Robust cascade-free predictive speed control for PMSM drives based on Extended State Observer

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Abstract
The direct predictive speed controller (DPSC) deals with the prediction of the motor speed based on precise mechanical parameters. However, the mechanical parameters are dependent on the practical applications and may not match with their actual values, which leads to inaccurate prediction of the motor behaviour and deteriorates the performance of the predictive algorithm. A three-order Extended State Observer is designed for a permanent magnet synchronous motor to observe the unknown overall disturbance of the system and compensate the speed prediction error, which reduces the usage of the mechanical constants and improves the robustness of the system against parameter uncertainties, accurate mechanical parameters become unessential. To improve the current dynamics, by using proper weighting of the position angle observation error, along with the overall disturbance, a new current controller is incorporated in the control law of developed PSC strategy. The proposed strategy is evaluated through experimental results with a two-level voltage source inverter. Finally, the proposed work is experimentally compared with a predictive speed control, by considering several performance indices.

1 | INTRODUCTION

During recent years, the finite control set model predictive control (FCS-MPC) strategy has emerged as an attractive solution for permanent magnet synchronous motor (PMSM) and power converters due to its intuitive concept, great flexibility and fast dynamic response [1–3]. The FCS-MPC predicts the future behaviour of the system states in each sampling instant based on the system model and selects the optimal actuation according to predefined optimization criteria (cost function) [4–6]. Compared to another predictive control techniques, one of the best features is the system non-linearities and limitations can be incorporated directly into the system model.

FCS-MPC can replace the cascaded control structure and modulation stage in conventional field orientation control (FOC) scheme, which provides a fast dynamic response in addition to good steady-state performance. In [7,8], the operating principle of FOC is used by FCS-MPC to design predictive current control (PCC) scheme. Similar methods are used to design predictive torque control (PTC) based on the principle of direct torque control (DTC) strategy [9,10]. All control variables of FOC and DTC are regulated by PCC, PTC without employing internal PI and hysteresis controllers. Both PCC and PTC only replace the internal control loops of FOC and DTC, the outer speed control loop is still employed by a PI controller to regulate the speed value. The band of the external speed loop is limited by the dynamic response of the internal current loops in a linear cascade control scheme. In [11], the predictive speed control (PSC) scheme is proposed. This scheme eliminates the speed PI controller, the motor speed and currents are manipulated simultaneously by the cost function. The PSC strategy uses a cascade-free structure which can improve the speed dynamic response compared to traditional cascade PI control [12]. Moreover, due to the absence of torque current reference, the torque current is uncontrolled in defined cost function, which may cause currents deterioration during steady-state operation. To improve the steady-state performance of currents. In [12], a principle of deadbeat control method is used to generate the torque current reference value, however, this method heavily depended on the accuracy of mechanical parameters and observed torque. Similar deadbeat control strategy is proposed...
in [13], a second-order Taylor expansion is used to generate the torque current reference. In [14–16], the maximum torque per ampere (MTPA) scheme is applied to PSC, the torque current reference is designed on the basis of the MTPA and field weakening trajectories, but the load torque disturbance is not considered. In [17], a linear controller based on speed errors is used to generate the q-axis reference current, it has a better current steady-state performance, but the tuning of controller is complicated and stability issues arise. In [18], active disturbance-rejection control is used to generate the torque reference, it is based on a one-order mechanical model, but the non-linear observer needs nine coefficients to tune and it is not a cascade-free structure, the robustness against load and mechanical parameters are not considered. In [19], a torque disturbance observer is used to generate the torque reference, it is also based on a one-order model and only considers the robustness against load torque.

On the other hand, In PSC strategy, the motor speed is predicted by using its discrete-time mathematical model of motor, but the identified mathematical parameters may not match with their actual values due to the measurement error or they may change during the operation of the motor. The load torque value $T_L$ is usually obtained as a main disturbance by online observations. Mechanical parameter mismatches and unknown disturbance lead to speed prediction errors [20]. An extended Luemberger observer has been adopted to estimate the torque and speed in [17]. A reduced order extended Kalman filter is presented to estimate the state variables for a two mass system in [21], including the angle, speed and load torque.

Several sliding-mode load torque observers are proposed to observe the load torque in [22–24], the inherent robustness of sliding mode control enhances its resistance to electrical parameter mismatches, but these PSC strategies do not consider the effect of mechanical parameter mismatches on the speed prediction. However, compared to electrical parameters such as inductance, flux and resistance, the mechanical parameter identifications of the motor are a more difficult process.

In this paper, the aforementioned problems are addressed by a three-order ESO, the load torque and the model errors caused by parameter mismatches are estimated as overall disturbance. The speed prediction value is compensated with the observed disturbance, which reduces the speed prediction error and current prediction error caused by parameter mismatches. The value of damping ratio $B$ is unessential, and the system has a strong robustness against the inertia variations. On the other hand, in order to improve system behaviour when encountering abrupt transient conditions, the observation error of the position angle, along with the overall disturbance are incorporated in the control law of MPC, as a torque current reference value. Hence, the developed PSC scheme achieves a good steady state performance with strong robustness. To assess the proposed PSC scheme, a two-mass system with PMSM and 2L-VSI is investigated. The proposed PSC strategy is experimentally evaluated under load torque and inertia variations. The proposed controller is experimentally compared with the PSC strategy proposed in [17] in terms of the steady-state performance, dynamic performance and the robustness.

### 2 | MATHEMATICAL MODEL OF MOTOR AND INVERTER

FCS-MPC strategy uses the system mathematical model to predict the future system behaviour. Owing to this reason, an accurate mathematical model is a key point for the implement of the control scheme. The PMSM and two-level inverter model used in this paper have been described in this section.

#### 2.1 | PMSM model

The system studied comprising PMSM and a two-level inverter is presented in Figure 1. For the convenience of derivation, the state-space model of PMSM in $ds$-frame is expressed as follows

$$\frac{di_d}{dt} = -\frac{R_i}{L_d}i_d + \frac{L_q}{L_d}\omega_e q + \frac{u_d}{L_d}$$  \quad (1)

$$\frac{di_q}{dt} = -\frac{R_i}{L_q}i_q - \frac{L_d}{L_q}\omega_e i_d + \frac{u_q}{L_q} - \frac{\psi_f}{L_q}\omega_e$$  \quad (2)

$$\frac{d\theta}{dt} = \omega_e$$  \quad (3)

$$\frac{d\omega_e}{dt} = ai_q + bo_e + cT_I$$  \quad (4)

where $a = 1.5p^2((L_d - L_q)i_d + \psi_f)/J$, $b = -B/J$, $c = -p/J$. $i_d$, $i_q$ are stator dq-axis currents and $u_d$, $u_q$ are stator dq-axis control voltages. $L_d$ and $L_q$ are dq-axis inductances. $\psi_f$, $R_i$ are permanent magnet flux linkage and stator inductances. $\omega_e$, $\theta$ and $p$ are rotor electrical angular speed, electrical angle and the number of pole pairs, $T_I$ is the load torque, while $J$ and $B$ are the moment of inertia and the viscous coefficient. When only $\theta$ and $\omega_e$ are considered, they are two-order system with a cascade integral form.

#### 2.2 | Power converter model

A conventional 2L-VSI is applied to drive the PMSM. This converter has eight switching states, which generates seven different voltage vectors to the PMSM as shown in Figure 2.
disturbance in the system, the observed overall disturbance is applied to compensate speed predictive model, which reduces the impact of mechanical parameter mismatches and load disturbance. Considering the implementation of the digital processor in practical system, a time step delay compensation is essential. The motor speed and currents are incorporated in the cost function simultaneously to constitute a cascade-free control structure. The \( d \)-axis reference current is set to zero and the \( q \)-axis reference current is generated with position angle error and the overall disturbance. The details of Figure 3 are introduced in the following texts.

### 3.1 State variables estimation based on ESO

Considering the mechanical parameter mismatches, the state-space description of motor position (Equation 3) and speed (Equation 4) can be described as follows:

\[
\begin{align*}
\frac{d\theta}{dt} &= \omega_e \\
\frac{d\omega_e}{dt} &= (a + \Delta a)i_q + (b + \Delta b)\omega_e + (c + \Delta c)T_l
\end{align*}
\]

Where \( \Delta a \), \( \Delta b \) and \( \Delta c \) are variations caused by parameter mismatches and considered as the 'internal disturbance', the load torque \( T_l \) is regarded as the 'external disturbance'. The ESO does not distinguish the 'internal disturbance' or 'external disturbance', but treats them as a new state variable, which is called 'overall disturbance'. The state-space description can be expressed as follows:

\[
\begin{align*}
\frac{d\theta}{dt} &= \omega_e \\
\frac{d\omega_e}{dt} &= ai_q + \Delta d
\end{align*}
\]

where \( \Delta d = \Delta ai_q + (b + \Delta b)\omega_e + (c + \Delta c)T_l \), and it is defined as the overall disturbance. Taking the overall disturbance \( \Delta d \) as a new extended state variable, for two-order system, a three-order ESO is used with the overall disturbance as another state variable. The three-order linear ESO can be designed as follows:

\[
\begin{align*}
e_1 &= \hat{\theta} - \theta \\
\frac{d\hat{\theta}}{dt} &= \hat{\omega}_e - \beta_{01}e_1 \\
\frac{d\hat{\omega}_e}{dt} &= ai_q + \Delta d - \beta_{02}e_1 \\
\frac{d\Delta d}{dt} &= -\beta_{03}e_1
\end{align*}
\]

### 3 PROPOSED PSC ALGORITHM BASED ON ESO

A robust PSC algorithm based on Extended State Observer (ESO) (PSCE) is proposed in this paper. Precise mechanical parameters and real-time load information are unessential. The control diagram of proposed PSC is shown in Figure 3, a linear three-order ESO is used to observe state variables and overall
In this form, ESO gives the estimation variables $\theta, \dot{\theta}, \Delta \dot{d}$ by taking the input value $\theta$, which are respectively the estimation of $\theta, \omega, \Delta d$. The estimation error can converge to sufficiently small value by selecting suitable coefficients $\beta_{01}, \beta_{02}, \beta_{03}$. It can be seen that a cascade integral form is used in ESO, all the system parameters do not appear in the estimation, but appear only in the disturbance, the estimation can be designed without precise system parameters, which provides strong robustness of observer dynamics.

The tuning of the coefficient is similar to high gain observer. The pole assignment technique is used to design the coefficients [25]. To simplify the parameter tuning, all the closed-loop poles are assigned at $-\omega$, the ESO gains can be parameterized as follows:

$$L = [\beta_{01} \beta_{02} \beta_{03}]^T = [3\omega \ 3\omega^2 \ \omega^3]^T \quad (9)$$

### 3.2 Speed prediction and compensation

The system model must be discretized in a time step to calculate the future states in FCS-MPC strategy. Assuming that the optimal voltage vector $u_t$ at last time instant has been selected and the sampling current, $i_s$, is conducted at $k$th time instant, when the forward Euler approximation is selected to discretize the system, the stator current at $(k + 1)$th instant can be expressed as follows:

$$i_d(k + 1) = \left(1 - \frac{T_i R_d}{L_d}\right)i_d(k) + \frac{L_d T_i}{L_d} \dot{\omega}_e(k)i_q(k) + \frac{T_i}{L_d} u_d(k)$$

$$i_q(k + 1) = \left(1 - \frac{T_i R_q}{L_q}\right)i_q(k) - \frac{T_i L_q}{L_q} \dot{\omega}_e(k)i_d(k) + \frac{T_i}{L_q} u_q(k) - \frac{T_i \Delta d}{L_q} \dot{\omega}_e(k) \quad (10)$$

where $T_i$ is the time interval. To reduce the quantization noise caused by speed measurement, the estimated speed $\dot{\omega}_e$ is used to calculate the current predictions.

As for the prediction of the speed, most PSC strategies predict the speed at next time instant according to the system dynamic Equation (4), which require a real-time precise torque value and mechanical parameters. The accuracy of the speed prediction value at next time performs a great importance to PSC strategy. The speed at $(k + 1)$th time instant is calculated according to Equation (7), and it can be expressed as follows:

$$\omega_q(k + 1) = \dot{\omega}_e(k) + T_i a i_q(k) + \Delta \dot{d}(k) \quad (12)$$

It can be noted that the damping ratio $B$ is not used in process of speed prediction, which proves that the speed prediction value calculated with Equation (12) has a robustness against the damping ratio $B$. The load and parameter mismatches are observed with overall disturbance $\Delta \dot{d}(k)$ and compensated to the speed dynamic model. A better observation ensures the accuracy of the speed prediction value, which reduces speed prediction error and brings a robustness against parameter mismatches or load disturbance.

In practice, the controller needs time to conduct the calculation process, and the optimal voltage vector can’t be applied to system immediately after the sampling process. Therefore, a time step delay compensation is essential. The future speed $\omega_q(k + 2)$ and currents $i_d(k + 2)$ at $(k + 2)$th time instant are predicted based on the present states of the system. Here, we have We made the following approximation, $\Delta \dot{d}(k) = \Delta \dot{d}(k + 1)$. The errors between the predictive values and the reference values are applied to the cost function to determine the optimal voltage vector at $(k + 1)$th time instant. The prediction process of state variables at $(k + 2)$th is similar to Equations (10)–(12).

### 3.3 Cost function design

In PSC strategy, the applied optimal voltage vector is determined by minimizing the cost function. The control objectives include the speed tracking, current tracking and current limitation. To regulate the speed, when a second-order norm is adopted, the speed error is incorporated in the cost function as follows:

$$C_\omega = \lambda_{oc}(\omega^*(k + 2) - \omega_e(k + 2))^2 \quad (13)$$

where $\lambda_{oc}$ is the weighting factor of speed, $\omega^*(k + 2)$ is the speed reference at $(k + 2)$th. Considering the mechanical time constant, $\omega^*(k + 2) \approx \omega^*(k)$.

To obtain a better current dynamic and steady-state performance, the $d$-axis current is driven and kept at zero, and the $q$-axis is tracked with the torque current reference $i_q^*$. The cost function is designed as

$$C_i = \lambda_d i_d^2(k + 2)^2 + \lambda_q \left(i_q^* - i_q(k + 2)\right)^2 \quad (14)$$

where $\lambda_d$ and $\lambda_q$ are the weighting factors of $d$-axis and $q$-axis currents.

In conventional linear controller with a cascade structure, the PI controller is most commonly used to generate the torque current reference $i_q^*$. However, the PI controller is not used in the cascade-free PSC strategy. In this paper, a new torque current reference $i_q^*$ has been defined as

$$i_q^* = m(\theta - \theta) - \frac{\Delta \dot{d}}{a} \quad (15)$$
The first part \( u_0 = m(\theta - \dot{\theta}) \) is a linear state error feedback control of the position error signal, which is a proportional control. \( m \) is proportional gain of the current controller and \( m > 0 \). Because the disturbance can be estimated and compensated by the second term \(-\Delta d/a\), the integral signal of error can be omitted. To reduce the system oscillation and improve the steady state performance of speed, the differential signal of error is also not used. The traditional PID scheme is improved to compensate the disturbance, by reducing the disturbance, the two-order system can be simplified as a standard cascade integral form as follows:

\[
\frac{d^2 \theta}{dt^2} = au_0
\]  

which realizes the linearization of the dynamic feedback of the system and simplifies the system control.

Besides that, the current reference should not exceed the max current limitation.

\[
i_q^* = \begin{cases} 
  i_q^*, & |i_q^*| \leq I_{q\text{max}} \\
  I_{q\text{max}} \cdot \text{sign}(i_q^*), & |i_q^*| > I_{q\text{max}} 
\end{cases}
\]  

where \( I_{q\text{max}} \) is the maximum \( q \)-axis current amplitude of the motor, and \( \text{sign}(x) \) is the Sign function, when \( x \) is larger than zero, its output is 1, and it is −1 when \( x \) is less than zero.

It’s important to control the stator current to avoid exceeding the current limitation, an additional term is added to the cost function.

\[
C_l = \begin{cases} 
  \lambda_{IM}, & |i_d| > I_{d\text{max}} \text{ or } |i_q| > I_{q\text{max}} \\
  0, & |i_d| \leq I_{d\text{max}} \text{ and } |i_q| \leq I_{q\text{max}} 
\end{cases}
\]

where \( I_{d\text{max}} \) is the maximum \( d \)-axis current amplitude of the motor, \( \lambda_{IM} \) is a large constant. When stator current amplitude exceeds the limitation, a larger cost function value will exclude the selected voltage vector.

The total cost function can be designed as a weighted sum of previous single cost function

\[
C = C_o + C_c + C_l
\]

The overall scheme of the proposed PSCE algorithm is shown in Figure 4, the execution steps of the algorithm are summarized as follows:

1. Measure the stator currents and the rotor position angular.
2. Observe the rotor position, the electrical angular speed and the overall disturbance according to Equation (8).
3. Calculate the torque current reference \( i_q^* \) according to Equation (15).
4. Predict the future \( d \)-axis current, \( q \)-axis current and electrical angular speed according to Equations (10)–(12), consider one time step delay compensation.
5. Enumerate and calculate the optimal voltage vector by minimize the cost function Equation (19).
6. Apply the optimal voltage vector and repeat steps 1–5.

### 4 | Characteristic Analysis of the PSCE Strategy

#### 4.1 | Tracking performance analysis

The accurate estimation of the overall disturbance \( \hat{\Delta d} \) is essential to weigh the tracking performance of the ESO. Assuming \( i_q = 0 \), the relationship between the estimated value \( \hat{\Delta d} \) and the actual value \( \Delta d \) of the overall disturbance in frequency domain can be expressed from Equation (8) as follows:

\[
\frac{\Delta \hat{d}(s)}{\Delta d(s)} = \frac{\beta_{03}}{s^3 + \beta_{01}s^2 + \beta_{02}s + \beta_{03}}
\]

The transfer function of the disturbance estimation error is expressed as follows:

\[
\frac{\Delta \hat{d}(s) - \Delta d(s)}{\Delta d(s)} = \frac{s^2 + \beta_{01}s + \beta_{02}}{s^3 + \beta_{01}s^2 + \beta_{02}s + \beta_{03}}
\]
When the observer gains are chosen as Equation (9), the estimation error transfer function is specified as follows:

$$\frac{\Delta \tilde{d}(s)}{\Delta d(s)} = -\frac{s(s^2 + 3\omega s + 3\omega^2)}{(s + \omega)^3}$$  \hspace{1cm} (22)

assuming that the input is a ramp signal, that is $\Delta d(t) = kt$, $k$ is the slope, the estimation error of disturbance is expressed as

$$E_d(s) = \Delta \tilde{d}(s) - \Delta d(s) = -\frac{s(s^2 + 3\omega s + 3\omega^2)}{(s + \omega)^3} \times \frac{k}{s^2}$$ \hspace{1cm} (23)

The steady-state estimation error of overall disturbance in time domain can be expressed as follows:

$$e_\infty = \lim_{s \to 0} \left( -\frac{s(s^2 + 3\omega s + 3\omega^2)}{(s + \omega)^3} \times \frac{k}{s^2} \right) = -\frac{3k}{\omega}$$ \hspace{1cm} (24)

Based on the transfer function expression of Equation (22), the estimation error responses of overall disturbance in time domain are shown in Figure 5. To simplify the index selection, according to Equation (7), the overall disturbance $\Delta d$ has the same dimension with $\Delta \omega e/dt$, which is the acceleration. In Figure 5a, different bandwidths $\omega$ increase from 1000 to 1600, stepped by 100 rad/s, are shown in the same figure under the condition of the overall disturbance $\Delta d(t) = t$. When the bandwidth is fixed at 1600, Figure 5b depicts the estimation errors in case of different slopes $k$ increase from 1 to 13, stepped by 2. The direction of the arrow is the direction of data increase. Evidently, the estimation error of overall disturbance exits a steady-state offset $-3k/\omega$, the larger $\omega$ leads less tracking errors and rapider speed to track the state variables. However, the system performance will deteriorate due to noise filtering as $\omega$ increase, the determination of $\omega$ is a trade-off between the states tracking and the noise suppression.

4.2 | Speed and current prediction error analysis

According to Equation (4), when no mechanical parameter mismatches happen, the speed prediction can be expressed as

$$\omega_e(k + 1) = \frac{1.5p^2T_s[(L_d - L_q)i_d(k) + \psi_f]i_q(k)}{J + \Delta J}$$ \hspace{1cm} (25)

when mechanical parameter mismatches happen, the speed prediction is expressed as

$$\omega_e(k) = \frac{1.5p^2T_s[(L_d - L_q)i_d(k) + \psi_f]i_q(k)}{J + \Delta J} - \frac{pT_s}{J + \Delta J}T_i + \left(1 - \frac{BT_i}{J + \Delta J}\right)\omega_e(k)$$

Hence, the speed prediction error between the error-free model (Equation 25) and model (Equation 26) subjected to parameter variations can be obtained as follows:

$$E_\omega = \omega_e^m(k + 1) - \omega_e(k + 1)$$

$$= -\frac{\Delta \tilde{d}(k)T_i}{(J + \Delta J)} = \frac{\Delta \omega_e(k + 1) - \Delta \omega_e(k)}{J + \Delta J}$$ \hspace{1cm} (27)

It can be seen that not only the parameter mismatches but also the instant currents, speed, and the load torque have effects on the speed prediction error. Especially, the $q$-axis current $i_q$ will change along with the load $T_i$, which causes different speed error between the dynamic and steady-state process. Usually, when the motor starts up, the load is not added in the dynamic process, and $i_q$ is set as the max current to ensure faster speed tracking. Assuming $i_d \approx 0$, $i_q = 2.5$ A, the speed increases in the process of startup, only the steady-state speed is considered, assuming $\omega_e = 50$ rad/s and $T_i = 0$ N m. The relationship between the speed prediction error and different degrees of parameter mismatches is shown in Figure 6a. It can be seen that the mismatches of inertia will lead to a large speed prediction error. However, the
mismatches of viscous damping lead little effect on the error of prediction speed. When the load is added to the motor and operated in steady state, assuming \(i_d = 0\), \(i_q = 1.45\) A, \(\omega_q = 50\) rad/s and \(T_l = 0.65\) N m, the relationship between the speed prediction error and different degrees of parameter mismatches is shown in Figure 6b. It can be noted that both two mechanical parameters lead less effect on the speed prediction error compared with the dynamic process. When motor operates at no load, \(i_q \approx 0\) A and \(T_l = 0\) N m, the sum of first term and second term in Equation (25) is almost zero, which is similar to the situation when the load is added to the motor.

From Equation (27), not only the mismatch of mechanical parameters but also the load \(T_l\) and the speed \(\omega_q\) are related to the speed prediction error. However, the electrical torque is almost equal to the load torque when motor operates at steady state, which means that the first term in Equation (27) satisfies

\[
-\Delta f_p T_l \left\{ 1.5 p \left[ (L_d - L_q) i_d + \psi_f \right] i_q - T_l \right\} \approx 0 \tag{28}
\]

So, the load torque has very little effect on the speed prediction error when motor operates at steady state.

On the other hand, the relationship between the speed prediction error and the steady-state speed under the condition of \(i_d \approx 0\) A, \(i_q = 1.45\) A, \(T_l = 0.65\) N m, \(\Delta f = f\) and \(\Delta B = 2B\), is shown in Figure 6c. It can be seen that the speed prediction error increases with steady-state speed. However, it is still very small in a wide range of speed. Therefore, the biggest challenge against the speed prediction error is to reduce the effect caused by the mismatches of inertia in the dynamic process.

According to Equations (10) and (11), the currents at \(\langle k + 2\rangle\)th time instant are calculated with the speed prediction value \(\omega(k + 1)\), the error of speed prediction will also cause the current prediction error. The current prediction error at \(\langle k + 2\rangle\)th time instant caused by speed mismatch can be expressed as follows:

\[
\Delta i_d(k + 2) = i_d^m(k + 2) - i_d(k + 2) = \frac{L_q T_l}{L_d} E_w i_q(k + 1)
\]

\[
\Delta i_q(k + 2) = i_q^m(k + 2) - i_q(k + 2) = \frac{-T_l E_w (L_d i_q(k + 1) + \psi_f)}{L_q} \tag{30}
\]

where \(i_d^m(k + 2)\), \(i_q^m(k + 2)\) are \(dq\)-axis current prediction values by using the inaccurate speed calculated with Equation (26), \(E_w\) is the speed prediction error defined in Equation (27).

It can be noted that the \(dq\)-axis current prediction errors are related to the speed prediction error \(E_w\) and the instant currents. The relationship between the \(dq\)-axis current prediction errors and instant currents and speed prediction error has been shown in Figure 7. It can be seen that the influence of speed prediction error on \(q\)-axis current prediction error is greater than that of \(d\)-axis current prediction error. However, both \(d\)-axis current and \(q\)-axis current prediction errors are very small. In fact, for the current prediction, inductance has the greatest influence on the current prediction error, then the resistance and flux linkage, and finally is motor speed. Related issues have been proposed in the literature [26,27]. The robustness against electrical parameters is not discussed in this paper.

A simulation comparison of the speed prediction error between the proposed PSCE strategy and the PSC strategy with extended Luengerber observer (PSCLE) [17] is shown in Figure 8. The speed prediction error is defined as follows:

\[
\Delta \omega_{error} = \omega_{e}(k + 2)_{mismatch} - \omega_{e}(k + 2)_{match} \tag{31}
\]

where \(\omega(e)(k + 2)_{mismatch}\) is the speed prediction value at \(\langle k + 2\rangle\)th time instant with parameter mismatches. \(\omega(e)(k + 2)_{match}\) is speed prediction value with no parameter variations. In PSCL method, an extended Luenberger observer is used to observe the electric angle, motor speed and load torque according to Equations (3) and (4). It is designed as follows:

\[
\frac{d\hat{x}}{dt} = A\hat{x} + Bu + Lv \tag{32}
\]

where \(x = [\theta, \omega, T_l]^T, v = y - \dot{y} = C(x - \hat{x}), L = [l_1, l_2, l_3]^T\). The system matrices \(A, B\) and \(C\) are derived from the
mechanical model in Equations (3) and (4) and the notation \(\hat{\cdot}\) is used to describe the estimated variables. The pole assignment technique is also applied to design the gains of extended Luenerger observer, three poles are set as the same value \(\omega = 1600\) and the gains are \(l_1 = 4.8 \times 10^3\), \(l_2 = 7.67 \times 10^5\), \(l_2 = -2.05 \times 10^3\).

After the speed and load values are estimated, the speed prediction value at next time is calculated according to Equation (25). Besides that, a linear current controller is adopted to generate the torque reference value \(i_q^*\) in PSCL strategy. Therefore, in the cost function of current tracking errors, \(C_c\), the torque current reference \(i_q^*\) is designed as an integral form

\[
i_q^* (k) = i_q^* (k - 1) + k_1 (\omega^* (k) - \omega (k)) + k_2 (\omega^* (k - 1) - \omega (k - 1))
\]  

(33)

where \(k_1\) and \(k_2\) are gains of the current controller. They are tuned according to [17] and designed as \(k_1 = 0.2\), \(k_2 = -0.198\). The speed reference is set as \(n = 300\, \text{rpm}\) and a load torque \(\langle T_i \rangle = 0.65\, \text{N m}\) is added at 0.15s.

The bandwidths of ESO and Luengerber observer are set the same value \(\omega = 1600\). In Figure 8a, the identified inertia \(J_0\) in the controller has been set as \(J_0 = 0.5\) J. It can be noted that the proposed PSCE strategy has less speed prediction error when parameter mismatches occur. Figure 8b shows the prediction error when identified inertia \(J_0 = 1.5\) J. It can be noted that the compensation effect for speed prediction error is better than when identified inertia is reduced. In a word, a more precise prediction value can be obtained with proposed PSCE strategy in a wide range of parameter mismatches.

The \(dq\)-axis current prediction errors at \((k + 2)\)th instant with PSCE and PSCL strategy under the condition \(J_0 = 1.5\) J have been shown in Figure 9. Compared to PSCL strategy, the \(dq\)-axis currents with PSCE strategy have less prediction error since the predicted speed is more accurate, which proves that the proposed PSCE strategy can reduce the current prediction errors caused by the inertia mismatches.

4.3 Weighting factors tuning

The tuning of the weighting factor is still a challenging process, it is usually based on empirical or heuristic method. FCS-MPC controls different variables by simply adding appropriate terms to the cost function, since the controlled variables are expressed in different units, which makes the determination of the weighting factors become very complex. Several solutions have
been proposed in [22,28,29], complex computational processes are required. In this paper, the system has been simulated in different speed and load conditions to tune the weighting factors, which satisfies the performance characteristics and system restrictions in a wide operating range. The $d$-axis and $q$-axis currents have the same unit, their weighting factors have been arbitrarily set equal as $\lambda_d = \lambda_q = 1$. Second, the weighting factor of the speed error $\lambda_{\text{u}}$ is determined in order to ensure that the speed keeps improved transient response without distorting the motor currents, Figure 10 has conducted a sensitivity analysis to the speed weighting factor $\lambda_{\text{u}}$. The speed responses under different $\lambda_{\text{u}}$ are shown in Figure 10a, the steady-state currents in $a/b$-axis are shown in Figure 10b. Table 1 has summarized the detailed speed and current information. It can be seen that the speed performs a faster response and a stronger anti-load-disturbance ability with a larger $\lambda_{\text{u}}$. However, the steady-state current total harmonic distortion (THD) increases with a larger $\lambda_{\text{u}}$. Both faster speed response and steady-state current performance should be considered.

The tuning of proportion gain $m$ is not complex, compared to the current reference proposed in PSCL strategy, only one gain is needed to determine. Figure 11 shows the simulation responses to a speed reference step and load step variation with different gains $m$, and the results are summarized in Table 2. The speed ripples are defined as the peak-to-peak values, the $q$-axis current ripples are defined two mean absolute errors as follows:

$$M_I = \frac{1}{N} \sum_{k=1}^{N} |e_I(k)| = \frac{1}{N} \sum_{k=1}^{N} |i_q(k) - \hat{i}_q(k)|$$

where $N$ is the total number of sampling points, $\hat{i}_q(k)$ denotes the target $q$-axis current, and $i_q(k)$ is the instant $q$-axis current.

It can be seen that the proposed torque current reference controller is not sensitive to the gain $m$, the speed ripple and speed drop increase a little with a larger $m$, and different $m$ have little effect on the current ripples, the stability issues are avoided.

### 4.4 Robustness analysis

Nearly all MPC strategies are rely on the mathematical model of system, it’s requisite to evaluate control system robustness to parameters variation. The robustness against mechanical parameter mismatches is simulated and discussed with proposed PSCE strategy. It should be noted that the viscous damping $B$ is not used in proposed PSCE strategy, which proves that the proposed method has robustness against the
viscous damping (b) Besides that, according to the discussion in Section 4.2, the variations of viscous damping $B$ have almost no effect on the speed prediction error, the effect of viscous damping is ignored and not discussed in this paper. In contrast, the moment of inertia $J$ has significant effect on the speed prediction error, the speed and current responses under the condition of inertia mismatches with proposed PSCE strategy are shown in Figure 12 and partial response characteristics of Figure 12 are summarized in Table 3. The motor operates at a medium speed ($n = 300$ rpm) and a medium torque ($T_l = 0.65$ N m).

It can be seen that the proposed method keeps stable with a wide range of inertia variations. Figure 12a shows the speed response with different inertia mismatches, when the identified inertia $J_0$ is larger than actual parameter, longer speed rise time and settling time are needed, the speed drop is less with the increase of identified inertia when the load is added. However, the current ripple remains almost unchanged, as shown in Figure 12b. When identified inertia is less than the actual value, speed overshoot occurs, the speed and current ripples increase more than the situation when identified inertia is larger than actual value. Certainly, the ability to against inertia variations is limited, excessive speed prediction error makes current and speed calculations inaccurate. After a lot of simulation tests, when the identified inertia satisfies $J_0 < 0.08$ J or $J_0 > 5$ J, the system oscillates and becomes unstable.

Figure 13 shows the speed and $q$-axis current responses with $J_0 = 0.5$ J under different steady-state speeds, the low speed ($n = 200$ rpm), medium speed ($n = 300$ rpm) and rated speed ($n = 400$ rpm) are tested. All the simulation results are summarized in Table 4. It can be seen that the speed ripples and speed drops increase with the improvement of steady-state speed, a longer speed reversion time is needed. However, the current ripple decreases a little, because when motor operates at its rated speed, the actual voltage vector will closer to six active voltage vector, which reduces current ripples.

The speed and $q$-axis current responses with $J_0 = 0.5$ J under different load torques are shown in Figure 14, the light torque ($T_l = 0.35$ N m), medium torque ($T_l = 0.65$ N m) and rated torque ($T_l = 0.95$ N m) are tested, and the simulation results are summarized in Table 5. It can be noted that different load torques perform diverse speed drops, and it has little influence on the speed ripples. As we have discussed in Section 4.2, different load torques have little effect on the
TABLE 4 Response characteristics of Figure 13a,b

| Parameters                  | Value |
|-----------------------------|-------|
| Steady-state speed $\omega_e$ (rpm) | 200   |
| Speed ripple $\Delta n_1$ (rpm) | 1.46  |
| Speed drop $\Delta n$ (rpm)    | 34.1  |
| Speed reversion time $t_r$ (ms) | 11.35 |
| Current ripple $\Delta I$ (A)  | 0.089 |

![Simulation responses with $J_0 = 0.5$ J under the condition of different load torques. (a) Speed. (b) Current of phase B](image)

**FIGURE 14** Simulation responses with $J_0 = 0.5$ J under the condition of different load torques. (a) Speed. (b) Current of phase B

speed prediction error. However, the load torque is associated with the overall disturbance, accurate estimation is the premise to reduce speed prediction error. When the load torque is added, the overall disturbance is approximately considered as a step signal, that is $\Delta d(t) = k$, where $k$ is the amplitude of the overall disturbance. Because the observed disturbance lags behind the actual value, the greater the disturbance, there will be a larger initial observation error, and a larger speed drop occurs. When the motor operates at steady-state, according to Equation (23), the estimation error of disturbance can be described as follows:

$$E_d(s) = \Delta d(s) - \Delta d(s) = -\frac{s(s^2 + 3ao + 3a^2)}{(s + \alpha)^3}\frac{k}{s}$$ (35)

and the steady-state estimation error can be expressed as

$$e_\infty = \lim_{s \to 0} \left(-\frac{s(s^2 + 3ao + 3a^2)}{(s + \alpha)^3}\frac{k}{s}\right) = 0$$ (36)

It can be noted that different load torques perform zero state error, so different load torques perform little effect on the speed ripples. The bandwidth of the ESO should be large enough to guarantee an accurate load torque estimation.

## 5 | EXPERIMENTAL RESULTS

The proposed PSCE strategy and the method proposed in [17] (PSCL) have been tested on the experimental setup. Figure 15 shows the controller platform and PMSM used, the parameters of the PMSM are shown in Table 6. Two PMSM with same parameters compose a two-mass system. The left PMSM is controlled with all PSC strategy, and the right PMSM is controlled as the load motor with a standard PI current controller, the latter has been tuned with the Ziggler-Nichols method to ensure a rapid current response. Both the proposed control algorithm and PI scheme have been implemented on Texas Instruments LAUNCHXL-
TABLE 7 Parameters of proposed PSCE strategy

| Symbol  | Quantity                          | Values |
|---------|-----------------------------------|--------|
| $\lambda_w$ | Weighting factor of speed       | 0.05   |
| $\lambda_d$ | Weighting factor of $d$-axis current | 1      |
| $\lambda_q$ | Weighting factor of $q$-axis current | 1      |
| $\lambda_{IM}$ | Current limitation constant | $10^5$ |
| $M$ | Coefficient of the current controller | 60     |
| $I_{d \text{ max}}$ | Maximum $d$-axis current limitation | 0.3 A  |
| $I_{q \text{ max}}$ | Maximum $q$-axis current limitation | 2.5 A  |
| $\Omega$ | Bandwidth of ESO | 1600   |
| $U_{dc}$ | DC-link voltage | 24 V   |

F28379D platform. A 200 MHz DSP on the board can guarantee adequate processor performance to execute all programs. Two 2L-VSI driving modules are applied to control each motor separately by using Texas Instruments BOOSTXL-DRV8305. Two identical current sampling modules are used for current measurement. The quadrature photoelectric encoder with a resolution of 10,000 pulses has been used as position sensor for the PMSM.

FIGURE 16 Tracking performance of position angel and speed.
(a) ESO. (b) Luenberger observer

FIGURE 17 Observed disturbance and the torque current reference.
(a) PSCE strategy. (b) PSCL strategy

The embedded code technique has been applied to guarantee the consistency of simulations and experiments. It should be noted that a dead time with 1.5 $\mu$s is added to the inverter, and the influence of the dead time to the strategy is not discussed in this paper. The sample time for PSCE and PSCL strategy are both set as 100 $\mu$s. The execution process concludes the time of PSC algorithm and load motor algorithm. For PSCE strategy, it is found about 80 $\mu$s, and it is about 94 $\mu$s for the PSCL strategy.

5.1 Tracking performance of ESO

In this section, the performance of ESO is compared with the Luenberger observer of PSCL strategy. All adjusted parameters of proposed PSCE strategy are presented in Table 7. The same configuration process and parameters have been used for the PSCL strategy.

The tracking performance of ESO and Luenberger observer are shown in Figure 16. Figure 16a has validated that the on-line ESO performs a rapid and accurate tracking of the state variables. At $t = 0.15$ s, a medium step load ($T = 0.65$ N m) results a transient speed decrease, the ESO can still tracks the speed reference and the overall disturbance rapidly in the dynamic process. Figure 16b depicts the actual
state variables and estimated state variables observed by extended Luenberger observer. Both of two observers can estimate the state variables well when no parameter mismatches happen.

Rapid and accurate tracking performance helps the proposed PSCE strategy achieve rapid and accurate tracking of the speed. The observed disturbance and the torque current reference value are shown in Figure 17. Compared to the ESO, the load torque is directly observed in Luenberger observer, precise values of the moment of inertia \( J \) and viscous damping \( B \) are needed to ensure the rapid and accurate torque tracking. However, only \( J \) is used in the ESO, the load torque and unknown disturbance caused by mechanical parameters are both observed as the overall disturbance, which reduces the

requirements for the system model accuracy. Besides that, with proposed PSCE strategy, the torque current reference associated with overall disturbance is shown in Figure 17a, and torque current reference \( i_q^* \) of PSCL strategy is depicted in Figure 17b, it is noted that the torque current reference has a large negative overshoot when load is added, and the current ripples occur. The overshoot is avoided with proposed PSCE method and makes the torque current reference \( i_q^* \) smoother.

### 5.2 Dynamic and steady-state performance

When no mechanical parameter mismatches happen, the dynamic and steady-state performance of the proposed PSCE strategy and PSCL strategy are shown in Figure 18, whereas all response characteristics are tabulated in Table 8. A medium speed reference step \((n = 300 \text{rpm})\) and medium load step \((T_L = 0.65 \text{ N m})\) are added to the motor. It is noted that PSCL strategy has a faster speed response but about 2% overshoot occurs, and a longer settling time is needed. Nearly no overshoot appears with the proposed PSCE strategy. Both the PSCE strategy and the PSCL strategy possess the characteristics of good speed control performance and anti-load disturbance ability. The motor speed can track its reference quickly, for PSCE strategy, there is a 36.06rpm speed drop when the motor is under abrupt change of load, and it's about 36.53 rpm for the PSCL strategy. The speed ripple of PSCE is

### FIGURE 18 The comparison of dynamic and steady-state performance. (a) PSCE strategy. (b) PSCL strategy

### TABLE 8 Characteristics of PSCE and PSCL strategy

| Parameter/Symbol | PSCE  | PSCL |
|------------------|-------|------|
| Speed rise time \( t_r \) (ms) | 12.82 | 12.45 |
| Speed drop \( \Delta n \) (rpm) | 36.06 | 36.53 |
| Speed ripple (rpm) | 1.96 | 1.74 |
| Speed overshoot (%) | 0 | 2.7 |
| Current THD (%) | 10.86 | 11.09 |

### FIGURE 19 Steady-state phase B current frequency spectrum. (a) PSCE strategy. (b) PSCL strategy
about 1.96 rpm, and it is 1.74 rpm PSCL strategy. Both two PSC strategies have a fast dynamic of the speed due to the cascade-free control structure, the speed rise times are about 12 ms.

The frequency spectrum of steady-state phase current \( i_B \) with two methods are shown in Figure 19. With the proposed PSCE method, the total harmonic distortion (THD) of the current is around 10.86\%, and it is around 11.09\% with PSCL strategy. The frequency spectrum of PSCE and the PSCL strategy exhibits similar characteristics, both two schemes successfully mitigate the high-frequency components in the phase currents. The average switching frequency of two controllers is calculated as follow

\[
f_{avg} = \frac{\sum_{i=1}^{2} \frac{f_{S_{ak}} + f_{S_{bk}} + f_{S_{ck}}}{6}}
\]

where \( f_{S_{ak}} \) is the average switching frequency, during a time interval of power semiconductor number \( i \) of phase \( k \), with \( i \in \{a, b, c\} \) and \( k \in \{a, b, c\} \).

The average switching of PSCE strategy is 2.718 kHz, and it is around 2.692 kHz with PSCL strategy. The PSCE and PSCL strategy have similar frequency spectrum because they are both based on the FCS-MPC scheme with no modulator.

To examine the dynamic speed change characteristics eliminating the impact of the load torque observer, the motor reverses at 0.04 s and its dynamic responses with PSCE and PSCL strategies are shown in Figure 20. It can be noted that the motor can reverse quickly without overshoot by using proposed PSCE strategy. Both the PSCE strategy and the PSCL strategy can limit the maximum currents amplitude in case of startup and reversal due to the non-linear constraint in the cost function. The max phase currents are limited at 2.5 A, which proves the effectiveness of the cost function.

5.3 | Robustness analysis

1. Robustness against inertia variations: To test the case of parameter mismatches, the identified motor inertia in the controller is changed to different values and the system response has been analysed compared to the PSCL strategy. The speed reference is set as a medium speed (\( n = 300 \) rpm) and a medium load torque (0.65 N m) is added. The dynamic and steady-state responses with the identified inertia variations for proposed PSCE strategy and PSCL strategy are shown in Figures 21 and 22, whereas all response characteristics are tabulated in Table 9. When the identified inertia is changed as \( J_0 = 1.5 \) J, although the speed
the principle of minimizing cost functions. Besides that, the stability is also sensitive to the gain of the linear current controller. The response for a larger range of inertia variation errors is shown in Figure 23, the PMSL fails to start up with the PSCL strategy, but it still performs a good performance with PSCE strategy, which proves that the proposed algorithm has a strong robustness with a wide range of variation of inertia.

2. **Robustness under different speeds:** In this section, the proposed PSCE strategy under different operating points are tested. When parameter mismatches occurs, different steady-state speeds cause different speed prediction errors. The identified inertia is set as $J_0 = 0.5 \text{ J}$ and load torque is $T_0 = 0.65 \text{ N.m}$. The dynamic and steady-state performance under the condition of different steady-state speeds with proposed PSCE strategy are shown in Figure 24, the low speed ($n = 200 \text{ rpm}$), and rated speed ($n = 400 \text{ rpm}$) are tested. All the speed and current response characteristics are summarized in Table 10. It can be noted that the speed overshoot decreases with a larger steady-state speed, and the speed drop and speed ripple increase due to a larger speed prediction error. A better current response can be obtained when the speed is low. However, compared to the medium speed ($n = 300$) in Figure 22a, we can note that when the speed is near to its rated speed, the current THD

### Table 9: Response characteristics of Figures 21 and 22

| Parameter/Symbol      | PSCE   | PSCL   |
|-----------------------|--------|--------|
| Identified inertia $J_0$ | 0.5 J  | 1.5 J  |
| Speed rise time $t_r$ (ms) | 10.92  | 21.89  |
| Speed drop $\Delta n$ (rpm) | 38.95  | 32.98  |
| Speed ripple (rpm)     | 2.2    | 2.4    |
| Speed overshoot (%)    | 6.73   | 0      |
| Current THD (%)        | 12.29  | 12.69  | 17.07  | 14.55  |
will also decrease a little because the actual voltage vector has almost reached the boundary of the voltage.

3. **Robustness under different loads:** Different load torques are tested with proposed PSCE strategy under the condition of $J_0 = 0.5$ J and $n = 300$ rpm. The light load ($T_l = 0.35$ N m), and rated load ($T_l = 0.95$ N m) are tested. The speed and current responses are shown in Figure 25 and summarized in Table 11. It can be noted that the proposed scheme performs a good speed and current responses under different load torques, better current performance can be obtained when a heavy load is added but the speed drop increases, longer speed reversion time is needed, the performance to resist load disturbance depends on the ability to disturbance estimation, compared to light load, it's more sensitive to a heavy load.

### 6 CONCLUSION

A PSC strategy based ESO has been developed. The proposed PSEC strategy has a cascade-free structure, presenting an excellent robustness with wide range variations of inertia. To compensate the speed prediction error caused by load torque and parameter mismatches, a three-order ESO is developed to observe the speed and overall disturbance. Then, the observed speed and disturbance are used to predictive the state variables at next time instant. Besides that, a new torque current reference is incorporated into the cost function to avoid oscillation.

![Figure 24](image1)

**FIGURE 24** Response to different speed reference steps with $J_0 = 0.5$ J. (a) Low speed $n = 200$ rpm. (b) Rated speed $n = 400$ rpm

![Figure 25](image2)

**FIGURE 25** Response to different load torques with $J_0 = 0.5$ J. (a) Light load $T_l = 0.35$ N m. (b) Rated torque $T_l = 0.95$ N m

| Parameter          | Value  |
|--------------------|--------|
| Steady-state speed (rpm) | 200    |
| Speed drop $\Delta n$ (rpm) | 33.63  |
| Speed ripple (rpm)      | 1.98   |
| Speed overshoot (%)     | 10.08  |
| Current THD (%)         | 7.80   |

| Parameter          | Value  |
|--------------------|--------|
| Load torque $T_l$ (N m) | 0.35   |
| Speed drop $\Delta n$ (rpm) | 20.03  |
| Speed ripple (rpm)      | 2.1    |
| Speed reversion time $t_r$ (ms) | 9.66  |
| Current THD (%)         | 17.05  |

| Parameter          | Value  |
|--------------------|--------|
| Steady-state speed (rpm) | 400    |
| Speed drop $\Delta n$ (rpm) | 49.55  |
| Speed ripple (rpm)      | 2.5    |
| Speed overshoot (%)     | 4.3    |
| Current THD (%)         | 11.73  |
and to improve the current steady-state performance. Moreover, after a comparison, the proposed PSCE strategy has a good performance and better robustness compared to the method proposed in [17], the feasibility and effectiveness of proposed algorithm have been verified with simulation and experimental results.

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