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Direct Power Control of Brushless DC Motor Drive

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Abstract

Recently, due to significant increase in demands of electric motors, design and manufacturing of high efficiency motors and related variable speed drives have been regarded by many suppliers. Among several kinds of motors, the brushless DC (BLDC) motor has many advantages including high torque capability. In this paper, for the first time, the possibilities of direct power control (DPC) of BLDC motors fed by a voltage source inverter have been studied. Principles of this method have been separately evaluated. The BLDC motor has been driven with three control method. The results show that the DPC technique enjoys all advantages of pervious method such as fast dynamic and ease of implementation, without having the previous method problems. The Simulations were carried out for the closed-loop speed control systems under various load conditions to verify the proposed methods. A modified DPC method with 12 sectors is presented to improve the performance of the direct power control method for BLDC motor drive. Theoretical analysis and performance of the developed controller is confirmed via simulation at different speed and under various disturbances.

Keywords: *Direct power control (DPC), brushless DC motor (BLDCM), hysteresis control, automotive, drive*

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INTRODUCTION

The electric drive system is a vital part to drive any motor. The electric drive system is used to control the position, speed and torque of the electric motors. Many works has been done on power converter topologies, control scheme of the electric drive systems and on the motor types in order to enhance and improve the performance of the electric motors so as to exactly perform and do what is required [1]. Brushless DC (BLDC) motors have some advantages over conventional brushed motors and induction motors. Some of these are; better speed versus torque characteristics, high dynamic response, high efficiency, long operating life, noiseless operation and higher speed ranges. In addition BLDC motors are reliable, easy to control, and inexpensive. Due to their favorable electrical and mechanical properties, BLDC motors are widely used in servo applications such as automotive, aerospace, medical, instrumentation, actuation, robotics, machine tools, and industrial automation equipment and so on recently [2].

Control of the BLDC motors can be done using various techniques. Most common techniques are: (a) dc link current control, (b) direct torque control (DTC). The first one is most common method of BLDC motor control and control structure is very simple. The other method is in the space vector control category because they utilize both magnitude and angular position of space vectors of motor variables, such as the voltage and flux. They are employed in high performance applications, such as positioning drives or electric vehicles. Most of presented methods for power control of BLDC motors are based on current control and use PI or hysteresis current regulators as internal loops [3,4]. Direct power control is a control method that directly selects output voltage vector states based on the power and flux errors using hysteresis controllers and without using current loops. In this respect, it is similar to the well know direct torque control (DTC) method described in the literatures for various AC motors [5].

What is in common among these applications is that they all are power output devices needed to provide real power to the load. Direct power control (DPC) technique basically is applied to generators, but it has been tried to employ it to control of electrical motors instead of DTC technique, due to problems of torque estimation and dependency to the motor's parameters in DTC. Therefore, DPC technique enjoys all advantages of DTC such as fast dynamic and ease of implementation, without having the DTC's problems. However, publications about direct power control are mainly aimed at either rectifiers [6], converters [7,8], dual-fed induction generators (DFIG) [9,10] or permanent magnet synchronous generators (PMSG) [11,12], and there isn't any research about using the DPC technique for BLDC motor.

This paper develops the DPC control strategy for BLDC motor is used. Developed DPC strategy can be used for power conversion directly. The paper is organized as follows; section "Principles of Brushless DC Motor Drive" gives an overview of the BLDC motor drive and then its modeling is presented in section Dynamic Modeling of BLDC Motor. Section Direct Power Control of BLDC Motor proposes the original DPC strategy and employing it for BLDC motor. Simulation results are presented in the subsequent section to demonstrate the performance of the proposed control strategy in different conditions. Finally, conclusions are given in section Conclusion.

PRINCIPLES OF BRUSHLESS DC MOTOR DRIVE

In 1962 the basic idea of the BLDC motor was introduced so that switching circuits were used for DC motor commutation. But the BLDC motors were not able to set up in power more than 5 hp that is why they weren't in the industrial place. With the advancement of permanent magnet materials in motors, the product line of BLDC motors low and high power (0.5 to 300 hp) startup since 1992. A BLDC motor is an AC synchronous motor with permanent magnets on the rotor and windings on the stator. Most BLDC motors have three phase stator windings, while their rotors can have several pairs of rotor magnet poles. Figure 1 is a schematic diagram of a three-phase BLDC motor with one pair of rotor magnet poles. The energized stator windings create an electromagnetic field, and the rotor is attracted to align with the stator field. When current is supplied to the stators in an appropriate sequence, the stator electromagnetic field rotates and drives the rotor magnets. The stator electromagnetic field and the rotor usually rotate at the same speed, and the phase lead between the stator field and the rotor needs to be maintained to generate constant torque. Measurement of the rotor position is needed for a BLDC motor's operation to properly sequence the stator current.

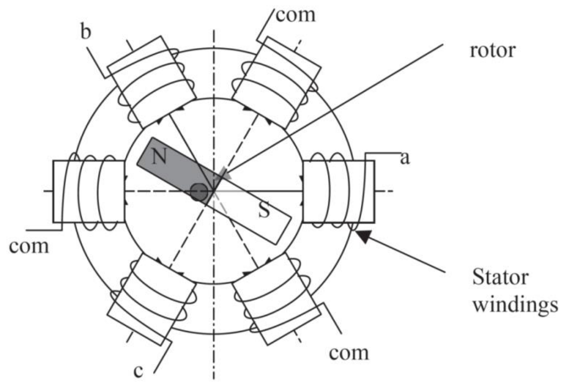


Fig. 1: *Schematic Diagram of a Three-Phase BLDC Motor with One Pair of Rotor Permanent Magnet Poles.*

The BLDC motor produces three-phase back-EMFs having trapezoidal shapes, as shown in Figure 2, whose magnitudes are directly proportional to the speed. It shows also the phase currents as well as the signals of hall-effect position sensors for a typical BLDC motor.

It has been proved that with equal air gap peak flux density and equal RMS current, BLDC motor develops 15% more torque than comparable permanent magnet synchronous (PMS) motor [13]. On the other hand, BLDC machine needs slightly more PM material than PMS machine for the same amount of power. The main drawback of BLDC motors is their torque ripple, mainly due to the delay in switching phases where square wave current is switching from one phase to another. This problem can be mitigated with employing the suitable control algorithms that is the objective of this study.

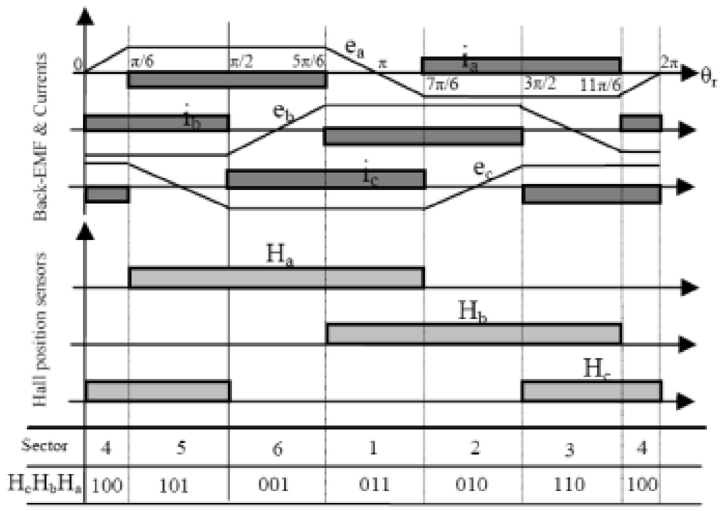


Fig. 2: Back-EMF Voltage and Phase Currents of BLDC Motor.

Figure 3 shows the schematic diagram of a typical three-phase BLDC motor control system. In the outer loop control system, the BLDC motor control system plays the role of its actuator, so the objective of BLDC motor control is to develop appropriate desired torque for the outer loop system. The suitable modulation technique is needed to control the inverter/rectifier. Comparison of the PWM (Pulse Width Modulation) method and SVM (Space Vector Modulation) shows that the SVM method utilizes the DC bus voltage better than PWM method and provides 15% higher voltage factor [14].

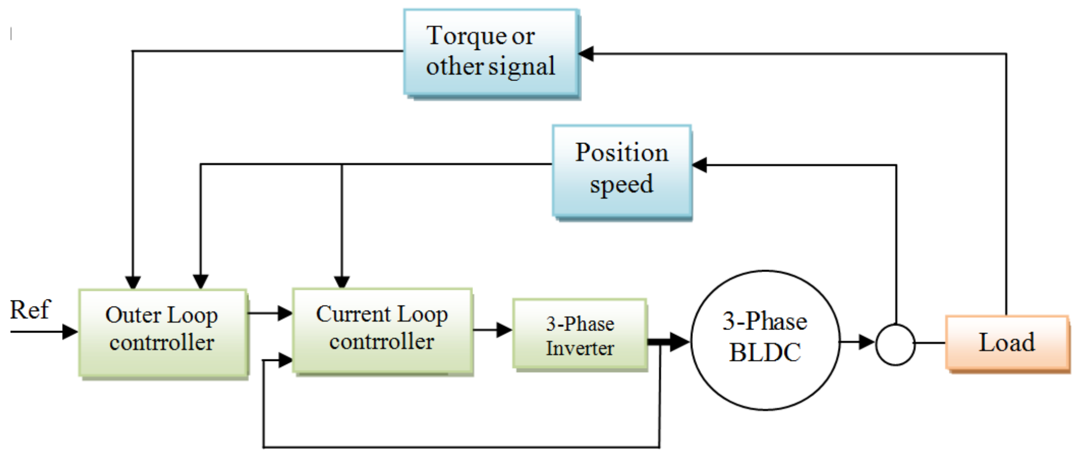


Fig. 3: Schematic Diagram of a Typical BLDC Motor Control System.

In DTC of BLDC motors, the actual control variable torque is very difficult to measure in practice. The feedback applied to the torque controller is exclusively estimated through algorithms thus is vulnerable to many factors such as model accuracy, parameter change etc. In DPC, actual real power as feedbacks for the controllers can be easily measured through voltage and current in a real system, reflecting the real actual values of the control variables. The research presented in this paper is devoted to the possibility of DPC of BLDC motors that would be similar to the DTC, with the accompanying simplicity of implementation and independence of motor parameters.

DYNAMIC MODELING OF BLDC MOTOR

Figure 4 shows the equivalent circuit of a three-phase BLDC motor. The analysis is based on the following assumptions for simplification [15, 16]:

- The motor is not saturated.
- Stator resistances and inductances of all windings are equal.
- All three phases have an identical induced EMF shape.
- Power semiconductor devices in the converter are ideal.
- Iron losses are negligible.

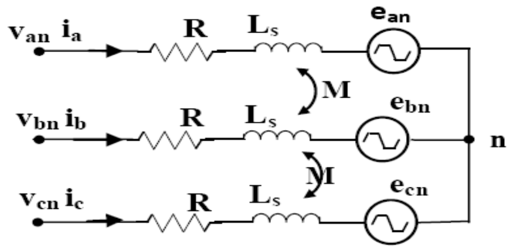


***Fig. 4:** Equivalent Circuit of BLDC Motor.*

With these assumptions and some simplifications, the phase voltage equations of the BLDC motor can be expressed as:

$$\begin{bmatrix} v_{an} \\ v_{bn} \\ v_{cn} \end{bmatrix} = \begin{bmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & R \end{bmatrix} \times \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} L_s - M & 0 & 0 \\ 0 & L_s - M & 0 \\ 0 & 0 & L_s - M \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_{an} \\ e_{bn} \\ e_{cn} \end{bmatrix} \tag{1}$$

where, e_{xn}, v_{xn}, i_x, R, L_s and M represent phase back-EMF voltage, terminal-to-neutral voltage, phase current, phase resistance, phase self-inductance, and mutual inductance, respectively. The motion equation can be represented as:

$$\frac{d}{dt}\omega_r = \frac{T_e - T_L - B\omega_r}{J} \tag{2}$$

that B, J and ω_r denote viscous friction, inertia and rotor speed, respectively.

DIRECT POWER CONTROL OF BLDC MOTOR

The main issue in DPC is the correct calculation of the power. If the stator winding loss and core loss are small enough to be neglected, the input electrical power is the rotational losses are small and negligible, the electrical input power can be approximated as the mechanical output power. Thus,

$$P_{in} \cong P_e = P_{out} \tag{3}$$

where, P_{in}, P_e and P_{out} represent the electrical input power, the electromagnetic power and the mechanical output power, respectively. The mechanical input power can be expressed as:

$$P_{out} = T_{em}\frac{\omega_r}{P} \tag{4}$$

The electromagnetic torque of a BLDC motor in the synchronously rotating d-q reference frame can be expressed as [17–19]:

Same as the electromagnetic power. If also the

$$T_{em} = \frac{3P}{4}\left[\left(\frac{dL_{ds}}{d\theta_e} i_{sd} + \frac{d\varphi_{rd}}{d\theta_e} - \varphi_{sq}\right) i_{sd} + \left(\frac{dL_{qs}}{d\theta_e} i_{sq} + \frac{d\varphi_{rq}}{d\theta_e} + \varphi_{sd}\right) i_{sq}\right] \tag{5}$$

Substituting the torque in Eq. (4) with (5), the output power becomes:

$$P_{out} = \frac{3\omega_r}{4}\left[\left(\frac{dL_{ds}}{d\theta_e} i_{sd} + \frac{d\varphi_{rd}}{d\theta_e} - \varphi_{sq}\right) i_{sd} + \left(\frac{dL_{qs}}{d\theta_e} i_{sq} + \frac{d\varphi_{rq}}{d\theta_e} + \varphi_{sd}\right) i_{sq}\right] \tag{6}$$

where

$$\varphi_{sd} = L_{sd} i_{sd} + \varphi_{rd} \tag{7}$$

$$\varphi_{sq} = L_{sq} i_{sq} + \varphi_{rq} \tag{8}$$

θ_e is the rotor electrical angle, p is the number of poles, i_{sd}, i_{sq} are d and q-axes currents, L_{ds}, L_{qs} are d and q-axes stator inductances, and φ_{rd}, φ_{rq}, φ_{sd} and φ_{sq} are d and q-axes rotor and stator flux linkages, respectively. If L_{ds} and L_{qs} to be constant, then Eq. (6) can be rewritten as:

$$P_{out} = \frac{3\omega_r}{4}\left[\left(\frac{d\varphi_{rd}}{d\theta_e} - \varphi_{rq}\right)i_{sd} + \left(\frac{d\varphi_{rq}}{d\theta_e} + \varphi_{rd}\right)i_{sq} + (L_{ds} - L_{qs})i_{sd}i_{sq}\right] \quad (9)$$

For the non-salient-pole rotor there is:

$$L_{sd} = L_{sq} \quad (10)$$

The flux linkages and stator currents in the stationary α-β reference frame can be expressed as:

$$\varphi_{r\alpha} = \varphi_{rd}\cos\theta_e - \varphi_{rq}\sin\theta_e \quad (11)$$

$$\varphi_{r\beta} = \varphi_{rd}\sin\theta_e + \varphi_{rq}\cos\theta_e \quad (12)$$

$$i_{s\alpha} = i_{sd}\cos\theta_e - i_{sq}\sin\theta_e \quad (13)$$

$$i_{s\beta} = i_{sd}\sin\theta_e + i_{sq}\cos\theta_e \quad (14)$$

and the power equation can be simplified as:

$$P_{out} = \frac{3}{2}\frac{\omega_r}{2}\left[\frac{d\varphi_{r\alpha}}{d\theta_e}i_{s\alpha} + \frac{d\varphi_{r\beta}}{d\theta_e}i_{s\beta}\right] = -\frac{3}{2}\frac{\omega_r}{2}\left[\frac{e_\beta}{\omega_e}i_{s\alpha} + \frac{e_\alpha}{\omega_e}i_{s\beta}\right] \quad (15)$$

where, e_α and e_β are back-EMF obtained from the look up table.

Switching Table

The electromagnetic torque produced in the motor is:

$$T_{em} = \frac{2}{3}p\,\mathrm{Im}(i_s\varphi_s^*) \quad (16)$$

Substituting the torque in (4) with (17), the real output power becomes:

$$P_{out} = \frac{2\omega_r}{3}\mathrm{Im}(i_s\varphi_s^*) = \frac{2}{3}\frac{\omega_r}{L_s}\varphi_s\varphi_r\sin(\theta_s - \theta_r) \quad (17)$$

Since the magnitude of the stator flux is kept constant and the rotor flux does not change much due to its inertia, the rotor speed and angle can be considered constant too. The formula above shows that the change of output power depends only on the change of stator voltage angle. The stator voltage vector that can increase the stator angle needs to be raised in order to increase the output power. The real output power equation obtained above is only valid for explanation of the principles of power control. However, it is not appropriate for the purpose of estimating the actual power in simulations. The demand power is controlled via hysteresis controller type that has two level output as shown in Figure 5. The values are b_p=1 and b_p=0 represents an increase and a decrease of the power, respectively. The task of the state selector in the direct power control is to select the required voltage vectors of the inverter.

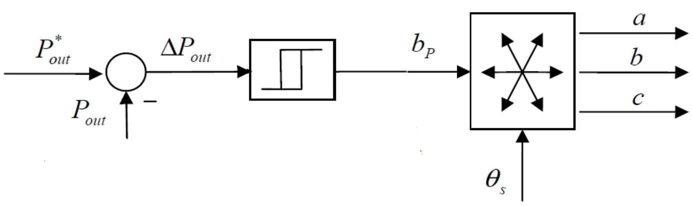


Fig. 5: *Block Diagram of the Inverter State Selection.*

Figure 6 shows non-zero voltage space vectors for BLDC motor. A whole voltage cycle of 360º is divided equally into six sectors; each one spanning 60º.

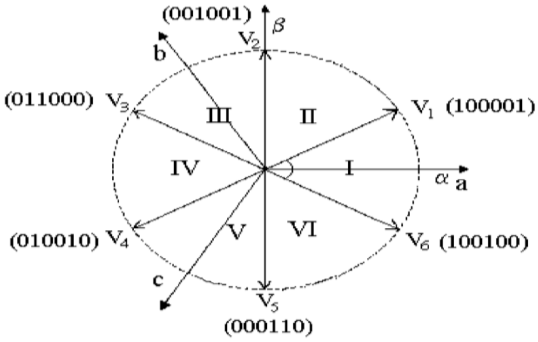


Fig. 6: *Non-Zero Voltage Space Vectors for BLDC Motor.*

To understand more about switching mode in the DPC control structure, the reference power is assumed to be higher than the actual power, in the area -30° to 30° (sector I) as shown in the Figure 6, that the power changes is expresses by b_p=1. In this mode, for the real power follows the reference power, V_2 should be applied. In the same manner, if the actual power value is greater than the reference power, the power changes is expressed with b_p = 0 that, in this case V_5 vector is applied to reduce the amount of the real power. Switching instructions is applied to the inverter shown in the Figure 5. According to explain above, inverter switching pattern with considering power variations is presented in Table 1.

Table 1: *State Selection look-up Table.*

b_p	Sector 1	Sector 2	Sector 3	Sector 4	Sector 5	Sector 6
b_p=1	V_2	V_3	V_4	V_5	V_6	V_1
b_p=0	V_5	V_6	V_1	V_2	V_3	V_4

Modified DPC with Twelve Sectors

In the classical DPC, there are several drawbacks: Sluggish response (slow response) in both start up and changes in either power, Large and small errors in power are not distinguished. In other words, the same vectors are used during start up and step changes and during steady state. First idea that comes up, when it is tried to improve the DPC by means of changing the tables, is to use 12 sectors as shown in Figure 7. Hence, instead of having as a first sector the zone from -30º up to 30º, it will be from 0º up to 30º. This novel stator flux locus is introduced in Figure 8. Due to the fact that the tangential voltage vector component is very small and consequently its power variation will be small as well. According to explain, inverter switching pattern with considering power variations is presented in Table 2.

Table 2: *State Selection Look-up table with 12 Sector.*

b_p	S_1	S_2	S_3	S_4	S_5	S_6	S_7	S_8	S_9	S_{10}	S_{11}	S_{12}
b_p=1	V_4	V_5	V_6	V_7	V_8	V_9	V_{10}	V_{11}	V_{12}	V_1	V_2	V_3
b_p=0	V_{10}	V_{11}	V_{12}	V_1	V_2	V_3	V_4	V_5	V_6	V_7	V_8	V_9

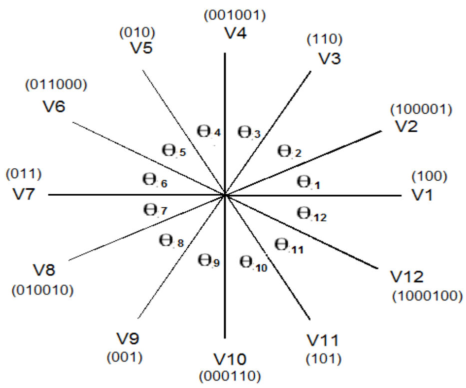
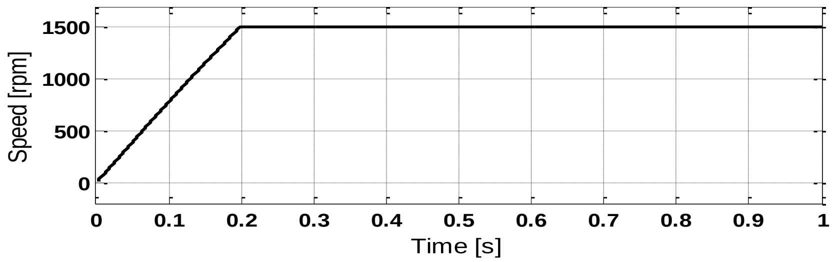


Fig. 7: *Twelve Sector Modified DPC.*

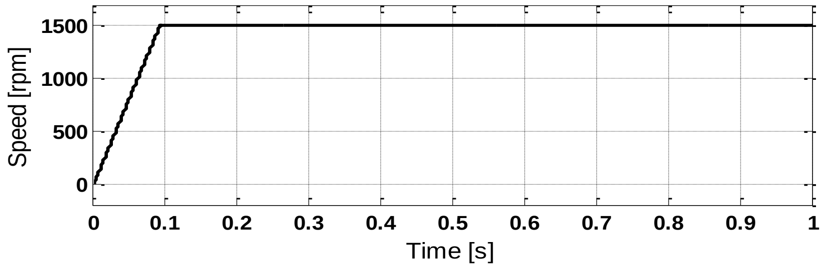
SIMULATION RESULTS

The simulation is carried out using MATLAB/Simulink. The parameters of BLDC motor used in the simulations are listed in Appendix A. The BLDC motor using by DPC, DTC and dc link current control method has been driven. The simulation results are shown in Figure 8 through Figure 11.

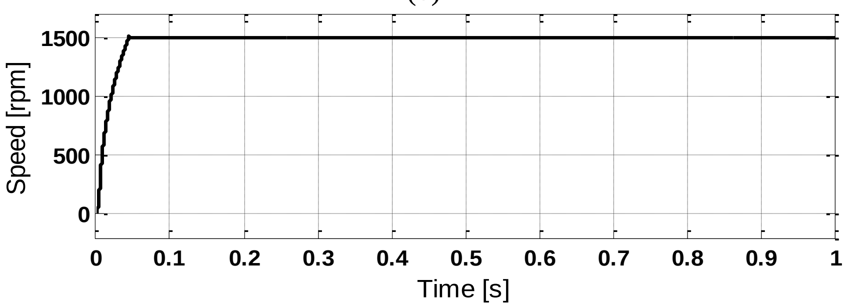
As seen in Figure 8, the response of the speed is good and acceptable in all three methods. However, the time to reach the final in the method of DPC is less than the other methods.



(a)



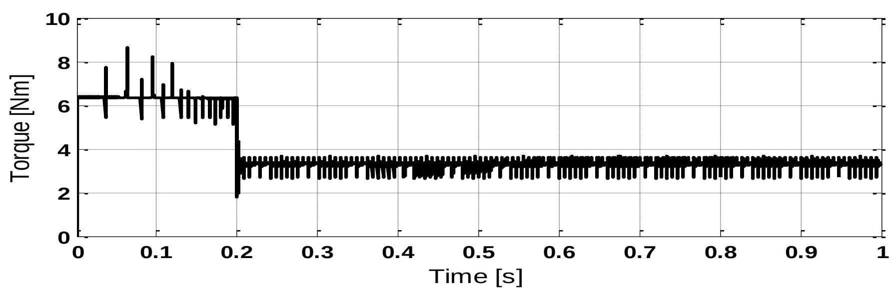
(b)



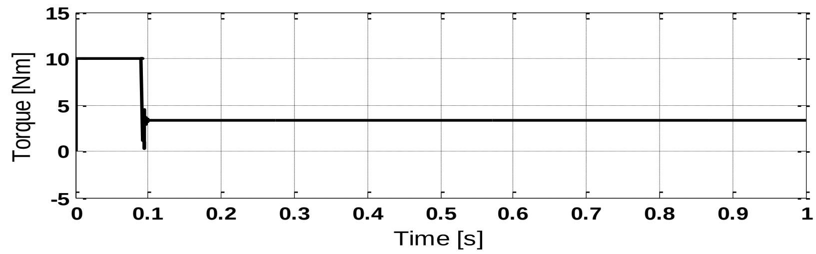
(c)

Fig. 8: *Response of the Speed of BLDC Motor, (a) DC Link Current Control, (b) DTC, (c) DPC.*

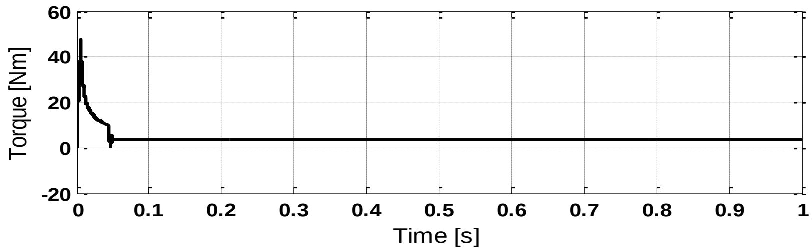
Figures 9 and 10 show the response of power and torque of BLDC motor, respectively. The ripple of power and torque in dc link current method compared to the other method increases.



(a)

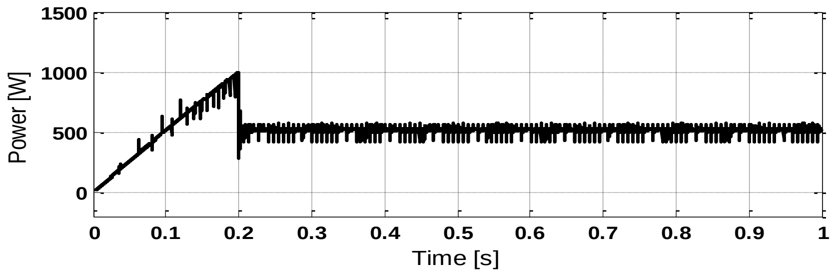


(b)

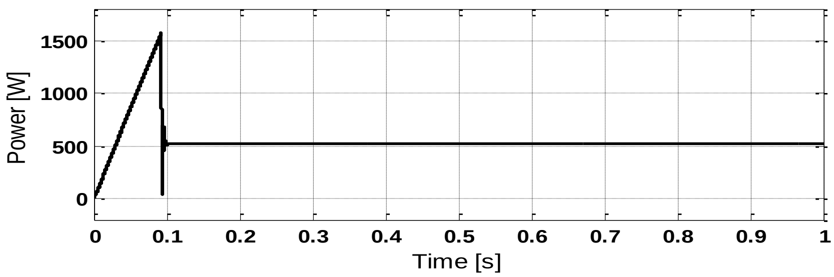


(c)

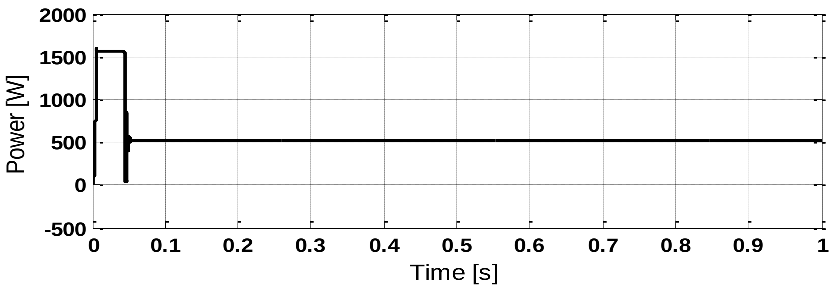
Fig. 9: *Response of the Torque of BLDC Motor, (a) DC Link Current Control, (b) DTC, (c) DPC.*



(a)



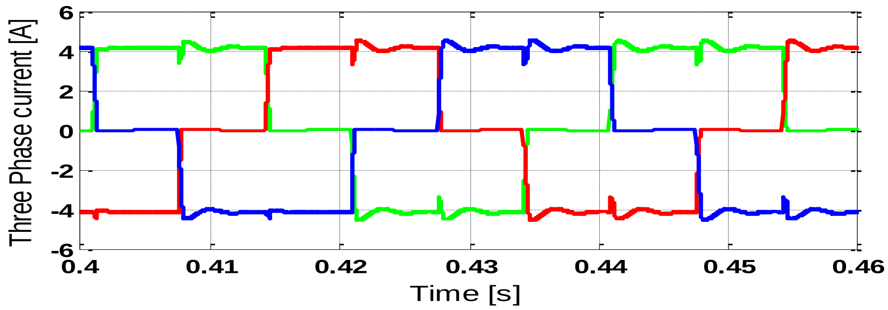
(b)



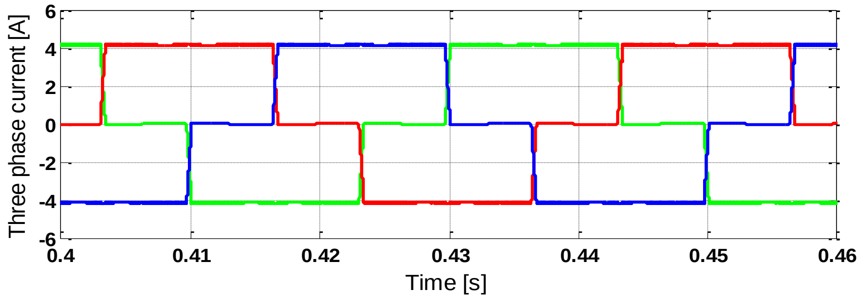
(c)

Fig. 10: *Response of the Power of BLDC Motor, (a) DC Link Current Control, (b) DTC, (c) DPC.*

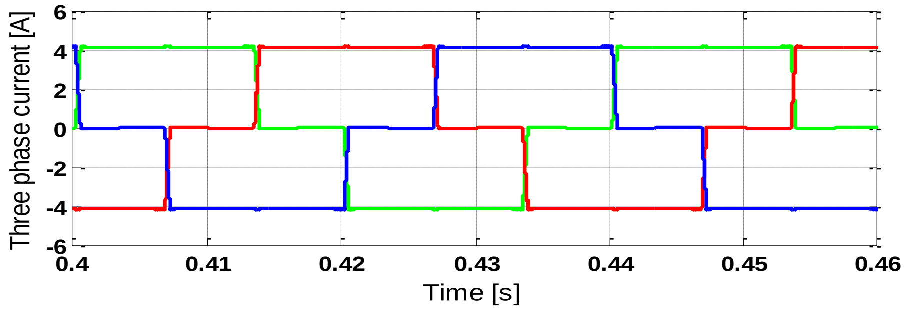
Figure 11 shows the three-phase current of BLDC motor that in DPC and DTC methods are suitable rectangular compared to dc link current control.



(a)



(b)



(c)

Fig. 11: *Three phase current of BLDC motor, (a) dc link current control, (b) DTC, (c) DPC.*

Control of Motor's Power

In this part of the simulation, BLDC motor is driven with DPC method. At first a reference power of 500 W is assumed. Next, the reference power of 400 W is applied at t =2 sec. The hysteresis band for control of power is 5% around the reference value. The waveforms of generated power, speed, torque and phase current are shown in Figure 12. The power tracking has good response in transient and steady state situations. The power has followed changing the reference power as well. By decreasing the power, the speed of the motor decreases. However, the response of the actual power has overshot. This is resulted from anti-windup phenomenon that causes the overshot in the response of the speed and power. The magnitude of phase current remains constant, because torque is constant.

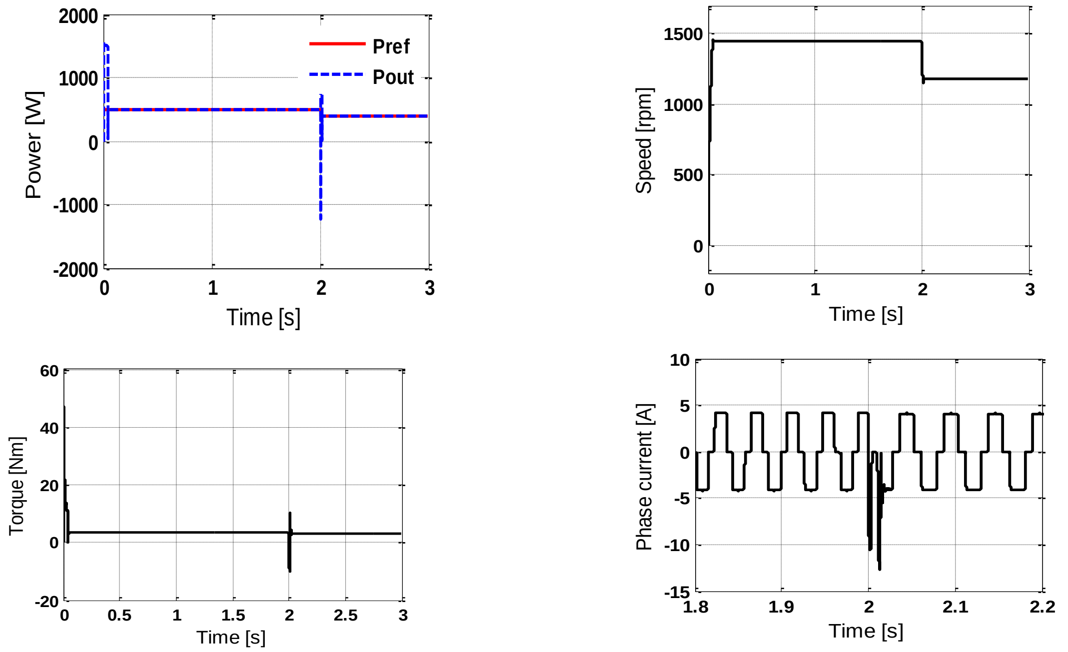


Fig. 12: *Tracking of the Reference Power via DPC Technique for BLDC Motor.*

Control of Motor's Speed

In next case the tracking of speed motor is simulated. The speed of motor is assumed at 1300 RPM. Suddenly at t = 2 sec, the reference voltage changes to 1700 RPM. The simulation results are shown in Figure 13.

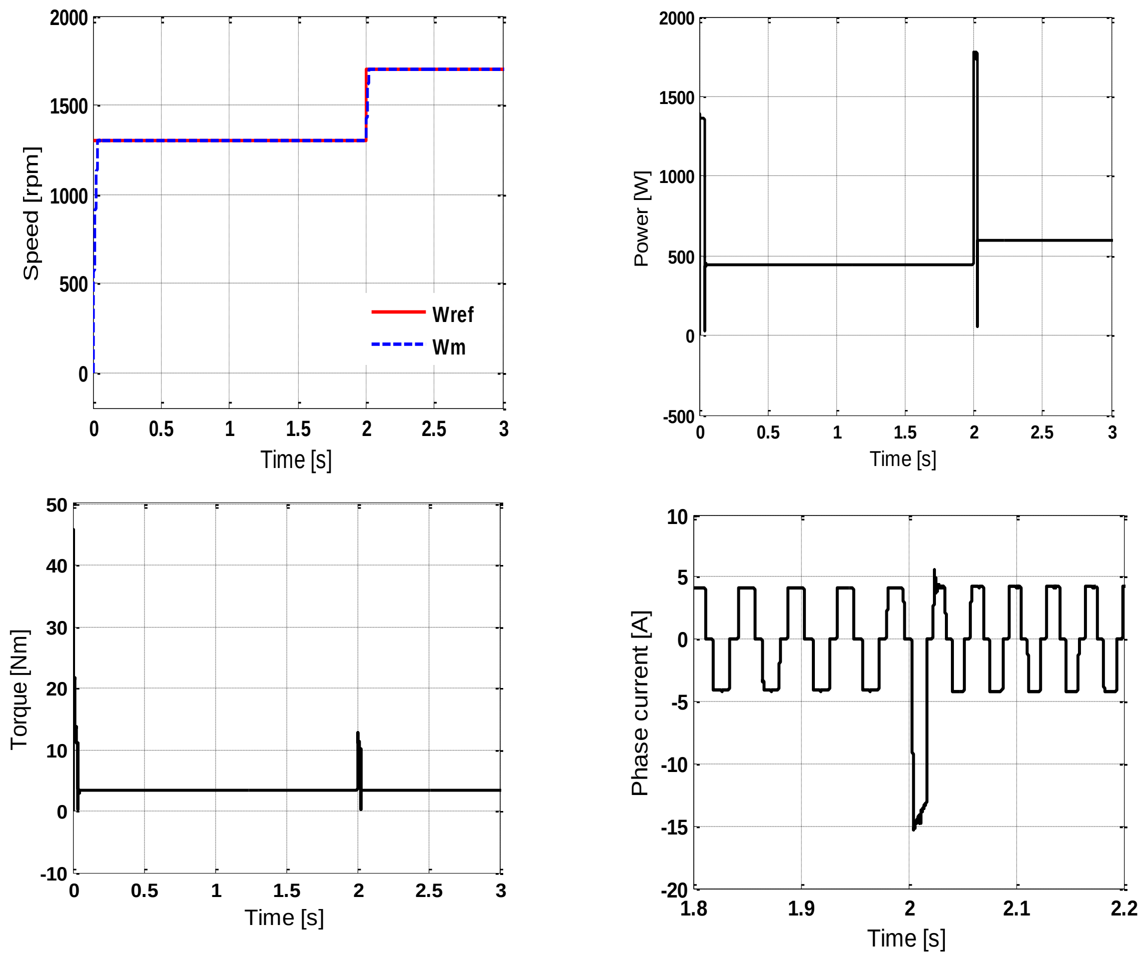
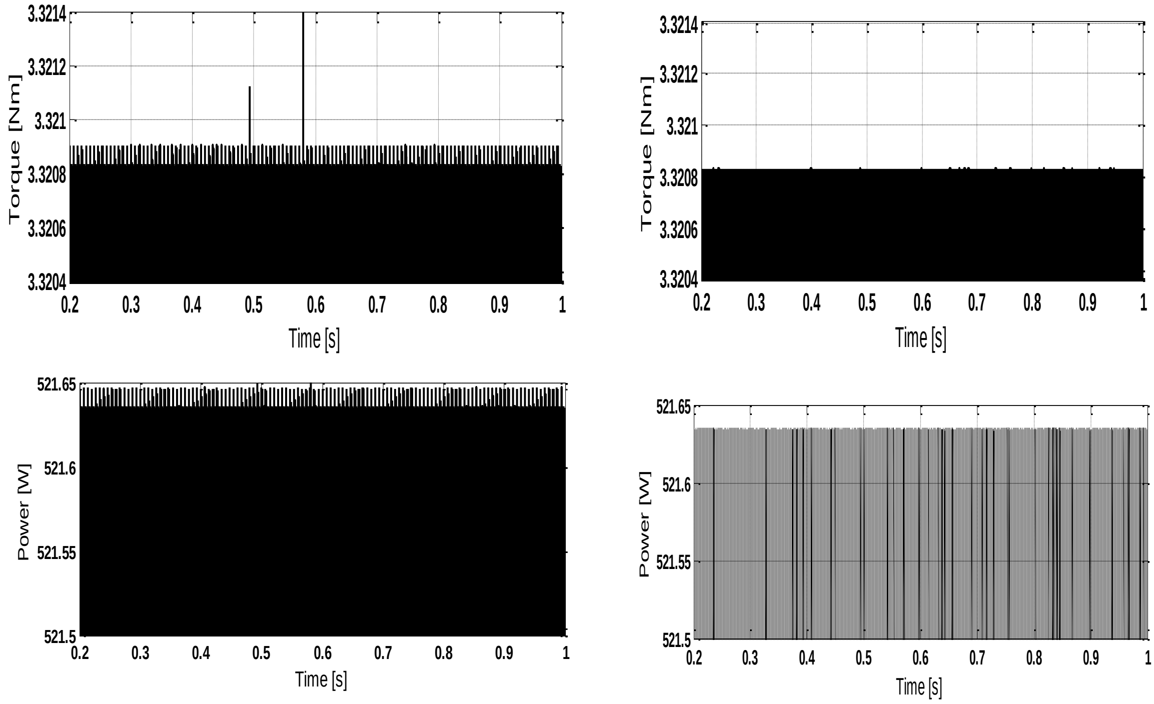


Fig. 13: *Tracking of the Reference Speed via DPC Technique in BLDC Motor Drive.*

As shown in Figure 13, the speed tracking has a good response in steady state and in transient situations. To increase of the speed, generated power is increased. The load torque is constant and developed torque follows it and reaches to it at steady state. The magnitude of phase current in steady state remains constant, because the torque is constant.

Modified DPC with Twelve Sector

In this part of the simulation, BLDC motor is driven by using DPC method whit 12 sectors. Figure 14(a) shows magnification power and torque of BLDC motor using by conventional DPC algorithm. The Power and torque ripple by using DPC algorithm with 12 sectors is less than the conventional DPC mode in Figure 14(b).



(b) (a)

Fig. 14: *Torque and Power Ripple, (a) Conventional DPC, (b) Twelve Sector Modified DPC.*

CONCLUSION

In this paper, the DPC technique for controlling of BLDC motor have been studied. According to simulations performed it was observed that changing the reference power as well be followed and has a good response to change the load. The Simulation results show that this control scheme for BLDC motor has all the advantages of direct torque control. In addition, in the DPC method sensitive to parameters is less. Actual values of the controlled variable applied to control system and the dynamic response of DPC method is faster than the DTC method. One of the major advantages of the DPC method compared to the DTC method that it is can be easily estimated actual power for control system. To improve the performance of this method of control, the direct power control with 12 sectors can be alternative to conventional DPC method to decrease the power and torque ripple of BLDC motor and Instantaneous changes in torque and power waveforms.

APPENDIX A

Table 3: *Brushless DC Motor Parameter.*

Parameter	Value	Parameter	Value
V_{dc}	300 [V]	p	2
n	1500 [RPM]	T_L	3 [Nm]
R	0.4 [Ω]	J	0.004 [kg.m^2]
L	13 [mH]	B	0.002 [N.m/(rad/sec)]

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