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Research on Motor Control of Dual Motor Hybrid Vehicle

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Abstract: The stability and robustness of the control system for a dual hybrid system's permanent magnet synchronous motor are analysed. Various control techniques, such as current vector control, flux weakening control, PI current control, and SVPWM control, are examined. The motor operates in different modes including initialization mode, normal mode, fault mode, active discharge mode, and power down mode. To ensure occupant safety and prevent damage to vehicle components when facing obstacles like high resistance or steep uphill slopes, motor stall control is implemented. Active short control is defined to avoid feedback of motor current to the battery through the continuous current diode of the IGBT and minimize excessive braking torque generated by the back electromotive force after closing the three-phase bridge arm at high speeds. Finally, successful validation of the motor control design is achieved through real vehicle testing.

1. Introduction

Due to the increasing concern regarding energy shortages and the severe impact of greenhouse gases, there is a growing focus on new energy vehicles. Hybrid vehicles commonly utilize permanent magnet synchronous motors due to their lightweight design, compact size, high torque output, and excellent braking performance. Çavuş et al. [1] proposed a novel approach for controlling flux weakening in direct torque controlled induction motors operating at high speeds. Sun et al. [2] presented an article introducing a hybrid control strategy based on dynamic coordination control principles for switched reluctance motors (SRMs). Jiang et al. [3] introduced a speed disturbance control method based on sliding mode control for PMSLMs. Hu Zhang et al. [4] introduced a predictive control strategy that combines an enhanced predictive control method with an observer to forecast motor currents and system disturbances using a decoupled model, aiming to improve efficiency and recovery performance in electric vehicle operations. Ling Zheng et al.[5] analyzed fuzzy PID control strategy enabling online adjustment of PID parameters for adaptive capabilities and improved suppression of motor torque ripple. Junchao Jing et al.[6] conducted a comprehensive analysis of P2.5 hybrid motor current control as well as motor mode and path regulation to introduce a motor control strategy.

Considering the design goals and development considerations, Geely has developed a range of motor control strategies within their dual system control system. These strategies include current regulation, mode management, path guidance, jerk prevention, and shuffle prevention. The motor operates in different modes such as initialization mode, normal operation mode, fault mode, active discharge mode, and power down mode. Real-world tests have proven the successful implementation of these motor control strategies in improving stability and driving performance while achieving other desired objectives. This approach has been effectively utilized to support the introduction of Geely's 01 hybrid electric vehicle.

2. Motor control introduction

The motor in the dual motor hybrid system is two three-phase permanent magnet synchronous motor P1 and P2 integrated with the DHT. As shown in Figure 1 and Table 1, the P2 motor is located in front of the gear.

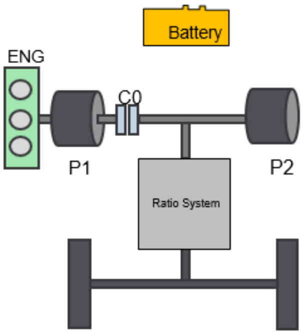

Figure 1: Dual-drive hybrid system overall layout

Table 1: The ISG motor main parameter

P2 Motor Peak Power	110kw
P2 Motor Peak Torque	320Nm
P1 Motor Peak Power	60kw
P1 Motor Peak Torque	180Nm
Invertor Peak Power	60kw
Voltage Range	280V-420V
The Cool Mode	Oil Cooling

2.1. Field weakening control based on voltage feedback

The voltage space vector control structure of current control is shown in the Figure 2. The system is mainly composed of field weakening control based on voltage feedback, current PI control, voltage duty cycle calculation based on SVPWM control strategy (Space Vector PWM).

The fixed excitation magnetomotive force in a permanent magnet synchronous motor (PMSM) is generated by the permanent magnet, thus necessitating an increase in the stator direct axis demagnetization current through flux weakening control to achieve voltage balance at high speeds. As the formula (1) is shown, the field weakening control is activated when the requested voltage amplitude exceeds the actual voltage. By employing a voltage control strategy, the flux weakening algorithm ensures optimal torque operation throughout the entire field-weakening region. The difference between feedback voltage and inverter's maximum output voltage is used to determine the field weakening speed. The final speed is based on the field weaning speed and the actual speed, which is shown in formula (2)-(4). k_{usage} is the voltage usage. $n_{field\ weakening\ speed}$ is the field weakening speed n_{final} the final motor speed. U_{actual} is the actual high voltage. $U_{calibration}$ is the calibration voltage level. Based on torque requirements, final motor speed, and the high voltage, the requested inverter DQ currents id and iq are computed using both MTPA control strategy and field weakening control strategy.

$$\sqrt{{u_d}^2 + {u_q}^2} - \frac{U_{act} * k_{usage}}{\sqrt{3}} \geq U_{upper} \tag{1}$$

$$n_{final} = n_{actual} * \frac{U_{calibration}}{U_{actual}} + n_{field\ weakening\ speed} \tag{2}$$

$$n_{field\ weakening\ speed} = \int U_{error} * I_{gain} \mathrm{dt} \tag{3}$$

$$U_{error} = \frac{U_{act} * k_{usage}}{\sqrt{3}} - \sqrt{{u_d}^2 + {u_q}^2} \tag{4}$$

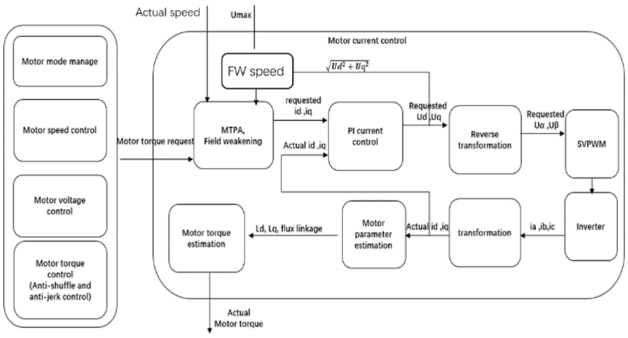

Figure 2: The motor current control sketch

2.2. Motor mode control

The paper presents an algorithm that enables closed-loop torque control of a permanent magnet synchronous machine and provides various operational modes. The motor controller determines the operational modes, except in case of a malfunction where corrective action is taken to ensure safety. Depending on the requested motor control mode signal from vehicle controls and current diagnostic settings, different modes such as initialization mode, normal operation mode, power down mode, active discharge mode or fault modes can be entered.

Fault mode takes precedence over initialization mode and normal operation mode, causing the system to enter Fault mode when a fault condition occurs. Control actions are taken based on the severity of the fault. Software protection handles the first level of fault reaction by implementing selectable gate drive disablement or shorted conditions in the inverter system. In case of hardware faults such as under voltage, over voltage, and over current, hardware protection is activated as the second level of defence. Hardware protection status overrides software fault status requests.

According to the safety goal of the motor controller, it is required to turn off the motor output when the motor controller fails, so that its torque is close to zero. For permanent magnet synchronous motors, this can be achieved by turning off the insulated gate bipolar transistor three phase bridge arm at low speed. However, the main disadvantage of this method is that when the motor is running at high speed, after the three-phase bridge arm is closed, due to the existence of the motor's back electromotive force, the motor current will feed back to the electric pool through the continuous current diode of the IGBT, which will produce a large braking torque. Another way to turn off the torque output of a permanent magnet synchronous motor is to perform a three-phase active short circuit of the motor. The main disadvantage of active short circuit operation is that there will be a large transient current in the process of switching active short circuit, and after entering the steady state, a certain braking torque will be output.

2.3. Motor stall control

This paper presents a novel design for a blocking protection strategy, which ensures the safety of vehicle occupants and prevents damage to vehicle components when encountering obstacles such as high resistance or steep uphill slopes.

2.3.1. Motor Stall Detection

When the motor speed is below 10rpm and the motor torque is above 160Nm, the stall detection starts and if the motor is stuck for more than 1s, the torque derating function starts.

2.3.2. Motor Stall Derating Strategy

The conventional linear power reduction strategy design when entering the stall state, a linear reduction of the motor output torque is set in order to mitigate the risk of sustaining high torque and current for an extended period. However, this approach does not provide comprehensive protection for vehicle occupants. When encountering blockages on inclined road surfaces, it fails to ensure both occupant safety and vehicle stability. In cases where the slope is steep or the vehicle cannot initiate forward motion on an incline, due to the linear reduction of torque output, if the reduced torque falls below the gravitational component down the slope, static maintenance and backsliding become unattainable. The stalling strategy designed in this paper shown in Figure 3 is that after entering the stalling state, the frequency of the inverter is down from 10kHz to 4kHz. The maximum current I_p output can be maintained for t1 time, then the motor max current is linearly decreased to the stall current I_k, which can be maintained for t3 time, and then the motor max current linearly decreases to continuous standstill current I_c. After t5 time, the peak current can be reached again and the first cycle ends. During the motor stall condition, the motor cooling flow is set max flow 10L/min.

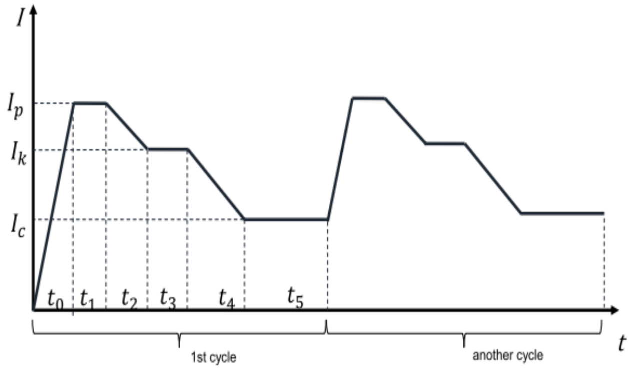

Figure 3: Motor stall control

2.4. Test Result and analysis

2.4.1. Motor ASC mode test

Because the voltage range of the vehicle battery is 280V-420V, the BEMF (back electromotive force) at each speed is first tested on the bench to reach 280V. The test results are shown in the Table 2. When the P2 motor speed exceeds over 7200rpm and the BEMF exceeds 280V(the battery voltage) and the reverse charge current from the motor to the battery reaches 50A. Therefore, the motor enters into the ASC mode when the motor speed exceeds over 7200rpm and the motor enters into the freewheel mode when the motor speed drops below 7200rpm.

Table 2: The motor speed of motor mode transition from freewheel to ASC

Battery voltage(V)	Motor speed(rpm)	Battery current(A)
280	7200	-50
320	8200	-50
360	9200	-50
400	10200	-50

When testing the motor ASC torque, the bench motor is used to drive the motor from the input end to rotate; As shown in Table 3, the motor will enter the ASC mode at different speed (from 2000rpm to 15000rpm) and continue to keep ASC mode in the constant speed. The initial temperature of the motor stator is 85℃ and the oil pan is 85℃. Cooling water flow is 10L/min, water temperature is kept 65 ℃, oil pump is set at the max speed. When the P2 motor enters the active short-circuit fault, the engine can be directly driven, and the P2 motor will rotate at this time. In order to avoid hardware damage caused by excessive temperature of P2 motor in ASC mode, it is necessary to set the P2 motor to enter freewheel mode at a certain speed. The P2 motor temperature should be under 130℃.The test results are shown in Table 3 and the P2 motor cannot be overheated when the P2 motor in the ASC mode. The motor final equilibrium temperature when the motor stays in the ASC mode at different speed.

Table 3: The motor final equilibrium temperature when the motor stays in the ASC mode at different speed

Motor speed	ASC torque	Final temperature
2000	-17	111.8℃
3000	-11	110.6℃
4000	-8.1	114.9℃
5000	-6.3	115.4℃
6000	-4.9	117.4℃
7000	-4.3	117.9℃
8000	-3.8	119.6℃
9000	-3.4	121.1℃
10000	-3.2	122.9℃
11000	-3.1	122.3℃
12000	-3.1	124.3℃
13000	-3	125.26℃
14000	-3	126.7℃
15000	-2.95	128.1℃

2.4.2. Motor fault mode test

To further verify that the motor fault mode control function, the test which is shown in Figure 4 and Figure 5 is performed in the vehicle. In Figure 4, at 9s, the P2 motor fault occurs, the motor mode has changed to fault mode and the inverter mode changes to the freewheel mode due to the low motor speed. At 9.5s, the engine is started and the C0 clutch is requested to slip mode. The C0 clutch torque request is calculated based on slip PID control. The driver torque request is all distributed to the engine. The test result shows that the driver torque control can be satisfied by the engine and not influenced by the P2 motor. The motor can be at freewheel mode and the P2 temperature is stable. In figure 6, at 98s, the P2 motor fault occurs, the motor mode has changed to fault mode and the inverter mode changes to the ASC mode due to the high motor speed. At 98.1s, the C0 launch mode is requested and the C0 clutch is requested to slip mode. The test result also shows that even if the P2 motor enters into ASC mode and the vehicle can be drived by the engine. The motor can be at ASC mode and the P2 temperature is not overheated. Therefore, the engine can run stably during the P2 fault mode based on the Figure 4 and Figure 5 test results.

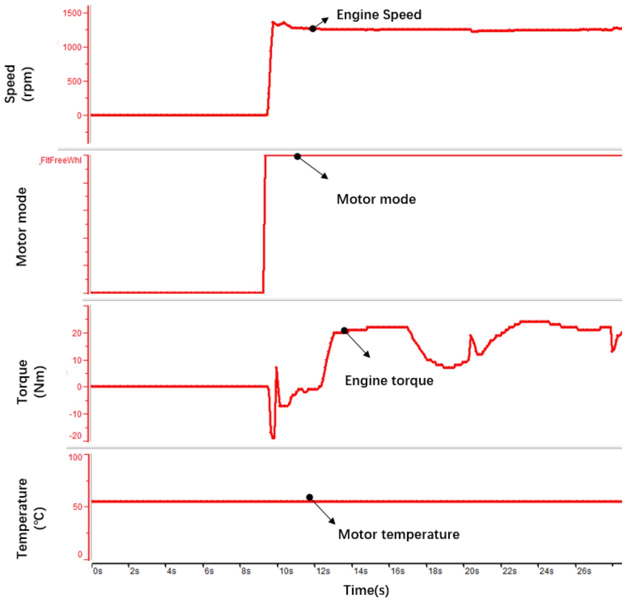

Figure 4: C0 launch control when P2 motor fault occurs and enters freewheel mode

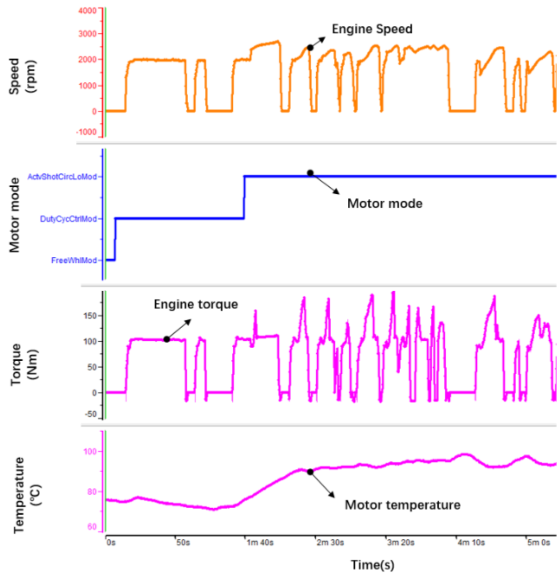

Figure 5: C0 launch control when P2 motor fault occurs and enters ASC mode

2.4.3. Motor stall test

To further verify that the motor stall mode control function, the test which is shown in Figure 6 is performed in the vehicle. In Figure 6, at 9.9s, the P2 motor torque is 314Nm and the motor speed is 0 rpm, the stall detection starts. At 10.9s the motor has changed to stall mode and the P2 motor torque decreases to 80% of the max P2 motor torque capacity. At 30.5s, the P2 motor torque decreases to 65% of the max P2 motor torque capacity. From 9.9s to 10.9s, the inverter phase W is 441A, the inverter phase U is -391A, the inverter phase V is -50A. The inverter max temperature is 67°C.From

10.9s to 30.9s, the inverter phase V is 372A, the inverter phase W is -279A, the inverter phase U is -93A. The inverter max temperature is 67℃. From 30.9s to 220s, the inverter phase V is 292A, the inverter phase W is -275A, the inverter phase U is -17A. The inverter max temperature is 65℃. The max motor temperature can be 124℃and can be balanced. The motor temperature and inverter temperature cannot be overheated when the motor stalls.

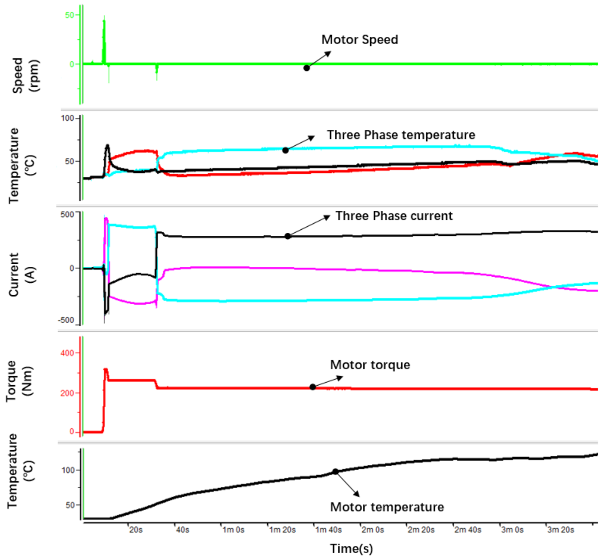

Figure 6: P2 motor stall test

2.4.4. Motor field weakening test

To further verify that the motor field weakening control function, the tests shown in Figure 7 and Figure 8 are performed in the vehicle. In Figure 8, at 26.2s, the field weakening control is activated when the requested voltage amplitude is above the actual voltage. The field weakening speed is limited within 500rpm, the requested id current and iq current cannot satisfied from 26s to 33s.The requested P2 motor torque is 130Nm and the actual P2 motor torque is 88Nm. In Figure 8, at 81s, the field weakening control is activated when the requested voltage amplitude is above the actual voltage. The field weakening speed limit is increased within 700rpm, the requested id and iq can be satisfied from 81s to 85s. The actual P2 motor torque can match up the requested P2 motor torque.

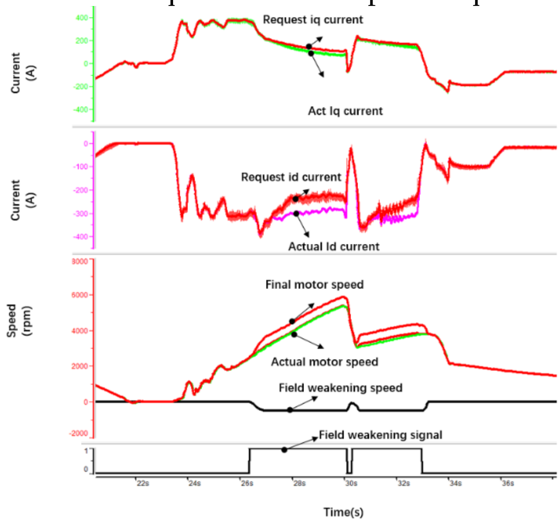

Figure 7: Insufficient motor field weakening test

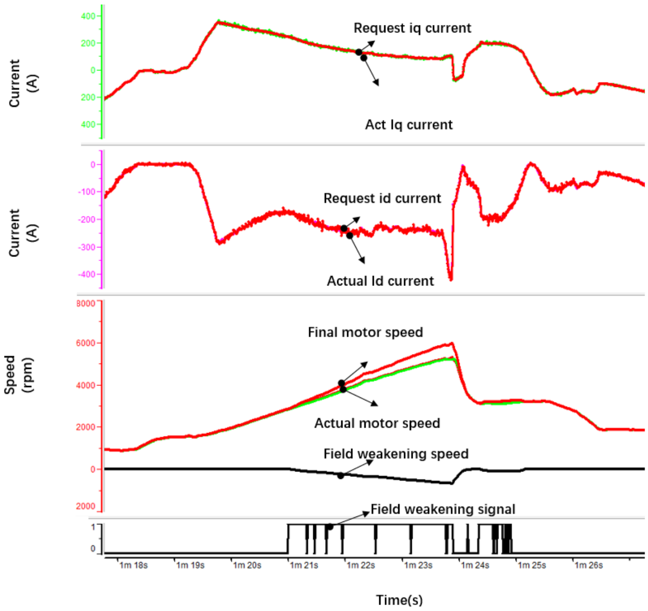

Figure 8: Sufficient motor field weakening test

3. Conclusions

By conducting an analysis on the control of dual hybrid motor current and motor mode, it is possible to achieve stable and precise motor control. In order to ensure the safety of vehicle occupants and prevent damage to vehicle components when faced with obstacles such as high resistance or steep uphill slopes, we have implemented motor stall control. To avoid situations where the motor current feeds back to the battery through the continuous current diode of the IGBT, leading to a significant braking torque generated at high speeds due to the presence of back electromotive force in the motor after closing the three-phase bridge arm, we have introduced active short control. Through successful vehicle testing, improvements have been made in terms of comfort performance.

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