

Sensorless speed control current for a Brushless DC motor

Luis G. González García and Domingo Cortés

ESIME Culhuacan, National Institute Polytechnic, Mexico.
luisesame@hotmail.com, domingo.cortes@gmail.com

Abstract. This paper presents a controller for the speed of a Brushless DC motor (BLDC). The control strategy does not require to measure the phase currents neither the back-electromotive forces. The strategy is based on connecting and disconnecting the power supply that feed the motor inverter. By manipulating on-time of the power supply the average current of the motor windings are indirectly modified. In this way the desired speed is achieved requiring only to measure the rotor speed. The rotor speed can be estimated using the position sensors that are normally included with brushless motor. Hence the controller proposed does not need other sensors than that are already included with the motor. The obtained results show that the proposed control achieves tracking of speed references and is robust to load changes.

1 Introduction

Brushless DC Motors (BLDC) have very useful properties such as a high torque per unit volume, are highly efficient, maintenance free and can be manufactured in a wide variety of sizes and power. Due to these advantages BLDC's are used in a wide range of industrial applications, such as computer systems, automotive, aerospace, etc. However, control of these motors are more complicated than a conventional DC motor.

The three phase BLDC are most common between applications; a wide variety of drivers have been proposed for this kind of motors ranging from relatively some simple to highly complex. Most of these drivers need to measure current in each phase or to measure the Back-electromotive force (Bemf) [1], [2], [3], [4], [5], [6]. This involves using several sensors which in some cases may become costly.

In [7], [8], [9] aims to control the speed of the BLDC by sliding mode control. This strategy is efficient but complex at the same time as it requires knowledge currents or Bemf. Another way to control the speed BLDC is using hall effect sensors of position. These sensors indicate rotor position, that information is used by an algorithm that determines the time logical operation of the inverter circuit that feeds the BLDC. With this, only controls the duty cycle of switches [10], [11]. Recently, there have been methods to vary the speed rotor with the output a DC-DC converter or AC-DC used to power the three-phase inverter.

This achieves the supply voltage inverter, namely, increases or decreases the voltage supply BLDC windings[12], [13], [14], [15] and [16].

In this paper a new control strategy for BLDC motor is presented, this strategy needs not to measure current or B_{emf} . The controller here proposed is based on the direct connection and disconnection of the power supply. This eliminates the need for a DC-DC converter or AC-DC to power the inverter. By eliminating the control sensors complexity, cost and size of the controller decreases.

2 The brushless DC motor

2.1 Functioning description

Contrary to the conventional DC motor where the stator generates a permanent field and the rotor has a variable field, in BLDC motor the rotor field is permanent while the stator must generate a variable field. This eliminates the need brushes to bring power to the rotor but complicates the field that should generate in the stator. To generate the variable field in the stator, BLDC motor is fed by square waves, supplied by a three phase inverter. The switching signals of the switches are subject to the position of the rotor.

In Figure 1 shows that the activation sequence is each of the motor windings. The conventional configuration inverter-motor assembly to achieve this sequence BLDC activation is shown in figure 2. The manner in which the switches for feeding circuit to the BLDC are turned on and off are shown in Table 1. Note that an important condition, for correct operation of BLDC is feeding only two windings at the same time by every step of switching.

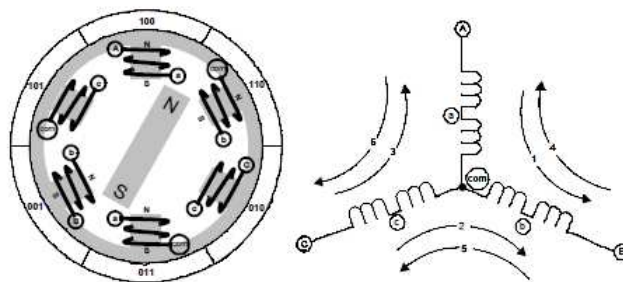


Fig. 1. Switching Sequence

In many applications, the desired motor behavior is to keep the motor at the same speed, despite changes in load. Generally, this goal has to be achieved with a control fast, efficient, robust and simple.

Most control strategies speed for BLDC motors require measurement of Back-electromotive force (B_{emf}) in each phase of the motor or its respective currents.

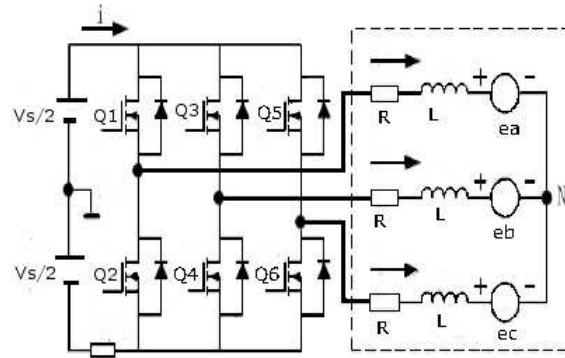


Fig. 2. BLDC conventional configuration

Table 1. Signals from the Hall effect sensor

Degree	H1	H2	H3	Switches
$0^\circ - 60^\circ$	1	1	0	Q1 Q4
$60^\circ - 120^\circ$	2	1	1	Q1 Q6
$120^\circ - 180^\circ$	3	0	1	Q3 Q6
$180^\circ - 240^\circ$	4	0	1	Q3 Q2
$240^\circ - 300^\circ$	5	0	0	Q5 Q2
$300^\circ - 360^\circ$	6	1	0	Q5 Q4

In figure 3 shows a general schematic of these strategies. Under this scheme, the processing currents or Back-electromotive forces to determine the on or off of the transistors is typically complex.

2.2 Mathematical model

The mathematical model of BLDC motor is given by two parts: one electric and one mechanical. In this paper, to simplify the simulation model of BLDC the following considerations are made:

- The three phases of the stator are symmetrical.
- The magnetic circuits which are generated in the BLDC interior are ignored.
- The switches are ideal.
- Parasitic elements losses are ignored.

Voltage equation: Equations voltage of the three phase BLDC are obtained from the electrical diagram shown in figure 4. They can be expressed as:

$$V_a = R_a i_a + L_a \frac{di_a}{dt} + e_a \quad (1)$$

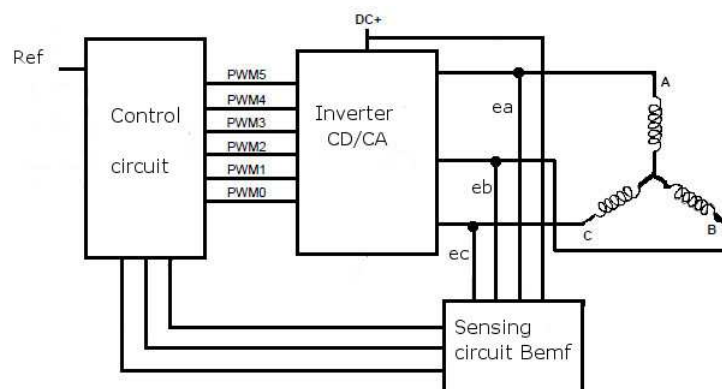


Fig. 3. Control by electromotive force

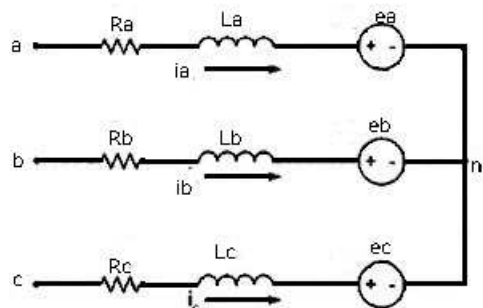


Fig. 4. Electrical Schematic of BLDC Motor

$$V_b = R_b i_b + L_b \frac{di_b}{dt} + e_b \quad (2)$$

$$V_c = R_c i_c + L_c \frac{di_c}{dt} + e_c \quad (3)$$

where: V_a, V_b, V_c are the voltages of the stator windings; e_a, e_b, e_c are back-electromotive force of each phase; i_a, i_b, i_c are the currents of the stator, L_a, L_b, L_c are the inductance of each stator coil; R_a, R_b, R_c are the resistance of each coil in the stator. For simplification, assume that $R_a = R_b = R_c = R$, inductance $L_a = L_b = L_c = L$, and each phase is separated 120° obtaining the ideal form of the Bmf(e_a, e_b, e_c).

Electric torque: The BLDC motor electrical torque is generated by the interaction of the currents in the stator and magnetic fields of the rotor magnets. Equation of electric torque can be expressed as:

$$T_e = e_a i_a + e_b i_b + e_c i_c \quad (4)$$

Mechanical torque: On the other hand, the equation of mechanical torque can be expressed as:

$$T_e = B\omega + J \frac{d\omega}{dt} + T_L \quad (5)$$

where: T_e is the mechanical torque, T_L is the load torque, B is the damping coefficient; ω is the angular velocity the rotor, J is the moment of inertia. Note that knowledge of the mechanical torque implies the speed of the rotor. this is measured by an optical encoder installed on the same rotor, such device is capable of measure revolutions per minute.

3 Description of the proposed control strategy

The scheme of the proposed control strategy is shown in Figure 5. The main idea is to connect or disconnect the inverter power supply depending on the sign of the speed error. That is

$$V_a = V_b = V_c = uV_s \quad (6)$$

where

$$u = \begin{cases} 0 & \text{if } \sigma(x, t) < 0 \\ 1 & \text{if } \sigma(x, t) > 0 \end{cases} \quad (7)$$

and

$$\sigma = \omega_{ref} - \omega \quad (8)$$

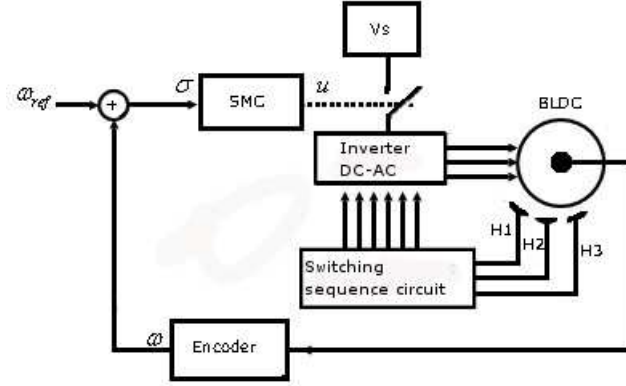


Fig. 5. Proposed topology

Note that the controller given by (6-8) is an sliding mode control (SMC) with one simple sliding surface consisting of the error between instantaneous velocity at the rotor (ω) and a speed of reference (ω_{ref}).

The control proposed causes that power supply that feed the inverter (V_s) to be connected or disconnected depending on the speed error. In this way the average of line voltages changes according to the speed error. This in turn modifies the winding currents causing that the speed be adjusted.

Is important to point out that this control strategy modifies the winding currents without requiring a complex algorithm to control the on-off instants of the switches inverter. Instead, the switches inverter states, just depend on the rotor position. Hence, the simple logic shown in the Table 1 is only necessary to control the inverter switches. Note that in the controller proposed the hall effects sensors play two roles: to control the inverter switches and to measure the rotor speed. These sensors are usually considered as part of the motor, hence it can be considered that this control strategy is sensorless.

Let us to show that the speed rotor does indeed depend on V_s . Rewriting(5), it can be expressed as an equation of angular velocity:

$$\frac{d\omega}{dt} = T_e - B\omega - T_L \quad (9)$$

Substituting (4) into (9) yields an expression of the speed in terms of currents,

$$\frac{d\omega}{dt} = (k_t (i_a + i_b + i_c)) - B\omega - T_L \quad (10)$$

To visualize how the speed can be a function of line voltages, the winding current i_a , i_b and i_c are replaced for each phase, namely (1), (2) and (3) are replaced in (10) obtaining

$$\frac{d\omega}{dt} = k_t \left[\frac{V_a}{R} - \frac{L}{R} \frac{di_a}{dt} - \frac{e_a}{R} \right] + k_t \left[\frac{V_b}{R} - \frac{L}{R} \frac{di_b}{dt} - \frac{e_b}{R} \right] + k_t \left[\frac{V_c}{R} - \frac{L}{R} \frac{di_c}{dt} - \frac{e_c}{R} \right] - B\omega - T_L \quad (11)$$

From (11) it can be seen that the instantaneous speed depends of input voltages, as well as Back-electromotive forces and winding currents. Furthermore, substituting (6) in (1), (2) and (3) yields

$$uV_s = R_a i_a + L \frac{di_a}{dt} + e_a \quad (12)$$

$$uV_s = R_b i_b + L \frac{di_b}{dt} + e_b \quad (13)$$

$$uV_s = R_c i_c + L \frac{di_c}{dt} + e_c \quad (14)$$

To show that the winding currents does depends on the control signal u let rewrite (12-14) as

$$\frac{di_a}{dt} = \frac{1}{L} (-R_a i_a + uV_s - e_a) \quad (15)$$

$$\frac{di_b}{dt} = \frac{1}{L} (-R_b i_b + uV_s - e_b) \quad (16)$$

$$\frac{di_c}{dt} = \frac{1}{L} (-R_c i_c + uV_s - e_c) \quad (17)$$

Since the control variable u can have two values it can be considered the following cases:

1. When the rotor speed is above the control reference ($\sigma > 0$) then $u = 0$ therefore 15 can be expressed as

$$\frac{di_a}{dt} = \frac{1}{L} (-R_i i_a - e_a) \quad (18)$$

From (18) it can be seen that when the inverter supply voltage becomes zero, at some point the winding current tends to decrease, for this reason the rotor speed will be affected by reducing the back emf.

2. When the rotor speed is below the control reference ($\sigma < 0$) then $u = 1$, therefore

$$\frac{di_a}{dt} = \frac{1}{L} (-R_i i_a + V_s - e_a) \quad (19)$$

From (18) and (19) can be seen independent switching of the inverter switches. To only connected and disconnected the inverter supply voltage.

4 Simulation results

The results presented were obtained with the software MatLab/Simulink and with the values of EU-437255326 BLDC motor, that are shown in Table 2. The motor is used in testing of speed control for applications automotive. The Rated speed of this motor is 2820rpm. However, with minimum load (0.02 Nm) can reach up 3000 rpm. The rated torque of the motor is about 2.92 Nm, this is the torque was used in the simulations to change from minimum to maximum torque in the moment 0.07 s.

Figure 6 shows the rotor speed (in revolutions per minute, rpm) controlled with the proposed strategy. The reference speed was 1500 rpm, it can be seen from the figure that rotor speed tends to the reference value. The figure also shows the reference and the following control by a time less than 50ms. At 0.1s there is a change in the reference speed from 1500 to 2000 rpm. It can be seen the control adjusts the rotor speed to follow a the new reference value. The control signal (u) directly affects voltage. The supply voltage has a connection time dependents the sliding surface proposal (σ) for speed control.

Table 2. Motor Parameters EU-437255326

Parameter	Units	Value
Supply voltage	volts DC	50
Rated Speed	rpm	2820
Rated torque	Nm	2.92
Rated current	Amps	20.2
Rated power	Watts	861
Torque constant	Nm/amps	0.164
Back-emf	volts/krpm	17.1
Winding resistance	ohms	0.106
Inductance coil	mH	0.428
Motor constant	Nm/sqrtwatt	0.516
Rotor inertia	g-cm ²	4943
Number of poles		4

Figure 7 shows the behavior in the supply voltage of the motor, the connection and disconnection was observed of the inverter supply voltage.

The motor must have the same speed in the rotor, despite the change of minimum to maximum torque on the motor. In the simulation, the figure 8 shows this change into the 0.07s time, from the minimum to maximum torque. In the same figure, it can be seen the robustness of the control to maintain the reference speed rotor despite the change in the torque required. Note that the signal control u is adjusted from the change caused by the load.

Figure 9 shows the change in the reference in the instant 0.1s to 2000 rpm. Even with the maximum torque, the proposed control adjusts the connection time of the inverter supply voltage to stabilize the rotor speed and can be fol-

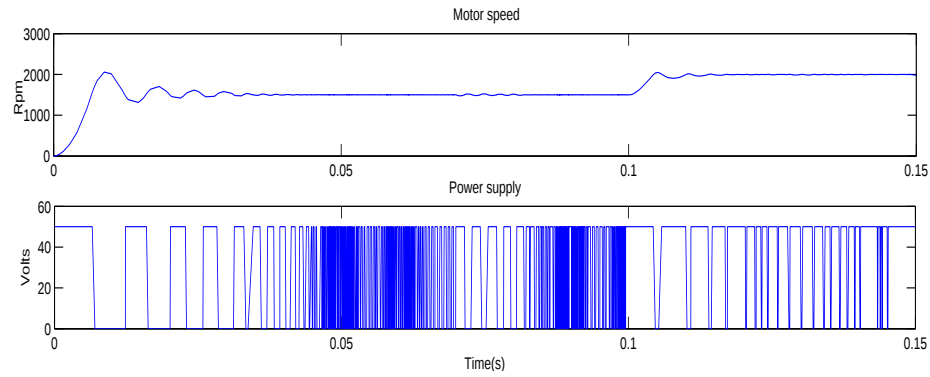


Fig. 6. Rotor speed and supply voltage V_s

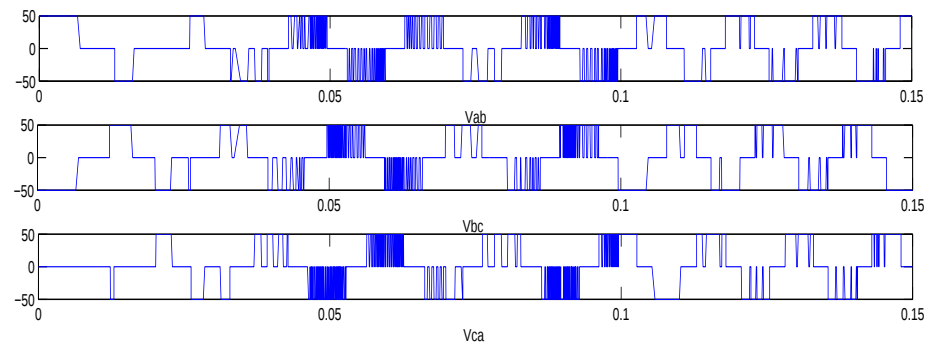


Fig. 7. Line voltages V_{ab} , V_{bc} , V_{ca}

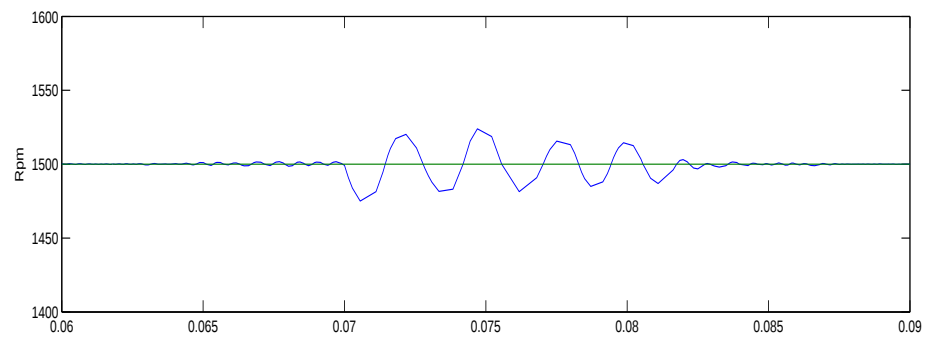


Fig. 8. Disturbance load change in 0.07s

lowing the new reference. This shows that the proposed control to the BLDC speed is robust. Note that the response time is small.

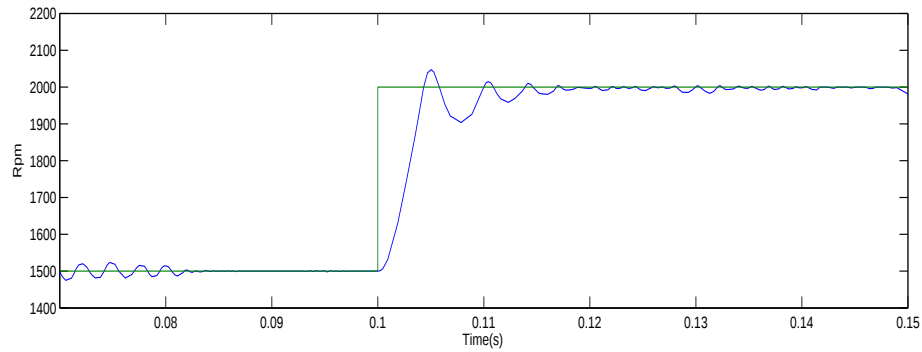


Fig. 9. Maximum torque with speed change in 0.1s

The Figure 10 shows the winding currents in each phase of the BLDC motor. The torque change and the reference change can be seen respectively.

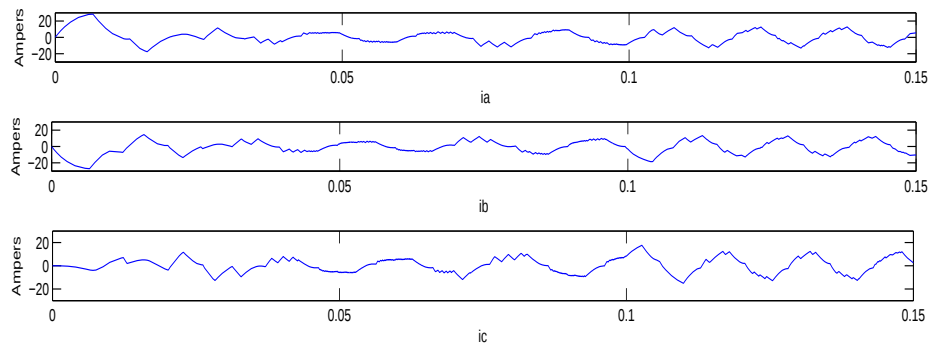


Fig. 10. Currents i_a , i_b and i_c

The shape of the Bemsf signals is shown in figure 11, it has the ideal shape of a BLDC motor type trapezoidal. The Bemsf are used in other ways to control the rotor speed, with using special circuits for the detection thereof.

In Figure 12 shows the behavior of the winding current in phase a (i_a) and e_a Bemsf. When the reference and torque changed is observed in the same figure.

In simulation at full speed with full torque supporting the motor, the results obtained in figure 13. In this figure there are some pulses must have to

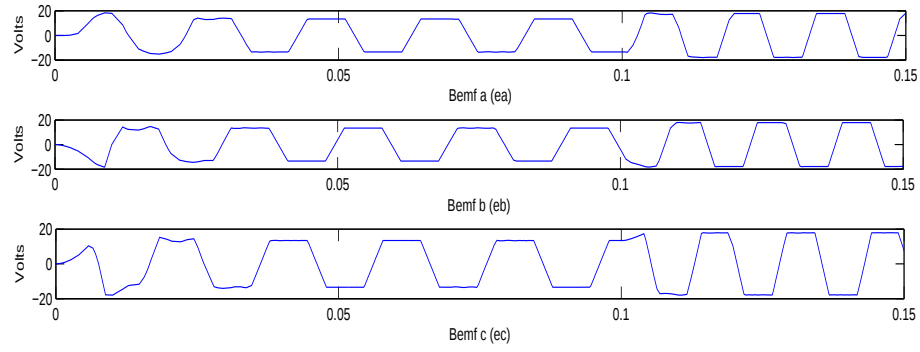


Fig. 11. Back electromotive force per phase e_a , e_b y e_c

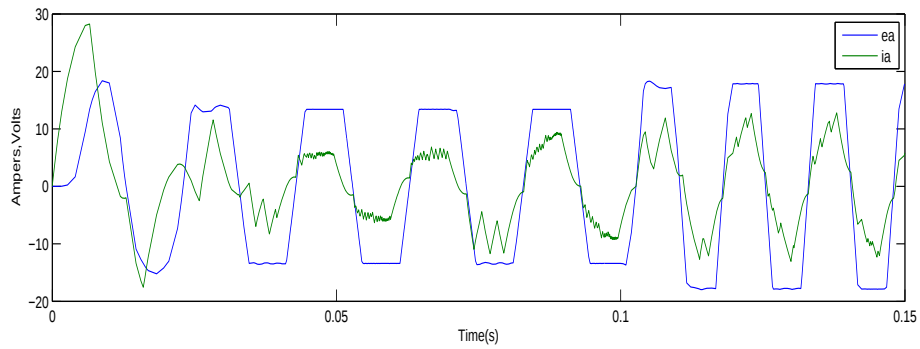


Fig. 12. Current i_a and Bemf e_a

decrease. Consider adding a PI term (Proportional Integral controller) in the sliding surface proposed in this paper will improve results.

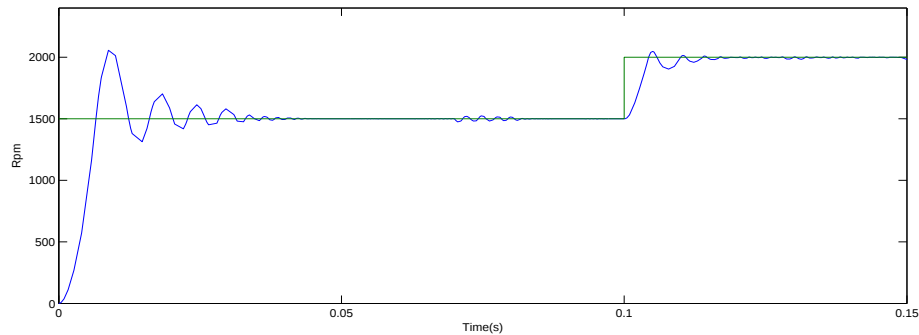


Fig. 13. BLDC speed

5 Conclusions

The technique developed in this paper shows that it is possible to have a control for BLDC speed without measuring the current or Back-electromotive forces of each motor phase. The method relies on the use of a sliding surface that depends on the rotor speed error. This error is used to connect or disconnect the inverter power supply. In this way an indirect control of the winding currents is achieved. The resulting system only needs a sensor that is included in the motor already and only modifies a single variable: the inverter power supply. The complete scheme results simple to implement, sensorless and simple electronics. A practical implementation of the strategy is being developed to corroborate the simulation results presented.

References

1. Tzuen-Lih Chern, Ping-Lung Pan, Yu-Lun Chern, and Der-Min Tsay, "Sensorless Speed Control of BLDC Motor Using Six Step Square Wave and Rotor Position Detection," *Industrial Electronics and Applications (ICIEA)*, 2010 the 5th IEEE Conference on, pp.1358 - 1362, 15-17 June 2010.
2. Ming Lu; Yaohua Li, "New Design for Sensorless BLDC Motor Using Half-Bridge Driver Circuit", *E-Product E-Service and E-Entertainment (ICEEE)*, 2010 International Conference on, pp. 1-4.
3. Concarì, C.; Troni, F., "Sensorless control of BLDC motors at low speed based on differential BEMF measurement", *Energy Conversion Congress and Exposition (ECCE)*, 2010 IEEE, pp. 1772 - 1777.

4. Joon Sung Park; Jun-Hyuk Choi; Bon-Gwan Gu; In-Soung Jung, "BLDC drive control of electric water pump for automotive application", Vehicle Power and Propulsion Conference (VPPC), 2010 IEEE , pp. 1-5.
5. Jezernik, K.; Horvat, R., "Predictive VSS switching control of a three-phase inverter", Predictive Control of Electrical Drives and Power Electronics (PRECEDE), 2011 Workshop on , pp. 40-46.
6. Jin-soek Jang; Byung-taek Kim , "Minimization of par ripple in a BLDC motor using an improved DC link voltage control method", Telecommunications Energy Conference, 2009. INTELEC 2009. 31st International , pp. 1-5.
7. Yan Xiaojuan; Liu Jinglin , "A novel sliding mode control for BLDC motor network control system ", Advanced Computer Theory and Engineering (ICACTE), 2010 3rd International Conference on , vol. 2, pp. 289-293.
8. Jonghyun Jeon; Sanggun Na; Hoon Heo , "Cascade Sliding Mode — New Robust PID contro for BLDC motor of In-wheel system ", Environment and Electrical Engineering (EEEIC), 2011 10th International Conference on ,pp. 1- 4.
9. Rath, Jagat Jyoti; Saha, Suman; Ikkurti, Hanumath Prasad , "Sliding mode scheme for speed and current control of brushless DC (BLDC) motor " ,Advances in Engineering, Science and Management (ICAESM), 2012 International Conference on , pp. 450 - 455 .
10. Duma, R.; Dobra, P.; Dobra, M.; Sita, I.V. , "Low cost embedded solution for BLDC motor control ",System Theory, Control, and Computing (ICSTCC), 2011 15th International Conference on , pp. 1-6.
11. Lee, B.K.; Kim, T.H.; Ehsani, M. , "On the feasibility of four-switch three-phase BLDC motor drives for low cost commercial applications: topology and control ",Applied Power Electronics Conference and Exposition, 2001. APEC 2001. Sixteenth Annual IEEE , pp. 428 - 433 vol.1.
12. Khopkar, R.; Madmi, S.M.; Hajiaghajani, M.; Tohya, H.A. "A low-cost BLDC motor drive using buck-boost converter for residential and commercial applications " ,Electric Machines and Drives Conference, 2003. IEMDC'03. IEEE International . vol. 2, 2003 , pp. 1251 - 1257 vol.2
13. Kumar, A.A.; Dahake, H.; Bhattacharya, N.; Singh, D. , "Solar Power Based Impedance - Source Converter for BLDC Motor with Closed Loop Control ",Process Automation, Control and Computing (PACC), 2011 International Conference on , pp. 1-6.
14. Karthikeyan, J.; Sekaran, R.D., "DC-DC converter CSI fed BLDC motor for defence applications ",Recent Advancements in Electrical, Electronics and Control Engineering (ICONRAEECE), 2011 International Conference on , pp. 68-72.
15. Xiaofeng, Zhang; Lu Zhengyu, "A New BLDC Motor Drives Method Based on BUCK Converter for par Ripple Reduction",Power Electronics and Motion Control Conference, 2006. IPEMC 2006. CES/IEEE 5th International , pp. 1-4, .
16. Maharajan, M.P.; Muthu, P.; Palpandian, M.; Kannadasan, S. , "Analysis of low harmonics and high efficient BLDC motor drive system for automotive application " ,Recent Advancements in Electrical, Electronics and Control Engineering (ICONRAEECE), 2011 International Conference on , pp. 526-531.