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Using DTC Method to Reduce Torque Ripple in BLDC Sensorless Motors

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ABSTRACT

In this paper to estimate the rotor position in sensorless BLDC motor drive, the method of the ratio functions line by line flux is used. This method, compared to other methods which are evaluated to estimate the rotor position, has low software and hardware volume and therefore, its implementation is easy and also manufacturing cost is less. Also this method has an appropriate efficiency in a wide range of speed and estimate the rotor position is independent of speed and rotor frequency. Also in this paper, Direct Torque Control (DTC) method is used to design sensorless BLDC motor drive. DTC is one of the most innovative and efficient methods in control of the electrical machine. High speed in response to changes in torque, simplicity of implementation, independence to machine parameters and needs of less computation are the advantages of this method. At the end of this paper, simulation results by using software MATLB shows good function of sensorless BLDC motors with DTC method.
KEYWORDS: Sensorless, BLDC motor, DTC method, torque.

1. 1 INTRODUCTION

Using of DC motors has high propagation in industry because of the salient features such as, extensive control of speed, high efficiency and so on. The only disadvantage of this motor is its need of the commutator and the brushes, because these components are constantly being eroded and therefore they increase the needs of motor to service and maintenance. In order to escape from the problems with the help of the magnetic field property, control of DC motors is electrical. These types of motors are called Brushless DC Motor (BLDC) [1].

For BLDC motors, generally hall sensors are used to determine the angular position of the rotor [2]. Using electro mechanical sensors not only increases the cost and complexity of hardware drive, it will also decrease the stability and reliability. Dirty working conditions, temperature and existence of high mechanical vibrations due to the sensitivity of the position sensors, can cause many problems. So it is not recommended to use the mechanical position sensors in applications of space, limited and inaccessibility, and finished price are important and or the high capability of the system reliability is considered. So a lot research has been done for sensorless drives to be able to position, speed and torque without using position sensors mounted on the rotor shaft [3, 4]. Conventional methods of sensorless control are classified into five categories.

The first method, is based on back-emf [5]. Reducing the range of back-emf at low speeds and the problems associated with its measurement, the existence of voltage noise and measurement errors and poor performance of this method at low speeds is among the disadvantages of this method. The second method, is a method of estimating stator leakage flux [6]. Creating errors of integration at low speeds, high computational volume and being sensitive to changes of motors parameters is among the disadvantages of this method. The third method is to use a variation of the stator inductance [7]. This poor performance at low speeds and high volume of hardware and software that increase the price of motors, is disadvantage of this method. The fourth method, is methods which are based on control theory [8]. This method is not efficient in noisy feedback signals and also at low speeds will have many errors.

To solve problems of these methods, in this paper to estimate the rotor position of sensorless BLDC motor drive, the method of using functions of the line by line flux which is the same method of using suitable functions of back-emf, is used. This method compared to other methods, has low hardware and software volume and therefore, its implementation is easy and cost less. It also has an appropriate efficiency in a wide range of speeds and estimate of the rotor position is independent of the rotor speed and frequency, therefore, has not the existing problems in back-emf measurement methods such as frequency dependence and motors speed and measurement problems and filtering [9, 10]. Modeling

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Motor and drive based on DTC, is the most effective modeling of BLDC motor drive which can be used for various reasons. DTC method due to its simplicity and high-speed in response to changes in the torque reference, is considered one of the most efficient control techniques of electrical machine, which can be used for control types electric machines.

In this paper, we have tried to evaluate the performance and also simulated DTC control method. High speed in response to changes in torque, implementation simplicity, lack of dependence on machine parameters and need of low computation is another advantage of this method [11-14]. For BLDC motor trapezoidal wave form of back-emf is used in order to minimize the torque ripple and to maximize productivity and torque capability. The results of BLDC motor simulation by MATLAB software shows the simplicity and good performance of this method in control of the motor.

2-sensorless control method to estimate the rotor position

In this paper to estimate the rotor position of sensorless BLDC motor drive the method of functions of line by line flux is used. Phase-to-neutral voltages equation is achieved as in equation (1).

$$\begin{aligned}
V_a &= Ri_a + L\frac{di_a}{dt} + \frac{d\lambda_{ar}}{dt} = Ri_a + L\frac{di_a}{dt} + \frac{d(k_e f_{ar}(\theta))}{dt} = Ri_a + L\frac{di_a}{dt} + k_e.\frac{d\theta}{dt}.\frac{d(f_{ar}(\theta))}{d\theta} \\
V_b &= Ri_b + L\frac{di_b}{dt} + \frac{d\lambda_{br}}{dt} = Ri_b + L\frac{di_b}{dt} + \frac{d(k_e f_{br}(\theta))}{dt} = Ri_b + L\frac{di_b}{dt} + k_e.\frac{d\theta}{dt}.\frac{d(f_{br}(\theta))}{d\theta} \\
V_c &= Ri_c + L\frac{di_c}{dt} + \frac{d\lambda_{cr}}{dt} = Ri_c + L\frac{di_c}{dt} + \frac{d(k_e f_{cr}(\theta))}{dt} = Ri_c + L\frac{di_c}{dt} + k_e.\frac{d\theta}{dt}.\frac{d(f_{cr}(\theta))}{d\theta}
\end{aligned} \tag{1}$$

In the above equation, k_e is called coefficient back-emf. In equation (1), λ_{ar} is consists of a fixed amount plus a periodic function of rotor position (θ). $f_{ar}(\theta)$ function is the flux leakage of phase-a which are changed with rotor position. Most manufacturers of BLDC motors, don't put the star connection rotor in disposal of the user, Therefore, the equation of line by line voltage V_{ab} by using equation (1), is obtained as follows.

$$V_{ab} = R(i_a - i_b) + L\frac{d(i_a - i_b)}{dt} + k_e.\omega.\frac{df_{abr}(\theta)}{d\theta} \tag{2}$$

In relation (2), ω and $f_{abr}(\theta)$, are respectively, rotor speed and function of line by line flux. We define a new function as equation (3).

$$H(\theta)_{ab} = \frac{df_{abr}(\theta)}{d\theta} = \frac{1}{\omega.k_e}\left[(V_a - V_b) - R(i_a - i_b) - L\left(\frac{di_a}{dt} - \frac{di_b}{dt}\right)\right] \tag{3}$$

In equation (3), $H_{ab}(\theta)$ has changed with rotor position and it is used for the estimation of the rotor position. To delete speed ω in equation (3), we can use two function of line by line $H_{xy}(\theta)$ and achieve new equation (4).

$$G_2(\theta) = \frac{H(\theta)_{bc}}{H(\theta)_{ab}} = G(\theta)_{bc/ab} = \frac{\left[(V_b - V_c) - R(i_b - i_c) - L\left(\frac{di_b}{dt} - \frac{di_c}{dt}\right)\right]}{\left[(V_a - V_b) - R(i_a - i_b) - L\left(\frac{di_a}{dt} - \frac{di_b}{dt}\right)\right]} \tag{4}$$

Function $H(\theta)_{bc}$ and $H(\theta)_{ca}$ are obtained just like equation (4). Figure 1 displays the changes of the functions $G_1(\theta)$, $G_2(\theta)$ and $G_3(\theta)$ according to rotor angular position. According to this figure, the time of commutation are based on the points which these functions include the maximum of range. To estimate the rotor position and determination of commutation points can use $G_1(\theta)$, $G_2(\theta)$ and $G_3(\theta)$ functions alternatively.

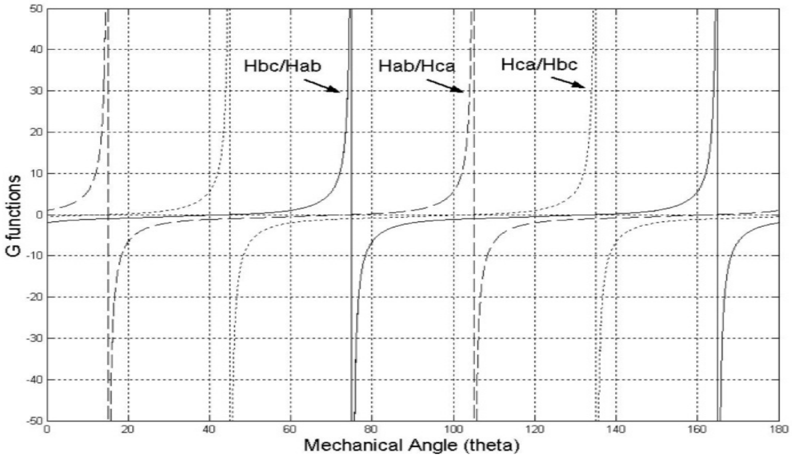


Figure 1. *Changes of $G_i(\theta)$ functions according to the rotor angular position*

Also table 1 listed the respective of G(θ) used functions in the different operating range of 60 degrees. With combine of respective of these functions we can obtain a continuous and unit G(θ) and it can be used to estimate the commutation points.

Table 1. *Used G(θ) functions in each operating mode BLDC Motor*

Functions	Operating range	Mode
$G_1(\theta)$	0<θ< π/6 and 11π/12<θ<2π	1 and 4
	5π/6<θ<7π/6	
$G_2(\theta)$	π/6<θ<π/2	2 and 5
	7π/6<θ<9π/6	
$G_3(\theta)$	π/2<θ<5π/6	3 and 6
	9π/12<θ<11π/6	

3- Direct Torque Control (DTC) method

The electromagnetic torque of a permanent-magnet brushless machine in the synchronously rotating–reference frame can be expressed as follows [11].

$$T_e = \frac{3}{2}\frac{P}{2}[(\frac{d\lambda_{rd}}{d\theta_e} - \lambda_{rq})I_{sd} + (\frac{d\lambda_{rq}}{d\theta_e} + \lambda_{rd})I_{sq} + (L_{d0} - L_{q0})I_{sd}I_{sq}] \quad (5)$$

$$\lambda_{sd} = \lambda_{rd} + L_d I_{sd} \quad , \quad \lambda_{sq} = \lambda_{rq} + L_q I_{sq} \quad (6)$$

Torque pulsations are associated mainly with the flux harmonics, the influence of higher order harmonics in the stator winding inductance usually being negligible. Therefore the electromagnetic torque can be expressed as follows.

$$T_e = \frac{3}{2}\frac{P}{2}[(\frac{d\lambda_{rd}}{d\theta_e} - \lambda_{sd})I_{sd} + (\frac{d\lambda_{rq}}{d\theta_e} + \lambda_{sd})I_{sq} + (L_{d0} - L_{q0})I_{sd}I_{sq} \quad (7)$$

The electromagnetic torque equation, for BLDC motor, with either a nonsalient-or salient-pole rotor, can then be simplified as follows.

$$T_e = \frac{3}{2}\frac{P}{2}(\lambda_{sd}I_{sq} - \lambda_{sq}I_{sd}) \quad (8)$$

or, in the stationary–reference frame, as:

$$T_e = \frac{3}{2}\frac{P}{2}(\lambda_{s\alpha}I_{s\beta} - \lambda_{s\beta}I_{s\alpha}) \quad (9)$$

Where $I_{s\alpha}$, $I_{s\beta}$, $\lambda_{s\alpha}$, and $\lambda_{s\beta}$ are the α and β axes stator currents and flux linkages, respectively, viz.

$$\lambda_{s\alpha} = \lambda_{sd}Cos\theta_e - \lambda_{sq}Sin\theta_e \quad , \quad \lambda_{s\beta} = \lambda_{sd}Sin\theta_e + \lambda_{sq}Cos\theta_e \quad (10)$$

$$I_{s\alpha} = I_{sd}Cos\theta_e - I_{sq}Sin\theta_e \quad , \quad I_{s\beta} = I_{sd}Sin\theta_e + I_{sq}Cos\theta_e \tag{11}$$

For nonsalient-pole brushless machines with a nonsinusoidal stator flux linkage, the electromagnetic torque, for BLDC motor, can be simplified as:

$$T_e = \frac{3}{2}\frac{P}{2}[(\frac{d\lambda_{rd}}{d\theta_e} - \lambda_{rq})I_{sd} + (\frac{d\lambda_{rq}}{d\theta_e} + \lambda_{rd})I_{sq}] \tag{12}$$

In the rotating-axes reference frame, or as in the stationary–reference frame.

$$T_e = \frac{3}{2}\frac{P}{2}[\frac{d\lambda_{r\alpha}}{d\theta_e}I_{s\alpha} + \frac{d\lambda_{r\beta}}{d\theta_e}I_{s\beta}] \tag{13}$$

$$\lambda_{r\alpha} = \lambda_{rd}Cos\theta_e - \lambda_{rq}Sin\theta_e \quad , \quad \lambda_{r\beta} = \lambda_{rd}Sin\theta_e + \lambda_{rq}Cos\theta_e \tag{14}$$

The stator flux-linkage vector can be obtained from the measured stator voltages $V_{s\alpha}$ and $V_{s\beta}$ and currents $I_{s\alpha}$ and $I_{s\beta}$.

$$\lambda_{s\alpha} = \int(V_{s\alpha} - R_s I_{s\alpha})dt \quad , \quad \lambda_{s\beta} = \int(V_{s\beta} - R_s I_{s\beta})dt \tag{15}$$

The magnitude and angular position of the stator flux-linkage vector is obtained as:

$$\lambda = \sqrt{\lambda_{s\alpha}^2 + \lambda_{s\beta}^2} \quad , \quad \theta = tan^{-1}(\frac{\lambda_{s\beta}}{\lambda_{s\alpha}}) \tag{16}$$

$$\lambda_{r\alpha} = \lambda_{s\alpha} - L_s I_{s\alpha} \quad , \quad \lambda_{r\beta} = \lambda_{s\beta} - L_s I_{s\beta} \tag{17}$$

Six nonzero-voltage space vectors are defined for a BLDC drive as shown in figure 2. Figure 3 show the idealized phase current waveforms for BLDC operation, and their relationship with the voltage space-vector sectors and switching states [11].

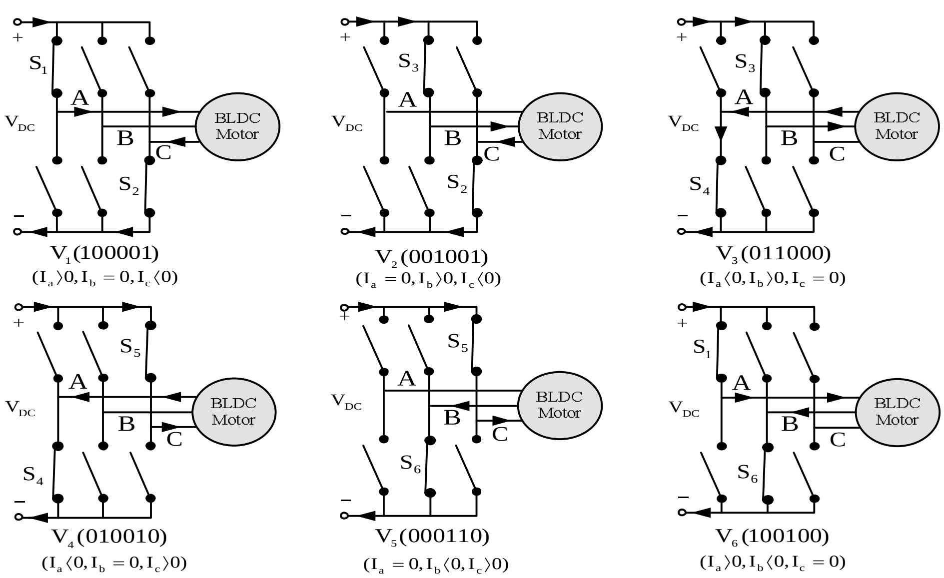


Figure 2. *Six nonzero-voltage space vectors are defined for a BLDC drive*

In a BLDC drive, however, only two phases are conducting in the 120 conduction mode, except during commutation periods when all three phases conduct, the unexcited phase conducting via a freewheeling diode. Since the upper and lower switches in the same phase leg may both be simultaneously off in BLDC drive, irrespective of the state of the associated freewheel diodes [Figure. 2] six digits are required to represent the states of the inverter switches, one digit for each switch. Thus, the voltage space vectors V_1, V_2, V_3, V_4, V_5 and V_6 are represented as switching signals (100 001), (001 001), (011 000), (010 010), (000 110), (100 100), respectively, where, from left to right, the logical values express the states of the upper and lower switching signals for phases A, B and C, respectively. The zero-voltage space vector is defined as (000 000).

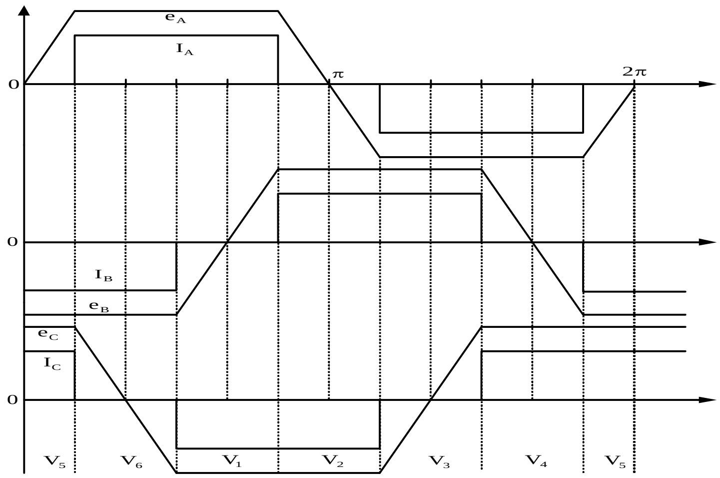


Figure 3. *Show the idealized phase current waveforms for BLDC operation*

Figure 4 shows a schematic of a DTC BLDC drive [11]. As can be seen from table 2, the switching pattern of the inverter can be determined according to the stator flux-linkage and torque status from the outputs of two regulators shown in figure 4, and the sector in which the stator flux linkage is located at that instant of time. In each sector, if the actual stator flux linkage is the same as the commanded stator flux linkage ($\lambda = 0$), only one nonzero-voltage space vector and a zero-voltage vector are used to control the increase (T=1) or decrease (T=0) of the torque, since during any 60 degree electrical period only two phases are excited and controlled in a BLDC drive, as indicated in Table II. In addition, when the actual flux linkage is smaller than the commanded value ($\lambda = 1$), the nonzero-voltage space vector is used to increase the flux linkage, while when the actual flux linkage is greater than the commanded value ($\lambda = -1$), the nonzero-voltage space vector is used to decrease the stator flux linkage.

Table 2. *Switching table for DTC of BLDC drive*

Torque	Flux	Sector					
		1	2	3	4	5	6
1	1	V_1	V_2	V_3	V_4	V_5	V_6
	0	V_2	V_3	V_4	V_5	V_6	V_1
	-1	V_3	V_4	V_5	V_6	V_1	V_2
0	1	V_1	V_2	V_3	V_4	V_5	V_6
	0	V_0	V_0	V_0	V_0	V_0	V_0
	-1	V_3	V_4	V_5	V_6	V_1	V_2

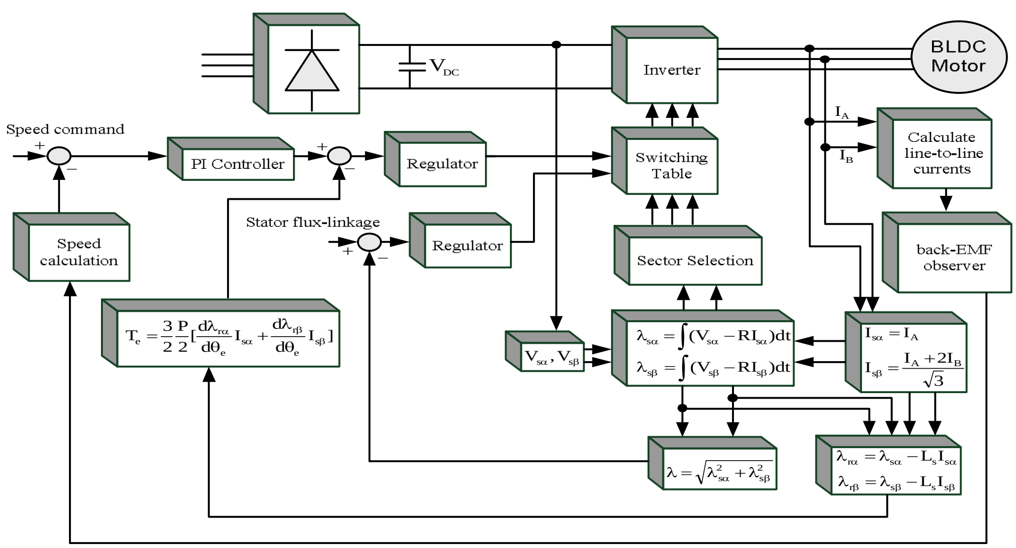
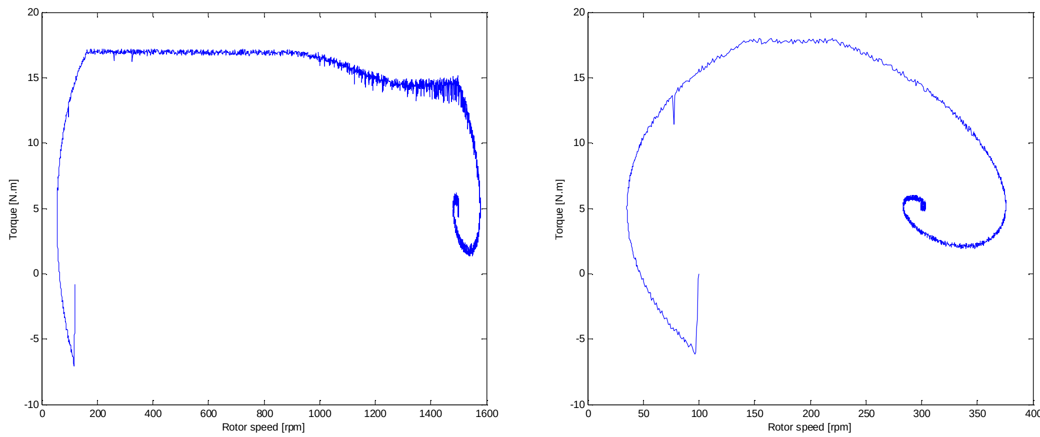


Figure. 4. *Schematic of DTC BLDC drive*

4 - Simulation results

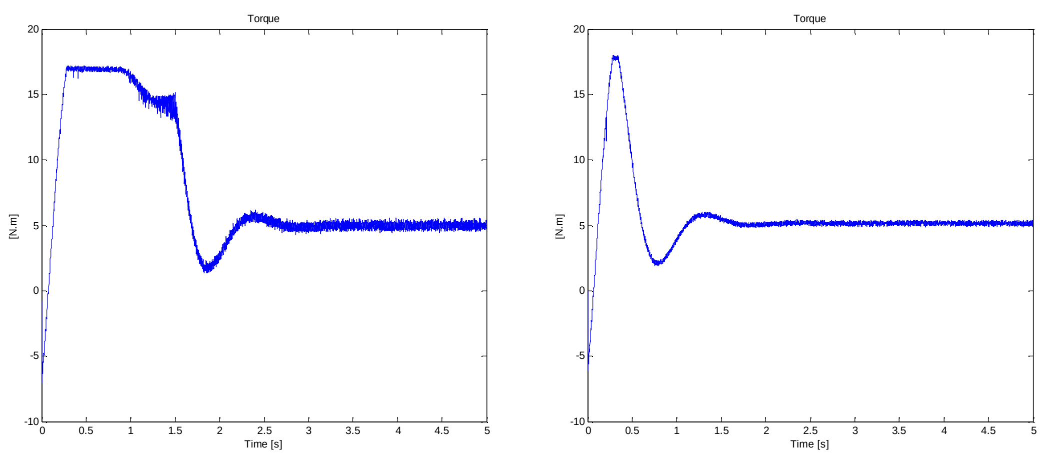
In the this section, simulation results for sensorless BLDC motor corresponding speed of 300 rpm and 1500 rpm are shown. In this paper the initial speed considered 100 rpm. In figure 5, the curve of torque is shown according to motor speed. As observed in this figure, the motor torque is swing around the reference value (5Nm) and after a few switches reaches its reference value.



$\omega = 1500 rpm$ $\omega = 300 rpm$

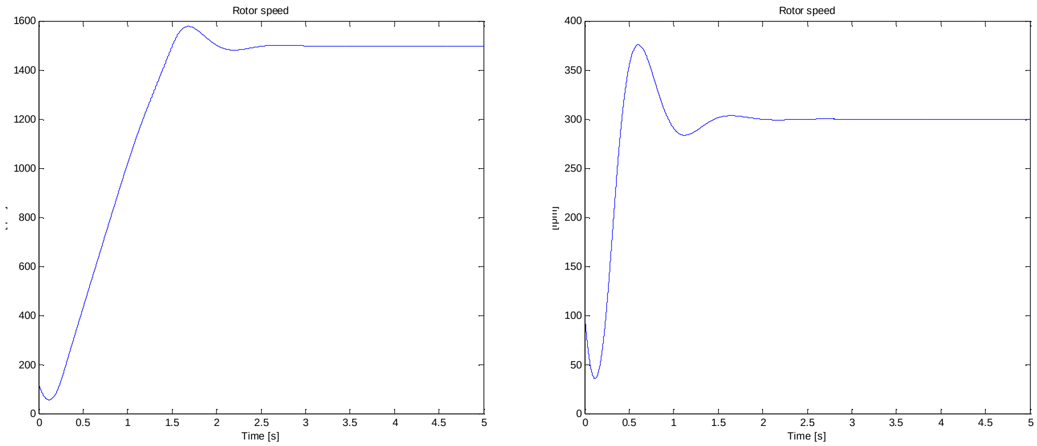
Figure 5. *Curve of changing torque according to motor speed*

Generated torque is shown in figure 6, phase-c current reaches to its final level before the phase-b current reaches to zero. The results of phase-a current decreased and as the result is shown in figure 6, the torque decrease in range of time in commutation. According to these figures, the average value of the torque is 5Nm and torque follows reference value well. Also it can be seen that the torque according to the figure 6, has a little ripple, which is the main advantages of DTC method. The speeds of the motor is shown in the figure 7.



$\omega = 1500 rpm$ $\omega = 300 rpm$

Figure 6*. Motor torque*



$\omega = 1500rpm$ $\omega = 300rpm$

Figure 7. *Motor speed*

In figure 8, waveform of the current phase a, b and c are magnified to study better. The waveform of phase-a, existing pulse in current, is seen in the middle of the guidance range 120 degree. The pulses created by commutation between the two phases b and c. BLDC motor trapezoidal waveform voltage back-emf used in order to minimize the torque ripple and maximize productivity and torque capability.

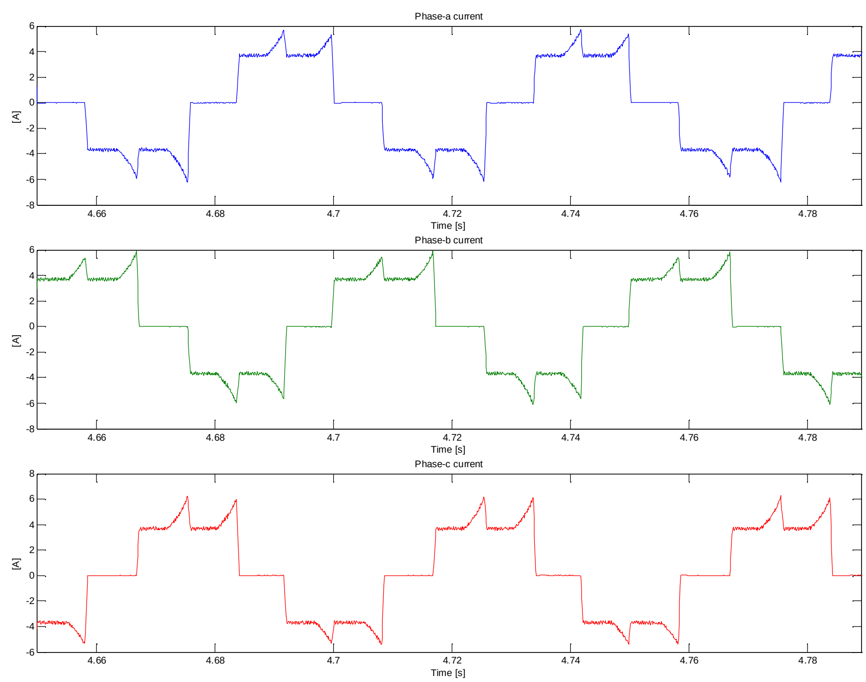


Figure 8-a. *Figure of magnified waveform phases current for* $\omega = 300rpm$

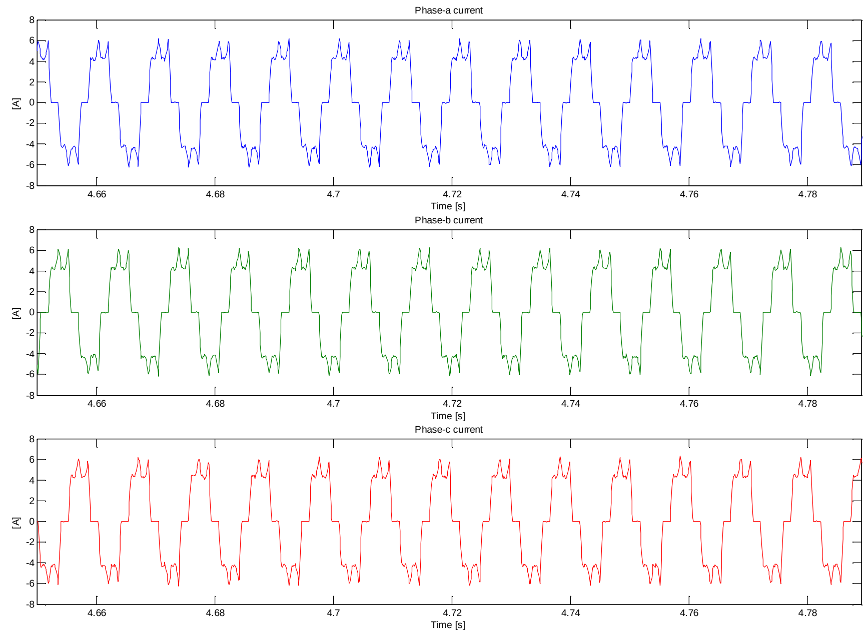
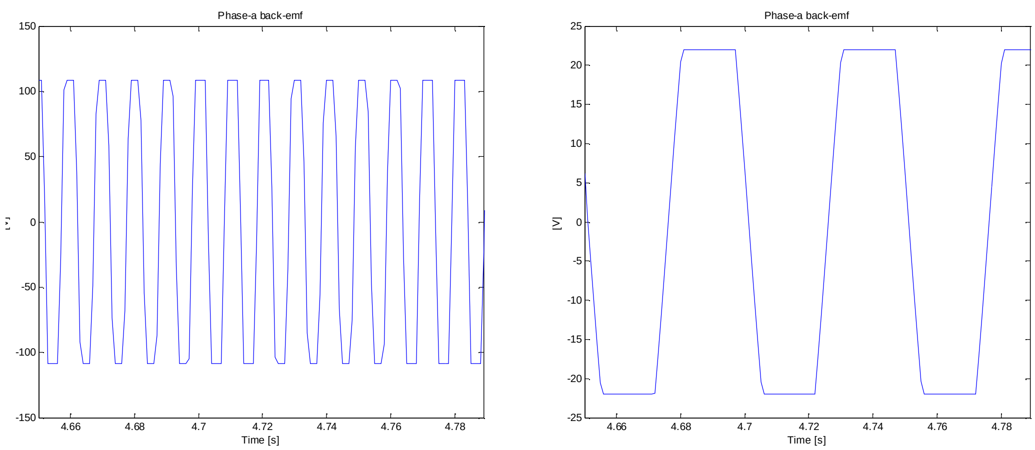


Figure 8-b. *Figure of magnified waveform phases current for* $\omega = 1500rpm$

Magnifications of waveform back-emf for phase-a are shown in figure 9. According to this figure, back-emf range of voltage in Steady state at speed of 300 rpm equals to 22.2 volts and in speed of 1500 rpm equals to 109.5 volts.



$\omega = 1500rpm$ $\omega = 300rpm$

Figure 9. *Figure magnification of waveform of back-emf phase-a*

As seen in the simulation results, DTC method for low and high speeds, in sensorless BLDC motors, has good results.

5-Conclusion

In this paper to estimating rotor position of sensorless BLDC drive motor we have been used the method that using functions of the ratio of line by line flux. This method compared with other methods, has little hardware and software volume and therefore, its implementation is easy and construction costs less. Also this method has suitable efficiency in wide range of speeds and estimate the rotor position is independent of frequency and speed of the rotor, so it has not the existing problems in the method of measuring the back-emf, such as frequency dependence and motor speed.

In continuance is used direct torque control method (DTC) for the design of sensorless BLDC motor drive. DTC method due to its simplicity and high speed in response to changes in the torque reference is considered one of the most efficient methods for control of electrical machines, which can be used for control of many types of electric machines. In this paper we try to evaluate the operation style and simulation of DTC control. High speed in response to changes in torque, ease of implementation, independence on machine parameters and a low computation, are the advantages of this method.

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