VŠB– Technical University of Ostrava
Faculty of Electrical Engineering and Computer Science
Department of Electronics

The Simulation Model of a Permanent Magnet Synchronous Motor for FPGA Applications and HIL Testing.
Simulační model synchronního motoru s permanentními magnety pro FPGA aplikace a HIL testování

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Description:

1. Perform a theoretical research in the field of simulation models of electric motors and their use for FPGA applications within HIL testing.
2. Make an analytical description of synchronous permanent magnet motor.
3. Design the simulation model of the selected electromotor using the MATLAB / Simulink environment and test its basic properties.
4. Modify the simulation model so that it can be used for FPGA RT testing. Then implement this adjustment.
5. Implement the simulation model into the HIL testing device and test its properties with the real electronic control unit of the electric drive.
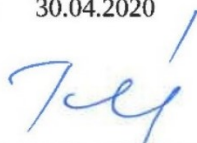
References:

[1] PERELMUTER, V.: Electrotechnical Systems: Simulation with Simulink® and SimPowerSystems™, 450 pages, CRC Press 2013, ISBN: 978-1466514027
[2] DUMAN, E., CAN, H. and AKIN, E.: FPGA based Hardware-in-the-Loop (HIL) simulation of induction machine model, 2014 16th International Power Electronics and Motion Control Conference and Exposition, Antalya, 2014, pp. 616-621. doi: 10.1109/EPEPEMC.2014.6980564

Extent and terms of a thesis are specified in directions for its elaboration that are opened to the public on the web sites of the faculty.

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I hereby declare that this master's thesis was written by myself. I have quoted all the references I have drawn upon.

Ostrava, July 17, 2020   ....

I hereby agree to the publishing of the master's thesis as per s. 26, ss. 9 of the Study and Examination Regulations for Master's Degree Programmes at VŠB-Technical University of Ostrava.

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Abstract

The concept is to create a Simulink model based on the mathematical model of the Permanent Magnet Synchronous Motor; Frequency convertor is used to control the speed of the motor (0 to max RPM). Mathematical equations are derived. As per the derivations the Simulink block is created. All the blocks are from Simulink libraries. The model is converted into code and loaded into a FPGA, this chip will be tested in a HIL testing machine for various conditions and the simulation results from the SIMULINK and HIL testing are compared.

Keywords: Mathematical Modelling, SIMULINK, FPGA, HIL testing, simulation.

Abstrakt

Cílem práce je vytvořit simulační model PMSM v prostředí Simulink, založený na matematickém modelu synchronního motoru s permanentními magnety. Simulovaný frekvenční měnič se používá k řízení otáček motoru (0 až max. RPM). Jsou odvozeny matematické rovnice. Na základě odvozených rovnice je vytvořen model v prostředí Simulink. Všechny bloky jsou ze základních knihoven Simulinku. Model PMSM je poté s využitím speciálních bloků a knihoven převeden na simulační model pro FPGA apliakce. Výsledný model je nahrán do FPGA čipu testovacího zařízení HIL a bude využíván pro testování řídicích jednotek elektrických pohonů. Výsledky simulací z prostředí Simulink a reálné aplikace HIL jsou porovnány.

Klíčová slova: Matematické modelování, SIMULINK, FPGA, HIL testování, simulace.

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LIST OF ABBREVIATIONS

B	Friction
BDCM	Brushless Dc Motor
CSI	Current Source Inverter
IGBT	Insulated Gate Bipolar Transistor
IPM	Interior Permanent Magnet
J	Inertia
L	Self-inductance
P	Number of poles
PI	Proportional integral
PM	Permanent magnet
PMSM	Permanent Magnet Synchronous Motor
Q	Quadrature or interpolar axis
SPM	Surface Permanent Magnet
VSI	Voltage Source Inverter

LIST OF SYMBOLS

f_c	Crossover Frequency
i_a, i_b, i_c	Three Phase Currents
i_d	d-axis Current
i_f	Equivalent permanent magnet field current
i_q	q-axis Current
I_m	Peak Value of Supply Current
L_d	d-axis self-inductance
L_q	q-axis self-inductance
L_{ls}	Stator leakage inductance
L_{dm}	d-axis magnetizing inductance
L_{qm}	q-axis magnetizing inductance
L_s	Equivalent self-inductance per phase
R_S	Stator resistance
T_e	Torque developed
V_d	d-axis voltage
V_q	q-axis voltage
ρ	Derivative operator
λ_d	Flux linkage due d-axis
λ_f	PM flux linkage or Field flux linkage
λ_q	Flux linkage due q-axis
θ_r	Rotor position
ω_m	Rotor speed
ω_r	Electrical speed
ω_{rated}	Motor rated speed

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INTRODUCTION

Permanent Magnet Synchronous Motors are broadly utilized in low and mid power applications, for example, computer-based equipment's, automation, automotive, movable speed drives, and electric vehicles. The development in the market of PMSM drives has requested the need of Simulation tools equipped for handling of motor drive simulations. These techniques have helped the way toward growing new frameworks including engine drives, by decreasing expense and time. These tools have the abilities of performing dynamic simulations of engine drives in a visual domain to encourage the improvement of new system. In this work, the simulation circuit will incorporate every sensible part of the drive system. This enables the determination of voltage and current from the inverter and motor under transient and steady state conditions. The losses in different parts of the system is determined and it facilitate the design of the inverter.

A permanent magnet synchronous motor is a synchronous motor, in which the inductor consists of permanent magnets. The main difference between PMSM and induction motor is the rotor. PMSM's efficiency is approximately 2% more than a highly efficient induction motor, if the stator design and the variable frequency which is used to control is same. If it is like the previous case also it has better performance (in terms of power/volume, torque/inertia).

The use of permanent magnets (PM) in construction of electrical machines brings the subsequent benefits like, no electricity is absorbed by the sector excitation system and thus there are not any excitation losses which suggests substantial increase within the efficiency, higher torque and output power per unit volume compared to electromagnetic excitation, better dynamic performance than motors with electromagnetic excitation (higher magnetic flux within the air gap), simplification of construction and maintenance, reduction of lifetime cost for a few sorts of machines.

Cage induction motors are the foremost popular electric motors within the 20th century. Recently, due to the fast progress made within the field of power electronics and control technology, the applications of induction motors to electrical drives have increased. the most advantages of cage induction motors are their simple construction, easy maintenance, no commutator or slip rings, low price and high reliability. The disadvantages are their lower efficiency and poorer power factor than PM synchronous motors. the utilization of PM motors in electrical drives has become a more attractive option than induction motors. The improvements made within the field of semiconductor.

Drives mean that the control of PM motors has become easier and price effective with the likelihood of operating the motor over an outsized speed range and still maintaining an honest efficiency and power factor. the worth of rare-earth element magnets also are coming down making these motors more popular.

1. PMSM constructions and types

A PMSM consist of a rotor (rotating part) and stator (stationary part).
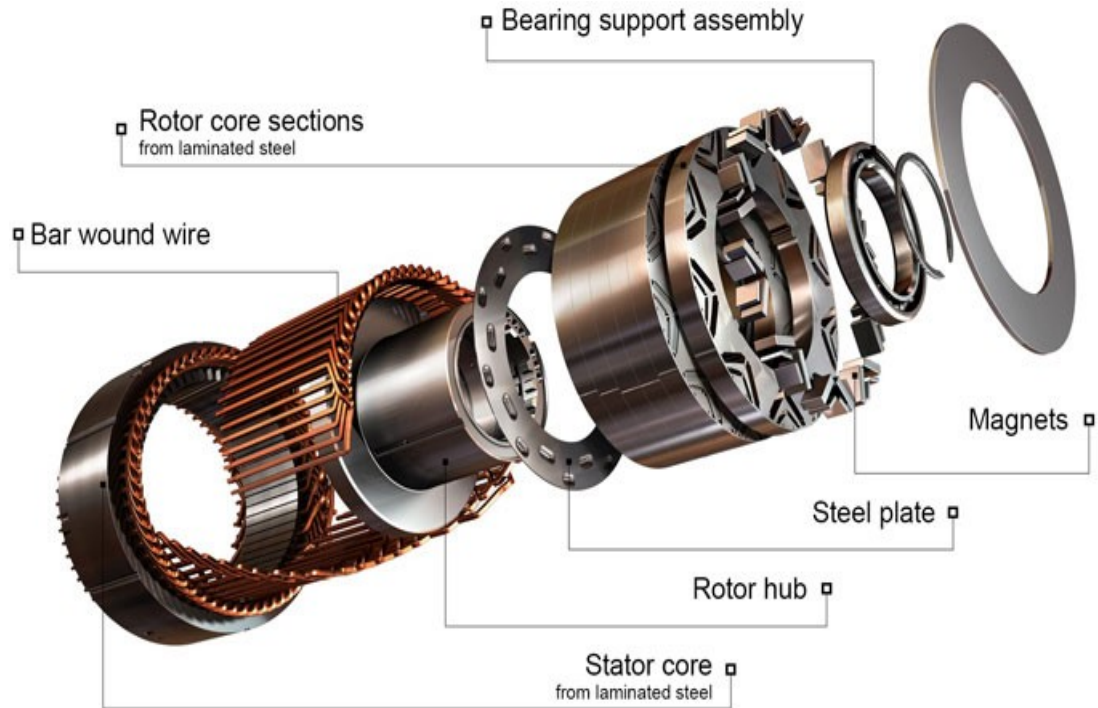
Figure 1 Permanent Magnet Synchronous Motor[1]

There is rotor present inside the stator (*Figure 2 on the* left) and there are structures with external rotors (*Figure 2 on the right*).
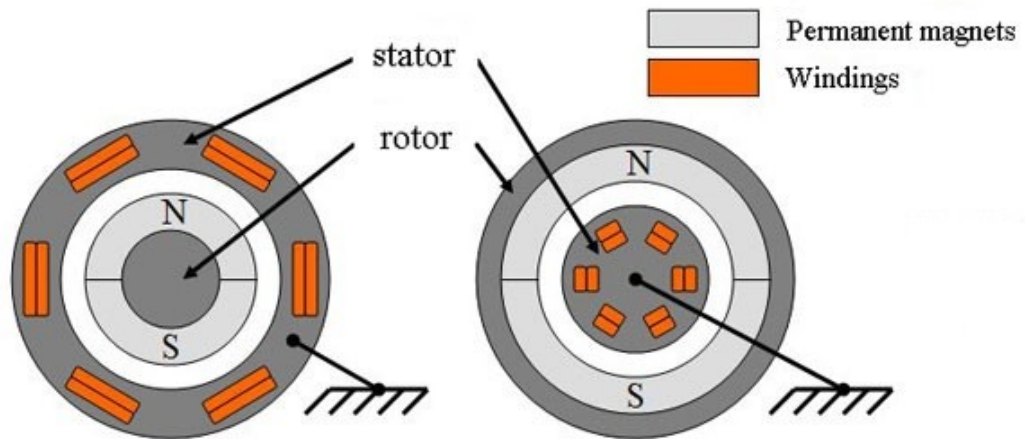
Figure 2 Types of Rotor Positions on the Motor [1]

The rotor has permanent magnets. According to the design of the rotor, there are two types:

- Motors with salient pole rotor.
- Motors with non-salient pole rotor.

A motor with non-salient pole rotor has a direct and quadrature inductances $L_q = L_d$ and for an motor with salient pole rotor it's the opposite $L_q \neq L_d$. The following *Figure3* shows the cross section of different rotors with different L_q, L_d ratio. Magnets are marked in black. Also, the image e, f shows axially layered rotors, image c, h shows the rotors with barriers [1].

$L_d{<}L_q$
a)

$L_d{=}L_q$
b)

$L_d{>}L_q$
c)

$L_d{>}L_q$
d)

$L_d{<}L_q$
e)

$L_d{>}L_q$
f)

$L_d{<}L_q$
g)

$L_d{>}L_q$
h)
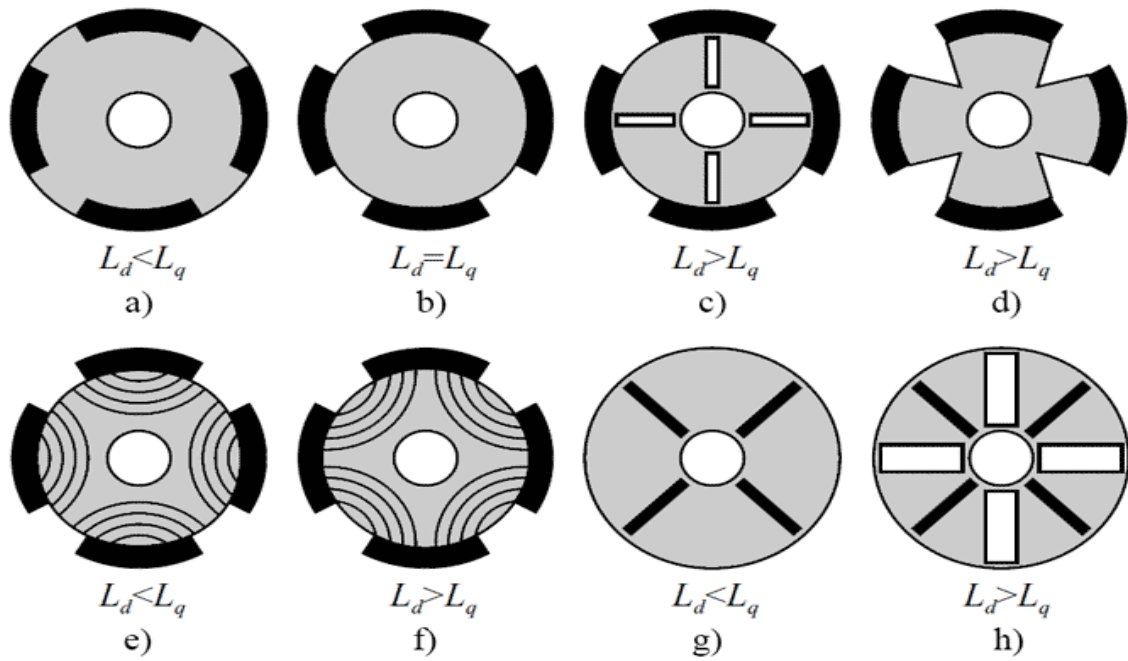
Figure 3 Types of Magnet Position in the Motor [1]

Also, according to the design of the rotor, the PMSM are divided into:

- Surface PMSM. (*Figure 4*)
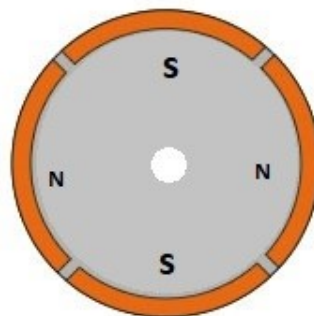
Figure 4 Surface PMSM [1]

- Interior PMSM. (*Figure 5*)

Figure 5 Interior PMSM [1]

The stator consists of an outer frame and a core with windings. The most common is 2 and 3 phase winding design. Depending upon the design of the stator, a PMSM can be:

- With distributed winding. (*Figure 6*)
  In this the number of slots per pole and phase $Q = 2, 3, ..., k$.

- With concentrated winding. (*Figure 7*)
  In this the number of slots per pole and phase $Q = 1$. The slots are evenly spaced around the circumference of the stator. The two coils forming the winding can be connected both in series and parallel. The main disadvantage of such windings is the impossibility of influencing on the form of the EMF curve.

The form of the back EMF of the electric motor can be Trapezoidal or Sinusoidal.

The form of the EMF curve in the conductor is determined by the distribution curve of the magnetic induction in the gap around the stator circumference. The magnetic induction in the gap under the salient pole of the rotor has a trapezoidal shape. The EMF induced in the conductor has the same form.

1.2. Working Principle of the Permanent Magnet Synchronous Motor

The working principle of PMSM is same as the synchronous motor, when 3-phase stator winding is energized from a 3-phase supply, then a rotating magnetic field is induced in the gap. At synchronous speed the rotor field poles locks the rotating magnetic field to produce torque (according to Ampere's Law), thereby forcing the rotor continues to rotate. (*Figure 8*).

As we know that the synchronous motor are not self-starting, the PMSM should be started in some ways, as there is no winding on the rotor, induction windings for starting is not applicable for such motors, so a variable frequency power supply is used for this purpose.
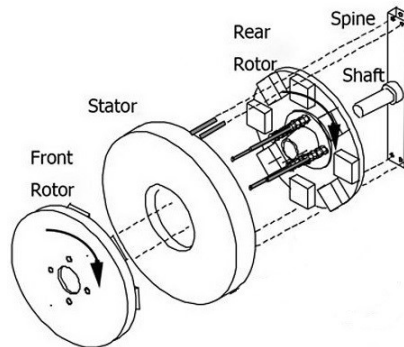
Figure 8 Working of a PMSM [2]

The quasi sinusoidal distribution of magnetic flux round the air gap is achieved by tapering the magnet thickness at the pole edges and by employing a shorter magnet pole arc typically 120º. The quasi sinusoidal current wave forms are achieved through the utilization of PWM inverters and this might be current regulated to supply the simplest possible approximation to a pure wave. the utilization of short pitched distributed or concentric winding is strictly an equivalent as in ac motors. static magnet synchronous machines generally have same operating and performance characteristics as synchronous machines. A static magnet machine can have a configuration almost just like that of the traditional synchronous machines with absence of slip rings and a field coil.

The development of PMSM went on thanks to the invention of novel magnetic materials and rare-earth element materials. PMSM give numerous advantages in scheming recent motion management systems. Energy efficient PMSM are designed thanks to the supply of static magnet materials of high magnetic flux.

In synchronous motors the rotor rotates at the speed of stator revolving field. The speed of the revolving stator field is named as synchronous speed. The synchronous speed are often found by the frequency of the stator input supply, and therefore the number of stator pole pairs. The stator of a 3-phase electric motor consists of distributed sine three phase winding, whereas the rotor consists of an equivalent number of p-pole pairs as stator, excited by permanent magnets or a separate DC supply source.

1.3. Control Methods of Permanent Magnet Synchronous Motor

A PMSM requires a control system to drive the motor in required conditions. There are many types of techniques implemented to control the system. The following table explains the main methods that are widely used across the industries. (*Table 1*).

CONTROL				ADVANTAGES	DISADVANTAGES
Sinusoidal		Scalar		Simple control scheme	Control is not optimal, not suitable for tasks where the variable load, loss of control is possible
	vector	Field oriented control	With position sensor	Smooth and precise setting of the rotor position and motor rotation speed, large control range	Requires rotor position sensor and powerful microcontroller inside the control system
			Without position sensor	No rotor position sensor required. Smooth and precise setting of the rotor position and motor rotation speed, large control range, but less than with position sensor	Sensorless field-oriented control over full speed range is possible only for PMSM with salient pole rotor, a powerful control system required
		Direct torque control		Simple control circuit, good dynamic performance, wide control range, no rotor position sensor required	High torque and current ripple
Trapezoidal		Open loop		Simple control scheme	Control is not optimal, not suitable for tasks where the variable load, loss of control is possible
	Cosed loop	With position sensor (Hall sensors)		Simple control scheme	Hall sensors required. There are torque ripples. It is intended for control of PMSM with trapezoidal back EMF, when controlling PMSM with sinusoidal back EMF, the average torque is lower by 5 %.
		Without sensor		More powerful control system required	Not suitable for low operation. There are torque ripples. It is intended for control of PMSM with trapezoidal back EMF, when controlling PMSM with sinusoidal back EMF, the average torque is lower by 5 %.

Table 1 Control Methods of PMSM [1]

- For simple tasks for example computer fans, toy car, etc. we can use trapezoidal control Hall sensors.
- For tasks that requires high performance, we can use field-oriented control.

1.3.1. Trapezoidal control

This is a simplest method to control a PMSM, the motor drive can be controlled with a trapezoidal back EMF and at the same time , we can able to control the motor drive with a sinusoidal back EMF, but then the average torque that is produced will be 5% less, also the torque ripple will be 14% of the maximum value. There are two types in this one is with feedback and other is without feed under trapezoidal control.The one without feedback (open loop control) is not optimal and may lead that the PMSM can go out of synchronism (loss of controllability).

The one with feedback (closed loop control) is of two types:
- ➢ Trapezoidal control by position sensor (usually by Hall sensors). (*Figure 9*).
- ➢ Trapezoidal control without sensor (Sensorless trapezoidal control).

Three hall sensors are placed in the electric motor to determine the rotor position in terms of angle with accuracy of ± 30 degrees. With this type of control, if there is a ripple torque at the output as a result then the stator current vector takes only six positions for one period of rotation.

Figure 9 Trapezoidal Control by Position Sensor [1]

1.3.2. Field Oriented Control

In this method we can control the speed and torque independently with great accuracy. Also the position of the rotor can be determined by:
- • Position sensor. (*Figure 10*).

  The following sensors can be used to determine the angle:
- ➢ Inductive: resolver, inductosyn, etc.
- ➢ Optical.
- ➢ Magnetic: magneto-resistive sensors.

Figure 10 Field Oriented Control with Position Sensor [1]

1.3.3. Sensoreless Control

Thanks to the advanced development of microprocessors, since the 1970's this method began to be developed to control the brushless AC motors. At the beginning the angle was estimated based on the property of the electric motor to generate back EMF during rotation. The motor back EMF contains information about the position of the rotor, therefore, by calculating the value of the back EMF in the stationary coordinate system, you can calculate the position of the rotor. But when the rotor is not rotating, the back EMF suitable for determining the position of the motor rotor at low speed.

There are 2 types of techniques that are commonly used to start the motor:

➢ Start by the scalar method (*Figure 11*) – start on a predetermined characteristic of voltage dependence to frequency. But the scalar control severely limits the capabilities of the control system and the parameters of the electric drive.

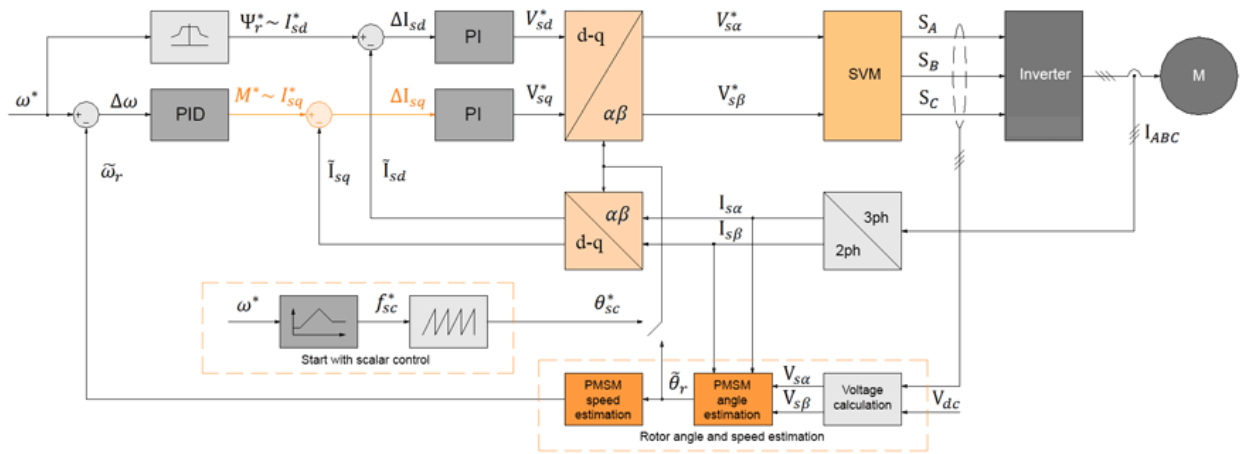➢ High frequency signal injection method but it works only with the salient pole PMSM.

Figure 11 Sensoreless Control [1]

The difficulties in estimating the rotor position due the reasons: one is scalar speed estimation and therefore the second is initial position of rotor isn't known. The non-measurable variables of PMSM are estimated by the observers. For zero-speed application, salience tracking technique is taken into account as appropriate, where back-Emf technique fails at low speed. The methods generally won't to estimate the rotor position are tracking observer, tracking state filter and arctangent calculation. The sliding mode observer having sigmoid switching function, effectively suppressed the oscillation of system. The cut-off frequency of LPF is tuned to rotor speed, in order that the rotor speed becomes real-time and tunable. In PMSM vector system with space vector PWM voltage source inverter (SVPVM-VSI), the only shunt current sensing with model reference adaptive system (MRAS) for rotor position sensorless control method is implemented.

2. Mathematical Model Of PMSM

Detailed modelling of PM motor drive system is required for proper simulation of the system. The d-q model has been developed on rotor reference frame as shown in (*figure 12*) below. At any time t, the rotating rotor d-axis makes and angle *θr* with the fixed stator phase axis and rotating ***stator mmf*** makes an angle α with the rotor d-axis. ***Stator mmf*** rotates at the same speed as that of the rotor[3].
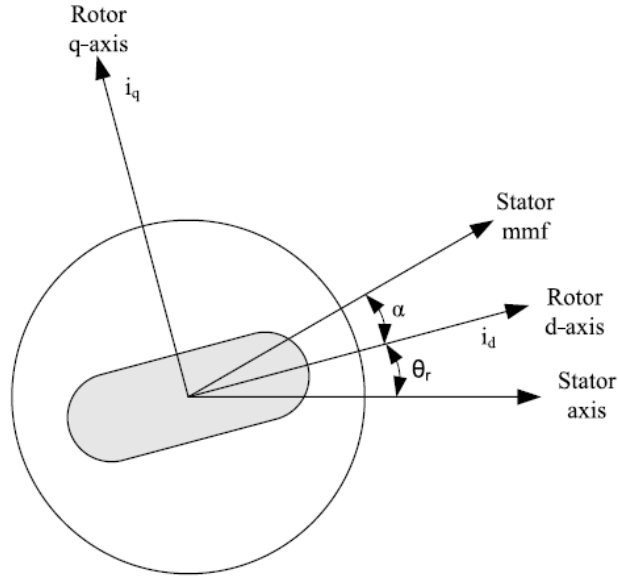

Figure 12 d-q Model developed on Rotor Reference Frame [3]

The model of PMSM without damper winding has been developed on rotor reference frame using the following assumptions:

1) Saturation is neglected.
2) The induced EMF is sinusoidal.
3) Eddy currents and hysteresis losses are negligible.
4) There are no field current dynamics.

Voltage equations are given by:

Stator voltage in the q axis: $\quad V_q = R_s i_q + \omega_r \lambda_d + \rho \lambda_q$ $\hspace{3cm}$ **(2.1)**

Stator voltage in the d axis: $\quad V_d = R_s i_d - \omega_r \lambda_q + \rho \lambda_d$ $\hspace{3cm}$ **(2.2)**

Flux Linkages are given by

Stator flux in the q axis: $\quad \lambda_q = L_q i_q$ $\hspace{5cm}$ **(2.3)**

Stator flux in the d axis: $\quad \lambda_d = L_d i_d + \lambda_f$ $\hspace{4.5cm}$ **(2.4)**

Substituting equations (2.3) and (2.4) into (2.1) and (2.2)

$$V_q = R_s i_q + \omega_r (L_d i_d + \lambda_f) + \rho L_q i_q \hspace{3cm} \textbf{(2.5)}$$

$$V_d = R_s i_d - \omega_r L_q i_q + \rho (L_d i_d + \lambda_f) \hspace{3cm} \textbf{(2.6)}$$

Arranging equations (2.5) and (2.6) in matrix form,

$$\begin{pmatrix} V_q \\ V_d \end{pmatrix} = \begin{pmatrix} R_s + \rho L_q & \omega_r L_d \\ -\omega_r L_q & R_s + \rho L_d \end{pmatrix} \begin{pmatrix} i_q \\ i_d \end{pmatrix} + \begin{pmatrix} \omega_r \lambda_f \\ \rho \lambda_f \end{pmatrix} \hspace{2cm} \textbf{(2.7)}$$

The developed torque motor is being given by,

$$T_e = \frac{3}{2}\left(\frac{P}{2}\right)(\lambda_d i_q - \lambda_q i_d) \tag{2.8}$$

The mechanical Torque equation is,

$$T_e = T_L + B\omega_m + J\frac{d\omega_m}{dt} \tag{2.9}$$

Solving for the rotor mechanical speed form equation 2.9,

$$\omega_m = \int \left(\frac{T_e - T_L - B\omega_m}{J}\right) dt \tag{2.10}$$

and

$$\omega_m = \omega_r \left(\frac{2}{P}\right) \tag{2.11}$$

2.1. Parks Transformation and Dynamic d-q Modelling

This transformation converts vectors in balanced two-phase orthogonal stationary system into orthogonal rotating reference frame. Basically, the three reference frames considered during this implementation are [5][7][11]:

- Three-phase coordinate system, during which Ia, Ib, and Ic are co-planar three-phase quantities at an angle of 120 degrees to every other.
- Orthogonal stationary coordinate system, during which Iα (along α axis) and Iβ (along β axis) are perpendicular to every other, but within the same plane because the three-phase coordinate system.
- Orthogonal rotating coordinate system, during which Id is at an angle θ (rotation angle) to the α axis and Iq is perpendicular to Id along the q axis.
-

The dynamic *d-q* modelling is used for the study of motor during transient and steady state. It is done by converting the three phase voltages *abc* currents to *dqo* variables by using Parks transformation. Converting the phase voltages variables V_{abc} to V_{dqo} variables in rotor reference frame the following equations are obtained.

$$\begin{bmatrix} V_q \\ V_d \\ V_o \end{bmatrix} = \frac{2}{3}\begin{bmatrix} \cos\theta_r & \cos(\theta_r - 120) & \cos(\theta_r + 120) \\ \sin\theta_r & \sin(\theta_r - 120) & \sin(\theta_r + 120) \\ 1/2 & 1/2 & 1/2 \end{bmatrix}\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \tag{2.12}$$

Convert V_{dqo} to V_{abc}

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} \cos\theta_r & \sin\theta_r & 1 \\ \cos(\theta_r - 120) & \sin(\theta_r - 120) & 1 \\ \cos(\theta_r + 120) & \sin(\theta_r + 120) & 1 \end{bmatrix}\begin{bmatrix} V_q \\ V_d \\ V_o \end{bmatrix} \tag{2.13}$$

2.2. Equivalent Circuit of Permanent Magnet Synchronous Motor

Equivalent circuits of the motors are used for study and simulation of motors. From the d-q modeling of the motor using the stator voltage equations the equivalent circuit of the motor can be derived. Assuming rotor d axis flux from the permanent magnets is represented by a constant current source as described in the following equation $\lambda f = L_{dm} * i_f$, figure below is obtained.
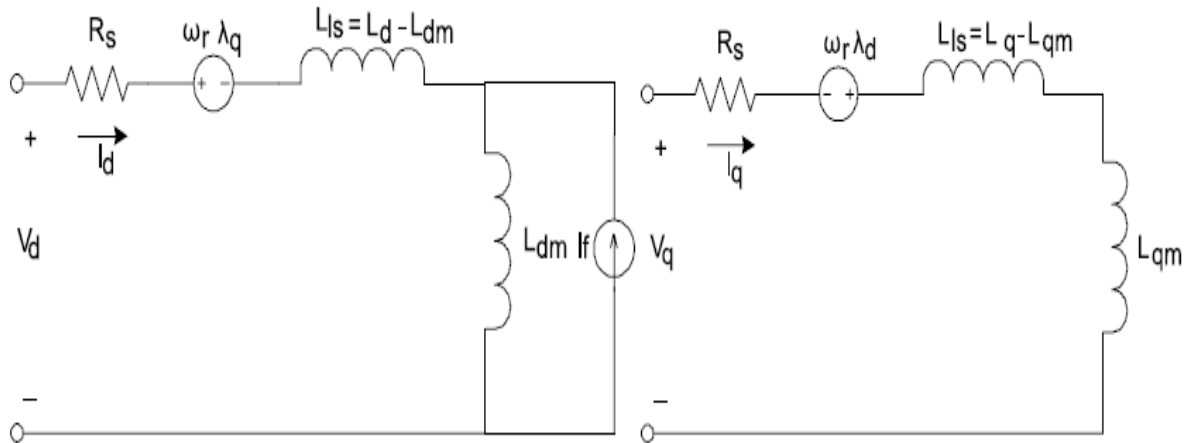

Figure 13 Equivalent Circuit of PMSM

2.3. PM Motor Control

Control of PM motors is performed using field-oriented control for the operation of synchronous motor as a dc motor. The stator windings of the motor are fed by an inverter that generates a variable frequency variable voltage. Instead of controlling the inverter frequency independently, the frequency and phase of the output wave are controlled using a position sensor as shown in figure below.
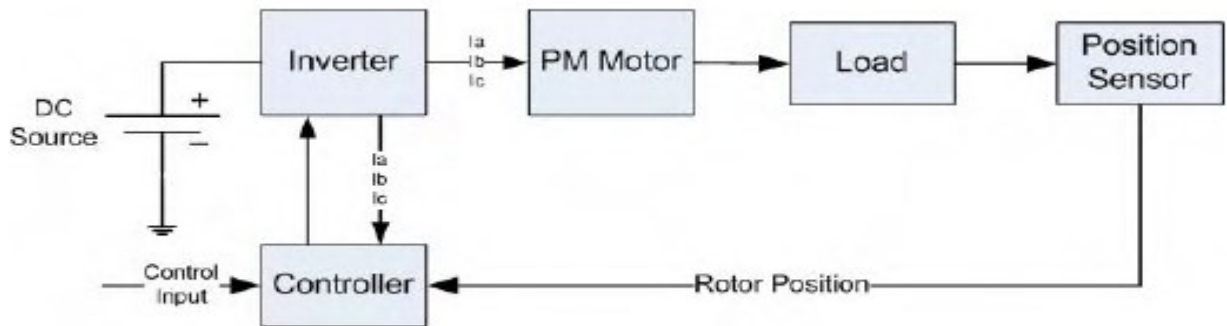

Figure 14 PM Motor Control [3] [5]

Field oriented control was invented in the beginning of 1970s and it demonstrates that an induction motor or synchronous motor could be controlled like a separately excited dc motor by the orientation of the **stator mmf** or current vector in relation to the rotor flux to achieve a desired objective. For the motor to behave like DC motor, the control needs knowledge of the position of the instantaneous rotor flux or rotor position of permanent magnet motor. This needs a resolver or an absolute optical encoder. Knowing the position, the three phase currents can be calculated. Its calculation using the current matrix depends on the control desired. Some control options are constant torque and flux weakening. These options are based in the physical limitation of the motor and the inverter.

The limit is established by the rated speed of the motor, at which speed the constant torque operation finishes and the flux weakening starts as shown in figure below.
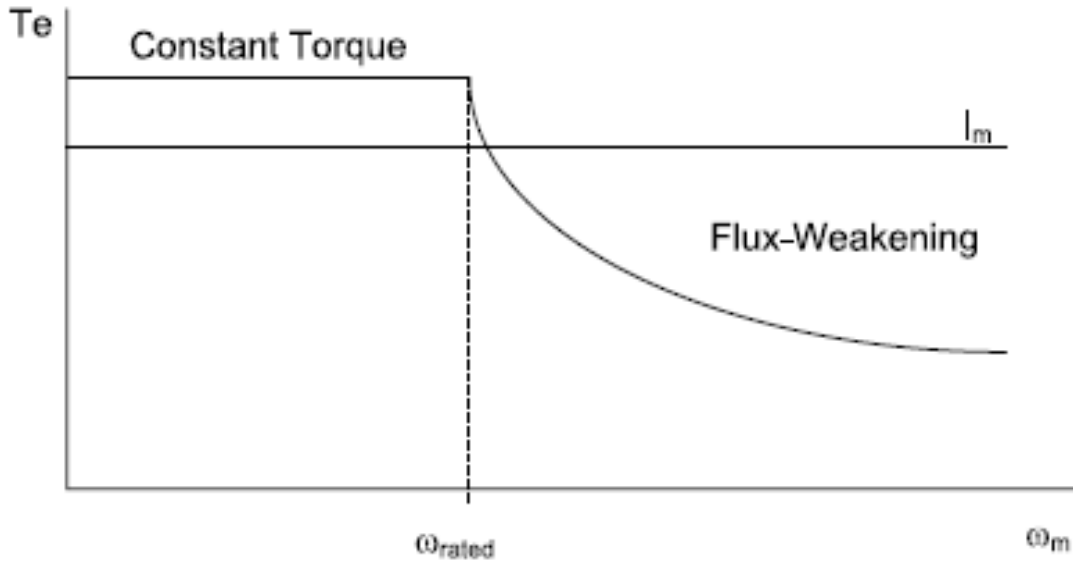

Figure 15 Steady State Torque Vs Speed [3]

2.4. Field Oriented Control of PM Motors

FOC was invented within the beginning of 1970s and it demonstrates that an induction motor or electric motor might be controlled sort of a separately excited DC motor by the orientation of the stator mmf or current vector in reference to the rotor flux to realize a desired objective. For the motor to behave sort of a DC motor, the control needs knowledge of the position of the instantaneous rotor flux or rotor position of static magnet motor. This needs a resolver or an absolute optical encoder. Knowing the position, the three phase currents are often calculated. Its calculation using the present matrix depends on the control desired. Some control options are constant torque and flux weakening. These options are based within the physical limitation of the motor and therefore the inverter.

The PMSM control is equivalent to that of the dc motor by a decoupling control known as field-oriented control or vector control. The vector control separates the torque component of current and flux channels in the motor through its stator excitation. The vector control of the PM synchronous motor is derived from its dynamic model.

Considering the currents as inputs, the three currents are:

$$i_a = I_m \sin(\omega_r t + \propto) \tag{2.14}$$

$$i_b = I_m \sin(\omega_r t + \propto - \frac{2\pi}{3}) \tag{2.15}$$

$$i_c = I_m \sin(\omega_r t + \propto + \frac{2\pi}{3}) \tag{2.16}$$

Writing equations (2.14) to (2.15) in the matrix form:

$$\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \begin{bmatrix} \cos(\omega_r t + \alpha) \\ \cos(\omega_r t + \alpha - \frac{2\pi}{3}) \\ \cos(\omega_r t + \alpha + \frac{2\pi}{3}) \end{bmatrix} [I_m] \tag{2.17}$$

Where α is the angle between the rotor field and stator current phasor, $\boldsymbol{\omega_r}$ is the electrical rotor speed.

The previous currents obtained are the stator currents that must be transformed to the rotor reference frame with the rotor speed $\boldsymbol{\omega_r}$, using Park's transformation. The q and d axis currents are constants in the rotor reference frames since α is a constant for a given load torque. As these constants, they are like the armature and field currents in the separately excited dc machine. The q axis current is distinctly equivalent to the armature current of the dc machine; the d axis current is field current, but not in its entirety. It is only a partial field current; the other part is contributed by the equivalent current source representing the permanent magnet field. For this reason, the q axis current is called the torque producing component of the stator current and the d axis current is called the flux producing component of the stator current.

Substituting equation (2.17) is obtain $\boldsymbol{i_d}$ and $\boldsymbol{i_q}$ in terms of $\boldsymbol{I_m}$ as follows

$$\begin{pmatrix} i_q \\ i_d \end{pmatrix} = (I_m)\begin{pmatrix} \sin\alpha \\ \cos\alpha \end{pmatrix} \tag{2.18}$$

Using equations (4.1), (4.2), (4.8) and (6.5) the electromagnetic torque equation is obtained as given below.

$$T_e = \frac{3}{2} * \left(\frac{P}{2}\right) * \left[\frac{1}{2}\left(L_d - L_q\right)I_m^2 \sin2\alpha + \lambda_f I_m \sin\alpha\right] \tag{2.19}$$

3. PMSM simulation model in Simulink

In this chapter based on the mathematical model of the PMSM, a SIMULINK model was designed to see results in form of graph. To study the working of PMSM, a proper simulation tool is needed. This tool should have the capacity to do complex problem-solving capability to perform such a dynamic simulation. With the growth of advanced computer machines and technologies several systems are available for simulations such as ACSL, EASY5, PSCSP and ESL these are basically used for electrical simulations and EMTP, PSPICE, SPICE2, and ATOSEC5 for simulation of both electrical and electronic circuits. IESE and SABER are good examples for handling user defined models in general purpose electrical network simulation programs. SIMULINK is an extension of the MATLAB and it has the advantage of performing complex dynamic simulations, and you can from a wide variety of graphical user interfaces that has high flexibility which allow the user to set the functions however they want [16].

➢ Initialisation of necessary parameters in Matlab,
Rs = 1.2; %ohm
Rc = 416; %ohm
L_q = 12.5e-3; %mH
L_d = 5.7e-3; %mH
lamda_af = 123e-3; %mweber/turns
P = 4; %Number Of Poles

V = 230; %V Line Voltage
f = 60;

B = 0;
T_L = 10;
T_d = 0;
J = 0.0001584;

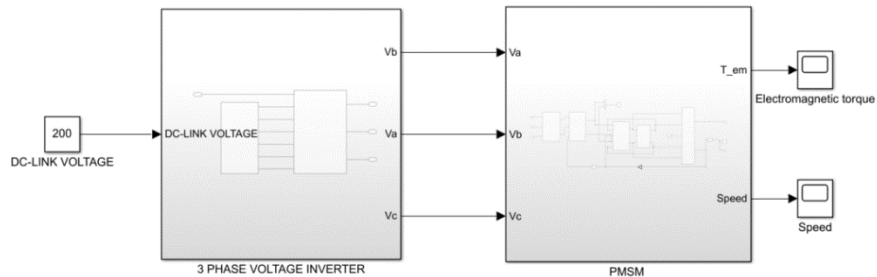➢ The main block consists of a DC-LINK VOLTAGE, 3 PHASE VOLTAGE INVERTER, PMSM.

Figure 16 Simulink Model of PMSM

3.1. Three Phase Voltage Inverter

The DC-link voltage is necessary to run an induction motor with an inverter. The 3-phase voltage consist of PWM control and a IGBT module.
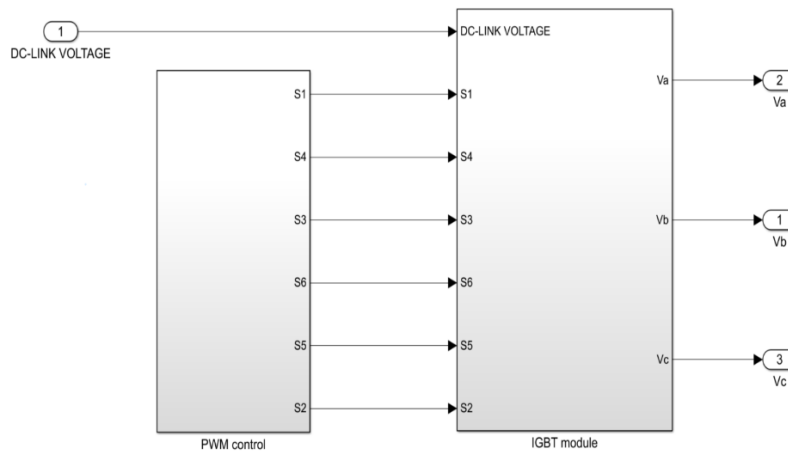

Figure 17 Simulink Block of Three Phase Voltage Inverter

Three phase inverter contains a DC voltage source and 6 power ON/OFF switches connected to the PMSM. Selection of the inverter switches must be carefully done supported the necessities of operation, ratings and therefore the application. There are several devices available within the market

and these are thyristors, bipolar junction transistors (BJTs), MOS field effect transistors (MOSFETs), insulated gate bipolar transistors (IGBTs) AND circuit close up thyristors (GTOs). It has been inferred that MOSFETs and IGBTs are preferred within the industry due to its advantages that the MOS gating permits high power gain and control advantages. MOSFET is taken into account to be universal power ON/OFF device for low power and low voltage applications, whereas IGBT has wide acceptance within the motor drive applications and other application within the low and medium power range. the devices when utilized in motor drives applications require an inductive motor current path provided by antiparallel diodes when the switch is turned off.

3.1.1. PWM control

PWM – Pulse Width Modulation is an effective of controlling the speed of an induction motor. There are variable techniques available to control the speed of the motor, which are, by varying the slip by changing the resistance of the rotor or voltage of the terminal and varying synchronous speed by changing the supply frequency or by changing the number of poles. Changing the resistance of the rotor requires rotor-wounded induction motor and any resistances inserted to the rotor circuit will reduce the machines efficiency. Changing the voltage of the terminal has limited range of speed control. Special stator windings are needed in case of changing the number of poles. So, the best method of varying the speed is to vary the frequency of the supply. The speed depends on the rate of rotation of its magnetic field or the synchronous speed, which is directly proportional to the change in supply frequency. Pulse Width Modulation technique is used to control the supply frequency of the three phase voltage applied to the motor from the IGBT inverter circuit, hence allowing the speed to be varied with respect to the frequency of the reference signa, input to the PWM signal generator [10].
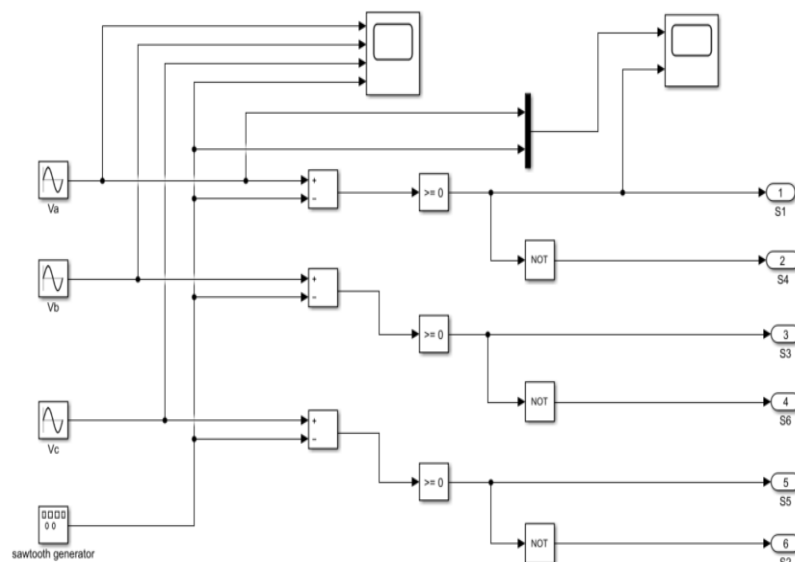

Figure 18 Simulink Block of PWM Control

3.1.2. IGBT module

IGBT – Insulated Gate Bipolar Transistor may be a minority carrier device, which has high input impendence and therefore the capability to hold large bipolar current. Normally it's a semiconductor unit with input characteristics of a MOSFET and output characteristics of a bipolar transistor, making it a voltage-controlled bipolar device. While these two inputs and outputs are integrated monolithically on one silicon die, it's often necessary to feature a freewheeling or anti parallel diode to get the fully functional switch, although in some cases the freewheeling diode isn't necessary. The diode can incorporated monolithically or co-packed or as a discrete diode external to the IGBT package. IGBT's improve dynamic performance and efficiency and reduce the extent of audible noise. it's equally suitable in resonant mode converter circuits. Optimized IGBTs are available for both low conduction loss and low switching loss. one among the more common applications is to use as a switching component in voltage source inverter circuits. These inverters are commonly utilized in power supply and control applications. the most advantage of using this IGBTs within the convertors is thanks to simplicity, modularity of the converter simple gate drive, elimination of snubber circuits thanks to the square Safe Operating Area (SOA), low switching losses, improved protection characteristics (over-current and short fault) and simpler electrical and mechanical design of the converters. These advantages make the IGBTs a really popular and promising switching devices [13][12].

In contrast to grid connected ac motor drives, which are essentially constant frequency, power electronic devices (e.g. inverters), offer voltage supplies that are variable in both frequency and magnitude and are wont to operate ac motors at frequencies aside from the availability frequency. Motor-control applications include mainly variable voltage, phase and frequency inverters. the aim of a power converter is to supply a controllable voltage and frequency and supply an ac output waveform from a DC link circuit. This DC link is usually supplied by a controllable or uncontrollable AC-DC converter. Variable voltage and frequency waveforms are required to work variable speed drives, UPS, active filters, compensators etc. which are only a few sorts of applications. Pulse-width modulated; variable-speed motor drives are an application compatible for IGBTs.

Generally , two basic sorts of inverters exist: Voltage-source inverters (VSI), employing a dc link capacitor and providing a switched voltage waveform, and current-source inverters (CSI), employing a dc link inductance and providing a switched current waveform at the motor terminals. CS-inverters are robust operational and reliable thanks to the insensitivity to short circuits and noisy environments. VS-inverters are more common compared to CS-inverters. since the utilization of Pulse Width Modulation (PWM) allows efficient and smooth operation, free from torque pulsations and cogging. Furthermore, the frequency range of a VSI is higher and that they are usually more inexpensive in comparison to CSI drives of an equivalent rating.
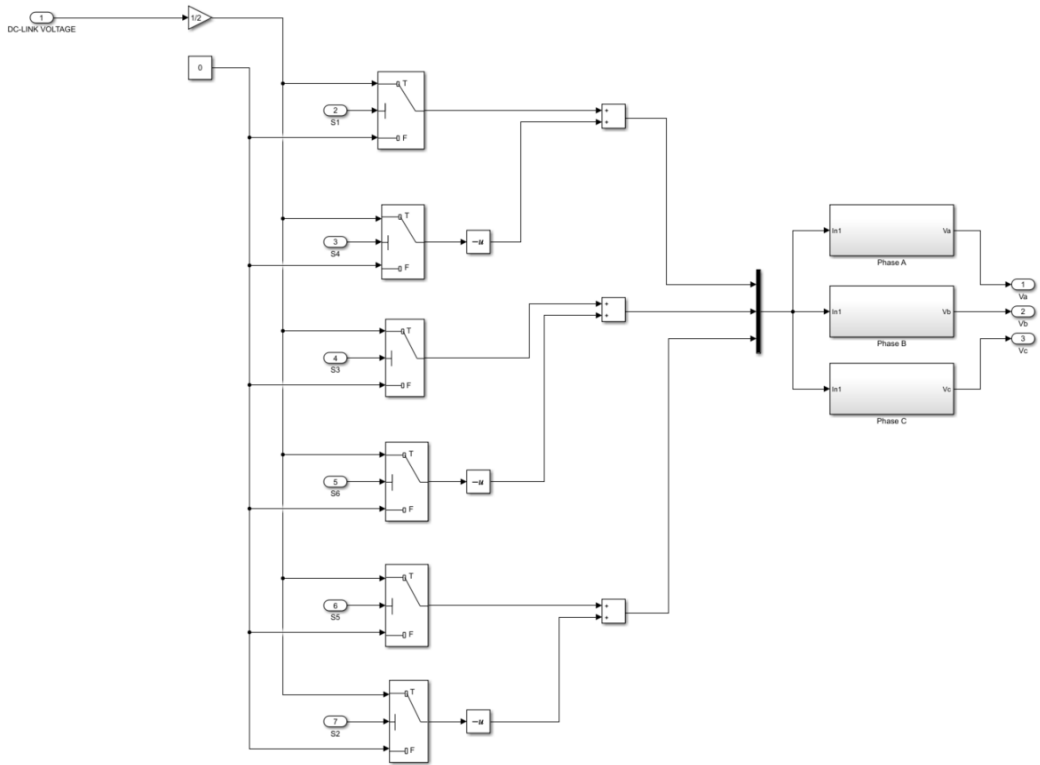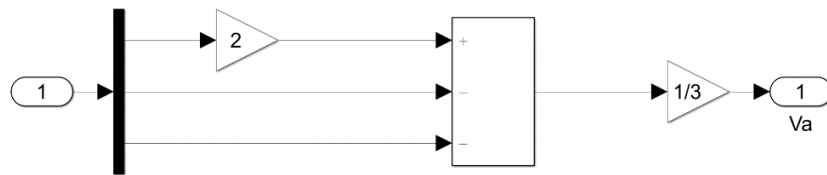
Figure 19 Simulink Block of IGBT Module

➢ PHASE A

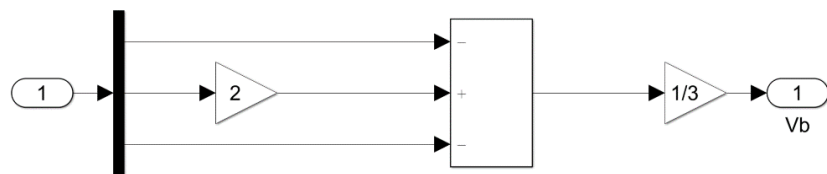*Figure 20 Simulink Block of Phase A*

➢ PHASE B

Figure 21 Simulink Block of Phase B
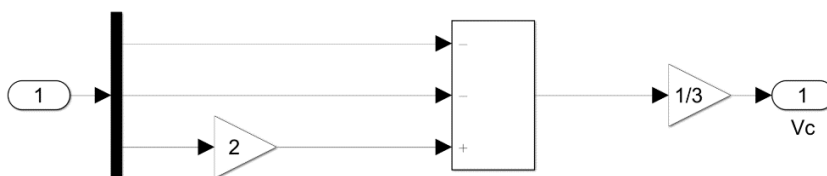
➢ PHASE C

Figure 22 Simulink Block of Phase C

3.2. Block of Permanent Magnet Synchronous Motor

This block consists of Clarke transformation, Parks transformation, Flux in dq axis, an Electrical sub-system, a Mechanical sub-system.

3.2.1. Clarke Transformation

The alpha-beta (αβγ) transformation is also known as Clarke transformation, is a mathematical transformation employed to simplify the analysis of three-phase circuits. Conceptually it is similar to dq0 transformation. One of the αβγ transformation is the generation of the reference signal used for space vector modulation of three phase inverters [5][7][11].
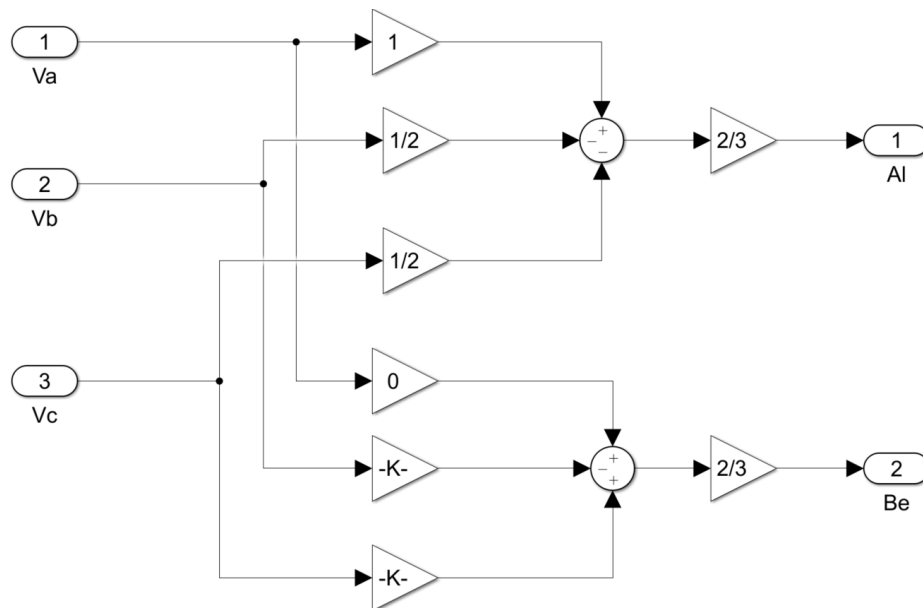

Figure 23 Simulink Block of Clarke Transformation

3.2.2. Parks Transformation

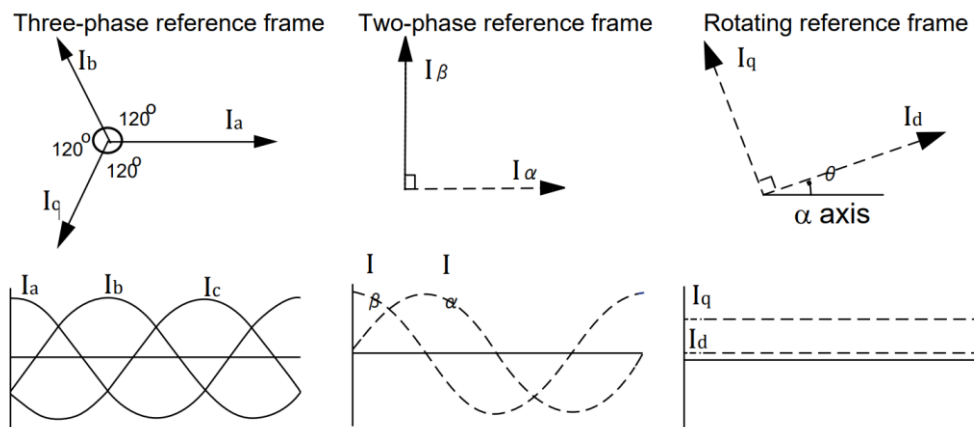The below figure shows the three reference frames.

Figure 24 Reference Frames in Parks Transformation
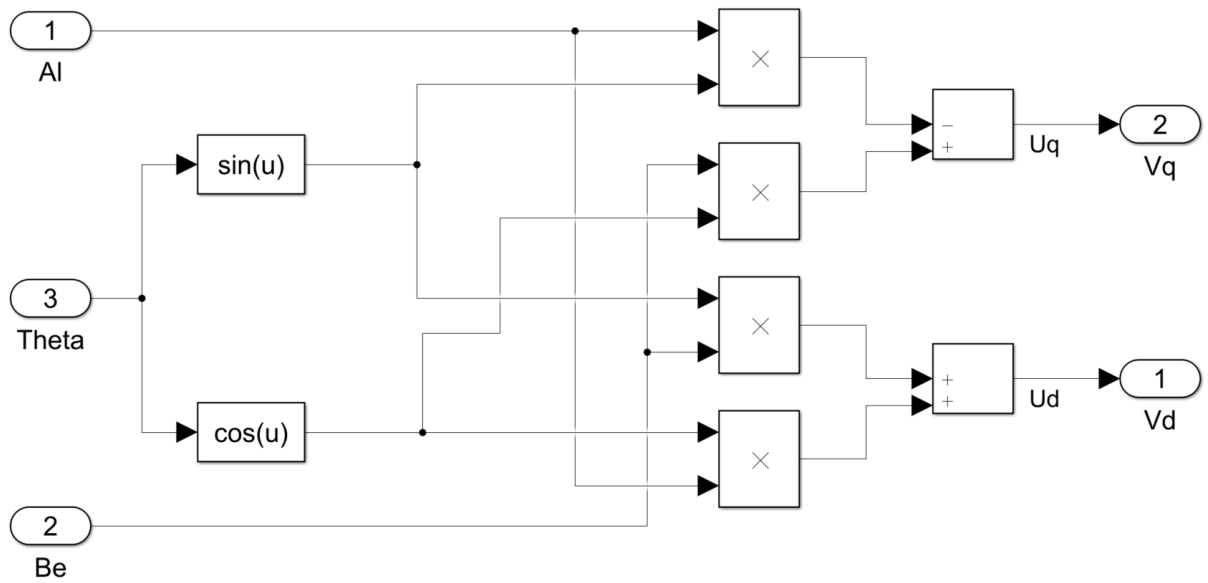
Figure 25 Simulink Block of Parks Transformation

3.2.3. Flux In dq Axis

By re-arranging equations (2.1) and (2.2),

$$\text{Lamda\_d,} \quad \lambda_q = \int V_q - R_s i_q - \omega_r \lambda_d \tag{3.1}$$

$$\text{Lamda\_q,} \quad \lambda_d = \int V_d - R_s i_d - \omega_r \lambda_q \tag{3.2}$$

where, λ_d and λ_q are the flux linkage due to d and q axis correspondingly,

ω_r is the electrical speed,

V_d and V_q are the d-axis and q-axis voltage,

R_s is the stator resistance

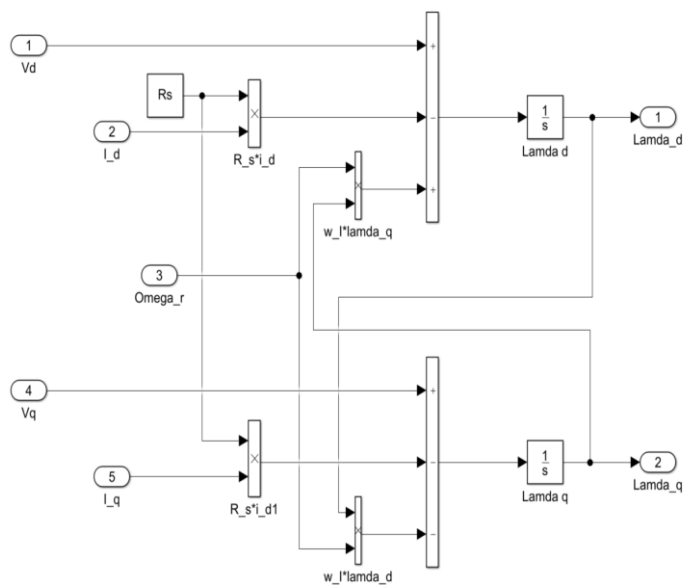i_d and i_q are the d-axis and q-axis current

Figure 26 Simulink Block of Flux in d-q Axis

3.2.4. Electrical Sub-System

By re-arranging equations (2.3) and (2.4),

$$\text{i\_q}, \ i_q = \frac{\lambda_q}{L_q} \tag{3.3}$$

$$\text{i\_d}, \ i_d = \frac{\lambda_d - \lambda_f}{L_d} \tag{3.4}$$

where, i_d is the d-axis current, i_q is the q-axis current,

λ_f is the PM flux linkage or Field flux linkage.
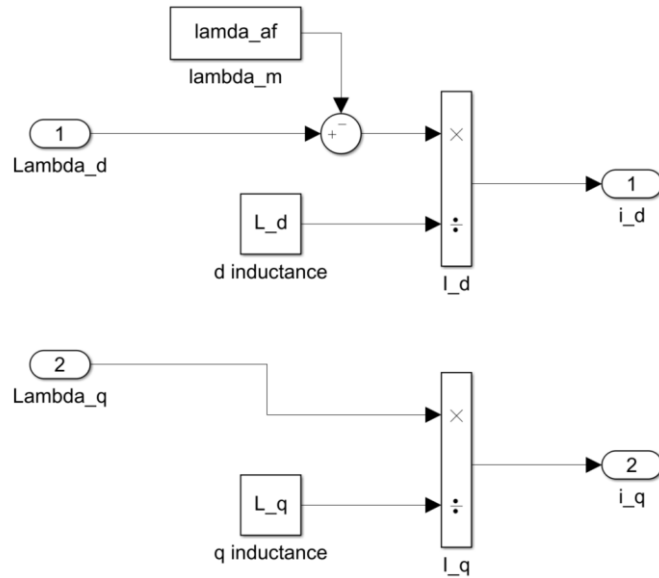
Figure 27 Simulink Block of Electrical Sub-system

3.2.5. Mechanical Sub-System

This block is derived from the equations,

➢ The developed torque motor is,

$$T_e = \frac{3}{2}\left(\frac{P}{2}\right)(\lambda_d i_q - \lambda_q i_d) \tag{2.8}$$

➢ The mechanical Torque equation,

$$T_e = T_L + B\omega_m + J\frac{d\omega_m}{dt} \tag{2.9}$$

➢ Solving for the rotor mechanical speed form equation 5.9,

$$\omega_m = \int\left(\frac{T_e - T_L - B\omega_m}{J}\right)dt \tag{2.10}$$
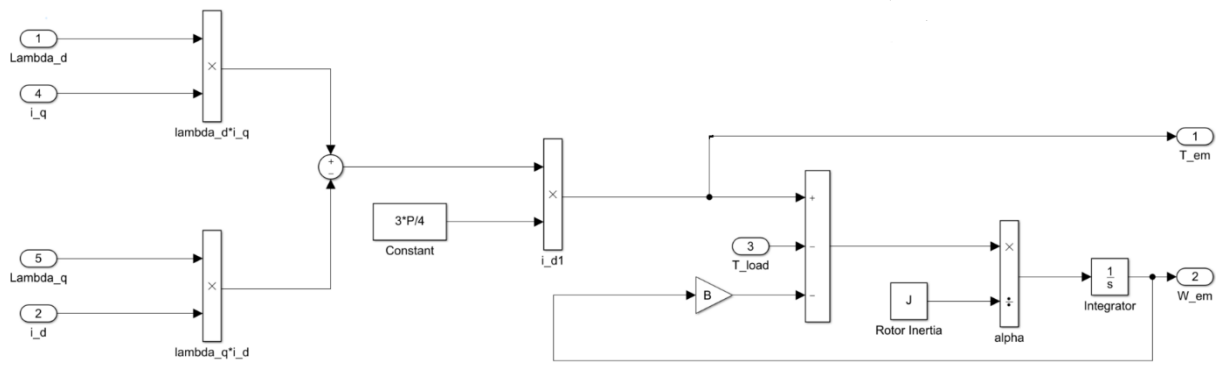
Figure 28 Simulink Block of Mechanical Sub-system

To obtain the mechanical speed from the electrical speed,

$$\omega_m = \omega_r \left(\frac{2}{P}\right) \tag{2.11}$$
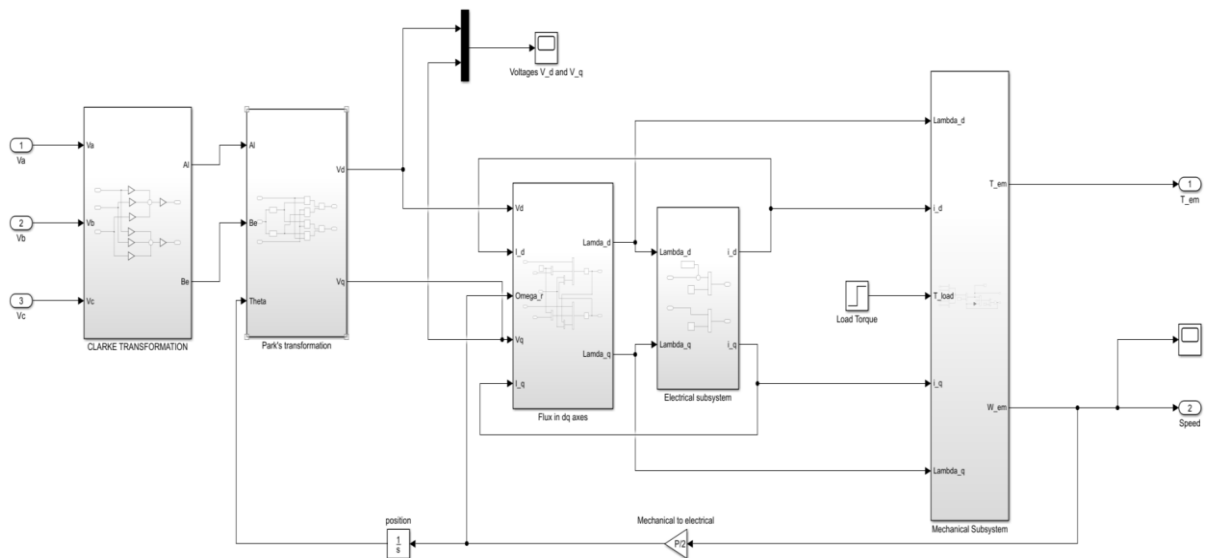
Figure 29 Simulink Block of PMSM.

4. Simulation Results,

➢ Output voltages Va, Vb, Vc from three phase voltage inverter,
➢ Where violet one is Va, blue one is Vb, orange one is Vc.
➢ In this conduction between each voltage there is 120º phase difference. Therefore only 2 switches is ON at any instant.
➢ X-axis represents time (µs) and Y-axis represents voltage (V).
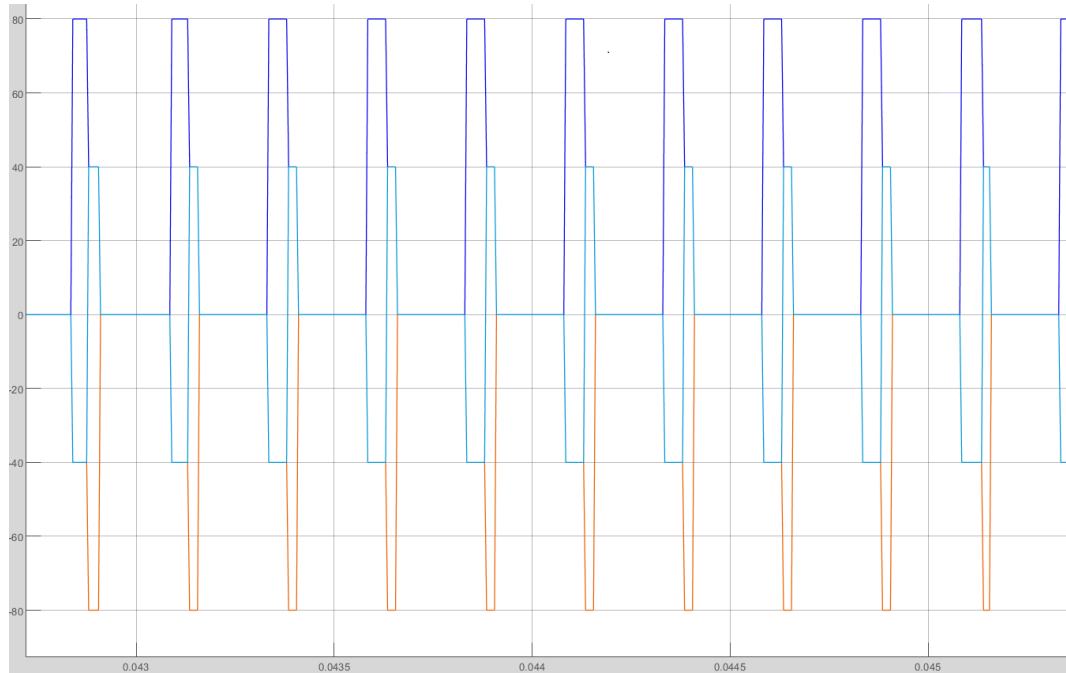
Figure 30 Output voltages from Three Phase Voltage Inverter

➢ Voltages Vd and Vq after parks transformation.
➢ X-axis represents time (µs) and Y-axis represents voltage (V).
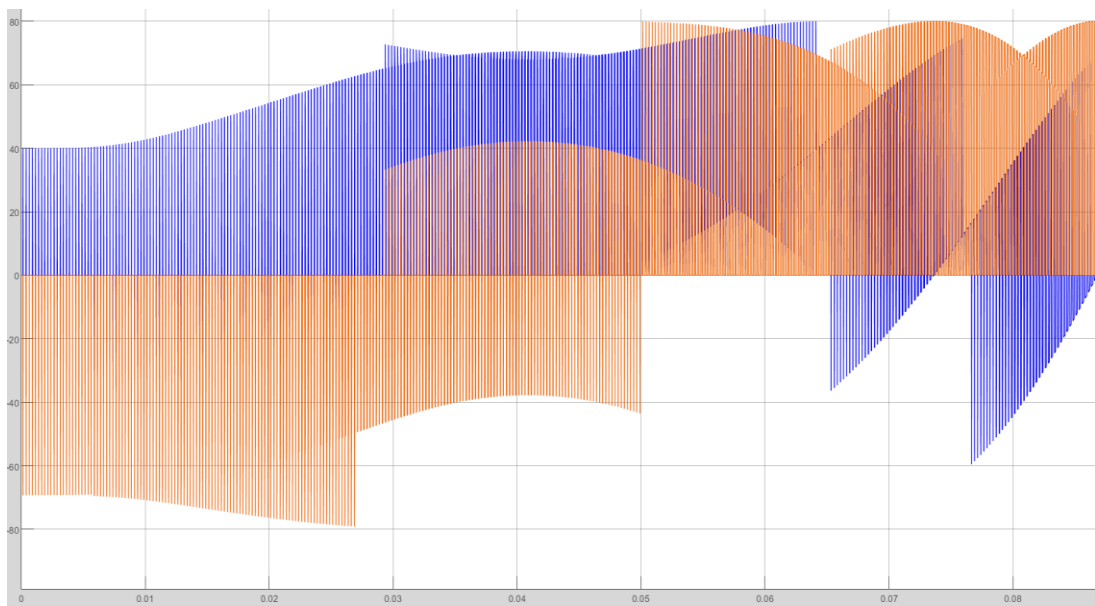
Figure 31 Voltages V_d and V_q after Parks Transformation

- Electromagnetic torque.
- X-axis represents time (µs) and Y-axis represents Torque (Nm).
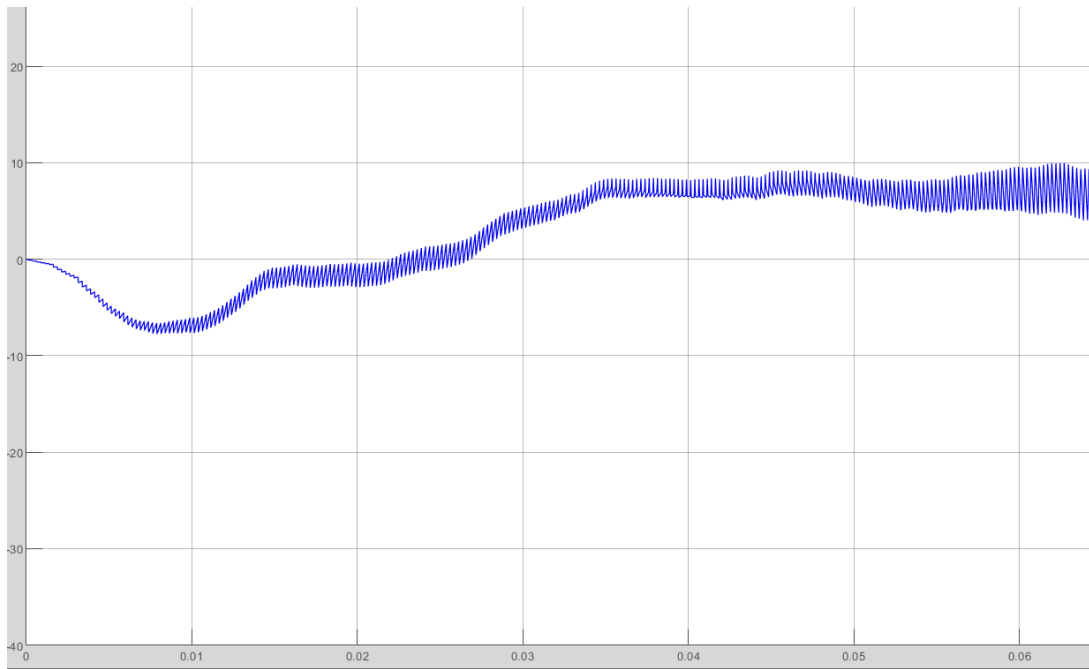
Figure 32 Electro-magnetic Torque – T$_e$

- Electrical speed.
- X-axis represents time (µs) and Y-axis represents speed (rpm).
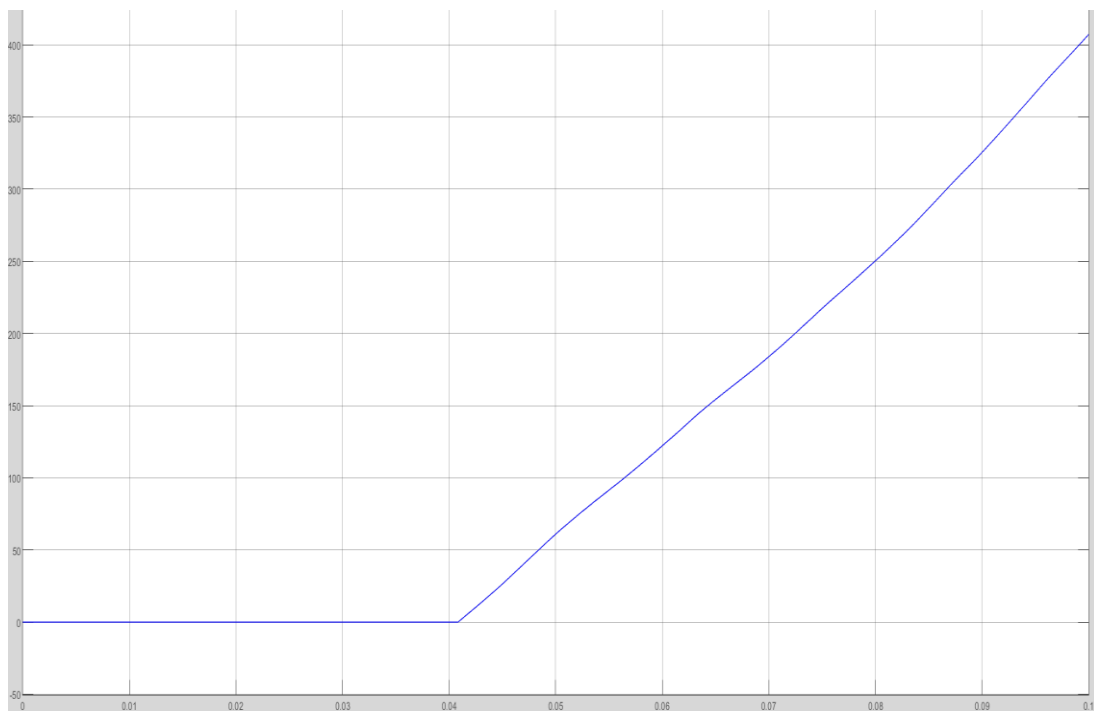
Figure 33 Electrical Speed – W$_e$

5. Real-Time Simulation of PMSM on FPGA for HIL Testing

Due to unusual circumstances of COVID-19, practical implications were not done for this testing.

A real-time simulator of a PMSM drive implemented on an FPGA card. Real-time simulation of PMSM drives enable thorough testing of control strategies and rapid deployment of vehicular or industrial applications. The PMSM model is predicated on Park transform with a coordinate system on the rotor and assumes sinusoidal flux induction.

Nowadays, before employing a motor controller with a true motor drive, it is a common industrial engineering practice to test a controller against a simulated motor model running in real-time. This has several advantages. for instance, the simulated motor drive are often tested with borderline conditions that might damage a true motor, often a costly prototype. The motor itself may be under development in parallel to the controller and therefore might not even be available. While testing, a controller is interfaced with the real-time simulated motor drive through a group of proper I/Os: this is called hardware-in-the-loop (HIL) simulation. Modern, fast digital motor drive controllers can have a really small sampling time below 10 microseconds and therefore requires that its real-time, simulated motor have a computational time much lower than this value. This requirement exists because the computational time for the model (including the I/O access times) adds a delay within the loop of the ultimate closed-loop response of the controlled motor. If this added delay is just too large (a real motor has no such latency), the HIL simulation may diverge from the response of the controller with a true motor. Additionally, in applications with pulse width modulation (PWM) frequencies greater than 10-20 kHz and with PWM-synchronized acquisition of the analog input signals by the controller, the simulator must have a sample rate sufficiently small for its analog outputs to generate the PWM waveform with enough resolution. For example, synchronous acquisition can be tricky if the simulator generates less then 10 analog output points (e.g., motor currents) per PWM period [17].

5.1. Field Programmable Gate array

The concept of Field Programmable Gate Array (FPGA) is an microcircuit technology during which users can reorganize the Logic Elements (LE) consists and reconfigure the interconnections of those units. during a FPGA chip, the logic functions are implemented by LEs which are placed as a two-dimensional array over the chip area then the intersections of those array units are connected by fuses technology to develop more complex functions. Addition, the sting sides of this two-dimensional array are utilized in order to achieve general and special purposes of input/output variables that are required by logic functions as parameters. FGPA technology makes it possible to develop the hardware designs of the processes which can't be wiped out real-time by software implementation. In run time, the developed hardware design doesn't need any software code so FPGA provides to accelerate and enhance the real-time processes in varied application areas like image processing, network interfaces, security algorithms, generating the very speed input/output variables in real-time models, the most boards of robots especially unmanned controlled types then on. Nowadays, the recognition of FPGA has been gained wide currency thanks to the reducing the prices of FPGA developing kits and accessories [18].

5.2. Hardware in the Loop Simulation

Hardware-in-the-loop (HIL) simulation may be a sort of real-time simulation. you employ HIL simulation to check your controller design. HIL simulation shows how your controller responds, in real time, to realistic virtual stimuli. We will also use HIL to work out if your physical system (plant) model is valid.

In HIL simulation, you employ a true -time computer as a virtual representation of your plant model and a real version of your controller. The figure shows a typical HIL simulation setup. The personal computer (development hardware) contains the real-time capable model of the controller and plant. the event hardware also contains an interface with which to regulate the virtual input to the plant. The controller hardware contains the controller software that's generated from the controller model. The real-time processor (target hardware) contains code for the physical system that's generated from the plant model [19].
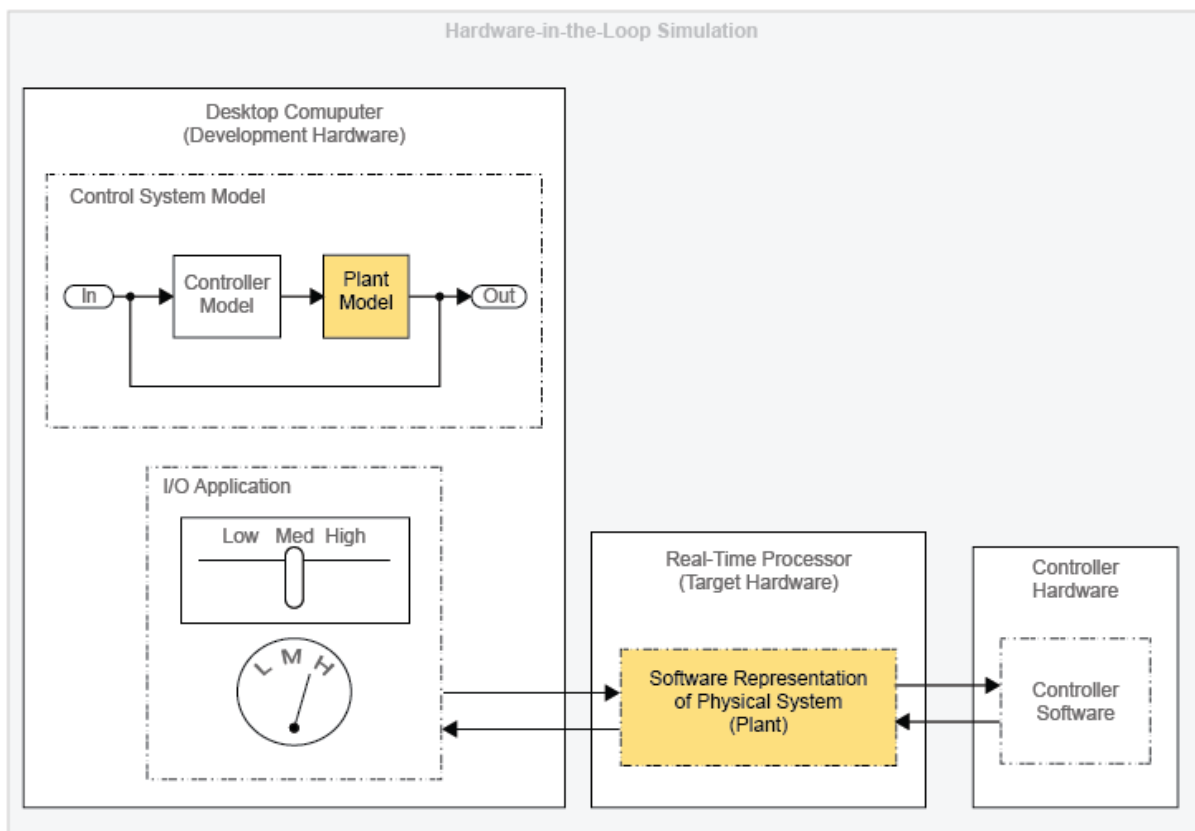
Figure 34 Hardware in the Loop Simulation [18]

Use HIL simulation to check the planning of your controller once you are performing Model-Based Design (MBD). The figure shows where HIL simulation fits into the MBD design-to-realization workflow.

Validation involves using actual plant hardware to check your controller in real-life situations or in environmental proxies (for example, a pressure chamber). In HIL simulation, you are doing not need to use real hardware for your physical system (plant). you furthermore may don't need to believe a naturalistic or environmental test setup. By allowing you to use your model to represent the plant, HIL simulation offers benefits in cost and practicality.

There are several areas during which HIL simulation offers cost savings over validation testing. HIL simulation tends to be less costly for design changes. you'll perform HIL simulation before validation within the MBD workflow, so you'll identify and redesign for problems relatively early the project. Finding problems early includes these benefits:

➢ Your team is more likely to approve changes.

➢ Design changes are less expensive to implement.

In terms of scheduling, HIL simulation is a smaller amount expensive and more practical than validation because you'll set it up to run on its own. HIL simulation is more practical than validation for testing your controller's response to unusual events. for instance, you'll model extreme weather like earthquakes or blizzards. you'll also test how your controller responds to stimuli that occur in inaccessible environments like deep sea or region.
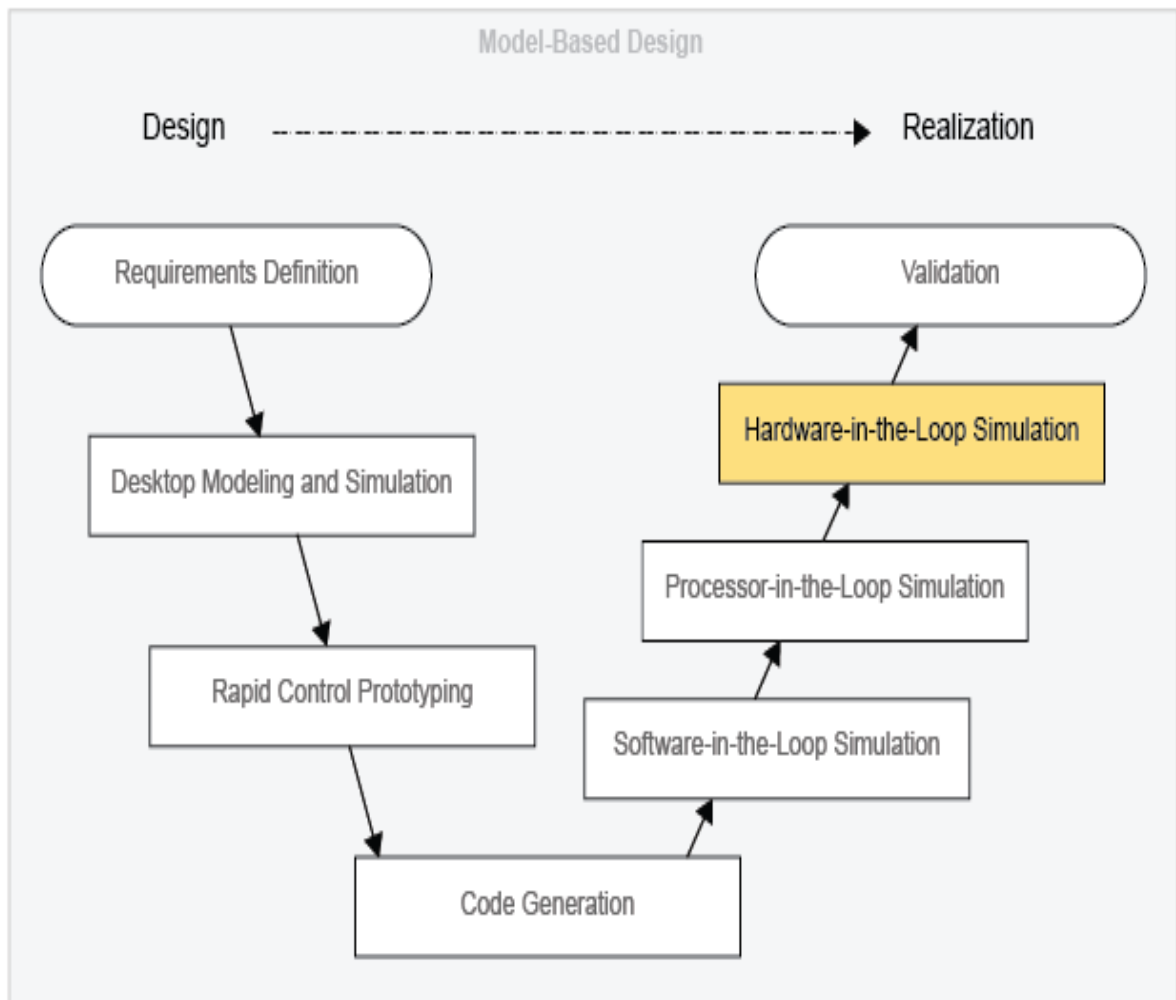

Figure 35 Model Based Design [19]

5.3.   Information about the FPGA applications and HIL testing

We have VTsytem from Vector Informatik for HIL testing, that's contains VT2516Acard with FPGA circuit.

TECHNICAL DATA				
Parameter	Min.	Type	Max.	Unit
FPGA series	Altera® Cyclone IV E			
FPGA type	EP4CE75			
Usable clock frequencies (can be selected independent for every FPGA project with the VT System FPGA Manager)	10,40,80			MHz
FPGA Size (logic elements)	75000			LE

Table 2 Technical Data of Implemented FPGA

➢ Cyclone IV FPGA Features:
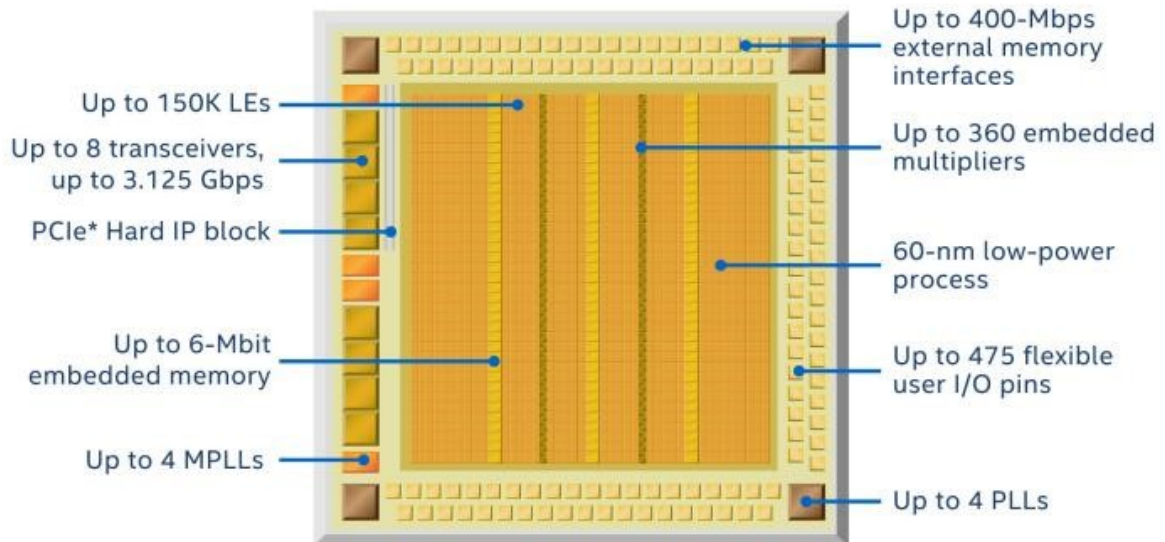
Figure 36 Features of Cyclone IV FPGA [19]

The key features are Power, Embedded multipliers, Memory blocks, Clock networks & PLLs, Configuration & remote system upgrades and SEU mitigation. The types of connectivity that are available are Transceivers, External memory interfaces, I/O features [20].

5.4.   VT System – Modular Test Hardware

VT system is a scalable and modular systems for efficient HIL testing. To test ECUs thoroughly, it's not only necessary to attach the communication networks to the test system, it's also necessary to attach the I/O interfaces. This task is handled by the Vector VT System. It simplifies the setup of test benches and HIL test systems immensely, because it integrates all circuit components needed to attach an I/O channel in one module. Examples of I/O channels are an ECU's output for controlling a headlamp or input for connecting a brightness sensor [21].

When performing functional testing the ECU has got to be tested in an environment during which it can see no difference between the important vehicle environment and therefore the testing environment.

The I/O lines of the ECU are connected to the modular VT System and when necessary original sensors and actuators too. The PC with the CANoe is connected via a quick, Ethernet-based real-time network port. This makes it easy to create flexible test systems with little integration or wiring effort.

Some of the main advantages are, Minimal wiring effort for test setups, Voltage range adapted to automotive applications, Seamless integration into CANoe and All relevant test components are integrated into one device:

➢ Measurement hardware with signal conditioning.
➢ Relays e.g. for switching short-circuits.
➢ Electronic load for actuator simulation.
➢ Resistance decade for simulation of a sensor.

5.4.1. Application areas

With the VT system test systems for the function test of ECUs and vehicle networks are often assembled. CANoe is that the associated test automation software. The modular design of the VT System allows to create test solutions starting from simple test setups to complex test systems:

➢ Dedicated test systems for individual ECU.
➢ Universal function testers for ECUs and subsystems.
➢ Flexible test hardware for the developer's work station.

5.4.2. Digital module VT2516A

The VT2516A module is connected to up to 16 mainly digitally used I/Os of an european, i.e. for signals with 2 states. In real vehicles for instance, coding connectors, switches or signal lamps could also be connected to those pins. This module is additionally available as a variant (VT2516A FPGA) with user programmable FPGA [21]. Functions for each channel:

➢ Various signal paths to the first sensor or the first actuator are switched via relays and are connected to a bus bar. The relays could also be used, for instance, to disconnect the road (broken wire simulation).
➢ Relay for brief circuit between an input line and ground or battery voltage.
➢ Relay for a connected external load, pull-up or pull-down resistor.
➢ Sampling of a digital input value with configurable voltage threshold.
➢ Determination of PWM signal parameters (frequency and duty cycle).
➢ Voltage measurement with calculation of instantaneous and average values.
➢ Digital output with adjustable high and low levels.
➢ Autonomous output of a touch stream loaded into module.
➢ Generation of a PWM signal.

Technical Data	
VT2516A	
Input voltage	-40 V … +40 V
Input current (via relays)	Max. 800 mA
Threshold	0 … 25 V
PMW frequency (PWM measurement)	20 mHz … 200 kHz
Voltage measurement	
A/D converter (per channel, internal)	12 Bit / 1 kSamples/s
Output of digital signal	
High level, low level	0 … 25 V
Output current	Max. 30 mA
Frequency of generated PWM signal	20 mHz … 25 kHz
Basic Data	
Supply voltage (via backplane)	12 V ±10%
Power consumption (all relays off)	Typ. 8 W
Power consumption (32 relays active)	Typ. 13 W

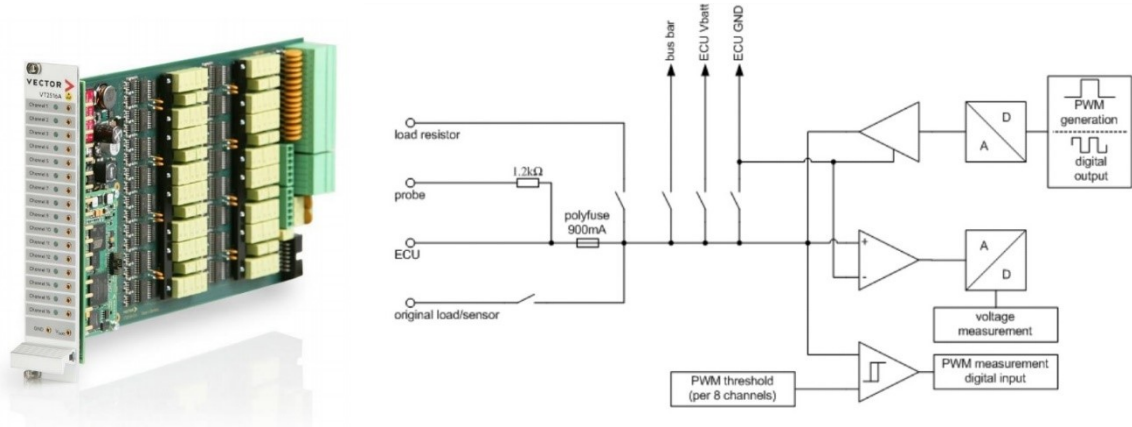*Table 3 Technical Data of VT2516A [20]*

Figure 37 Digital Module VT2516A & Schematic of one channel of the VT2516A [20]

Some VT System modules are available as FPGA variant with a processor board which incorporates a second, user programmable FPGA. This FPGA has access to the I/O hardware on the VT System modules and communicates with CANoe and thus allows the implementation of customer specific functionality. Some main features are:

➢ Measurement data conditioning or signal generation, which can't be covered with the quality VT System modules functionality.

➢ Time critical functions are often sourced bent the FPGA hardware rather than executing them software-based with CANoe.

➢ Description of FPGA functionality with VHDL or via graphical schematic entry with Simulink®.

➢ Easy development and management of FPGA projects by support of VT System FPGA Manager.

For detailed information for using the VT module's user programmable FPGA, follow this [22] reference. This article gives a step-by-step instruction the way to create a system variable that's then used for the communication between CANoe on one side and therefore the VT module, where it's been computed by the built-in FPGA, on the opposite side.

5.5. DSP Builder for FPGA

DSP Builder may be a high-level synthesis technology that optimizes the high-level, untimed netlist into low level, pipelined hardware for your target FPGA device and desired clock rate. DSP Builder for FPGAs consists of several Simulink* libraries that allow you to implement DSP designs quickly and simply. DSP Builder implements the hardware as VHDL or Verilog HDL with scripts that integrate with the software and therefore the simulator [23].

You can create designs without having detailed device knowledge and generate designs that run on a spread of FPGA families with different hardware architectures. DSP Builder allows you to manually describe algorithmic functions and apply rule-based methods to get hardware optimized code. The advanced blockset is especially fitted to streaming algorithms characterized by continuous data streams and occasional control. for instance, use DSP Builder to make RF card designs that comprise long filter chains.

After specifying the specified clock frequency, target device family, number of channels, and other top-level design constraints, DSP Builder pipelines the generated RTL to realize timing closure. By analysing the system-level constraints, DSP Builder can optimize folding to balance latency versus resources, with no need for manual RTL editing.DSP Builder advanced blockset includes its own timing-driven IP blocks which will generate high performance FIR, CIC, and NCO models.

5.5.1. Features of DSP Builder for Intel FPGAs

➢ Automatic pipelining to enable timing closure.
➢ Automatic folding.
➢ Easy to match and target different device families.
➢ High-performance floating-point designs.
➢ Wizard-based interface (system-in-the-loop) to configure, generate, and run hardware verification system.

5.5.2. Design Structure for Intel FPGAs Design Structure

Organize your DSP Builder designs into hierarchical Simulink subsystems. Every top-level design must contain an impact block; the synthesizable top-level design must contain a tool block.

Note: DSP Builder design can only have one synthesizable top-level design, which may contain many subsystems (primitive and IP blocks) to assist organize your design. Any primitive blocks must be within a primitive subsystem hierarchy and any IP blocks must be outside primitive subsystem hierarchies.

5.5.3. The Top – Level Design

A DSP Builder advanced blockset top-level design consists of, A Simulink testbench, which provides design inputs and allows you to research inputs and outputs, Top-level configuration blocks, Optional memory interface specification and stimulus blocks.

➢ *External Memory* block to configure an external memory interface.
➢ *BusStimulus* and *BusStimulusFileReader* blocks to stimulate Avalon-MM interfaces during simulation.

➢ *Edit Params* block as a shortcut to opening a script setup_<*model name*>.m for editing.

The top-level design must have an impact block to specify RTL output directory and top-level threshold parameters

Note: Every DSP Builder design must have Control block to permit you to simulate or compile your design. don't place the Device block within the top-level design. DSP Builder propagates data types from the testbench to the synthesizable top-level design.

5.5.4. The Synthesizable Top-Level Design

The synthesizable top-level design may be a Simulink subsystem that contains a tool block, which sets which family, part, and speed grade to focus on. The synthesizable top-level design is at the highest level of the generated hardware files. The synthesizable top-level design can contains further level of hierarchies that include primitive subsystems.

Note: Only use primitive blocks inside primitive subsystems. Optionally, you'll include more *LocalThreshold* blocks to override threshold settings defined above the hierarchy.

5.5.5. The Primitive Subsystem

Primitive subsystems are scheduled domains for *Primitive* and *IP* library blocks. A primitive subsystem must have, a *SynthesisInfo* block, with synthesis style set to *Scheduled*, in order that DSP Builder can pipeline and redistribute memories optimally to realize the specified clock frequency and Boundary blocks that delimit the primitive subsystem:

➢ *ChannelIn* (channelized input),
➢ *ChannelOut* (channelized output),
➢ *GPIn* (general purpose input)
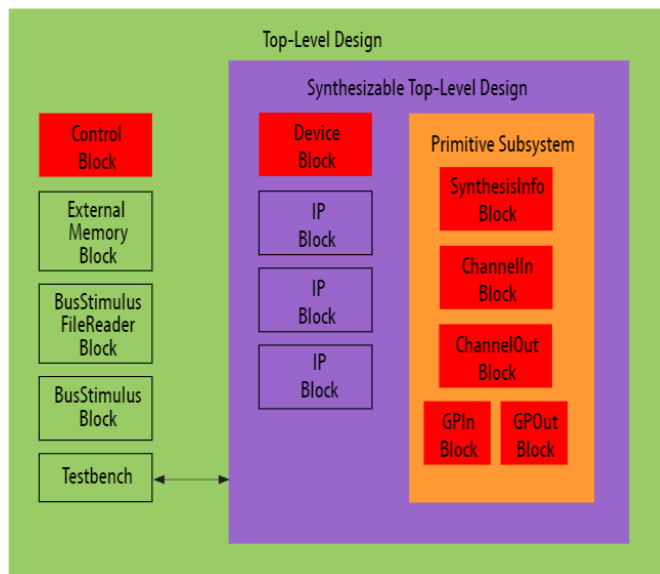➢ *GPOut* (general purpose output).

Figure 38 The Relationship of the synthesizable Top-level Design [23]

and a Primitive Subsystem. Mandatory blocks are in red.

DSP Builder synchronizes connections that undergo an equivalent boundary block.Use system interface blocks to delimit the boundaries of scheduled domains within a subsystem. Within these boundary blocks DSP Builder optimizes the implementation you specify by the schematic. DSP Builder inserts pipelining registers to realize the required system clock rate. When DSP Builder inserts pipelining registers, it adds equivalent latency to parallel signals that require to be kept synchronous in order that DSP Builder schedules them together. DSP Builder schedules signals that undergo an equivalent input boundary block (*ChannelIn* or *GPIn*) to start out at an equivalent point in time; signals that undergo an equivalent output boundary block (*ChannelOut* or *GPOut*) to end at an equivalent point in time. DSP Builder adds any pipelining latency that you simply increase achieve f_{MAX} in balanced cuts through the signals across the planning. DSP Builder applies the correction to the simulation at the boundary blocks to account for this latency in HDL generation. The primitive subsystem as an entire remains cycle accurate. you'll specify further levels of hierarchy within primitive subsystems containing primitive blocks, but no further primitive boundary blocks or IP blocks.

Use *SampleDelay* blocks only to specify relative sample offsets of data-streams; don't use for pipelining.

For detailed Information for advanced DSP blocks set for MATLAB/Simulink follow this [23] reference.

CONCLUSION

A detailed Simulink model for a PMSM drive system with field-oriented control has being developed and operation below and above rated speed has been studied Simulink has been chosen from several simulation tools because its flexibility in working with analog and digital devices. Mathematical models are often easily incorporated within the simulation and therefore the presence of various toolboxes and support guides simplifies the simulation of huge system compared to Spice. Simulink is capable of showing real time results with reduced simulation time and debugging. within the present simulation measurement of currents and voltages in each a part of the system is feasible, thus permitting the calculation of instantaneous or average losses, efficiency of the drive system and total harmonic distortion.

In Automotive industry, HIL simulation has been effectively developed and verified to be very efficient and effective in several autonomous driving circumstances in features, functions and algorithm development, testing and verification. This enables an modern and feasible to debug and validate system architecture and communication hardware and software for control processors, sensors and actuators. With virtual world sensors, the HIL simulation are often extended to simulating multiple vehicles networking with each other under traffic, and with surrounding environment. Under an equivalent architecture as implemented in prototype vehicle, the HIL simulation, with an equivalent processors, actuators, sensors and other hardware devices within the loop, has proved to be especially beneficial for developing, testing, debugging and verifying an outsized and sophisticated system under lab setup. Thus it'll shorten the control development time and reduce the value.

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