Torque Fluctuation Suppression Strategy of Integrated Electric Drive System Based on the Principle of Minimization of Instantaneous Current Tracking Error

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ABSTRACT Integrated electric drive system (IEDS) is a complex dynamic system composed of many mechanical and electrical systems. Because of the coupling impact of the nonlinear characteristics of these subsystems and the defect of the current decoupling method, the traditional vector control (VC) strategy fails to fully exploit the dynamic response of IEDS and remove the dynamic coupling of current. As a result, The IEDS torque fluctuation in the traditional VC strategy is high. To improve this problem, an IEDS electromechanical coupling model is established firstly, which takes account into the nonlinear characteristics of the motor and the transmission system. Secondly, the ideal voltage which can minimize the instantaneous current tracking error (ICDE) is obtained by the revised d-q voltage model and the particle swarm optimization (PSO) algorithm, and the ICDE is the difference between real current and current target in a step period. Finally, an IEDS torque fluctuation suppression strategy based on the look-up table is proposed. Simulation shows that the proposed control strategy, compared with the traditional VC strategy, not only effectively improves the current control performance of the current loop but also greatly reduces the torque fluctuation.

INDEX TERMS Electric vehicle, integrated electric drive system, electric current loop, optimization, torque fluctuation.

I. INTRODUCTION

An integrated electric drive system (IEDS) has the advantages of good noise vibration and harshness (NVH) performance, high power density, and small size, as shown in Fig. 1. It is a hotspot in the application and research of pure electric vehicles power systems. However, IEDS in the traditional VC strategy has problems of high torque fluctuation and low control accuracy, which are more obvious in high-speed conditions [2], [3]. In recent years, researchers reduced the dynamic torque fluctuation of IEDS mainly by optimizing motor structure parameters, transmission system structure parameters, and motor control strategy.

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FIGURE 1. IEDS structure and application scenario diagram.

In the optimization of motor structure parameters, the groove effect caused by magnetic circuit saturation and motor
body processing (such as magnetic circuit asymmetry and fixed rotor coaxial difference) will cause motor torque ripple, hence researchers reduce the fluctuation of motor torque by optimizing motor parameters. Zheng et al. [4] added embedded analytical mapping function (EAMF) obtained from the analytical model into the Ridge Regression (RR) algorithm, established the objective function through EAMF-RR and finite element data, and optimized the motor structural parameters by combining k-nearest Neighbor algorithm and whale optimization algorithm. Taking torque fluctuation as the optimization object, Naeimi et al. [5] used optimized the iron part width of the rotor and the baffle width along the d-axis and q-axis. Jeong et al [6] minimized the difference between the torque value of the defined rotor position and the constant target average torque value under limited material usage to reduce torque ripple. Liu et al [7] proposed a novel structure of shape optimization for the stator pole and rotor pole. They used the method of the quadratic polynomial regression (PR) models combined with the Pareto multi-objective genetic algorithm to optimize the switched reluctance motor, and the optimized switched reluctance motor (SRM) can drastically reduce the torque ripple by 72.7% than the initial SRM. Zhang et al. [8], by taking slot torque and torque ripple as optimization objects, optimized the topology of the rotor core with an optimization algorithm, and studied the influence of iron core on air gap flux density, back potential harmonics, slot torque, and torque ripple. Zhao et al. [9] determined the key induction motor design parameters and proposed a new induction motor design method, which enables the motor to have higher efficiency, weak magnetic capacity, and compliance. Although the above methods improve this problem, most of them focus on the theoretical research stage and are difficult to implement in engineering [10].

There are nonlinear factors that interfere with the stability of IEDS torque transmission at the meshing gear sets, each drive shaft, and bearing. The existing research on torsional vibration control of transmission system mainly considers the influence of time-varying stiffness of bearing, clearance, flexibility, time-varying meshing stiffness of gear, transmission error, backlash, friction excitation, and other factors on torsional vibration characteristics of the transmission system. Qiao et al. [11] developed a finite element method to simulate the dynamic response of a two-stage gear drive system, taking into account the time-varying stiffness of bearings, shaft flexibility, and gear meshing stiffness. Wang et al. [12] proposed a helical gear pair dynamics model considering time-varying mesh stiffness and tooth surface friction, and verified the effectiveness of the model, to explore the influence of tooth surface friction on the dynamic characteristics of helical gear transmission. Kubur et al. [13] established a dynamic model of a multi-axis helical gear reducer composed of N flexible shafts by the finite element method, considering the flexibility of bearings and shells. Fernandez et al. [14] combined the hybrid formula for calculating meshing force with the nonlinear flexibility method of bearings, and the calculation of meshing force adopted a dual method combining numerical and analytical methods. Li et al. [15] established the two parallel shaft gear transmission model and studied the effects of parameters such as rotation speed, meshing damping, gear modulus, and precision on the system dynamic characteristics. Chen et al. [16] established the rotor dynamic model of the double-helical gear transmission system, they also studied the influence of input speed and time-varying stiffness on system characteristics and concluded that the axial force has a significant influence on the natural frequency and the mode shape of the double-helical gear transmission system. Lu et al. [17] established the coupling dynamics model of the multi-stage gear transmission subsystem and the box subsystem, and the study showed that the acceleration of the rotor was mainly excited by the gear meshing frequency and its harmonics. Reference [18] and [19] also studied the influence of average load, load fluctuation, system damping, and tooth clearance on the resonance characteristics of the system, and analyzed the relationship between average load and continuous meshing, unilateral impact, and bilateral impact. Although researchers have done much work on the internal factors of the transmission system, few studies have considered the interference from the system input signal, the influence of transmission on the motor, and the interaction between multiple systems.

Motor performance depends not only on hardware but also on control strategy. The control of motor current is very crucial since the current has a direct influence on the motor torque [20], [21]. The traditional control strategy uses the d-q vector decoupling control method to control motor current [22], [23], [24]. Whereas this current control method has a decoupling error, and the error will be amplified with increasing motor speed [25], [26]. As a result, the accuracy of IEDS output will decrease. Researchers have proposed some methods to control current more accurately, such as model predictive control [27], [28], direct torque control [29], [30], and mixed H2/H∞ control [31], [32].

Model control prediction (MPC) [27], [28] predicts the system output according to the current state and current prediction model. By solving the objective function under system constraints, the system can obtain the future control sequence, and then the first element of the control sequence is executed in the actuator. At last, the process is repeated at the next moment to achieve accurate current tracking. However, MPC is difficult to be applied to IEDS because of its large computation. Different from VC’s directional control of rotor flux, direct torque control (DTC) [29], [30] cancels the rotation coordinate transformation and directly controls the stator flux directionally. Firstly, it calculates the amplitude of the torque and flux by measuring the voltage and current of the motor stator in real. Secondly, it controls the stator flux amplitude and the angle between stator flux and rotor flux by the calculation results and target commands. Thirdly, it outputs the required space vector voltage to control the torque and flux. Although DTC has a simple structure and fast running speed, it also has some problems, such as high torque fluctuation and low switching frequency at low speed.
Mixed H2/H∞ control [31], [32] combines the advantages of optimum control (H2 control) and robust control, which reduce effectively the tracking error while taking into account the convergence rate and system robustness. However, this method has a high demand on the system model accuracy and fails to deal with nonlinear constraints well. In recent research, it can be concluded that the application of this control method in real is more difficult than that in simulation [33]. Because of the defects of these methods, VC is still the most mainstream PMSM control method of the automotive industry.

Based on the study above, there is still the problem that the current decoupling error of the traditional d-q decoupling control method leads to the output torque error, which means that the accuracy of IEDS output cannot be guaranteed. Meanwhile, investigating the control performance of the traditional control strategy on IEDS is challenging because few studies have comprehensively considered the combined effect of the motor system, transmission system, and electromechanical coupling. As a result of the current decoupling error in the traditional VC strategy and the lack of research on the performance and law of the IEDS electromechanical coupling model, IEDS torque fluctuation will increase. In this study, the IEDS electromechanical coupling model is established, which takes account into the nonlinear characteristics of the electrical system and the gear transmission system. The revised voltage model then calculates the d-q axis ideal voltage, and the PSO, which follows the principle of minimum error of instantaneous current tracking (PMEICT), is used to optimize the ideal voltage that could not be provided during the actual motor operation. Finally, by querying the look-up table, the ideal voltage is acquired, and an IEDS torque fluctuation suppression strategy based on PMEICT is proposed.

The defects of traditional VC are studied in this paper, and a torque fluctuation suppression strategy is proposed based on the inherent defects of the current loop in VC and the characteristics of IEDS. The rest of this study is structured as follows. Section II establishes the IEDS electromechanical coupling model, and studies the influence of current decoupling error and nonlinear characteristics of subsystems on torque fluctuation. Section III shows the concrete method of PMEICT implementation. Section IV compares the performance of the traditional VC strategy and the proposed strategy through simulation in steady and dynamic conditions. Finally, Section V concludes the main points of this study.

II. VECTOR CONTROL CHARACTERISTICS OF IEDS SYSTEM BASED ON THE INFLUENCE OF ELECTROMECHANICAL COUPLING

The performance of IEDS is primarily affected by the motor torque ripple and the nonlinear factors of the transmission system, and the control strategy that ignores the gear drive system fails to fully harness the potential of IEDS [27]. Therefore, an IEDS electromechanical coupling model is established in this section, and the influence of current decoupling error and system nonlinear characteristics on motor torque is studied.

According to the structure of the electric vehicle transmission system, the torsional vibration model of IEDS can be obtained once the differential moment of inertia is equivalent to the main reducer, as shown in Fig. 2. Equation (1) is a 4-dof dynamic model of the transmission system that may be established using the lumped parameter method and neglecting the component translational vibration.

\[
M \ddot{\Theta} + C \dot{\Theta} + K \Theta + E(t, \Theta) = F_T
\]

where, \(\Theta\) is the component angle vector; \(M, C\) and \(K\) are mass matrix, damping matrix and stiffness matrix, respectively; \(E(t, \Theta)\) is the disturbance excitation vector; \(F_T\) is the external force, and the specific meanings and values of parameters in the equation are presented in Table 1. Set the dynamic transfer error \(x(t) = R_2 \theta_2(t) - R_3 \theta_3(t)\) and \(\delta = [-b, [e(t) - x(t)] \cos \beta_h, b]\), the value of \(\delta\) corresponds to the following three cases in (2). As shown in the equation at the (top/bottom) of the next page, where, \(\beta_h, k_m\) and \(B\) are the base circle helix angle, time-varying meshing stiffness and motor shaft rotational damping, respectively; \(\theta_1, \theta_2, \theta_3\) and \(\theta_9\) are motor shaft angle, active helical gear angle, passive helical gear angle and other transmission parts equivalent angle respectively; \(e(t)\) is the meshing error and other helical gear parameters are shown in Table 2.

In gear meshing transmission, clearance is usually left between tooth profiles to form lubricating oil film in order to avoid the expansion of teeth due to friction and heat. However, the clearance will lead to impact between teeth and affect the transmission smoothness, hence the IEDS driveline model takes into account gear clearance. Set \(\bar{x} = x - e(t)\), according to the torsional vibration model of helical gear pair, the meshing force of the gear pair can be expressed as:

\[
F_m(x) = e_m (\bar{x} - \dot{e}(t)) \cos^2 \beta_h + \begin{cases} k_m [(x-e(t)) \cos \beta_h - b] \cos \beta_h & \bar{x} \cos \beta_h > b \\ 0 & -b \leq \bar{x} \cos \beta_h \leq b \\ k_m [(x-e(t)) \cos \beta_h + b] \cos \beta_h & \bar{x} \cos \beta_h < -b \end{cases}
\]

The mathematical expression of gear meshing error is:

\[
e(t) = e_m + e_c \sin(Z_1 \theta_2 + \varphi).
\]
where, $e_{mb}$ is the constant value of meshing error, and $e_{r}$ is the amplitude of meshing error, both of which are related to gear manufacturing accuracy; $\varphi$ is the initial phase of meshing error.

The output speed and torque of the system will fluctuate even when the same torque is applied, because changes in gear meshing stiffness cause changes in gear profile variables. As a result, when modeling a gear system, it is important to take the change in gear meshing stiffness into account. In the meshing process of a single pair of gear teeth, the length of the contact line increases first and then decreases with the rotation of the active gear. Therefore, the angular state of the active gear represents the time-varying meshing stiffness of helical gear. The relationship between the meshing stiffness and the angular displacement of the active gear is shown in Fig. 4 [34].

**B. PMSM MODEL**

After applying the double-reaction theory to analyze PMSM and ignoring the influence of magnetic field saturation effect, hysteresis, and eddy current loss, the mathematical model of PMSM in the rotor synchronous rotation coordinate system may be constructed and its stator voltage balance equation is expressed as follows:

$$\begin{align*}
\begin{bmatrix}
u_{s1} \\
u_{s2}
\end{bmatrix} &= \begin{bmatrix}
R_s & 0 \\
0 & R_s
\end{bmatrix} \begin{bmatrix}
u_{s1} \\
u_{s2}
\end{bmatrix} + \begin{bmatrix}
d / dt - \omega_c \\
\omega_c
d / dt
\end{bmatrix} \begin{bmatrix}
\psi_{s1} \\
\psi_{s2}
\end{bmatrix}. \quad (4)
\end{align*}$$

where $K$ and $C$ are given by

$$K = \begin{bmatrix}
k_{s1} & -k_{s1} & 0 & 0 \\
k_{s1} & k_m R_2^2 \cos^2 \beta_b & -k_m R_2^2 \cos^2 \beta_b & 0 \\
0 & k_m R_2 R_3 \cos^2 \beta_b & k_m R_2 R_3 \cos^2 \beta_b & k_m R_2 R_3 \cos^2 \beta_b \\
0 & 0 & 0 & k_s2
\end{bmatrix},$$

$$C = \begin{bmatrix}
c_{s1} + B & -c_{s1} & 0 & 0 \\
-c_{s1} & c_m R_2^2 \cos^2 \beta_b & -c_m R_2^2 \cos^2 \beta_b & 0 \\
0 & -c_m R_2 R_3 \cos^2 \beta_b & c_m R_2 R_3 \cos^2 \beta_b & c_s2 \\
0 & 0 & -c_s2 & c_s2
\end{bmatrix}.$$
where the stator flux $\psi_{sd}$ and $\psi_{sq}$ are shown in (5):

$$
\begin{bmatrix}
\psi_{sd} \\
\psi_{sq}
\end{bmatrix} =
\begin{bmatrix}
L_d & 0 \\
0 & L_q
\end{bmatrix}
\begin{bmatrix}
i_{sd} \\
i_{sq}
\end{bmatrix}
+ 
\begin{bmatrix}
\psi_f
\end{bmatrix}.
$$

(5)

In the above two equations, $u_{sd}$/$u_{sq}$, $i_{sd}$/$i_{sq}$ and $\psi_{sd}$/$\psi_{sq}$ represent the stator voltage, stator current and stator flux in the d-q coordinate system respectively; $R_s$, $\omega_e$ and $L_d$/$L_q$ are stator resistance, rotor angular velocity and d-q axis stator inductance respectively; $\psi_f$ is the rotor permanent magnet flux. After substituting (5) into (4) and performing the Laplace transform, the following equation is obtained:

$$
\begin{bmatrix}
u_{sd} \\
u_{sq}
\end{bmatrix} =
\begin{bmatrix}
R_s + sL_d & -\omega_cL_q \\
\omega_cL_d & R_s + sL_q
\end{bmatrix}
\begin{bmatrix}
i_{sd} \\
i_{sq}
\end{bmatrix}
+ 
\begin{bmatrix}
0 \\
\omega_c\psi_f
\end{bmatrix}.
$$

(6)

The torque balance equation of PMSM has been expressed in (1). Distinguished from surface permanent magnet synchronous motor (SPMSM) and interior permanent magnet synchronous motor (IPMSM), electromagnetic torque can be expressed as:

$$
T_m = \begin{cases} 
\frac{3}{2}P_n i_{sq}\psi_f & \text{SPMSM} \\
\frac{3}{2}P_n i_{sq}(L_d - L_q) + \psi_f & \text{IPMSM}
\end{cases}
$$

(7)

where $P_n$ represents the number of pole-pairs. The relation between electrical angular velocity and mechanical angular velocity is as follows:

$$
\omega_e = P_n\omega_m = P_n\dot{\theta}_1.
$$

(8)

### C. ELECTROMECHANICAL COUPLING MODEL OF IEDS BASED ON TRADITIONAL VC STRATEGY

The performance of IEDS depends not only on the hardware but also on the control strategy [35]. This study uses the most mainstream VC strategy as the IEDS control strategy to establish an IEDS electromechanical coupling model in the Simulink environment, which comprehensively considers the transmission system, motor system, and control strategy, as shown in Fig. 5.

In Fig. 5, the speed controller generates the d-q axis stator reference current by the actual speed and the target speed, and the reference current then enters the current loop’s PI controller after being compared with the actual current $i_{sd}$/$i_{sq}$. After flux compensation and axis transformation, $u_{d0}$/$u_{q0}$ output by the PI current controller is used as the inverter target output voltage $u_{s\alpha}$/$u_{s\beta}$, and SVPWM turns $u_{s\alpha}$/$u_{s\beta}$ into the inverter control signal. Finally, the voltage $u_{sq}$/$u_{sb}$/$u_{sc}$ required by PMSM is output. To achieve the double closed-loop control, the state of working circuit and rotor supplied by the PMSM sensor is transmitted back to the speed controller and current controller. MTPA and SVPWM represent maximum torque per ampere control and space vector pulse width modulation strategy respectively.

### D. INFLUENCE OF DEFECTS OF TRADITIONAL D-Q DECOUPLING CONTROL METHOD ON MOTOR TORQUE

The impact of the traditional current decoupling method’s decoupling error on torque ripples is represented in the current loop design. By transforming (6), the design principle of...
TABLE 4. Electromagnetic torque fluctuation of IEDs electromagnetic coupling model and pure motor model under different working conditions.

| Target speed (rpm) | Pure motor model | IEDS electromechanical coupling model |
|--------------------|------------------|-------------------------------------|
|                    | Load torque (Nm) | Electromagnetic torque fluctuation (Nm) | Load torque (Nm) | Electromagnetic torque fluctuation (Nm) | Proportion of fluctuation increase (%) |
| 1000               | 15.18            | 4.133                               | 25              | 5.141                               | 24.40                              |
| 2000               | 15.18            | 4.155                               | 25              | 5.25                               | 26.34                              |
| 3000               | 15.18            | 4.228                               | 25              | 5.649                               | 33.61                              |
| 4000               | 15.18            | 4.354                               | 25              | 6.118                               | 40.52                              |
| 2000               | 3.94             | 4.147                               | 5               | 5.059                               | 21.99                              |
| 2000               | 9.11             | 4.151                               | 15              | 5.164                               | 24.40                              |
| 2000               | 21.25            | 4.163                               | 35              | 5.374                               | 29.09                              |
| 2000               | 27.32            | 4.174                               | 45              | 5.436                               | 30.23                              |

The current loop is as follows:

\[
\begin{bmatrix}
    u_{d0} \\
    u_{q0}
\end{bmatrix} =
\begin{bmatrix}
    R_s + sL_d & 0 \\
    0 & R_s + sL_q
\end{bmatrix} \begin{bmatrix}
    i_{sd} \\
    i_{sq}
\end{bmatrix}.
\]

(9)

where

\[
u_{d0} = u_{sd} + \omega_L q_{2} l_{sq} \quad \text{and} \quad u_{q0} = u_{sq} - \omega_L (L_q i_{sd} + \psi_f).
\]

Combining the decoupling method and PI controller in Fig. 4, the voltage of the two axes is:

\[
\begin{align*}
    i_{sd}^* &= \left( k_p d + \frac{k_i d}{s} \right) (i_{sq}^* - i_{sq}) - \omega_L L_q l_{sq} \\
    i_{sq}^* &= \left( k_p q + \frac{k_i q}{s} \right) (i_{sq}^* - i_{sq}) + \omega_L (L_q i_{sq} + \psi_f)
\end{align*}
\]

(10)

In (10), the traditional PI controller is adjusted according to the two transfer functions of $1/(R_s + sL_d)$ and $1/(R_s + sL_q)$, and the coupling of flux compensation term is ignored. According to (6), the value of the cross-coupling term is proportional to motor speed, therefore the current regulating ability of the current loop by the current decoupling method decreases with increasing speed, resulting in a loss in IEDS performance. As a result, a current control strategy that minimizes the current decoupling error must be proposed.

E. ELECTROMECHANICAL COUPLING CHARACTERISTICS OF IEDS UNDER THE TRADITIONAL VC STRATEGY

The torque fluctuation of the IEDs electromechanical coupling model and pure motor model is simulated at the operating conditions of constant speed-variable torque and constant torque-variable speed, respectively, to study the effect of electromechanical coupling on IEDS performance under the traditional VC control strategy. To guarantee identical motor operating conditions, the IEDS output shaft load torque split by transmission ratio was set as pure motor model load torque, as illustrated in Table 4.

The following conclusions can be drawn from the above studies: (1) The torque fluctuation of the two models increases with the rotational speed, demonstrating that the decoupling error caused by the traditional current decoupling method increases with the rotational speed, reducing torque control precision; (2) The torque fluctuation of the two models increases slightly with the target torque, demonstrating that the target torque has little influence on the torque fluctuation; (3) When the transmission system is combined, the fluctuation of motor torque increases obviously, and the increase of rotational speed and torque make intensifies the internal excitation of the transmission system with high inertia and gear transmission nonlinear factors. As a result, the fluctuation increases with the rotational speed and torque. The above results indicate that the traditional current decoupling method reduces IEDS torque accuracy, and electromechanical connection between subsystems increases the amplitude of IEDS torque fluctuation, thus it is required to study the IEDS torque fluctuation suppression strategies.

III. IEDS TORQUE FLUCTUATION SUPPRESSION METHOD BASED ON PMEICT

To reduce the torque fluctuation of IEDS, the current tracking error of the traditional current decoupling method, which rises with speed, should be reduced. As a result, in this section, a current regulator based on the revised d-q voltage model and PSO is proposed.

A. IDEAL VOLTAGE ACQUISITION BASED ON REVISED D-Q VOLTAGE MODEL

The PMEICT based multi-constrained current tracking problem is an instantaneous decision optimization problem that must to be phased. As a result, the d-q voltage model is discretized into (11), and the discrete interval represents the motor’s electrical constant $T_s$.

The PMEICT based multi-constrained current tracking problem is an instantaneous decision optimization problem that must to be phased. As a result, the d-q voltage model is discretized into (11), and the discrete interval represents the motor’s electrical constant $T_s$.

\[
\begin{bmatrix}
    u_{sd}(k) \\
    u_{sq}(k)
\end{bmatrix} = \begin{bmatrix}
    \left( R_s - \frac{L_d}{T_s} \right) - \omega_L (k) L_d \\
    \omega_L (k) L_d - \frac{L_q}{T_s}
\end{bmatrix} \begin{bmatrix}
    i_{sd}(k) \\
    i_{sq}(k)
\end{bmatrix}
\]

\[+ \begin{bmatrix}
    \frac{L_d}{T_s} & 0 \\
    0 & \frac{L_q}{T_s}
\end{bmatrix} \begin{bmatrix}
    i_{sd}(k+1) \\
    i_{sq}(k+1)
\end{bmatrix} + \begin{bmatrix}
    0 \\
    \omega_L (k) \psi_f
\end{bmatrix}
\]

(11)

where $\omega_L (k)$ and $i_{sd/sq}(k)$ represent the rotor electric angular velocity and stator current, respectively, at the current stage of the system. $i_{sd/sq}(k+1)$ is the ideal current generated by the speed control loop based on the now speed and the target speed, and it is also the target of current tracking by...
the current control loop; hence, $i_{sd}^*(k+1)$ is utilized to determine the ideal voltage. With now $\omega_e(k)$, $i_{sd/sq}(k)$ and current target $i_{sd/sq}(k+1)$, the ideal voltage $u_{sd/sq}(k)$ can be obtained by the revised voltage model. As indicated in Fig.6, the ideal voltage $u_{sd/sq}(k)$ will operate on the motor through coordinate transformation and inverter to yield $\omega_e(k+1)$, $i_{sd/sq}(k+1)$ and $i_{sd/sq}(k+2)$.

At the same time, the constraints of the system’s maximum current and voltage on the computation should be considered. In the traditional VC strategy, a current and voltage limiting module is usually added to prevent it from exceeding the system restriction. As a result, the control system’s workload during online calculation is raised. The proposed method, on the other hand, can complete this task offline. The constraints of motor stator current $i_s$ and stator voltage $u_s$ are shown as follows:

$$i_s = \sqrt{i_{sd}^2 + i_{sq}^2} \leq i_{\text{max}}$$  \hspace{1cm} (12)
$$u_s = \sqrt{u_{sd}^2 + u_{sq}^2} \leq U_{\text{dc}}/\sqrt{3}$$  \hspace{1cm} (13)

where $i_{\text{max}}$ and $U_{\text{dc}}$ are the maximum of stator current and DC voltage, respectively. In the actual calculation, due to the current and voltage constraints, a portion of the ideal voltage obtained from the revised d-q voltage model will exceed the system’s maximum actual stator voltage in the actual calculation. As a result, an optimization algorithm is used to minimize the current tracking error by optimizing the d-q axis ideal voltage $u_{sd/sq}$ when the system cannot meet the demand, and the optimization result is stored in the look-up table.

**B. IDEAL VOLTAGE CORRECTION METHOD BASED ON PSO**

The system can theoretically track the target current error-free if the electrical system can apply any ideal voltage obtained from the d-q voltage model described to the IEDS. However, the application of voltage is hampered by the actual system performance, as shown in Equations (12) and (13). The voltage, which cannot be provided, is optimized based on the actual system parameters to maximize system resource utilization and minimize the current tracking error. In the optimization process of ideal voltage, the known quantities $i_{sd}(k)$, $i_{sq}(k)$ and $\omega_e(k)$ are get first. Second, using the $u_{sd}(k)$ and $u_{sq}(k)$ generated by the optimization algorithm, the current $i_{sd}(k+1)$ and $i_{sq}(k+1)$ at the next moment under the corresponding voltage combination are predicted. Finally, iterate through the process again and save the parameters with the smallest error. The calculation principle is shown in (14).

$$\begin{bmatrix} i_{sd}(k+1) \\ i_{sq}(k+1) \end{bmatrix} = \begin{bmatrix} (1 - \frac{R_s}{L_d}) & \frac{\omega_e(k)L_s}{L_d} \\ \frac{\omega_e(k)L_d}{L_s} & (1 - \frac{R_s}{L_q}) \end{bmatrix} \begin{bmatrix} i_{sd}(k) \\ i_{sq}(k) \end{bmatrix}$$
The fitness function of the optimal current tracking control strategy in specific operating conditions can be expressed as:

\[ J(\vec{i}_{sd}/\vec{i}_{sq}, \vec{i}^*_sd/\vec{i}^*_sq) = \sqrt{[i_{sd}(k+1)-i^*_sd(k+1)]^2 + [k*[i_{sq}(k+1)-i^*_sq(k+1)]^2} \]

where superscript \( q \) and subscript \( n \) represent the iteration number and particle number, respectively; \( \rho \) is the inertia of velocity update (set to 0.8); \( \alpha_1 \) and \( \alpha_2 \) are self-learning factors and group learning factors, respectively (set to 0.5 and 0.5, respectively); \( \gamma_1 \) and \( \gamma_2 \) are random distribution factors between [0,1]; and \( PB_n \) and \( GB_n \) represent the individual historical optimum and global optimum, respectively. Considering the amount of computation, set \( N_{particle} \) and \( N_{iter} \) to 15 and 20, respectively. The end criteria of optimization iteration are:

\[ |GB - \frac{\sum_{n=1}^{N_{particle}} PB_n}{N_{particle}}| \leq \varepsilon, \]

where \( \varepsilon \) is the convergence standard of PSO.
IV. SIMULATION VERIFICATION OF IEDS TORQUE FLUCTUATION SUPPRESSION STRATEGY

The effectiveness of the torque fluctuation suppression strategy is verified in this section. The IEDS electromechanical coupling model is established in the MATLAB/Simulink environment. The traditional PI current regulator and the proposed current regulator are used in IEDS respectively to compare the torque fluctuation. To simulate the real operating condition as much as possible, this section verifies the effectiveness of the proposed strategy in steady-state conditions and dynamic conditions, respectively.

A. SIMULATION VERIFICATION UNDER STEADY-STATE CONDITION

To verify the effectiveness of the strategy proposed in steady-state driving conditions, the target speed of PMSM and the load torque of IEDS are set to 2000rpm and 25Nm, respectively. The results are as follows: Fig. 9 compares current tracking of the d-q axis; Fig. 10-12 compares current fluctuation of the d-axis, q-axis, and three-phase current of IEDS motor with traditional control strategy and the proposed control strategy, respectively; Fig. 13 compares electromagnetic torque fluctuation of IEDS with two strategies. In Fig. 9 to Fig. 13, the simulation using the traditional control strategy is on the left panel, and the simulation using the proposed control strategy is on the right panel. The results show that the PMEICT-based torque fluctuation suppression strategy proposed in this study can greatly reduce the current tracking error, with the amplitude of d-q current fluctuation decreasing by 38.82% and 53.36%, respectively. Meanwhile, the three-phase current fluctuation decreases significantly, as does the electromagnetic torque fluctuation by 49.56%.

V. SIMULATION VERIFICATION UNDER DYNAMIC CONDITION

The torque fluctuation simulations of the two strategies under the conditions of constant speed-variable torque and variable speed-constant torque are shown in Table 5. Due to the large order of magnitude of flux compensation term, the d-q axis voltage is extremely sensitive to the changes in the rotor electric angular velocity. As a result of the restriction of the electrical system’s actual capacity, the electromagnetic torque fluctuation range under control of the two strategies increases with rotational speed. However, the proposed control strategy still outperforms the traditional current decoupling method in terms of torque fluctuation suppression.
B. SIMULATION VERIFICATION UNDER DYNAMIC CONDITIONS

Because IEDS is primarily in dynamic condition, the performance of IEDS in dynamic condition under the traditional control strategy and the proposed control strategy is simulated to further validate the effectiveness of the proposed strategy. The PMSM target speed and IEDS load are set separately by period. The target speed of 0 s-0.1 s, 0.1 s-0.2 s, 0.2 s-0.3 s, 0.3 s-0.4 s and 0.4 s-0.5 s are 1000 rpm, 2000 rpm, 3000 rpm, 4000 rpm and 5000 rpm, respectively. The load of IEDS is 40 Nm and 20 Nm at 0 s-0.25 s and 0.25 s-0.5 s, respectively. Fig. 14 compares the electromagnetic torque response of PMSM, and Fig. 15 compares speed response of PMSM.

In Fig. 15, the PMSM torque increases to its maximum at each target speed change in order to reach the target as quickly as possible, then decreases and tends to stabilize in the second half of each 0.1 s. At 0.25 s, the IEDS target torque drops from 40 Nm to 20 Nm, indicating that the electromagnetic torque does not reach a stable state. When the torque under the traditional strategy in the stable state is compared to the torque under the proposed strategy, it can be seen that the IEDS electromagnetic torque fluctuation is lower under the proposed control strategy. Meanwhile, the proposed strategy is based on PMEICT, and its core idea is to maximize the electric system’s power in order to bring the actual current close to the ideal current. By observing the part where the motor reaches the maximum torque at each speed.

FIGURE 14. Comparison of PMSM torque fluctuation.

FIGURE 15. Comparison of PMSM rotational speed.
In Table 5, the amplitude of electromagnetic torque fluctuation of the traditional control strategy and the proposed strategy under different steady-state conditions.

| Operating condition (rpm/Nm) | IEDS electromagnetic torque fluctuation amplitude under the traditional strategy (Nm) | IEDS electromagnetic torque fluctuation amplitude under the proposed strategy (Nm) | Amplitude reduction ratio (%) |
|-------------------------------|---------------------------------|---------------------------------|-------------------------------|
| 1000/25                      | 5.141                           | 2.587                           | 49.68                         |
| 2000/25                      | 5.25                            | 2.648                           | 49.56                         |
| 3000/25                      | 6.649                           | 3.026                           | 46.43                         |
| 4000/25                      | 6.118                           | 3.503                           | 42.74                         |
| 2000/5                       | 5.059                           | 2.569                           | 49.22                         |
| 2000/15                      | 5.164                           | 2.593                           | 49.79                         |
| 2000/55                      | 5.374                           | 2.706                           | 49.65                         |
| 2000/45                      | 5.436                           | 2.745                           | 49.50                         |

As shown in Fig. 14 and Fig. 15, the speed curve slope increases with increasing electromagnetic torque, and the speed response of PMSM under the proposed control strategy is faster than that under the traditional control strategy. Based on the analysis above, the proposed control strategy can greatly reduce the electromagnetic torque fluctuation and improve the motor speed response compared with the traditional control strategy.

V. CONCLUSION

The current decoupling error in the control strategy and the nonlinear factors between PMSM and gear transmission system cause the high torque fluctuation of IEDS. To improve this problem, an electromagnetic coupling model of IEDS considering the nonlinear factor of the electrical system and gear transmission system comprehensively is established in this study. The motor’s d-q voltage model is discretized, and the ideal voltage command is then obtained by setting the speed loop’s current goal as the current at the next moment. The PMEICT is established to handle voltage directives that the system is unable to fulfill, and the voltage that can best meet the real current reaching the current target while taking into account the limitations of the system is optimized using the PSO multi-objective optimization algorithm. Finally, an IEDS torque fluctuation suppression strategy based on PMEICT was proposed by look-up table instead of the current regulator. The simulation shows that the proposed control strategy, compared with the traditional VC strategy, can not only reduce the torque fluctuation of IEDS by up to 49.68% under stable conditions, but also effectively reduce the torque fluctuation and improve the speed response under dynamic conditions.

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