Research on System Control and Energy Management Strategy of Flux-Modulated Compound-Structure Permanent Magnet Synchronous Machine

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(Invited)

Abstract—The flux-modulated compound-structure permanent magnet synchronous machine (CS-PMSM), composed of a brushless double rotor machine (DRM) and a conventional permanent magnet synchronous machine (PMSM), is a power split device for plug-in hybrid electric vehicles. In this paper, its operating principle and mathematical model are introduced. A modified current controller with decoupled state feedback is proposed and verified. The system control strategy is simulated in Matlab, and the feasibility of the control system is proven. To improve fuel economy, an energy management strategy based on fuzzy logic controller is proposed and evaluated by the Urban Dynamometer Driving Schedule (UDDS) drive cycle. The results show that the total energy consumption is similar to that of Prius 2012.

Index Terms—CS-PMSM, energy management strategy, flux-modulated, hybrid electric vehicle, system control.

I. INTRODUCTION

In recent years, electric vehicles (EVs) and hybrid electric vehicles (HEVs) have drawn wide attention[1]. The plug-in hybrid electric vehicle (PHEV) is installed with a larger battery compared with conventional full-hybrid HEVs, enabling longer distance of pure electric mode operation with less emissions. To achieve optimal energy distribution, a power split device is required, linking the internal combustion engine (ICE), generator and electric motor together. At present, the planetary gear system used in Toyota Prius is a most mature power-splitting scheme. However, as a pure mechanical device, the planetary gear set has problems of vibration, noise and abrasion[2]. To solve these problems, researchers have proposed various pure electrical schemes based on compound-structure electric machines[3-6]. However, most of the schemes have brushes, with problems of low reliability of brushes and difficult cooling of the inner rotor, limiting their applications.

A brushless electrical scheme based on the magnetic field modulation principle named flux-modulated compound-structure permanent magnet synchronous machine (CS-PMSM) was proposed, as shown in Fig.1. It is composed of a brushless double-rotor machine (DRM) and a conventional permanent magnet synchronous machine (PMSM). The brushless DRM has two rotors. One is the PM rotor, the other is the modulating ring rotor, which is formed by the alternant placement of magnetic and non-magnetic blocks. The modulating ring rotor is connected to ICE, while PM rotor-1 is coupled with PM rotor-2 which is connected to final drive. The brushless DRM provides the speed difference between ICE and wheels, and transmits the torque of ICE in a certain proportion. Motor-2, formed by stator-2 and PM rotor-2, provides the torque difference between ICE and wheels. Therefore, the ICE can work in high efficiency area regardless of HEV’s operating condition[7,8]. Without brushes, the problems in those pure electrical schemes with brushes are solved.

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Unlike conventional PMSMs, the brushless DRM works on the magnetic field modulation principle. The matching of the pole pair numbers, the wide speed range of the input and the output lead to its wide current frequency range. Because of its wide frequency range, the couplings between the d- and q-axis current control should be considered. In this paper, an improved control strategy of the hybrid electric drive system with the decoupled current controller is proposed. An energy management strategy based on the brushless DRM system is proposed. The fuzzy logic brake controller is designed to achieve the maximum energy recycling. Then the system model is built and evaluated by the Urban Dynamometer Driving Schedule (UDDS) drive cycle.

II. THE HYBRID ELECTRIC DRIVE SYSTEM BASED ON MAGNETIC FIELD MODULATION PRINCIPLE

A. Principle of Flux-Modulated CS-PMSM

The operating principle of the brushless DRM follows the magnetic field modulation principle[7]. On the basis of that, the pole pair numbers of stator-1, PM rotor-1 and magnetic blocks satisfy,

$$p_S + p_{PM} = N_R$$  \hspace{1cm} (1)

where $p_S$ and $p_{PM}$ are the pole pair numbers of stator-1 and PM rotor-1, respectively, $N_R$ is the number of the magnetic blocks of the modulating ring rotor.

To generate steady torque, the speeds of the stator magnetic field, the PM rotor and the modulating ring rotor can be expressed as,

$$p_S \Omega_s + p_{PM} \Omega_{PM} = N_R \Omega_R$$  \hspace{1cm} (2)

where $\Omega_s$, $\Omega_{PM}$ and $\Omega_R$ are the rotating speeds of the stator magnetic field, the PM rotor and the modulating ring rotor, respectively. Meanwhile, the torques of the stator, the PM rotor and the modulating ring rotor can be expressed as,

$$\frac{T_R}{N_R} = \frac{T_S}{p_S} = \frac{T_{PM}}{p_{PM}}$$  \hspace{1cm} (3)

where $T_R$, $T_S$ and $T_{PM}$ are the electromagnetic torques of the modulating ring rotor, the stator and the PM rotor.

B. Mathematical Models of Flux-Modulated CS-PMSM

To simplify the analysis, saturation, eddy currents and hysteresis losses are neglected.

Flux linkage equations can be expressed as,

$$\psi_{d1} = L_{d1}i_{d1} + \psi_{f1}$$
$$\psi_{q1} = L_{q1}i_{q1}$$
$$\psi_{d2} = L_{d2}i_{d2} + \psi_{f2}$$
$$\psi_{q2} = L_{q2}i_{q2}$$  \hspace{1cm} (4)

where $\psi_{d1}$, $\psi_{q1}$, $\psi_{d2}$, $\psi_{q2}$ are the d- and q-axis flux linkages of stator-1 and stator-2; $\psi_{f1}$ and $\psi_{f2}$ are the flux linkages produced by PM rotor-1 and PM rotor-2; $L_{d1}$, $L_{q1}$, $L_{d2}$, $L_{q2}$ are the d- and q-axis inductances of stator-1 and stator-2; $i_{d1}$, $i_{q1}$, $i_{d2}$, $i_{q2}$ are the d- and q-axis currents of stator-1 and stator-2, respectively.

Voltage equations of the CS-PMSM can be expressed as,

$$u_{d1} = R_{d1}i_{d1} + p\psi_{d1} - (N_R \Omega_R - p_{PM} \Omega_L)\psi_{q1}$$
$$u_{q1} = R_{q1}i_{q1} + p\psi_{q1} + (N_R \Omega_R - p_{PM} \Omega_L)\psi_{d1}$$
$$u_{d2} = R_{d2}i_{d2} + p\psi_{d2} - p_{PM} \Omega_L \psi_{q2}$$
$$u_{q2} = R_{q2}i_{q2} + p\psi_{q2} + p_{PM} \Omega_L \psi_{d2}$$  \hspace{1cm} (5)

where $u_{d1}$, $u_{q1}$, $u_{d2}$, $u_{q2}$ are the d- and q- axis voltages of stator-1 and stator-2; $R_1$ and $R_2$ are the winding resistances of stator-1 and stator-2; $p$ is differential operator; $p_{PM}$ and $p_{PM2}$ are the pole pair numbers of PM rotor-1 and PM rotor-2.

Without electromagnetic coupling between the brushless DRM and motor-2, the electromagnetic torque generated by stator-1 and motor-2 can be calculated independently,

$$T_{S1} = \frac{3}{2} (-p_{S1} \psi_{q1} i_{d1} + p_{S1} \psi_{d1} i_{q1})$$
$$T_{M2} = \frac{3}{2} (-p_{PM2} \psi_{q2} i_{d2} + p_{PM2} \psi_{d2} i_{q2})$$  \hspace{1cm} (6)

where $T_{S1}$ and $T_{M2}$ are the electromagnetic torque generated by stator-1 and motor-2, respectively. Then, the motion equations can be expressed as,

$$J_R \frac{d\Omega_R}{dt} = -N_S T_{S1} + T_{ICE} + R_R$$
$$J_{PM} \frac{d\Omega_{PM}}{dt} = p_{PM} T_{S1} + T_{M2} - T_L + R_{PM}$$  \hspace{1cm} (7)

where $J_R$ and $J_{PM}$ are the moments of inertia of the modulating ring rotor and PM rotor-2; $T_{ICE}$ and $T_L$ are torques provided by ICE and final drive; $R_R$ and $R_{PM}$ are the resistance functions of input rotor (i.e., the modulating ring rotor) and output rotor (i.e., PM rotor-1 and PM rotor-2), respectively.

C. System Control Diagram

The control diagram of the flux-modulated CS-PMSM system is shown in Fig.2.
III. CONTROL OF HYBRID ELECTRIC SYSTEM

A. Control of Brushless DRM

In (5), there are cross couplings related to rotating speed of stator magnetic field and stator inductances. Usually, conventional control strategies treat them as disturbance signals. The cross couplings have little effects on system control at low frequency. But the effects can’t be ignored at high frequency. Because of the brushless DRM’s wide speed range of stator magnetic field, it is important to decouple the current controller for its rapidity and stability.

Assume that \( \omega_R = N_b \Omega_R \), \( \omega_{PM} = N_{PM1} \Omega_L \). According to (4) and (5), the current control diagram of the brushless DRM based on the conventional PI controller is shown in Fig.3.

![Fig. 3. Current control diagram of the brushless DRM based on conventional PI controller.](image)

To simplify the analysis, voltage equations expressed by complex vectors are employed. Assume that mapping from d- and q- axis components to complex vectors are given by\([9]\),

\[
f_{qI} = f_q - j f_d
\]

where \( f_{qI} \) is the variable (e.g. \( u, i \)) expressed by complex vectors, \( f_q \) and \( f_d \) are the d- and q- axis components.

By the mapping (8), the voltage equation of the brushless DRM can be expressed as,

\[
u_{qMI} = R_{L1} i_{qMI} + [p + j(\omega_R - \omega_{PM})]\left(L_{qMI} i_{qMI} - j L_{dMI} i_{dMI}\right)
\]

\[
+ (\omega_R - \omega_{PM}) \psi_{fI}
\]

(9)

For flux-modulated brushless DRMs, \( L_{dMI} = L_{qMI} = L_s \). Therefore, (9) can be simplified as,

\[
u_{qMI} = R_{L1} i_{qMI} + L_s \left[p + j(\omega_R - \omega_{PM})\right] i_{qMI} + (\omega_R - \omega_{PM}) \psi_{fI}
\]

(10)

The current control diagram of the brushless DRM with complex vectors is shown in Fig.4.

![Fig. 4. Current control diagram of the brushless DRM with complex vectors.](image)

Usually, PWM inverters are equivalent to first order inertia elements, whose time constants are the periods of the PWMs.

The effects on system control produced by PWM inverters are ignored when the switch frequency is very high. Then the open loop transfer function can be expressed as,

\[
G(s) = \frac{K_p \left(s + \frac{K_i}{K_p}\right)}{s L_1 \left(s + \frac{R_1}{L_1} + j(\omega_R - \omega_{PM})\right)}
\]

(11)

Considering that the controller is a first order system, conventional PI current controllers regard the couplings as disturbances. The imaginary parts of the poles are ignored. When \( K_p / K_i = R_1 / L_1 \), pole-zero cancellation makes the system steady. The ignored \( j(\omega_R - \omega_{PM})L \) has minor effects on system control at low frequency. However, the effects can’t be ignored at high frequency. To extend the frequency range and enhance the stability of the system, controller correction is necessary. A common way is to introduce a positive feedback, as shown in Fig.5.

![Fig. 5. Current control diagram with decoupled state feedback.](image)

The open loop transfer function can be expressed as,

\[
G(s) = \frac{K_p \left(s + \frac{K_i}{K_p}\right)}{s L_1 \left(s + \frac{R_1}{L_1}\right)}
\]

(12)

By PI adjustment, the effects can be eliminated with pole-zero cancellation.

However, this method requires d- and q- axis inductances in advance. Large parameter error will affect the performance greatly. Another system correction method is to introduce an imaginary zero, as shown in Fig.6, realizing the pole-zero cancellation as well.

![Fig. 6. Modified current control diagram with imaginary zero introduction.](image)

The open loop transfer function can be expressed as,

\[
G(s) = \frac{K_p \left(s + \frac{K_i}{K_p} + j(\omega_R - \omega_{PM})\right)}{s L_1 \left(s + \frac{R_1}{L_1} + j(\omega_R - \omega_{PM})\right)}
\]

(13)
Fig. 9 shows the speeds and torques of the system working in hybrid driving mode, which keeps the operating point of the ICE fixed and changes the load. Fig. 10 shows the speeds and torques of the system working in ICE regulation mode, which keeps the load fixed and changes the operating point of the ICE.

According to Fig. 9, when load changes, the operating point of the ICE keeps unchanged. According to Fig. 10, the change of ICE operating point won’t affect the output. It indicates that the flux-modulated CS-PMSM decouples the speeds and torques between the ICE and the load. Speeds are decoupled by speed regulation of the brushless DRM, and the torques are decoupled by torque regulation of motor-2.

IV. ENERGY MANAGEMENT STRATEGY

The energy management strategy realizes the management and distribution of the system energy, which is important for dynamic and economic performances of the vehicle. The energy management strategy requires: 1) meeting drive requirements (reflected by accelerator and brake); 2) keeping the SOC in a reasonable range, neither overcharge nor overdischarge; 3) reducing fuel consumption and emissions. The flux-modulated CS-PMSM system is a new type of power split device for HEVs. Its energy management strategy is investigated in this paper. Considering that the HEV is a multivariable nonlinear system, it is hard to build a precise mathematic model. Therefore, the fuzzy logic control, which is based on experience and insensitive to parameter variation, is employed in the energy management strategy, making the system robust and easy to control[11,12].

A. Design of Energy Management Fuzzy logic Controller

a) Design of Fuzzy logic Drive Controller

Compared with conventional vehicles, the HEVs realize the decoupling of ICE and output. When the vehicle drives, the fuzzy logic controller decides the state of ICE on the basis of

The system model is built in Matlab/Simulink. The pole pair numbers of stator-1 and PM rotor-1 are 4 and 17, respectively, and the magnetic block number of the modulating ring is 21. Then the system is simulated in two different modes. One is the hybrid driving mode, the other is the ICE regulation mode.

**B. System Simulation**

The reference torques of the brushless DRM and motor-2 are given by Fig. 8.

![Fig. 8. Control diagram of CS-PMSM system](image)

The system model is built in Matlab/Simulink. The pole pair numbers of stator-1 and PM rotor-1 are 4 and 17, respectively, and the magnetic block number of the modulating ring is 21. Then the system is simulated in two different modes. One is the hybrid driving mode, the other is the ICE regulation mode.
drive requirements, SOC and vehicle speed, making the ICE most efficient.

![Schematic diagram of fuzzy logic drive controller.](image1)

The fuzzy logic drive controller is shown in Fig. 11. The inputs are SOC, vehicle speed and signal from accelerator, and the output is the speed of ICE. Every input has five fuzzy sets: VL, L, M, H and VH, as shown in Fig. 12 (a), (b) and (c). The output has seven sets for precise control of ICE operating point: VVL, VL, L, M, H, VH, VVH, as shown in Fig. 12 (d).

![Membership functions of fuzzy logic drive controller.](image2)

Control rules are the core of fuzzy logic controller, reflecting the intention of controller. The rules are based on following ideas:

1. When the vehicle speed is low and the SOC is high, shut down the ICE. The vehicle is driven by the motor alone.
2. In different speed ranges, the SOC and the drive torque requirement decide the operating mode.
3. When the vehicle speed is high, the vehicle works in hybrid drive mode.

The relation between the input and output of the fuzzy logic drive controller is shown in Fig. 13 (a) and (b).

![Relation between the input and output of the fuzzy logic drive controller.](image3)

b). Design of Fuzzy logic Brake Controller

HEVs can work in three brake modes: mechanical brake, electromagnetic brake and hybrid brake. When the vehicle brakes, the requirements of security and reliability should be considered firstly, and the energy should be recycled maximally. The fuzzy logic controller decides the brake torque distribution between mechanical brake and electromagnetic brake on the basis of brake requirement, SOC and vehicle speed.

The fuzzy logic brake controller is shown in Fig. 14. The inputs are SOC, vehicle speed and signal from brake. Their membership functions are shown in Fig. 12 (a), Fig. 12 (b) and Fig. 15 (a). The output is brake factor $K_d$, which is the ratio of
the motor braking torque to the maximum motor torque. The membership function of it is shown in Fig.15 (b).

The rules of the fuzzy logic brake controller are based on following ideas:

1. When the SOC is high, $K_d$ is small.
2. When the SOC is low, $K_d$ varies with vehicle speed and brake torque requirement.
3. As the SOC goes up, $K_d$ decreases gradually.

The relation between the input and output of the fuzzy logic brake controller is shown in Fig.16 (a) and (b).

**Fig. 14.** Schematic diagram of fuzzy logic brake controller.

**Fig. 15.** Membership functions of fuzzy logic brake controller.

**Fig. 16.** Relation between the input and output of the fuzzy logic brake controller.

### B. Simulation of Energy Management Strategy

The model is built in Cruise and the Urban Dynamometer Driving Schedule (UDDS) drive cycles are used to evaluate the system performances. The choices of ICE, drive motor, battery and vehicle parameters refer to those of Plug-in HEV Prius 2012. Parameters of the system are shown in TABLE I.

<table>
<thead>
<tr>
<th>Parameters of System</th>
<th>Units</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>ICE</td>
<td>Type</td>
<td>Four-cylinder gasoline engine</td>
</tr>
<tr>
<td></td>
<td>Displacement</td>
<td>1.8L</td>
</tr>
<tr>
<td></td>
<td>Maximum torque</td>
<td>172N·m</td>
</tr>
<tr>
<td>Motor</td>
<td>Max power</td>
<td>68kW</td>
</tr>
<tr>
<td></td>
<td>Max torque</td>
<td>201N·m</td>
</tr>
<tr>
<td></td>
<td>Max speed</td>
<td>8000r/min</td>
</tr>
<tr>
<td>Battery</td>
<td>Type</td>
<td>NiMH</td>
</tr>
<tr>
<td></td>
<td>Capacity</td>
<td>4.4kWh</td>
</tr>
<tr>
<td></td>
<td>Power level</td>
<td>27kW</td>
</tr>
<tr>
<td>Brushless DRM</td>
<td>$p_s$</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>$p_{PM}$</td>
<td>17</td>
</tr>
<tr>
<td></td>
<td>$N_R$</td>
<td>21</td>
</tr>
<tr>
<td></td>
<td>Mass</td>
<td>1588kg</td>
</tr>
<tr>
<td></td>
<td>Final ratio</td>
<td>3.905</td>
</tr>
<tr>
<td></td>
<td>Windward area</td>
<td>1.745m²</td>
</tr>
<tr>
<td></td>
<td>Drag coefficient</td>
<td>0.3</td>
</tr>
<tr>
<td></td>
<td>Rolling resistance coefficient</td>
<td>0.009</td>
</tr>
<tr>
<td></td>
<td>Tire friction coefficient</td>
<td>0.95</td>
</tr>
<tr>
<td></td>
<td>Wheel radius</td>
<td>0.287m</td>
</tr>
<tr>
<td></td>
<td>Fuel density</td>
<td>0.76kg/L</td>
</tr>
<tr>
<td></td>
<td>Fuel calorific value</td>
<td>44000kJ/kg</td>
</tr>
</tbody>
</table>

The simulation of vehicle speed is shown in Fig.17. The result shows that the vehicle speed follows the reference speed well. Other simulation results are shown in Fig.18-21. It indicates that when the SOC is high and the vehicle speed is low, the ICE keeps closed, and the vehicle is driven by motor alone; when the speed goes up, the ICE starts and the vehicle is driven by the ICE and the motor together; when the SOC is about 0.5, the battery works in battery maintenance state, when the SOC goes down, start the ICE, when the SOC goes up, shut down the ICE.

The operating points of the ICE are shown in Fig.22. The blue curve, the red curve and the green curve are the maximum
torque curve, the optimal efficiency curve and the operating curve of the ICE, respectively. It shows that the ICE always works in optimal efficiency state.

The total driving distance is 48km, and the energy consumption comparisons between the CS-PMSM and the Prius 2012 system in same test conditions are shown in TABLE II. It shows that the total energy consumption is 0.5% more than that of the Prius 2012 system.

<table>
<thead>
<tr>
<th></th>
<th>CS-PMSM</th>
<th>Prius 2012 system</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel consumption</td>
<td>1.5L</td>
<td>1.4L</td>
</tr>
<tr>
<td>Electricity consumption</td>
<td>1.57kWh</td>
<td>2.49kJ</td>
</tr>
<tr>
<td>Total energy consumption</td>
<td>56046.48kJ</td>
<td>55762.00kJ</td>
</tr>
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</table>
V. Conclusion

This paper proposes an improved control strategy of the flux-modulated CS-PMSM. To solve the problem of couplings between d- and q- axis current control, a modified current controller is proposed. Then the system control strategy is simulated in different operating conditions. The results show that the speeds and the torques of the ICE and the output are decoupled. The energy management strategy based on the brushless DRM system is proposed. To recycle the energy maximally, the fuzzy logic brake controller is designed. The results show that the ICE always works in optimal efficiency state, the battery is controlled optimally and the total energy consumption is similar to that of Prius 2012.

References

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