Research on Direct Torque Control for the Electrical Variable Transmission

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***Abstract*—This paper focused on the control requirements of electrical variable transmission for hybrid electric vehicle, and different control algorithm of electrical variable transmission are compared and analyzed. The direct torque control is a more reasonable control strategy for solving the torque fluctuation which is caused by magnetic coupling. The simulation results demonstrate the feasibility of the proposed method, and it can be adopted as a new theory and method for the study of hybrid electric vehicle.**

Keywords- hybrid electrical vehicle; Electrical variable transmission; electric drive system; control strategy; direct torque control

I. INTRODUCTION

The electrical variable transmission(EVT) can operate as a continuously variable transmission(CVT), which can achieve the energy integration or disbranch between electrical energy and mechanical energy, so EVT can work as a drivetrain component to achieve high power density[1,2]. The current study for EVT has made great progress, but in actual application, there are still a lot of work to do. Particularly, a good dynamic control strategy is necessary to research.

The electric drive system for hybrid electric vehicle(HEV) is different from the traditional electric drive system and electric servo system, which generally prefer torque control to the precise speed control, and needs higher reliability to adapt the significant change of work condition. Vector control is the main control strategy used in HEV for the electric drive system, which improves the operation performance and control performance greatly. However, the decoupling algorithm is complex and sensitive to the motor parameters, and in the HEV control system, the motor parameters change greatly, which will reduce the dynamic performance of vector control system. Meanwhile, the vector control also needs a speed sensor to obtain accurate speed signal for field orientation, and the speed sensor reduces the robustness of the HEV control system. Direct torque control(DTC) is a new high performance drive technology, which has the advantages such as fast dynamic torque response, relatively simple algorithm, high robustness. So DTC is a very suitable control strategy used in HEV, and it has been applied in some HEV control system.

The HEV system based on EVT is shown in Fig.1. EVT can get a lot of energy conversion modes, and it is especially suitable for application in HEV as the driving force separating device. This structure can replace CVT, starter, generator to realize the function of CVT mode, starter mode, generator mode, regenerative braking mode, pure electric mode, and auxiliary booster mode[3,4]. Based on these functions and the requirements of HEV control, EVT should guarantee the engine work in high efficient area and provide the drive torque to meet the HEV's dynamic driving requirements. However, as a four ports electro-mechanical energy converter, EVT share the outer rotor, two mechanical ports, two magnetic field, so there are mechannical and electrical couplings, and a large number of decoupling calculation is essential[5,6]. Moreover, motor parameters will change in a large range with the HEV's ambient temperature, so the traditional control strategy is difficult to obtain good control characteristics. There has not even one solution to solve these problems which restrict EVT's application in HEV.

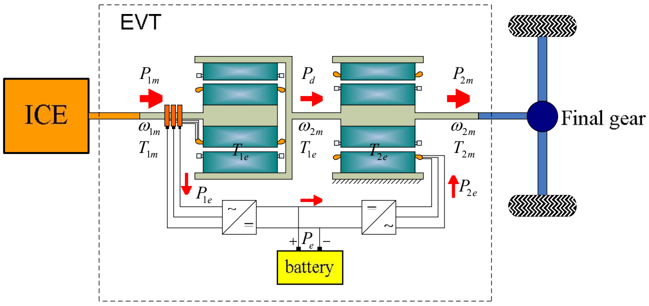

Fig.1 HEV system based on EVT

This paper analyzes DTC system for EVT, and the torque is directly calculated for closed loop control, reducing the coupling influence on the control algorithm. There is no need to use speed sensor, which can reduce the cost, reliability and structural issues.

II. EVT FEATURES AND CONTROL REQUIREMENT

EVT is an electromechanical converter with four ports, two electrical ports and two mechanical ports, which is composed of two induction motor arranged concentrically, as shown in Fig.2. The outer rotor and the stator makes up of the outer machine, the inner rotor and outer rotor makes up of the inner machine.

The outer rotor is common part of inner machine and outer machine, and the magnetic yoke of outer rotor is the common magnetic path, shown in Fig.3. There are not only the radial magnetic flux, but also the tangential flux.

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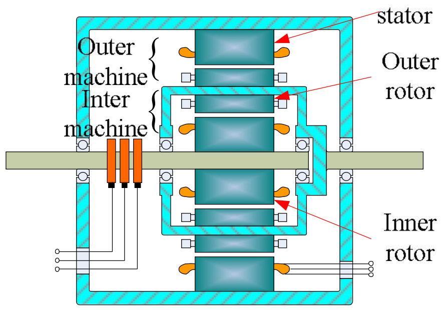

Fig.2 Electrical variable transmission

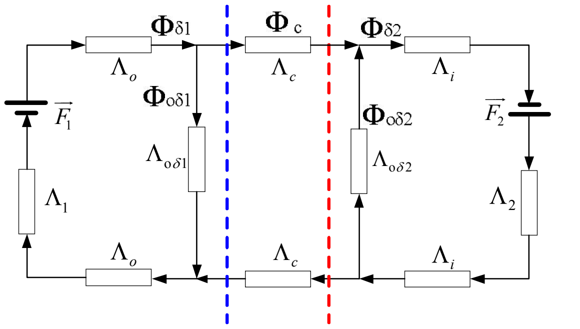

Fig.3 The equivalent flux path of EVT

Two sets of power windings produce two different magnetomotive forces, and the different magnetic field distributions are formed with the changing angle between two magnetic forces. There are three magnetic circuits, series conection magnetic path, parallel connection magnetic path and general state magnetic path, as shown in Fig.4. With the different operation modes of EVT, three magnetic states interchange, and it will bring forward different effects, in particular due to the tangential magnetic flux yoke saturation problem. Therefore, it is very important to research how to control the magnetic path to achieve a predetermined magnetic state.

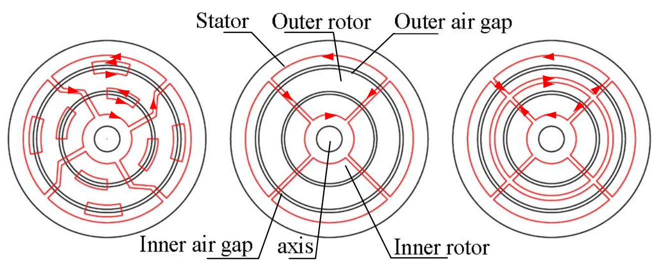

Fig.4 Three magnetic paths of EVT

In the process of EVT design, if the magnetic yoke thickness of outer rotor is increased, the coupling influence between the inner motor and outer motor can be reduced. Howerer, it is very difficult to design the cooling system for the two rotors which are installed in the interior of EVT, so the parameters of EVT will change widely which are affected by temperature. Furthermore, the outer rotor links respectively with stator magnetomotive and inner rotor magnetomotive, so the rotor parameters can not be measured exactly. Therefore, the vecter control which requires precise motor parameters can not achieve the theory result.

The field orient control adopt parameter reconstruct and state reconstruct in modern control theory, the decoupling of stator current was achieved through vector coordinate transform and rotor field orientation, so the induction motor's torque and rotor flux linkage can be controlled. In the rotor field orient control system, the rotor flux linkage model under dq coordinate can be written as follows:

$$\psi_r = \frac{L_m}{T_r p + 1} i_{sd} \tag{1}$$

$$\theta = \int (\omega_r + \omega_s) dt = \int (\omega_r + \frac{L_m}{T_r \psi_r} i_{sq}) dt \tag{2}$$

in the equations:

ψ_r is rotor flux linkage, θ is rotor's position angle, L_m is mutual inductance between the stator and rotor phase windings under two phase coordinate, $T_r = \frac{L_r}{R_r}$ is the rotor time constant, ω_r is electrical angular speed, ω_s is slip angular speed, i_{sd} and i_{sq} are stator current components in dq axis, p is the differential operator.

From formula (1) and (2) we can see that when the rotor time constant $T_r = \frac{L_r}{R_r}$ changes, it will cause predominant influence to accurate FOC, which will make the rotor orient position angle changes, and the decoupling relationship will be destroyed, so the torque will fluctuate and the dynamic response will deviated even make the control system cannot run stably. The rotor field orientation can be divided as three types according to rotor parameters' variation, they are exact orientation, leading orientation and lagging orientation.

Fig 5 show that when the rotor parameters are correct, through the close loop regulation to dq axis currents, the stator current i_s can be decomposed into i_{sd}^* and i_{sq}^* under orientation axis system ψ_r^* in rotor flux linkage observer model. As the same, the stator current i_s can be decomposed into i_{sd} and i_{sq} under the actual flux linkage ψ_r's axis system. Here we have $i_{sd} = i_{sd}^*$, $i_{sq} = i_{sq}^*$, and the induction motor's stator current can be decoupled with excitation component and torque component completely, so the induction motor's flux linkage and torque can be controlled to get a control performance as a DC motor.

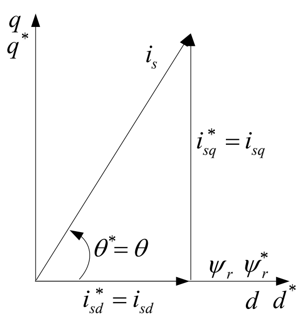

Fig.5 Exact orientation

When the induction motor's rotor parameters changes, if the actual rotor flux linkage orientation (d axis) lead to the observer's rotor flux orientation (d^* axis) as show in Fig.6 , the stator current i_s 's component under flux linkage observer's ψ_r^*'s orientation axis system and actual rotor flux linkage ψ_r 's orientation system will be not equal, here we have $i_{sd} > i_{sd}^*$, $i_{sq} < i_{sq}^*$, and the motor will work in over excitation condition, which will make motor's flux circuit saturation and overheat.

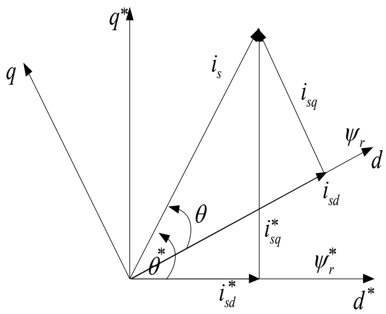

Fig.6 Leading orientation

Fig. 7 illustrated the condition when the actual rotor flux linkage orientation (d axis) lagged to observer's flux linkage orientation (d^* axis), here we have $i_{sd} < i_{sd}^*$, $i_{sq} > i_{sq}^*$, the motor will work in under excitation condition, which will affect the output torque and power.

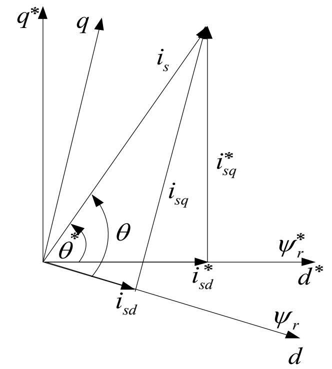

Fig.7 Lagging orientation

From the above analysis we can see that when the rotor parameters changed, the actual d, q axis component of stator current will not equal to the given component, which will cause deviation in flux and torque control under vector control system.

Based on the above analysis, the vector control is a decoupling strategy in steady state based the accurate field orientation, and there are some disadvantages used in EVT control system as follows:

- Orientation accuracy: decoupling of induction motor vector control system should based on the accurate motor parameters. In the EVT control system, the motor parameters change greatly with the magnetic saturation, skin effect, and temperature variation. The accuracy of rotor flux orientation will be affected by the change of motor parameters, which will reduce the dynamic performance of vector control system. Furthermore, the rotating coordinate transformation is according to the rotor field-oriented coordinate, and it is of large computation. EVT has two excitation magnetic field, so the computation is becoming much larger, and the real time requirement is reduced.
- Speed sensor requirement: vector control needs a speed sensor to obtain accurate speed signal for field orientation, then it is necessary to install two speed sensors for EVT which has two mechanical ports. The speed sensor increases the system cost and reduces the robutness of the HEV control system. Moreever, the inner motor of EVT controls the speed difference between the two mechanical ports, which requires two high accuracy speed sensors, otherwise it will result in cumulative errors detected.
- Indirect torque control: the torque control in the vector control system is indirect. The HEV using EVT control the motor torque to achieve the HEV's start, acceleration, deceleration and a series of operations. The fast, accurate, reliable torque control of EVT is essential in HEV system.

III. DIRECT TORQUE CONTROL FOR EVT

There is no need to obtain accuracy decoupling for DTC system, and more attention is paid to improve fast dynamic torque response. The DTC system is shown in Fig.8.

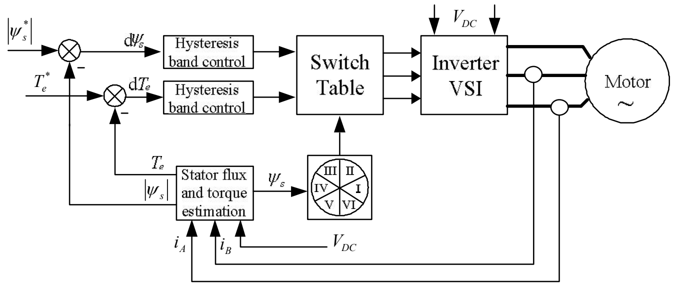

Fig. 8 The structure of DTC system

The appropriate voltage space vector is selected on the basis of electromagnetic torque bias and stator flux amplitude bias to reduce the deviation, then the respective control of electromagnetic torque and stator flux is achieved. Compared with vector control, DTC has the following characteristics:

- Strong robustness: the DTC system does not require accurate rotor parameters, and stator resistance is the unique parameter which is necessary to estimate stator flux. The robustness of DTC system is greatly enhanceed for the motor parameters.
- Simple control algorithm: there is no need of the rotating coordinate transformation and rotor field-oriented coordinate, so computation can be greatly reduced.
- No need of speed sensor: in the DTC system, there is no need of speed sensor to control electromagnetic

torque and stator flux, which will decrease the cost and enhance the system robustness.

- Improving the dynamic response: torque is directly controlled, so the system can get a fast response in the process of acceleration, deceleration and load changing.

By the analysis of the control system, the math models of inner motor and outer motor are established, and state space equation are given by:

$$\begin{bmatrix} \psi_{s1d} \\ \psi_{s1q} \\ \psi_{r1d} \\ \psi_{r1q} \end{bmatrix} = \begin{bmatrix} L_{s1} & 0 & L_{1m} & 0 \\ 0 & L_{s1} & 0 & L_{1m} \\ L_{1m} & 0 & L_{r1} & 0 \\ 0 & L_{1m} & 0 & L_{r1} \end{bmatrix} \begin{bmatrix} i_{s1d} \\ i_{s1q} \\ i_{r1d} \\ i_{r1q} \end{bmatrix} \tag{3}$$

$$\begin{bmatrix} u_{s1d} \\ u_{s1q} \\ u_{r1d} \\ u_{r1d} \end{bmatrix} = \begin{bmatrix} R_{s1}+L_{s1}p & -\omega_{s1}L_{s1} & L_{1m}p & -\omega_{s1}L_{1m} \\ \omega_{s1}L_{s1} & R_{s1}+L_{s1}p & \omega_{s1}L_{1m} & L_{1m}p \\ L_{1m}p & -(\omega_{s1}-\omega_1)L_{1m} & R_{r1}+L_{r1}p & -(\omega_{s1}-\omega_1)L_{r1} \\ (\omega_{s1}-\omega_1)L_{1m} & L_{1m}p & (\omega_{s1}-\omega_1)L_{r1} & R_{r1}+L_{r1}p \end{bmatrix} \begin{bmatrix} i_{s1d} \\ i_{s1q} \\ i_{r1d} \\ i_{r1q} \end{bmatrix} \tag{4}$$

$$T_{s1} = \mathrm{n}_{p1} L_{1m} (i_{s1q} i_{r1d} - i_{s1d} i_{r1q}) \tag{5}$$

in these equations:

the subscript s_1 is stator winding; r_1 is outer rotor's outer cage winding; u_{s1d} , u_{s1q} , i_{s1d} , i_{s1q} , ψ_{s1d} , ψ_{s1q} are *dq* frame stator voltages, stator currents and stator flux linkages respectively; u_{r1d} , u_{r1q} , i_{r1d} , i_{r1q} , ψ_{r1d} , ψ_{r1q} are *dq* frame outer rotor's outer cage winding voltages, currents and rotor flux linkages respectively; L_{s1} is stator inductance ; L_{r1} is outer rotor's outer cage winding inductance; L_{1m} is the mutual inductance between stator and outer rotor's outer cage winding.

$$\begin{bmatrix} \psi_{s2d} \\ \psi_{s2q} \\ \psi_{r2d} \\ \psi_{r2q} \end{bmatrix} = \begin{bmatrix} L_{s2} & 0 & L_{2m} & 0 \\ 0 & L_{s2} & 0 & L_{2m} \\ L_{2m} & 0 & L_{r2} & 0 \\ 0 & L_{2m} & 0 & L_{r2} \end{bmatrix} \begin{bmatrix} i_{s2d} \\ i_{s2q} \\ i_{r2d} \\ i_{r2q} \end{bmatrix} \tag{6}$$

$$\begin{bmatrix} u_{s2d} \\ u_{s2q} \\ u_{r2d} \\ u_{r2d} \end{bmatrix} = \begin{bmatrix} R_{s2}+L_{s2}p & -(\omega_{s2}-\omega_2)L_{s2} & L_{2m}p & -(\omega_{s2}-\omega_2)L_{2m} \\ (\omega_{s2}-\omega_2)L_{s2} & R_{s2}+L_{s2}p & (\omega_{s2}-\omega_2)L_{2m} & L_{2m}p \\ L_{2m}p & -(\omega_{s2}-\omega_1)L_{2m} & R_{r2}+L_{r2}p & -(\omega_{s2}-\omega_1)L_{r2} \\ (\omega_{s2}-\omega_1)L_{2m} & L_{2m}p & (\omega_{s2}-\omega_2)L_{r2} & R_{r2}+L_{r2}p \end{bmatrix} \begin{bmatrix} i_{s2d} \\ i_{s2q} \\ i_{r2d} \\ i_{r2q} \end{bmatrix} \tag{7}$$

$$T_{s2} = \mathrm{n}_{p2} L_{2m} (i_{s2q} i_{r2d} - i_{s2d} i_{r2q}) \tag{8}$$

in these equations:

the subscript r_2 is outer rotor's inner cage winding; s_2 is the inner's winding; u_{s2d} , u_{s2q} , i_{s2d} , i_{s2q} , ψ_{s2d} , ψ_{s2q} are *dq* frame inner's winding voltages, currents and flux linkages respectively; u_{r2d} , u_{r2q} , i_{r2d} , i_{r2q} , ψ_{r2d} , ψ_{r2q} are *dq* frame outer rotor's inner cage winding voltages, currents and rotor flux linkages respectively; L_{s2} is inner's winding inductance ; L_{r2} is outer rotor's inner cage winding inductance; L_{2m} is the mutual inductance between inner's winding and outer rotor's inner cage winding.

IV. SIMULATION AND ANALYSIS OF EVT CONTROL STRATEGY

The speed control and torque control can be used in the inner motor and outer motor of EVT. In the HEV system, the outer motor is required to provide vehicle drive torque, so the outer motor should adopt torque control. Inner motor control mode is more flexible, which can be determined according to the engine control mode. Most of the engines operate in the speed control mode, then the torque control can be also used in the inner motor. In the HEV system using EVT structure, the synthesis torque of inner motor and outer motor is used to drive vehicle forward.

Inner motor and outer motor are controlled using vector control, and the control system model is established in Matlab/Simulink. In the process of simulation, the system assumes that the rotor parameters is changing at third second and the load torque is increased 20N.m every one second. If there is no rotor parameter identification, with the change of load torque, stator current q axis component and d axis component can not match along with the load torque and rotor flux given. as shown in Fig.9, there are severe torque fluctuations, and EVT can not form a stable output torque.

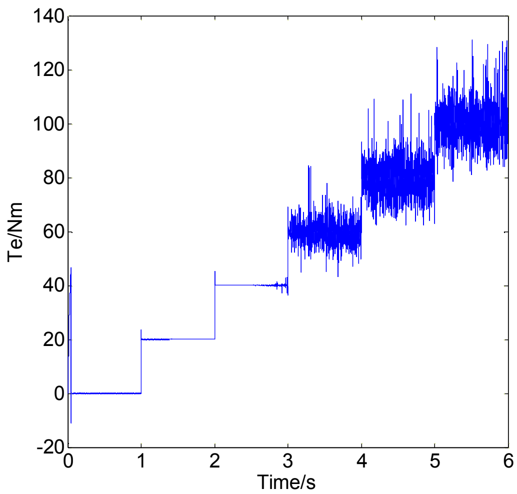

Fig.9 The torque output of EVT using vector control

Using the same simulation conditions for EVT torque control system, as shown in Fig.10, the EVT torque can achieve a fast dynamic response and stable output torque..

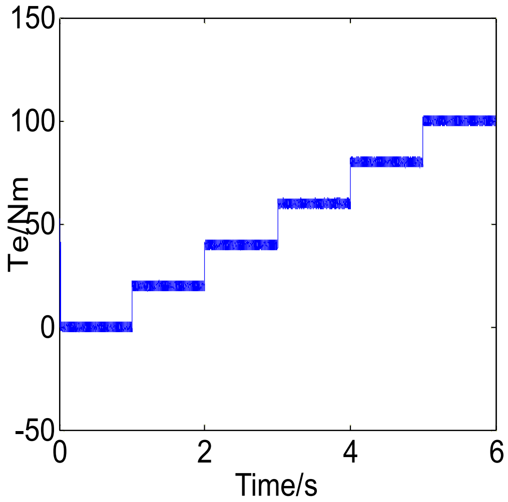

Fig.10 The torque output of EVT using DTC

V. CONCLUSION

This paper analyzed the control strategy of EVT used in HEV from the angle of actual application, and DTC is a more reasonable control strategy of EVT to solve the torque fluctuation. Then simulation model and results were given and discussed. This research gives a great help and design reference for EVT's further study and design.

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