Comparative Review Of PMSM And BLDCM Based On Direct Torque Control Method

Abdulaziz Bello, Ibrahim Muhammad Kilishi, Muntaka Musa Bari, Usman Abubakar

Abstract: The direct torque control theory has achieved great success in the control of BLDC motor and PMS Motor. Many researches was carried out to apply the idea of DTC of BLDCM to PMSM since 1990's.The DTC is applied by choosing the appropriate voltage vector based on the switching status of inverter which was determined by the error signals of reference flux linkage and torque with their measured real value acquired by calculating in the stationary reference frame by means of simply detecting the motor voltage or currents. Aiming at the DTC in PMSM Drives, this research presents the theoretical basis of the DTC for PMSM firstly. Then the difference between the application of DTC to PMSM and to BLDCM, their model on the rotor reference frame with their respective motor equations was explained and presented.

Keywords: Bldcmotor, DTC, inverter, motor equations, Pmsmotor, reference flux linkage, rotor reference frame, theory,

1 INTRODUCTION

Nowadays electrical drive systems consist of; DC source, power inverter, analog/digital controllers and sensors or resolvers. The improvements in the semiconductor power electronic components have enabled advanced control techniques with high controlling ability, switching frequency and the high efficiency. Many kinds of control algorithms have been applied and were simplified in terms of drivers due to the developments in software technology. Synchronous motor is in which AC flows in the armature winding and DC excitation is supplied to the field winding. The armature winding is almost invariably on the stator and is usually a three-phase winding. The speed of the synchronous machine under steady state conditions is proportional to the frequency of the current in its armature. The magnetic field created by the armature current rotates at the same speed as that was created by the field current on the rotor (which is rotating at synchronous speed). A synchronous motor, therefore, is a constant speed machine which always rotates with zero slip at synchronous speed, which depends on the frequency and the number of poles, as given by EQ. $\omega_e = (2\pi/(P/2))/(1/f) = 2/P\,(2\pi f) = 2/P\,\omega rad/s$, A synchronous motor can be operated as a motor or generator. By varying the field current, the power-factor can be controlled. [1] PMSMs are widely used in low and mid power applications such as computer peripheral equipments, robotics, adjustable speed drives and electric vehicles. In this work, we will see that the DTC scheme has been realized successfully in the PMSM through its rotor reference frame and motor equation.

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2. Comparison PMSM and BLDCM.

PMS motors are also classified based on the flux density distribution and the shape of the current excitation. They are listed into two categories, one of which is PM synchronous motors (PMSM) and the other is PM brushless motors (BLDC). PMSM, also called permanent magnet AC (PMAC) motors, has sinusoidal flux density, current and back EMF variation while the BLDC has rectangular shaped flux density, current variation and back EMF. Classification of these two motor types is explained in Table 1.

Property	PMSM	BLDCM
Phase current excitation	Sinusoidal	Trapezoidal
Flux density	Sinusoidal	Square
Phase back EMF	Sinusoidal	Trapezoidal
Power and Torque	Constant	Constant

Table 1: Classification of permanent magnet motors based on their excitation and back EMF waveforms, the figure below shows the phase back EMF waveforms of both PMS and BLDC motors

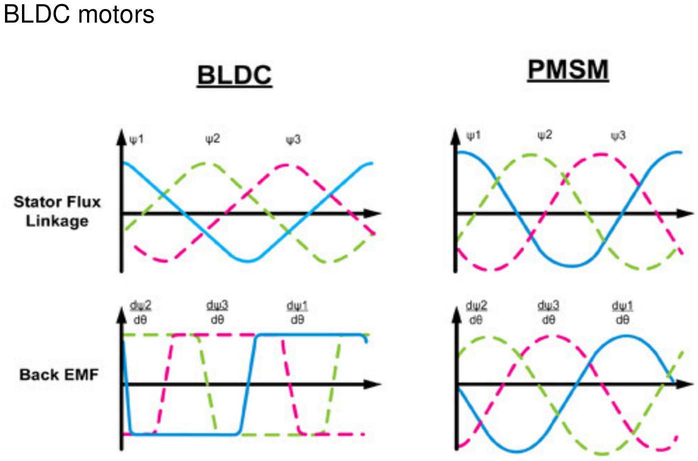

Figure 1: PMSM and BLDCM PBEMF waveforms

PMSM motors are quite similar to Brushless DC Motors (BLDCM), in that they have the same structure and the same components. Both motors have permanent magnets in the rotor that interact with the magnetic field produced by the stator coils. Nevertheless, PMSMs have a different phase Back-Electromotive Force (PBEMF), since the flux linkage between the stator and the rotor is not trapezoidal. In the

PMSM, the PBEMF is sinusoidal. This is an intentional effect produced by the way the coils in the stator are wound (in a sinusoidal fashion), while in the BLDCM the stator coils are evenly wound

2.1 The permanent-magnet motor technology

As with most motors, the synchronous motor (SM) has two primary parts. The non-moving is called the stator and the moving, usually inside the stator, is called the rotor. SM can be built in different structures. The permanent-magnet motor technology as with most motors, the synchronous motor (SM) has two primary parts. The non-moving is called the stator and the moving, usually inside the stator, is called the rotor. SM can be built in different structures: From the stator side three-phase motors are the most common. There are mainly two ways to generate a rotor flux. One uses rotor windings fed from the stator and the other is made of permanent magnets and generates a constant flux by itself. To obtain its current supply and generate the rotor flux, a motor fitted out with rotor windings require brushes. The contacts are, in this case, made of rings and do not have any commutator segment; the lifetime of both the brushes and the motor may be similar. The use of magnets enables an efficient use of the radial space and replaces the rotor windings, therefore suppressing the rotor copper losses. Advanced magnet materials such as Sm2Co17or NdFeB permit a considerable reduction in motor dimensions while maintaining a very high power density.

2.2 Model of PMSM on the rotor reference frame and motor equation

For high dynamic performance, the current control is applied on rotor flux (*dq*) reference system that is rotated at the synchronous speed. Stator magnetic flux vector ψs and rotor magnetic flux vector ψm can be represented on rotor flux (*dq*), stator flux (*x y*) reference system as shown in Fig.4. The angle between the stator and rotor magnetic flux (δ), is the load angle that is constant for a certain load torque. In that case, both stator and rotor fluxes rotate at synchronous speed. However under different loads, δ angle varies. Here, by controlling the stator current variation or the δ angle variation, the increase of the torque can be controlled.

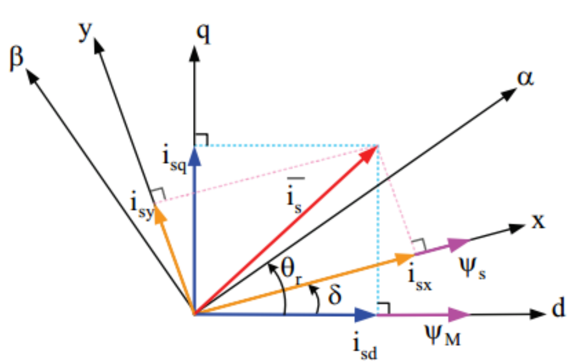

Figure 2: Stator and rotor magnetic fluxes in different reference systems

PMSM specifically has the following characteristics: (1) the machine is more robust, permitting a much higher speed of operation, (2) the effective air gap in the d^e-*axis* is larger than that in the q^e —*axis*, which makes the machine a salient pole with $Ldm < Lqm$, and (3) with the effective air gap being low, the armature reaction effect becomes dominant. The steady-state analysis of a sinusoidal PM machine with an equivalent circuit and phasor diagram remain the same as a wound field motor except that the equivalent field current *If* should be considered constant, that is, the flux linkage $\psi f = Ldm\ I'f$ = constant. The synchronously rotating frame transient equivalent circuit, as shown in **Fig. 1,**

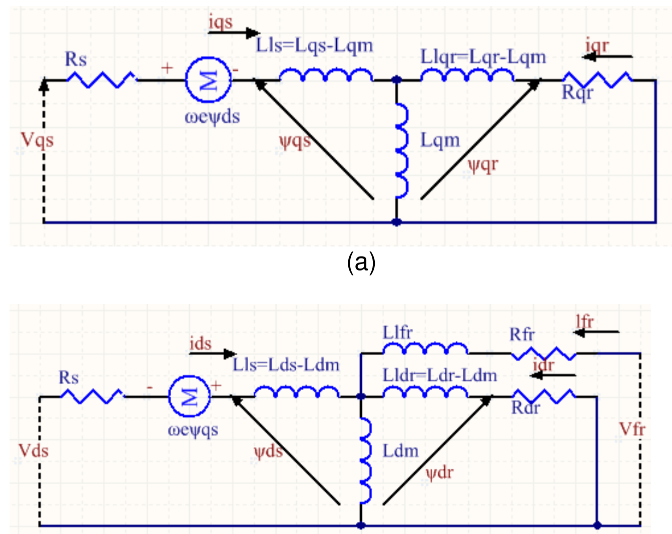

Figure 3: $d^e - q^e$ equivalent circuits of synchronous machines (a) q^e —axis circuit, (b)d^e-axis circuit

The steady-state model of the motor can be derived by equating all the time derivatives or S- related terms to zero. The following are the steady-state equations:

$$V_{qs} = R_s I_{qs} + \omega_e(\psi_f + L_{ds} I_{ds})$$

$$= R_s I_{qs} + V_f + X_{ds} I_{ds} \quad (1)$$

$$V_{ds} = R_s I_{ds} - X_{qs} I_{qs} \quad (2)$$

Also it holds here, except the machine may not have any damper winding. Fig. 2 shows the equivalent circuits where the finite core loss is represented by the dotted damper windings. Ignoring the core loss, the circuit equations can be written as

$$\psi\hat{}_f = L_{dm} I'_f \quad (5)$$

$$\psi'_{ds} = i_{ds}(L_{ls} + L_{dm}) = i_{ds} L_{ds} \quad (6)$$

$$\psi_{ds} = \psi\hat{}_f + \psi'_{ds} \quad (7)$$

$$\psi_{qs} = i_{qs}(L_{ls} + L_{qm}) = i_{qs} L_{qs} \quad (8)$$

Where:

$$T_e = \frac{3}{2}\left(\frac{P}{2}\right)(\psi_{ds} i_{qs} - \psi_{qs} i_{ds}) \quad (9)$$

And the torque equation is;

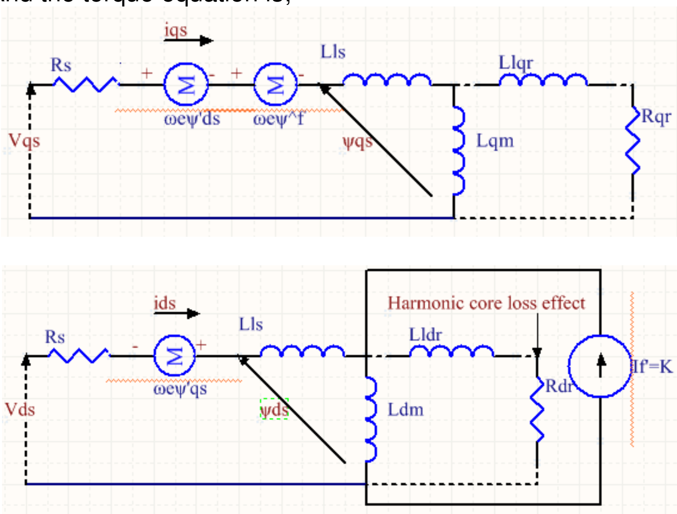

Figure 4: Synchronously rotating frame ($d^e - q^e$) equivalent circuits of IPM motor

Substituting Equation (5)-(8) in (3), (4), and (9) and simplifying, we can write

$$\frac{di_{qs}}{dt} = \frac{\omega_b}{X_{qs}}[V_{qs} - R_s i_{qs} - \frac{\omega_e}{\omega_b}X_{ds}i_{ds} - \frac{\omega_e}{\omega_b}V_f] \quad (10)$$

$$\frac{di_{ds}}{dt} = \frac{\omega_b}{X_{ds}}[V_{ds} - R_s i_{ds} - \frac{\omega_e}{\omega_b}X_{qs}i_{qs}] \quad (11)$$

$$T_e = \frac{3P}{4\omega_b}[(F'_{d_s} + V_f)i_{qs} - F_{qs}i_{ds}] \quad (12)$$

Where:

$V_f = \omega_b \hat{\psi}_f$, $X_{qs} = \omega_b L_{qs}$,

$X_{ds} = \omega_b L_{ds}$, $F_{ds}' = \omega_e \psi_{ds}'$

$F_{qs} = \omega_e \psi_{qs}$ And ω_e = Base Frequency.

These equations, which are valid for IPM as well as SMPM (except *Ldm=Lqm*), can be used for computer simulation study. Again, for steady-state Operation of the machine, the time derivative components equation (3) and (4) are zero, that is, these can be written in the form of equations (1) and (2), respectively

3 The Brushless DC Motor Technology

The BDCM motor is also referred to as an electronically commuted motor and, as there are no brushes on the rotor the commutation is performed electronically depending on the rotor position. The stator phase windings are inserted in the slots or can be wound as one coil on the magnetic pole. In DC Commutator motor, the current polarity is reversed by the commutator and the brushes, but in the brushless DC motor, the polarity reversal is performed by semiconductor switches which are to be switched in synchronization with the rotor position. Besides the higher reliability, the missing commutator brings another advantage. The commutator is also a limiting factor in the maximal speed of the DC motor. Therefore the BLDC motor can be employed in applications requiring high speed. Replacement of a DC motor by a BLDC motor place higher demands on control algorithm and control circuit. Firstly, the BLDC motor is usually considered as a three phase system. Thus, it has to be powered by a three phase power supply. Next, the rotor position must be known at certain angles, in order to align the applied voltage with the back-EMF. The alignment between the back-EMF and commutation events is very important. In this condition the motor behaves as a DC motor and runs at the best working point. But the drawbacks of the BLDC motor caused by necessity of power converter and rotor position measurement are balanced by excellent performance and reliability, and also by the ever-falling prices of power components and control circuits.

3.1Model of BLDCM on the rotor reference frame and motor equation

Modeling of a BLDC motor can be developed in the similar manner as a three-phase synchronous machine. Since there is a permanent magnet mounted on the rotor, some dynamic characteristics are different. Flux linkage from the rotor depends upon the magnet material. Therefore, saturation of magnetic flux linkage is typical for this kind of motors. As any typical three-phase motors, one structure of the BLDC motor is fed by a three-phase voltage source. The source is not necessarily to be sinusoidal. Square wave or other wave-shape can be applied as long as the peak voltage does not exceed the maximum voltage limit of the motor. Similarly, the model of the armature winding for the BLDC motor is expressed as follows:

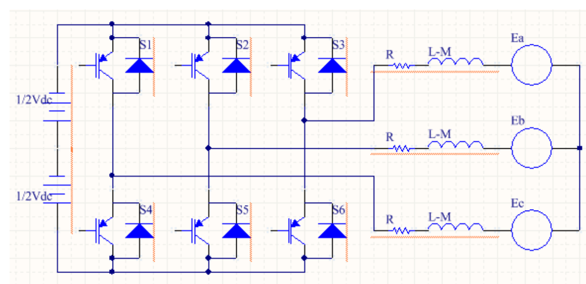

Figure 5: BLDC configurations with inverter.

$$V_a = Ri_a + L\frac{di_a}{dt} + E_a \quad (1)$$

$$V_b = Ri_b + L\frac{di_b}{dt} + E_b \quad (2)$$

$$V_c = Ri_c + L\frac{di_c}{dt} + E_c \quad (3)$$

Keys:
L is armature self inductance {Henry (H)},
R is armature resistance {Ohms (Ω)},
V_a, V_b, V_c Are terminal phase voltages {Volt. (V)},
i_a, i_b, i_c Are motor input current {Amp. (A)},
And E_a, E_b, E_c are motor back EMF {Volt. (V)}.
In the 3-phase BLDC motor, the back-EMF is related to a function of rotor position and the back-EMF of each phase has 120° phase angle difference so equation of each phase should be as follows:

$$E_a = K_w f(\theta)\omega \quad (4)$$
$$E_b = K_w f(\theta - 2\pi/3)\omega \quad (5)$$
$$E_c = K_w f(\theta + 2\pi/3)\omega \quad (6)$$

Keys:

K_w Is back EMF constant of single phase ($V/rad.s^{-1}$),
5 is the electrical rotor angle ($^{\circ}el$),
5 is the rotor speed ($rad.s^{-1}$).
The electrical rotor angle is equal to the mechanical rotor angle multiplied by the number of pole pair's p:

$$\theta = \frac{P}{2}\theta_m \quad (7)$$

Key:
θ_m Is mechanical rotor angle (rad). Total torque output can be represented as summation of that of each phase. Next equation represents the total torque output:

$$T_e = \frac{E_a i_a + E_b i_b + E_c i_c}{\omega} \quad (8)$$

T_e Is the total torque output (N_m),
The equation of mechanical part is represented as follows:

$$T_e - T_l = J\frac{d\omega}{dt} + B_\omega \quad (9)$$

Keys:
T_l Is load torque {Neutons per meter (N_m)},
J inertia of rotor and couple shaft {Kilogram per meter (Kgm^2)},
B friction constant ($Nms.rad^{-1}$)
The converter block was developed using equations below: (2)

$$V_a = (S_1)V_d/2 - (S_4)V_d/2 \quad (10)$$
$$V_b = (S_3)V_d/2 - (S_6)V_d/2 \quad (11)$$
$$V_c = (S_5)V_d/2 - (S_2)V_d/2 \quad (12)$$

4 Direct torque controls of PMSmotors

There are two control methods used for the PMSM; field or flux oriented control FOC and direct torque control DTC. The AC drives in which (FOC) is used field control enables to flux control. The rotor flux space vector is determined and regulated by the use of an angular velocity which is formed from the speed feedback and the stator current vector. The drawback of the flux vector control is that it requires a tachogenerator or an encoder for an optimum accuracy. This will absolutely increases the costs of the equipment. This method of "DTC" directly select the stator voltage vectors according to the errors between the reference and actual values of the torque and stator flux. Torque and flux are obtained and controlled directly using nonlinear transformations on hysteresis controllers, without carrying out coordinate transformations. Two-layer hysteresis band controller is applied for stator flux control and a three-layer hysteresis band controller is applied for torque control. DTC is an appropriately choosing than FOC method because of its high performance applications due to the advantages of reduction in computations [2] Since the torque and flux estimators in DTC needs and depends on the parameters identification and accuracy of the estimations, the estimation of the electromagnetic torque is essential for the whole system performance. In PWM and flux vector controlled drives, voltage and frequency were used as control variables and that are modulated and then applied to the motor. This modulator layer needs an additional signal processing time and restricts the torque and speed response. The idea behind DTC is to directly mix the stator flux vector by applying the appropriate voltage vector to the stator windings. This is done by using a pre-designed switching table to directly update the inverter's discrete switch positions whenever the variables to be controlled, the electromagnetic torque and the stator flux, exceed the hysteresis bounds around their references.

4.1 Previous work

There are several researches done in the choice of DTC rather than FOC, for example an investigation was made on the torque behavior of a single phase PMSM [3]. Also development on the reference flux vector calculation in space vector modulation for DTC. They extracted the voltage as a trigonometric function of the period and using the frame transformations, they calculated the usage periods of the zero vectors depending on the angular frequency of the current. However, this complicated control structure has been implemented in simulations but not experimentally completed. In torque graphs, there are long delay periods between the actual and calculated values [4]. Zero vectors were used in space vector modulation for DTC. Zero vectors are theoretically used in asynchronous motor's DTC. They tried to increase the application duration of the vectors that are used to enlarge the torque angles in low speed operation of the PMSM applications. However, in low speeds, using zero vectors for long period of time causes the fast changes in stator flux and the limit values are enforced. Moreover, switching losses of this implementation will be higher since 8 vectors are used instead of 6 [5]. DTC was applied without using a speed sensor but used only current and voltage sensors in order to determine the stator voltage vectors. In their results that they used a closed loop controller, they indicated that the calculated speed data oscillates too much [6]. DTC of the PMSM was applied by implementing a model predictive control algorithm that reduces the switching frequency and hence the switching losses. The proposed algorithm could reduce the switching losses by 50% and the THD by 25% [7]. DTC method was applied using LP filter in order to eliminate the harmonics by chosen its cutoff frequency in which the outputs of the comparators were applied to determine the appropriate voltage vector and stator flux space vector [8]. The simulation results show that, the system can run smoothly and still it has perfect dynamic and static characteristics for a speed of 1500 rpm and the fuzzy self-adapting PID controller have less regulating time and it is stronger, robust compared to the traditional PI controller [10].

5 Contributions

It is clear that the electromagnetic torque is directly proportional to the y-axis component of the stator current [9]. Dependency on less number of parameters is the main advantage of the stator current control. It is possible to say that in a practical application, the estimation technique shown in equation (12) requires knowledge of inductances. The estimated instantaneous electric torque is easily compared with a reference value to achieve a fast torque control. At the same time, the stator flux linkage is compared with the reference value to ensure sufficient magnetization of the motor. The torque of the PMSM is controlled by monitoring and controlling the armature current since electromagnetic torque is proportional to the current. Moreover, DTC is appropriate for an efficient control of the torque and flux without changing the motor parameters and load. Also the flux and torque can be directly controlled with the inverter voltage vector in DTC. Two independent hysteresis controllers are to be used in order to satisfy the limits of the flux and torque. These are the stator flux and torque controllers. DTC process of the permanent magnet synchronous motor is explained. It is concluded that DTC can be applied for the permanent magnet synchronous motor and is reliable in a wide speed range more than that of BLDCM. Especially in applications where high dynamic performance is demanded DTC has a great advantage over other control methods due to its property of fast torque response.

6. Conclusion

Since the introduction of DTC a lot of research has been done to improve the performance of DTC drives while maintaining the good properties such as low complexity, good dynamic response, and high robustness. This thesis explained the mathematical equations related to the application of DTC in PMSM. The equations show that the change of torque can be controlled by keeping the amplitude of the stator flux linkage constant and increasing the rotating speed of the stator flux linkage as fast as possible. The amplitude and rotating speed of the stator flux linkage can be controlled by selecting the proper stator voltage vectors. The technology and model of PMSM and BLDCM on the rotor reference frame with their respective motor equations were presented also differences in terms of DTC principles were presented. Finally it shows from the above review of DTC principles in PMSM and BLDCM that the DTC implemented in PMSM having less level of torque and flux ripples and at the same time maintaining good torque response. Further work can be done on automation/simulation of PMSM and BLDCM based on DTC.

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