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Sensorless Direct Power Control of Brushless DC Motor Drive using Unknown Input Speed Observer

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Abstract
This paper proposes the speed control of brushless DC (BLDC) motor via direct power control (DPC) method as a novel and effective strategy in electrical drives applications. The DPC has some advantages rather than other control methods of BLDC motor including simpler control algorithm and faster dynamic response. In proposed BLDC motor drive based on DPC strategy, space vector modulation (SVM) voltage source inverter is employed. To enhance the drive reliability, a position sensorless strategy has been used for rotor position detection and current commutation. In developed sensorless strategy, an observer has been designed to predict the phase back-emf voltages using line voltages and currents. So, there is no need to position sensors and the cost is reduced. The performance of proposed sensorless DPC method has been verified via some simulations in Matlab under different speed and torque references.

Keywords: *Brushless DC motor, direct power control, sensorless, drive, observer*

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INTRODUCTION
In recent years, taking into consideration latest advance in permanent magnet materials, solid state devices and microelectronic have resulted in new energy efficient drives using permanent magnet brushless DC motors. BLDC motors with features such as durability, high efficiency, easier control and high power density, have found many applications in different industries such as appliances, medical, industrial automation, servo drives, automotive, aerospace, computer peripheral equipment and electric vehicles [1]. In addition to the aforementioned advantages of BLDC motors, they have high acceleration capability due to small rotor inertia and high static torque characteristics of DC motors desired function of the high velocity.

The BLDC motor is similar with the permanent magnet synchronous motor in the structure and linear torque to current, or speed to voltage similar with DC motor. Then, variable speed operation and control are easier than other AC machines. Thus, given the undeniable benefits of permanent-magnet motor and increasing progress and improve engine operating characteristics of BLDC, the need to develop and improve the control performance of BLDC motor drives can be felt.

Control of BLDC motors can be done using various techniques. The most popular way to control BLDC motors is dc link current control. This method has a simple structure. Direct torque control (DTC) is another method which is in the space vector control category because they utilize both magnitude and angular position of space vectors of motor's voltage and flux. Comparing to conventional vector controlled drives; DTC possesses several advantages such as elimination of coordinate transformation, lesser parameter dependence and faster dynamic response [2]. The latest developed technique is direct power control (DPC). Most of presented methods for power control of BLDC machines are based on current control and using PI or hysteresis current regulators as internal loops [3].

During two last decades, direct power control has been a research topic in control of electrical machines. 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-known direct torque control (DTC) method described in the literatures for various AC motors [4] and lately for BLDC motors [5]. 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. To control the motor, the rotor angle is necessary to be known. On the other hand, reducing the manufacturing cost of BLDC motor drives is an attractive issue in commercial applications. It can be reduced more by elimination of position sensors and developing feasible sensorless methods. Furthermore, sensorless control is the only choice for some applications where these sensors cannot function reliably because of the harsh environments.

In this study, the direct power control for BLDC motors will be used. The paper is organized as follows: the following part presents an overview of the BLDC motor drive and its modeling, DPC strategy and employing it for BLDC motor followed by the proposed sensorless control method, simulation results to demonstrate the performance of the proposed control strategy and finally the conclusions are given.

BRUSHLESS DC MOTOR DRIVE

Brushless dc motor consists of a permanent magnet, which rotates (the rotor), surrounded by three equally spaced windings, which are fixed (the stator). Current flow in each winding produces a magnetic field vector. By controlling currents in the three windings, a magnetic field of arbitrary direction and magnitude can be produced by the stator.

The BLDC motor drive block diagram is shown in Figure 1. Assuming that the stator resistances of all the windings are equal and also self and mutual inductances are constant, the voltage equation of the three phases can be expressed as Eq. (1). In this equation, magnets, stainless steel retaining sleeves with high resistivity, and rotor-inducted currents are neglected and damper windings are not modeled [6].

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

Where; R_s , L_s , M are the resistance, inductance and mutual inductance of the stator and v, e and i are phase voltage, back emf voltage and phase current of the stator respectively [7]. BLDC motor has characteristics like a DC motor, whereas it is controlled the same as AC motors.

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 same as the electromagnetic power. If also the rotational losses are small and negligible, the electrical input power can be approximated as the mechanical output power. Thus,

$$P_{in} \cong P_e = P_{out}. \quad (2)$$

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:

$$p_{in} = T_{em} \frac{\omega r}{p}. \quad (3)$$

The electromagnetic torque of a BLDC motor in the synchronously rotating d-q reference frame can be expressed by [8]:

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

Substituting the torque in Eq. (3) with (4) the output power becomes:

$$P_{out} = \frac{3\omega_r}{4} \left[\left(\frac{dL_{sd}}{d\theta_e} i_{sd} + \frac{d\varphi_{rd}}{d\theta_e} - \varphi_{sq} \right) i_{sd} + \left(\frac{dL_{qs}}{d\theta_e} i_{sq} + \frac{d\varphi_{rq}}{d\theta_e} + \varphi_{sd} \right) i_{sq} \right]. \quad (5)$$

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} be constant, then Eq. (5) can be rewritten as:

$$P_{out} = \frac{3\omega_r}{4}\left[\begin{array}{l}\left(\frac{d\varphi_{rd}}{d\theta_e} - \varphi_{rd}\right)i_{sd} \\ +\left(\frac{d\varphi_{rq}}{d\theta_e} + \varphi_{rd}\right)i_{sq} \\ +\left(L_{ds} - L_{qs}\right)i_{sd}i_{sq}\end{array}\right]. \quad (6)$$

For the non-salient-pole rotor there is:

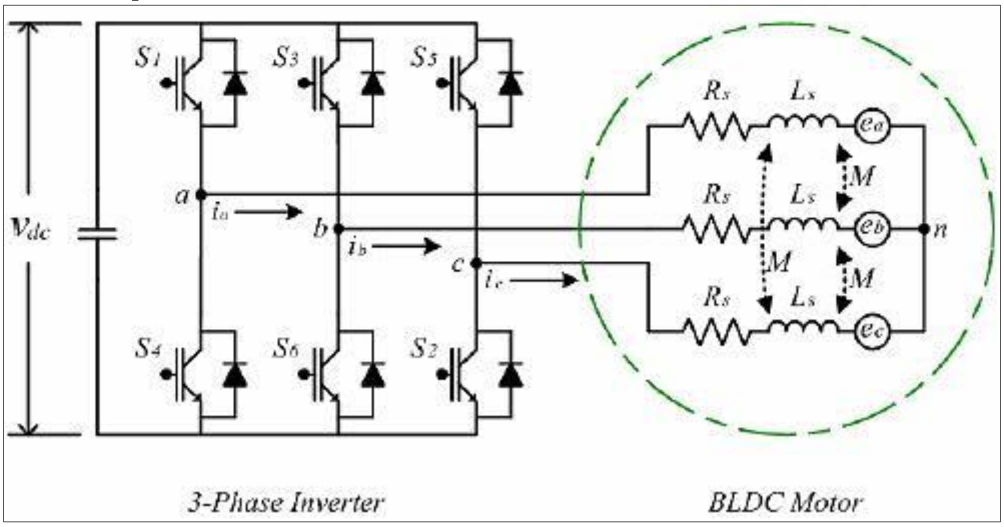


Fig. 1: *Three-Phase Equivalent Circuit for BLDC Motor.*

$$L_{sd} = L_{sq}. \quad (7)$$

The flux linkages and stator currents in the stationary $\alpha - \beta$ reference frame can be expressed as:

$$\varphi_{r\alpha} = \varphi_{rd}\cos\theta_e - \varphi_{rq}\sin\theta_e. \quad (8)$$

$$\varphi_{r\beta} = \varphi_{rd}\sin\theta_e + \varphi_{rq}\cos\theta_e. \quad (9)$$

$$i_{s\alpha} = i_{sd}\cos\theta_e - i_{sq}\sin\theta_e. \quad (10)$$

$$i_{s\beta} = i_{sd}\sin\theta_e + i_{sq}\cos\theta_e. \quad (11)$$

and the power equation can be simplified as:

$$P_{out} = -\frac{3}{2}\frac{\omega_r}{2}\left[\frac{d\varphi_{r\alpha}}{d\theta_e}i_{s\alpha} + \frac{d\varphi_{r\beta}}{d\theta_e}i_{s\beta}\right] = -\frac{3}{2}\frac{\omega_r}{2}\left[\frac{e_\alpha}{\omega_e}i_{s\alpha} + \frac{e_\beta}{\omega_e}i_{s\beta}\right]. \quad (12)$$

Where, e_α and e_β are back-emf obtained from the look up table. The electromagnetic torque produced in motor is:

$$T_{em} = \frac{2}{3}p\,\mathrm{Im}(i_s\varphi_s^*). \quad (13)$$

Substituting the torque in Eq. (3) with (13), the real output power becomes:

$$P_{out} = \frac{2\omega_r}{3}\mathrm{Im}\left(i_s\varphi_s^*\right) = \frac{2}{3}\frac{\omega_r}{L_s}\varphi_s\varphi_r\sin\left(\theta_s - \theta_r\right). \quad (14)$$

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 above formula 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 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 2. The values bp=1 and bp=0, represent 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.

Figure 3 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. 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 Figure 2 that the power changes is expresses by bp=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 bp=0 that, in this case V_5 vector is applied to reduce the amount of the real power. Switching instruction is applied to the inverter shown in Figure 2. According to explaination above, inverter switching pattern with considering power variations is presented in the Table 1.

PROPOSED SENSORLESS CONTROL METHOD

A BLDC motor requires an inverter and a rotor position sensor to perform commutation process because a permanent magnet synchronous motor does not have brushless and commentators in DC motors. However, the position sensor presents several disadvantages from the stand points of drive's cost, machine size, reliability, and noise immunity. Conventional sensorless control methods can be classified into several categories. Some of these methods are given below:

In the first category, the open phase current sensing method is a technique for detecting the conducting interval of free wheeling diodes connected in antiparallel with power transistors [9]. Secondly, the method detecting the third harmonic of back-emf is the technique to remove all the fundamental and other poly-phase components through a simple summation of three phase voltages [10–11]. Thirdly, the back-emf integrating method is a technique applying the principle that integration is constant from zero crossing point (ZCP) to 30° [12–13]. Finally, the open phase voltage sensing method is a scheme estimating the rotor position indirectly by using the ZCP detection of open phase's terminal voltage [14]. In this paper, sensorless control method utilizing an unknown input observer is used. This sensorless control method incorporating an unknown input observer is independent of the rotor speed for a BLDC motor drive. It is based on the fact that the rotor position can be detected by using trapezoidal back-emf of BLDC motors [15]. Since a back-emf of the BLDC motor is not measured directly, it is estimated by the unknown input observer.

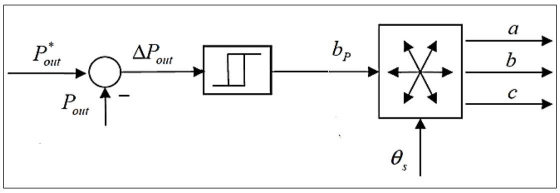


Fig. 2: *Block Diagram of the Inverter State Selection.*

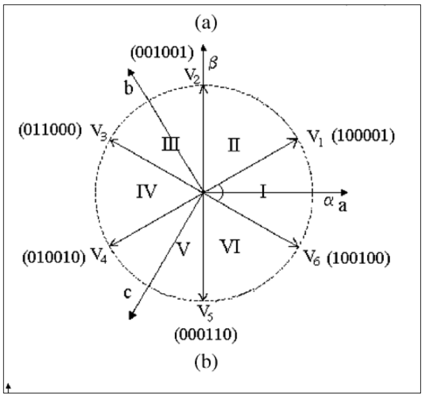


Fig. 3: *Non-Zero Voltage Space Vectors for BLDC Motor.*

Table 1: *Switching Table.*

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

This unknown input observer is constructed by a back-emf regarded as an unknown input and state of the BLDC motor drive system. The sensorless control method using the unknown input observer can be obtained as follows: First line-to line back-emf estimation using the unknown input observer since the neutral point of the BLDC motor is not offered, it is difficult to construct the equation for one phase. Therefore, the unknown input observer is considered by the following line-to-line equation:

$$\frac{di_{ab}}{dt} = -\frac{2R_S}{2L} i_{ab} + \frac{1}{2L} v_{ab} - \frac{1}{2L} e_{ab}. \tag{15}$$

In Eq. (15) i_{ab} and v_{ab} can be measured, therefore they are "known" state variables. On the other hand, since e_{ab} cannot be measured, this term is considered as an unknown state. Eq. (15) can be rewritten in the following matrix form:

$$\frac{dx}{dt} = Ax + Bu + Fw. \tag{16}$$

$$y = cx. \tag{17}$$

Where;

$$A = \left[-\frac{2R_s}{2L} \right], B = \left[\frac{1}{2L} \right], F = \left[-\frac{1}{2L} \right] \tag{18}$$

$$x = [i_{ab}], u = [v_{ab}], w = [e_{ab}], y = [i_{ab}], C = [1] \tag{19}$$

The back-emf is regarded as an unknown disturbance and can be represented by a differential equation:

$$\frac{dz}{dt} = Dz. \tag{20}$$

$$w = Hz. \tag{21}$$

Where;

$$D = \begin{bmatrix} 0_{(\delta-1)\times 1} & I_{(\delta-1)} \\ 0_{1\times 1} & 0_{1\times(\delta-1)} \end{bmatrix}, \quad H = \begin{bmatrix} I_1 & 0_{1\times(\delta-1)} \end{bmatrix} \tag{22}$$

I is identity matrix and δ is degree of polynomial expression under:

$$w = \sum_{i=0}^{\delta} a_i t^i, \qquad \delta \geq 1. \tag{23}$$

Where, a_i denotes a set of unknown coefficient vectors. In cases of no experimental information about disturbance, a_i can be defined as $a_i = 0$. The entire system can be expressed by the augmented equation observer that introduces disturbances of differential equation form modeling the back-emf. The augmented model can be shown as Eq. (24) and (25):

$$\frac{dx_a}{dt} = A_a x_a + B_a u. \tag{24}$$

$$y = C_a x_a. \tag{25}$$

Where;

$$A_a = \begin{bmatrix} -\frac{2R_s}{2L} & -\frac{1}{2L} \\ 0 & 0 \end{bmatrix}, x_a = \begin{bmatrix} i_{ab} \\ e_{ab} \end{bmatrix}, B_a = \begin{bmatrix} \frac{1}{2L} \\ 0 \end{bmatrix},$$
$$u = [v_{ab}], y = [i_{ab}], C_a = [1 \quad 0]. \tag{26}$$

The degree of polynomial expression for disturbance is established by $\delta = 1$. Since, the system displayed by Eq. (24) and (25) is observable, it is possible to compose the following observer:

$$\frac{d\tilde{x}_a}{dt} = A_a \tilde{x}_a + B_a u + K(y - \tilde{y}). \tag{27}$$

K is the gain matrix of the observer [12]. If the gain of the observer is selected properly, this observer can accurately estimate line-to-line currents and back-emfs of the motors [16]. Figure 4 shows a block diagram of the proposed back-emf observer.

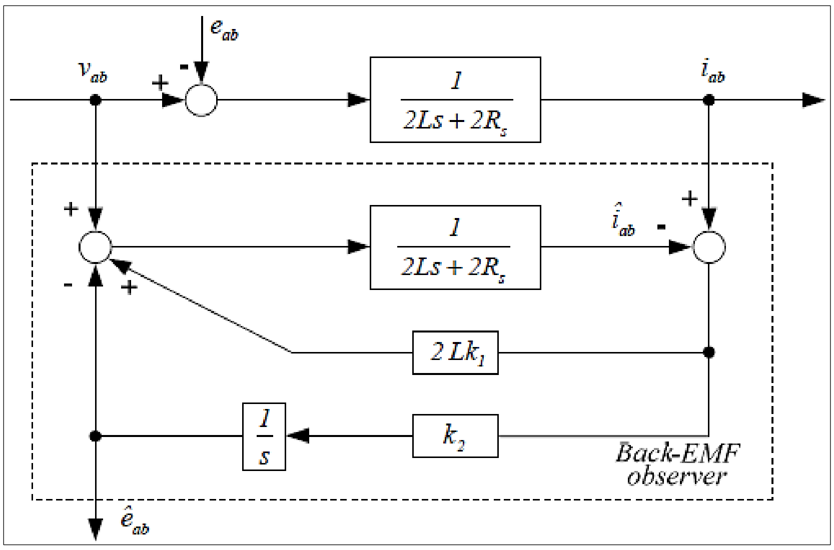
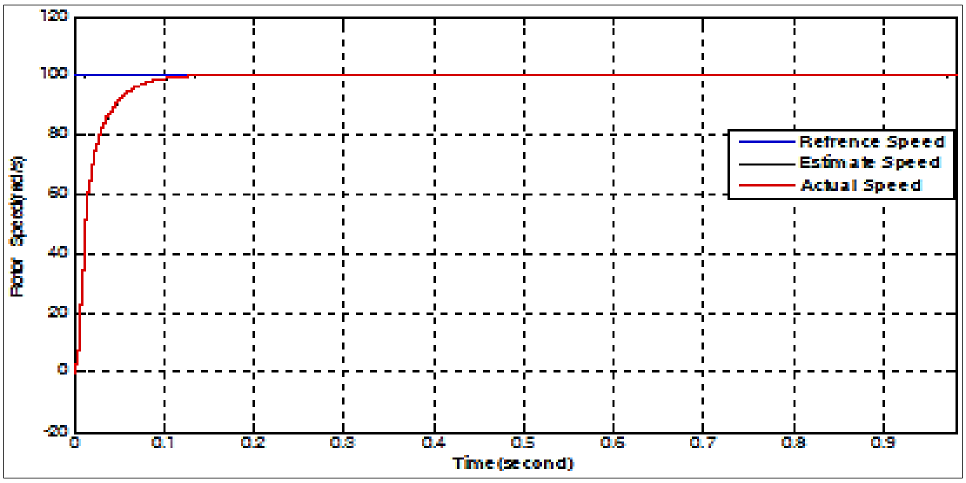


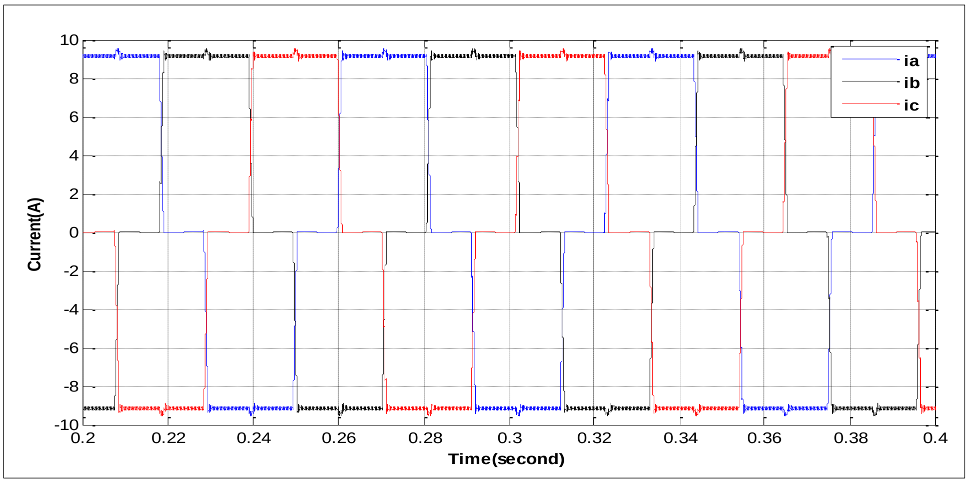
Fig. 4: *Block Diagram of the Proposed Back-EMF Observer.*

SIMULATION RESULTS

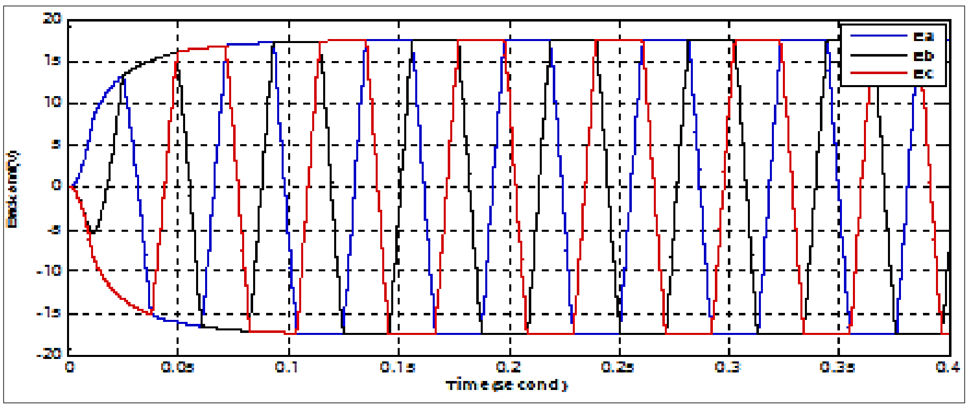
The simulation is carried out using MATLAB/Simulink. The parameters of BLDC motor used in simulations are given in Table 2. Firstly, under rated load torque, a reference speed of 100 rad/sec is assumed. The waveforms of speed, phase current and back-emf voltage are shown in Figure 5. The speed estimation as well as speed tracking has a good response in steady state and in transient situations. Moreover, the phase current waveforms are near to ideal quasi-square.



***(a)** Speed Reference Tracking.*



***(b)** Phase Current Waveforms.*



***(c)** Phase Back-EMF Voltage Waveforms.*

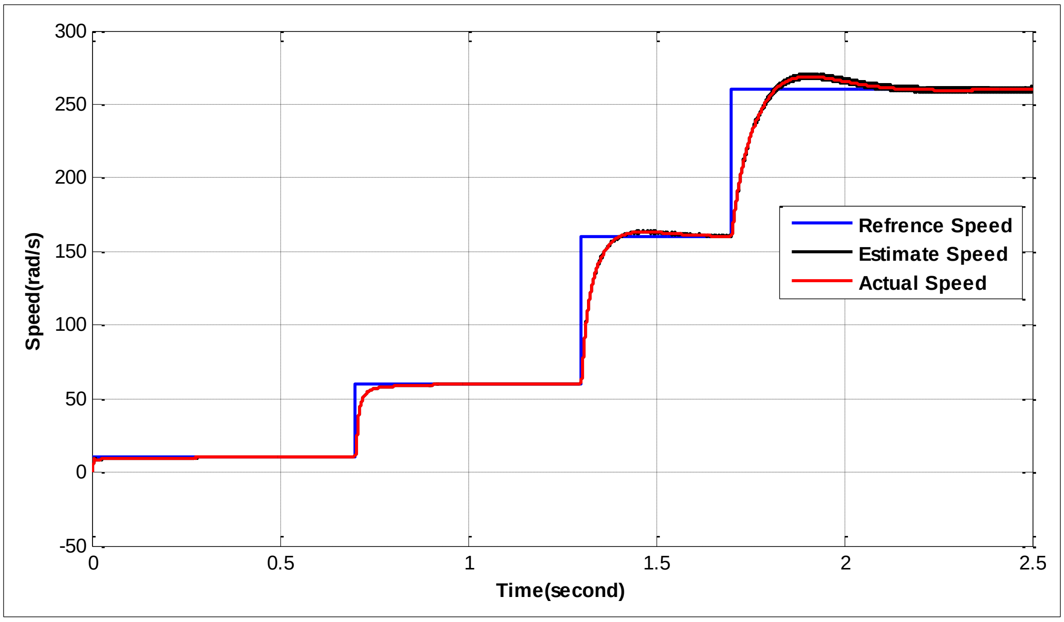
***Fig. 5:** Dynamic Performance of the DPC based BLDC Motor Drive at Speed Reference of 100 rad/sec.*

Table 2: *Brushless DC Motor Parameter.*

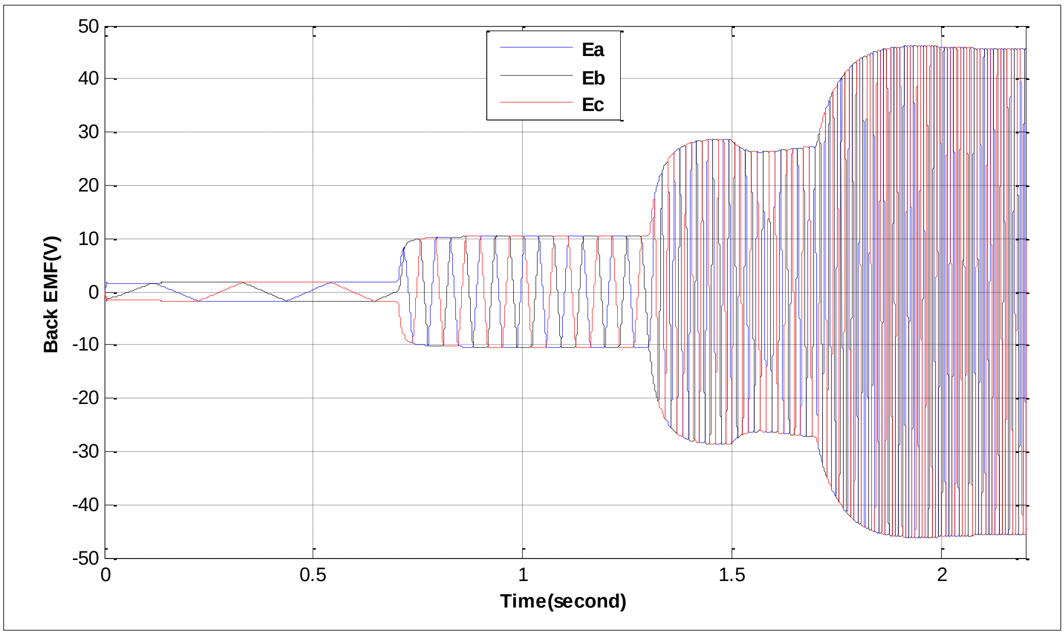
Number of Poles	P	2
Rated speed	ω_{rated}	1500 rpm
DC link voltage	V_{dc}	300 V
Self-inductance	L_s	13 mH
Phase resistance	R_s	0.4 Ω
Viscous damping coefficient	B	0.002 N.m/(rad/sec)
Moment of inertia	J	0.004 kg.m2
Load torque	C	3 N.m
flux linkage	$_m\lambda$	0.175 v.s

Figure 6 shows the dynamic response to variations of speed reference. The speed estimation and tracking is acceptable. The load torque is rated and as well as increasing of the speed, the motor power is rising.

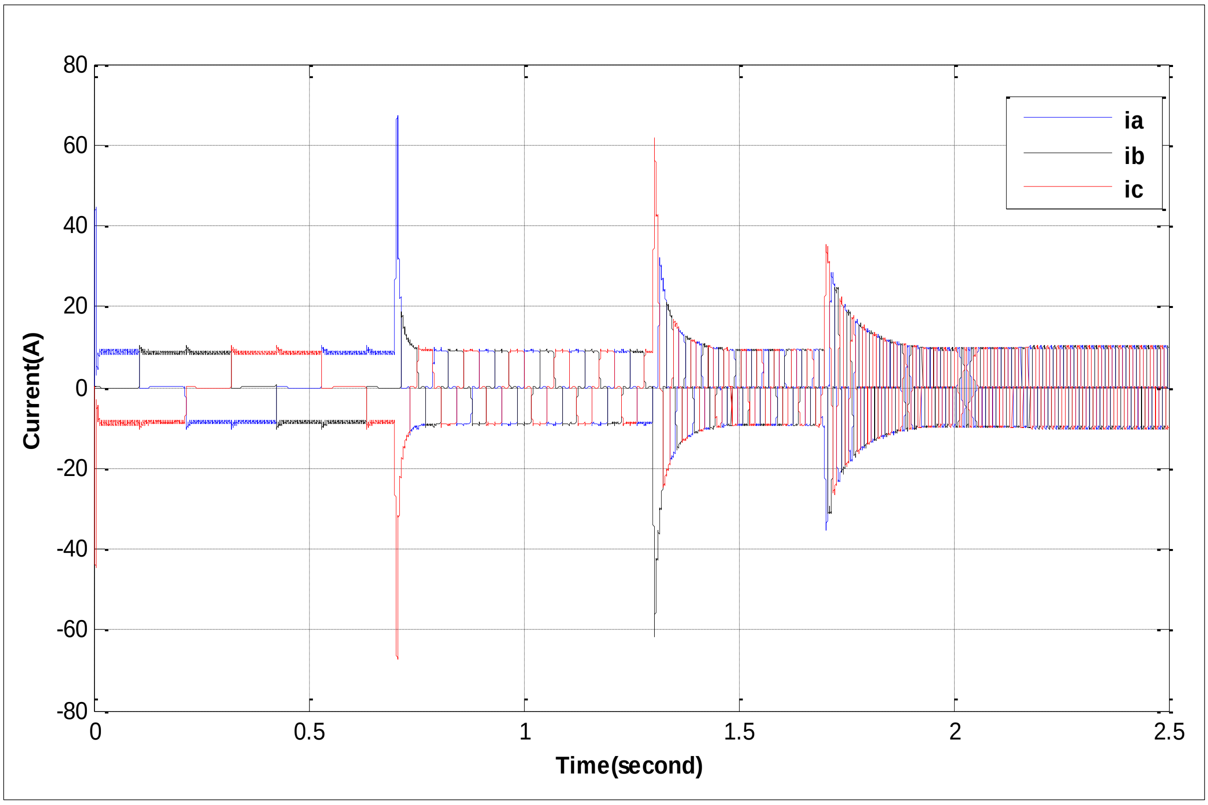
Figure 7 shows the dynamic response to variation of load torque at speed reference of 100 rad/sec. Speed estimation and tracking is well done. Also power of the motor is increasing.



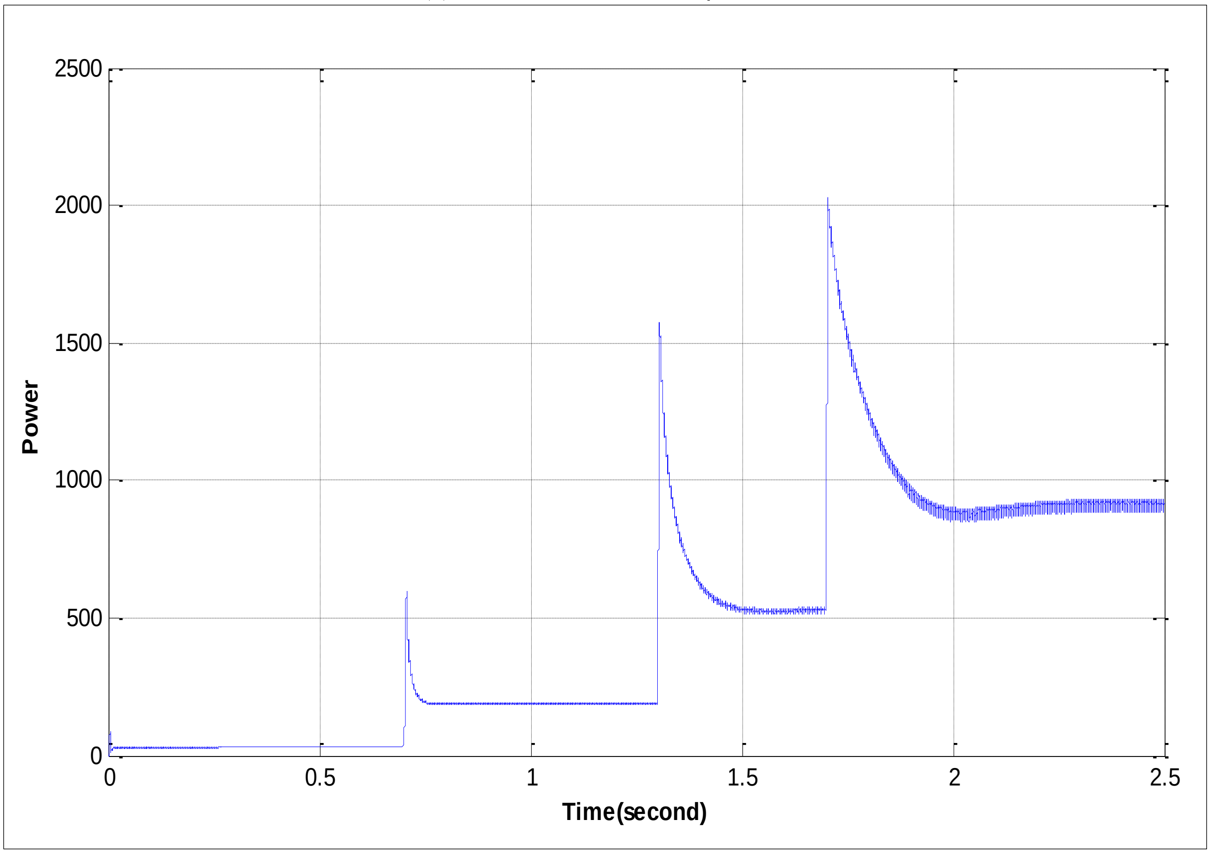
(a) *Speed Reference Tracking.*



(b) *Phase Back-EMF Voltage Waveforms.*

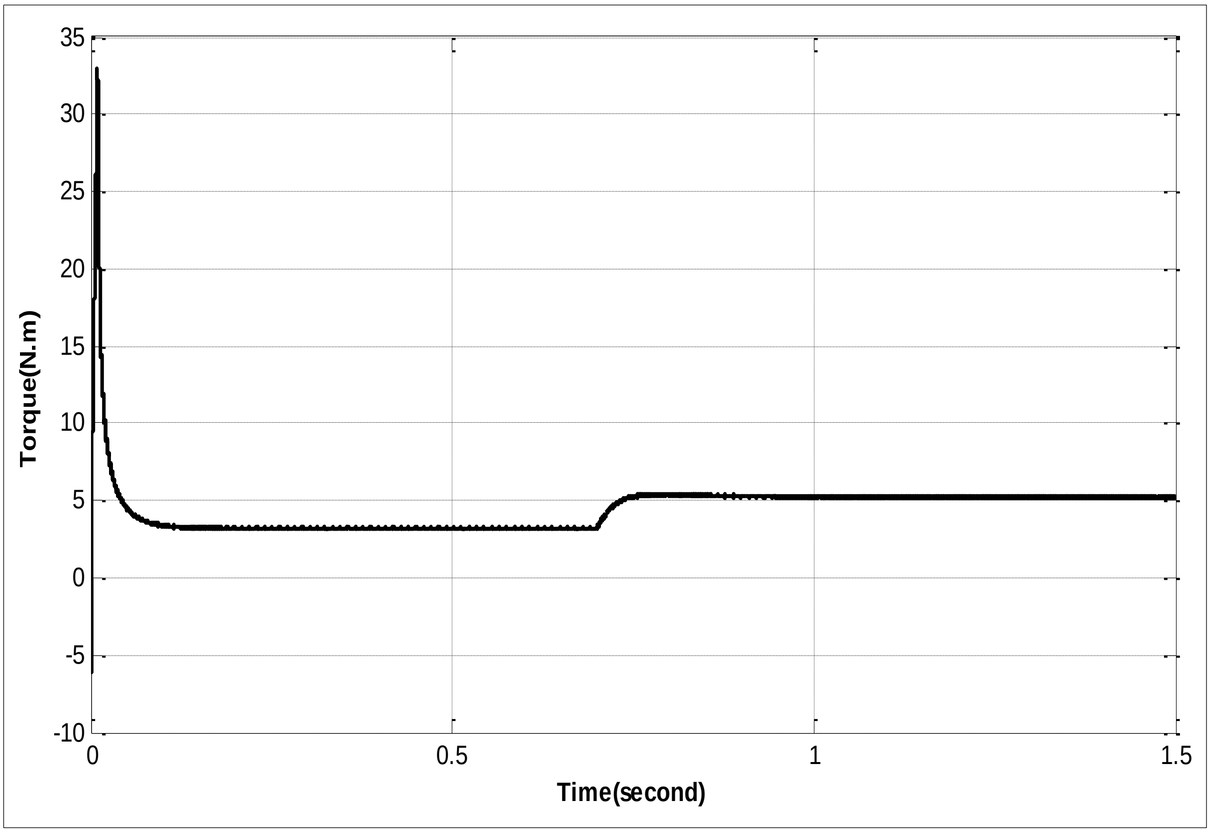


(c) Phase Current Waveforms.

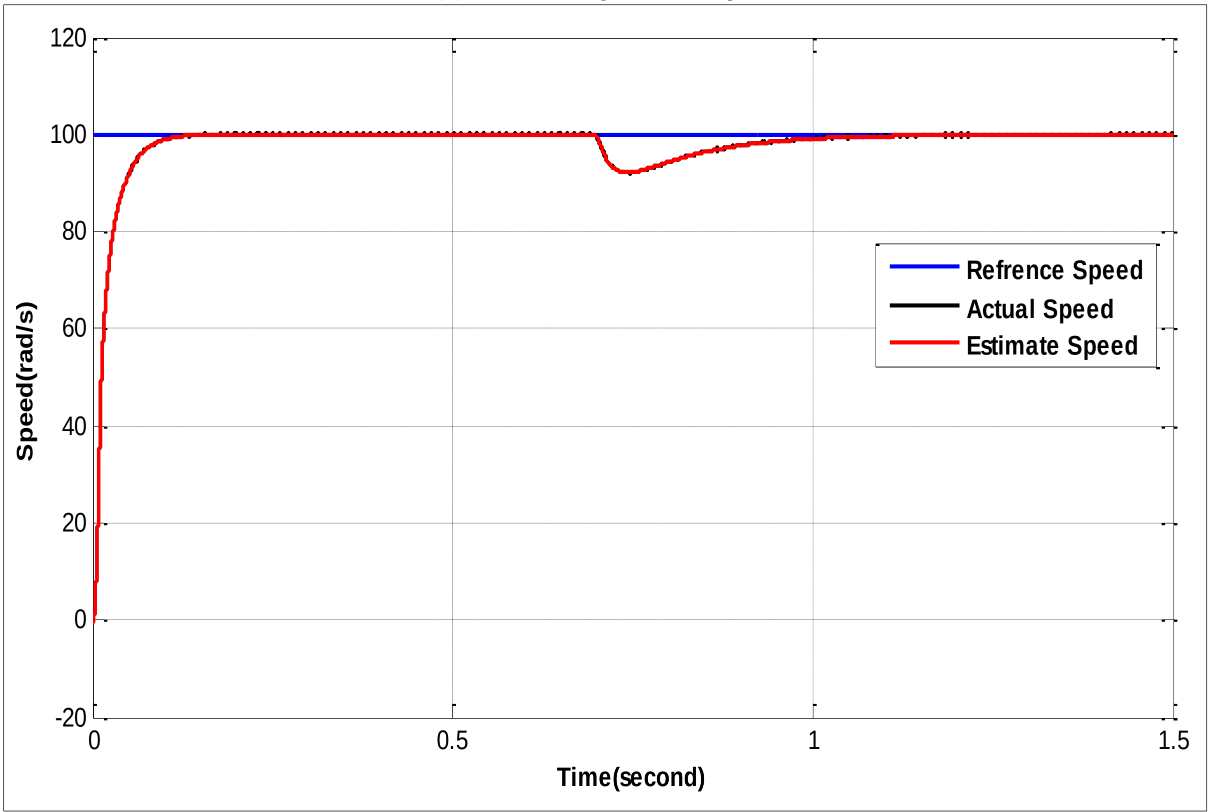


***(d)** Motor's Power.*

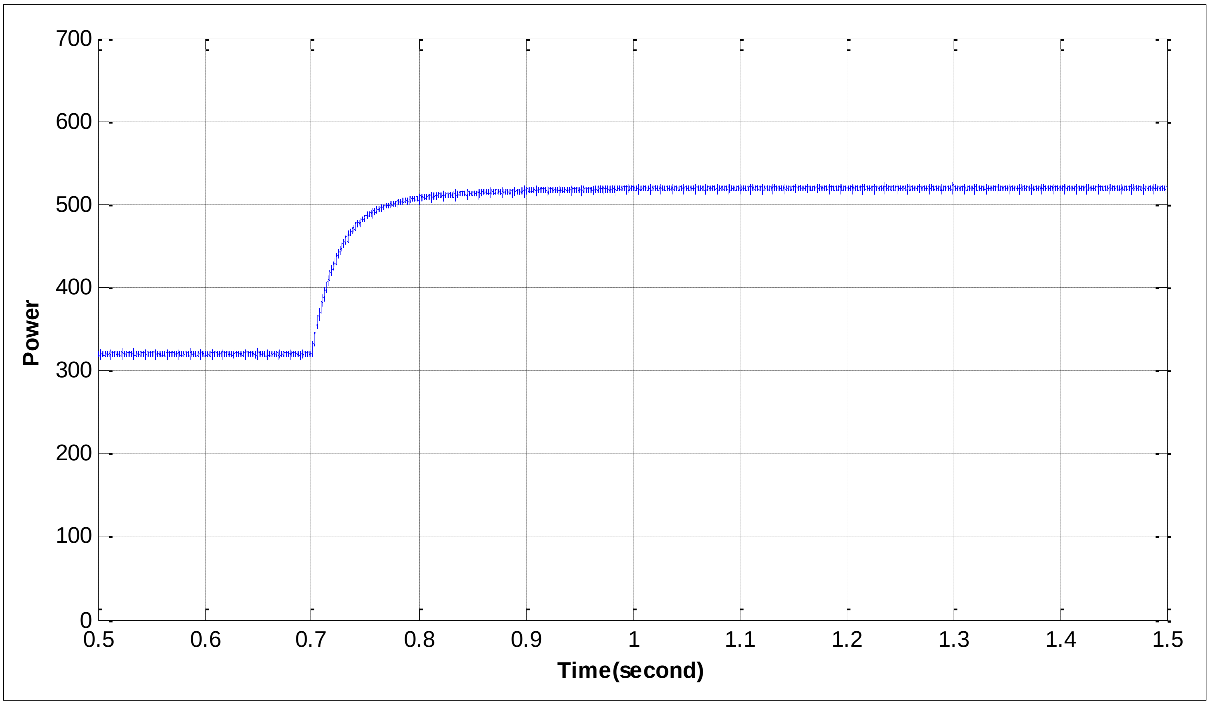
***Fig. 6:** Dynamic Response to Step Variations of Speed Reference.*



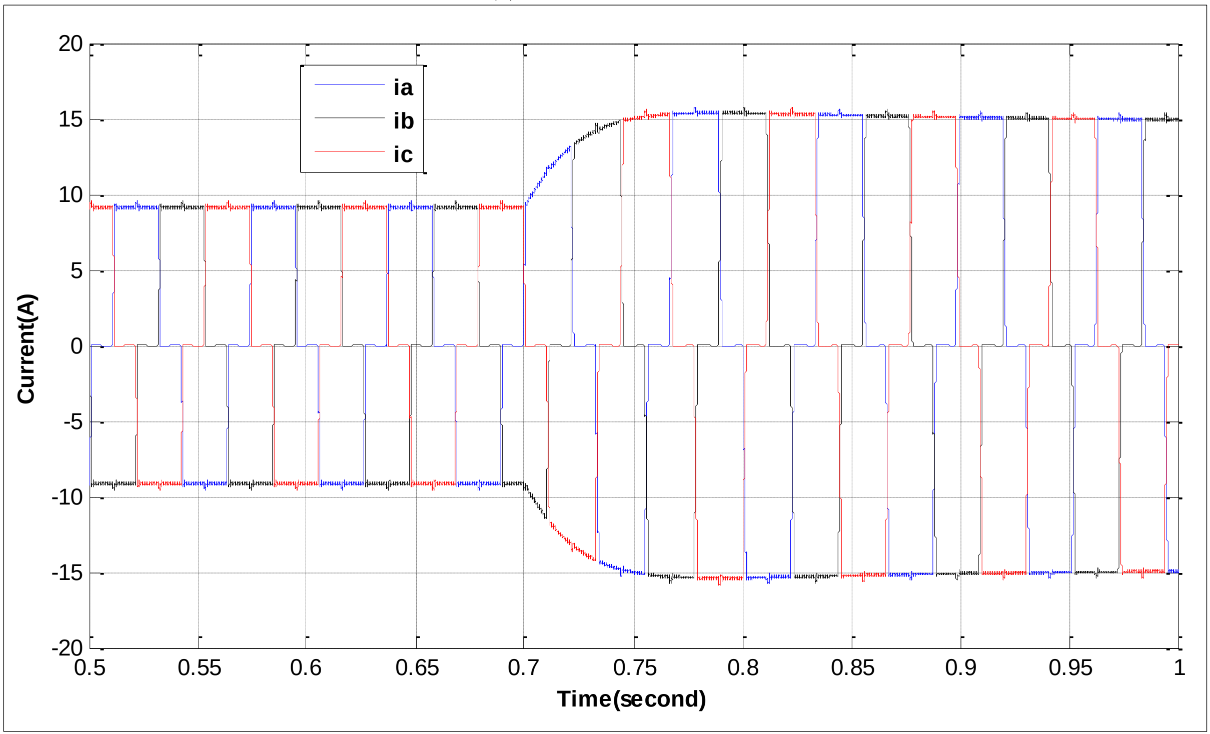
(a) Electromagnetic Torque.



(b) Speed Reference Tracking.



***(c)** Motor's Power.*



***(d)** Phase Current Waveforms.*

***Fig. 7:** Dynamic Response to Step Variation of Load Torque at Speed of 100 rad/sec.*

CONCLUSIONS

In this paper, the direct power control has been employed to speed control of brushless DC motor. Position and speed of rotor is estimated using the unknown input observer. This observer can be obtained effectively by using the equation of augmented system and an estimated line-to-line back-emf that is modeled as an unknown input. As a result, the actual rotor position as well as the machine speed can be estimated strictly even in the transient state from the estimated line-to-line back-emf. The Simulation results show that this control scheme for BLDC motor has all the advantages of traditional direct torque control. In addition, in this method sensitive to parameters is less. One of the major advantages of the DPC method compared to the DTC method is that it is can be easily estimate actual power for control system.

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