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Direct Torque Control of Permanent Magnet Synchronous Motors

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1. Introduction

Modern electrical drive systems consist of; power electronics components, transformers, analog/digital controllers and sensors or observers. The improvements in the semiconductor power electronic components have enabled advanced control techniques with high switching frequency and the high efficiency. Complex control algorithms have been widely used and got simplified in drivers due to the developments in software technology. DC, asynchronous and synchronous motors are frequently used motor types with these driver systems. New kinds of motors are developed like linear motors, step motors, switching reluctance motors, and permanent magnet synchronous motors. Permanent magnet synchronous motors are used where in general high demands are made with regard to speed stability and the synchronous operation of several interconnected motors. They are suitable for applications where load-independent speeds or synchronous operation are required under strict observance of defined speed relations within a large frequency range.

As the technology gets improved, studies on PMSM such as direct torque control method have been improved as well. DTC has many advantages such as faster torque control, high torque at low speeds, and high speed sensitivity. The main idea in DTC is to use the motor flux and torque as basic control variables, identical to the DC drives. In order to emulate the magnetic operating conditions of a DC motor, the information regarding the rotor status is required to perform the field orientation process of the flux-vector drive. This information should be obtained by feeding the rotor speed and angular position back by using a pulse encoder. Encoders are costly and they add more complexity to the overall system.

Several methods have been developed to obtain the rotor position and angular speed from the electrical measurements and computations in order to eliminate the need for sensors. The idea behind such methods is to manipulate the motor equations in order to express motor position and speed as functions of the terminal quantities. In (Adreescu & Rabinovici, 2004) self tuning speed controller and Luenberger observer was proposed, however it is still necessary to use an encoder for rotor position detection. Most of the methods; however, work only when the rotor is anisotropic and if the dependence of the inductance on the rotor position is accurately known; moreover, the speed is not estimated, thus the drive is not completely without mechanical sensors (Yan et al, 2005). On the other hand, it can be reported that the method in (Bolognani et al, 1999) can a viable solution for the online determination of the rotor position and speed of a PMSM. In (Ichikawa et al, 2003) extended

electromotive force model is used to estimate the rotor position. However, this method is based on expert knowledge. Some researchers have proposed a combination of current and flux linkage estimation (Rahman & Toliyat, 1996), (Toliyat et al, 2002) or methods including Kalman filters, fuzzy logic, and neural network observers to obtain the rotor position angle (Dan et al, 2004), (Grzesiak & Kazmierkowski, 2007). Recently, researchers have tried to reduce the torque pulses and harmonics in PMSM. In addition, (Sozer et al, 2000) presented an inverter output filter system for PWM derives to reduce the harmonics of surface mounted permanent magnet synchronous motor (SPMSM), it shows some effectiveness in reducing switching harmonics, but very large circulating current between inverter output and filter elements is required to reshape the motor terminal voltage which may violate the inverter's current limit.

Efficiency is important due to the energy scarcity of the world and higher performance is needed for modern motion control applications. PMSM offer efficiency advantages over induction machines when employed in variable speed drives. Since much of the excitation in the PMSM is provided by the magnets, the PMSM will have smaller losses associated with the magnetizing component of the stator current. The stator current may be almost purely torque producing in a PMSM drive while in an induction machine drive there is always a large magnetization current present. Due to the synchronous operation of the PMSM, rotor losses are greatly reduced. The application of the PMSMs for low speed operation in direct drives is an economic alternative for the induction motors with gearboxes. Since the speed of the direct drive PMSMs is lower than the speed of the induction motors with the gearboxes, the risk of torque harmonics appearing at the mechanical resonances is increased in the speed range of normal operation. Permanent magnet motors have been used for decades in low power applications such as servo drives and domestic appliances. Recently, the PMSM drives have been developed further and are used in industrial applications requiring high torque at low speed. PMSM drives are replacing standard induction motors with gearboxes in, for example, paper and textile industry, special applications for marine (Laurila, 2004). However, PM synchronous motors can not be fed directly from the mains supply and need to be driven by the AC motor drives. Similar to the induction machine, vector control method is employed for the PM synchronous motors to obtain high bandwidth torque control performance. For vector control, the rotor flux angle needs to be known by the AC motor drive. Therefore, sensors (e.g. an incremental encoder) on the motor shaft are utilized to sense the rotor flux angle and AC motor drives use this angle information for vector coordinate transformations. With vector coordinate transformations, the AC motor in the control coordinates is converted to a DC motor where torque control is a simple issue of current control to be achieved by the current regulator. Thus, the vector control method enables high bandwidth torque control of an AC machine, which brings high bandwidth of speed and position control (Geyer et al, 2010).

Although machine drives with modern control techniques have brought high performance and robustness to the motion control area, research has continued for developments in the AC motors and drives technology. The motivation is to improve the technology for high efficiency and for high performance. The literature study regarding to the direct torque control of the permanent magnet synchronous machines is presented in this chapter.

The theory of the direct torque control was developed by (Depenbrock, 1985) for the first time for asynchronous motors.

(Takahashi and Noguchi, 1986) developed the direct torque control only using the torque routines for asynchronous motors.

(Depenbrock, 1988) presented the direct self control theory. According to this theory, the variations in operation frequency are obtained by the algebraic calculations from the Heyland-Ossanna circular diagram based on the torque demand feed-back.

(Pillay and Krishnan 1989) modeled the permanent magnet synchronous motor by state-space variables and accomplished the torque analysis. This study was a very significant step for the permanent magnet synchronous machine studies.

(Adnanes, 1990) developed the torque analysis of the permanent magnet synchronous machine in per unit mode and obtained the detailed the mathematical relationship between the flux and torque.

(Raymond and Lang, 1991) presented the real-time adaptive control of the PMSM by using the Motorola 68020 microprocessor. The motor model was linearized for the proposed controller and the nonlinear effects of the inverter and system dynamics that can not be modeled were omitted. The mechanical parameters were estimated so that they could be taken into account for the controller.

(Pelczewski et al., 1991) performed the optimal model tracking control of the PMSM. In order to have the controller doing the computations, motor model and its linearization were required.

(Matsui and Ohashi, 1992) proposed a DSP based adaptive controller for PMSM. Therefore, they proved that the DSPs can be implemented in motor controls as well.

(Chern and Wu, 1993) presented the position control of the PMSM by using the variable oriented controller. The controller instantaneously does the calculations depending on the unknown load and motor parameters. The system model is required and the computations require very long periods of time.

(Ogasawara and Akagi, 1996) realized the position estimation of the PM motors for zero and low speed conditions according to the saliency.

(Zhong et al., 1997) completed one of the first academic studies in the field of direct torque control of the permanent magnet synchronous machines.

(Zhong et al., 1999) proposed the direct torque control of the permanent magnet synchronous motor using two level torque hysteresis controller.

(Rahman et al., 1999) achieved the direct torque control by using a method based on obtaining the d and q-axis voltages using certain coefficients.

(Luukko, 2000) developed the switching table for the direct torque control by adding the zero vectors to the vector selection algorithm.

(Vaez Zadeh, 2001) experimentally achieved the constant torque control on a vector controller by using the TMS320C31 DSP. In this study, the torque did not respond well in terms of the desired torque value and response time, since the DSP technology was not sufficient to implement the dynamic behavior of the motor.

(Tan et al., 2001) and Martins et al. (2002) proposed to reduce the torque ripples and fix the switching frequency in AC drive systems by using a multi-level inverter. These methods result in better waveforms, reduce the distortions, and are capable of operating in lower switching frequency. However, on the other hand, they require more number of switching devices. Moreover, the control strategies of these methods are very complicated.

(Dariusz et al., 2002) implemented the space vector modulation by using a DSP and achieved the direct torque control.

(Balazovic, 2003) published a technical guide that describes the torque control and vector control of the permanent magnet synchronous motor. This publication has been referred in many similar studies of the industry and academia.

(Tang et al., 2004) used the space vector modulation in order to reduce the torque ripples and they got good results. Developed control algorithm required two PI controllers and the estimation of the reference voltage and the switching sequence of the selected vectors.

(Zhao et al., 2004) achieved the control of the very high speed (200000 rpm) permanent magnet synchronous machine by using a DSP.

(Popescu et al., 2006) investigated the torque behavior of a single phase permanent magnet synchronous motor.

(Jolly et al., 2006) performed the control of the permanent magnet synchronous machine in constant power region.

(Luukko et al., 2007) presented the different rotor and load angle estimation methods for the direct torque control. They directly calculated the load angle from the PMSM equations. In these calculations, they used the tangent function. When the results of the DSP controlled inverter and the motor test setup are investigated, it is seen that the rotor angle estimation has oscillations. The error between the actual and estimated rotor angle variations get larger in the periods when the oscillations are larger. It is revealed that PID coefficients should be kept very high in order to compensate this error.

(Chen et al., 2007) designed an output filter for a direct torque controlled inverter. The filter is composed of an RLC filter and an isolation transformer. This study is interesting since it includes both the transformer design and the soft switching techniques in power electronics. Furthermore, it is true that the transformer and RLC based filter will add significant cost to the system instead as compared to the developments in the generation of inverter switching signals in terms of controls.

(Noriega et al., 2007) designed a fuzzy logic controller for the DTC. They used the torque error and the stator current for the fuzzy logic membership functions. In addition to the simulation studies, they used an AC motor drive setup called Platform III by implementing fuzzy logic functions to the software of this setup. Both simulation and the experimental results show that the stator current is not in a wave form and it has some uncertain and random shapes. As compared to the PI controlled DTC method, stator current is much more distorted.

(Wang et al., 2007) developed 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.

(Zhao et al., 2007) developed a fourth order sliding mode observer for the surface mounted permanent magnet synchronous motor. According to the motor parameters, it is seen that the motor was a high power low speed motor. In simulations, the model available in Matlab&Simulink library was implemented. The authors stated that fuzzy logic can be employed to address the chattering issues commonly occur in sliding mode controls.

(Swierczynski et al., 2008) applied the DTC method onto a high power PMSM by using an inverter that is driven by the space vector modulation method. In this study, they used DSPACE 1103 control unit in which the Matlab Simulink simulation models can be directly applied. In this study, it was not required to design a speed controller. This is mainly due to the fact that the vehicle operator can control the speed according to the different driving conditions.

(Yutao et al., 2008) used the radial basis neural network functions to exploit the reference torque in a rectangular step functions. They attempted to reduce the torque vibrations and make it in a rectangular shape which is not in fact.

(Cui et al., 2008) researched on a high performance DTC system based on a DSP. They performed simulation and experimental studies. However, in their studies, the controls execution time completed in 130 μ s.

(Li et al., 2008) used zero vectors in space vector modulation for DTC. Zero vectors are theoretically used in asynchronous motor's direct torque control. 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.

(Jilong et al., 2008) proposed an improved Kalman filter in order to sensor-less estimation of the rotor's initial position in DTC. For this reason, they employed the high frequency signal injection method. Since the high frequency signal is weak, it would not help the rotor's motion. Therefore, rotor speed is assumed to be zero. The computation intensity is very high due to the fact that the voltage and current quantities are obtained through differential inequalities depending on the speed.

(Guo et al., 2009) applied the space-vector modulation in a matrix converter for DTC application in naval vehicles. In this study, the signals for the matrix converter is generated by a DSP where the dual space modulation method was used. However, it is seen that the current drawn by the matrix converter has very high total harmonic distortion.

(Sanchez et al., 2009) achieved the direct torque control without using a speed sensor but using only current and voltage sensor 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.

(Siahbalaee et al., 2009) studied the copper losses by flux optimization for their direct torque controlled PMSP in order to reduce the torque and flux oscillations.

(Liu et al., 2009) tried to use the predictive control method in direct torque control. There are limited number of studies in the literature using predictive control in direct torque control. Experimental results were obtained by using a DSP. However, in the experimental results, they implemented complicated trigonometric functions. In the experimental results, much more flux drop can be observed as compared to their simulation results. They could apply the proposed application by reducing the flux reference.

(Inoue et al., 2010) linearized the torque control system of a direct torque controlled buried magnet synchronous motor and they acquired the torque response depending on a constant gain coefficient. They calculated the PI coefficients that are updated according to the estimated torque values by a new gain scheduling method.

(Geyer et al., 2010) achieved the direct torque control of the PMSM 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%.

2. Permanent magnet synchronous motor technology

Permanent magnet synchronous motors are different from the wound field synchronous motors. However the stator structure of a permanent magnet synchronous motor is similar

to the wound field synchronous motors, the difference is only between the rotor structures. In the wound field synchronous motors, field is created on the rotor by separate excitation through the brushes (slip rings), where the field of the permanent magnet synchronous motors is created by the permanent magnets placed on the rotor. Therefore, permanent magnet synchronous motors are brushless motors. Since they are brushless, they are more robust than the DC motors; and since the field is created by permanent magnets and there are not any rotor currents, they are more efficient than the induction motors, where the rotor field currents cause rotor copper losses. However costs of PMSM are higher than DC and induction motors because of the high permanent magnet and production costs. Also, the reliability of these motors is questionable under certain circumstances such as magnetic property loss due to high working temperatures etc. Nevertheless, such properties as high efficiency, high torque, high power, small volume, and accurate speed control make permanent magnet synchronous motors preferred for chemical fiber industry (spinning pumps, godets, drive rollers), texturing plants (draw godets), rolling mills (roller table motors), transport systems (conveyor belts), glass industry (transport belts), paper machines, robotic automation, electrical household appliances, ship engines and escalators. Permanent magnet synchronous motors are classified mainly into two groups with respect to their rotor structures as; Surface Mount Permanent Magnet (SMPM) Synchronous Motors and Interior Permanent Magnet (IPM) Synchronous Motors. SMPM motors have the permanent magnets mounted on the outer surface the rotor, and IPM motors have the permanent magnets buried in the rotor core. SMPM motors are also classified into two types with respect to the stator winding as; concentrated winding and distributed winding. Concentrated winding SMPM motor's back-emf waveform is trapezoidal; distributed winding SMPM motor's back-emf waveform is sinusoidal. Concentrated winding SMPM motors are called as Brushless DC (BLDC) motors and driven with trapezoidal signals. The distributed winding SMPM motors are called as Permanent Magnet AC (PMAC) motors and driven with sinusoidal signals. PMAC motors are also designated as servo motors or brushless AC motors. PMAC motors are generally built with strong magnetic material Samarium Cobalt (SmCo_5 , $\text{Sm}_2\text{Co}_{17}$) and Neodymium Iron Boron (NdFeB). They have high dynamic performance, high efficiency, robustness, high torque density and significantly better short-time overload capability than induction motors (400% to 150%). PMAC motors are mostly employed in high performance servo (robotics, machining, etc.) applications. Some PMAC motors are built with low cost permanent magnet materials (Ferrites) to be used in low cost (fan) applications. IPM motors are newly developed motors with high torque density, high efficiency characteristics as the SMPM motors and additionally provide field weakening operation, which is impossible with the SMPM motors. IPM motors are preferred in the industrial applications such as adjustable speed drives as a replacement for the squirrel cage induction motors, to improve the efficiency and the performance. In contrast to the induction motors, IPM motors also have the advantage of providing position control loop with accuracy, without a shaft encoder (Omer & Hava, 2010). Standard induction motors, designed to run at 750-3000 rpm, are not particularly well suited for low speed operation. Normally gearboxes are used to reduce the speed from, for example, 1500 rpm to 600 rpm. A gearless PMSM drive of 600 rpm replaces as a solution, in contrast to conventional using of 1500 rpm induction motor. Because a gearbox takes up space and needs maintenance as well as considerable quantities of oil. Eliminating the gearbox saves space, installation costs and improved efficiency of the drive.

2.1 Permanent magnet synchronous motor design types

The location of the magnets on the rotor and their specifications determine the performance of the motor therefore various designs are possible. The simple representations of the frequently used designs are given below. Other designs are derived from these two.

1. Placing the magnets on the rotor surface (SMPM)
2. Placing the magnets inside the rotor (IPM)

2.1.1 Placing the magnets on the rotor surface (Surface mounted magnet rotor)

Magnets are mounted on the rotor in forms of strips or arcs. The rotor configuration shown in Fig.1 adopts surface-mounted magnets which are often glued onto rotor surface. Since the relative permeability of the magnets is almost the same as for air, such design possesses very small rotor saliency and these are sometimes referred to as “nonsalient” designs. By filling the gaps between the magnets partially with iron, a significant rotor saliency can be achieved which offers the possibility to utilize the reluctance torque. The greatest drawback of this common design is the low endurance of the magnets to the centrifugal forces. Therefore these motors are preferred in low-speed applications to avoid detachment of the magnets. These motors are commonly known as surface permanent magnet motors (SMPM). A simple representation is shown in Fig.1.

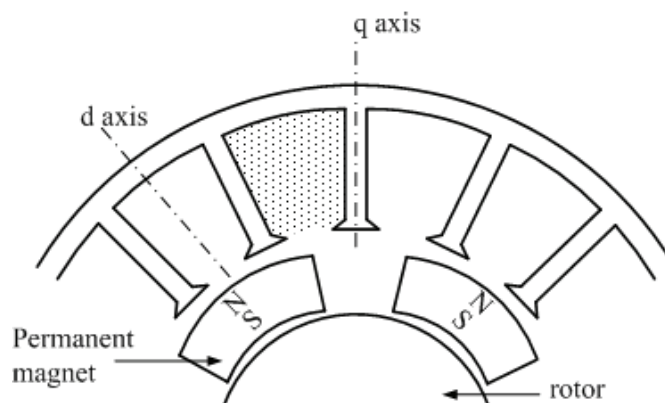


Fig. 1. Magnets placed on the rotor surface

2.1.2 Placing the magnets inside the rotor

Air gap induction of the previous design is limited and the magnets being exposed to high centrifugal forces under high speeds have led to different designs. Here, the magnets are placed in the cavities bored in the rotor. The magnets are surrounded by magnetic materials instead of air.

The magnets now have a better resistance to centrifugal forces therefore they are more suitable for high speed applications. The efficiency values of these motors are also higher than other magnet motors. The main disadvantage is their high costs. Placement of the magnets in the rotor is a high tech process that requires fine labour. These motors are commonly known as interior permanent magnet synchronous motor (IPMSM). These magnet motor designs are mainly in two types.

2.1.2.1 Radially placed interior magnet structure

As seen in Fig.2 magnets are placed around the rotor axis buried and radially magnetized. These motors have small air gap, and low armature reaction. Flux density in the air gap can

be higher than inside the magnet, thus the low-cost Ferrit magnets can be utilized for high torque density. The surface where the magnets come in contact with the rotor is coated with a non magnetic material to avoid magnetic short-circuit. However these materials have high costs.

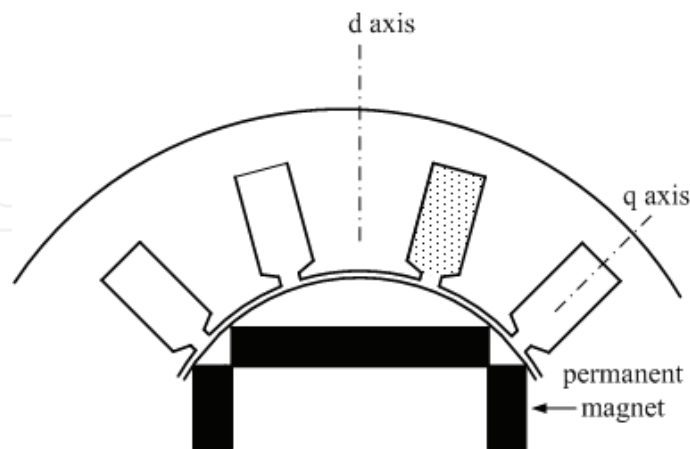


Fig. 2. Radially placed interior magnet structure

2.1.2.2 Symmetrically buried magnet structure

Permanent magnets are again buried in the rotor but are placed pointing the main axis. The most important feature of this design is to constitute induction at the poles independent from the working point of magnets. Through to this feature, air gap induction can be increased to high levels. Since the magnets are buried in the rotor, they have a great resistance to the centrifugal forces. Symmetrically buried magnet structure is shown in Fig.3.

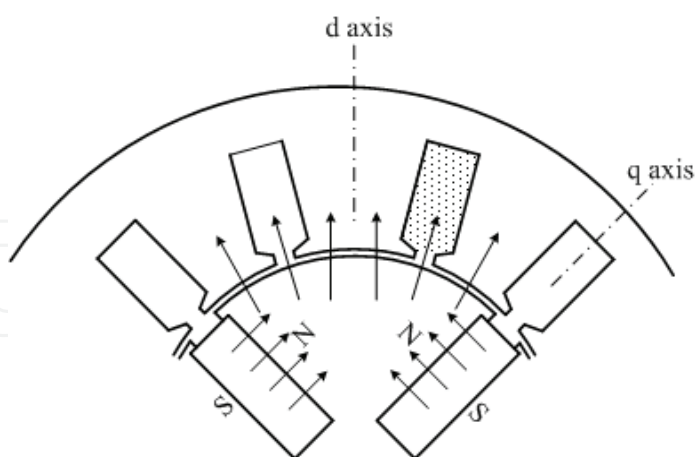


Fig. 3. Symmetrically buried magnet structure

When buried magnets are used, $L_{sd} \neq L_{sq}$ and the electromagnetic torque also contains a reluctance torque. The fact that three-phase symmetrical sinusoidal quantities are transformed into two DC components through the well known Park transformation has made modelling of PMSM in the rotor-fixed dq reference frame used almost exclusively for control purposes.

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 ψ_s and rotor magnetic flux vector ψ_M can be represented on rotor flux (dq), stator flux (xy) 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.

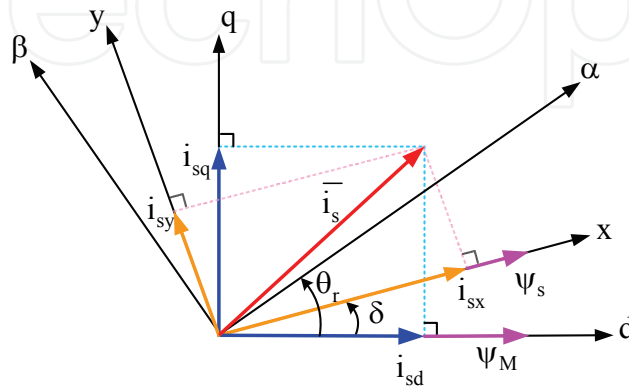


Fig. 4. Stator and rotor magnetic fluxes in different reference systems

The mathematical equations are given below (Vas, 1998). Stator current vector can be represented on rotor flux (dq) reference system as (i_{sd}) (i_{sq}) and the electromagnetic torque is related with these vectors.

$$\psi_{sd} = L_{sd}i_{sd} + \psi_M \quad (1)$$

$$\psi_{sq} = L_{sq}i_{sq} \quad (2)$$

$$u_{sd} = R_s i_{sd} + \frac{d}{dt} \psi_{sd} - \omega_r \psi_{sq} \quad (3)$$

$$u_{sq} = R_s i_{sq} + \frac{d}{dt} \psi_{sq} + \omega_r \psi_{sd} \quad (4)$$

$$\frac{d}{dt} i_{sd} = \frac{1}{L_{sd}} u_{sd} - \frac{R_s}{L_{sd}} i_{sd} + \frac{L_{sq}}{L_{sd}} \omega_r i_{sq} \quad (5)$$

$$\frac{d}{dt} i_{sq} = \frac{1}{L_{sq}} u_{sq} - \frac{R_s}{L_{sq}} i_{sq} + \frac{L_{sd}}{L_{sq}} \omega_r i_{sd} - \frac{\psi_M \omega_r}{L_{sq}} \quad (6)$$

$$T_e = \frac{3}{2} p (\psi_{sd} i_{sq} - \psi_{sq} i_{sd}) \quad (7)$$

$$T_e = \frac{3}{2} p [\psi_M i_{sq} - (L_{sq} - L_{sd}) i_{sd} i_{sq}] \quad (8)$$

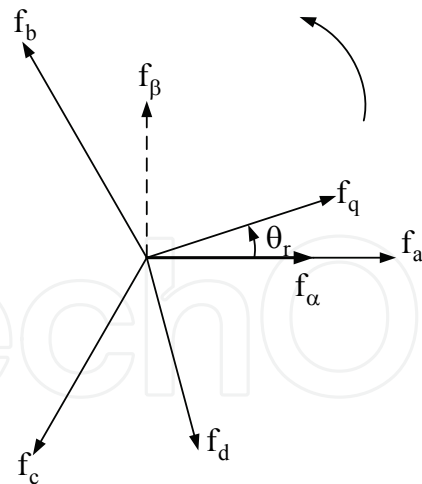


Fig. 5. Rotating reference frames

To simplify the modelling of the DTC drive, it is common practice to transform all variables from the three-phase system (abc) to an orthogonal (dq) reference frame with a direct (d) and quadrature (q) axis, where f represents the voltage, current or magnetic flux and θ_r is the rotor angle. $abc \rightarrow \alpha\beta$, Clarke Transformation (9) and $\alpha\beta \rightarrow dq$, Park Transformation (10) can be applied regarding reference frame theory. Here, equation (11) presents these both transformations in one matrix, $abc \rightarrow dq$.

$$\begin{bmatrix} \alpha \\ \beta \end{bmatrix} = \frac{2}{3} \begin{bmatrix} 1 & \cos(2\pi/3) & \cos(4\pi/3) \\ 0 & \sin(2\pi/3) & \sin(4\pi/3) \end{bmatrix} \begin{bmatrix} a \\ b \\ c \end{bmatrix} \quad (9)$$

$$\begin{bmatrix} \alpha \\ \beta \end{bmatrix} = \begin{bmatrix} \cos(\theta_r) & -\sin(\theta_r) \\ \sin(\theta_r) & \cos(\theta_r) \end{bmatrix} \begin{bmatrix} d \\ q \end{bmatrix} \quad (10)$$

$$\begin{bmatrix} d \\ q \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos(\theta_r) & \cos(\theta_r - 2\pi/3) & \cos(\theta_r - 4\pi/3) \\ -\sin(\theta_r) & -\sin(\theta_r - 2\pi/3) & -\sin(\theta_r - 4\pi/3) \end{bmatrix} \begin{bmatrix} a \\ b \\ c \end{bmatrix} \quad (11)$$

In Eq. (12), by using the vector representation shown in Fig.5, Eq. (13) is obtained and using the Park transformation, Eq. (14) is obtained.

$$\begin{bmatrix} f_d \\ f_q \end{bmatrix} = \begin{bmatrix} \cos \delta & -\sin \delta \\ \sin \delta & \cos \delta \end{bmatrix} \begin{bmatrix} f_x \\ f_y \end{bmatrix} \quad (12)$$

$$\sin \delta = \frac{\psi_{sq}}{|\psi_s|}$$

$$\cos \delta = \frac{\psi_{sd}}{|\psi_s|} \quad (13)$$

$$T_e = \frac{3}{2}P \left[\psi_{sd} (i_{sx} \sin \delta + i_{sy} \cos \delta) - \psi_{sq} (i_{sx} \cos \delta - i_{sy} \sin \delta) \right]$$

$$T_e = \frac{3}{2}P \left[i_{sx} \frac{\psi_{sd} \psi_{sq}}{|\psi_s|} + i_{sy} \frac{\psi_{sd}^2}{|\psi_s|} - i_{sx} \frac{\psi_{sd} \psi_{sq}}{|\psi_s|} + i_{sy} \frac{\psi_{sq}^2}{|\psi_s|} \right]$$

$$T_e = \frac{3}{2}P |\psi_s| i_{sy} \quad (14)$$

It is clear that the electromagnetic torque is directly proportional to the y-axis component of the stator current (Zhong et al, 1997). 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 (8) 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.

3. Direct torque control of permanent magnet synchronous motors

In general, there are two control methods used for the PMSM; field oriented control and direct torque control. The AC drives in which flux oriented control (FOC) is used field control leads to flux control. Here, rotor flux space vector is calculated and controlled by using the angular velocity which is derived from the speed feedback and the stator current vector. The greatest drawback of the flux vector control is the need for a tachogenerator or an encoder for high accuracy. This need definitely increases the costs of the system.

The basic principle of DTC is to 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 resolved and directly controlled using nonlinear transformations on hysteresis controllers, without performing coordinate transformations. A double layer hysteresis band controller is utilized for stator flux control and a three-layer hysteresis band controller is used for torque control. DTC is an alternative to field oriented control method in high performance applications due to the advantages of reduced computations (Swierczynski et al, 2008) Since the torque and flux estimators in DTC requires and relies on the parameters identification and accuracy of the estimations, the estimation of the electromagnetic torque is essential for the entire system performance.

In classical PWM and flux vector controlled drives, voltage and frequency are used as basic 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 key notion behind DTC is to directly steer 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. The switching table is derived on the basis of the desired performance specifications on the controlled variables also include the balancing of the inverter's neutral point potential around zero.

3.1 Two - level inverter nonlinear continuous-time model

An equivalent representation of a three-phase two-level inverter driving a PMSM is shown in Fig.6. At each phase, the inverter can produce two different voltages $-u_{dc}/2$, $u_{dc}/2$ where u_{dc} denotes the voltage of the dc-link. The switch positions of the inverter can therefore be fully described using the three integer variables $v_a, v_b, v_c \in \{-1, 1\}$ where each variable corresponds to one phase of the inverter, and the values -1, 1 correspond to the phase potentials $-u_{dc}/2$, $u_{dc}/2$ respectively.

There are $2^3 = 8$ different vectors of the form $v_{abc} = [v_a, v_b, v_c]^T$. Using Eq. (11) these vectors can be transformed into the dq frame resulting in vectors of the form $v_{dq} = [v_d, v_q]^T$ as shown in Fig.7 where they are mapped into the two-dimensional dq plane. Even though they are commonly referred to as voltage vectors, this term describes the switch positions rather than the actual voltages applied to the machine terminals. The voltage vectors can be divided in two groups: six long vectors forming the outer hexagon and two zero vectors. The zero vectors correspond to the switch combinations (+1,+1,+1) and (-1,-1,-1), and short-circuit the machine terminals.

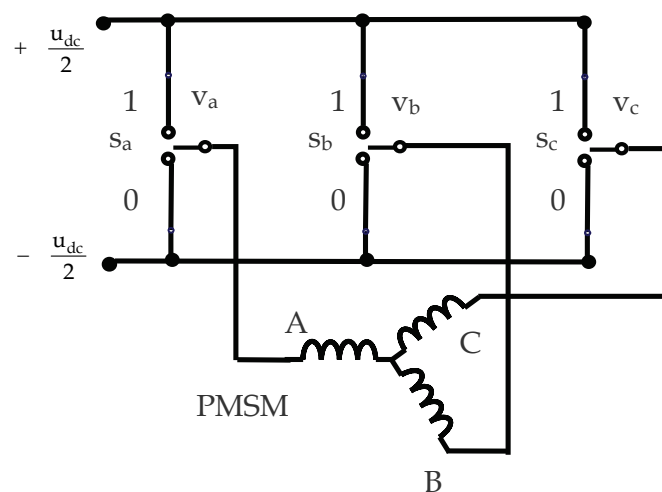


Fig. 6. Three-phase two-level inverter

3.2 Determination of the voltage space vector

The main principle of DTC is determination of correct voltage vectors using the appropriate switching table. The determination process is based on the torque and stator magnetic flux hysteresis control. Stator magnetic flux can be calculated using equation (15).

$$\bar{\psi}_s = \int_t^{t+\Delta t} (\bar{u}_s - R_s \bar{i}_s) dt \quad (15)$$

Eq. (15) shows that the stator magnetic flux and the voltage space vector are in the same direction. Therefore, amplitude and direction control of the stator magnetic flux is possible by selecting the suitable voltage space vectors. Voltage vector plane is divided into six parts as shown in Fig.7. Two adjacent vectors that yield the lowest switching frequency are selected in order to increase or decrease the amplitude respectively.

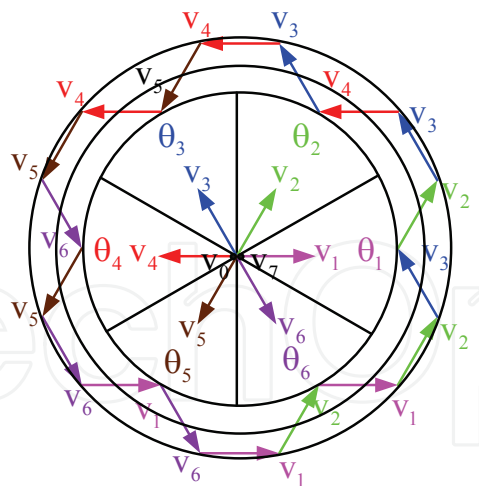


Fig. 7. Vectors of space vector modulation

Here, when the stator magnetic flux is moved clockwise in section 1, voltage space vector v_2 is selected in order to increase the stator magnetic flux amplitude and voltage space vector v_3 is selected in order to decrease the amplitude. When the stator magnetic flux moves clockwise, if still in section 1, v_6 is used to increase the amplitude and v_5 is used to decrease the amplitude. The torque of the permanent magnet synchronous motor can be controlled using DTC by means of controlling the stator magnetic flux rotation speed in cases where the stator magnetic flux amplitude is kept constant (Ozcira et al, 2008). Since the magnets on the rotor are continuously rotating, stator magnetic flux does not change when v_0 and v_7 zero vectors are used (Rahman et al, 1998). Zero vectors can be used to estimate the initial position of the rotor by a fixed active voltage vector while limiting current by applying zero vectors. In this position data is not used; therefore, zero vectors are not used within DTC for PMSM. Table 1. shows the suggested switching sequences. For these different states, the hysteresis controllers can be used as flux and torque hysteresis controllers.

ψ	T	θ					
		$\theta(1)$	$\theta(2)$	$\theta(3)$	$\theta(4)$	$\theta(5)$	$\theta(6)$
1	1	V_2 (110)	V_3 (100)	V_4 (101)	V_5 (001)	V_6 (011)	V_1 (010)
	0	V_7 (111)	V_0 (000)	V_7 (111)	V_0 (000)	V_7 (111)	V_0 (000)
	-1	V_6 (101)	V_1 (001)	V_2 (011)	V_3 (010)	V_4 (110)	V_5 (100)
0	1	V_3 (010)	V_4 (110)	V_5 (100)	V_6 (101)	V_1 (001)	V_2 (011)
	0	V_0 (000)	V_7 (111)	V_0 (000)	V_7 (111)	V_0 (000)	V_7 (111)
	-1	V_5 (001)	V_6 (011)	V_1 (010)	V_2 (110)	V_3 (100)	V_4 (101)

Table 1. Switching vectors

In Table 1. ψ denotes stator magnetic flux hysteresis controller output, T denotes torque hysteresis controller output, and θ represents magnetic flux sector. These vectors are

selected in order to provide the stator flux error within $2\Delta\psi_s$ bandwidth and the actual torque error in the $2\Delta t_e$ bandwidth at each switching period. The flux hysteresis controller output is $d\psi_s$. If an increase is needed for flux, it is assumed that $d\psi_s = 1$ and when a decrease is needed, it is assumed that $d\psi_s = 0$. Two level hysteresis controller is determined by Eq. (16).

$$d\psi_s = \begin{cases} 1, & |\psi_s| \leq \psi_{sref} - \Delta\psi_s \\ 0, & |\psi_s| \geq \psi_{sref} + \Delta\psi_s \end{cases} \quad (16)$$

The torque hysteresis controller output is dt_e . If an increase is needed at torque, it is assumed that $dt_e = 1$ and when a decrease is needed, it is assumed that $dt_e = -1$. If there is no change at actual torque, $dt_e = 0$. Three level hysteresis controller is determined by (17) for clockwise rotation and counter clockwise rotation by (18).

$$dt_e = \begin{cases} 1, & |t_e| \leq |t_{eref}| - \Delta t_e \\ 0, & |t_{eref}| \geq |t_{eref}| \end{cases} \quad (17)$$

$$dt_e = \begin{cases} -1, & |t_e| \leq |t_{eref}| + \Delta t_e \\ 0, & |t_{eref}| \geq |t_{eref}| \end{cases} \quad (18)$$

In direct torque method, three level torque comparator is used to select whether the inverter output voltage vector should be a torque-increasing vector or a torque-reducing vector. The appropriate vector is then applied for the duration of the sampling period. At low speed the torque increasing vectors are very effective at increasing the torque, whereas the torque reducing vectors are less effective. In contrast, at high rotor speeds, the torque-increasing vectors are less effective, whereas the torque reducing vectors are more effective. The result of this is that, at low speed, the torque tends to make a considerable excursion above the maximum torque hysteresis limit.

3.3 Determination of the stator flux space vector's sector

Stator flux space vector's sector (θ) should be known in order to select the appropriate switching vector. Space vector's angle determines the sector. Equation (19) helps to find the sector. This equation can be used when the switching signals will be generated.

$$\theta = \arctan \frac{\psi_{sd}}{\psi_{sq}} \quad (19)$$

In practice this mathematical operation is too complex for a DSP. Therefore, another alternative way can be used to determine θ . Equation (20) is calculated and due to result of this operation a Table 2 is constituted.

$$\sqrt{3}|\psi_{sq}| - |\psi_{sd}| \quad (20)$$

Ψ_{sd}	Ψ_{sq}	$\sqrt{3} \Psi_{sq} - \Psi_{sd} $	Sector(θ)
+	+/-	-	1.
+	+	+	2.
-	+	+	3.
-	+/-	-	4.
-	-	+	5.
+	-	+	6.

Table 2. Stator flux space vector’s sector

3.4 Stator flux control by using LP filter

In order to eliminate the errors of a pure integration in voltage model, a low pass (LP) filter should be used. Equation (15) defines stator magnetic flux in general form.

$$\bar{\Psi}_s = (\bar{V}_s - R_s \bar{I}_s) / j\omega_e$$

(21)

In equation (21) this general form is given in sinusoidal form where ω_e denotes stator flux angular frequency.

$$\bar{\Psi}_s' = (\bar{V}_s - R_s \bar{I}_s) / (j\omega_e + \omega_c)$$

(22)

ω_c denotes the low pass filter’s cut off frequency. In equation (22) Ψ_s' represents estimated stator flux but estimated flux isn’t equal to stator flux $\bar{\Psi}_s$ which used in equation (21). By using equation (21) and equation (22) stator flux can be obtained.

$$\bar{\Psi}_s = \bar{\Psi}_s' - j(\omega_c / \omega_e) \bar{\Psi}_s'$$

(23)

For this equation in the case of $\omega_e \gg \omega_c$ LP filter converges to the pure integrator. However maintain the clarity equation (24) can be derived.

$$\frac{\Psi_s'}{\Psi_s} \angle \varphi = \frac{\omega_e}{\sqrt{\omega_e^2 + \omega_c^2}} \angle \varphi$$

(24)

$$\varphi = \frac{\pi}{2} - \arctan(\omega_e / \omega_c)$$

(25)

By choosing a low cut off frequency, amplitude and phase errors decrease; however, as LP filter efficiency decreases, DC shift in current and voltage cannot be eliminated.

3.5 Observerless scheme for sensorless speed control based on DTC

The study includes low pass filter - flux estimator which utilizes voltage model on a direct torque controlled permanent magnet synchronous motor. Flux estimation techniques used for the high performance motor drivers are based on using the flux model, voltage model or both of these models together. Flux estimation with current model is used at low frequencies

and requires the stator current and the rotor speed data. The drawbacks of this method are its susceptibility to the changes of the rotor parameters at high speeds and its need of a speed sensor. For sensorless flux estimation, the voltage model is preferred. This model has a very high accuracy at high speeds. However, at low speeds due to the very low stator voltage, decrease of the ohmic voltage and component voltage diminish the error of the integration process increases. Accuracy of the flux estimation depends on the accuracy of the measured current, voltage and real parameters. In practice, the structure of the flux sensors and the error due to noise or a small DC shift of the transitional region, results in error accumulation at the integrator. In order to avoid that effect, an integrator with a LP filter is used instead of a pure integrator. DTC performance is highly sensible to determined voltage vector and is highly dependant to stator flux space vector being accurately estimated.

Current model isn't affected by the variations of the stator resistance however is sensible to changes of the rotor parameters at high speeds. Estimation process of the voltage model does not require rotor speed data. Therefore voltage model is preferred in sensorless applications and operation at moderate or high speeds. In voltage model, errors of current and voltage measurements affect the accuracy of the integral function. The errors occur because of the phase delay of the sensors, the errors of the transformer gain, shift of the measurement system and fault of the quantal errors of the digital system. Variation of the stator resistance with temperature also causes errors.

In order to avoid the shift of a pure integration in voltage model, a low pass (LP) filter integrator is used. LP filter eliminates the shifting but causes phase and amplitude errors. Therefore, the driver performance decreases especially at frequencies close to the cut-off frequency of the filter. Further study is available to improve the flux estimation using LP filter. The method utilizes an adaptive control system that depends on the force and the stator flux being orthogonal. Using an adaptive control complicates the simple DTC system. In this study a low pass filter which utilizes voltage model, is presented. The effects of the LP filter to the flux estimation performance and the practical aspects are analyzed in detail. Simulation results show that a low pass filter which utilizes voltage model on a direct torque controlled PMSM driver, can achieve a robust control.

The torque of the permanent magnet synchronous motor is controlled by monitoring and controlling the armature current since electromagnetic torque is proportional to the current. In DTC, torque and flux can be controlled independently since the stator flux is controlled directly with the stator voltage using Eqs. (26) and (27). Stator flux can be quickly controlled and the motor performance can be kept high. Moreover, torque is estimated by using current data provided by Eq. (28).

$$\psi_{\beta} = \int_t^{t+\Delta t} (u_{\beta} - R_s i_{\beta}) dt \quad (26)$$

$$\psi_{\alpha} = \int_t^{t+\Delta t} [(u_{\alpha} - R_s i_{\alpha}) + \psi_M] dt \quad (27)$$

$$T_{\text{est}} = p(\psi_{\alpha} i_{\beta} - \psi_{\beta} i_{\alpha}) \quad (28)$$

Here, current and voltage data on the α - β axis of the PMSM are the input variables. Position and speed data resulted from the estimation process are conveyed to the proper evaluations within the DTC control system. Estimation process of the voltage model is independent from the rotor speed data.

$$\omega_{\text{est}} = \frac{\psi_{\alpha} \frac{d\psi_{\beta}}{dt} - \psi_{\beta} \frac{d\psi_{\alpha}}{dt}}{\psi_{\alpha}^2 + \psi_{\beta}^2} \quad (29)$$

In this speed sensorless algorithm, only stator phase currents and inverter output voltages are measured. Torque and speed are estimated in an open-loop without using an observer, as given in the Eqs. (28), (29). A low-pass filter is accompanied to the results obtained from (29) in order to monitor the speed estimation. On the other hand, this method gives only the synchronous speed, not the mechanical speed for induction motor due to the slip speed. This implementation is applicable for general purpose PMSM drives.

Voltage vector for the DTC is determined by comparison of the estimated stator flux and torque values with their reference values. For high performance driver systems of permanent magnet synchronous motors, it is basically desired that the drive system should not be affected by parameter variations. The other criterion is that the speed must reach the reference value as quickly as possible when speed reference changes. Traditional PI and PID controllers are widely used as speed controllers in driver systems. Here, the speed controller consists of both a PI controller and an acceleration compensator.

Observerless scheme for sensorless DTC method is highly sensible to determined voltage vector and is highly dependent to the stator flux space vector. Therefore, stator flux space vector should be accurately estimated. The measured input values to the DTC control are only motor current and voltage. The voltage is defined from the DC-bus voltage and inverter switch positions. Since the inverter operates at high switching frequencies, undesired harmonic components can be produced.

4. Low-Pass Filter for Harmonics

It is desirable that the voltages and currents provided to the motor terminals do not include harmonic components. These harmonics may cause many unwanted effects such as electromagnetic interference (EMI) noise and high dv/dt which affect the motor control system as well (Chen et al, 2007). In such hysteresis controlled inverters, when the error per sampling time is large, the voltage vectors can no longer remain within the small hysteresis band. The LP filter can be used to affect the inverter switching frequency in order to decrease the stress on the inverter, so that PMSM is not affected by the variations and noises in entire system. Fig.8 shows the RLC filter, which plays the main role in reducing the high dv/dt of line to line voltages at motor terminals.

The transfer function of the filter is given by

$$\frac{V_o}{V_i} = \frac{R_1 C_1 s + 1}{C_1 L_1 s^2 + (r_1 + R_1) C_1 s + 1} \quad (30)$$

To obtain over damping response, the filter resistances is selected to be,

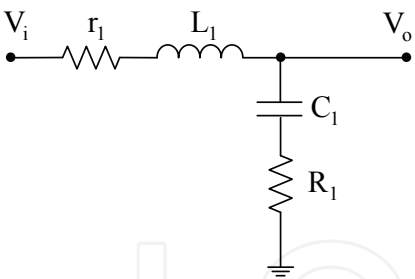


Fig. 8. RLC Low pass filter for harmonics

$$R_1 + r_1 > \sqrt{\frac{4L_1}{C_1}} \tag{31}$$

Cut off frequency ω_c is given by Eq. (32).

$$\omega_c = 1/\sqrt{L_1 C_1} \tag{32}$$

Here, the cut off frequency is approximately calculated to be 300 Hz and LP filter parameters are given in Table 3.

L_1	22 mH
C_1	500 μ F
R_1	200 Ω
r_1	0.2 Ω

Table 3. Filter parameters

By using (30) and the filter parameters, (33) is obtained. Here, the LP block is constructed with (33). In order to reduce ohmic losses, the series resistance r_1 is normally of small value, as shunt resistance R_1 is selected high enough to limit the currents drawn by the filter (Ozcira et al, 2008).

$$\frac{V_o}{V_i} = \frac{1}{11.10^{-5}s + 1} \tag{33}$$

The filter system is characterized by affecting inverter switching frequency in such a way to decrease switching stresses. The filter system uses dissipative elements to reshape motor voltage waveform to provide voltage to the motor windings.

5. Model verification of direct torque control algorithm

Direct torque control is used as the control method in simulations thus the operating principle of the DTC is described briefly. In principle the DTC is a hysteresis control - of the stator flux linkage and the torque that directly selects one of the six non-zero and two zero discrete voltage vectors of the inverter. The principal operation of the DTC is shown as a block diagram in Fig.9. The system includes a flux estimator which utilizes a voltage model on a direct torque controlled PMSM, and speed can also be estimated by using calculations with aid of the current and voltage data. The voltage and current signals are inputs to an

accurate motor model which produces the exact value of the stator flux and torque. Motor torque and flux comparators compare the actual values to the reference values that are produced by torque and flux reference controllers. The outputs from these controllers are updated every $10\mu\text{s}$ and they indicate whether the torque or flux has to be varied. Depending on outputs, the switching logic directly determines the optimum inverter switching signals (Bekiroglu & Ozcira, 2010). DTC method was applied and both flux and torque were controlled by hysteresis controllers; thus, the delays related to the PWM modulator were eliminated. Besides, a low-pass filter was implemented to reduce the harmonics and noise in the PMSM.

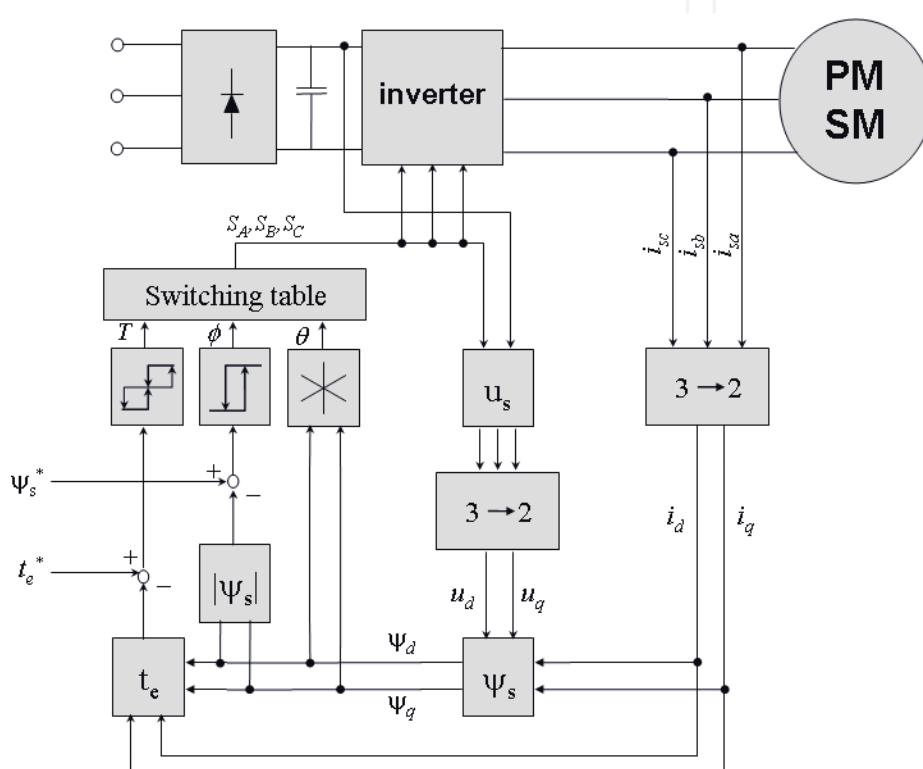


Fig. 9. Block diagram of the direct torque control (Luukko, 2000)

The control logic is implemented by a MATLAB® Function block that includes the software developed for this study. This function block determines the optimal switching vectors according to their sectors. The inverter is operated based on the different IGBT states given in Table 1 and Table 2. Since the inverter operates at high switching frequencies, undesired harmonic components can be produced. Simulink® model of low voltage - high power surface mounted PMSM is developed according to the dq model. The inverter DC bus voltage is 510V. During $t = [0, 0.4]$ interval, $\omega = 13 \text{ rad/s}$ and at $t = 0.4\text{s}$ $\omega = -13 \text{ rad/s}$ is applied as the reference speed. According to observe adaptation of the actual speed at $t = 0.2\text{s}$ 60 Nm is applied to load torque value.

Motor parameters are; $P_n = 18\text{kW}$, $I_n = 50\text{A}$, $R_s = 0.43\Omega$, $L_d = 25\text{mH}$, $L_q = 25\text{mH}$, $\psi_M = 1.58\text{Wb}$, $J = 2.16\text{kgm}^2$, $B_m = 0.005538$, $p = 10$

Fig.10 shows the speed control Simulink® diagram of the direct torque control for permanent magnet synchronous motor.

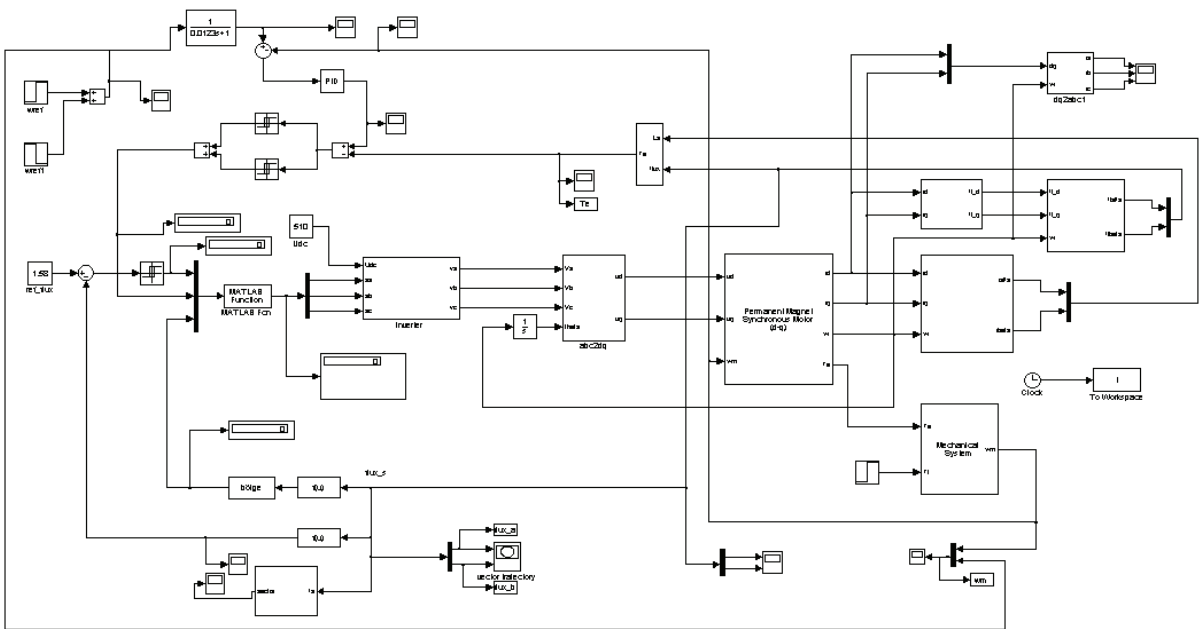


Fig. 10. Closed loop speed control system Simulink diagram of the PMSM with DTC.

6. Simulation results

The system dynamic responses are shown below with a sampling time 10μs.

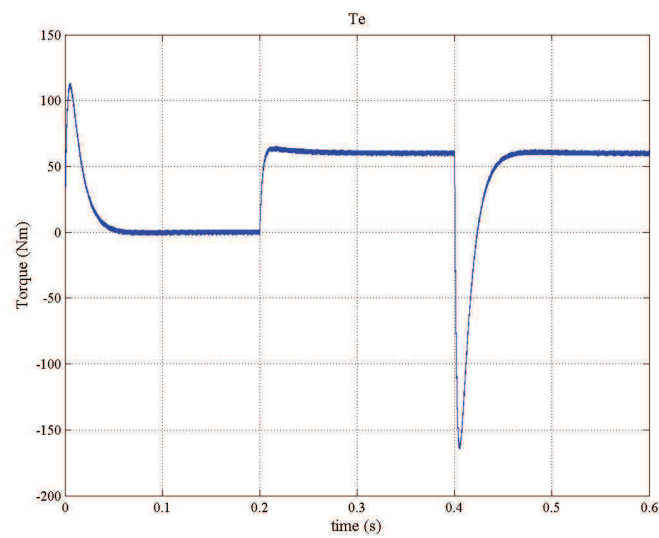


Fig. 11. Torque dynamic response

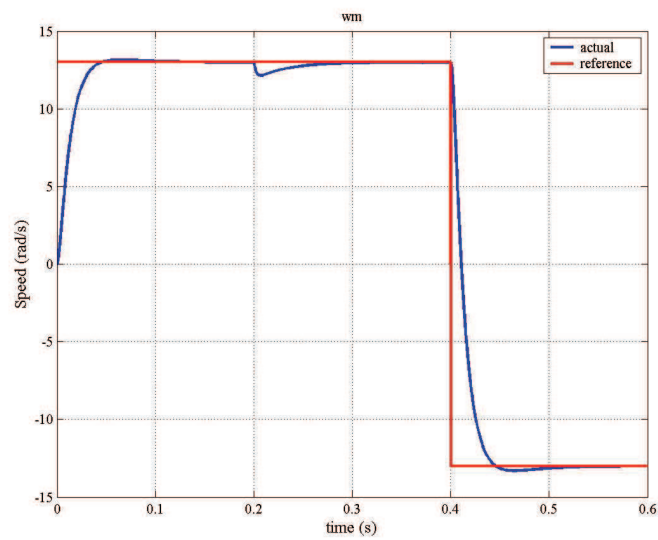


Fig. 12. Torque dynamic response

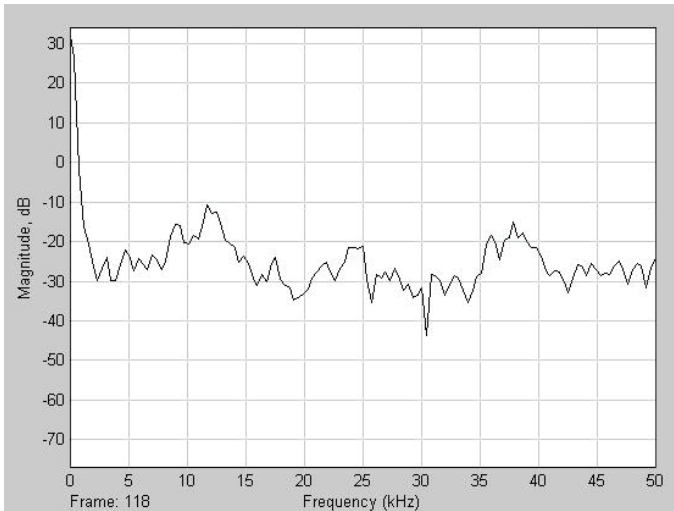


Fig. 13. Current harmonics without LP filter

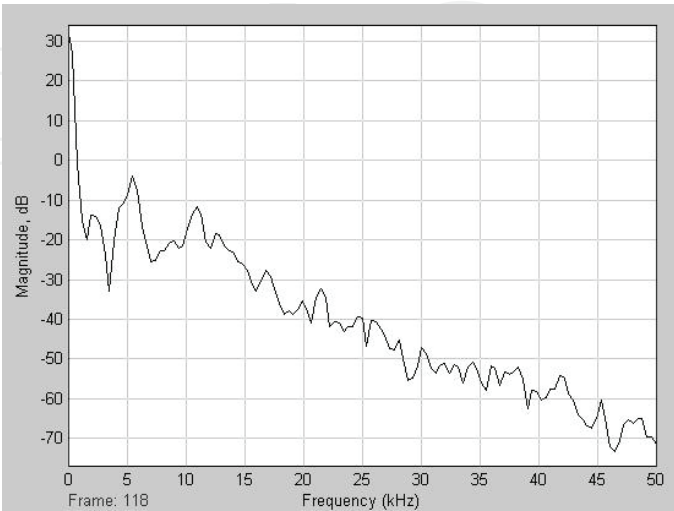


Fig. 14. Current harmonics without LP filter

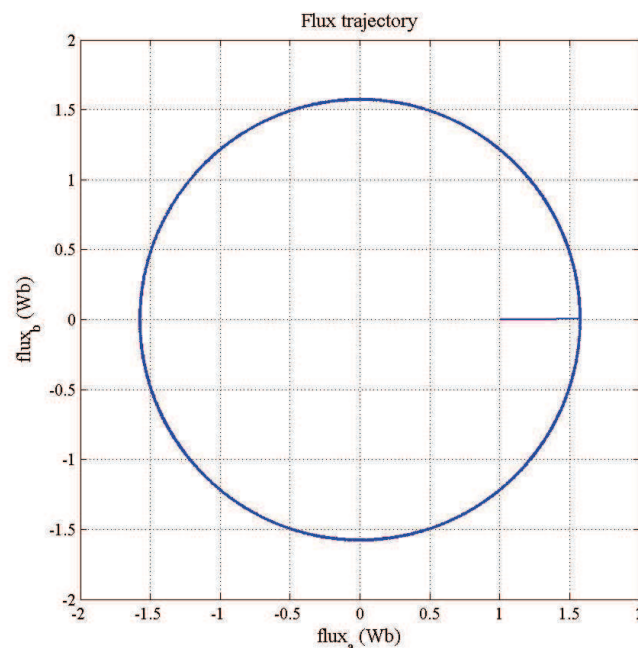


Fig. 15. Stator magnetic flux vector trajectory

7. Conclusion

DTC is intended 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 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 and a simulation is constituted. It is concluded that DTC can be applied for the permanent magnet synchronous motor and is reliable in a wide speed range. 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. In order to increase the performance, control period should be selected as short as possible. When the sampling interval is selected smaller, it is possible to keep the bandwidth smaller and to control the stator magnetic flux more accurately. Also it is important for the sensitivity to keep the DC voltage in certain limits.

As an improvement approach, a LP filter can be added to the simulation in order to eliminate the harmonics. In simulation, certain stator flux and torque references are compared to the values calculated in the driver and errors are sent to the hysteresis comparators. The outputs of the flux and torque comparators are used in order to determine the appropriate voltage vector and stator flux space vector.

When results with and without filters are compared, improvement with the filters is remarkable, which will effect the voltage in a positive manner. Choosing cut off frequency close to operational frequency decreases DC shift in the stator voltage. However, this leads to phase and amplitude errors. Phase error in voltage leads to loss of control. Amplitude error, on the other hand, causes voltage and torque to have higher values than the reference values and field weakening can not be obtained due to voltage saturation. Hence, cutoff frequency of LP filter must be chosen in accordance to operational frequency.

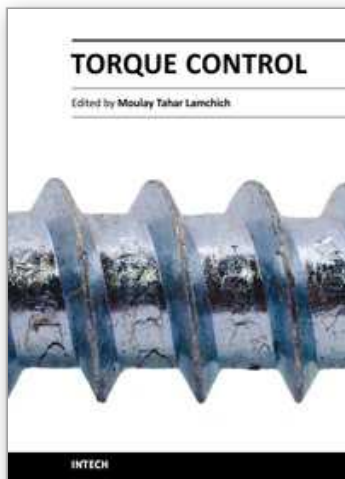
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