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COMPARATIVE ANALYSIS OF PERMANENT MAGNET SYNCHRONOUS MOTOR IN AMESIM AND OPENMODELICA SIMULATION ENVIRONMENTS

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For our families, who supported us unconditionally
and for Mustafa Kemal Ataturk who gave us,
the light of civilization and freedom...

Mert & Olgu

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Abstract

Even though Permanent Magnet Synchronous Machines (PMSM) are used with servo drives for a long period the developments in PMSM's technology, increased the availability in various typologies. With the new era of technology and Industry 4.0, new demands arise. In order to face this demand new products must appear in the market. Machines should have compact and highly efficient drive systems for a better control performance of PMSM. To be able to clearly analyze the performance of the motors, digitalization is the key factor to achieve more comparable and more customizable results. Thus, the commercial automation & electrification brands use various different simulation environments or create their own.

The purpose of this thesis is to compare and analyze two different simulation environments in the aspect of modelling a PMSM. Therefore, the measurable indicators have been created in both environments to be able to comment on them. In order to perform desired simulations to compare those modelling environments, a system with Field Oriented Control for PMSM has been modelled both in OpenModelica and Amesim. During the modelling process, rather than creating two identical models in two different environments by a mathematical approach, a state of art physical approach has been realized by using each software's specific blocks in order to understand their own strengths and weaknesses.

To be able to achieve this approach, PMSM has been introduced starting from its terminology. In the following chapter mathematical model of PMSM has been presented. Furthermore, in order to implement this mathematical model to control strategy, Park's and Clarke's Transformations have been deeply discussed. This theoretical background provides better understanding for the next chapter which includes the several types of control strategies for PMSM and especially Field Oriented Control. As the next step, simulations have been prepared and performed in OpenModelica and Amesim environments. The results of the simulations have been discussed in following.

In conclusion, it has been seen that, for modelling a PMSM control system, Amesim has its own specifically designed blocks which provides faster response of the system than OpenModelica. On the other hand, OpenModelica offers customizable and user-friendly solutions with more freedom. For the future of simulation environments OpenModelica seems more promising since it's an open source software, which is developed by professionals all around the world.

Sommario

Nonostante le macchine sincrone a magneti permanenti (PMSM) siano utilizzate con servo-drives da molto tempo, gli sviluppi della tecnologia PMSM hanno aumentato la disponibilità in varie tipologie. Con la nuova era della tecnologia e dell'Industria 4.0, sorgono nuove esigenze. Per far fronte a questa necessità, nuovi prodotti aventi queste caratteristiche devono apparire sul mercato. Per questo motivo, appunto, le macchine devono disporre di sistemi di azionamento compatti ed estremamente efficienti per migliorare le prestazioni di controllo di PMSM. Per essere in grado di analizzare chiaramente le prestazioni dei motori, la digitalizzazione è il fattore chiave per ottenere risultati più comparabili e più personalizzabili. Pertanto, i marchi commerciali dell'automazione e dell'elettrificazione o utilizzano diversi ambienti di simulazione o creano i propri.

Lo scopo di questa tesi è quello di confrontare e analizzare due ambienti di simulazione, diversi fra loro dal punto di vista della modellazione di un PMSM. Pertanto, gli indicatori misurabili sono stati creati in entrambi gli ambienti per essere in grado di discuterne. Al fine di eseguire le simulazioni per confrontare i loro ambienti di modellazione, il sistema di controllo Field Oriented per PMSM è stato modellato sia in OpenModelica che in Amesim. Durante il processo di modellazione, invece di creare due modelli identici in due ambienti diversi con un approccio matematico, è stato realizzato un approccio fisico allo stato artistico. I blocchi specifici di ciascun software sono stati utilizzati per comprendere i propri punti di forza e di debolezza.

Per essere in grado di raggiungere questo approccio, PMSM è stato introdotto a partire dalla sua terminologia. Nella parte seguente, è stato presentato il modello matematico di PMSM. Inoltre, al fine di implementare questo modello matematico per il controllo della strategia, sono state discusse le Trasformazioni di Park e Clarke. Questo antefatto teorico fornisce una migliore comprensione per il prossimo capitolo che include i diversi tipi di strategie di controllo per PMSM e in particolare Field Oriented Control. Nella fase successiva, le simulazioni sono state preparate ed eseguite in ambienti OpenModelica e Amesim. Anche in questo caso i risultati delle simulazioni sono stati discussi.

In conclusione, si è notato che per la modellazione di un sistema di controllo PMSM, Amesim ha i propri blocchi progettati che forniscono una risposta più veloce del sistema rispetto a OpenModelica. D'altronde, OpenModelica offre soluzioni personalizzabili e di facile utilizzo garantendo anche più libertà. Detto ciò, per il futuro degli ambienti di simulazione OpenModelica sembra più promettente grazie al suo software open source, sviluppato da professionisti provenienti da tutto il mondo.

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CHAPTER 1: INTRODUCTION

With the developments of Permanent Magnet Material Technology in the commercial area of production makes permanent magnet synchronous machines (PMSM) more available with various typologies.

Although Permanent magnet synchronous machines are being used with servo drives for a long time, new era of technology and industry 4.0 has created new demands thus consumer habits are changing faster than ever. To be able to supply this increasing rate of the market demand, new or modified products must be brought to the market. Machines must have modular and scalable drive systems and must be compact, highly efficient and easy to integrate.

To be able to control the PMSM the vector control is essential. The magnetic material quality affects reluctance of magnetic circuit of the machine therefore AC motor control is basically due to the magnetic properties of the permanent magnets. [1]

Permanent magnet materials have the relative permeability μ_r is almost equals to one. Which means that the direct air gap of the PMSM generally becomes very high also the inductance behaves as the machine does. However, PMSM with the magnets in which are located on the surface of rotor have rather low inductance.

The PMSM with the magnets in which are located on the surface of rotor has their synchronous inductance value in between $ld = 0.2-0.4$. The field weakening of a PM Machine needs to be taken in account by implementing a demagnetizing stator current. If the inductances are significantly low, the field weakening is not a reasonable alternative.

On the other hand, the Back Emf which has been created by the permanent magnets have proportional relationship with the rotation speed of the PMSM during the implementation of field weakening. Demagnetizing stator current has importance to make safer performance. In any case of losing the stator current affects the inverters stamina towards the voltage without harm.

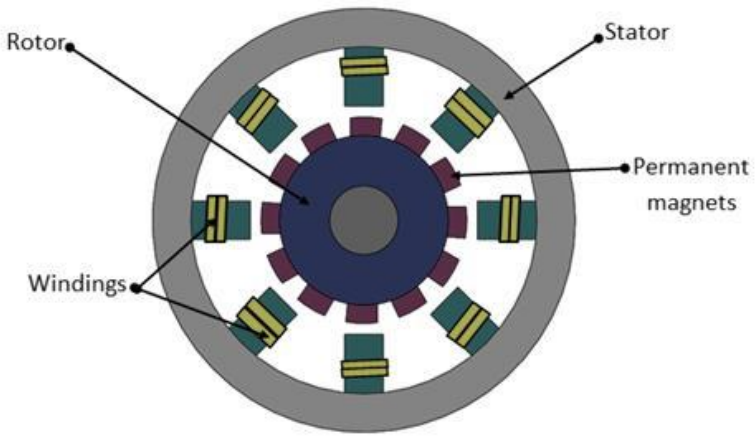

Figure 1.1: Permanent Magnet Synchronous Motor

Permanent Magnet machines have their own strategies in order to have being controlled. The most amount of control methods are based on Rotor Reference Frame. In this method it is necessary to have the information on the rotor angle. This means that not only the speed data from the encoder but also the definition of the initial rotor angle has the principle role of the method of Rotor Reference Frame [1].

PMSM have many advantages such as high torque density small size and low maintenance cost. The performance and cost optimization of motor control systems are attractive topics due to their nonlinear coupling and time depended.

There are two options of in general motor control theory which are Direct Torque and Vector Control Methods. Current voltage and Magnetic chain declared as vectors to this motor analysis approach.

Despite of the existence of different methods and formulas to be able to transform within those two alternative aspects of control techniques. The Computer simulation techniques is an efficient and convenient way of making analysis and develop the control strategies. With the technological developments of the simulation software sector faster, cheaper, customizable, agile and better fit for industry 4.0 solutions are being more achievable [3].

CHAPTER 2: PERMANENT MAGNET SYNCHRONOUS MACHINE

2.1 Electric Motor Family

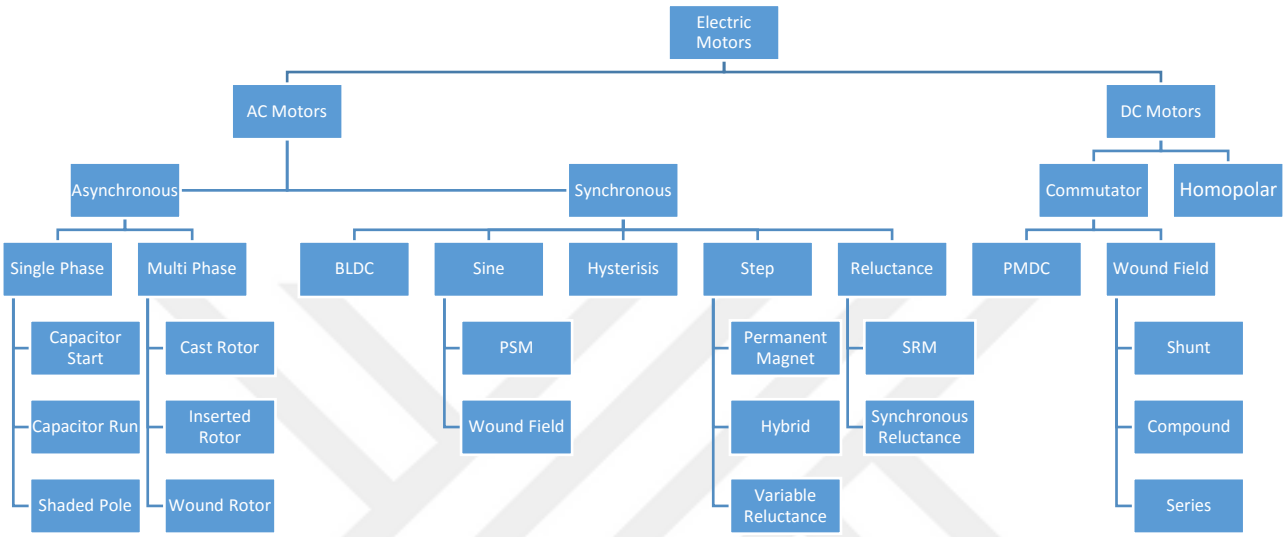

Figure 2.1: Electric Motor Family

In today's world an electrical motor can be powered in various ways. It can be powered by a direct current (DC) source, such as rectifiers and batteries. It can also be powered by an alternating current (AC) source, such as inverters and generators. As the Figure 2.1, AC motors can be divided into two parts: Synchronous and Asynchronous motors, respectively. In a synchronous machine there is no difference between the rotor speed and the stator's magnetic field speed, while in an asynchronous machine the rotor rotates at a speed which is less than the synchronous speed. The other division that should be considered is between brushed and brushless motors. In a brushed motor, there are brushes which are used to bring current to the windings through commutator. In a brushless motor there are no brushes to carry the currents, the magnetic field is changed by an amplifier. A commutation device triggers the amplifier in this type of machine. [6]

2.2 PMSM Terminology

2.2.1 Components of PMSM

A Permanent Magnet Synchronous Machine (PMSM) is composed of two elements: A rotor which is placed with permanent magnets and a wound stator. A sinusoidal EMF is induced along the air-gap, because of the distribution of the magnets and windings [2]. The stator windings are closed with a delta or star connection.

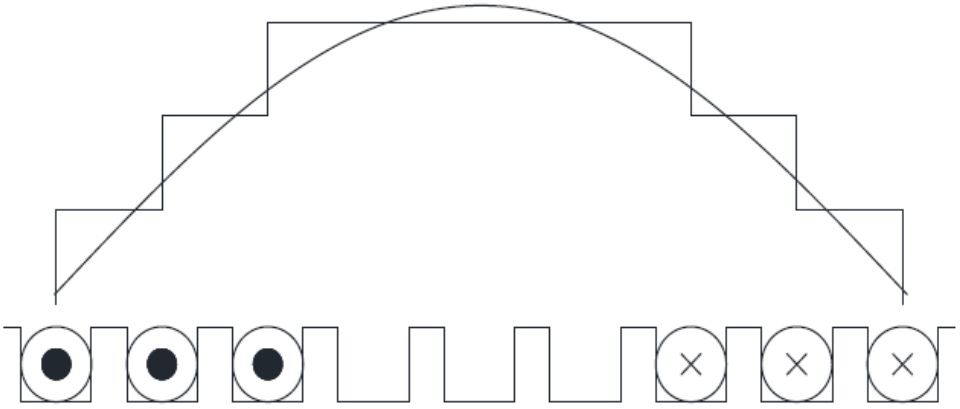

Figure 2.2: Magnetic field of a distributed winding [5]

At steady state condition the mechanical speed of the rotor is given as:

$$\omega_r = \frac{2 * \pi * f}{p} \tag{2.1}$$

Where *f* is the frequency of the voltage supply and *p* is the number of pole pairs. It should be noted there is no slip. The PMSM can be differ to two main types depend on the placement of permanent magnets: The first type is internal-mounted magnets (IMPM) which is with saliency. The second type are the surface-mounted magnets which are without saliency (SMPM). The SMPM has q fixed reluctance which doesn't change with the rotor angle, while the IMPM has a changing reluctance which varies with rotor angle. This is the main difference with this type of machines. Since SMPM has a fixed reluctance, this leads to a uniform air gap and equal inductances for *dq* axis (L_{sd} and L_{sq}) respectively [7].

2.2.2 Materials of Permanent Magnet

The mechanical and magnetic properties of the permanent magnet material is very important for the performance of the motor and it should be chosen wisely to obtain the best performance.

The first version of magnets was hardened steel. This type of magnets was magnetizing very easily. But the main drawback was that they were easy to demagnetized and holding very low level of energy. In the upcoming years other materials such as Aluminum, Nickel and Cobalt alloys (ALNICO) or Barium Ferrite or Samarium Cobalt (SmCo) were developed and used to produce permanent magnets [9]. Samarium Cobalt (SmCo) magnets have high levels of flux density but are very expensive. Neodymium Iron Boride (NdFeB) are the most common magnet material in these days.

2.2.3 Working Principle

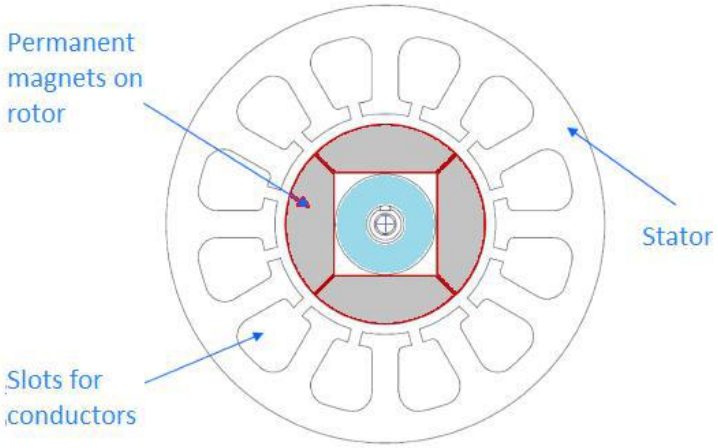

Figure 2.3: Brushless Motor

Since the rotor and the magnetic field rotates with the same angular speed, a brushless motor is a synchronous machine. It also has the permanent magnets and the motor is driven by alternating current (AC). Thus, it can also be defined as Permanent Magnet Alternating Current (PMAC) motor.

As it is seen in Figure 2.3 above, the permanent magnets are placed on the rotor, but the phase windings are placed on the stator. In order to generate a magnetic field, phases are powered alternately. This resulting magnetic field is always orthogonal to the field of permanent magnets. That's why the motor is considered synchronous. It's necessary to use an inverter to keep the motor synchronized all the time, so the winding currents on the stator which depend on the angular position of the rotor can be measured by a sensor. Brushless motors are generally divided into two types which are mainly differed by Back Electromotive Force.

• Sinusoidal Brushless Motor (PMSM)

1. Sinusoidal flux distribution in the air gap
2. Sinusoidal current waveform
3. Sinusoidal distributed stator windings

• Trapezoidal Brushless Motor (BLDC)

1. Rectangular flux distribution in the air gap
2. Rectangular current waveform
3. Concentrated stator windings

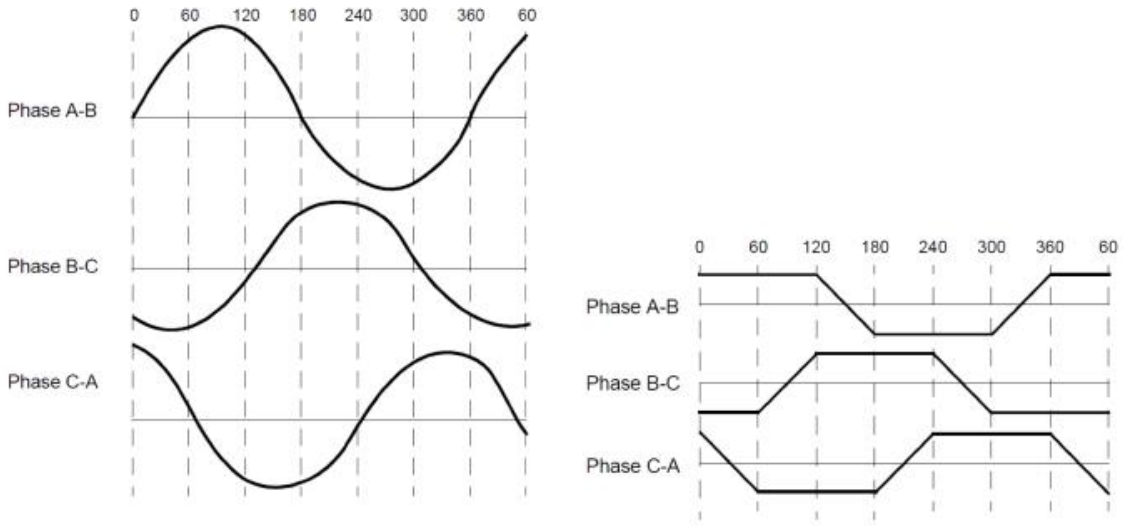

Figure 2.4: Comparison for BEMF between Sinusoidal and Trapezoidal Brushless Motors [6]

2.2.4 Configuration and Parameterization

Architecture of rotor has the main role to identify the Permanent Magnet Synchronous Machine (PMSM). There are many alternative combinations of positioning the rotor. Moreover, with the technological developments of the metallurgical science the rotors are can be ironless. Therefore, the structure of rotor made by lightweight metals and the magnets can be joined on rotor. Thus, the flux density has been distributed in the air gap of PMSM [1].

In this case the ironless rotor design effects on the magnetic material due to the positioning results of rotor and magnetic circuit this fact causes a problem of passing the air though.
As a solution a steel rim has been placed to be able to attaching of magnets on itself.

The design of thin rim can be laminated, nevertheless it causes high temperature on the rotor surface and the reason of this problem is basically time harmonics on the stator surface.

Voltage source inverters are essentials for adjust the current of the PMSM to be able to make it works better. The main aim of the inverter lays on a requirement of high frequency of switch mechanism due to the small amount of inductance on the magnet surface.

Servo motors are good examples in order to apply this architecture of PMSM because of their small amount of inertia needs. Figure 2.5 below shows that comparison of configurations of low inductance rotors.

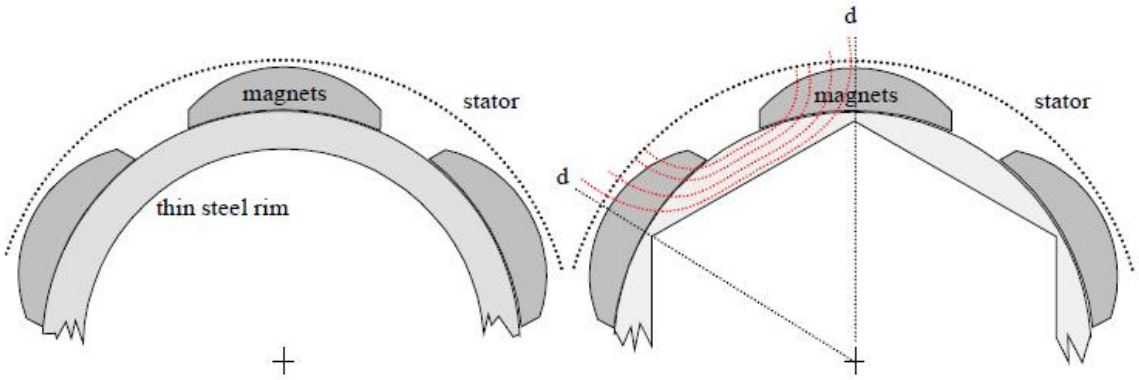

Figure 2.5: A low-inductance rotor configuration of a PMSM [1]

Asynchronous and Synchronous Machines may have similar structures of rotors electrically. Therefore, different combination alternative of designs for laminated rotors can serve particular characteristic for machine itself.

Moreover, not only the rotors of asynchronous and synchronous machines have similarities but also the stator of induction motor and permanent magnet motor have the same structures.

The permanent magnet can be attached on the surface of rotor likewise rigid rotors. The positioning of the magnets is various they could be completely in the rotor embedded partially. Furthermore, those magnets on different placements can make differentiation of the characteristics. There are several various architecture examples are shown by illustrations below in Figure 2.6.

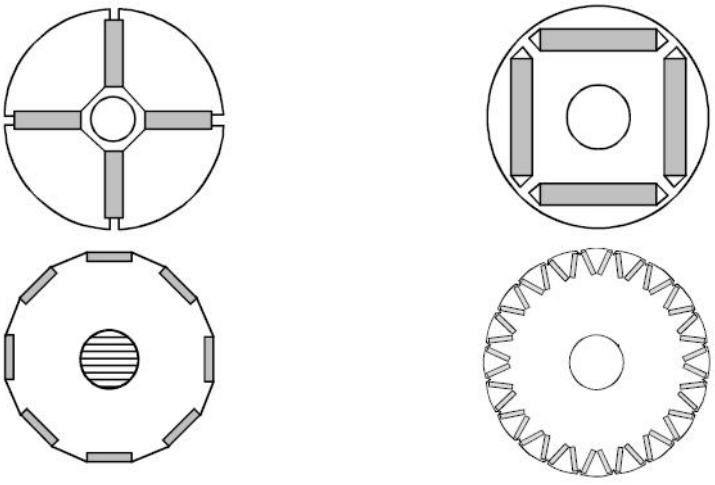

Figure 2.6: Laminated rotor configurations of PM machines with embedded magnets

Permanent magnet machines have their typical (Per Unit) PU values which make it different than the traditional synchronous and inductions machines on the market.

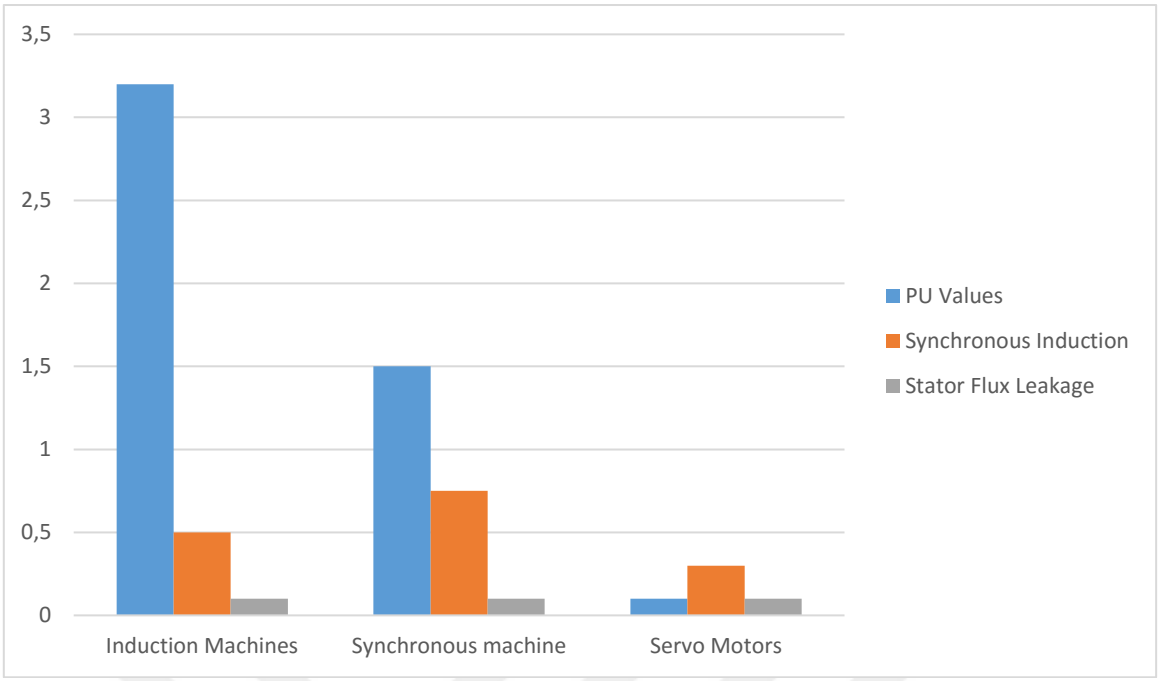

Figure 2.7: Comparison of servo motors and traditional induction and synchronous machines on the market

The comparison graph (Figure 2.7) above shows that there is a significantly difference for PU Values between Servo motors and other motors. The reason behind this fact is the magnetizing inductance level on the servo motors are dramatically lower than induction machines. However, stator leakages are equal and around 0,1 for all types of machines. Synchronous Induction levels are distributed between around l_s = 0.3 - 0.9.

The proportion of the stator flux leakage and synchronous inductance has a relationship due to amount of pole numbers on the magnet. This relationship causes the fact that stator flux can become up to half of the total amount of inductance.

One of the typical analysis of Permanent magnet machine is the load angle equations. This study can be observed with the implementation of PU values of phases to be able to achieve a certain load equation as below, after taking load angle as $\in \left(\frac{-\pi}{2}, \frac{\pi}{2}\right)$, ω_s as per-unit value:

$$P = 3\left(\frac{u_{sv}E_{PMv}}{\omega_s L_{sd}}\sin\delta + u_{sv}^2\frac{L_{sd}-L_{sq}}{2\omega_s L_{sd}L_{sq}}\sin 2\delta\right) \tag{2.2}$$

Moreover, Torque equation can be calculated as:

$$T = 3p\left(\frac{u_{sv}E_{PMv}}{L_{sd}}\sin\delta + u_{sv}^2\frac{L_{sd}-L_{sq}}{2L_{sd}L_{sq}}\sin 2\delta\right) \tag{2.3}$$

Depends on the architecture of pole for example non-salient pole the torque is related the inverse of inductance, thus if the objective is to be able to product high torque, Inductance level must be low. Due to the fact that interior electromagnetic force E_{PM} and E_F of PMSM cannot be taken into account as similarly only with changing of the field current [1].

To be able to achieve a significant amount of pull out Torque for Permanent Magnet Machines the synchronous inductances must have chosen low respectively. However, surface fixed magnets easily handle this case on the other hand if the magnets are embedded into machines, the value of PU reaches to one thus E_{PM} cannot reach above one.

CHAPTER 3: MATHEMATICAL MODEL OF PMSM

3.1 Three-phase reference frame (ABC) of PMSM

Figure 3.1 is a schematic diagram of cross section view of three-phase abc PMSM with *α-β* reference frame.

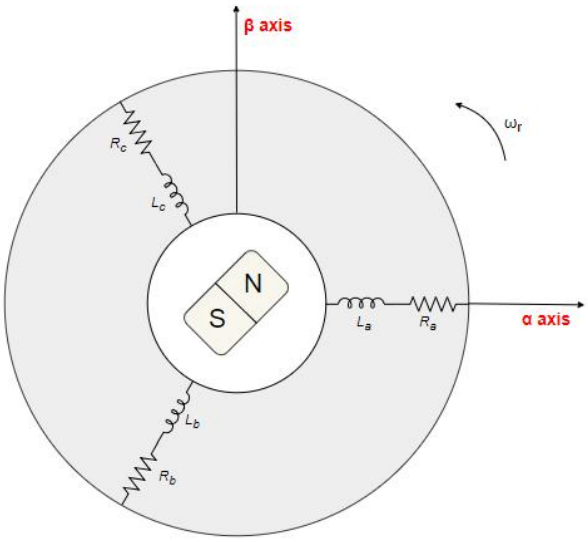

Figure 3.1: View of a three-phase PMSM

Stator windings have been equally distributed with 120 degrees in the motor space. Table 1 shows the components of schematic diagram of PMSM.

Stator Currents	Stator Voltages	Flux Linkages	Electrical Rotor Angle	Orthogonal Axis
i_a, i_b, i_c	u_a, u_b, u_c	$\psi_a\ \psi_b\ \psi_c$	Φ_r	α-axis β-axis

Table 1: The components of schematic diagram of PMSM

Three-phase abc model of PMSM has stator flux linkages shown as below:

$$\psi_a = L_{aa}i_a + L_{ab}i_b + L_{ac}i_c + \Psi_{PM}\cos(\phi_r) \tag{3.1}$$

$$\psi_b = L_{ba}i_a + L_{bb}i_b + L_{bc}i_c + \Psi_{PM}\cos\left(\phi_r - \frac{2\pi}{3}\right) \tag{3.2}$$

$$\psi_c = L_{ca}i_a + L_{cb}i_b + L_{cc}i_c + \Psi_{PM}\cos\left(\phi_r + \frac{2\pi}{3}\right) \tag{3.3}$$

The Matrix form of flux linkage given by:

$$\begin{bmatrix}\psi_a\\ \psi_b\\ \psi_c\end{bmatrix}=\begin{bmatrix}\Psi_{PM}(\phi_r)\\ \Psi_{PM}(\phi_r-\frac{2\pi}{3})\\ \Psi_{PM}(\phi_r+\frac{2\pi}{3})\end{bmatrix} \tag{3.4}$$

Flux linkages of equally distributed stator windings are:

$$\begin{bmatrix}\psi_a\\ \psi_b\\ \psi_c\end{bmatrix}=\begin{bmatrix}L_{aa} & L_{ab} & L_{ac}\\ L_{ba} & L_{bb} & L_{bc}\\ L_{ca} & L_{cb} & L_{cc}\end{bmatrix}*\begin{bmatrix}i_a\\ i_b\\ i_c\end{bmatrix}+\begin{bmatrix}\Psi_{PM}(\phi_r)\\ \Psi_{PM}(\phi_r-\frac{2\pi}{3})\\ \Psi_{PM}(\phi_r+\frac{2\pi}{3})\end{bmatrix} \tag{3.5}$$

Where Ψ_{PM} is the flux linkage established by the permanent magnet and L_{aa}, L_{bb}, L_{cc} are the self-inductances of the stator a-phase, b-phase, c-phase. On the other hand, the mutual inductances between a-phase and b-phase, b-phase and c-phase, c-phase and a-phase respectively are $L_{ab} = L_{ba}$, $L_{bc} = L_{cb}$, $L_{ca} = L_{ac}$. In the flux linkage equations, inductances functions of the rotor angle are the functions of the rotor angle ϕ_r.

The self-inductance of the stator windings can be defined as below (with taken into account of saliency):

$$L_{aa} = L_{1s} + L_{0s} - L_{ss}\cos(2\phi_r) \tag{3.6}$$

$$L_{bb} = L_{1s} + L_{0s} - L_{ss}\cos\left(2\left(\phi_r - \frac{2\pi}{3}\right)\right) \tag{3.7}$$

$$L_{cc} = L_{1s} + L_{0s} - L_{ss}\cos\left(2\left(\phi_r + \frac{2\pi}{3}\right)\right) \tag{3.8}$$

As stated in [10], due to saliency L_{ss} is the inductance fluctuation between the leakage inductance of the stator winding L_{ls} and average inductance L_{0s} due to air-gap flux.

Therefore, mutual inductances between the stator windings can be defined as:

$$L_{ab} = L_{ba} = -\frac{1}{2}L_{0s} - L_{ss}\cos\left(2\left(\phi_r - \frac{2\pi}{3}\right)\right) \tag{3.9}$$

$$L_{bc} = L_{cb} = -\frac{1}{2}L_{0s} - L_{ss}\cos\big(2(\phi_r + \pi)\big) \tag{3.10}$$

$$L_{ca} = L_{ac} = -\frac{1}{2}L_{0s} - L_{ss}\cos\left(2\left(\phi_r + \frac{2\pi}{3}\right)\right) \tag{3.11}$$

If the three-phase quantities do not contain any non-zero component the flux linkages of three-phase PMSM can be shown as below:

$$\psi_a = \left(L_{ls} + \frac{3}{2}L_{0s} - \frac{3}{2}L_{ss}\cos(2\phi_r)\right)i_a + \frac{\sqrt{3}}{2}L_{ss}\sin(2\phi_r)(i_c - i_b) + \Psi_{PM}\cos(\phi_r) \tag{3.12}$$

$$\psi_b = \left(L_{aa0} + \frac{3}{2}L_{0s} - \frac{3}{2}L_{ss}\cos\left(2\left(\phi_r - \frac{2\pi}{3}\right)\right)\right)i_b + \frac{\sqrt{3}}{2}L_{ss}\sin\left(2\left(\phi_r - \frac{2\pi}{3}\right)\right)(i_a - i_c) + \Psi_{PM}\cos\left(\phi_r - \frac{2\pi}{3}\right) \tag{3.13}$$

$$\psi_c = \left(L_{aa0} + \frac{3}{2}L_{0s} - \frac{3}{2}L_{ss}\cos\left(2\left(\phi_r + \frac{2\pi}{3}\right)\right)\right)i_c + \frac{\sqrt{3}}{2}L_{ss}\sin\left(2\left(\phi_r + \frac{2\pi}{3}\right)\right)(i_b - i_a) + \Psi_{PM}\cos\left(\phi_r + \frac{2\pi}{3}\right) \tag{3.14}$$

Simply the three-phase stator voltages are:

$$u_a = R_a i_a + \frac{d\psi_a}{dt} \tag{3.15}$$

$$u_b = R_b i_b + \frac{d\psi_b}{dt} \tag{3.16}$$

$$u_c = R_c i_c + \frac{d\psi_c}{dt} \tag{3.17}$$

Where R_a, R_b, R_c = R_s *are* the equal resistances of the stator a-phase, b-phase, c-phase respectively.

The total flux linkage $\underline{\psi_s^s}$ is equal to:

$$\underline{\psi_s^s} = \left(L_{ls} + \frac{3}{2}L_{0s}\right)\underline{i_s^s} + \frac{3}{2}L_{ss}e^{j2\phi_r}\underline{i_s^{s^*}} + \Psi_{PM}e^{j\phi_r} \tag{3.18}$$

The combination of the equation shown above becomes:

$$\underline{\psi_s^s} = \underline{L_s i_s^s} + \Psi_{PM}e^{j\phi_r} \tag{3.19}$$

$\underline{L_s}$ is mutual inductance and leakage of the permanent magnet.

3.2 Two axis reference frames: *αβ* to *dq*

All equations of stator voltage, flux linkage and current above have been presented based on three-phase permanent magnet machine on reference frame of α-*β*.

To be able to convert from fixed α-*β* frame to rotating *dq* reference frame quantity of functions need to be multiplied by $e^{-j\theta}$ for transformation. Thus, all the voltage current and flux linkage equations and self-inductances become time invariant coefficients.

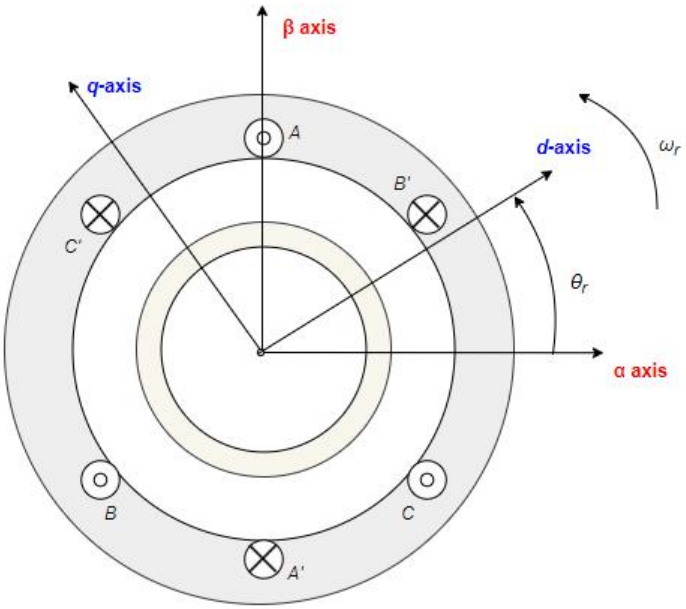

Figure 3.2: View of three-phase, two-pole PMSM

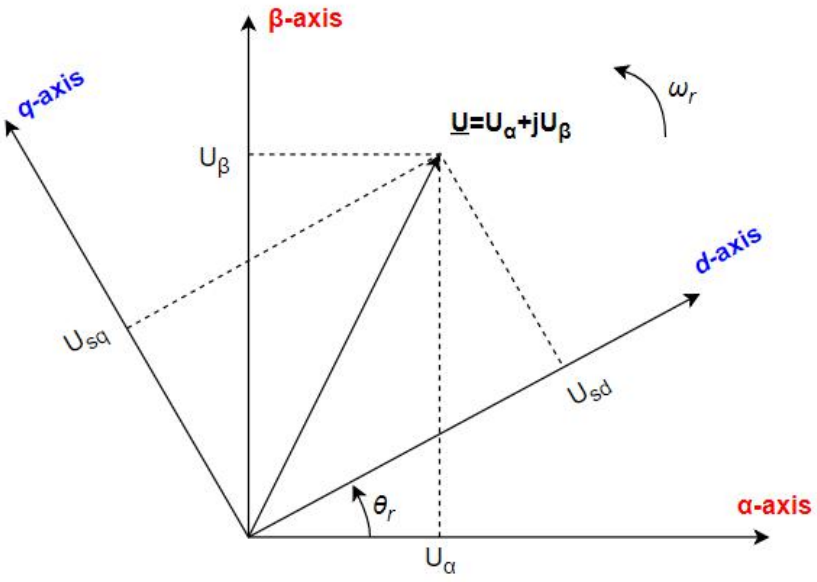

Figure 3.3: Coordinate transformation from α-β frame to d-q frame

Consider θ_r as transformation angle of *dq*. Therefore, the equation of transformation from α-*β* to *dq* is calculated as: $\underline{U}=U_\alpha+jU_\beta$

$$\begin{aligned}\underline{u_s} = \underline{u_s^s}e^{-j\theta_r} &= \left(u_{s\alpha} + ju_{s\beta}\right)(\cos\theta_r - j\sin\theta_r) \\ &= \left(u_{s\alpha}\cos\theta_r + u_{s\beta}\sin\theta_r\right) + j\left(u_{s\beta}\cos\theta_r - u_{s\alpha}\sin\theta_r\right) \\ &= u_{sd} + ju_{sq}\end{aligned} \tag{3.20}$$

In addition, matrix version of conversion equations is:

$$\begin{bmatrix}u_{sd}\\ u_{sq}\end{bmatrix} = \begin{bmatrix}\cos\theta_r & \sin\theta_r\\ -\sin\theta_r & \cos\theta_r\end{bmatrix}\begin{bmatrix}u_{s\alpha}\\ u_{s\beta}\end{bmatrix} \tag{3.21}$$

Extension of transformed relations between fixed and rotating frames of α-*β* and *dq* as shown as below respectively current voltage and flux linkages:

$$\underline{i_s} = \underline{i_s^s}e^{-j\theta_r} \tag{3.22}$$

$$\underline{u_s} = \underline{u_s^s}e^{-j\theta_r} \tag{3.23}$$

$$\underline{\psi_s} = \underline{\psi_s^s}e^{-j\theta_r} \tag{3.24}$$

Equation (3.23) shows that, in the α-*β* fixed frame stator voltage equation introduced as:

$$\underline{u_s^s} = \underline{u_s}e^{j\theta_r} = R_s\underline{i_s}e^{j\theta_r} + \frac{d}{dt}\left(\underline{\psi_s}e^{j\theta_r}\right) = R_s\underline{i_s}e^{j\theta_r} + \frac{d\underline{\psi_s}}{dt}e^{j\theta_r} + j\omega_r\underline{\psi_s}e^{j\theta_r} \tag{3.25}$$

Therefore, *dq* referenced frame stator voltage equation is shown as below:

$$\underline{u_s} = R_s\underline{i_s} + \frac{d\underline{\psi_s}}{dt} + j\omega_r\underline{\psi_s} \tag{3.26}$$

Where, ω_r is the electrical rotor speed. Similarly flux linkage equation in α-*β* fixed reference frame is calculated as below:

$$\underline{\psi_s} = \underline{\psi_s^s}e^{j\theta_r} = \left(L_{ls} + \frac{3}{2}L_{0s}\right)\underline{i_s}e^{j\theta_r} + \frac{3}{2}L_{ss}e^{j2\phi_r}\left(\underline{i_s}e^{j\theta_r}\right)^* + \Psi_{PM}e^{j\phi_r} \tag{3.27}$$

Correspondingly *dq* rotating frame PMSM has flux linkage $\underline{\psi_s}$ of:

$$\underline{\psi_s} = \left(L_{ls} + \frac{3}{2}L_{0s}\right)\underline{i_s} + \frac{3}{2}L_{ss}e^{j(2\phi_r - 2\theta_r)}\underline{i_s^*} + \Psi_{PM}e^{j(\phi_r - \theta_r)} \tag{3.28}$$

In our study field orientation is based on perfect alignment. Thus, the transformation angle of fixed frame *dq* is equal to rotor angle ($\theta_r = \phi_r$). In which simplifies the equation of flux linkage $\underline{\psi_s}$ shown as below:

$$\underline{\psi_s} = \left(L_{ls} + \frac{3}{2}L_{0s}\right)\underline{i_s} + \frac{3}{2}L_{ss}\underline{i_s^*} + \Psi_{PM} \tag{3.29}$$

The voltage and current equations of fixed dq frame respectively $\underline{i_s}$, $\underline{i_s^*}$, $\underline{u_s}$ can be simply expressed as shown below;

$$\underline{i_s} = i_{sd} + ji_{sq} \tag{3.30}$$

$$\underline{i_s^*} = i_{sd} - ji_{sq} \tag{3.31}$$

$$\underline{u_s} = u_{sd} + ju_{sq} \tag{3.32}$$

From this equation it is possible to express an extended equation for Flux linkage $\underline{\psi_s}$:

$$\underline{\psi_s} = \left(L_{ls} + \frac{3}{2}L_{0s} + \frac{3}{2}L_{ss}\right)\underline{i_{sd}} + j\left(L_{ls} + \frac{3}{2}L_{0s} - \frac{3}{2}L_{ss}\right)\underline{i_{sq}} + \Psi_{PM} \tag{3.33}$$

$$= L_{sd}\underline{i_{sd}} + jL_{sq}\underline{i_{sq}} + \Psi_{PM}$$

Where L_{sd} and L_{sq} presents the stator inductances in *dq* coordinates. After expanding the stator voltage equation (3.26), with respect to the equations (3.30), (3.32) and the last flux linkage equation above, we obtain the voltage equations in *dq* coordinates as below:

$$u_{sd} = R_s i_{sd} + L_{sd}\frac{di_{sd}}{dt} - \omega_r L_{sq} i_{sq} \tag{3.34}$$

$$u_{sq} = R_s i_{sq} + L_{sq}\frac{di_{sq}}{dt} + \omega_r L_{sd} i_{sd} + \omega_r \Psi_{PM} \tag{3.35}$$

It is known that for the single-phase phasors with RMS values $\underline{U}$ and $\underline{I}$, the power relation can be written as $P = R_e\{\underline{U}\,\underline{I^*}\}$. For a three-phase system the instantaneous power is expressed as [12]:

$$R_e\left\{\underline{u_s^s i_s^{s^*}}\right\} = R_e\left\{\underline{u_s}e^{j\theta_r}\left(\underline{i_s}e^{j\theta_r}\right)^*\right\} = R_e\left\{\underline{u_s i_s^*}\right\} \tag{3.36}$$

By using the space-vector definition,

$$\underline{u_s^s i_s^{s^*}} = \left(\frac{2K}{3}\right)^2\left(u_a + u_b e^{j\frac{2\pi}{3}} + u_c e^{j\frac{4\pi}{3}}\right)\left(i_a + i_b e^{j\frac{2\pi}{3}} + i_c e^{j\frac{4\pi}{3}}\right)^* \tag{3.37}$$

In order to reach the equation of instantaneous power, it is assumed that $i_a + i_b + i_c = 0$. By using the mathematical transformation $e^{-j\frac{2\pi}{3}} = e^{j\frac{4\pi}{3}}$, it can be written as:

$$P = \frac{3}{2K^2} R_e \left\{ \underline{u_s^s i_s^{s^*}} \right\} = \frac{3}{2K^2} R_e \left\{ \underline{u_s i_s^*} \right\} = u_a i_a + u_b i_b + u_c i_c \tag{3.38}$$

The electric power to the shaft can be expressed as below:

$$P_e = \frac{3}{2K^2} R_e \left\{ j\phi_r \underline{\psi_s} \underline{i_s^*} \right\} \tag{3.39}$$

Recalling the fundamentals of complex numbers, it can be written $z = x+jy$, and $\left[R_e\{j\underline{z}\} = R_e j(x+jy) = -y = -I_m\{\underline{z}\}\right]$, that's why the electrical power is rewritten as:

$$P_e = -\frac{3\phi_r}{2K^2} I_m \left\{ \underline{\psi_s i_s^*} \right\} = \frac{3\phi_r}{2K^2} I_m \left\{ \underline{\psi_s^* i_s} \right\} \tag{3.40}$$

To see the relationship between P_e, and T_e,, ω_r. The electrical power can be expressed as:

$$P_e = T_e \omega_r \tag{3.41}$$

Where T_e is the electrical torque and ω_r is the mechanical rotor speed. Mechanical rotor speed can be described as below:

$$\omega_r = \frac{\phi_r}{p} \tag{3.42}$$

Where ω_r is the electrical rotor speed and p is the number of pole pairs. The electrical torque can now be further expressed as:

$$T_e = \frac{P_e}{\omega_r} = \frac{pP_e}{\phi_r} = \frac{3\phi_r p}{2\phi_r K^2} I_m \left\{ \underline{\psi_s^* i_s} \right\} = \frac{3p}{2K^2} \left(L_{sd} i_{sd} i_{sq} - L_{sq} i_{sq} i_{sd} + \Psi_{PM} i_{sq} \right) \tag{3.43}$$

$$= \frac{3p}{2K^2} \left(\left(L_{sd} - L_{sq} \right) i_{sq} i_{sd} + \Psi_{PM} i_{sq} \right)$$

The relation between the electrical torque T_e and the load torque T_L is described as below:

$$J \frac{d\omega_r}{dt} = \frac{J}{p} \frac{d\phi_r}{dt} = T_e - T_L \tag{3.44}$$

Where J is the inertia of the motor. It should be noted that the complete load torque T_L consists of two parts. The first part is the speed independent part which is related to the viscous coefficient B, the second part is the extra load torque input $T_{L,extra}$.

$$T_L = B\omega_r + T_{L,extra} = \frac{B\phi_r}{p} + T_{L,extra} \tag{3.45}$$

The electrical rotor speed can be written depending on the electrical rotor position. In this equation ϕ_r stands for the electrical rotor position which is equal to the *dq* transformation angle θ_r. The mechanical rotor position is given by the equation below:

$$\phi_r = \frac{\theta_r}{p} \tag{3.46}$$

3.2.1 Equivalent circuit in *dq* reference frame

Usually Permanent Magnet Synchronous Machines are be placed on a *dq* reference frame which is fixed to the rotor as same as separately excited synchronous machines. Therefore, the equivalent circuit of the permanent magnet synchronous machine and the separately excited synchronous machine as shown as Figure 3.4 have almost similar architecture of equivalent circuit. [1]

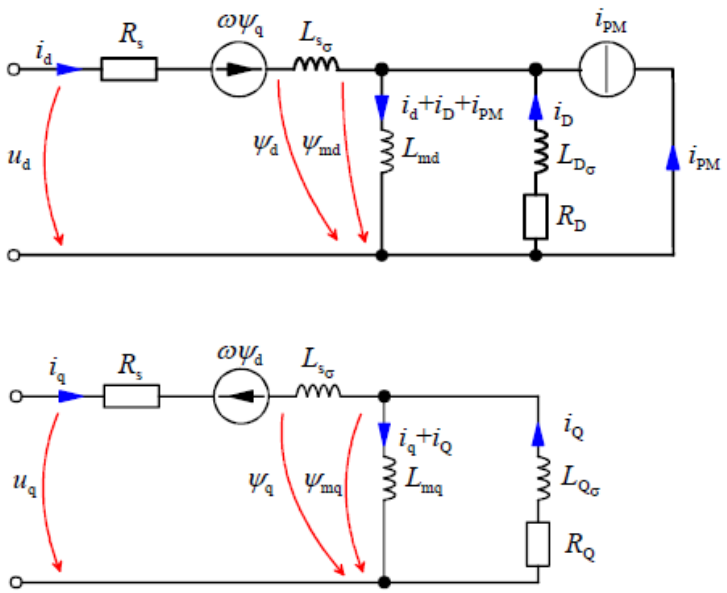

Figure 3.4: Equivalent circuits of a PMSM in d and q directions [1]

If damper windings optionally added on the equation of PMSM, the difference of voltage equation between separately excited synchronous machine and Permanent Magnet Machine is caused by lacking of field winding equation.

Hence, Permanent Magnet Machine voltage equations in the Rotor *dq* reference frame is:

$$u_{sd} = R_s i_{sd} + \frac{d\varphi_{sd}}{dt} - \omega_r \varphi_{sq} \tag{3.47}$$

$$u_{sq} = R_s i_{sq} + \frac{d\varphi_{sq}}{dt} + \omega_r \varphi_{sd} \tag{3.48}$$

$$0 = R_D i_D + \frac{d\varphi_D}{dt} \tag{3.49}$$

$$0 = R_Q i_Q + \frac{d\varphi_Q}{dt} \tag{3.50}$$

The components of flux linkage in the equations are determined by

$$\varphi_{sd} = L_{sd} i_{sd} + L_{md} i_D + \Psi_{PM} \tag{3.51}$$

$$\varphi_{sq} = L_{sq} i_{sq} + L_{mq} i_Q \tag{3.52}$$

$$\varphi_D = L_{md} i_{sd} + L_D i_D + \Psi_{PM} \tag{3.53}$$

$$\varphi_Q = L_{mq} i_{sq} + L_Q i_Q \tag{3.54}$$

The Field Current i_{PM} generates the flux linkage Ψ_{PM} of the permanent magnet can be considered as

$$i_{PM} = \frac{\Psi_{PM}}{L_{md}} \tag{3.55}$$

Thus, separately excited synchronous machines are not departed from an established course of flux linkage. On the other hand it is noticeable that the field current i_{PM}, and the saturation of the magnetizing inductance L_{md} are not constant.

3.2.2 Vector Diagram of PMSM

The vector diagram of a synchronous machine can be modified as vector diagram of the PMSM as shown in the figure below (Figure 3.5). The Flux linkage Ψ_{PM} created by permanent magnets are in the stator winding.

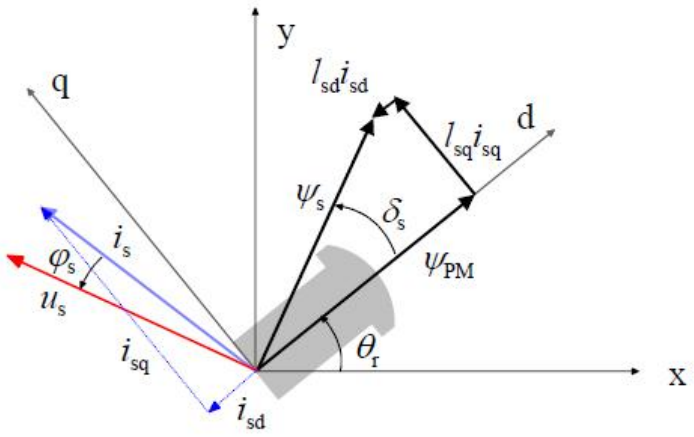

Figure 3.5: Vector diagram of PMSM [1]

In our study, damping effect on the permanent magnet synchronous machine are not taken into account. Therefore, the equation of the flux linkages is simplified as below:

$$\varphi_{sd} = L_{sd} i_{sd} + \Psi_{PM} \tag{3.56}$$

$$\varphi_{sq} = L_{sq} i_{sq} \tag{3.57}$$

Permanent magnet synchronous machines have the same cross field principle of separately excited synchronous machines calculating torque T_e. Thus the equation of torque is also valid for Permanent Magnet machine:

$$T_e = \frac{3}{2} p\left[\Psi_{PM} i_{sq} - \left(L_{mq} - L_{md}\right) i_{sd} i_{sq} + L_{md} i_D i_{sq} + L_{mq} i_Q i_{sd}\right] \tag{3.58}$$

There are four terms to define Cross Field Principle, that goal to produce a certain torque. The most important term is the first one, for most of the PM machines it's also the only term which depends on the flux linkage of the permanent magnets and the stator current. It's should be noted here the stator current is perpendicular to flux linkage. The difference between *d-axis* and *q-axis* inductances creates the second term of this principle. The terms which depend on damper currents are only valid in transients and machines where damper currents occur. In order to develop different control principles for the PM machines, the torque equation is generally used as the beginning point.

3.3 Fundamentals of Clarke's and Park's Transformation

The properties of the Clarke's and Park's Transformations are studied in this chapter. In the last chapter, while creating the mathematical model for a PMSM, the theoretical background of these transformations was also discussed. This chapter focuses more to express the transformations clearly. The voltages, currents and flux linkages are shown in matrix form as well as the related equations.

According to [14], which is stated in previous chapter, Clarke developed the transformation with two-phase variables α and β, which transforms stationary circuits to a stationary reference frame.

The Park's Transformation has *d* and *q* as the two-phase variables. The Park's Transformation eliminates the time varying inductances from the three-phase voltage equations. This can be considered as the most significant feature of Park's Transformation. The spinning of the rotor is the reason of this feature. While realizing the derivation process of the *dq* model of a PMSM, the assumptions below are made:

- Sinusoidal MMF distribution is produced
- Space harmonics in the air-gap are neglected
- Three-phase sinusoidal supply voltage is considered
- Eddy current and hysteresis effects are neglected
- Iron losses are neglected
- Resistances don't depend on temperature and frequency

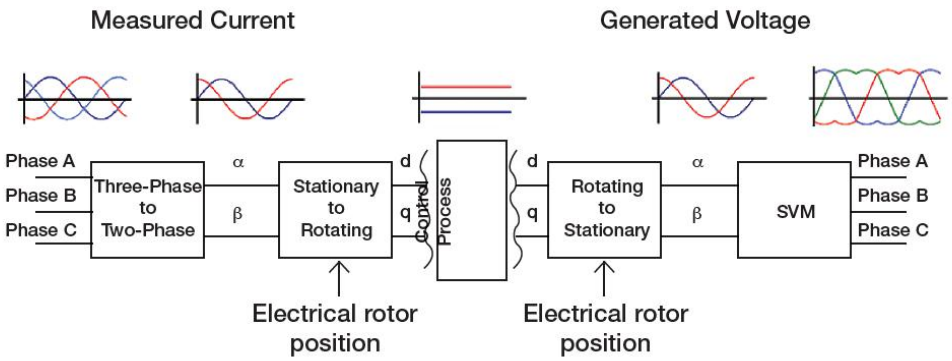

Figure 3.6: Basic Principle of Park's and Clarke's Transformation [11]

While working with Clarke's Transformation, a zero-sequence component should be added as the third variable to make the transformation invertible. As a result, the transformation can be written from *abc* three-phase stationary frame to *α-β* reference frame as below:

$$[S_{\alpha\beta 0}] = T_{\alpha\beta 0}[S_{abc}] \tag{3.59}$$

Where $[S_{\alpha\beta 0}] = [S_\alpha \quad S_\beta \quad S_0]^T$ and $[S_{abc}] = [S_a \quad S_b \quad S_c]^T$
In this equations *S* represents the voltage, current and flux linkage. The transformation matrix $T_{\alpha\beta 0}$ is written as [14]:

$$T_{\alpha\beta 0} = \frac{2}{3}\begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 1 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \tag{3.60}$$

As like the equation (3.59) the inverse transformation can be written as:

$$[S_{abc}] = T^{-1}_{\alpha\beta 0}[S_{\alpha\beta 0}] \tag{3.61}$$

By using the equation above, the inverse transformation matrix can be described as:

$$T^{-1}_{\alpha\beta 0} = \begin{bmatrix} 1 & 0 & 1 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} & 1 \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} & 1 \end{bmatrix} \tag{3.62}$$

For making the Park Transformation, a reference frame which is fixed on the rotor is needed. So, with respect to the rotor, it can be observed that stator and rotor variables are constant values.

As like the equations above, the transformation between three-phase stationary frame and *dq* reference frame is defined as:

$$\left[S_{dq0}\right] = T_{dq0}[S_{abc}] \tag{3.63}$$

Where $\left[S_{dq0}\right] = [S_d \quad S_q \quad S_0]^T$ and $[S_{abc}] = [S_a \quad S_b \quad S_c]^T$
Same as before, *S* represents the voltage, current and flux linkage. The *dq0* transformation matrix is constituted as [2]:

$$T_{dq0} = \frac{2}{3}\begin{bmatrix} \cos\theta_r & \cos\left(\theta_r - \frac{2\pi}{3}\right) & \cos\left(\theta_r + \frac{2\pi}{3}\right) \\ -\sin\theta_r & -\sin\left(\theta_r - \frac{2\pi}{3}\right) & -\sin\left(\theta_r + \frac{2\pi}{3}\right) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \tag{3.64}$$

The inverse transformation is:

$$[S_{abc}] = T_{dq0}^{-1}\left[S_{dq0}\right] \tag{3.65}$$

Where T_{dq0}^{-1} inverse transformation matrix is written as:

$$T_{dq0}^{-1} = \frac{2}{3}\begin{bmatrix} \cos\theta_r & -\sin\theta_r & 1 \\ \cos\left(\theta_r - \frac{2\pi}{3}\right) & -\sin\left(\theta_r - \frac{2\pi}{3}\right) & 1 \\ \cos\left(\theta_r + \frac{2\pi}{3}\right) & -\sin\left(\theta_r + \frac{2\pi}{3}\right) & 1 \end{bmatrix} \tag{3.66}$$

Based on the mutual inductance and self-inductance equations, which are mentioned the last chapter about modelling, all the stator inductances can be stated together in a matrix as below [8]:

$$L_{stator} = \begin{bmatrix} L_{aa} & L_{ab} & L_{ac} \\ L_{ba} & L_{bb} & L_{bc} \\ L_{ca} & L_{cb} & L_{cc} \end{bmatrix} \tag{3.67}$$

Because of the permanent magnet effect, the matrix which represents the flux linkages on the stator windings can be constituted as:

$$[\psi_r] = \begin{bmatrix} \Psi_{PM}\cos(\phi_r) \\ \Psi_{PM}\cos\left(\phi_r - \frac{2\pi}{3}\right) \\ \Psi_{PM}\cos\left(\phi_r + \frac{2\pi}{3}\right) \end{bmatrix} = \begin{bmatrix} \psi_{ra} \\ \psi_{rb} \\ \psi_{rc} \end{bmatrix} \tag{3.68}$$

It's easy to see that $\psi_{ra}, \psi_{rb}, \psi_{rc}$ represents the flux linkages on the stator windings, which are established by the permanent magnet.

Now we can rewrite the three-phase voltage equations as:

$$[u_s] = R_s[i_s] + \frac{d}{dt}[\psi_s] \tag{3.69}$$

$$[\psi_s] = [\psi_a \quad \psi_b \quad \psi_c]^T \tag{3.70}$$

$$[u_s] = [u_a \quad u_b \quad u_c]^T \tag{3.71}$$

$$[i_s] = [i_a \quad i_b \quad i_c]^T \tag{3.72}$$

Where $[\psi_s], [u_s], [i_s]$ represents the three-phase flux linkages, three-phase stator voltages and three-phase stator currents.

The flux linkages matrix for the three-phase stator windings is described as:

$$[\psi_s] = L_{stator}[i_s] + [\psi_{PM}] \tag{3.73}$$

Where, L_{stator} is the stator inductance matrix which is stated before $[\psi_{PM}]$ is the flux linkage matrix with respect to the permanent magnet.

Now, by using the Park's transformation matrix T_{dq0}, the three-phase flux linkages, three-phase stator voltages and three-phase stator currents are transformed as:

$$[\psi_{dq0}] = [T_{dq0}][\psi_s] \tag{3.74}$$

$$[u_{dq0}] = [T_{dq0}][u_s] \tag{3.75}$$

$$[i_{dq0}] = [T_{dq0}][i_s] \tag{3.76}$$

In *dq* reference frame, the equation for flux linkages can be obtained as:

$$[\psi_{dq0}] = [T_{dq0}]L_{stator}[T_{dq0}]^{-1} + [T_{dq0}][\psi_r] \tag{3.77}$$

$$[\psi_{dq0}] = [\psi_{sd} \quad \psi_{sq} \quad \psi_0]^T \tag{3.78}$$

$$[i_{dq0}] = [i_{sd} \quad i_{sq} \quad i_0]^T \tag{3.79}$$

The first term of the equation for $[\psi_{dq0}]$, which is $[T_{dq0}]L_{stator}[T_{dq0}]^{-1}$ is the transformation matrix. This matrix transforms the stator phase inductance matrix L_{stator} to the inductance matrix on the *dq* reference frame $[L_{dq0}]$.

$$[L_{dq0}] = [L_{sd} \quad L_{sq} \quad L_0]^T \tag{3.80}$$

If we simplify the right-hand side of the equation (3.77), we get the *dq* axis flux linkages, ψ_{sd} and ψ_{sq}, inductances, L_{sd} and L_{sq} and currents i_{sd} and i_{sq} as follows:

$$\psi_{sd} = \left(L_{ls} + \frac{3}{2}(L_{0s} + L_{ss})\right) i_{sd} + \Psi_{PM} = L_{sd} i_{sd} + \Psi_{PM} \tag{3.81}$$

$$\psi_{sq} = \left(L_{ls} + \frac{3}{2}(L_{0s} - L_{ss})\right) i_{sq} = L_{sq} i_{sq} \tag{3.82}$$

$$\psi_0 = L_{ls} i_0 \tag{3.83}$$

The next step is to derivate the voltages of the *dq* axis. If we take the equations (3.74), (3.75), (3.76) and write them into (3.69) we obtain the equations of the stator voltage in *dq* coordinates as follows:

$$[u_{dq0}] = [T_{dq0}] R_s [T_{dq0}]^{-1} [i_{dq0}] + [T_{dq0}] \frac{d}{dt} \left([T_{dq0}]^{-1} [\phi_{dq0}] \right) \tag{3.84}$$

where,

$$[u_{dq0}] = [u_{sd} \quad u_{sq} \quad u_0]^T \tag{3.85}$$

It should be taken into account that the stator resistance R_s is a scalar quantity, and the second term of the equation (3.84) has a derivation, the equation for the stator voltage can be rewritten as:

$$[u_{dq0}] = R_s [i_{dq0}] + [T_{dq0}] \left(\frac{d}{dt} \left([T_{dq0}]^{-1} \right) [\phi_{dq0}] + [T_{dq0}]^{-1} \frac{d}{dt} [\phi_{dq0}] \right) \tag{3.86}$$

After we expand the second term of the equation above, the final form of the stator voltage equation in *dq* coordinates will be:

$$[u_{dq0}] = R_s [i_{dq0}] + [T_{dq0}] \frac{d}{dt} \left([T_{dq0}]^{-1} \right) [\phi_{dq0}] + \frac{d}{dt} [\phi_{dq0}] \tag{3.87}$$

If we take the derivative of $[T_{dq0}]^{-1}$ as it's done before, the matrix will be:

$$\frac{d}{dt} [T_{dq0}]^{-1} = \omega_r \begin{bmatrix} -\sin\theta_r & -\cos\theta_r & 0 \\ -\sin\left(\theta_r - \frac{2\pi}{3}\right) & -\cos\left(\theta_r - \frac{2\pi}{3}\right) & 0 \\ -\sin\left(\theta_r + \frac{2\pi}{3}\right) & -\cos\left(\theta_r + \frac{2\pi}{3}\right) & 0 \end{bmatrix} \tag{3.88}$$

Where, ω_r is the rotor speed.

A new matrix is achieved after multiplying the transformation matrix $[T_{dq0}]$ with the matrix above. We reach the final form of the matrix by using trigonometric equations.

$$[T_{dq0}]\frac{d}{dt}[T_{dq0}]^{-1} = \omega_r \begin{bmatrix} 0 & -1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \tag{3.89}$$

After obtaining this equation we can write the expanded form of the stator voltage equation (3.87), by combining the equations (3.78), (3.79), (3.85), (3.89).

$$\begin{bmatrix} u_{sd} \\ u_{sq} \\ u_0 \end{bmatrix} = R_s \begin{bmatrix} i_{sd} \\ i_{sq} \\ i_0 \end{bmatrix} + \omega_r \begin{bmatrix} 0 & -1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} \psi_{sd} \\ \psi_{sq} \\ \psi_0 \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} \psi_{sd} \\ \psi_{sq} \\ \psi_0 \end{bmatrix} \tag{3.90}$$

After solving the equation above the first two variables u_{sd}, u_{sq} can now be expressed as below:

$$u_{sd} = R_s i_{sd} - \omega_r \psi_{sq} + \frac{d}{dt}\psi_{sd} = R_s i_{sd} - \omega_r L_{sq} i_{sq} + L_{sd}\frac{d}{dt} i_{sd} \tag{3.91}$$

$$u_{sq} = R_s i_{sq} + \omega_r \psi_{sd} + \frac{d}{dt}\psi_{sq} = R_s i_{sq} + \omega_r L_{sd} i_{sd} + \omega_r \Psi_{PM} + L_{sq}\frac{d}{dt} i_{sq} \tag{3.92}$$

The details are given below about the derivation of T_e as follows:

First the instantaneous input power P to the motor is introduced. The equation is given below:

$$P = u_a i_a + u_b i_b + u_c i_c \tag{3.93}$$

At the second step the three-phase voltages and currents must be transformed to dq reference frame, so the instantaneous input power P becomes:

$$P = \frac{3}{2}\left(u_{sq} i_{sq} + u_{sd} i_{sd}\right) \tag{3.94}$$

In the equation above we are neglecting the zero-sequence quantities. Then replacing u_{sq} and u_{sd}, the mechanical output power P_e becomes:

$$P_e = \frac{3}{2}\left(\psi_{sd}\omega_r i_{sq} - \psi_{sq}\omega_r i_{sd}\right) \tag{3.95}$$

Finally, by recalling the equations (3.41), (3.42), the electrical torque T_e is expressed as

$$T_e = \frac{P_e}{\omega_r} = \frac{pP_e}{\phi_r} = \frac{3p\phi_r}{2\phi_r}\left(\psi_{sd} i_{sq} - \psi_{sd} i_{sd}\right) \tag{3.96}$$

$$= \frac{3p}{2}\left(L_{sd} i_{sd} i_{sq} + \Psi_{PM} i_{sq} + L_{sq} i_{sq} i_{sd}\right)$$

$$= \frac{3p}{2}\left(\left(L_{sd} - L_{sq}\right) i_{sq} i_{sd} + \Psi_{PM} i_{sq}\right)$$

CHAPTER 4: CONTROL OF PMSM

4.1 Control methods for PMSM

Consideration of Sensorless based models there are two types of PMSM control method [15].

Those two control methods are:

Scalar PMSM Control:

Based on steady-state condition which is able to control frequency and magnitude V/f open loop control is an example of this type of control method.

Vector PMSM Control:

It works basically in all conditions which serve an opportunity to control both amplitude and frequency of the space vector. The common techniques of vector control are Field Oriented Control FOC and Direct Torque Control DTC [17].

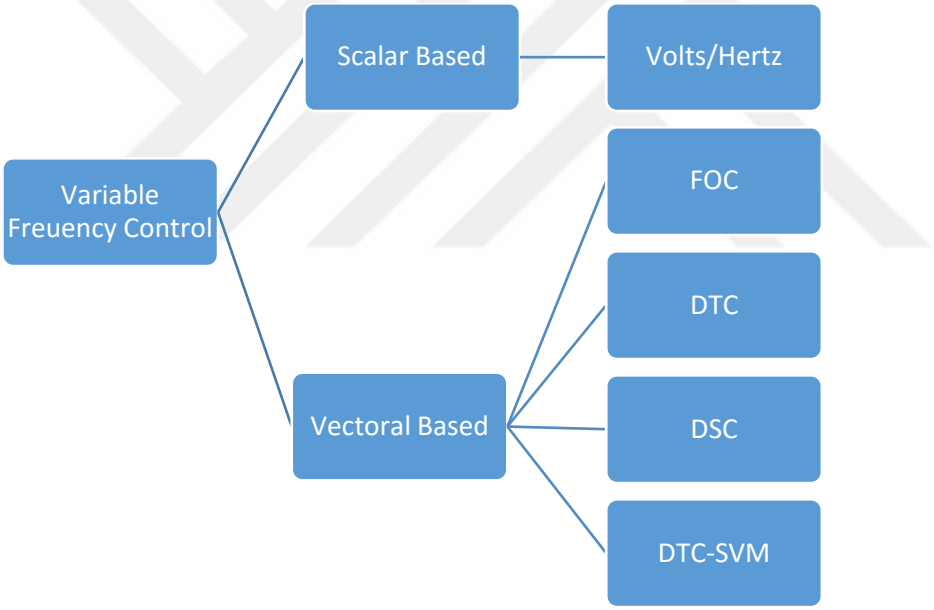

Figure 4.1: Control methods for PMSM

This chapter focuses on different control methods of PMSM. Basically, control methods can be divided in two types which are Vector and Scalar controls. Scalar control methods are based on steady-state condition on the other hand vector control considers the space vector which has an amplitude and position.

4.1.1 Scalar Control

Scalar control is only valid in steady state conditions. Thus, only the frequency and the magnitude of the voltage and current etc. can be controlled. Scalar control can be considered for example if several motors need to drive in parallel by the only source with an inverter.

4.1.1.1 Volts/Hertz Control

This control method doesn't have any feedback loop that's why it can be considered as open loop scheme. The main aim of this control logic to be able to keep stator flux constant at desired level therefore the motor can produce rated torque/ratio between the speed range.

Recalling the voltage equations related *dq* frame in (3.47) and (3.48):

$$u_{sd} = R_s i_{sd} + \frac{d\varphi_{sd}}{dt} - \omega_r \varphi_{sq} \tag{3.47}$$

$$u_{sq} = R_s i_{sq} + \frac{d\varphi_{sq}}{dt} + \omega_r \varphi_{sd} \tag{3.48}$$

Where, R_s stator resistance, ω_r angular velocity, u_{sd} , u_{sq} are stator voltage, ψ_s is the flux linkage and i_s is the stator current. Amplitude of voltage is linearly depended on angular frequency of the rotor if the stator flux considers as constant value. The principle of the method only works for stationary conditions.

4.1.2 Vector Control

Vector Control of PMSM is necessary to be able to become applicable as control method of simultaneously conducted three-phases.

PMSM motors from it is definition they have sinusoidal wave type of motors. In these motors the interaction of the magnetic flux by permanent magnets and phase conductions create the torque [8].

However, there are several different types of operation of creating two axis system which has mentioned on the Chapter 3, Mathematical Model, *dq* axis coordinates components generally have been taken in account.

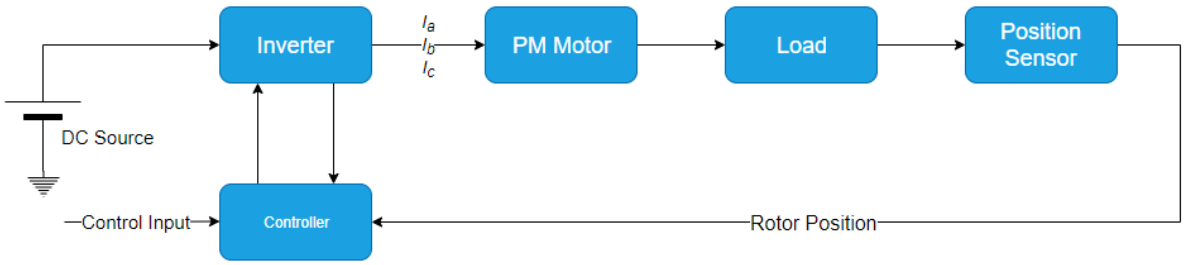

Figure 4.2: PMSM Drive System

4.1.2.1 Field Oriented Control (FOC)

In an AC Motor the field flux rotates but in the FOC the controller makes the stator flux rotate thus stator and field flux always kept orthogonal. Therefore, AC Motor behaves as DC Motor.

FOC requirements [16]:

- Stator current which is controlled independently should overcome the effects of winding resistance and flux leakage and induced voltage.
- There must be controlled or constant field flux
- There must be controlled orthogonal spatial angel between stator and rotator flux

4.1.2.2 Direct Torque Control

DTC Direct torque control principle is choosing directly the voltage vectors depends on the difference between actual and reference frame of flux linkage and torque values with selecting the value of voltage vector through table.

DTC has the advantage of simplicity with using the motor parameter of stator resistance.

Also, there is no requirements of pulse width modulation only one of the 6 VSI Voltage vectors necessarily applied during the sample period. Calculations have been done in a stationary reference frame without including actual rotor position. But for a synchronous motor rotor position must be known from the starting point. Due to low computational requirements DTC can be implement digitally. Despite of the fact that DTC has good dynamic performance it has poor performance in steady state.

4.1.2.3 Direct Self Control

Direct Self Control DSC has a similar control scheme as DTC. The characteristics of this methods are Inverter switching Frequency difference and excellent torque dynamics performance both constant flux and in field weakening regions. Low switching frequency and fast torque control advantages makes the DSC more convenient over DTC in high traction required applications.

4.1.2.4 DTC- Space Vector Modulation

In the DTC system the same active voltage vector is applied during the whole sample period and possibly several consecutive sample intervals which give rise to relatively high ripple levels in stator current flux linkage and torque. One of the proposals of DTC-Space Vector Modulation to minimize active voltage vector related problems. SVM can be consider as a synthesizer which can modulate the pulse width. Although having a good performance index instead of achieving the main aim of simplicity DTC it makes the model more complex.

This study focuses on Vector Control Method of PMSM with inverter. Motor Drive Systems are simulated on Amesim and OpenModelica.

4.2 Field Oriented Control

Field Oriented Control was introduced in the beginning 1970s [18]. It is one of the most important variations of vector control methods of PMSM. Field Oriented Control is based on the Park's Transformation in order to separate the effects on torque and flux linkage to two components. One of these components is the *d* axis current i_d, which affects the magnetic field and the flux linkage. The other component is the *q* axis current i_q, which affects the torque and the stator currents. This property makes the behavior of a Field Oriented Controlled PMSM is identical to a separately excited DC Machine [19].

It is known that if a synchronous machine is fed by three sinusoidal currents i_1, i_2 and i_3 to the three stator windings which are spaced by 120°, a constant amplitude magnetic field wave in the air gap is achieved. Which rotates with an angular velocity depends on the frequency of the currents. So, with the feedback of the stator currents and the rotor angle FOC is a very effective way to control the motor torque and the magnetic flux. The fast response and a very small ripple effect of torque, are the most distinct advantages of this control technique [5].

In order to implement this technique, two current controllers and a speed controller are used. One controller is to control the direct-axis component (i_d) and the other one is to control the quadrature-axis (i_q) component respectively.

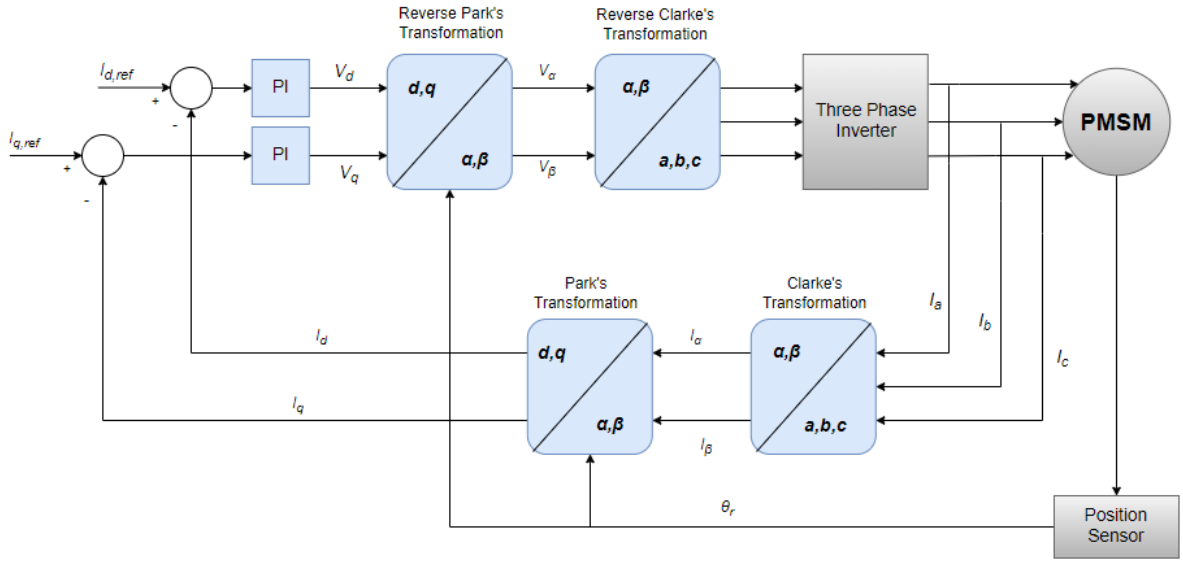

Figure 4.3: A complete block diagram of the FOC technique

A control mechanism as shown above Figure 4.3 works as following: First the reference speed, ω_{ref} is compared with the measured speed, ω_r. With the error signal ε_ω, these signals feed the PI controller. The controller compares the measured and reference speed and gives a torque command output.

The rotating magnetic field can be described by the current space phasor as:

$$\underline{i} = \frac{2}{3}\left(i_1 + \underline{a}i_2 + \underline{a^2}i_3\right) \tag{4.1}$$

where;

$$\underline{a} = e^{j\frac{2\pi}{3}} \tag{4.2}$$

And the zero component:

$$i_0 = \frac{1}{3}(i_1 + i_2 + i_3) \tag{4.3}$$

The zero component is generally avoided by control system designers because of the fact that it has no effect on changing the power output of the rotor. The current space phasor (4.3) and the zero component (4.5) could be written as a linear transform of the three stator winding currents i_1, i_2 and i_3. These components can be represented as the components of *dq* axis as by rotating the current space phasor to rotor fixed coordinate frame:

$$\underline{i^r} = \underline{i}e^{-j\theta_r} = i_{sd} + ji_{sq} \tag{4.4}$$

θ_r is the relative angle between stator and rotor frames. It is also possible to apply the space-phasor transformation for the voltages and the flux linkages as well. The flux related with the stator winding is described as:

$$\underline{\Psi} = \Psi_{PM} + L_{md}i_{sd} + jL_{mq}i_{sq} \tag{4.5}$$

The permanent magnet flux, $\Psi_{PM,}$ is associated with *d* axis. On the other hand, *p*, the number of pole pairs, is described with the repetition of stator winding. It is evident to say that the rotor with permanent magnet distribution, has the same number of pole pairs. So, the rotor will try to synchronize with the rotating magnetic field. That is why, rewriting the stator current space-phasor as a component related with the rotor is useful. Knowing about the rotor orientation will lead us to know also about the field orientation, so it is possible to control the field current i_{sd} and torque generating current i_{sq} independently.

The vector control is targeting to optimize the power consumption by having only one quadrature component which is the current component. So, it's only necessary current to generate torque. This operation is called as Maximum Torque per Ampere (MTPA) [20]. Having the only quadrature current component is ideal but it can't be used for all speed variations. In order to understand this phenomenon analyzing the steady state model would be useful. At steady state the voltage equations on *dq* axis is defined as below [4]:

$$u_{sd} = -\omega * L_{sq} * i_{sq} \tag{4.6}$$

$$u_{sq} = R_s * i_{sq} + \omega * \Psi_{PM} \tag{4.7}$$

Where ω is the angular frequency of the voltage supplied. The resulting space phasor diagram would be:

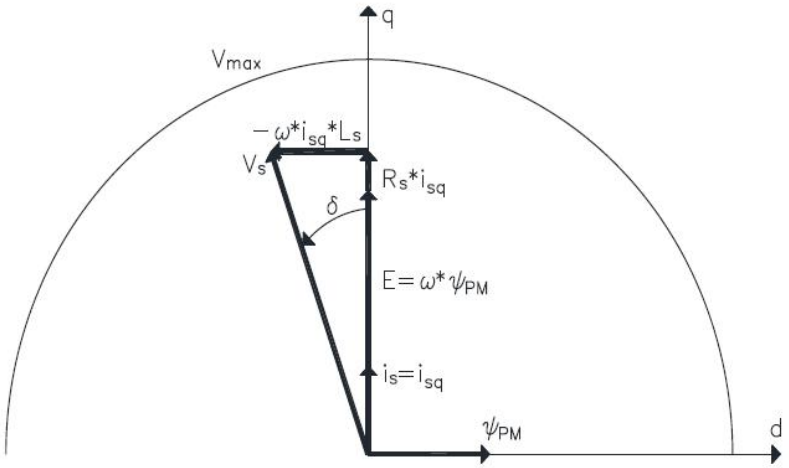

Figure 4.4: Vector diagram of PMSM with MTPA control [5]

The base speed is the value of the maximum reachable speed to keep the current on the quadrature axis. It is defined as:

$$\omega_b = \sqrt{\frac{V_{max}^2}{\left(\Psi_{PM}^2 + i_{max}^2 * L_{sq}^2\right)}} \tag{4.8}$$

V_{max} represents the maximum voltage of the power supply and i_{max} represents the maximum value of current due to the thermal limit of the stator coils. There is only one way to exceed the base speed. That way is to introduce a negative i_{sd}, that generates an opposite magnetic flux to the permanent magnets [21]. By this operation it is possible to reach higher speeds but at the expenses of torque. This is called Field Weakening. The maximum current becomes:

$$i_{max} = \sqrt{i_{sd}^2 + i_{sq}^2} \tag{4.9}$$

so

$$i_{sq} = \sqrt{i_{max}^2 - i_{sd}^2} \tag{4.10}$$

In Field Weakening operation region the power is constant but the torque is decreasing. If resistive losses are neglected the phasor diagram for this range of speed is given as:

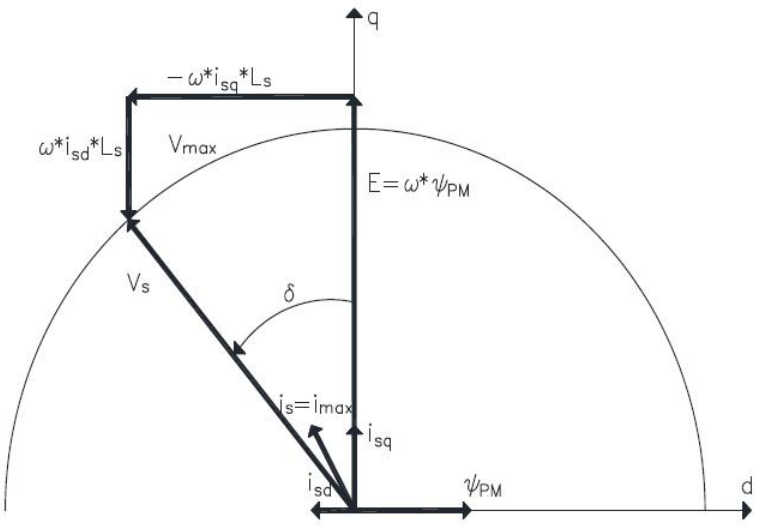

Figure 4.5: Vector diagram of PMSM with FW control [5]

Excessive Field Weakening can be very dangerous for the permanent magnets because of a possible demagnetization. Permanent magnet materials like samarium-cobalt or neodymium-iron-boron are recommended in order to avoid this, for PMSMs which require a wide range of speeds. If we continue to increase $i_{sd,}$ a point is reached where:

$$\omega * i_{sd} * L_s = -E \tag{4.11}$$

So, the current i_{sd} can be rewritten as:

$$i_{sd} = -\frac{E}{\omega * L_s} = -\frac{\Psi_{PM}}{L_s} \tag{4.12}$$

Since V_s has the same amplitude as $-\omega * i_{sq} * L_s$, in this condition, the equation becomes:

$$-\omega * i_{sq} * L_s = V_{max} \rightarrow i_{sq} = \frac{V_{max}}{-\omega * L_s} \tag{4.13}$$

Therefore, the total current decreases as the angular speed increases. If the Field Weakening operation is not considered, the reference value direct axis current ($i_{d,ref}$) should be zero.
In the block diagram in Figure 2.2, feedforward compensation is used in *d* and *q* PI controllers in order to enhance the system performance. By using the inverse Park's and Clarke's Transformation, the outputs of the controllers, $V_{d,ref}$ and $V_{q,ref}$, are transformed to *abc* domain voltages.

4.2.1 Torque Generation

The interaction between magnetic flux with the stator winding generates electromagnetic torque in the air gap of a PMSM. It is written with respect to the current space phasor as:

$$T_e = -\frac{3p}{2} Im(\underline{\Psi i^*}) \tag{4.14}$$

Since a permanent magnet synchronous machine has different magnetic conductance in the direction of d-axis and *q*-axis, we obtain the equation below:

$$T_e = \frac{2p}{3}\left(\Psi_{PM} i_{sq} + \left(L_{md} - L_{mq}\right) i_{sd} i_{sq}\right) \tag{4.15}$$

In this equation, L_{md} and L_{mq} represent the total main inductances in the *d* and *q* axis. It is known that for magnetically isotropic machines ($L_{md} = L_{mq}$), the electromagnetic torque is directly proportional to the product of the current i_{sq}, and the flux linkage of permanent magnet, Ψ_{PM} [13].

It should be noted that, for the machines with different, L_{md} and L_{mq} , an extra torque component has to considered, which is called as the reluctance torque. This torque component is represented in the above equation's second-hand term. It can be seen that it is proportional to $i_{sd.} i_{sq}$ and the differences between *dq* axis inductances ($L_{md} - L_{mq}$). It is desired to make the differences between inductances as large as possible to obtain a higher value of reluctance torque.

4.2.2 Losses

First of all, the total losses of the PMSM should be considered, in order to minimize the current losses. Ohmic losses and core losses will be shown. Ohmic losses (*copper losses*) are directly proportional to the total stator winding resistance, R_s, and the sum of the square of the winding currents,

$$P_{Cu} = R_s(i_1^2 + i_2^2 + i_3^2) = \frac{3}{2} R_s \underline{i_s i_s^*} \tag{4.16}$$

The core losses are generally considered in two components: Eddy current losses and hysteresis loses [22]. In this paper, Modelica Standard Library's Permanent Magnet Synchronous Machine model is used, thus the hysteresis losses are neglected. The total core losses are modelled with respect to voltage induced by the magnetic flux Ψ of the stator windings.

$$P_c = \frac{3}{2} G_c \left(\frac{d\Psi}{dt}\right)^2 \tag{4.17}$$

4.2.3 Voltage Induction

The voltage induced in stationary operating conditions is defined as:

$$\underline{u} = j\omega\underline{\Psi} = j\omega(\Psi_{PM} + L_{md}i_{sd}) - \omega L_{mq}i_{sq} \tag{4.18}$$

For $i_{sq}=0$, the voltage induced, only depends on the flux linkage of the permanent magnet, i_{sd}, and the angular speed ω_r (3.42).

If we have zero current in both *d* and *q* axis, the voltage induced, increases with speed ω, linearly. When the voltage induced, exceeds the maximum voltage value, the Field Weakening operation must be applied to increase speed. This can be done by a negative *d* axis current component which reduces the total magnetic flux of the stator windings. [13]

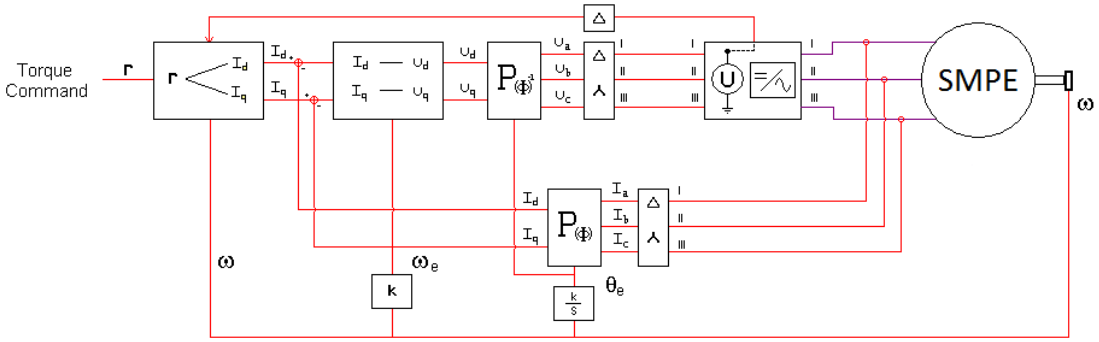

Figure 4.6: Field Oriented Control Scheme for PMSM

4.2.4 Steps of Field Oriented Control

1. The stator currents are measured
2. The stator currents are converted into a two-phase system (α, β) by using the Clarke's Transformation
3. The rotor angle is calculated
4. The $\alpha\beta$ currents are converted into the *dq* coordinate system by using the Park's Transformation
5. The quadrature axis current component and the direct axis current component are controlled separately by the controllers. i_q controls the torque production and i_d controls the air-gap flux.
6. The output stator voltage vector is converted back from the *dq* coordinate to the two-phase system fixed with the stator by using the Inverse Park's Transformation
7. The output three-phase voltage is generated after transforming back from $\alpha\beta$ to *abc* domain by using the Clarke's Transformation.

CHAPTER 5: SIMULATION OF PMSM

In this chapter OpenModelica and LMS Amesim simulation environments are introduced. Two models with the same purposes are built by using each software's distinctive models. This model includes Field Oriented Control for a PMSM. Each model takes a reference torque as input and controls the quadrature axis current i_q in order to reach the desired torque. A reference speed is also introduced to the motor to command when and how fast to reach the desired speed. In section 5.4, the simulation results are shown to see how the models are compatible and how the simulation environments affect the results.

5.1 Modelica Environment

Modelica is an object-oriented, multi-domain modelling language for modelling complex systems. In 1978, during his PhD thesis Hilding Elmqvist has created The Dymola Modelling Language [23]. The main goal of this modelling language was to adopt a physical modelling approach rather than a mathematical modelling approach. In order to unify various languages Hilding Elmqvist developed Modelica modelling language in 1996. The main goal of Modelica was to have one modelling language which is compatible with various domains so the models wouldn't be limited by a particular tool.

The modelers can create models in Modelica, by using DAEs to describe systems rather than transforming them to ODEs. This capability came to life after Pantelides developed the DAE index reduction algorithm [24]. It is possible to model discrete variables and continuous variables together, also simulate them in the same system at the same time.

The design approach of The Modelica creates models where there is no specific direction or flow of equations. Once the model is built, The Modelica tools decides of the flow and usage of variables. While creating a model, a Modelica code is also created by the tool. Then the compiler compiles it into a code, which is then solved by DAE solver.

5.2 Introduction to OpenModelica

OpenModelica is a free and open-source environment for modelling and simulating dynamic systems. It is based on Modelica modelling language. The software is developed by Open Source Modelica Consortium. The goal of the OpenModelica is to create an Open Source Modelica modelling and simulation based on the free software which is distributed in binary and source code for academic and industrial usage.

5.2.1 OpenModelica Library

All the components used in this paper are based on the Standard Modelica Library by the Modelica Association. The main blocks in order to design a PMSM control system are designed in this section.

5.2.1.1 *SM_PermanentMagnet*

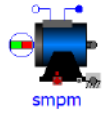

Figure 5.1: SM Permanent Magnet Block

This block represents a three-phase Permanent Magnet Synchronous Machine where the resistance and stray inductances are directly modelled in stator phases. The model then uses the space-phasor transformation and a rotor-fixed *AirGap* model. The model, models the excitation of permanent magnet with a constant equivalent excitation current which feeds the *d*-axis. The model has a damper cage which is a Boolean parameter. The losses related to the model are as the following:

- Core losses (only eddy current losses, no hysteresis losses)
- Stray load losses
- Permanent magnet losses
- Friction losses
- Heat losses in stator windings resistances
- Optional: Heat losses in damper cage resistances

5.2.1.2 *RotorDisplacementAngle*

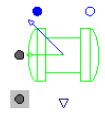

Figure 5.2: RotorDisplacementAngle Block

This block calculates rotor lagging angle by measuring the stator voltages, then transforms them to the space-phasor in stator-fixed coordinate system. Then rotates the space-phasor to the rotor-fixed coordinate system and calculates the angle of this space-phasor.

5.2.1.3 *Speed*

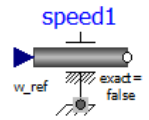

Figure 5.3: Speed Block

In this model the input signal *ω_ref* defines the reference speed in [rad/s]. The input signal is provided by a *TimeTable* block.

5.2.1.4 *VoltageController*

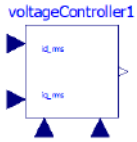

Figure 5.4: VoltageController Block

The block has two inputs for the desired RMS values of d and *q* component of space-phasor current in rotor fixed coordinate. i_{d_rms} and i_{q_rms} respectively. By taking the rotor position as another input, the actual three-phase currents are measured then transformed into the *dq* coordinate system. The block contains two PI-controllers in order to determine the necessary *d* and *q* voltages. These voltages are transformed back with inverse Park's Transformation to three-phase voltages and the block gives output. This block can be used to feed a voltage source which feeds a permanent magnet synchronous machine.

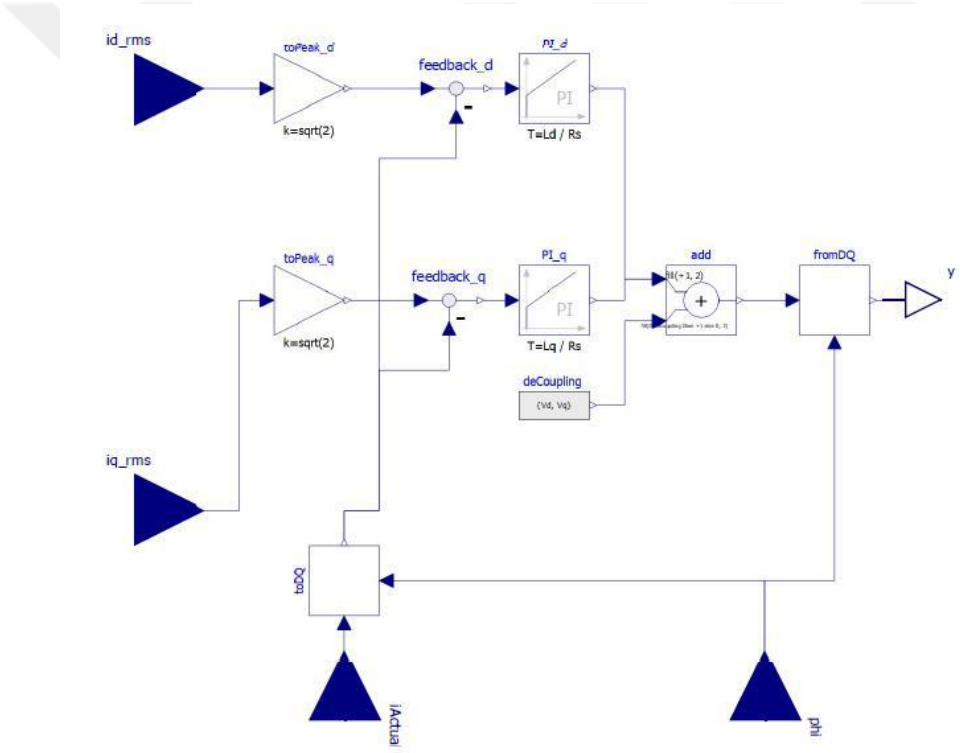

Figure 5.5: Inside of the VoltageController Block

The block diagram of the *VoltageController* is given in Figure 5.5. The PI controllers for each of the *d* and *q* component, and the blocks for Park's and inverse Park's Transformation can be clearly seen.

5.2.1.5 *vfController*

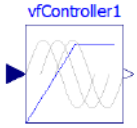

Figure 5.6: vfController Block

The amplitude of voltage is linearly dependent on frequency in this block. But it is limited by the nominal RMS voltage per phase. The sine-waves same with the number of phases are provided as output signal. These sine-waves can be used to feed the block *SignalVoltage.*

5.2.1.6 *CurrentContoller*

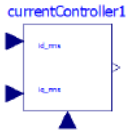

Figure 5.7: CurrentController Block

Just like the *VoltageController*, this block takes the desired RMS values of d and *q* component of space-phasor current in rotor fixed coordinate and the rotor position as its inputs. Then it calculates the three-phase currents. This block can be used to feed a *SignalCurrent* block. But since it doesn't contain PI controllers, it cannot be used to control a PMSM drive system.

5.2.2 Modelling of PMSM in OpenModelica

There are three different ways to model a synchronous machine in OpenModelica. First approach can be based on modelling like Matlab-Simulink, such as to create model with mathematical operators: gains, sum, integrators, etc. The second approach is to make the model by using and connecting electrical and mechanical components. This type of modelling gives the user a space to make changes and specific configurations. But it may be slower than the third approach. The third approach is to use ready-to-use model of OpenModelica Library. This approach is very useful if the modeler deals with a relatively complex system with many components. The OpenModelica Library's *SM_PermanentMagnet* block is used in this paper to model PMSM control system.

In order to model PMSM control system, the following blocks are used in OpenModelica: *Ground, Star, SM_PermanentMagnet, TerminalBox, RotorDisplacementAngle, Speed, VoltageController, SignalVoltage, TimeTable, VoltageQuasiRMSSensor, CurrentQuasiRMSSensor, CurrentSensor, SpeedSensor, AngleSensor, TorqueSensor, and Constant.*

The first step of modelling the control system is to have the *SM_PermanentMagnet* block respectively. The plugs of this motor model are connected to *TerminalBox*. The parameters for this block are number of phases and the type of terminal connection, which is star for this work. Two *Star* blocks are used to represent that the system is multi-phase. Two *Ground* blocks are

used respectively. *RotorDisplacementAngle* block is connected to the flange of SM_*PermanentMagnet* block. The purpose of this block is discussed in Section 5.2.1.2. On the other hand, a *TorqueSensor* block is connected to the same flange from one side and on the other side it's connected to the flange of *Speed*. Other connection of *Speed* block is connected to *TimeTable*. These blocks define when the motor shaft will reach to a particular speed value. The sensor blocks *SpeedSensor* and *AngleSensor* are also connected to the flange of *SM_PermanentMagnet* block. The output of *AngleSensor* (phi) is the input of *VoltageController*. The other input of *VoltageController* is the three-phase stator winding currents, so a *CurrentSensor* block is used to have this information. After having the information for rotor angle and stator winding currents, we need i_{d_rms} and i_{q_rms} values to complete the connections of *VoltageController* block. A *Constant* block is used to define i_{d_rms}. For i_{q_rms}, the output of the torque sensor and the reference torque value are compared and then the required current is given as the output of the *Integrator* block. The formulation used in *Integrator* block is described as:

$$T_e = p.\left(L_{sd} - L_{sq}\right) i_{sd} i_{sq} + p.\sqrt{\frac{3}{2}}.\psi_{fl} i_{sq} \tag{5.1}$$

After this *VoltageController* block can be used to feed the *SignalVoltage* which feeds the permanent magnet synchronous machine and closes the control loop.

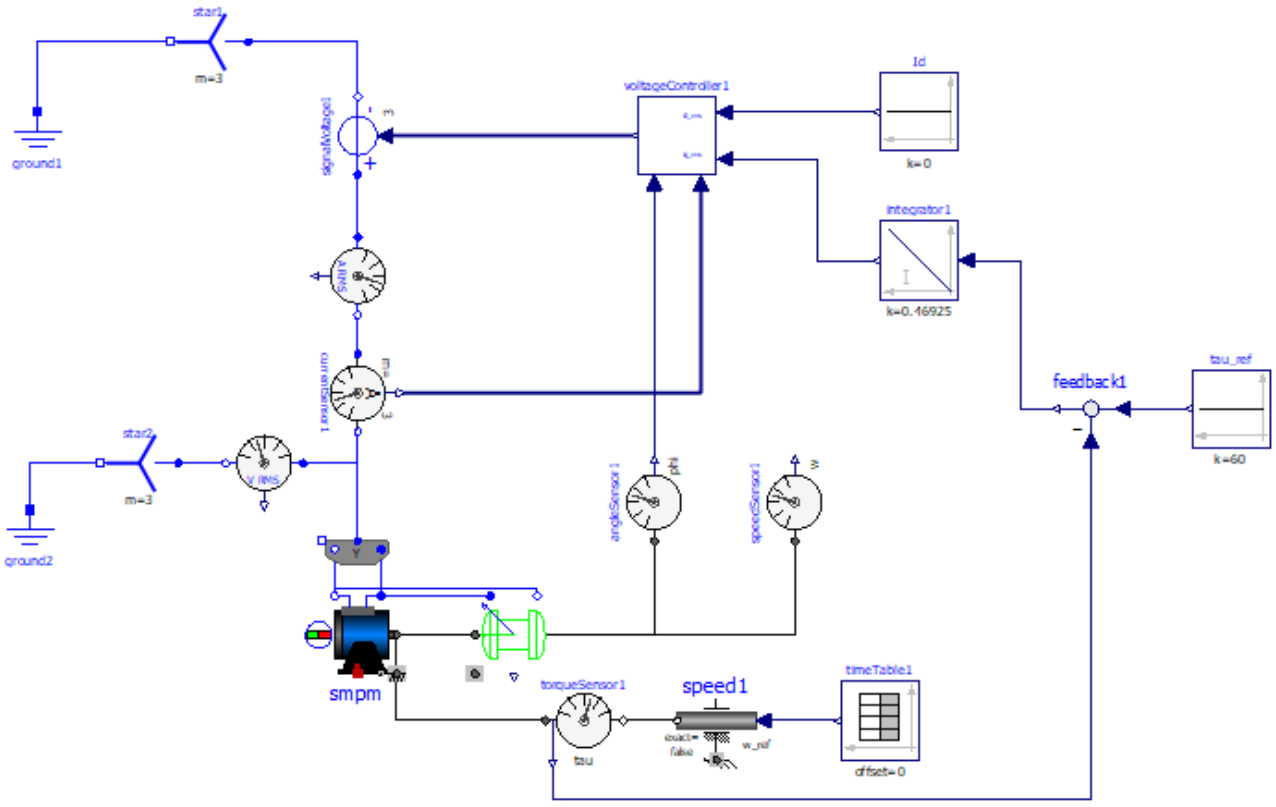

Figure 5.8: PMSM with FOC in OpenModelica

Parameter	Value	Unit	Parameter	Value	Unit	Parameter	Value	Unit
VsOpenCircuit	112.3	V	*Lmd*	9.55e-4	H	*Rrd*	0.03	Ω
Jr.Start	0.29	kg.m2	*Lmq*	9.55e-4	H	*Rrq*	0.03	Ω
Js	0.29	kg.m2	*Rs*	0.04	Ω	*tau_ref*	60	Nm
P	2		*alpha20s*	0	1/K	*w_ref*	104.72	rad/s
fsNominal	50	Hz	*Lszero*	3.18e-4	H	*kid*	0	
TrOp	20	degC	*Lssigma*	3.18e-4	H	*m*	3	
TsOp	20	degC	*Lrsigmad*	1.592e-4	H	*Ld*	12.73e-4	H
TsRef	20	degC	*Lrsigmaq*	1.592e-4	H	*Lq*	12.73e-4	H

Table 2: PMSM parameters for simulation

The gain and time constant for PI controller of the *d* axis current is given below:

$$k = \frac{1}{R_s} \tag{5.2}$$

$$T = \frac{L_d}{R_s} \tag{5.3}$$

The gain and time constant for PI controller of the *q* axis current is given below:

$$k = \frac{1}{R_s} \tag{5.4}$$

$$T = \frac{L_q}{R_s} \tag{5.5}$$

An alternative model in OpenModelica is also made for a comparison. This model doesn't contain a feedback and integrator, so it doesn't decide the *q*-axis current which is required for the reference torque. The model takes the required *q*-axis current as the input instead of the reference torque. Even if this model is not the replica of Amesim model, the reason for creating this model will be discussed in following section 5.4.

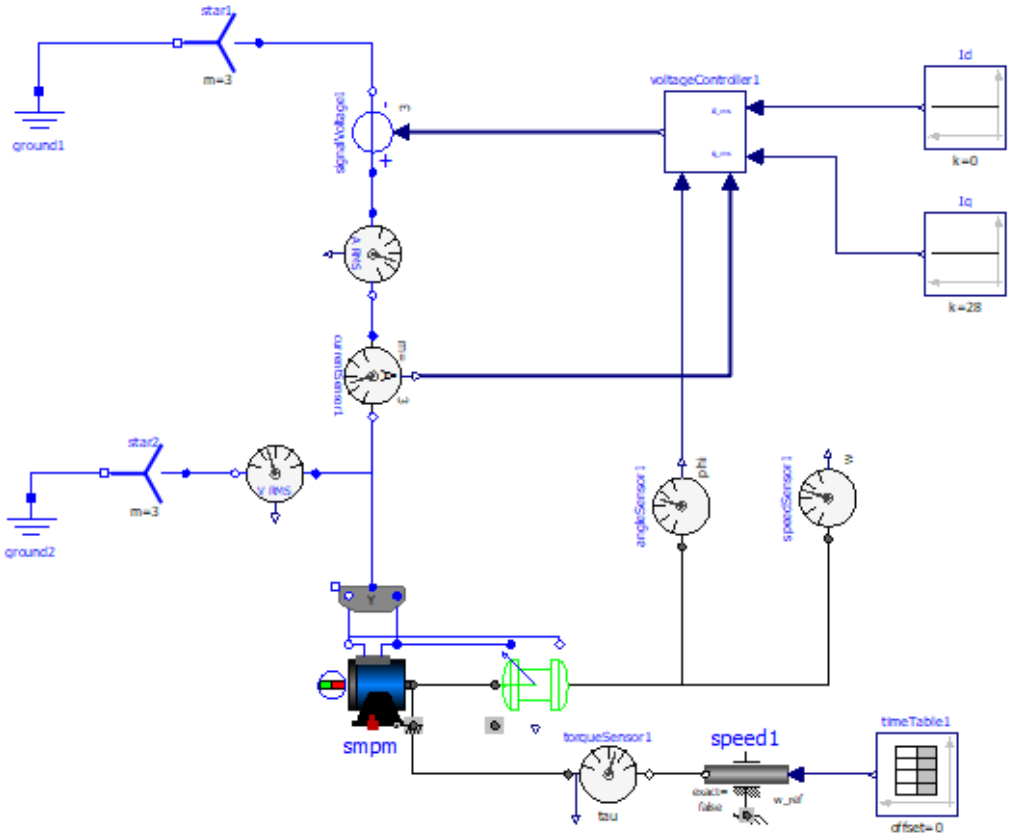

Figure 5.8: PMSM basic model without feedback in OpenModelica

5.3 Introduction to LMS Amesim

LMS Amesim is a simulation software for the modelling and analysis of multi-domain systems by Siemens. The software contains a set of tools to model, analyze and simulate the performance of mechatronic systems. It's possible to model a system's electrical, mechanical, thermal, hydraulically or pneumatically behavior. These models are described by using non-linear time-dependent analytical equations. The libraries of Amesim are written in C language and they also support Modelica. Amesim is based on Bond graph theory.

The libraries of Amesim contain predefined components for different physical domains. The components of the system have to be connected to each other, where they have several inputs and outputs. The input of one component is the output of one other. So, it's feasible to say that there's a flow in Amesim block diagrams, which is kind of similar to Matlab/Simulink.

5.3.1 Amesim Library

Amesim comes with its Standard Library and contains many modules for creating mechanical, hydraulic and electrical modules. But Amesim has very useful ready-to-use components that make the modelling of some specific systems very easy. The main blocks in order to design a PMSM control system are discussed in this section.

5.3.1.1 *Torque vector control for Synchronous Machine with Permanent Excitation*

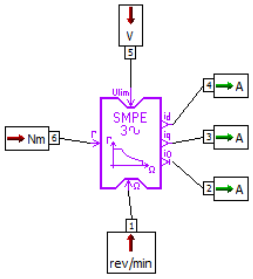

Figure 5.9: Torque vector control for Synchronous Machine with Permanent Excitation Block

This is a torque control block for a Permanent Magnet Synchronous Machines (PMSM). There are three inputs which are the torque command, RMS voltage and the measured rotary velocity of the motor shaft. By taking these inputs, the block calculates the *dq* frame currents $i_{d,}$ i_q and the zero component i_0. This block controls the torque as a function of voltage and current.

5.3.1.2 *Currents control loop in the Park frame for Synchronous Machine with Permanent Excitation*

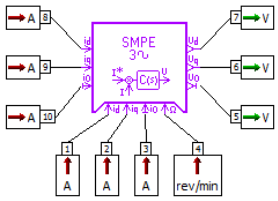

Figure 5.10: Currents control loop in the Park frame for Synchronous Machine with Permanent Excitation Block

This block models the current control loops in the Park frame for Permanent Magnet Synchronous Machine. It includes two control loops, for the currents on Park's *d* and *q* axis respectively. The emf disturbances in the control chains aren't taken into account. PI type controllers are used. Each PI gain is set by using pole placement method. The block has seven inputs in total, these are the reference *dq* frame currents $i_{d,}$ i_q and the zero component i_0, measured *dq* frame currents i_d, i_q and the zero component i_0, and the rotor angular velocity Ω. The outputs of these blocks are the *dq* frame voltages V_d and V_q. The integral and proportional gains for the current PI controllers are given by:

$$Kp_d = \frac{L_{sd}}{T_{aud}} \tag{5.6}$$

$$Ki_d = \frac{R_{s0}}{T_{aud}} \tag{5.7}$$

$$Kp_q = \frac{L_{sq}}{T_{auq}} \tag{5.8}$$

$$Ki_q = \frac{R_{s0}}{T_{auq}} \tag{5.9}$$

The outputs are defined by:

$$V_d = Kp_d(I_d - I_{d,ref}) + Ki_d \int_0^t (I_d - I_{d,ref})dt + E_d \tag{5.10}$$

$$V_q = Kp_q(I_q - I_{d,ref}) + Ki_q \int_0^t (I_q - I_{d,ref})dt + E_q \tag{5.11}$$

5.3.1.3 *Direct Park's transformation*

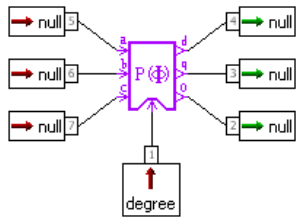

Figure 5.11: Direct Park's transformation Block

This block is used to apply the direct Park's transformation into three quantities with power conservation.

5.3.1.4 *Reverse Park's transformation*

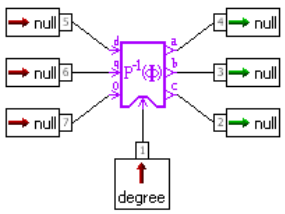

Figure 5.12: Reverse Park's transformation Block

This block is used to apply the reverse Park's transformation to three quantities with power conservation.

5.3.1.5 *Average 3 phase inverter*

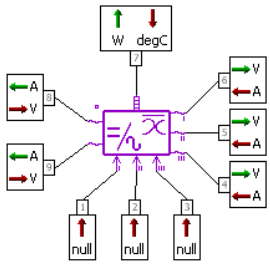

Figure 5.13: Average 3 phase inverter Block

This block is an average model of a three-phase inverter working in continuous conduction mode. Conduction and switching losses are computed. The output phase voltages are exactly equal to the input voltage set points and the losses are passes to the input DC current. The inverter model also has a thermal port. Switching dynamics are not computed.

5.3.1.6 *Synchronous machine with permanent excitation no dampers*

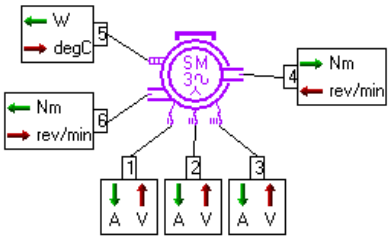

Figure 5.14: Synchronous machine with permanent excitation no dampers Block

This is permanent magnet synchronous machine block of Amesim Library. The machine windings are balanced, two different connections are possible (*star and delta*). The machine is reversible so it can work either as a motor or a generator. The model takes the three-phase voltages which are directed by the inverter and gives torque output. The model also has a thermal port. The fluxes can be expressed in the Park frame, a rotating reference whose position is given by the electrical angle. The stator phases *A, B, C* are then replaced by phases *d, q*:

$$\psi_{sd} = L_{sd} i_{sd} + \sqrt{\frac{3}{2}} \psi_{fl} \tag{5.12}$$

$$\psi_{sq} = L_{sq} i_{sq} \tag{5.13}$$

The base equations for the *dq* phases:

$$U_{sd} = R_s i_{sd} + \frac{d\psi_{sd}}{dt} - \omega_e \psi_{sq} \tag{5.14}$$

$$U_{sq} = R_s i_{sq} + \frac{d\psi_{sq}}{dt} + \omega_e \psi_{sd} \tag{5.15}$$

The electromagnetic torque is given by:

$$T_{el} = -p\left(\psi_{sd} i_{sq} - \psi_{sq} i_{sd}\right) \tag{5.16}$$

5.3.1.7 *Rotary speed sensor with offset and gain*

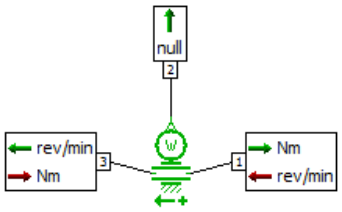

Figure 5.15: Rotary speed sensor with offset and gain Block

This block is an angular velocity sensor. It is normally used between a rotary load and a rotary shaft. The arrow at the icon bottom defines the positive convention of the velocity. However, the output signal at port 2 wouldn't depend on the side of the rotary load it's connected to. The other ports have the information about the angular velocity and torque.

5.3.2 Modelling of PMSM in Amesim

Amesim has very advanced ready-to-use blocks for modelling a PMSM control system which make the modelling process relatively shorter, but it can also be said that the software doesn't give as much freedom as Modelica gives to its users. It is not possible to create your own block with a sub model, as it is in Modelica or Simulink.

In order to model PMSM control system, the following blocks are used in Amesim:

Torque vector control for Synchronous Machine with Permanent Excitation, Currents control loop in the Park frame for Synchronous Machine with Permanent Excitation, Direct Park's transformation, Reverse Park's transformation, Phase to line voltage transformation, Line to phase current transformation, Average 3 phase inverter, Voltmeter, Variable voltage source, Amperemeter, Synchronous machine with permanent excitation no dampers, Rotary speed sensor with offset and gain, Rotary node transferring a velocity to two ports and adding 2 torques, Rotary damper, Conversion of signal to a rotary speed in rev/min, Integrator, Unit conversion, Line to phase RMS voltage, Constant signal.

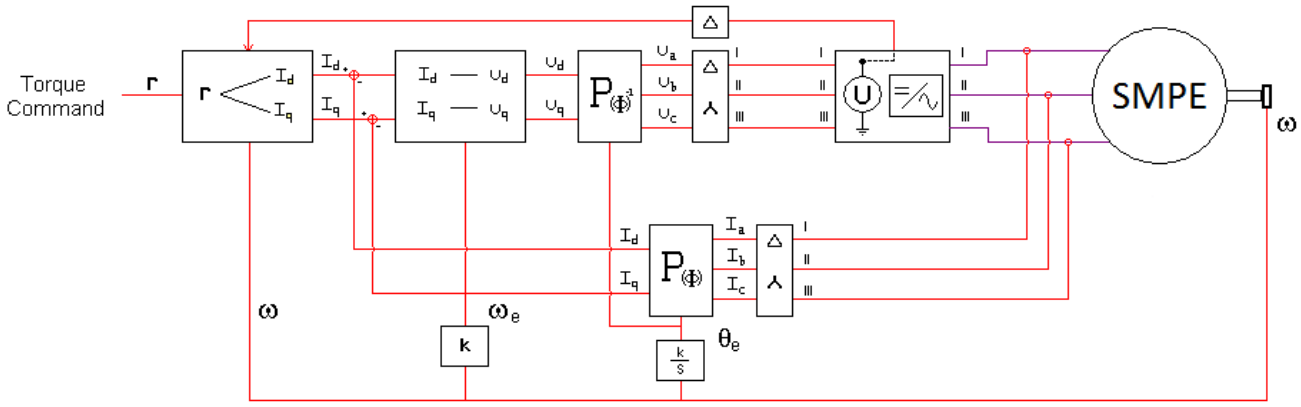

Figure 5.16: Field Oriented Control Block Diagram for PMSM in Amesim

The first step of the modelling is to have *Synchronous machine with permanent excitation no dampers*, this block needs a voltage supply so *Average 3 phase inverter* and *Variable voltage source* are connected to system. A *Voltmeter* block is also used to get the RMS voltage value. Three *Amperemeter* blocks are used in order to measure each of the three-phase currents. After translated in *Line to phase current transformation* block, these currents are entering into *Direct Park's transformation* as its inputs. Direct Park's Transformation as happening inside this block, so the outputs will be the currents in *dq* frame. After this point a *Currents control loop in the Park frame for Synchronous Machine with Permanent Excitation* block is needed. This block takes the measured *dq* frame currents as inputs as well as the reference *dq* frame currents and gives voltage outputs after controlling these currents by two PI controllers. The angular velocity of the rotor is also needed by this block, thus a *Rotary speed sensor with offset and gain* is used for this purpose. Till this point the Direct Park's Transformation has happened, that's why a block which does the Reverse Park's Transformation is needed. That block is called *Reverse Park's transformation.* After translated in *Phase to line voltage transformation* block, it is connected to *Average 3 phase inverter.* A *Torque vector control for Synchronous Machine with Permanent Excitation* block should be used to give the reference currents to *Currents control loop in the Park frame for Synchronous Machine with Permanent Excitation* block, thus it's added to the system. Now we can also connect the RMS voltage value that we obtain from *Voltmeter* block to this *Torque vector control for Synchronous Machine with Permanent Excitation* block. But it should be noted that a line to phase voltage translation is necessary. This block as well takes the angular velocity output of *Rotary speed sensor with offset and gain.*

Finally, it takes a constant input as torque command. Two blocks are used in order to define the relationship between the torque and angular velocity, these blocks are: *Rotary node transferring a velocity to two ports and adding 2 torques, Rotary damper.* It should be noted that the same parameters are used for both models in OpenModelica and LMS Amesim, which are given in Table 2.

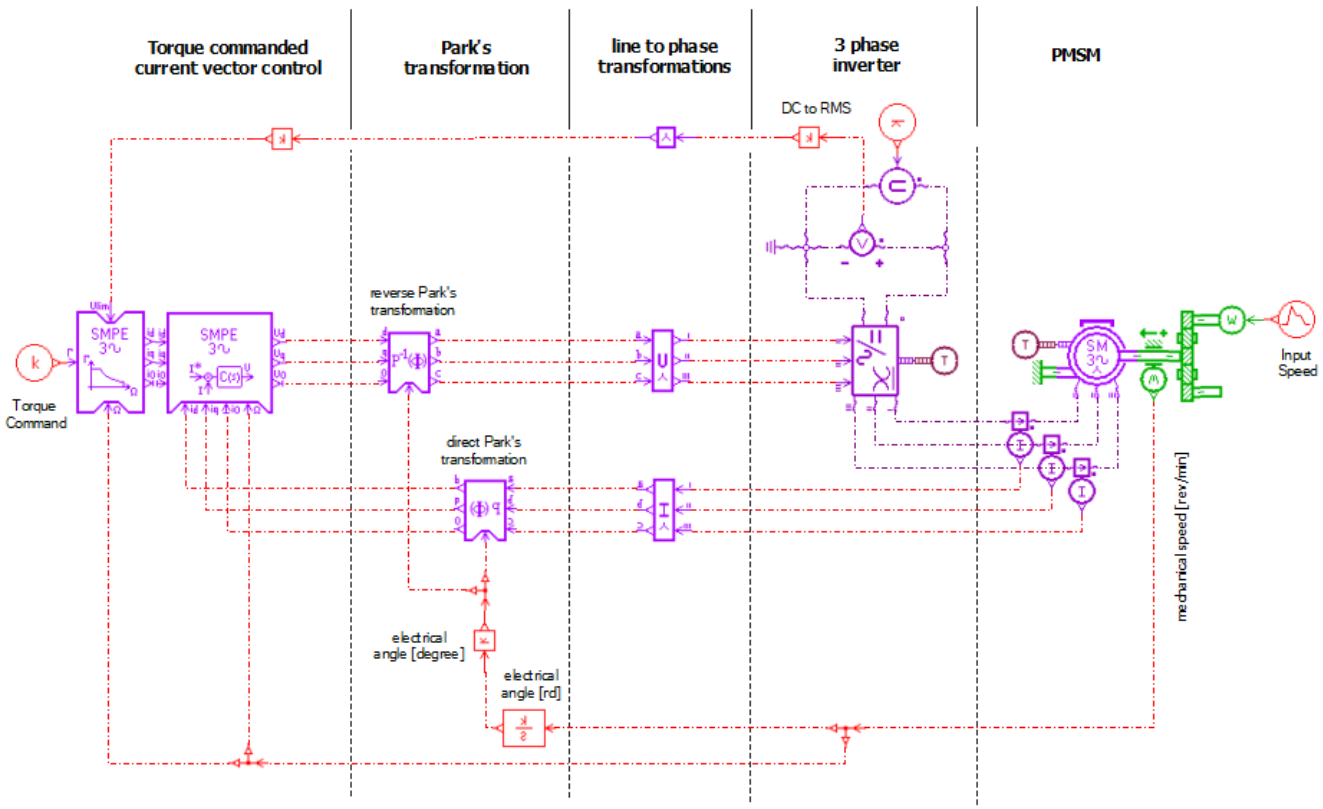

Figure 5.17: Complete block diagram of Field Oriented Control for PMSM in Amesim

5.4 Simulation Results

Till this point, three PMSM models are created in two different modelling environments. In this section the results of the simulations are discussed. The first comparison is for the stator winding voltages between OpenModelica and LMS Amesim. For this simulation the model with the feedback is used in OpenModelica. The simulation time is 10 seconds and the number of intervals is 20000. The results are given for 1 second and steady-state conditions in order to see the beginning behavior and steady-state behavior of the machine. The results are given in Figure 5.18, 5.19, 5.20 and 5.21.

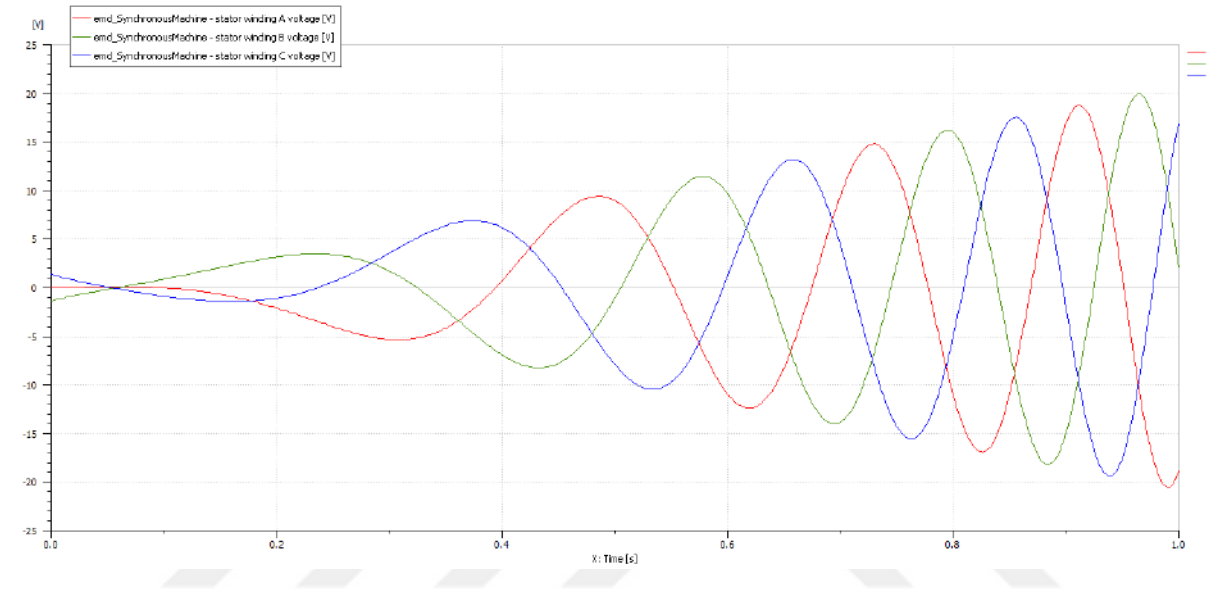

Figure 5.18: Stator winding voltages in LMS Amesim for the 1st second

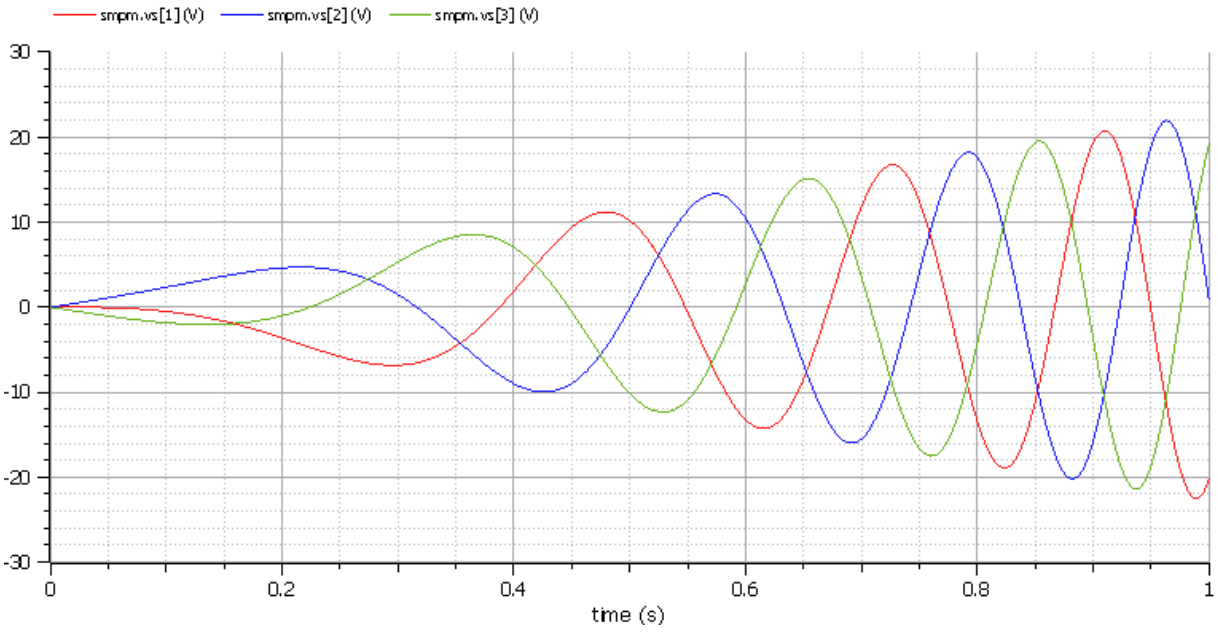

Figure 5.19: Stator winding voltages in OpenModelica for the 1st second

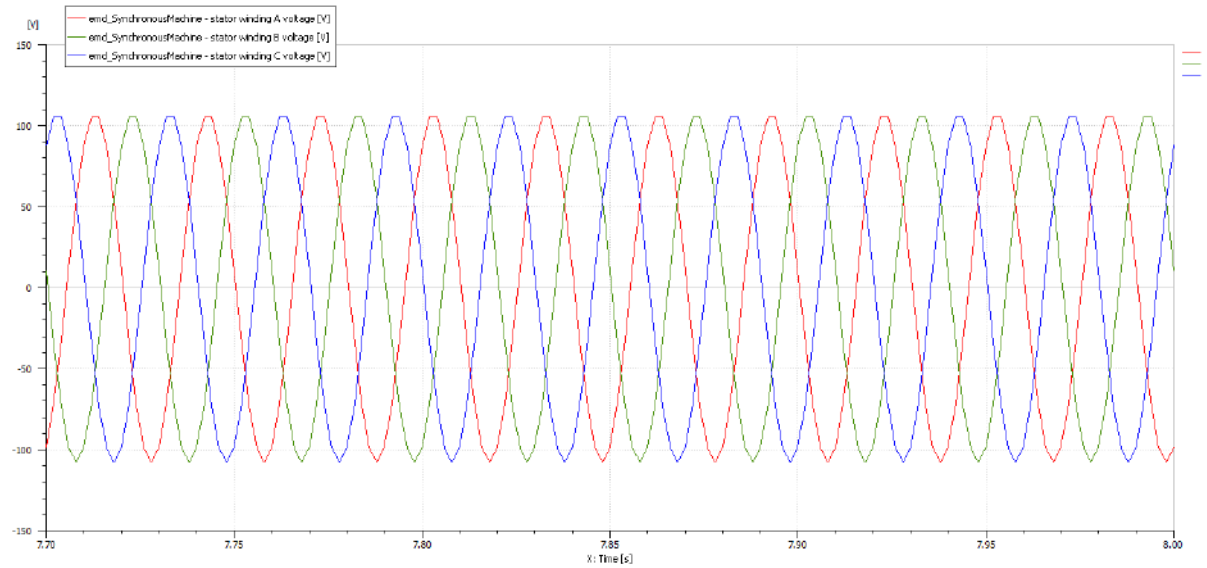

Figure 5.20: Stator winding voltages in LMS Amesim at steady-state

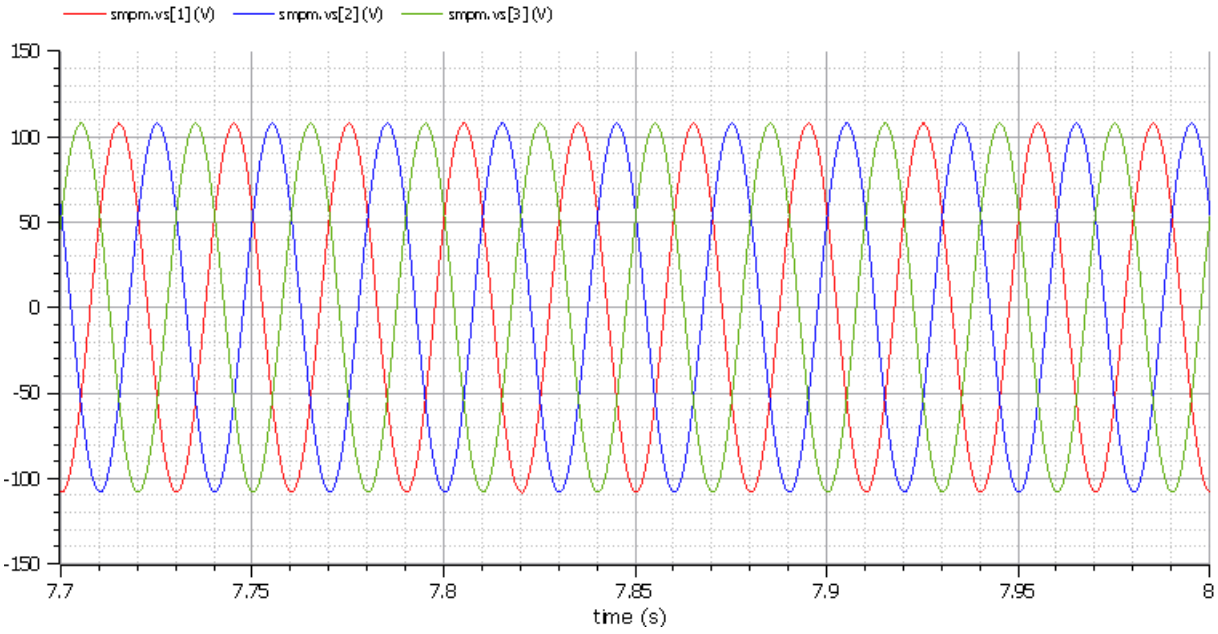

Figure 5.21: Stator winding voltages in OpenModelica at steady-state

The second comparison is for stator winding currents between OpenModelica and LMS Amesim. The models, simulation time and intervals are same with the ones for stator winding voltages. The results are as given below:

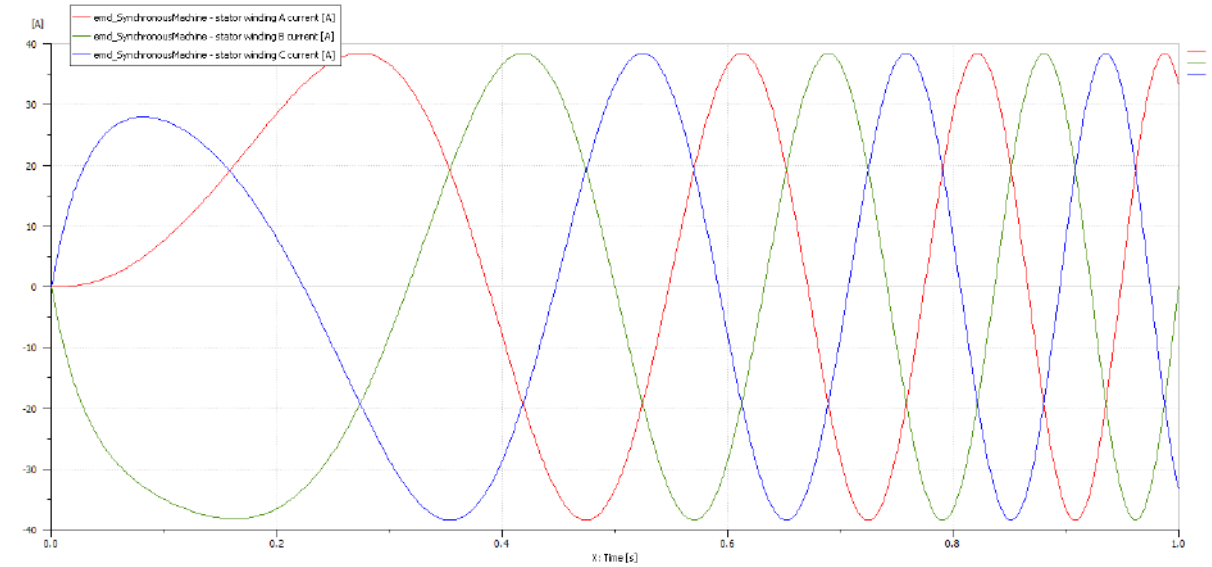

Figure 5.22: Stator winding currents in LMS Amesim for the 1st second

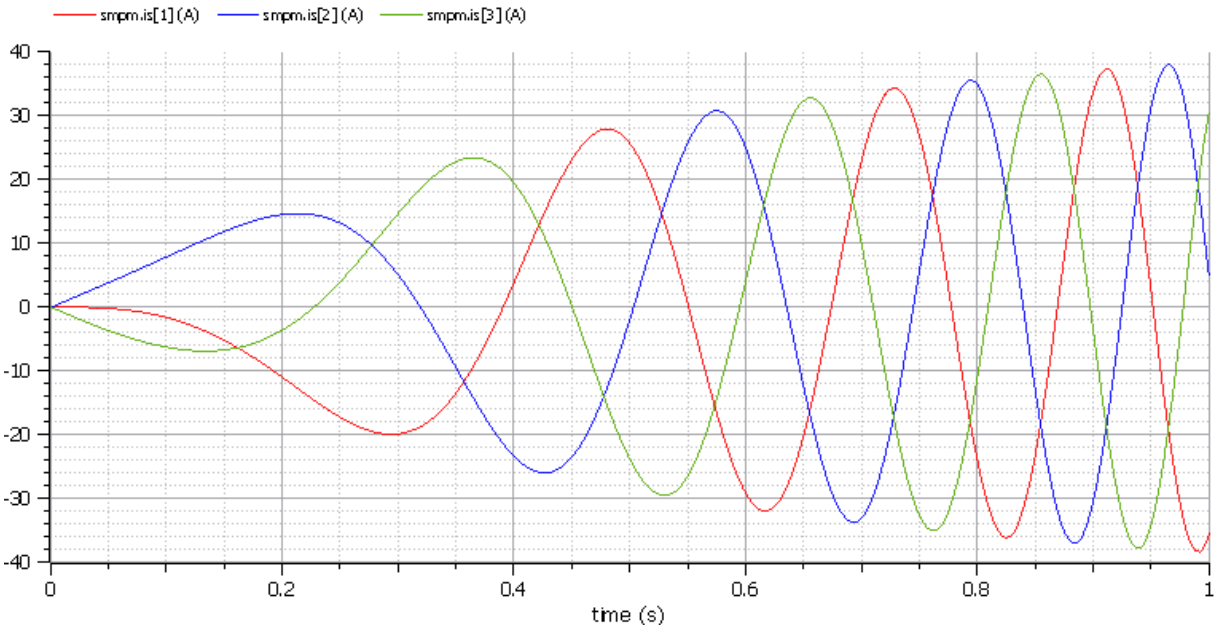

Figure 5.23: Stator winding currents in OpenModelica for the 1st second

As seen above in Figure 5.22, the stator winding currents in LMS Amesim dramatically increase. On the other hand, the stator winding currents in OpenModelica increases smoothly as torque increases, which will be discussed further. However, if we apply the quadratic current directly as it's done in basic model without feedback in OpenModelica, it can be easily seen that the results given in Figure 5.24 are getting closer to LMS Amesim results given in Figure 5.22.

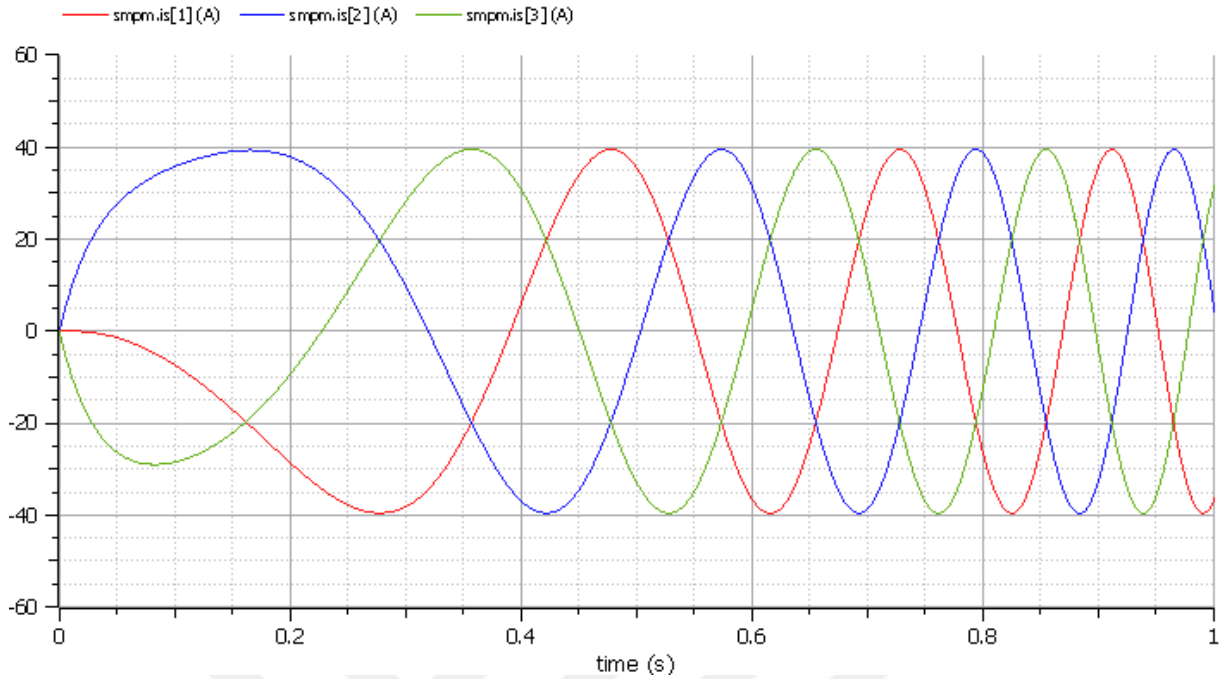

Figure 5.24: Stator winding currents in OpenModelica for the 1st second (Model without feedback)

The main reason for these visual and numerically trends of stator winding current graphs (Fig. 5.22 and 5.24) is not using a feedback algorithm for deciding the required quadrature current for the reference torque in OpenModelica. Instead, the required quadrature current is given directly to replicate the behavior of the model in LMS Amesim. Even though both models in OpenModelica and LMS Amesim are taking a reference torque and calculating the required quadrature current, the model in OpenModelica spends some more time for this operation. On the other hand, LMS Amesim model acts like as it takes the required current directly, which can be clearly seen from the results in Figure 5.22. This faster response in LMS Amesim is the advantage of using the block called *Torque vector control for Synchronous Machine with Permanent Excitation.* This block is specially designed for modelling and controlling PMSM, which comes with the standard LMS Amesim Library and creates a faster simulation effect.

The third comparison is for voltages and currents in *dq* axis. The simulation time is 10 seconds in order to see steady-state behavior, and the number of intervals is 20000. The results are given in Figure 5.25 and 5.26. In order to see the setting time differences between LMS Amesim and OpenModelica, the graphs for currents are given for 5 seconds.

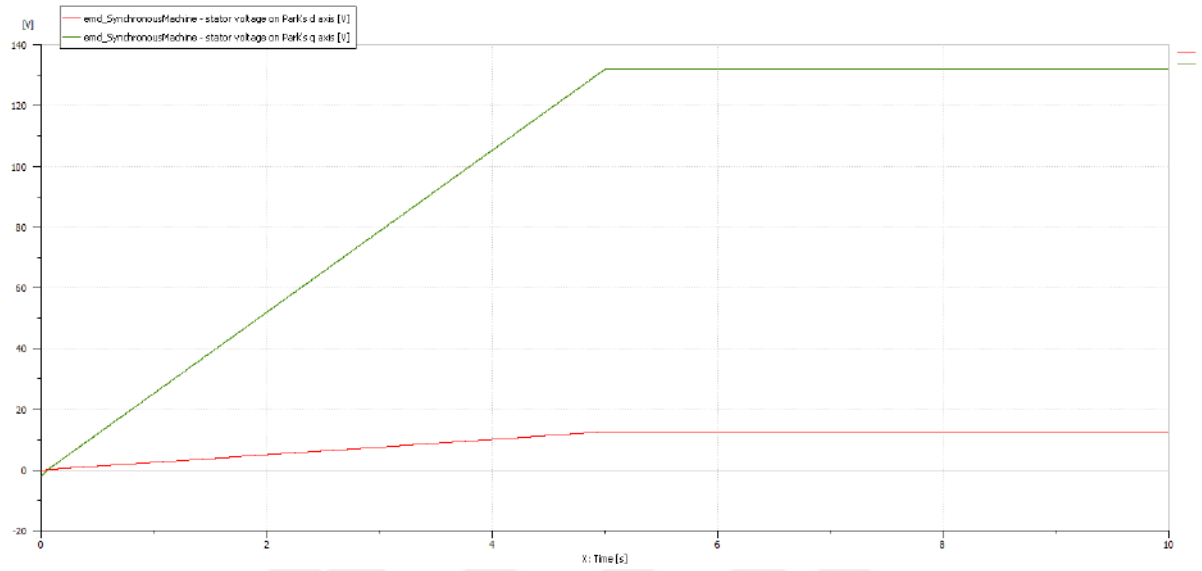

Figure 5.25: $V_d - V_q$ voltages in LMS Amesim for 10 seconds

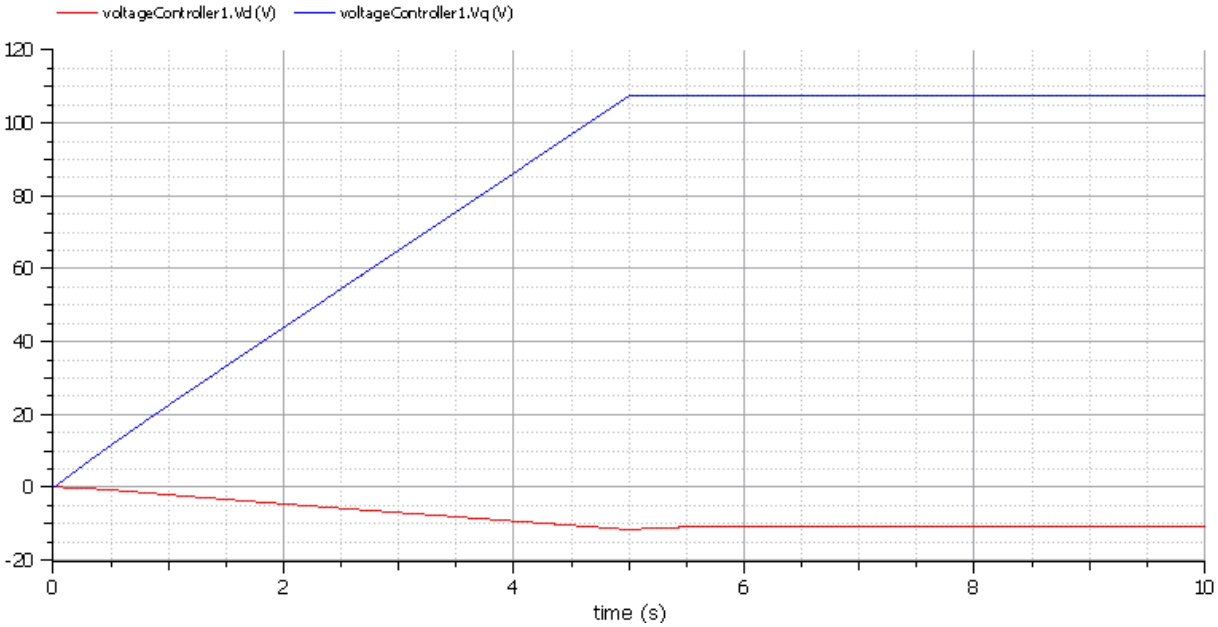

Figure 5.26: $V_d - V_q$ voltages in OpenModelica for 10 seconds

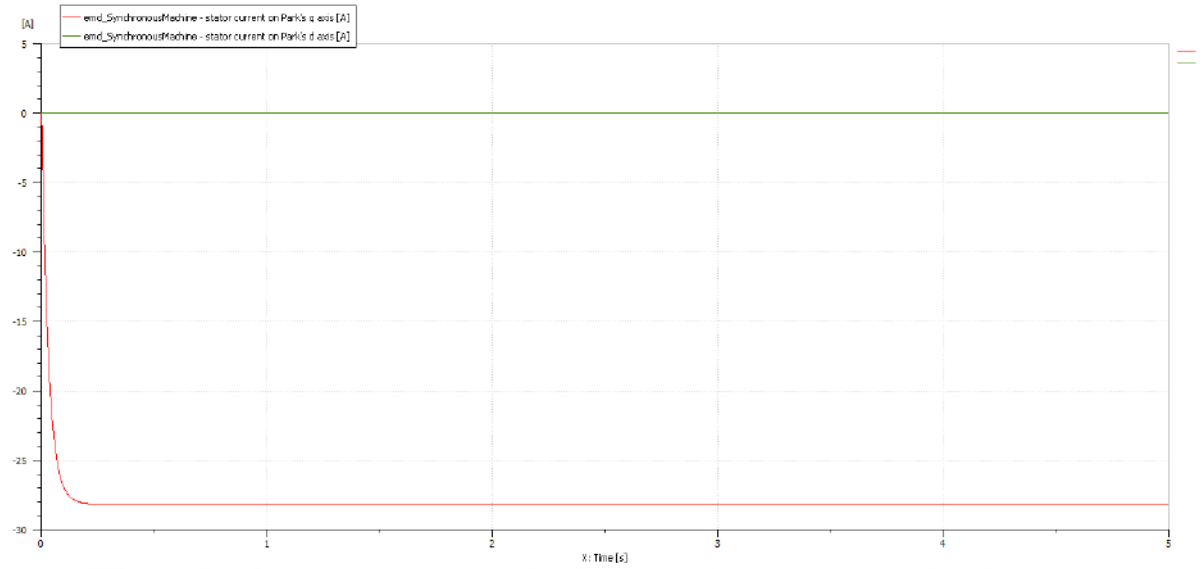

Figure 5.27: $I_d - I_q$ currents in LMS Amesim

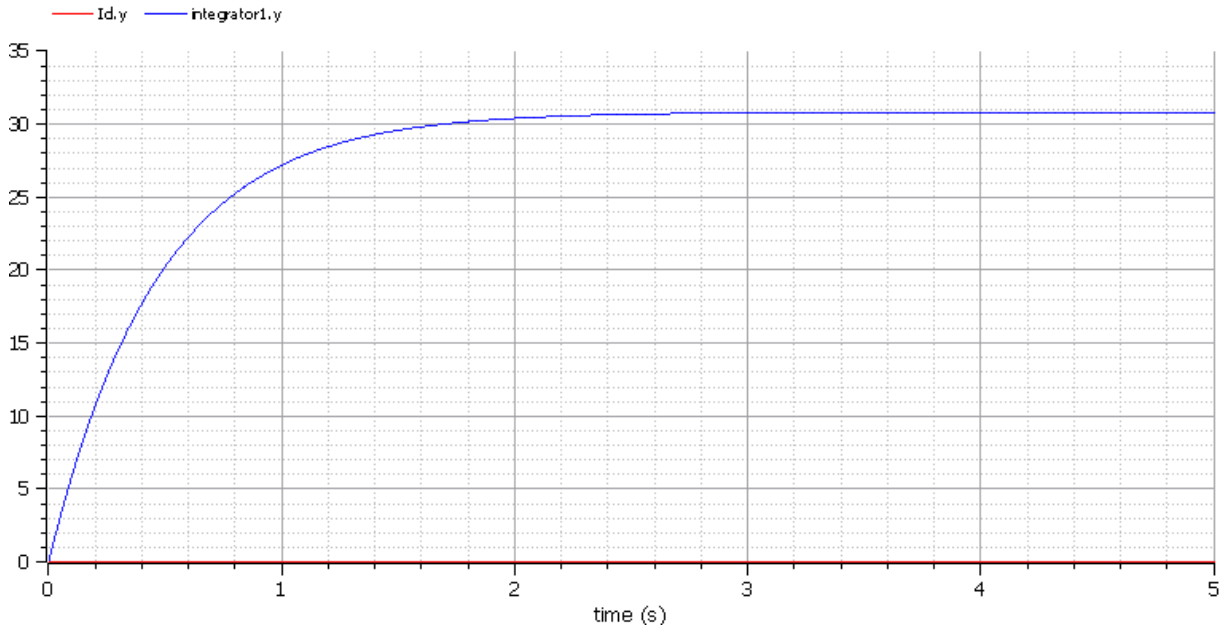

Figure 5.28: $I_d - I_q$ currents in OpenModelica

The model in LMS Amesim, it can work either as a motor or as a generator. In LMS Amesim, rotary velocities at a port are oriented, their direction is defined by the causality. This shift causes an exchange of power and vector direction of rotation. If we consider the values of the torque and the rotary velocity as positive, the power output of the mechanical port of the machine also has a positive value. Since the direction is defined by oriented quantity, it becomes like an input power as like the machine takes the power from outside. In order to comply with this convention, the input torque command is multiplied by -1 inside the block. That's why several outputs have different sign than OpenModelica.

The final simulations are achieved to see the output torque. The simulation time is 10 seconds and number of intervals are 20000. For the result in Figure 5.30 the basic model without feedback is used in OpenModelica.

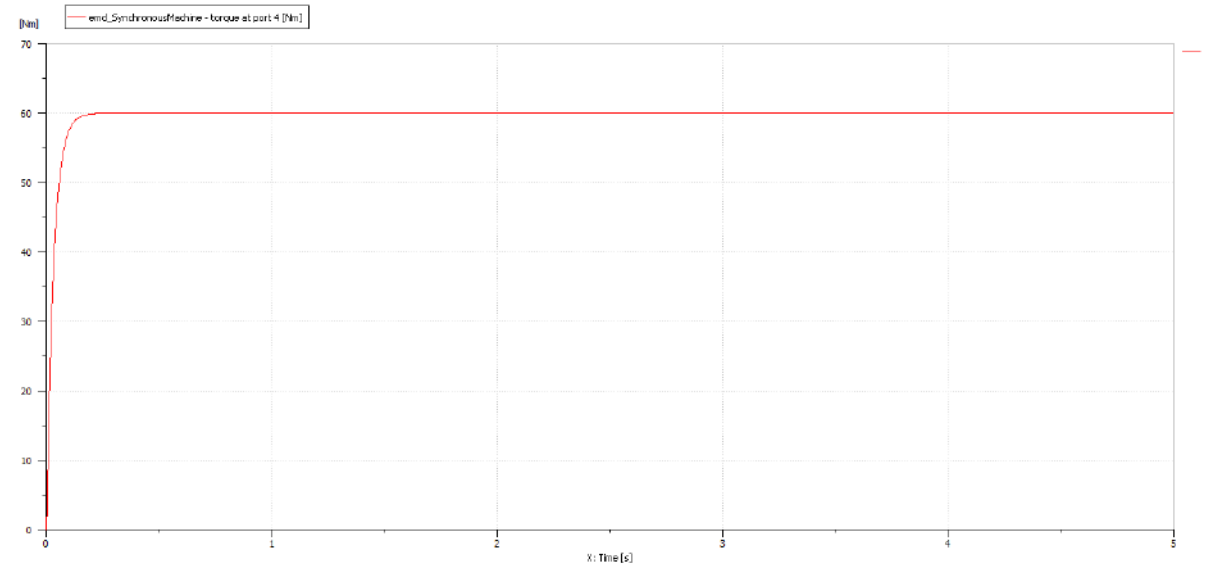

Figure 5.29: Torque output in LMS Amesim

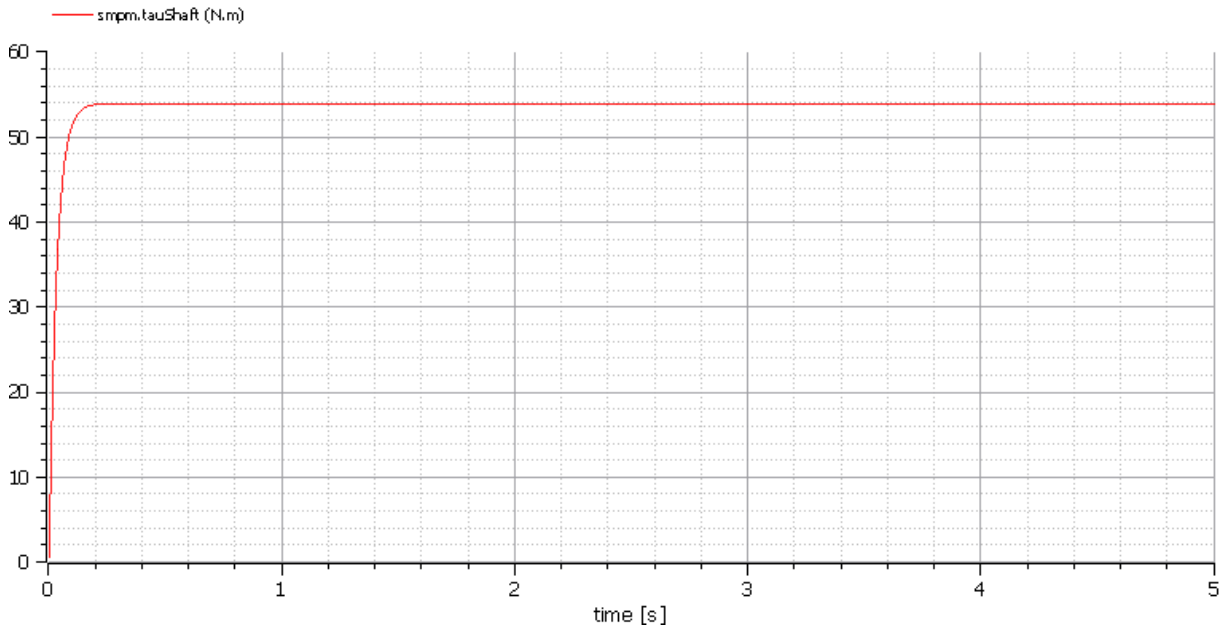

Figure 5.30: Torque output in OpenModelica (Basic model without feedback)

As seen in Figure 5.29 and 5.30 the torque output reaches its reference value around 0.2 seconds. The response of LMS Amesim is very fast due to its specially purposed blocks as discussed before.

In Figure 5.31, the result of the model with feedback in OpenModelica is given. It can be seen that the settling time becomes longer since the model has to decide quadrature current itself. For the first 5 seconds the machine speed is increasing and becomes constant after. That's where the torque value decreases a bit and settles at the reference torque which is 60 Nm for this simulation.

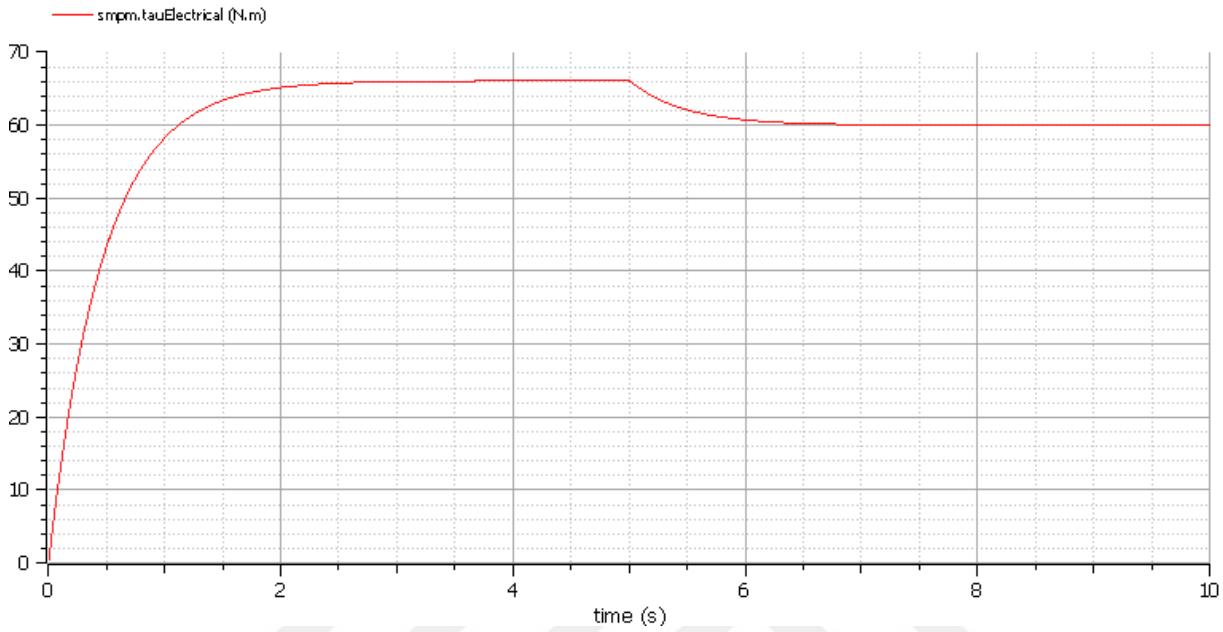

Figure 5.31: Torque in OpenModelica

At last, Figure 5.32 shows the relation between quadrature current and electrical torque, which is proportional to each other as expected.

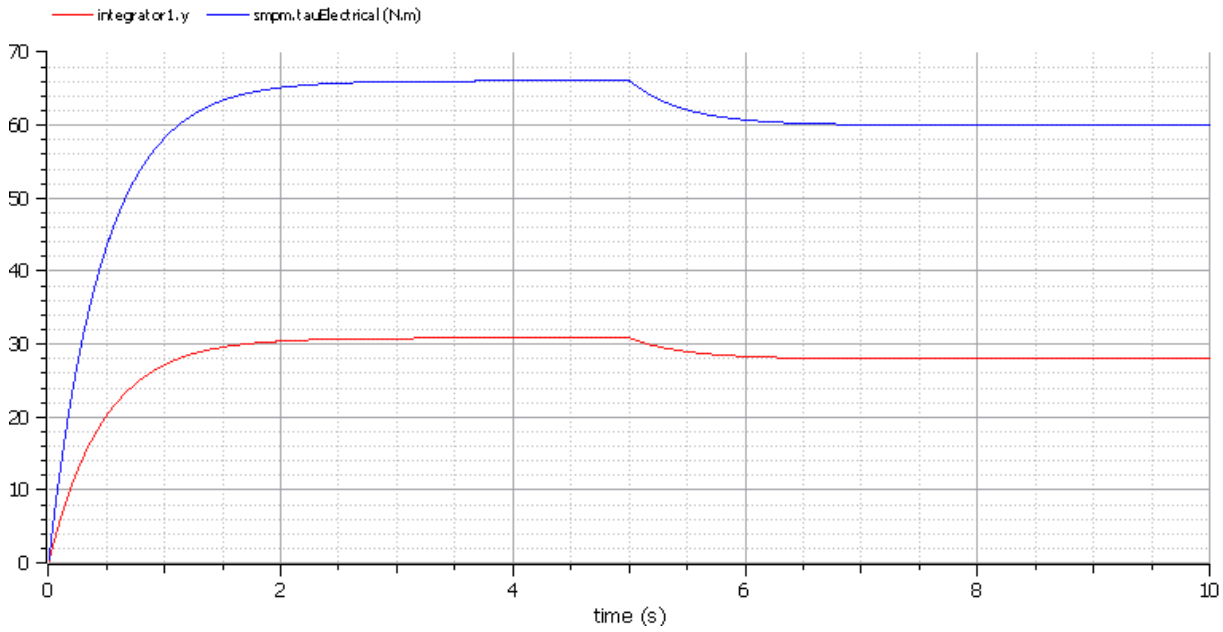

Figure 5.32: Torque - I_q relation in OpenModelica

CHAPTER 6: CONCLUSION

This thesis presents a comparison between two different simulation environments for modelling a Permanent Magnet Synchronous Motor with Field Oriented Control. The terminological fundamentals, mathematical model, control strategies of PMSM were discussed for a better understanding of modelling process. The Clarke's and Park's Transformations were implemented in mathematical model in order to transform three-phase coordinates to *dq* reference frame. Field Oriented Control was taken as a base during the modelling process of PMSM drive system.

The modelling approach of OpenModelica and LMS Amesim were analyzed and each software's distinctive properties were discussed. The simulations were performed in order to compare these software then the voltage, current and torque responses of the models were given and evaluated.

According to the simulation results, models which have been used in OpenModelica and LMS Amesim are compatible with each other, since they have very similar type of responses. However, minor differences occurred in settling time. Simulation results also proved that the reason behind the case of LMS Amesim has a faster settling time than OpenModelica, is under favor of LMS Amesim's specific block design for PMSM control. On the other hand, the model in OpenModelica loses response time while deciding the required i_q for the desired torque. In OpenModelica, another PMSM Control model which does not include feedback mechanism was designed to be able to replicate LMS Amesim Simulation results. Therefore, the required i_q were directly given to the system as input. In this case, torque response results of OpenModelica and LMS Amesim became closer to each other, which verified that Amesim's specific blocks gave itself a significant advantage in terms of modelling a PMSM drive system.

However, OpenModelica proved itself as one of the most useful object-oriented modelling environments. Also, it should be said that Amesim hasn't got special purpose blocks designed for every type of engineering challenge respectively. So, it can be said that Amesim might be handier for some specific cases, but OpenModelica provides solutions in a vast area of engineering problems. Besides OpenModelica is an open source simulation environment and it is continuously developed by designers all around the world, which increases the content of OpenModelica day by day.

So, it would be beneficial as a future work to develop new libraries in OpenModelica not only for becoming competitive with commercial simulation software but also it would definitely increase its importance in the real-time cases such as predictive maintenance to enhance IoT features in engineering technology.

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