BLDC Motor Control for Electric Vehicle Based On Digital Circuit and Proportional-Integral Controller

Bambang Sujanarko

Department of Electrical Engineering, University of Jember, Indonesia

ABSTRACT: This paper describes a simple circuit controller of Brushless Direct Current (BLDC) motor for electric vehicle implementation. This control based on the function relationship between the Hall sensor logics and currents that should be supplied on each phase of the motor. The function then simplified using Karnaugh-Map method and implemented using digital circuit. Pulse Width Modulation (PWM) added to produce six triggers that used to regulate the inverter current. Proportional Integral (PI) control based on Ziegler–Nichols also added to PWM circuit to improve motor speed performance. The controller are successfully applied using Matlab-Simulink and simulation results show that the controller have simpler circuit and have better speed performance than conventional controller.

KEYWORDS: Brushless Direct Current, Electric Vehicle, Digital Circuit, Proportional Integral, Pulse Width Modulation, Karnaugh-Map, Ziegler–Nichols.

I.INTRODUCTION

Electric vehicle have some advantages over internal combustion engine automobiles, including a significant reduction of air pollution, reduced gas emissions, and reducing energy dependence on diminishing oil reserves. Electric vehicle will use electricity stored in the battery to drive the motor, and the power can be recharged with electricity generation using renewable energy. From various electric motors, the most suitable motor for electric vehicle is BLDC motors, because these motors have high reliability, high power density, high efficiency, low maintenance requirements, low cost and lower weight [1].

BLDC motors are normally powered by conventional three phase inverters which are controlled based on the rotor positions information obtained from Hall position sensors or simply Hall sensors [1-3]. Three phase windings use one Hall Sensor each and provide three overlapping signals giving a 60° wide position range. Whenever the magnetic poles pass near the sensors, a high or low signal will produce to indicating North or South Pole is passing the pole. The rotor position information is used to generate six trigger signals for power inverter [1-5]. BLDC controls that convert Hall signals to six trigger signals frequently built using microcontroller. In these controls the software difficult to implemented for person who non familiar with microcontroller. BLDC controls with microcontroller on the market also have unsatisfactory performance, because a lot of these control frequently damage or not working properly because protection in the control system is too sensitive.

In this research, a simple BLDC control will be design using digital circuit to overcome the difficulties in the design of control with microcontroller. Basic digital integrated circuits will be used to realize the relationship between Hall sensor signals and current inverter to the motor. Digital circuit must be simple, so the system used a simplification method of logic circuit function that is Karnaugh- Map method. To get a good speed performance, the control added a PWM method and PI controller. PWM method used to current regulated of inverter that flow to motor, and PI controller used to get a good respond performance of motor speed. PWM realized using op amp circuit and PI constant determine using Zieger-Nichols tuning. If the motor have agood performance, it means electric vehicle also in the good performance. To verify the proposed control, this research used a modeling of BLDC motor and control for electrical vehicle implementation. These models then build on Matlab-Simulink circuit [8-10], and data from simulation of this circuit analyzed to get performance improvement.

II.LITERATURE REVIEW AND SYSTEM MODEL

As the name suggests, the BLDC motor that also referred to as an electronically commutated motor, is not have brushes on the rotor, and the commutation is performed electronically at certain rotor positions. BLDC motor is driven by rectangular or trapezoidal voltage coupled with the given rotor position. The voltage strokes must be properly aligned between the phases, so that the angle between the stator flux and the rotor flux is kept close to 90 to get the maximum developed torque. BLDC motors often incorporate either internal or external Hall position sensors to sense the actual rotor position [1-7, 11-13]. Rotor position can also be detected without sensors [1-4]. Fig. 1 (a) shows BLDC motor photograph. In the research used 1000 W BLDC motor, 48 V and 950 RPM. This motor has main component stator windings, rotor magnet and Hall sensor as shown in Fig. 1 (b), that is a transverse section of BLDC. BLDC motor has model as shown in Fig.2.

a. BLDC motor photograph
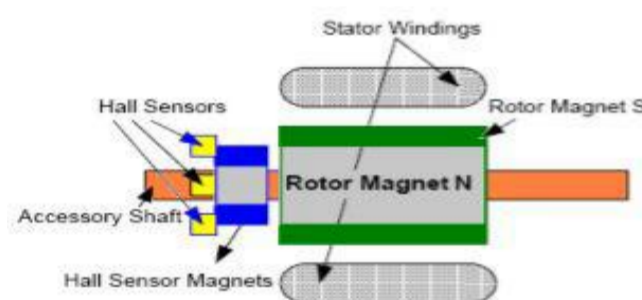
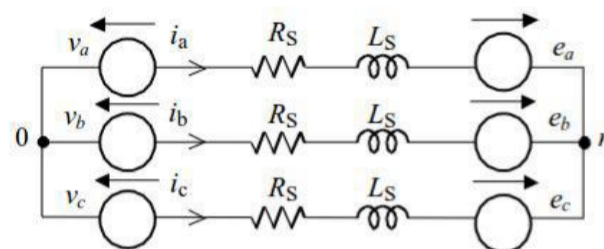b. BLDC transverse section [4]

Fig.1 BLDC motor

Fig. 2 Electrical model of BLDC motor [11-13]

Based on Fig.2 and if BLDC motor produce trapezoidal back EMF e_a, e_b and m, so the exited current i_a, i_b and i_c waveform is preferably rectangular. If the series resistance winding R_s assume equal and the self and mutual inductance L_s also in equal, so the electric equation of BLDC motor is shown in equation (1) [11-13].

$$\begin{bmatrix} v_{an} \\ v_{bn} \\ v_{cn} \end{bmatrix} = \begin{bmatrix} R_s & 0 & 0 \\ 0 & R_s & 0 \\ 0 & 0 & R_s \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} L_s - M & 0 & 0 \\ 0 & L_s - M & 0 \\ 0 & 0 & L_s - M \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \quad (1)$$

The interaction between magnetic field on the winding and permanent magnet, produce electromagnetic torque as shown in equation (2), where ω_n is the mechanical speed of rotor of BLDC. Therefore the equation motion of this motor is shown in equation (3), where T_L is load torque, B is damping constant and J is moment inertia of shat and load [11-13].

$$T_e = \frac{e_a i_a + e_b i_b + e_c i_c}{\omega_m} \qquad (2)$$

$$\frac{d\omega_m}{dt} = \frac{T_e - T_L - B\omega_m}{J} \qquad (3)$$

For six step BLDC control, the power will be deliver from two phases as shown in equation (4), where I is the current amplitude and E is amplitude of back-EMF. Using equation (2) and (4), the electric torque can also express as equation (5), where k_t is motor torque constant [11-13].

$$P_o = \omega_m T_e = 2EI \qquad (4)$$

$$T_e = 2k\phi I = 2k_t I \qquad (5)$$

Complete BLDC drive system shown in Fig. 3. This system usually consists of BLDC motor (5), inverter (1), Hall Effect sensors (4), controller (3) and driver circuit (2) [13]. The position sensor (4), usually Hall sensor, give sign of position the permanent magnet in the windings. These positions generally indicate using three bits data. These data then entered in a control circuit (3) to convert in the 6 trigger signals for inverter (1), which usually composed from power device like MOSFET or IGBT. In the control circuit, the trigger signals also regulate to desire direction and speed of rotation. Before enter to the inverter, the trigger signals entered to the driver circuit (2). In this circuit, the signals will be matching to the switch devices. Finally, by condition of switch of   inverter, the   power flow to windings. Hall sensor then detects new position and the process will be return to control circuit.
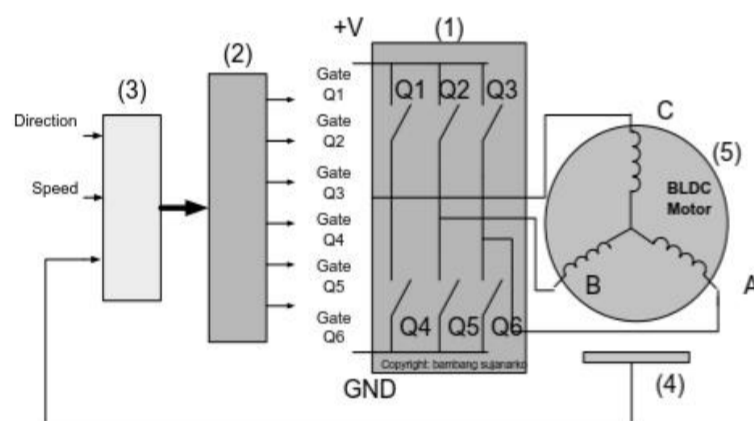

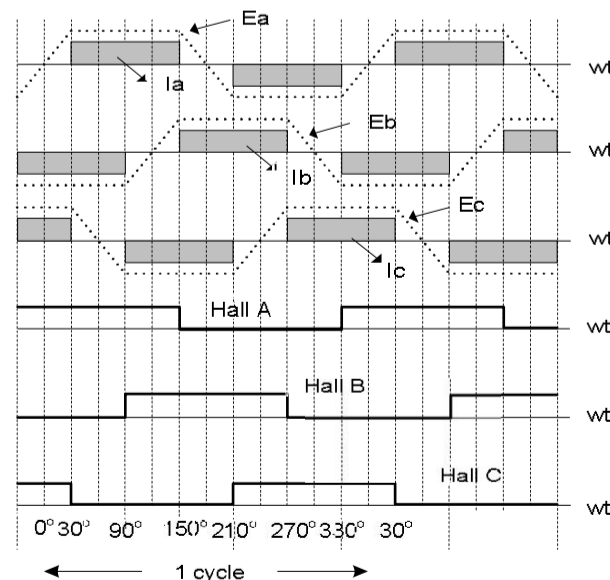Fig.3 BLDC drive system [13]

Fig.4 Back-EMFs, current and Hall position sensors waveform of BLDC motor [13]

BLDC drive produce six different pattern in one cycle. Because there are six pattern of commutation, so it called six step commutations. The signal pattern shown in Fig. 4. This figure show the waveforms of Back-EMFs (E_a, E_b, E_c), current (I_a, I_b, I_c) and Hall position sensors (Hall A, Hall B and Hall C). Back-EMFs in this figure is the trapezoidal type, other type of Back-EMFs is sinusoidal. In this figure, the first commutation occurs in 30° until 90°, the 2th in 90°

until 150°, the 3th in 150° until 210°, the 4th in 210° until 270°, the 5th in 270° until 330° and the 6th in 330° until 30° [13]. The relationship among waveform can be expressed using Table 1 [13]. In this table, Dir. is direction rotary of BLDC motor, if Dir.=1, the direction is in the right, otherwise if Dir.=0, the motor direction is Left. Together with Hall A, Hall B and HallC, the current in the motor can generate using give trigger on Q1 until Q6 ON or OFF. Logic 1 means ON and logic 0 means OFF. Using Karnaugh-Map simplification, this table produces a simple logic function in equation (6)-(11) [13].

Table 1 Relationship among direction, the position of Hall sensor and switching in the inverter

	Dir.	H_C	H_B	H_A	Q_1	Q_2	Q_3	Q_4	Q_5	Q_6
	1	1	0	1	1	0	0	0	1	0
	1	1	0	0	0	0	1	0	1	0
CW	1	1	1	0	0	0	1	1	0	0
	1	0	1	0	0	1	0	1	0	0
	1	0	1	1	0	1	0	0	0	1
	1	0	0	1	1	0	0	0	0	1
	0	0	0	1	0	0	1	1	0	0
	0	0	1	1	0	0	1	0	1	0
CCW	0	0	1	0	1	0	0	0	1	0
	0	1	1	0	1	0	0	0	0	1
	0	1	0	0	0	1	0	0	0	1
	0	1	0	1	0	1	0	1	0	0

$$Q_1 = Dir\overline{H_B}H_A + \overline{Dir}H_B\overline{H_A} \tag{6}$$

$$Q_2 = Dir\overline{H_C}H_B + \overline{Dir}H_C\overline{H_B} \tag{7}$$

$$Q_3 = Dir H_C\overline{H_A} + \overline{Dir}H_C H_A \tag{8}$$

$$Q_4 = Dir H_B\overline{H_A} + \overline{Dir}H_B H_A \tag{9}$$

$$Q_5 = Dir H_C\overline{H_B} + \overline{Dir H_C}H_B \tag{10}$$

$$Q_6 = Dir\overline{H_C}H_A + \overline{Dir}H_C\overline{H_A} \tag{11}$$

In a BLDC, there are two phases simultaneously active with square wave excitation and in the magnet distance approximately equal to the pole arc, the electric torque (T_e) is given as equation (12) [13]. Substitute equation (12) to (2), the angular speed of BLDC motor can be arranged into equation (13). If V produce from voltage supply (V_s) using PWM method with D duty cycle, the voltage (V) can calculate using equation (14) [13] and finally become equation (14).

$$T_e = N_p N_t N_{spp} P I B_r L_x R_x \tag{12}$$

$$\omega \cong k \frac{3EI}{N_p N_t N_{spp} P I B_r L R} \cong kE \cong kV \tag{13}$$

$$\omega \cong kDV_s \tag{14}$$

To improve BLDC speed in the better respond and stability, BLDC controller equipped with Proportional Integral (PI) controller. P and I Constanta can determine using various methods. Among these methods, Zieger-Nichols method is the simplest. Ziegler-Nichols method has two types, i.e. the closed loop method and open loop method. Tuning of Zieger Nichols accepted in stability region, if the ratio of the amplitudes of subsequent peaks in the same direction (A_2/A_1) is approximately 1/4. Fig.5 (a) show open loop respond of system that accepted using Zieger-Nichols tuning and Fig.5 (b) shows how to determine parameters in the Zieger-Nichols tuning. While Table 2 shows equation of constanta of PID controller using Zieger-Nichols. Using Fig.5 and Table 2, Kp, Ti and Td can calculated.
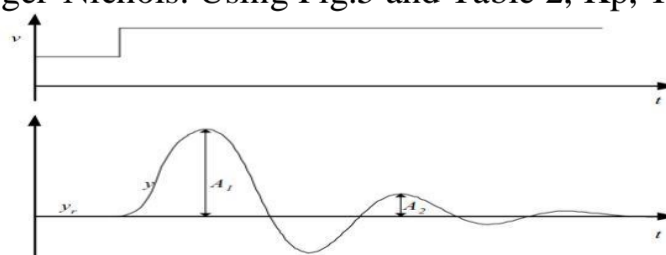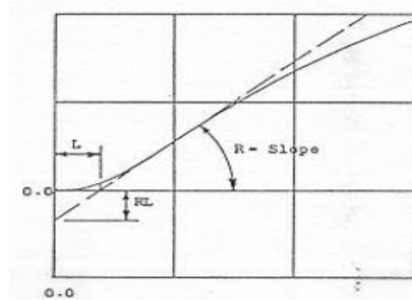

a.   Open loop respond

b.   Parameter

Fig.5 Open loop responds of system that accepted and determine of parameter using Zieger Nichols tuning

Table 2 Equation constantas of PID controller using Zieger Nichols

	K_p	T_i	T_d
P controller	$\frac{1}{LR/U}$	∞	0
PI controller	$\frac{0.9}{LR/U}$	$3.3L$	0
PID controller	$\frac{1.2}{LR/U}$	$2L$	$0.5L = \frac{T_i}{4}$

III.SIMULATION CIRCUIT

If back-EMF of BLDC assume have 120 degree phase shift with respect to each other and all phase current is equal, so based on equation (1) until (3), the state space BLDC is shown in equation (15) and (16) [12]. Implementing these state space equations will make model more complex, therefore these equation is divided to two simple models, that is electrical and mechanical model. Using Simulink Matlab these model shown in Fig.6 and Fig.7. Control unit of BLDC drive system consist of digital circuit and PWM circuit. Implementation of digital equation (6) until (11) is shown in Fig.8 [13]. While PWM circuit as result of equation (14) is shown in Fig.9. Using load of electric vehicle modeled on simulink block and inverter on Universal Bridge. Simulation model of BLDC motor for electric vehicle is shown in Fig.10.

$$\begin{bmatrix} i_a' \\ i_b' \\ \omega_m' \end{bmatrix} = \begin{bmatrix} -\frac{R}{L} & 0 & 0 \\ 0 & -\frac{R}{L} & 0 \\ 0 & 0 & -\frac{\beta}{J} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ \omega_m \end{bmatrix} + \begin{bmatrix} \frac{2}{3L} & \frac{1}{3L} & 0 \\ -\frac{1}{3L} & \frac{1}{3L} & 0 \\ 0 & 0 & \frac{1}{J} \end{bmatrix} \begin{bmatrix} V_{ab} - E_{ab} \\ V_{bc} - E_{bc} \\ T_e - T_l \end{bmatrix} \qquad (15)$$

$$\begin{bmatrix} i_a \\ i_b \\ i_c \\ \omega_m \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ -1 & -1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ \omega_m \end{bmatrix} \qquad (16)$$
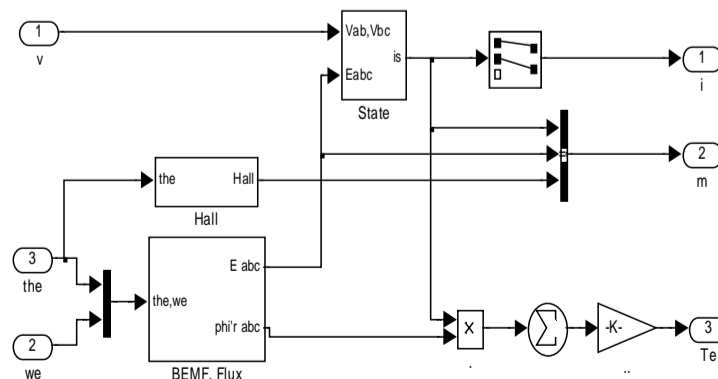

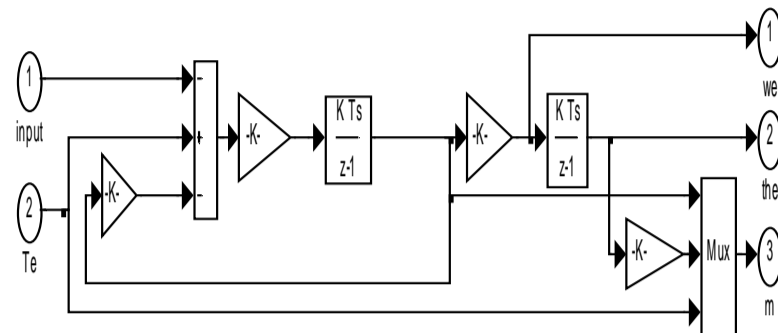Fig.6 Electrical Simulink model of BLDC
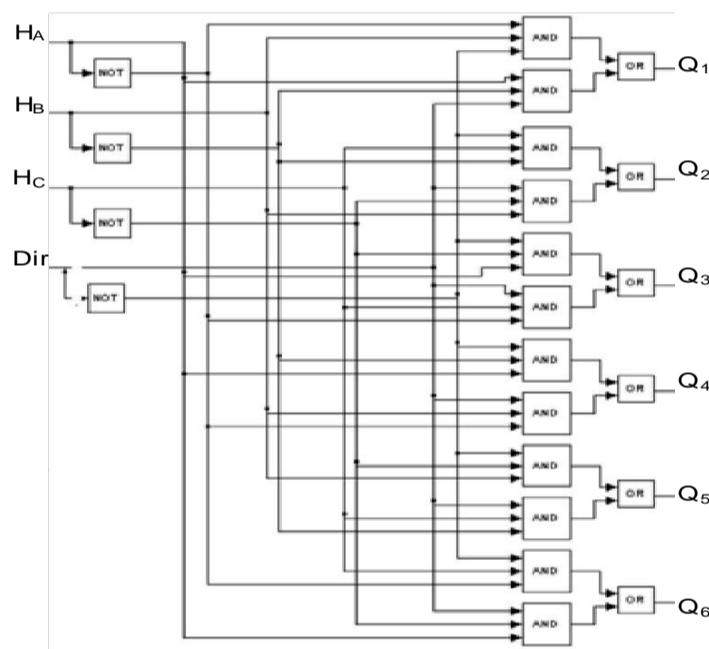
Fig.7 Mechanical Simulink model of BLDC
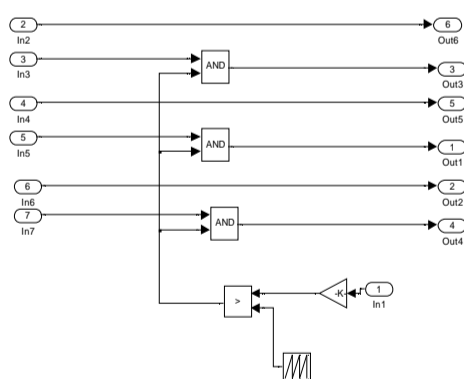

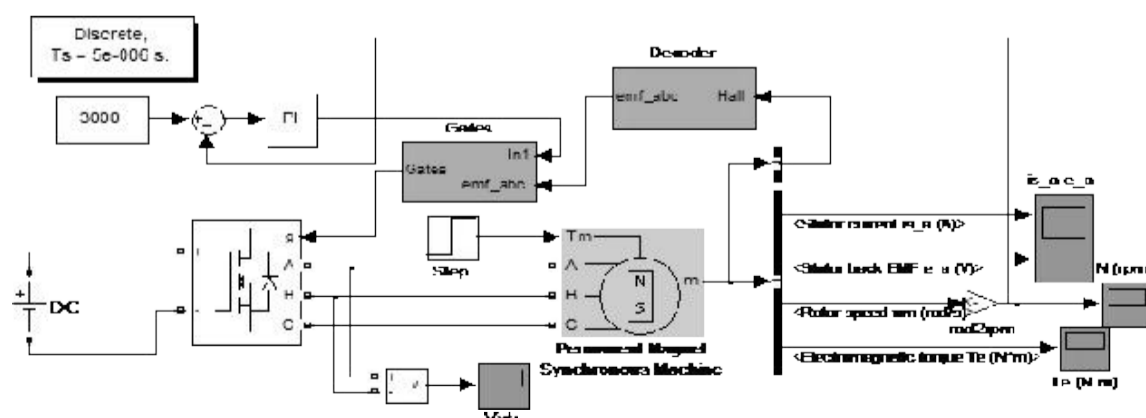Fig.8 Digital circuit model

Fig.9 PWM model

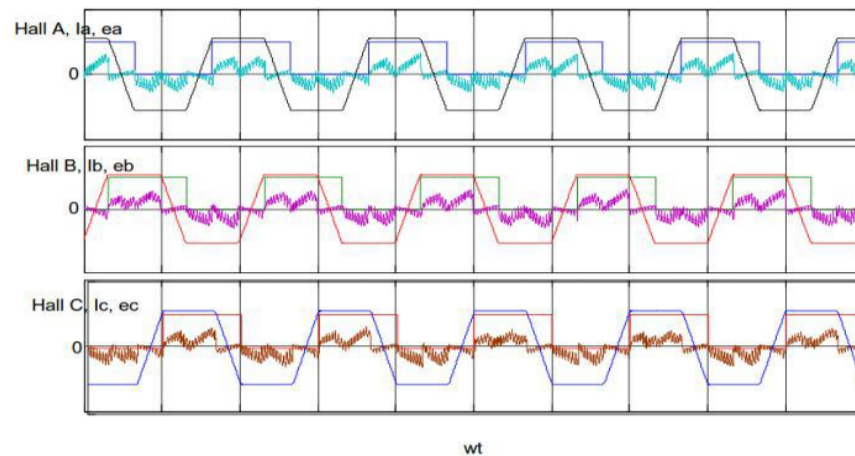Fig.10 Simulation model of BLDC motor for electric vehicle

Fig.11 Relationship among Hall signal waveform, back-EMF and BLDC motor current

IV. RESULT AND DISCUSSION

Control circuit can produce signal equal to the expectation waveform. Fig.11 show relationships among Hall signal waveform (HallA-HallC), back-EMF (ea-ec) and BLDC motor current (Ia-Ic). This relationship show that the proposed control produce correct function. In this figure, the parameter amplitudes were adjusted to give a proportional figure. Beside produce correct signal, the proposed control also produces a simple circuit. The digital circuit on Fig.8 can implement using TTL or CMOS digital IC, as example IC TTL 7408 or IC CMOS 4073 for AND gate, IC TTL 7432 or IC CMOS 4071 for OR gate.
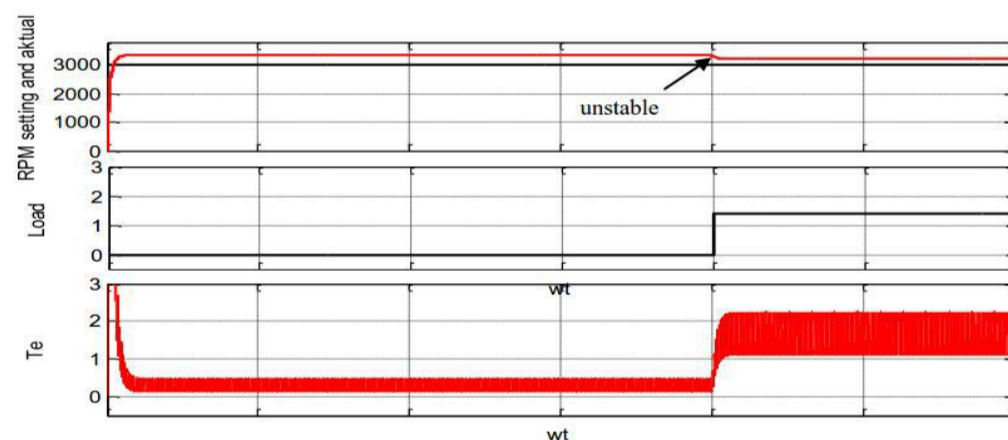

Fig. 12 Simulation result electric model without PI control

PWM circuit can implement using Opamp circuit. This circuit consists of triangle wave generator and a comparator that compare DC voltage setting and triangle signal from triangle generator. The result of this circuit is PWM signal trigger that duty cycle regulated for power electronic device in the low position. Using adjust the DC voltage setting, the current of the BLDC motor can regulated, so the motor speed can also regulated easily.
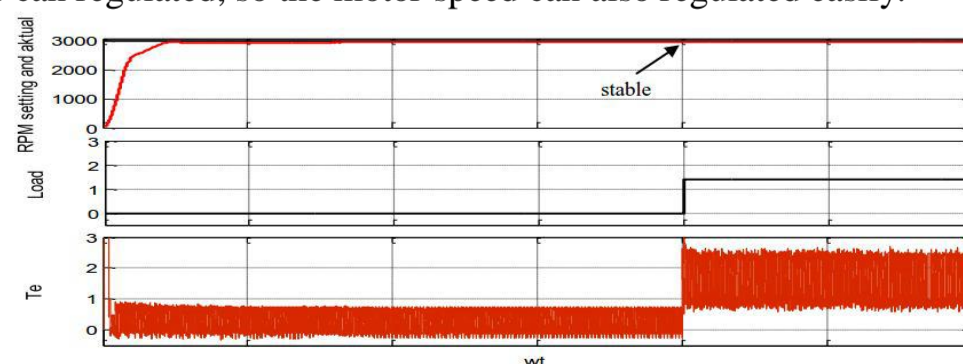

Fig.13 Simulation result electric model using PI control

Simulation using dynamic load in this electric vehicle model without PI control show that the speed of this electric vehicle is unstable as shown in Fig. 12. Unstable condition shown by arrow on this Figure. When the load changes from 0 to 1.5 N, the motor speed decrease from 3200 to 3100 RPM. If PI control added in the system, the speed of electric vehicle using the same dynamic load is stable as shown in Fig.13. Implementation of this PI control can be an Opamp circuit, where P is a voltage gain op amp and I is an Opamp integrator circuit. Gain in the P and I, must be

calculate first using Table 2. Before and after the load cahnges from 0 to 1.5 N, the speed of BLDC motor sable on setting 3000 RPM.

V.CONCLUSION

BLDC motor control for electric vehicle can design using a simple digital circuit. Using Karnaugh-Map simplification of Hall position signal and current of motor that realized on gate trigger of power semiconductor switches, this circuit easy to build and can produce control signal like other controls. To regulated speed and improve performance, a PWM and PI control added to this digital circuit. Result simulation show that this control has good performance, because in the dynamic load the speed can stable and regulated on setting point.

REFERENCES

1.   Ali Emadi, "Handbook of Automotive Power Electronics and Motor Drives", Taylor & Francis Group, CRC Press, 2005.
2.   Padmaraja Yedamale, "Brushless DC (BLDC) Motor Fundamentals", Microchip Technology Inc., 2003
3.   Sathyan, A., Milivojevic, N., Young-Joo Lee, Krishnamurthy, M.; Emadi, A., "An FPGA-Based Novel Digital PWM Control Scheme for BLDC Motor Drives", Industrial Electronics, IEEE Transactions on, Vol.: 56, Issue: 8, pp.: 3040 – 3049, 2009.
4.   Atmel Corporation, "AVR498: Sensorless control of BLDC Motors using ATtiny261/461/861-Application Note", Atmel Corporation, 2009.
5.   Bambang Sujanarko, "Brushless Direct Current (BLDC) Motor Controller Using Digital Logic For Electric Vehicle", National Conference ReTII ke-7 Tahun 2012, STTNAS Yogyakarta, 2012.
6.   Bambang Sujanarko, "Desain Kontrol PWM Pengatur Kecepatan Motor BLDC Untuk Mobil Listrik", National Conference Semantik Tahun 2013, UDINUS Semarang, 2013.
7.   Padmaraja Yedamale, "AN885 Brushless DC (BLDC) Motor Fundamentals- Application Notes", Microchip Technology, 2003.
8.   The MathWorks, "Matlab Guide", MathWorks, Inc., 2013.
9.   Loeb, M.L., Rindos, A.J., Holland, W.G., Woolet, S.P., "Gigabit Ethernet PCI adapter performance", Network, IEEE, Vol. 15, Issue: 2, pp. 42 – 47, 2001.
10.   Advantech, "PCI-1711/L Entry-level 100 kS/s, 12-bit, 16-ch PCI Multifunction Card", Advantech.
11.   Krishnan. Rramu, "Electric motor drive: modeling. Analysis and control", Prince Hall. Inc., 2001
12.   Bhim Singh   and Sanjeev Singh , "State of the Art on Permanent Magnet Brushless DC Motor Drives", Journal of Power Electronics, Vol. 9, No. 1, 2009
13.   Bambang Sujanarko, Bambang Sri Kaloko, Moch. Hasan, "BLDC Motor Control Using Simulink Matlab and PCI", International Review of Modeling and Simulations (IREMOS), Vol. 6, n. 6, December, 2013
14.   Ogata, Katsuhiko,"Teknik Kontrol Otomatik, Jilid 2", Jakarta : Erlangga, 1997.

Dr. Sarvepalli Radhakrishnan (1888-1975), former President of India, was one of the most erudite of Hindu scholars of all times. He was at once a philosopher, author, statesman and educationalist and India celebrates his birthday - the 5th of September - as "Teacher's Day" every year.