CASE STUDY

Research on suspension control strategy based on finite control set model predictive control with state feedback control-PID for maglev yaw system of wind turbine

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Abstract
The maglev yaw system (MYS) of wind turbine adopts the maglev-driving technique instead of the traditional gear-driving technique, so it has the advantages of short downtime and low cost of operation and maintenance. However, it is vulnerable to the nonlinear time-varying disturbance caused by the random change of wind speed and direction. This paper proposes a dual-loop suspension control strategy based on the finite control set model predictive control (FCS–MPC) with state feedback control (SFC) to improve the dynamic response and anti-disturbance ability of the MYS. First, the mathematical models of the MYS are built. Second, in order to realise the stable suspension control, the outer loop controller for suspension air gap tracking is designed by combining SFC with proportional integral differential, and the inner loop controller for maglev current tracking is designed by adopting FCS–MPC with delay compensation. Finally, the simulation and experimental results show that the proposed control strategy has better robustness and dynamic response property comparing with the existing control strategies, and the maglev system of MYS can realise smooth and reliable operation. The proposed suspension control strategy is substantiated to be effective and feasible.

1 | INTRODUCTION

The yaw system is one of the essential parts of the horizontal axis wind turbines (HAWT). The traditional yaw system uses gear-driving technique, and it has some drawbacks such as complicated structure, periodic lubrication, multi-motor driving, inconvenient maintenance and high fault rate. In order to overcome the aforementioned shortcomings, the maglev yaw system (MYS) was presented in Refs. [1,2]. It adopts the maglev-driving technique, and the nacelle is always at the suspended state in the whole yawing process; as a result, the MYS has many advantages such as no lubrication needed, simple structure, short downtime and low cost of operation and maintenance.

Nevertheless, because of the inherent nonlinearity and open-loop instability of the maglev system (MS), the suspension control of the MS faces challenges, especially when the wind speed increases sharply or the wind direction changes abruptly, and the MYS is disturbed by uncertainty. Therefore, how to control the MS effectively and improve its dynamic response and anti-interference ability are some of the key problems to be solved [3,4].

In recent years, the main control methods involved in the yaw system of HAWT include neural network control [5,6], variable structure adaptive fuzzy logic control [7], model predictive control (MPC) [8,9], proportional integral differential (PID) control [10] and so on [11–14]. Most of the existing literatures focus on the traditional gear-driven yaw system, and only a few of them are based on MYS [2–8]. Ref. [2] presents a suspension control method based on MPC with the state equation and applies this method to MYS. Considering that the state equation is expanded by Taylor formula and there is a deviation between the linearised MYS and the nonlinear MYS due to neglecting the higher order term, a model mismatch compensator is proposed to improve the robustness of MYS in Ref. [8]. Up to now, the main suspension control methods include PID control, fuzzy logic control, sliding mode control (SMC), neural network and Genetic Algorithm (NNGA), etc. These methods are mainly applied in the suspension control of...
maglev bearing [15–17], maglev train [18–20], maglev plane motor [21–23] and maglev ball [24].

PID control is widely used because of its simple structure and easy implementation. However, the effect of single PID control is not ideal when dealing with nonlinear system. In order to further improve the anti-interference performance and dynamic tracking performance of the MS, based on the modern optimization theories, the optimal PID controllers for the suspension air-gap tracking control have been developed using some well-known intelligent control algorithms such as bat-inspired algorithm [25], firefly algorithm [26], extremum seeking [27], NNGA [28] and particle swarm optimization [24].

In addition, the design of the fuzzy controller for the unstable nonlinear maglev switching system is presented in Ref. [29]. The position of the maglev ball remains constant when the disturbance is exerted on the system. Ref. [30] presents an adaptive neural-modulus and SMC, which can effectively reduce the effects of disturbances and parameter changes of MS. A suspension control method based on NNGA is proposed in Ref. [31], in which the structure of identification is modelled by multilayer feedforward neural network, and the parameters of neural network are optimised by GA. A robust $H_{\infty}$ controller is designed in Ref. [32], the nonlinear model and controller are synthesised by using parallel distributed compensation (PDC) technique, and the sufficient conditions are given to guarantee the robustness of the complex nonlinear system and improve the anti-interference ability of the MS. The above literatures, with the participation of intelligent control, have improved the performance of the MS to some extent. However, as a practical matter, these intelligent methods are likely to affect the control effect of the system, because of the rough fuzzy control rules, the long training time and large training data for NNGA. Meanwhile, the intelligent control methods based on on-line learning and identification can optimise the design of controller and improve the performance of the system but increase the difficulty of the controller design and the calculation load of the processor.

MPC is an online optimal nonlinear control theory algorithm with simple concept and multivariable control capability. The existing MPC is divided into continuous model predictive control (CMPC) and finite control set model predictive control (FCS–MPC). So far, only few studies applied MPC into the MS. Ref. [33] presents a methodology for the construction of an explicit nonlinear control law via approximation of the nonlinear constrained finite-time optimal control (CFTOC), which improves the dynamic response of the system. A generalized predictive control algorithm is proposed in Ref. [34], which uses input and output data to adjust the parameters of the controller, thus ensuring the stability of the system and suppressing the vibration of the orbit. In Ref. [35], it built a state-dependent autoregressive maglev model of maglev steel ball based on Gaussian radial basis function neural network and designed a model predictive controller for it. In Ref. [36], it used the fast nonlinear MPC to realise the stable tracking under the mass change of the suspension object. The above literatures mainly involve the CMPC, which ignores the discrete characteristics of the power converter and fails to consider the delay caused by the computational burden of predictive control.

Based on the defects mentioned above, the discrete characteristics of the maglev converter (MC) are fully considered in this paper; the FCS–MPC is applied to the MS, and its optimal output is selected by on-line evaluation of the finite switching state. The control scheme is simple and flexible. Moreover, FCS–MPC has advantages of fast dynamic response, being capable of realizing the multi-objective optimal control, etc. Its cost function $J$ can contain multiple variables of system, such as voltage, current, speed, flux, common mode voltage and angle [37–41]. So far, FCS-MPC has been successfully applied in fields such as new energy [42] and motor drive [43].

This paper aims to realise stable suspension control of the MS for ensuring the stable and reliable operation of the MYS. For this purpose, we propose the FCS–MPC with delay compensation as the inner loop current control strategy to improve the dynamic response performance of MS. On the other hand, the state feedback control (SFC) with PID (SFC–PID) is proposed as the outer loop suspension air gap tracking control strategy to increase the anti-disturbance performance of MS and to solve the problem of difficult determination of the controller design parameter using the Routh stability criterion.

This paper is organised as follows. The mathematical models of the MYS are established in Section 2. In Section 3, the suspension controller based on FCS–MPC with SFC–PID is designed, and the stability analysis is given as well. Sections 4 and 5 contain the simulation and experimental results of the proposed control strategy, respectively. The conclusion is addressed in Section 6.

2 | MAGLEV YAW SYSTEM AND ITS MODELLING

2.1 | Maglev yaw system

As shown in Figure 1, the MYS consists of a maglev and driving system, a support system (including tower, suspension bracket and nacelle) and guide bearings, etc. The maglev and driving system contains a synchronous disc motor that includes the suspension electromagnet (or rotor) and the stator. The prototype of the MYS is shown in Figure 2.

Figure 3 shows the structure of MS of the MYS, where $F (i, \delta)$ is the electromagnetic suction, $i$ is the maglev current, $mg$
where $k_1 = \frac{\mu_0 N^2 S}{4}$; $\mu_0$ is permeability of vacuum; $N$ is coil turns of the stator; $S$ is the effective area of the stator core; $R$ is the resistance of the stator windings of the MYS.

Based on the Taylor series expansion of (1) at the equilibrium point, and ignoring the higher order term, the linear mathematical model of the MS can be obtained as follows [2]:

$$\begin{align*}
\{ m\ddot{\delta}(t) &= -k_1 \Delta \delta(t) - k_1 \Delta i(t) + f_\delta(t) \\
\Delta u(t) &= R \Delta i(t) + L_0 \Delta i(t) - k_1 \Delta \delta(t) 
\end{align*}$$

(2)

where $L_0$ is defined as the air gap inductance at the equilibrium point and $L_0 = \frac{2k_1}{\delta_0}$. $k_1, k_2$ are the current stiffness coefficient and the displacement stiffness coefficient of the rotating body, respectively, and defined as follows:

$$k_1 = \frac{\partial F}{\partial i} |_{(i_0, \delta_0)} = 2k_1 \frac{i_0}{\delta_0} \quad k_2 = \frac{\partial F}{\partial \delta} |_{(i_0, \delta_0)} = -2k_1 \frac{i_0^2}{\delta_0^2}$$

where $i_0, \delta_0$ are the maglev current and the suspension air gap at the equilibrium point, respectively.

3 | SUSPENSION CONTROL STRATEGY OF MAGLEV YAW SYSTEM

The objective of suspension control of MYS is to ensure that the suspension air gap keeps its reference value unchanged at the equilibrium point during the rotating process whether the disturbance exists or not. The suspension air gap depends on the maglev current. Hence, the suspension control employs the dual closed loop control system with outer loop for air gap control and inner loop for current control in this paper. For ensuring the rapid dynamic response and strong anti-disturbance capability of the MS, the inner loop current controller adopts the FCS–MPC control strategy, while the outer loop suspension air gap tracking controller adopts the SFC–PID control strategy.

3.1 Air-gap tracking control

PID control is widely used in industry because of its strong robustness and insensitive to the change of the controlled object parameters. Compared with the traditional output feedback control, the SFC can effectively realise the stability control of the system. Therefore, we combine SFC with PID to design the air gap tracking controller for improving the anti-disturbance ability of the system.

Since the mechanical displacement stiffness $k_2$ is negative in the absence of feedback control, it is difficult to achieve stable suspension under the disturbance condition if only controlling the maglev current to generate sufficient restorative force. For this reason, SFC is introduced and its control law is selected as:
\[ \Delta i(t)_1 = k_p \Delta \delta(t) + k_D \Delta \dot{\delta}(t) + k_a \Delta \ddot{\delta}(t) \quad (3) \]

where \( k_p, k_D \) and \( k_a \) are feedback gains, which are air gap gain, speed gain and acceleration gain, respectively.

On the other hand, PID control law is:

\[ \Delta i(t)_2 = k_p \Delta \delta(t) + k_I \int \Delta \delta(t) dt + k_D \Delta \dot{\delta}(t) \quad (4) \]

where \( k_I \) is the integral gain.

Combing SFC control law \( \Delta i(t)_1 \) with PID control law \( \Delta i(t)_2 \) mentioned above, the maglev current control law of SFC–PID controller is selected as:

\[ \Delta i(t) = k_p \Delta \delta(t) + k_I \int \Delta \delta(t) dt + k_D \Delta \dot{\delta}(t) + k_a \Delta \ddot{\delta}(t) \quad (5) \]

where the \( k_p \) control provides the electromagnetic force to offset the negative restoring force caused by the negative mechanical displacement stiffness \( k_z \); the \( k_D \) control provides enough positive damping to make the MS stable; the \( k_I \) control reduces the steady-state error of the system and the \( k_a \) control is for further improving the static stiffness of MS, which is helpful to improve the anti-disturbance ability of MS.

The designed SFC–PID controller is shown in Figure 4.

In order to determine the parameters of SFC–PID controller \( k_p, k_I, k_D \) and \( k_a \), substituting (5) into (2), we can get:

\[
\begin{bmatrix}
\Delta \delta(t) \\
\Delta \dot{\delta}(t) \\
\Delta \ddot{\delta}(t)
\end{bmatrix} = A \begin{bmatrix}
\int \Delta \delta(t) \\
\Delta \delta(t) \\
\Delta \dot{\delta}(t)
\end{bmatrix} + \begin{bmatrix}
0 \\
0 \\
1/m
\end{bmatrix} f_d(t)
\]

\[ y = \begin{bmatrix}
0 \\
1 \\
0
\end{bmatrix} \begin{bmatrix}
\int \Delta \delta(t) \\
\Delta \delta(t) \\
\Delta \dot{\delta}(t)
\end{bmatrix}^T \]

where

\[
A = \begin{bmatrix}
0 & 1 & 0 \\
0 & 0 & 1 \\
-k_p k_l & -k_c k_p & -k_c k_D \\
m + k_z k_c & m + k_z k_c & m + k_z k_c
\end{bmatrix}
\]

From the matrix \( A \), the characteristic polynomial of the system can be obtained as follows:

\[
f = w_1 | \dot{\delta}^* - \dot{\delta}(k + 2) | + w_2 | i^* - \bar{i}(k + 2) | \quad (8)
\]

where \( f \) is the cost function of MC, \( w_1 \) and \( w_2 \) are weighting factors; \( \dot{\delta}(k+2) \) and \( \bar{i}(k+2) \) are the predicted values of the axial speed and maglev current of the rotating body, respectively; and superscript \( p \) represents the predicted values of the corresponding variables; \( \dot{\delta}^* \) and \( i^* \) are the reference values of the axial speed and the maglev current of the rotating body at the equilibrium point, respectively; and \( \dot{\delta}^* = 0, i^* \) is obtained as follows: (1) calculating the deviation of suspension air gap by \( \Delta \delta(k) = \delta_0 - \delta(k) \), (2) calculating \( \Delta i_{ref} \) by the SFC–PID controller according to (5), and (3) \( i^* \) is calculated by \( i^* = \Delta i_{ref} + i_0 \).

The two-quadrant H-bridge chopper circuit (shown in Figure 7) is employed as the MC. It can be seen from Figure 6 that the MC uses only two active switches (VD1 and VD2) which are both switched on and off simultaneously, so the MC operates in two modes (switching states) only.
define the state variables of the MS as: \( x_1 = \delta(t), x_2 = \dot{\delta}(t), x_3 = i(t) \), and then substitute them into (1), the state space description of the MS can be put forward by rewriting (1) as follows:

\[
\begin{bmatrix}
\dot{x}_1 \\
\dot{x}_2 \\
\dot{x}_3 
\end{bmatrix} =
\begin{bmatrix}
0 & m & 0 \\
-m & R & -x_2/x_1 \\
0 & 0 & 1 
\end{bmatrix}
\begin{bmatrix}
x_2 \\
x_3 \\
0 
\end{bmatrix}
+ \begin{bmatrix}
0 \\
0 \\
x_1/(2k_1) 
\end{bmatrix} u(t)
\] (9)

where \( u(t) \) is control input, that is the output voltage of the MC.

According to the forward Euler approximation formula, there is:

\[
\dot{x}_i = dx_i/dt \approx [x_i(k+1) - x_i(k)]/T
\] (10)

where \( x_i(k) \) is the state variable value \( x_i \) at \( k \)th sampling instant and \( T \) is the sampling period.

By applying (10) to (9), the maglev current and the axial speed of the rotating body at \( (k+1) \)th sampling instant can be predicted by using the output voltage \( u(k) \) of the MC for all switching state as follows:

\[
\begin{align*}
\vec{v}(k+1) &= [1 - RT\dot{\delta}(k)/(2k_1) + T\dot{\delta}(k)/\dot{\delta}(k)] \cdot i(k) + [T\dot{\delta}(k)/(2k_1)] \cdot u(k) \\
\vec{\delta}(k+1) &= f_d(k)T/m + gT - (k_1T/m) \cdot \dot{i}(k) + \ddot{\delta}(k)
\end{align*}
\] (11)

For the large-scale MYS, its gravity of the rotating body \( mg \) is great, so the suspension force \( F_i, \dot{\delta} \) required is large; thus, the inductance of its suspension winding is larger and the maglev current response time is longer. In order to mitigate the effects of time delay caused by computation and large inductance of the suspension windings, the time delay compensation should be considered. For this end, the overall control process of the proposed FCS–MPC for the MS is implemented as the following sequences and its flow chart as shown in Figure 7.

**Step 1** measuring the maglev current \( i(k) \) and the suspension air gap \( \delta(k) \) at \( k \)th sampling instant;

**Step 2** applying the optimal voltage vector \( u(k-1)_{\text{opt}} \) determined in previous control interval;

**Step 3** estimating the maglev current and the axial speed of the rotating body at \( (k+1) \)th sampling instant.
by using the applied optimal voltage vector $u(k-1)_{opt}$ according to (11) as follows:

$$
\begin{align*}
\dot{i}(k + 1) &= [1 - RT\delta(k)/(2k_1) + T\dot{\delta}(k)/\delta(k)] \cdot i(k) \\
\delta(k + 1) &= f_d(k)T/m + gT - (k_1T/m) \cdot \dot{i}^2(k)/\delta^2(k) \\
&\quad + \dot{\delta}(k)
\end{align*}
$$

(12)

**Step 4** predicting the maglev current and the axial speed of the rotating body at $(k+2)$th sampling instant for all voltage vector by combining (12) and (11) as follows:

$$
\begin{align*}
\ddot{\delta}(k + 2) &= [1 - RT\delta(k + 1)/(2k_1) + T\dot{\delta}(k + 1)/\delta(k + 1)] \\
&\quad \times i(k + 1) + T\dot{\delta}(k + 1) \cdot u(k + 1)/(2k_1)] \\
\dot{\delta}(k + 2) &= f_d(k + 1)T/m + gT - (k_1T/m) \cdot \dot{i}^2(k + 1)/\delta^2(k + 1) \\
&\quad + \dot{\delta}(k + 1)
\end{align*}
$$

(13)

According to (10), there is:

$$
\delta(k + 1) = \dot{\delta}(k + 1)T + \delta(k)
$$

(14)

Equation (13) can be rewritten by substituting (14) into it as:

$$
\begin{align*}
\ddot{\delta}(k + 2) &= [1 - RT(\dot{\delta}(k + 1) + \delta(k)) + T\dot{\delta}(k + 1)]/2k_1 \\
&\quad \times i(k + 1) + T(\dot{\delta}(k + 1) + \delta(k)) \cdot u(k + 1) \\
\dot{\delta}(k + 2) &= f_d(k + 1)T/m + gT - (k_1T/m) \cdot \dot{i}^2(k + 1)/\delta^2(k + 1) \\
&\quad + \dot{\delta}(k + 1)
\end{align*}
$$

(15)

**Step 5** evaluating the predicted variables through the cost function (8);

**Step 6** determining and storing the optimal voltage vector $u(k)_{opt}$ by minimizing the cost function (8).

Integrating the aforementioned outer loop suspension air gap tracking controller (shown in Figure 4) and inner loop maglev current controller (shown in Figure 5), the block diagram of the overall control structure of the maglev controller can be obtained, as shown in Figure 8.

### 4 | SIMULATION

In order to validate the effectiveness of the proposed control strategy (SFC–PID)–(FCS–MPC), a simulation model is built based on MATLAB/Simulink. The comparative studies with other four control strategies, PID–PID, (SFC–PID)–PID and PID–(FCS–MPC), are carried out. Simulation parameters are shown in Table 1.

**Table 1** Simulation parameters of MS

| Parameter | Value | Parameter | Value |
|-----------|-------|-----------|-------|
| $g$ (m/s²) | 9.8   | $\delta_a$ (mm) | 10 |
| $m$ (kg) | 50    | $i_a$ (A) | 3.3 |
| $N$ | 6400  | $\mu_0$ (T/m) | $4\pi \times 10^{-7}$ |
| $S$ (mm²) | 235,050 |

4.1 | Simulation for dynamic response performance

To verify the dynamic response performance of the proposed control strategy, the control effects of the aforementioned four control strategies under the non-disturbance condition are taken into account. The response time $t_e$, suspension air-gap deviation $\Delta\delta = \delta_t - \delta(t)$ and maglev current deviation $\Delta i = i_t - i(t)$ are selected as the performance indexes. In which, $t_e$ reflects the
**Figure 9** Suspension air-gap under non-disturbance condition

**Figure 10** Maglev current under non-disturbance condition

**Figure 11** Curve of suspension air gap and disturbance $f_d^*$
dynamic response performance of the controller, \( \Delta \delta \) and \( \Delta i \) reflect the adjustment ability of the controller. The simulation results are shown in Figures 9 and 10.

**Note:** The subscripts 1, 2, 3 and 4 of the four indexes in figures (the same hereinafter) represent the control strategy of PID–PID, (SFC–PID)–PID, PID–(FCS–MPC) and the proposed (SFC–PID)–(FCS–MPC), respectively. The former of each strategy refers to the outer loop suspension air gap tracking control algorithm, while the latter refers to the inner loop maglev current control algorithm.

It can be seen from Figures 9 and 10 that during the starting period, for the maximum deviation of suspension air gap, there is \( \Delta \delta_4 > \Delta \delta_3 > \Delta \delta_2 > \Delta \delta_1 \), and for the response time to reach the steady state, there is \( t_{s4} = t_{s2} > t_{s3} = t_{s4} \); for the maximum deviation of maglev current, there is \( \Delta i_4 > \Delta i_3 > \Delta i_2 > \Delta i_1 \), and for the response time to reach the steady state, there is \( t_{s4} = t_{s2} > t_{s3} = t_{s4} \). From the above analysis, the deviations \( \Delta \delta_4 \) and \( \Delta i_4 \) are minimal, and the response time \( t_{s4} \) are shortest, which shows that the proposed control scheme (SFC–PID)–(FCS–MPC) has the stronger ability of adjusting control and dynamic response, and can converge quickly to the steady state. Amplifying the start-up current waveform in Figure 10, it can be found that there is a reverse current when PID is adopted in the inner loop, while there is no reverse current in the FCS–MPC, and the current characteristics is improved.

### 4.2 Simulation for anti-disturbance performance

Due to its inherent non-linear and unstable property, the MS is vulnerable to uncertain disturbance. In order to further verify the anti-disturbance ability of the proposed control scheme, we consider the variable disturbance condition.
**FIGURE 14** Curve of maglev current error under disturbance $f_d^*$.
For simulating the uncertain disturbance caused by the small change of wind direction, the disturbance force \( f_d^* = 0.2\sin(2\pi ft) \) is applied at 50s, its frequency is 0.04 Hz. Figures 11–14 shows the simulation waveform under the disturbance force \( f_d^* \).

Figure 11 shows the track curve of the suspension air gap under the disturbance. It can be seen that the suspension air gap fluctuation is \( \Delta\delta_1 > \Delta\delta_2 > \Delta\delta_3 > \Delta\delta_4 \) by enlarging the tracking curve of the air gap under the disturbance. From the suspension air gap tracking error curve given in Figure 12, it can be concluded that the PID–PID control has the largest fluctuation, the steady-state error is 0.04 mm, the (SFC–PID)–(PCS–MPC) control has the smallest fluctuation and the steady-state error is 0.005 mm.

Figure 13 shows the track curve of maglev current under the disturbance. From the maglev current tracking error curve...
given in Figure 14, it can be concluded that the maximum fluctuation is controlled by (SFC–PID)–(FCS–MPC) and PID–(FCS–MPC) and the steady-state error is 0.055 A, the fluctuation is minimised and the steady-state error is 0.02 A under (SFC–PID)–PID and PID–PID control. The object of MYS control in this paper is to ensure the stable suspension of MYS when the wind direction changes in a small range, so the fluctuation of the suspension air gap determines the anti-interference performance of MYS. In summary, the scheme not only meets the basic requirements of automatic control theory, but also improves the anti-jamming performance of MYS.

Taking into account the limited laboratory conditions, experimental verification cannot give periodic variation of the interference. As a result, the disturbance force $f_d^* = 0.2\text{pu}$ is applied at 50s, the disturbance force $f_d^*$ = 0 is applied at 100s. Figures 15–18 shows the simulation waveform under the corresponding interference.

Figure 15 shows the suspension air-gap tracking curve under the disturbance, it can be seen that the suspension air-gap fluctuation is $\Delta \delta_1 > \Delta \delta_2 > \Delta \delta_3 > \Delta \delta_4$ by amplifying the air-gap trace curve under the disturbance. From the suspension air-gap tracking error curve given in Figure 16, it can be concluded that the maximum fluctuation is 0.04 mm under PID–PID control, and the minimum fluctuation is 0.005 mm under (SFC–PID)–(FCS–MPC) control. From the maglev current error tracing curve given in Figure 18, it can be concluded that the maximum fluctuation is obtained under the control of (SFC–PID)–(FCS–MPC) and PID–(FCS–MPC), the steady-state error is 0.055 A, and the fluctuation is
minimised under the control of (SFC–PID)–PID and PID–PID, the steady-state error is 0.03 A. Compared with PID control, the current ripple of FCS–MPC is slightly large. The simulation results show that the current ripple of FCS–MPC is 0.5%, and the current ripple of FCS–MPC will not cause MYS vibration.

5 | EXPERIMENTAL RESULTS

In order to further verify the effectiveness of the proposed control strategy, an experimental platform with DSP28035 and a two-quadrant H-bridge chopper circuit as the MC is built, as shown in Figure 19 and a series comparative experiments are carried out. Experimental parameters are shown in Table 1.

5.1 | Experiments for dynamic response performance

Based on the experimental platform shown in Figure 19, the comparative experiments for dynamic response performance of MS are carried out under the non-disturbance condition using the aforementioned four control schemes.

Both of the suspension air gap $\delta(t)$ and maglev current $i(t)$ during the starting period are shown in Figures 20 and 21. As can be seen from Figure 21, their response time to reach the steady state has the relationship as $t_{s1} > t_{s2} > t_{s3} > t_{s4}$. By enlarging the suspension air gap curve at steady state, the maximum steady state error is 10% under PID–PID control, and the minimum steady state error is 1% under (SFC–PID)–(FCS–MPC) control. As can be seen from Figure 21, the maglev current achieves the desired control goal. These experimental results demonstrate...
that the proposed control scheme has the shortest response time and the smallest steady-state error.

5.2 | Experiments for anti-disturbance performance

In order to further verify the anti-disturbance ability of the proposed control strategy, the four control schemes are compared by experiments: the disturbance $f_d = 0.2$ pu is applied at 10 s and removed at 14 s. The experimental results are shown in Figures 22 and 23, respectively.

It can be seen from Figure 22 that both of the air gap fluctuation and the steady-state error are large under PID–PID control by amplifying the air gap tracking curve under the disturbance, while the steady-state error is minimum under (SFC–PID)–(FCS–MPC) control. The maglev current using (SFC–PID)–(FCS–MPC) and PID–(FCS–MPC) control scheme has the fastest dynamic response and the larger amount of regulation as shown in Figure 23. All of these results demonstrate that the proposed control scheme has better anti-disturbance ability and dynamic response performance.

Furthermore, in order to illustrate that the switching frequency is not constant under the control of FCS–MPC, the experimental waveforms of the switching state (i.e. the pulse width of the driving signal of the switches VD1 and VD2) using PID–(FCS–MPC) and (PID–SFC)–(FCS–MPC) are given in Figures 24 and 25, respectively. In Figures 24 and 25, at the interval (a), no disturbance is exerted on the system; at the interval (b), a disturbance is applied on the system and at the interval (c), the disturbance is removed.

The results using the (PID)–(FCS–MPC) control scheme are shown in Figure 24 and analysed as follows.

First, it can be seen from Figure 24(b) and 24(d) that the switching times in Figure 24(b) are higher than those in Figure 24(d) in a non-disturbance condition, which shows that the switching frequency $F_s$ at the interval Figure 24(a) is higher than that at the interval Figure 24(c) in a non-disturbance condition. Second, as can be seen from Figure 24(c), the change of switching state at the interval Figure 24(b) is sparse under disturbance condition, this means that the switching frequency is lower, so the switching frequency at the interval Figure 24(a) is higher than that at the interval Figure 24(b). To sum up, under the control of (PID)–(FCS–MPC), the
switching frequency under the disturbance condition is lower than that in a non-disturbance condition.

The results using the (PID–SFC)–(FCS–MPC) control scheme are shown in Figure 25 and analyzed as follows:

First, it can be seen from Figures 25(b) and 25(d) that the switching times in Figure 25(d) are little higher than that in Figure 25(b) in a non-disturbance condition, the switching frequency at the interval Figure 25(a) is slightly higher than that at interval Figure 25(c) in a non-disturbance condition. Second, by comparing Figure 25(b) with Figure 25(c), it is found that the disturbance has no obvious effect.

In summary, from the analysis of the experimental results, the disturbance has no obvious effect on the switching frequency under the control of (PID–SFC)–(FCS–MPC). When adopting the (PID)–(FCS–MPC) control scheme, the switching frequency under the disturbance condition is lower than that in non-disturbance condition. However, when adopting the (PID–SFC)–(FCS–MPC) control scheme, the switching frequency remains high both in a non-disturbance and under the disturbance condition. In one word, the switching frequency is not constant under FCS–MPC control, and it varies in the non-disturbance and under disturbance conditions.

The object of this paper is to ensure the stability of MYS when the wind direction changes in a small range. Therefore, the performance of the air gap controller plays a decisive role in the whole MYS. The simulation and experimental curves of the suspension air gap show that the proposed control scheme has the shortest response time and the smallest steady-state error. It shows that the MS can converge to steady state at a faster rate by using the proposed control scheme. The simulation and experimental curves of maglev current show that the current ripple produced by PID control is small, and the current ripple produced by FCS–MPC is slightly large. The main reason is that the direct output of FCS–MPC is switching state, and the switching frequency is not fixed because no modulation is required. However, compared with FCS–MPC, PID control needs modulation and has a fixed switching frequency so the current ripple is small. In summary, the scheme proposed in this paper improves the anti-interference performance and dynamic response performance of the MS.
6 | CONCLUSION

This paper has introduced the MYS of HAWT and proposed a dual-loop suspension control scheme (SFC–PID)–(FCS–MPC) to improve the anti-disturbance ability and the dynamic response performance of the MS in the MYS. Comparative simulation and experimental studies have shown that the proposed control scheme has the minimum steady-state error and the shortest response time under the non-disturbance condition, which indicates that the MS has a better dynamic response performance. At the same time, the suspension air gap can accurately track its reference value under the variable disturbance condition, which indicates that the MS has a strong anti-disturbance ability. The feasibility and effectiveness of the proposed control scheme have been verified. The proposed suspension control scheme provides a useful solution to guarantee the MS operating smoothly and reliably with good robustness and dynamic response performance. Finally, the conclusions are summarised as follows:

(i) A suspension air gap controller is designed by combining SFC with PID control, and the stability of the controller is analyzed based on Routh stability criterion. Compared with the existing control methods, this method does not need on-line and off-line training, the calculation burden is reduced and the design is simple and convenient for engineering application.

(ii) The discrete characteristics of power converters are fully considered, the FCS–MPC is applied to the MS, the optimal output is selected by on-line evaluation of the finite switching state and the control scheme is simple and flexible. First, compared with the traditional FCS–MPC, the number of voltage vector selection is reduced, and the effective voltage vector is applied to the prediction model. Second, considering the optimal performance of the whole system, both the suspension air gap and the maglev current are included in the cost function. Finally, in order to avoid the influence of the computational burden on the system control, two-step prediction is used to derive the predictive model by time-delay compensation.

(iii) The simulation and experimental results show that the outer-loop SFC with PID improves the dynamic response and anti-interference performance of the suspension air gap, and it has little effect on the performance of the maglev current. The inner-loop FCS–MPC not only increases the dynamic response ability of the maglev current but also enhances the anti-interference performance of the MYS.

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