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Brushless DC Motor Control Strategy for Hybrid Electric Vehicle by using Predictive Direct Torque Control

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Abstract: Hybrid Electric Vehicle (HEV) is a vehicle with two sources of activation power which is Internal Combustion Engine (ICE) as a primary mover and Brushless DC Motor (BLDCM) as a secondary mover. BLDCM functions as the supplier of additional torque so that HEV can reach speed setpoint based on reference model. The BLDCM torque control uses Predictive Direct Torque Control (PDTC). PDTC is the development of direct torque control with additional mechanism to predict torque. The result of experiment shows that the performance of PDTC is better than DTC with error steady state = 0.66 rpm, RMSE = 6.33 rpm, current ripple 0.899 A and torque ripple 0.012.

Key words: Hybrid Electric Vehicle HEV (HEV), Brushless DC Motor (BLDCM), Predictive Direct Torque Control (PDTC), mechanism, performance, development

INTRODUCTION

Hybrid Electric Vehicle (HEV) is a vehicle that uses energy activator from at least two different sources. The general combination of energy activator are Internal Combustion Engine (ICE) and electric motor. The main purpose of HEV development are to increase the efficiency of fuel consumption to decrease the vehicle's output gas and betterment of HEV speed respond. Many research concerning about the control method of HEV, such as hybrid controller (Adel *et al*., 2010), fuzzy gain-scheduling proportional-integral controller (Syed *et al*., 2009), optimal neuro-fuzzy control (Mohebbi *et al*., 2005), adaptive neural PID controller (Zhang *et al*., 2011), fuzzy logic controller (WU, 2012).

The development of Brushless DC Motor (BLDCM) aims to solve the problem of brush on DC motor that needs an extra treatment. BLDCM is mostly used in application that needs high durability, high efficiency, big energy but small dimension and weight of motor (Gupta *et al*., 2009).

Direct Torque Control (DTC) is initially developed to control the induction motor. The basic concept is based on electromagnetic torque dan fluxlinkage setting. The sequence switching on inverter is set based on torque error and flux error. DTC has not only the better dynamic performance but also easy to be implied (Gupta *et al*., 2009). Many research about motor drive and DTC such as fixed inverter switching frequency (Singh, 2012), improved DTC with PWM approach based on the approximate voltage function (Kwak *et al*., 2014) and neural network for DTC of BLDC motor (Gupta *et al*., 2009).

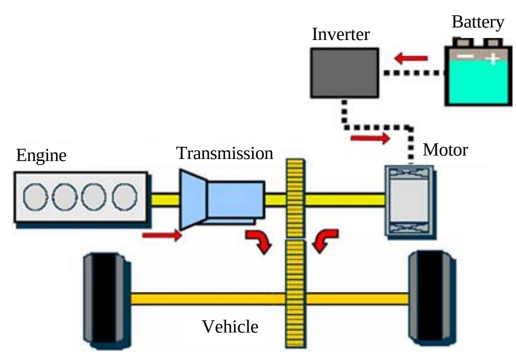

Fig. 1: Parallel hybrid electric vehicle (Mohebbi *et al*., 2005)

This study discuss about the development of DTC control by using mechanism of torque prediction for BLDCM that is implemented as the actuator of HEV.

HYBRID ELECTRIC VEHICLE

Hybrid Electric Vehicle (HEV) is vehicle that takes its power from the combination at least two sources of energy actuator such as Internal Combustion Engine (ICE) and electric motor (Syed *et al*., 2009). HEV can be divided into three types: series HEV, parallel HEV and HEV power split. This experiment uses parallel HEV (Fig. 1 and 2). Specifications of ICE and BLDCM is given in Table 1 and 2:

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Fig. 2: Parallel hybrid electric vehicle simulator

Table 1: Specifications of ICE

Items	Specification
Type	2 stroke
Cylinder capacity	33.8 cc
Speed	8000 rpm
Power	0.81 kW
Control method	Manual throttle

Table 2: Specifications of BLDCM

Items	Specification
Voltage	48 V
Number of pole	4
Power	350 W
No load speed	2400 rpm
Torque	1.9 N.m

Sistem modelling: Identification of ICE parameter is done by using Strejc method based on plot respond of ICE speed. Figure 3 shows respond plot of ICE speed:

Mathematic model of ICE:

$$G_{ICE}(s) = \frac{0.894\times10^{-4}s+305.52\times10^{-4}}{0.000161s^2+0.0254s+1} \quad (1)$$

Mathematic model of load:

$$G_L(s) = \frac{1}{0.445\times10^{-4}s+152\times10^{-4}} \quad (2)$$

Reference model is a guide model for controller to increase HEV respond. Mathematic model of model reference:

$$G(s) = \frac{19.23}{0.008s+1} \quad (3)$$

Identification BLDCM parameter is used by analyzing the result of measurement (Table 3). BLDCM matemathic model is derived from stator equivalent series (Fig. 4). Stator voltage equivalent:

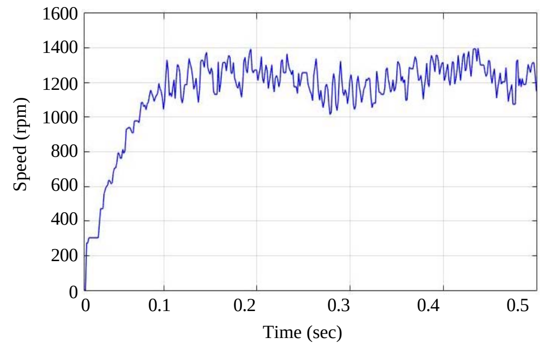

Fig. 3: Respond plot of ICE speed

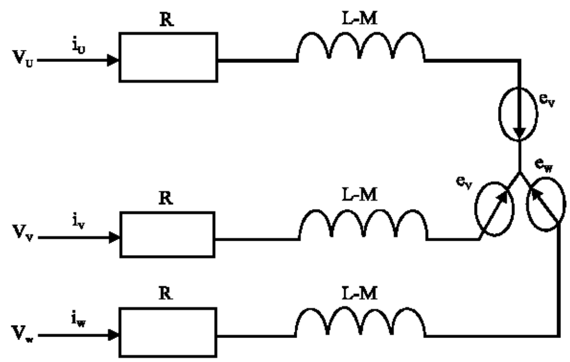

Fig. 4: Stator voltage equivalent circuit (Singh, 2012)

Table 3: Result of BLDC parameter identification

Parameters	Mark/Units
Number of pole	4
Power strain	48 V
Stator resistance	0.85 Ω
Stator inductance	0.0142 H
Mutual inductance	0.0136 H
Constant of torque	0.366 Nm/A
Constant of back emf	0.09 V/rps

$$L\frac{di_U}{dt} + Ri_U + M\frac{di_v}{dt} + M\frac{di_W}{dt} + e_U = V_U \quad (4)$$

$$L\frac{di_V}{dt} + Ri_V + M\frac{di_W}{dt} + M\frac{di_U}{dt} + e_V = V_V \quad (5)$$

$$L\frac{di_W}{dt} + Ri_W + M\frac{di_U}{dt} + M\frac{di_V}{dt} + e_W = V_W \quad (6)$$

Stator current equation:

$$\frac{d}{dt}\begin{bmatrix} i_U \\ i_V \\ i_W \end{bmatrix} = D^{-1}\left\{ RI\begin{bmatrix} i_U \\ i_V \\ i_W \end{bmatrix} + I\begin{bmatrix} V_U \\ V_V \\ V_W \end{bmatrix} - I\begin{bmatrix} e_U \\ e_V \\ e_W \end{bmatrix}\right\} \quad (7)$$

The back EMF equation:

$$e_U = K_e \omega_m F(\theta_e) \quad (8)$$

$$e_V = K_e \omega_m F\left(\theta_e - \frac{2\pi}{3}\right) \quad (9)$$

$$e_W = K_e \omega_m F\left(\theta_e - \frac{4\pi}{3}\right) \quad (10)$$

BLDCM torque Eq. 11:

$$T_M = \frac{K_{TM}}{3}\left[F(\theta_e)i_U + F\left(\theta_e - \frac{2\pi}{3}\right)i_V + F\left(\theta_e - \frac{4\pi}{3}\right)i_W\right] \quad (11)$$

where, V_U, V_V, V_W is phase voltages of the three phase stator winding (V). i_U, i_V, i_W is phase currents of the three-phase stator winding (A). e_U, e_V, e_W is the back EMF (V). R is the phase resistance (Ω). L is the phase inductance (H). M the mutual inductance of the three phase winding (H). T_M is the electrical torque of BLDCM (N.m). K_{TM} is the electrical torque's constant of BLDCM (N.m/A). θ_e is the electrical angle.

Six step commutation: A hall sensor is used to detect the rotor position rotor. BLDCM works in conduction domain 120° three phases. Sensor hall's output signal produces the combination of 3 binary digit that changes every 60° (Fig. 5). Commutation is done by adjusting current polarity i_U, i_V, i_W through switching process on six transistor based on sensor hall output (Table 4). Simulation diagram of HEV with Matlab Simulink is shown in Fig. 6.

Predictive mechanism: Predictive Direct Torque Control (PDTC) is the development of Direct Torque Control (DTC). PDTC structure has mechanism of torque prediction to repair DTC respond. The equation for speed is as:

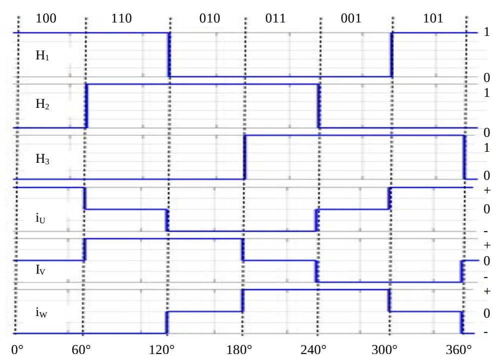

Fig. 5: Sensor hall output and current polarity (Kwak *et al*., 2014)

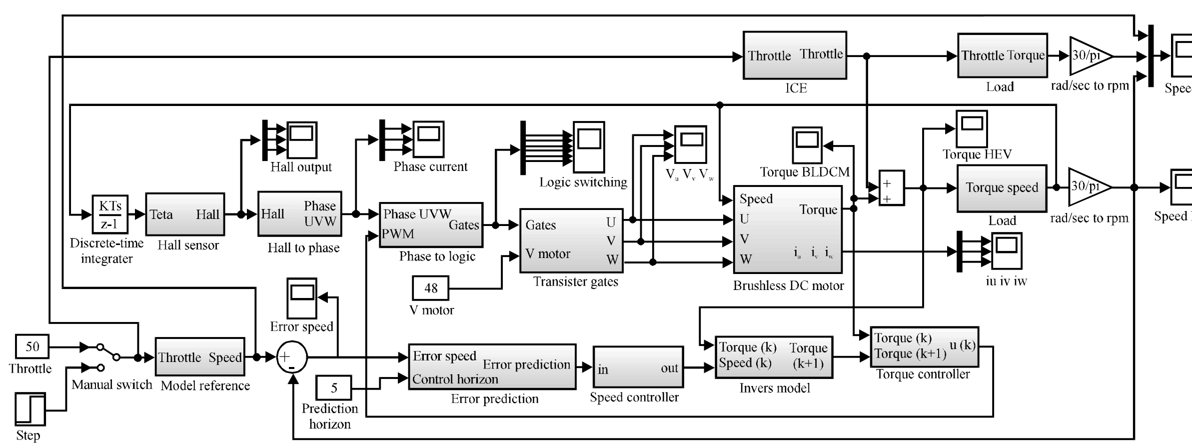

Fig. 6: Simulation diagram of HEV with simulink

Table 4: Switching transistor with six step commutation

Switching interval	Sequential number	Sensor output H_1	H_2	H_3	Phase current U	V	W	Switch On
0°-60°	0	1	0	0	+	0	-	Q1, Q6
60°-120°	1	1	1	0	0	+	-	Q3, Q6
120°-180°	2	0	1	0	-	+	0	Q2, Q3
180°-240°	3	0	1	1	-	0	+	Q2, Q5
240°-300°	4	0	0	1	0	-	+	Q4, Q5
300°-360	5	1	0	1	+	-	0	Q1, Q4

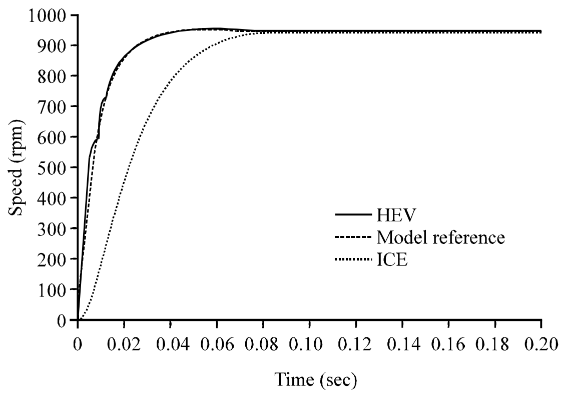

Fig. 7: Speed respond HEV with DTC

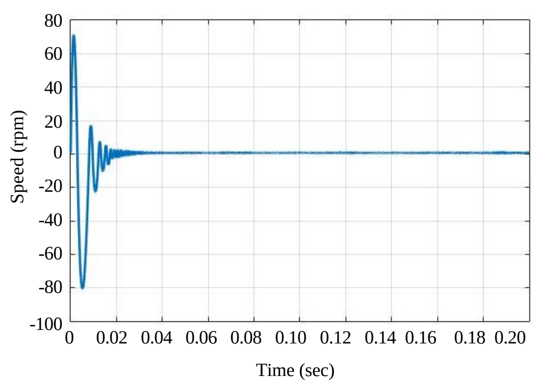

Fig. 8: Speed error HEV with DTC

$$y(k) = A e^{-\frac{T_s}{\tau_\bullet}k} \quad (12)$$

Prediction of speed error for step (k+n):

$$e(k+n) = e^{-n\frac{T_s}{\tau_\bullet}y(k)} \quad (13)$$

Invers model equation that change the input of speed error prediction becomes motor reference torque:

$$\tau(k) = 8.9126\,\omega(k) - 8b8823\,\omega(k-1) - \tau(k-1) \quad (14)$$

Where:

- $y(k)$ = The speed at time (k)
- $e(k)$ = The error at time (k)
- $T_{s=}$ = The sampling time
- $\tau_\bullet$ = The reference time prediction

Test HEV with direct torque controller: The test is conducted by giving gain speed regulator $K_p = 50$, $K_i = 5$, gain torque controller $K_p = 50$, $K_i = 5$. The plot of speed respond (Fig. 7) shows the speed rate on steady state = 946.5 rpm. Speed error plot (Fig. 8) shows that error

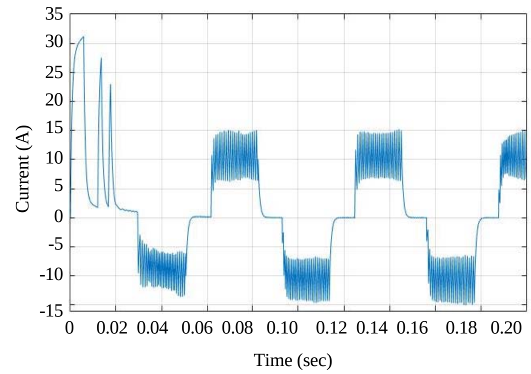

Fig. 9: Current respond with DTC

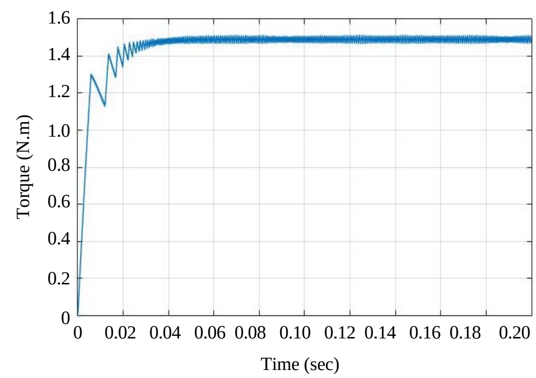

Fig. 10: HEV torque respond with DTC

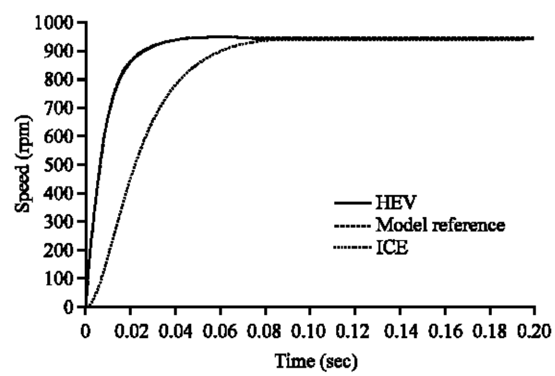

Fig. 11: Speed respond HEV with PDTC

oscillates into zero. The error steady state 0.9514 rpm, RMSE = 8.198 rpm and error percentage RSME = 0.966%.

The plot of current respond (Fig. 9) shows the current ripple 8.83 A. The plot of HEV torque respond (Fig. 10) shows the current ripple 0.055 Nm.

Test of HEV with predictive DTC: The test is conducted with gain rate of speed regulator $K_p = 50$, $K_i = 5$, gain torque controller $K_p = 50$, $K_i = 5$ and prediction horizon = 50. Speed respond HEV (Fig. 11) shows the

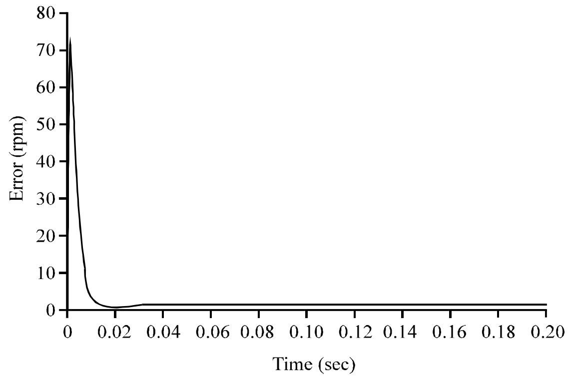

Fig. 12: Speed error HEV with PDTC

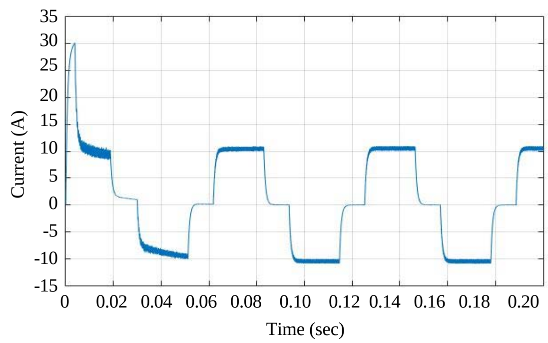

Fig. 13: Current respond with PDTC

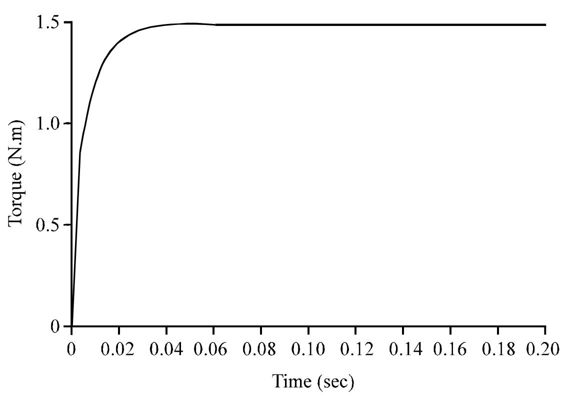

Fig. 14: HEV torque respond with PDTC

speed rate steady state = 945.9 rpm. Plot of speed error (Fig. 12) shows the rate of error steady state = 1.61 rpm, RMSE = 6.53 rpm and percentage RMSE = 0.68%.

The plot of current respond (Fig. 13) shows the current ripple 0.899 A. The plot of HEV torque respond (Fig. 14) shows the current ripple 0.012 Nm.

CONCLUSION

Control BLDCM with PDTC is able to improve HEV torque and speed respond. The simulation result shows that PDTC is better than conventional DTC in which PDTC has smaller current riplle, torque riplle and RMSE.

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