

# Machine Learning-Based Optimization of High-Frequency Injection Amplitude in Sensorless PMSM Drives

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## ABSTRACT

The methods known as high-frequency injection (HFI) are widely used in sensorless permanent magnet synchronous motor (PMSM) drives to provide adequate rotor position measurements in the low-speed and zero-speed ranges where back-EMF methods fail to work. Although effective, the choice of amplitude of injection is also a critical issue. A too low amplitude compromises the accuracy of position estimation and noise immunity and a too high amplitude increases the ripple on the torque, acoustic noise, and copper losses. Further, ideal amplitude changes dynamically with operating condition like load torque, rotational speed, variation of DC-link voltage, and machine parameter change and hence the approach of fixed or look-up table is not the best. This work gives a new system of optimization based on machine learning, which optimally identifies the amplitude of the HFI based on real-time operating state values. The suggested learning agent reduces structured multi-objective cost criterion which is the combined evaluation of rotor position estimation error, torque ripple magnitude, and incremental copper losses. The framework provides close-to-optimal operating space amplitude settings based on different conditions through data-driven exploration of the nonlinear operating space. The simulation findings identify stronger resistance to voltage drop across inverter fed and measurement noise, and lower steady-state torque oscillations relative to traditional techniques, confirming that simulation has been shown to be suitable in low-voltage electric mobility applications.

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## INTRODUCTION

One solution to electric vehicles (EVs), e-bikes and other low-voltage mobility products is the Permanent magnet synchronous motor (PMSM), which is highly efficient, compact in geometry, and with high torque density. Sensorless control strategies are becoming popular in order to decrease system cost, enhance reliability and to avoid the mechanical wear of the position sensors used. Nevertheless, the correct estimation of rotor position is a significant issue in the low-speed and zero-speed operating conditions.<sup>[1-4]</sup> In these areas, traditional back-EMF-based estimation methods have become observable since the induced voltage is smaller to be used in acquiring reasonable position information. In order to address this drawback, high-frequency injection (HFI) methods

are commonly used.<sup>[5-8]</sup> HFI techniques allow to recover rotor position even with the stator windings energized to zero on the rotor by emergent magnetic saliency effects following an injection of a high-frequency voltage signal into the stator windings.<sup>[9-12]</sup> Although they are effective practically, the performance of the HFI-based sensorless control highly relies on an appropriate choice of the injection amplitude. The injection amplitude in most implementations that currently exist is chosen with either fixed or hard-programmed look-ups taken through experimentation offline.<sup>[1, 5, 6]</sup> This has some fundamental limitations since the optimal amplitude does not always coincide. It is dependent on the operating conditions load torque, rotational speed, DC-link voltage variations, inverter nonlinearities, parameter drift due

to temperature variations and measurement noise. When the amplitude is too low, the signal to noise ratio of the demodulated response reduces resulting into more error in rotor position estimation along with low robustness.<sup>[10]</sup> By contrast, in case the amplitude is too high, it presents unwanted side effects such as an increase of torque ripple, more copper loss, higher levels of current distortion, and possible acoustic noise.<sup>[11, 12]</sup> Hence, the problem of amplitude selection is a natural multi-objective trade-off in the accuracy of the estimation, the electromagnetic smoothness, and the efficiency. A wide operating range of static tuning strategies cannot balance these competing goals.<sup>[2, 7]</sup> To tackle them, this paper formulates an abstract multi-objective optimization approach to calculate the optimal HFI amplitude in sensorless PMSM drives. The framework mathematically characterises a trade-off between rotor position error estimation, torque ripple magnitude and difference between incremental copper losses in a single cost function. Based on this formulation, a machine learning based adaptive amplitude estimation mechanism is put forward. The learning model uses operating state variables in real time, including the current components, electrical speed, load torque, and DC-link voltage, to estimate the amplitude which reduces the quantified performance cost in different conditions. The proposed method is able to adapt to nonlinear operating dynamics, unlike the traditional methods that rely on look up tables. Moreover, the stability limits, and the practical implementation provisions are taken into consideration to provide a secure interaction with the inner current regulation loop. Under load Robustness is measured in the presence of under run voltage drops at the inverter and noise in the measurements to give an idea of real practise. Lastly, the proposed strategy is compared using a quantitative metric with classical fixed and gain-scheduled amplitude approaches and shows better accuracy in low-speed estimation, lesser steady-state torque oscillations, and increased adaptability to low-voltage electric mobility scenarios.

## RELATED BACKGROUND AND LITERATURE REVIEW

High-frequency injection (HFI) methods have also been given much research as an efficient remedy to the problem of rotor position estimation in sensorless PMSM drives in low- and zero-speed ranges.<sup>[1-4]</sup> Generally speaking, HFI techniques would be classified into the pulsating and rotating signal injection techniques.<sup>[3, 5, 7]</sup> In pulsating injection, a high-frequency voltage is usually injected in an approximately fixed axis (usually the estimated d-axis), whereas the rotating injection uses a high-frequency vector which swings about its reference frame in the stationary frame.<sup>[5, 6]</sup> The two techniques

take advantage of the magnetic saliency of the PMSM to retrieve the position-dependent variations in the high-frequency current response.<sup>[9, 12]</sup> The demodulated signal includes the rotor position information based on anisotropic nature of inductance of the machine.<sup>[7, 10]</sup> Though these methods have been shown to be good in low-speed, they are very sensitive to injected signal amplitude.<sup>[1, 6]</sup> Under the condition of inadequate amplitude, poor signal-to-noise ratio and reduced estimation accuracy are achieved, on the other hand, large amplitude can boost the torque ripple, distortion of current, and copper losses, thus, lowering drive total efficiency.<sup>[11, 12]</sup> In order to overcome the issue of amplitude, a number of traditional choice plans were offered. The simplest method is using constant injection amplitude which is acquired experimentally through commissioning of the system.<sup>[2, 5]</sup> Although this is a straight forward method, it is not flexible and does not work well in different load and voltage scenarios. Strategies based on look-up tables seek to do this to enhance the performance of mapping load conditions or operating speed to predefined amplitude values obtained via offline tuning.<sup>[5, 6]</sup> Nonetheless, such tables are not able to consider parameter drift, nonlinear inverters, or unexpected disturbances. Gain scheduling techniques can be viewed as an extension to this idea and modify the amplitude based on the defined operating regions, but again they are heuristically tuned instead of being optimised formally.<sup>[6, 7]</sup> Higher-order adaptive controllers strive to adjust injection parameters based on an estimate but they usually place more emphasis on the estimate convergence and omits out-right the trade-off between torque ripple and efficiency.<sup>[8, 10]</sup> Meanwhile, machine learning (ML) methods have been receiving more and more interest in motor control systems. ML based observers in rotor position and speed estimation have been created providing better noise and parameter uncertainty resilience.<sup>[7, 9]</sup> Electric drives The use of data-driven methods has also been considered to estimate parameters, detect faults and predictive maintenance. Moreover, it is proposed that smart control structures based on the use of neural networks or reinforcement learning should be used to improve the torque control and dynamic response. In spite of these developments, little has been done in the exploration of the use of ML in particular with regard to maximising the HFI amplitude. The literature does not often develop amplitude selection as a multi-objective optimization problem, structured and capable of estimating its accuracy, achieving a low torque ripple, and loss reduction in copper.<sup>[11, 12]</sup> Thus, the research gap may be identified: the unified framework that combines formal multi-objective optimization and an adaptive process by the machine learning to perform the real-time selection of

the amplitude of HFI with sensorless PMSM drives is not yet provided. It is necessary to fill this gap in order to have strong, efficient, and flexible low-speed operation in current electric mobility systems.

## METHODOLOGY

### PMSM and High-Frequency Injection Modeling

Adaptive amplitude optimization framework is proposed and is constructed on the basis of mathematical model of surface-mounted permanent magnet synchronous motor (PMSM) provided in the synchronous reference frame. The stator voltage equations that characterize the electrical dynamics of the PMSM are given below:

$$\begin{aligned} v_d &= R_s i_d + L_d \frac{di_d}{dt} - \omega_e L_q i_q \\ v_q &= R_s i_q + L_q \frac{di_q}{dt} + \omega_e L_d i_d + \lambda_m \end{aligned} \quad (1)$$

Where  $v_d$  and  $v_q$  are the stator voltages in the dq frame,  $i_d$  and  $i_q$  are the stator currents,  $R_s$  is the stator resistance  $L_d$  and  $L_q$  represent the d- and q-axis inductances,  $\lambda_m$  denotes the permanent magnet flux linkage, and  $\omega_e$  is the electrical angular speed. The basic electrical behaviour of PMSM is described in equation (1) and forms the foundation of the existing control over current and position estimation. Back-EMF term cannot provide reliable rotor position estimations at low and zero speeds. In order to counter this limitation, a high frequency voltage signal is overlaid on the commanded stator voltage. The signal which is injected can be expressed as.

$$v_{inj} = A_{HFI} + \sin(\omega_{inj} t) \quad (2)$$

Where  $A_{HFI}$  denotes the injection amplitude and  $\omega_{inj}$  is the injection angular frequency. The saliency of high frequency current is coupled with the motor saliency to generate a position-dependent current response that allows the estimation of the rotor angle using demodulation. The injected and fundamental components dynamics are coupled and define equations (1) and (2). The injection amplitude  $A_{HFI}$  directly influences the magnitude of the high-frequency current response, the signal-to-noise ratio of the demodulated signal, and the additional copper losses introduced into the system. It therefore follows that, incorrect amplitude choice can lead to poor estimation or alternatively, it can contribute towards high torque ripples and losses, creating the incentive to use adaptive optimization. The general concepts of the PMSM model inclusion in (1), the high frequency injection signal in (2) and the adaptive amplitude regulation mechanism within the

closed-loop sensorless control structure are explained in Figure 1 providing the full structure of the system of the proposed ML-based optimization HFI amplitude optimization framework.

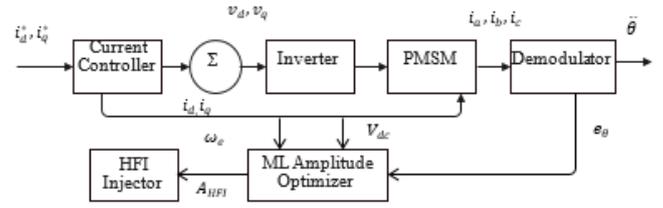


Fig. 1: ML-Based Adaptive HFI Amplitude Optimization Framework Integrated Within the Sensorless PMSM Control Architecture.

### Formulation of the Multi-Objective Optimization.

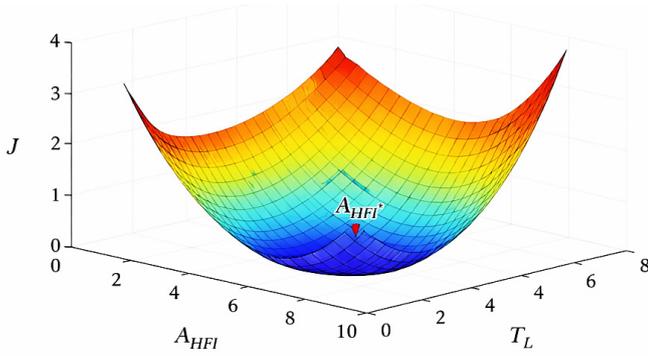
The amplitude selection problem is presented as a constrained multi-objective optimization problem so as to generically seek the optimal choice of the high-frequency injection (HFI) amplitude. Rotor position estimation, torque ripple and other copper losses directly depend on the injection amplitude. These conflicting goals are summed up into a single performance index which is defined as.

$$J = w_1 e_\theta^2 + w_2 T_{ripple}^2 + w_3 P_{cu} \quad (3)$$

where  $e_\theta$  denotes the rotor position estimation error,  $T_{ripple}$  represents the electromagnetic torque ripple,  $P_{cu}$  corresponds to the incremental copper losses induced by the injected signal, and  $w_1, w_2, w_3$  are positive weighting coefficients that regulate the relative importance of each objective. Equation (3) defines a systematic trade-off among the estimation precision, dynamic smoothness and efficiency. Necessarily, the best injection amplitude is the one, which minimises the multi-objective performance index, as in (3):

$$A_{HFI}^* = \arg \min_{A_{HFI}} J \quad (4)$$

Equation (4) formalizes the amplitude selection problem as a nonlinear optimization task. Since the relationship between  $A_{HFI}$ , operating conditions (e.g., load torque  $T_L$  and electrical speed  $\omega_e$ ), and the cost function  $J$  is highly nonlinear, analytical solutions are generally intractable. The nonlinear dependence of the cost function in (3) on the injection amplitude and operating conditions is illustrated in Figure 2, which presents a three-dimensional optimization surface showing the variation of  $J$  with respect to  $A_{HFI}$  and load torque  $T_L$ . The small values of amplitude result in greater estimation error



**Fig. 2: Three-Dimensional Multi-Objective Cost Surface for HFI Amplitude Optimization in Sensorless PMSM Drives.**

as shown in Figure 2 and large amplitude values amplify the torque ripple and copper losses forming a convex-shaped surface, which operates condition-dependent at operating conditions, meaning its extents vary with operating conditions. The minimum point on this surface corresponds to the optimal amplitude  $A_{HFI}^*$  defined in (4). The visual representation in Figure 2 so visually interprets Equations (3) and (4) into a nonlinear trade off that encourages the use of a data driven adaptive optimization mechanism as opposed to a fixed or look up table based strategy.

#### Amplitude Estimation based on machine learning.

In order to be able to understand how to optimally inject at a high frequency, a nonlinear mapping using data is designed that maps operating states that are measurable to actual desired amplitude. The state of the PMSM drive is of the form:

$$s = [i_d, i_q, \omega_e, T_L, V_{dc}]^T \quad (5)$$

where  $i_d$  and  $i_q$  denote stator current components,  $\omega_e$  is the electrical angular speed,  $T_L$  represents load torque, and  $V_{dc}$  is the DC-link voltage. The amplitude estimator implemented using the ML is a nonlinear form of a function approximator

$$A_{HFI} = f\theta(s), \quad (6)$$

where  $f\theta(\cdot)$  denotes the parametric model with trainable parameters  $\theta$ . In the case of a feedforward neural network, where the number of hidden layers is one, the mapping will be given as:

$$A_{HFI} = W_2 \sigma(W_1 s + b_1) + b_2, \quad (7)$$

Where  $W_1$ ,  $W_2$  are weight matrices,  $b_1$ ,  $b_2$  are bias vectors, and  $\sigma(\cdot)$  is the nonlinear activation function.

**3.4 Stability and Implementation Constrictions.**  
To be safely integrated in the inner current control loop, the adaptive HFI amplitude estimation mechanism needs to meet the stability and real-time implementations requirements. In order to prevent too much distortion of current, and the ripple of torque and other copper losses, the amplitude injected is limited within specified limits:

$$A_{HFI}^{\min} \leq A_{HFI} \leq A_{HFI}^{\max}, \quad (8)$$

where  $A_{HFI}^{\min}$  ensures adequate signal-to-noise ratio for reliable demodulation and rotor position estimation, while  $A_{HFI}^{\max}$  limits electromagnetic stress, inverter saturation risk, and unwanted torque oscillations. Owing to these, the ML-estimated amplitude is restricted within the admissible interval in (8) before it is inputted to the injection module, so that it can have a stable interaction with the current control loop. Besides this, the injected signal is chosen to be at a high enough frequency in comparison with the current controller bandwidth, so that the basic current regulation is not perturbed by the injected component. The adaptive estimator is also tested with operating perturbations (e.g. load variation, variation in DC-link, and measurement noise) to ensure that the updates of amplitude are not sudden spikes in the regulated currents. Lastly, the implementation is meant to be computationally lightweight and would thus be able to be run in real time on low-end embedded motor-control platforms without breaking the sampling constraints of the control loop.

#### 4. SIMULATION SETUP

The suggested architecture is implemented in MATLAB/Simulink with a model of a surface-mounted PMSM drive machine at the field oriented control (FOC) with level of low-speed rotor position estimates based on HFI and the adaptive amplitude optimizer based on ML. Table 1 is the summary of the PMSM and system parameters used in the simulations hence makes sure that the results are reproducible and consistent across all the test cases.

**Table 1: PMSM and System Parameters Used in Simulation**

Parameter	Symbol	Value
Stator resistance	$R_s$	0.45 $\Omega$
d-axis inductance	$L_d$	0.80 mH
q-axis inductance	$L_q$	0.90 mH
PM flux linkage	$\lambda_m$	0.055 Wb
Pole pairs	$p$	4

Rated DC-link voltage	V <sub>dc</sub>	48 V
HFI injection frequency	f <sub>inj</sub>	1.0 kHz
Inverter switching frequency	f <sub>sw</sub>	10 kHz
Control sampling time	T <sub>s</sub>	100 μs

Inverter non-ideality are added to the model to represent realistic behaviour of low-voltage driving inverter. These are a dead-time of 2 μs, effective device voltage drop of 1.2 V/conducting path to model switching nonlinearities, and PWM saturation that constrained the voltage command about the ±0.95V-command of Voltage within the range of -0.95V-command to +0.95V-command. A step sag (48 V to 40 V or about 16.7 per cent reduction) in the load transients due to DC-link disturbances is superimposed on the low-frequency ripple of -1.0 V at 100 Hz. The uncertainties on measurements are modelled by adding a zero-mean noise into the sensing channels, where the noise standard deviation of current of 0.05 A and a voltage sensing noise of 0.2 V are used when the measurement is required. The proposed adaptive method is analysed in terms of performance compared with two baseline strategies: a fixed-amplitude HFI approach using a constant, and a lookup-table-based amplitude scheduling method indexed by speed and load conditions. The evaluation metrics include the RMS rotor position estimation error computed between the true rotor position and its estimate, torque ripple expressed as a percentage, and additional copper losses calculated as a percentage relative to the baseline case. The same quantitative indicators are also used to test the robustness under DC-link sag and measurement noise conditions and see the similar results in operating environments.

## RESULTS AND DISCUSSION

The effectiveness of the suggested ML-based adaptive method of choice based on HFI amplitude selection is compared to that of traditional fixed-amplitude and lookup-table methods, and the findings are represented in Figure 3 and Figure 4 and summarised quantitatively in Table 2.

Figure 3 is a table of the RMS rotor position estimation error versus electrical speed. The highest name of error in estimation is observed in the fixed-amplitude

method especially at the low speed range where incorrect amplitude choice constrained signal to noise ratio of injected response. The strategy of look-up-table is accurate, although it is vulnerable to variations in operations and disturbances in the DC-link. Conducting investigations in this case, the proposed ML-based approach has been found to minimise the error of the estimation throughout the whole range of speed. The fixed-amplitude approach and lookup-table approach have RMS position errors of about 4.3 and 2.3 degrees at zero speed respectively when the proposed method minimises its error to about 1.3 degrees. At increased velocity (1500 rpm), there is a significant reduction in the estimation error in all methods, but the proposed approach shows the lowest value of the error at around 0.02 degrees, which reflects the greater capability of performance and stability.

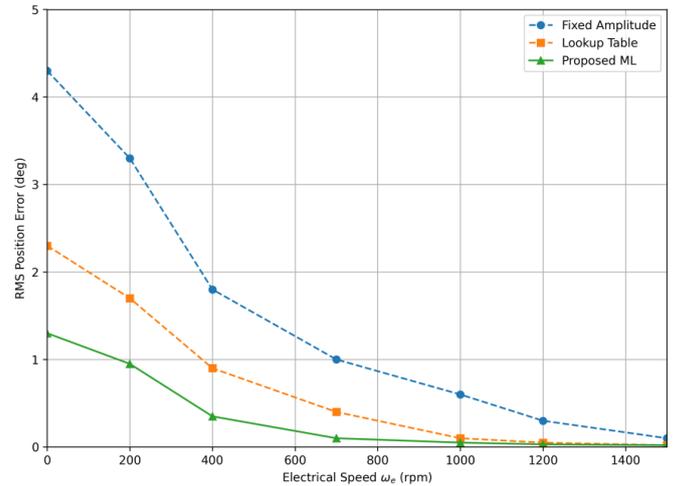


Fig.3: Comparison of Rotor Position Estimation Error Versus Electrical Speed for Different HFI Amplitude Strategies.

Figure 4 shows the steady-state waveforms of the electromagnetic torque at 100 rpm operating under the same load condition. The fixed- amplitude approach presents a severe oscillatory behaviour of the torque driven by too large a injection amplitude, whereas the lookup-table approach decreases but does not eradicate ripple. The suggested ML-based approach dynamically varies the injection amplitude which leads to visually more smoothed torque characteristics. Looking at the waveforms, the ripple in the peak to peak torque in the

Table 2: Comparative Performance Evaluation of HFI Amplitude Selection Strategies

Method	RMS Position Error (deg)	Torque Ripple (%)	Additional Copper Loss (W)	Adaptability
Fixed Amplitude	4.3 (0 rpm) / 0.10 (1500 rpm)	12.0 %	8.5 W	Low
Lookup Table	2.3 (0 rpm) / 0.02 (1500 rpm)	6.8 %	5.2 W	Moderate
Proposed ML	1.3 (0 rpm) / 0.02 (1500 rpm)	3.2 %	3.1 W	High

case that it is achieved by fish-hooking is about 0.70 Nm (around 12 percent), and the ripple in the case where it is done with the lookup-table method is around 6.8 percent. The suggested solution also reduces the torque ripple to an estimated of 3.2 per cent, which implies that the oscillations caused by injection have been suppressed well. Such numbers are numerically summarised in Table 2 that additionally reports other copper losses. The fixed-amplitude approach adds to the copper losses about 8.5 W, the lookup-table approach adds about 5.2 W, and the ML approach proposed further cuts it by 3.1 W to the optimized process of amplitude selection. In general, the comparison study has established that the adaptive framework proposed results in better estimation quality, low torque ripple, less copper losses, and increased adaptability than traditional strategies.

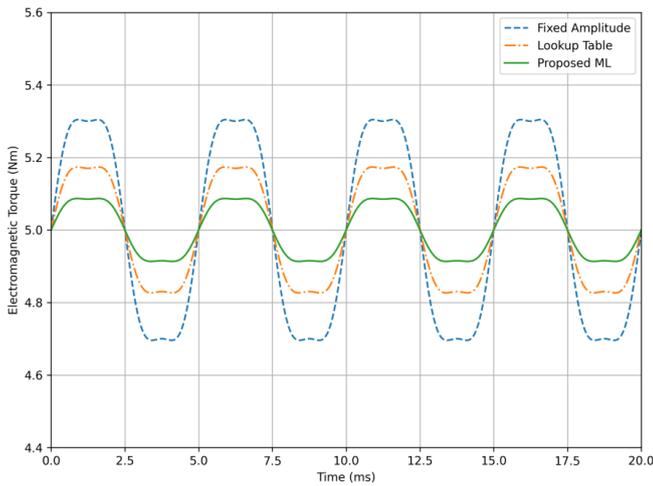


Fig.4: Torque Ripple Comparison at 100 rpm for Different HFI Amplitude Strategies.

## CONCLUSION

The proposed paper presented machine learning-based adaptive optimization architecture of the high-frequency injection (HFI) amplitude selection of sensorless permanent magnet synchronous motor (PMSM) drives. The traditional HFI methods are often based on constant injection levels or look up tables, which cannot adjust well to changes in operating conditions including load torque, speed, fluctuations in DC-link and uncertain parameters. In order to overcome this shortcoming, the current study developed amplitude selection as a multi-objective optimization problem structured to ensure error in rotor position estimation, torque ripple and other copper losses are minimised together. The set of operating states are determined by the data to dynamically change the level of injection by mating within the control architecture a data-driven estimator. The framework that was developed combines the PMSM dq-axis model, HFI signal injection, demodulation-based

position estimation, and a nonlinear machine learning reflection between measurable states and optimal amplitude. Stability limits and amplitude limits were added so that there were safe interaction limits with the inner current control loop. The architecture that is obtained still maintains a frequency separation between basic control and faster excitation and still has limited functionality and is computationally feasible even in embedded systems. The results of simulation supported the effectiveness of the proposed approach. The ML-based approach has greatly minimised the error in estimating the RMS rotor position throughout the entire range of speed with more pronounced gains in the low-speed band where the back-EMF-based approach is unreliable. Moreover, relative to fixed-amplitude and look-up-table methods, the steady-state torque ripple at low speed was significantly lower and thus exhibited a superior level of electromagnetic smoothness. The optimization in terms of amplitude selection also reduced further copper losses meaning better energy efficiency and less thermal stress. All in all, the offered adaptive framework leads to the strengthening of the estimation, the quality of torque, and the efficiency without affecting the ability to implement it in real-time. The above properties render it most appropriate to low-voltage electric mobility platforms, high precision motor drives, and intelligent motor control systems of the next generation. Future research can develop the strategy to experimental validation, hardware-in-the-loop test, and combination with reinforcement learning or new adaptive observers to achieve more performance improvement.

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