b. During simulation, a fixed-step mode is employed, and the calculation period is $1.0 \times 10^{-5}$ s, while the switching period of the power transistors is 0.1 ms. In terms of the experimental devices, insulated gate bipolar transistor (IGBT) devices are adopted to constitute the inverter, of which switching frequency is 10.0 kHz. DSP TMS320F28335 serves as the digital processor, and the control algorithms are executed on it. An induction motor is coupled to the test machine, providing load torque. The state information, such as currents and voltages, can be transmitted to the host computer, which can further record the data for analysis.

4.1. Simulation Results

The purposes of simulation require that first the control performances before and after using the proposed decoupling strategy need to be compared, proving that the decoupling method is able to improve the system control performance. Second, when the inductance mismatch issue occurs, the steady-state performances before and after the inductance identification method is applied to the decoupling control process should be compared, verifying that the proposed parameter identification method is effective.

Figure 6a shows the speed and current performance without using the decoupling strategy, and Figure 6b shows the system performance of the proposed decoupling VC method (without parameter mismatch). The simulation setups are as follows. Between 0 and 2.0 s, the motor speeds up to 300 rad/s (high speed) under 4.5 Nm. Then, the motor speed levels off until 3.0 s when the rotor speed decreases at 50 rad/s (low speed). For the sake of analytical simplicity, during simulation the $d$-axis current reference is set as zero, and there is no current limit when the motor speeds down. Four interesting phenomena can be seen. First, the settling time during acceleration is 0.75 s without decoupling, but it becomes 0.55 s after the decoupling strategy is adopted. This proves that the coupling effects influence the system dynamics. Second, the settling time during deceleration in Figure 6a,b is similar (0.04 s and 0.06 s, respectively), illustrating that the proposed decoupling strategy does not sacrifice the system dynamics remarkably. Third, when the motor runs stably, the $d$-axis current cannot track the reference value accurately, but this issue is solved after using the decoupling method. Undoubtedly, the proposed decoupling strategy can improve the steady-state performance. Finally, when the motor speed declines at 3.0 s, the magnitudes of the $d$- and $q$-axis currents are larger in Figure 6a in comparison with those in Figure 6b. Comparatively speaking, in addition to the currents used for the torque generation (both the $d$- and the $q$-axis currents contribute to the electromagnetic torque generation for IPMSMs), without decoupling techniques larger currents can be generated by the strong coupling effects. Overall, the coupling effects influence both the dynamics and the steady-state
performance of the IPMSM, and the proposed decoupling strategy is able to improve the system performance.

![Diagram](image-url)

**Figure 5.** Simulation and experimental setups: (a) simulation system; (b) experimental test bench.

![Graphs](image-url)

**Figure 6.** Comparative results before and after the proposed decoupling method is applied: (a) performance of VC without decoupling technique; (b) performance of the proposed decoupling VC.
Figure 7 shows the control performance of the proposed decoupling VC method with the inductance mismatch, while Figure 8 depicts the corresponding system performance after the proposed inductance identification method based on the Luenberger disturbance observer is utilized. The simulation setups are as follows. The speed reference is set as the rated value constantly before 0 and 5.0 s, and the d-axis current is controlled to be maintained at zero. It can be noticed that first, regardless of the inductance mismatch, the motor speed can stabilize at the desired level, which benefits from the automatic speed regulator (ASR). Secondly, when the inductances used for decoupling the VC are mismatched, both the d- and the q-axis currents increase, and this is unwanted. Comparatively, after employing the proposed inductance identification method, the d-axis current can nearly track the reference value, while the q-axis one sees a decreasing trend; these are similar to those in Figure 6b. In addition, Figure 8b shows that the estimated inductances are pretty accurate. These prove that the proposed inductance identification strategy based on the Luenberger disturbance observer is effective, and meanwhile, it can be used to enhance the robustness of the decoupling VC strategy.

Figure 7. System performance when inductance mismatch issue occurs without inductance identification: (a) \( L_{d,m} = 3L_d, L_{q,m} = 0.5L_q \); (b) \( L_{d,m} = 0.5L_d, L_{q,m} = 3L_q \).

Figure 8. System performance when inductance mismatch issue occurs with the proposed inductance identification method incorporated: (a) \( L_{d,m} = 3L_d, L_{q,m} = 0.5L_q \); (b) \( L_{d,m} = 0.5L_d, L_{q,m} = 3L_q \).
Overall, the simulation results demonstrate that the proposed decoupling VC can ensure a high system performance. In addition, with the proposed inductance identification technique incorporated, the decoupling strategy is strongly robust against parameter mismatch. Hence, they are valuable in real applications.

4.2. Experimental Results

The experiment was carried out to verify the effectiveness of the proposed decoupling VC strategy and the proposed inductance identification strategy. It deserves to be mentioned that the inductances and resistance in Table 1 are pretty accurate because they are measured by different engineers using different instruments, including an ohmic meter and an inductance meter. Hence, in practice, it is reasonable to treat them as the real parameters of the motor. In this part, the experiment is divided into two parts: dynamic analysis and steady-state performance analysis.

(a) Dynamic performance analysis

Figure 9 illustrates the dynamic performance of the system when the proposed decoupling strategy is adopted. First, the settling time is about 0.5 s, which is similar to the simulation results. In addition, no speed overshoot can be seen because the PI parameters are well-tuned. Overall, the motor shows good dynamics.

(b) Steady-state performance analysis

First of all, Figure 9 shows that the \( i_d \)-axis current can track the reference \( i_{d,\text{ref}} = 0 \) accurately. To further prove that the proposed control strategy has good steady-state performance, Figure 10 compares the experimental results under different situations: without parameter mismatch, with parameter mismatch, and with parameter identification. Figure 10a shows the system performance of the decoupling VC strategy at the speed of 300 rad/s when the parameters match with the real ones. It can be seen that the speed levels off at 300 rad/s, and the \( d \)-axis current is zero. In terms of the \( q \)-axis current, it is around 2.0 A. In Figure 10b, assume that the inductances used for the decoupling strategy are mismatched \( L_{d,m} = 3L_d \), \( L_{q,m} = 0.5L_q \). Although the speed can track the reference value, the magnitudes of the currents increase \( i_q \) rises to 2.5 A), and the trend is consistent with the simulation results in Figure 7. In the process, the static \( d \)-axis current errors appear. It can be concluded that the parameter mismatch issue influences the steady-state performance. Figure 10c presents the system performance when the parameter mismatch issue occurs, and the proposed inductance identification strategy is applied. The \( d \)-axis current can now track the reference value well. Additionally, the \( q \)-axis current declines to the normal level. These prove that the proposed inductance identification-based decoupling method has strong robustness against parameter mismatch. Finally, Figure 10d depicts the inductance identification results. Obviously, the proposed Luenberger disturbance observer-based inductance identification method is effective.

4.3. Discussion of Obtained Results

On the one hand, the simulation and experimental results prove that the proposed decoupling VC and inductance identification methods are effective. First, in comparison with the results of the traditional VC that does not adopt the decoupling strategy, large current surges disappear in the dynamic process when the proposed decoupling VC strategy is utilized for motor control. This indicates that the proposed method is able to suppress the coupling effect of IPMSMs. Second, when implementing the proposed decoupling VC method, the steady-state performance degrades if the inductances are mismatched, proving that the parameter mismatch issue influences the decoupling scheme. However, after using the estimated inductances, the system performance gets better. Hence, the proposed decoupling VC strategy can reduce the parameter mismatch impacts, achieving one of the main goals of this study. Finally, the inductances can be identified accurately in both the simulation and the experimental tests. There is no doubt that the proposed inductance identification method based on the Luenberger disturbance observer is effective.
On the other hand, compared to [2], which shows large current surges caused by the strong coupling effect, in which the traditional control strategy is adopted, the advantages of the proposed decoupling VC scheme are obvious. In other words, the coupling effects can be reduced by using the proposed decoupling VC strategy.

![Figure 9. Dynamic performance of the proposed decoupling VC strategy.](image)

*Figure 9. Dynamic performance of the proposed decoupling VC strategy.*

![Figure 10. Steady-state performance: (a) without inductance mismatch; (b) with parameter mismatch ($L_{d,m} = 3L_d, L_{q,m} = 0.5L_q$), but no inductance identification; (c) with parameter mismatch ($L_{d,m} = 3L_d, L_{q,m} = 0.5L_q$) and inductance identification incorporated; (d) inductance identification results.](image)

*Figure 10. Steady-state performance: (a) without inductance mismatch; (b) with parameter mismatch ($L_{d,m} = 3L_d, L_{q,m} = 0.5L_q$), but no inductance identification; (c) with parameter mismatch ($L_{d,m} = 3L_d, L_{q,m} = 0.5L_q$) and inductance identification incorporated; (d) inductance identification results.*

5. Conclusions

The IPMSMs are characterized by strong coupling, which influences the performance of the traditional VC algorithms. To solve the issue, this paper proposes a decoupling VC strategy. Considering that the inductance mismatch issue has a marked influence on the proposed decoupling VC strategy, a novel inductance identification method is developed. The main contributions and novelties can be summarized as follows:

1. By designing and analyzing the deviation decoupling VC strategy, the parameters that influence its control performance are revealed, and it is found that the $d$- and $q$-axis inductances have more remarkable impacts compared to the other parameters. This was never addressed previously so as to be meaningful.

2. Targeting the inductance mismatch issue, a novel inductance identification technique based on the Luenberger disturbance observer is developed, with its stability analyzed. In detail, a Luenberger observer is developed for disturbance estimation, and
relying on the close relation of the mismatched inductances and the disturbances, the inductances can be identified. It deserves to be mentioned that the Luenberger observer theory has seldom been employed for parameter identification, making the proposed strategy innovative and valuable in both academic and industrial areas.

(3) During the study, the reasons why the Luenberger observer cannot be used to directly estimate the stator inductances were illustrated for the first time, enriching the relevant theory concerning the Luenberger observer.

(4) Simulation and experiment were carried out to validate the proposed decoupling strategy and parameter identification method. From the obtained results, it can be seen firstly that the decoupling VC strategy reduces the current surges caused by the coupling effect. In addition, by using the proposed inductance identification method, the inductances of the motor can be detected, and meanwhile, the negative impacts of inductance mismatch on the decoupling VC strategy can be rejected. Overall, the proposed decoupling VC strategy with reduced parameter mismatch impacts is effective.

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