POLITECNICO DI TORINO

Master's Course Degree in Electrical Engineering

Master's Degree Thesis

Sensorless PM Motor Control for Washing Machines Applications

Supervisors:

Prof. Radu BOJOI

Dott. Sandro RUBINO

Internship Tutor:

Marco VALERIO

Candidate

Giulia SCAGLIONE

Academic Year 2020 - 2021

Abstract

The main focus of this master thesis is the implementation of Permanent Magnet motor control strategies for washing machine applications. In particular, the application is a belt-driven horizontal axis washing machines using an IPM motor. This work has been developed in collaboration with Haier Europe in order to develop an efficient motor control to exploit properly the motor selected for this application. What has been proposed is the Direct Flux Vector Control (DFVC) implemented with the integration of High Frequency Injection (HFI) method to detect initial rotor position and sensorless technique of active flux concept in Stator Flux Observer (SFO).

More particularly, this thesis explores all the aspects concerning the preliminary studies carried out on the electric motors used in this type of electric drive. Magnetic Model Identification (MMI) was analyzed and performed in order to obtain the perfect knowledge of motor behavior through electromagnetic and performance maps.

The proposed method has been validated through Simulink simulation and, experiments, in the POLITO laboratories, obtaining satisfactory results. The adopted solution is the best for this type of application in terms of torque capacity and high starting torque, Constant-Power Speed Ratio (CPSR) region, energy consumption, high dynamic response and performance in general respecting the specific requirements of a washing machine unit.

Index

List of Tables

List of Figures

Acronyms

MCU MicroController Unit

DD Direct Drive

BD Belt Drive

USA United States of America

UM Universal Motor

IM Induction Motor

PMSM Permanent Magnet Synchronous Motor

BPM Brushless Permanent Magnet

SMPM Surface Mounted Permanent Magnet

IPM Interior Permanent Magnet

PMASR Permanent Magnet Assisted Synchronous Reluctance

Syr-R Synchronous Reluctance

AC Alternate Current

DC Direct Current

TRIAC Triode Alternating Current

DSP Digital Signal Processor

FOC Field Oriented Control

I-FOC Indirect - Field Oriented Control

D-FOC Direct - Field Oriented Control

P Proportional

PI Proportional Integral regulator

BLDC Brushless DC

EMF Electro-motive force

VFD Variable-Frequency Drive

PWM Pulse-Width modulation

PM Permanent Magnet

MUT Motor Under Test

MTPA Maximum Torque Per Ampère

MTPV Maximum Torque Per Ampère

CPSR Constant-Power Speed Ratio

MMI Magnetic Model Identification

UCG Uncontrolled Generator

LUT Look-Up Table

DFVC Direct Flux Vector Control

HFI High Frequency Injection

SFO Stator Flux Observer

CVC Current Vector Control

DTC Direct Torque Control

MPC Model-based Predictive Control

DB DeadBeat

MRAS Model Reference Adaptive System

PLL Phase-Locked Loop

MAF Moving Average Filter

LPF Low Pass Filter

VSI Voltage Source Inverter

Introduction

New technologies and new inventions of all kinds have entered in our lives since the last century. Some revolution seems to take place inside our homes to improve the life quality. Washing machines are improving year after year in terms of energy consumption reduction and new washing features.
The market and the field of research are moving to use more efficient motors without using advanced motor control using position sensors. This is the case with Permanent Magnet Synchronous Motor (PMSM) which are slowly replacing all Induction Motor (IM). Synchronous motors work differently from asynchronous ones and can certainly work better if used and exploited properly.
The main purpose of this master's thesis is to propose a new sensorless motor control for horizontal axis washing machines.
The best strategies and techniques for using an IPM motor in home appliances and how to identify its main characteristics will be reported here.

The thesis work is organized as follows:

- 1^{st} Chapter: "**Washing Machines Features**".
  This chapter provides a small glimpse of the history of the invention of washing machines from when they were born until today, how they differ from each other and what are their main characteristics.

- 2^{nd} Chapter: "**Motor Control Strategies for Washing Machines**".

This chaptes focuses on electrical motor along their magnetic models. In addition this chapter emphasizes the importance of magnetic model on the motor control; In addition, all types of motor control strategies and sensorless methods are also presented;

- 3^{rd} Chapter: "**Proposed Sensorless Motor Control Strategy**".
  This chapter describes the proposed sensorless Direct Flux Vector Control (DFVC) scheme;

- 4^{th} Chapter: "**Simulation Results**".
  The results of the simulations obtained are shown here, giving a preliminary view of the advantages and disadvantages of the new strategy used before testing in the POLITO laboratory;

- 5^{th} Chapter: "**Experimental Results**".
  Experimental results obtained in the POLITO laboratory using a belt-driven washing machine;

Chapter 1

Washing Machines Features

1.1 Background of washing machines

From the end of the 18th century the first washing machines were invented and introduced for the use we know today: washing and cleaning clothes. At that time, washing machines were hand-powered. These used a system composed of some wooden parts, cylinders operated by a part of the handle where the clothes passed to be rubbed so that this could reproduce the movement of the hand made to clean the clothes through the water.

Figure 1.1: Early washing machines[**2**].

Washing machines were not yet used for commercial purposes until 1850, when steam washing machines were introduced. They still remained manually operated, and it wasn't until the early 1900s that electric washing machines became popular.

It was in the first decades of the 1900s that various companies began to manufacture electric and then fully automatic washing machines; in the end, centrifuging machines have surpassed and also established the types of wringers used to wring wet clothes.

Figure 1.2: Modern Haier and Candy washing machines. (left)[**14**],(right)[**15**]

Nowadays, washing machines are fully electric and automatic. The only thing that changes for each washing machine of the different companies on the market is the control used for the entire operation. In fact, this will be the main aspect to focus on and a new one will be proposed to be used for Haier Group Candy washing machines.

1.2 Washing machines and their features

1.2.1 The operation

The washing machines work thanks to the use of electric motors that are automatically controlled through their connection with a MicroController Unit (MCU). The whole operation of a washing machine can be divided into 2 main categories: washing operation (wash) and spinning operation (spin). Between the two operating conditions there is a pump that removes excess water and continues to operate even during the spin phase where the excess water comes from the centrifugal force of the cloths moving in the direction of the spin.[**1**]

1.2.2 Constructive aspects

Typically washing machines are made of sheet steel and zinc coated to prevent rust. Depending on the company, the spin tub can be made of stainless steel or enameled iron, while for the washing tank, which is usually seen only when the washing machine box is open, enameled iron or plastic is used. Many parts of the product are made of plastic such as the pump, tank guards and agitator. The transmission part is made of cast aluminum. While hoses, MCUs, inverters and motors are bought by companies that build and sell them. [**1**]

1.3 Categories of washers

As mentioned before, the washing machine can be divided into a few main categories. The main characteristics of the washers are shown below.

1.3.1 Washing Machines Capacity

A main aspect of washing machines is the capacity they have. The capacity of a washing machine indicates how many clothes in kg can be washed with one load. For this reason, washing machines can be divided into:

- **5 kg washer**: actually for $5 - 6$kg of dry laundry;
- **7 kg washer**: for $7 - 8$kg of dry laundry;
- **9 kg washer**: for $9 - 10$kg of dry laundry;
- **10+kg washer**: for more than 10kg of dry laundry.

The capacity of washing machines always refers to dry clothes instead of drying machines which have capacity which refers to wet clothes.[**20**] Of course, every washing machine has its own laundry programs and not all of them include the full load. If the maximum load of laundry is respected then the washing efficiency of the washing machine is better because it does not require excess energy and water.[**21**]

1.3.2 Front Load and Top Load washers

- **Front Load Washers/Horizontal axis**: thanks to the horizontal axis the garments can be washed by rubbing one garment against the other. They have lifters or paddles that are arranged in the direction of the rotation axis in the drum and are essential because they divide the clothes during the wash cycle and help direct the flow of water. They can be easily replaced if broken. They consume less water and energy, their washing cycles are more silent and delicate for the garments and finally it is easy to introduce bulky garments inside them.

The disadvantages are that due to the scarce use of water, they find it difficult to wash and there is the risk of keeping dirty clothes and bad smells. The washing cycles are at least twice as long as the second ones.[**6**]
The electric motors used for horizontal belt washing machines are typically Universal Motor (UM), three-phase AC Induction Motor (IM) and three-phase AC Permanent Magnet Synchronous Motor (PMSM). [**42**]

Figure 1.3: Front Load washers [**16**].

- **Top Load Washers/Vertical axis**:they are very cheap and are the least expensive in the sales market. Their performance is good and the cycles are not too long. The downside is that they waste too much water and energy. If they have the agitator in the wash tub, this is very aggressive for fabric clothes and it is difficult to put large quilts and blankets. If they have the impeller in the washing tank, this allows you to wash dirty clothes better and can use more or less water depending on the efficiency of the chosen washing cycle. Their price is good but not as cheap as the other type of top loaders. But one of the main things is that they are very noisy and for appliances this can be very serious to think about before buying.[**6**] The electric motors used for top loading washing machines are typically Universal Motor (UM), Brushless DC (BLDC) motors Induction Motor (IM), Permanent Magnet Synchronous Motor (PMSM).

Figure 1.4: Top Load washers [**17**].

Top loading washing machines are also divided into two other categories depending on the internal use of the washing tank:

- Top Load **agitator** washer: they have the agitator in the center of the spin tub in the direction of the vertical rotation axis and allows you to better scrub and wash the clothes thanks to a back and forth movement.

Figure 1.5: Top Load Agitator washers. (left)[**12**],(right)[**13**]

- Top Load **impeller** washer:they have the impeller which is a disk based on the bottom of the basket that rotates trying to reproduce the movement of the front load washer and therefore to make the clothes rub together.

Figure 1.6: Top Load Impeller washers, (left)[**12**],(right)[**7**]

1.3.3 Belt Drive and Direct Drive washers

- **Belt Drive (BD)**: it means that the washing machine works thanks to the belt transmission between the drum and the electric motor.

- **Direct Drive (DD)**: this means there is no belt and no belt drive. The electric motor is the one directly connected to the drum so that they rotate together.

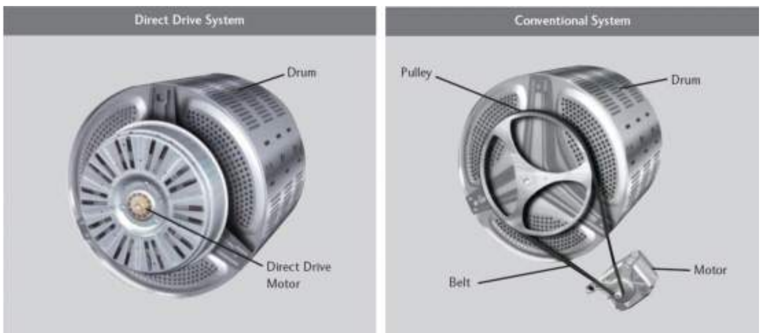


Figure 1.7: (left)Direct Drive washer; (right)Belt Drive washer. [**11**]

Belt Drive washers: they are shown in 1.6 and the figure shows the use of small electric motors. In fact, their speed is very high because they convey it to the drum. The speed reduction is given by the transmission ratio. Electric motors used for this application tend to be small, with stator packs ranging from 30mm to 55mm. The pole pairs are very low in number as they have to rotate at high speed. The transmission speed also affects the mechanical torque required to drive the drum. In fact, the electromagnetic torque is very low as the number of pole pairs is rather low but this torque, net of all torque losses, must be multiplied by the transmission ratio.

The transmission Ratio is defined as:

$$r = \frac{\omega_m}{\omega_d} \text{ and } r = \frac{T_d}{T_m}$$

Where:

- T_m and ω_m are the mechanical torque and mechanical speed of the electric motor;
- T_d and ω_d are the mechanical torque and mechanical speed of the drum.

Figure 1.8: Belt drive of a washing machine. [**18**]

The electric motor, as shown 1.7, is small and is placed at the bottom of the washing machine box, under the drum. The motor may usually be positioned without eccentricity with respect to the axis of rotation as it appears in that figure, or it can be placed with some eccentricity.

Direct Drive (DD) washers: they have no belt and belt drive so there is no transmission ratio to increase the electromagnetic torque. In fact, the electric motor used has a large number of poles so as to obtain a high nominal torque at the output, at low operating speed values, which is substantially equal, considering all the torque losses, to the mechanical torque required by the drum to be driven. Constructively a DD washer requires this type of motor having a large diameter and a rotor with a high number of magnets. This solution offers high reliability because the system has greater stability, reduced noise and consumption and its life is much longer than other types of drives.[**11**]

Figure 1.9: Direct Drive of a washing machine. [**19**]

Thanks to this particular drive, the belt slipping is also avoided as this can appear when starting a washing machine and does not allow starting. The benefits of using this type of drive can be seen during startup and normal full load operation.[**38**] During start-up, the drum of washing machines begins to rotate 1 second earlier than a washing machine with belt drive. This happens due to the weight and design of the direct drive motor: the perfect design that fits into the drum allows you to avoid any shaking or noise during the normal operation of the washing machines, the greater weight favors the centrobaric stabilization of this type of washing machine. During normal operation (washing cycle), the drum passes from positive speed to negative speed and in this situation the change is very quick. The electric motors used for this type of application are the Universal Motor (UM), Brushless DC (BLDC) motors, Permanent Magnet Synchronous Motor (PMSM).

1.3.4 Washing machines in the worldwide market

Since the mid-1900s, washing machines have spread all over the world. Their use has become essential and more than 80% of households in North America and Europe own a washing machine.[**5**] Depending on the continent, the sales market for washing machines changes. Generally washing machines can be divided into different categories based on their mechanical transmission (Direct Drive, Belt Drive) and / or their rotation axis (Front Load / Axis H, Top Load / Vertical-Axis) and their capacity. Top loading washing machines are also divided into 2 types depending on the component used to scrub the cloths: agitator or impeller.
Returning to the distribution sales market, three main types of washing machines can be considered:

1. **Top Load Agitator** washing machines: they are the most widespread and have been on the market for about sixty years. Their price is very low and this is how they became and are still the best sellers on the American continent.

2. **Front Load** washing machines: they are more efficient than the first category. they consume less water and energy as said in 1.3.2. They are the most used in Europe.

3. **Top Load Impeller** washing machines: they wash heavily soiled clothes better and are more efficient in terms of the amount of water and energy used. Their price is good for their performance.[**6**] These are the ones to be found easily in Asian countries.

The best-selling washing machines in America are the front-loading agitator washing machines and this fact is due to the low price and ease of use. Almost 75% of United States of America (USA) population buys top-loading washing machines and if they have bought a front-loading washing machine, they return to

top-loading washing machines after a few years. [**8**]
While in Europe the best-selling washers are front-loading. The main factor is that they save space in one apartment unlike the others and waste less energy and water. Also, the front loading washer requires more maintenance while the top loaders are more reliable.

1.4 Electric motors and Electrical drives

The operation of washing machines is determined by the coordination of the various electrical and electronic components. One of them is the electric motor. Therefore, it is not difficult to imagine that, since electric washing machines came on the market, different types of electric motors have been used and some of them have replaced others. In all these years, in fact, 3 different motors have been used:

- **AC single-phase Universal Motor (UM)**;
- **AC 3-phase Induction Motor (IM)** ;
- **AC/DC 3-phase Brushless Permanent Magnet - BPM**: or tipically defined as Brushless Permanent Magnet (BPM).

1.4.1 Universal Motor - UM

Universal motors have been the most employed one in modern washing machines. The universal motor is a switched series wound motor and can be used for Alternate Current (AC) and Direct Current (DC). Its construction has been modified to be able to run AC applications for household appliances such as washing machines. This motor has a single phase which is wired around the stator and rotor (or armature). The stator creates a magnetic field; the conductors are arranged in coils in the stator and are connected to the rotor windings via commutator and brush commutation. It is a simple and compact structure, it has high speed capability but the speed/torque characteristic is governed by a quadratic relationship: the speed decreases in a quadratic manner as the motor load increases. The main disadvantages are due to the high switching losses of the brushes, the presence of harmonics, inrush current and loud noise.[**31**] In fact, its efficiency starts at 40% and decreases around 25% as the currents increase.[**31**] If the current is alternating it means that the resulting magnetic field alternates its polarity synchronously with the power supply. Eventually the mechanical force created by the interaction between the current in the coils and the resulting magnetic field is consistent with the direction of rotation.

This type of motor provides a high starting torque, possibility to rotate forwards and backwards simply by switching the windings with respect to the armature. They can run at high speed but their brushes are not as efficient and need frequent maintenance. Universal motors are light and compact, making them perfect for household appliances.[**25**], [**26**]

These electric motors are easy to control and Triode Alternating Current (TRIAC) switch is used for that. TRIAC is defined as a three terminal AC switch and the gate command is positive or negative, it will conduct either way so that current can flow in both directions.[**30**] Triac Control is a speed control that operates in closed loop. The speed of the drum and therefore the speed of the motor is the required value and the control provides two possibilities of speed ramp. The engine speed is detected and measured by a tachogenerator and then converted into analog voltage. The setpoint/speed reference is given as an external input and is given to a linear regulator. Obviously the programmed ramp must already be sent.[**29**] To increase or decrease the motor speed, the firing angle of a thyristor such as the TRIAC is activated early or late respectively. Depending on the firing angle of the thyristor, the AC voltage and waveforms of the currents applied to the motor are cut less or more. The entire TRIAC control depends on the gate commands which can be positive or negative triggers to apply positive or negative voltages to the anode. Therefore, to delay the gate command, it is necessary to change the settings of the potentiometer. The concept behind this control is that to change speed you have to change the frequency of the line voltage that the electric motor sees.[**30**]

Considering both the TRIAC and the thyristor, both can be used. But the former allows current to flow in both directions, so any kind of gate command will activate the TRIAC while the latter can only direct current in one direction and only activates with a positive gate command. Furthermore, the thyristor is more reliable than a TRIAC.[**30**]

It is typically used for front loading washing machines.

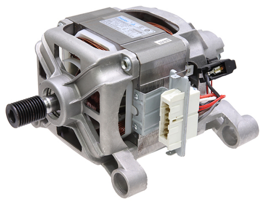


Figure 1.10: AC single-phase universal motor for washing machines. (left) [**37**], (right) [**32**].

1.4.2 Induction Motors - IM

The first three-phase motors that replaced the universal ones were the induction AC motors. These motors require a sophisticated motor control algorithm based on the microcontroller implementation or Digital Signal Processor (DSP) which processes the signal processing in real time. In addition, to the electronic component, the speed control algorithm requires a tachogenerator or an encoder for speed detection.

The great performance of using this control is due to the internal current control loop which uses the indirect vector control algorithm which is characterized by a high dynamic response to reach the required setpoints. [**27**]
The main difference between indirect and direct vector control is that the former uses an indirect method to estimate theta (electrical frequency of rotor quantities) instead of the latter which uses the rotor flux observer to obtain theta.

The Indirect - Field Oriented Control (I-FOC) is presented in the following diagram:

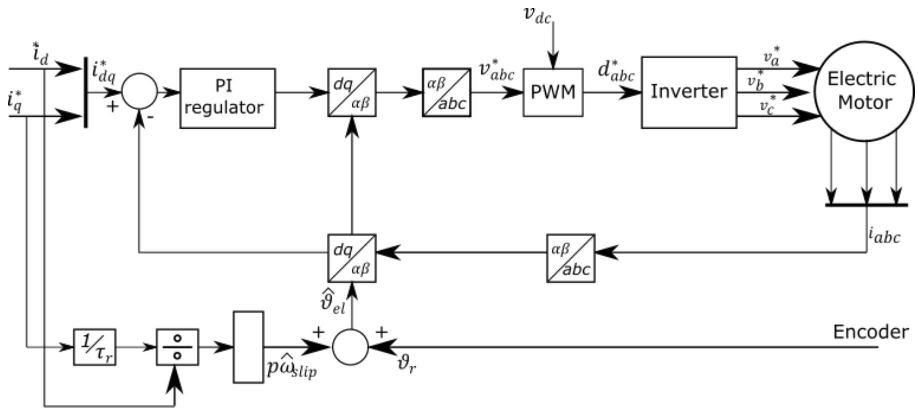


Figure 1.11: I-FOC for Induction Motors

Where τ_r is the electric rotor constant $\dfrac{L_r}{R_r}$.

The field-oriented control is implemented in a (d,q) reference rotating frame, where the d-axis is completely defines by the rotor flux vector. In this case, the electromagnetic torque equation is simplified and it is determined by the rotor flux λ_r and i_q stator current.

Furthermore the current loop in the figure 1.11, it has an outer speed loop. The output of the PI regulator of speed loop is generally the reference torque T^*. Scaling the reference torque with the proper factor $(\frac{2}{3} \cdot \frac{1}{pp \cdot k_r})$, I_q^* current is

obtained. $k_r = \dfrac{L_m}{L_r}$.
The I_d^* current is provided by a flux weakening block. Especially that is needed for motor operation above the base speed. The motor currents can be measured with one or three shunts mounted on to the inverter legs or simply to the DC bus. The choice depends on the economic aspect during the project period. This control is very sensitive to temperature variation since it takes into account the τ_r, rotor time constant that influences the slip estimate. Hence, its performance may have some limitations. This is why a D-FOC scheme is preferred for this motor and this type of appliance applications. The D-FOC methods use the sensorless method to obtain the electrical position of the rotor flux vector. For an induction motor, the rotor flux observer uses a reduced order closed loop estimator or, in some cases, an open loop estimator. The latter are not to be preferred because they cannot perform well at low speeds. Similar methods are used for PMSM.

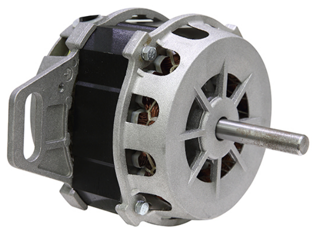


Figure 1.12: Induction Motor (IM) for washing machines.[**33**]

1.4.3 Brushless Permanent Magnet Motor - BPM

Permanent Magnet Brushless motors represents the entire category of synchronous motors that do not have brushes and commutators and have permanent magnets on the rotor. Indeed, in this main group are defined:

- **Brushless DC Motor - BLDC**: it is a synchronous motor without using a winding with brushes and a collector between the stator and rotor. The DC power supply is provided in the stator coils and thanks to a closed loop electronic controller that switches the DC currents a magnetic field is produced. This magnetic field rotates in space followed by the rotor due to the interaction between the stator field and rotor field produced by the magnets. Constructively it is very similar to PMSM but can also be a commutated reluctance motor and an induction asynchronous.[**36**]

Figure 1.13: Brushless DC (BLDC) motor for washing machines.[**37**]

- **Permanent Magnet Synchronous Motor (PMSM)**: is a large category of electric motors which includes all synchronous motors equipped with permanent magnets in the rotor part. They are typically supplied with AC currents. A general PMSM is showed in figure 1.12.

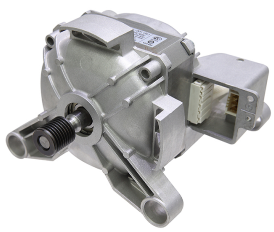


Figure 1.14: Permanent Magnet Synchronous Motor (PMSM) for washing machines.[**34**]

Permanent Magnet Synchronous Motor are generally classified into three categorie:

1. **Spoke type**: with vertical or v-shape magnets;
2. **Surface Mounted Permanent Magnet (SMPM)**;
3. **Interior Permanent Magnet (IPM)**.

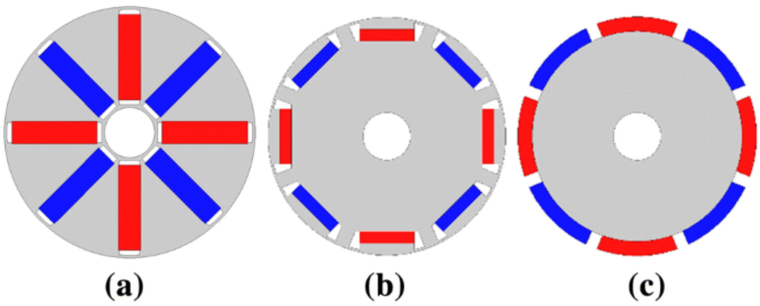


Figure 1.15: Focus on different type of rotor: (a) IPM motor with inserted rotor magnet spoke type v-shape, (b) IPM motor with embedded rotor magnets, (c) SMPM motor.[**44**]

Usually the stator windings can be distributed or concentrated with integer or fractional slots. During faults such as short circuits or overloads and during flux weakening operation, the main problem can be partial or total demagnetization of magnets. Furthermore, when operating in high-speed regions, the magnet-induced back-EMF can be so high that it exceeds the bus voltage and thus stresses the inverter structure.[**43**] Induction Motor (IM), Synchronous Reluctance (Syr-R), Permanent Magnet Synchronous Motor (PMSM) are similar to the BLDC motors category but those mentioned above are the main ones used for washing machine applications

The BLDC motors are typically preferred over Universal Motor due to the absence of brushes, their high power density, high efficiency and high dynamic range and low maintenance.

Permanent Magnet Synchronous Motor are slowly replacing Induction Motor due to their higher power density and higher efficiency and, moreover, they have no slip, so the speed of electrical quantities can be easily estimated or observed. The former have a higher initial cost than the latter but the first category has smaller and more compact motors than the others. Obviously Permanent Magnet Synchronous Motor are unable to start without a variable frequency drive but their performance surpasses this main aspect.

Control strategies and sensorless methods for PMSM will be discussed in the next chapters 2 and 3. Furthermore, the main focus of this thesis is to propose an alternative sensorless control strategy of an Interior Permanent Magnet (IPM) that is included in the PMSM category.

1.4.4 Electrical motors for specific uses

Over the years and various studies, particular motors have been developed since new drives and applications entered the industrial market. In the late 1990s, direct drive washing machines entered the retail market with the use of the BLDC motor connected to the drum of the washing machines.

- **Umbrella Motor**:
  According to the 2001 article [**38**], umbrella motors had begun to be used for direct drive applications for washing machines. Also included is the retarder which is located between the drum and the electric motor. It is heavier because it is larger, for example, than the induction motor, but it is used by connecting it to the thinnest shaft directly to the washing basket and in this way decreases the moment of inertia. In this way, during the washing cycle, it is easier and faster to change the positive and negative.[**38**] The noise and shaking are quite reduced due to the design and weight of the umbrella motor and also due to the use of rubber seals between the retarder and the motor

instead of having metallic friction noise.

Figure 1.16: Umbrella motor for DD applications.[**41**]

- **Pancake Motor**:

  The electric motor used for direct drive application in washing machines is the Pancake motor. Pancake motor is supplied by AC current; constructively, it has an internal stator made of laminations of ferromagnetic material that has windings in the stator teeth. Stator windings are usually concentrated because this can actually improve the performance since leakage inductance gets bigger. The outer rotor ring has a large amount of thin permanent magnets to also have a large amount of pole pairs and it contains the stator. The whole construction is, in fact, flat and rotates with the drum tub.
  Other generic characteristics are:

  - 1) range of continuous torque of $4 \div 800$ Nm;
  - 2) range of torque production of $14 \div 1450$ Nm;
  - 3) it can be supplied by DC bus voltage up to 600 V;
  - 4) low cogging torque (low torque ripple);
  - 5) high leakage inductance;
  - 6) tange of outer diameters of $110 \div 485$ mm.

  Information provided by [**49**].

  It goes in flux weakening region when it reaches $120 \div 150$ rpm speed. The motor results to have high torque density, high lifetime, high efficiency and this is because of the quiet operation and compact design. They can be called frameless too because they can interface directly to the system without frame, housing, bearing and this reduces costs [**49**].

The example is shown in figure 1.17.

Figure 1.17: Pancake motor. (left) [**39**], (right) [**19**].

- **IPM or PMASR motor**:
  In the last years IPM motor became the most common in home appliances. They, indeed, can offer a major production of electromagnetic torque than the SMPM motors due to the rotor anisotropy that allows two torque contributions (magnet torque and reluctance torque). Interior Permanent Magnet (IPM) motors are the most widely used and feature a permanent magnet inside the rotor as a spoked type. The IPM motor will be analyzed in detail in the next chapters.

Chapter 2

Motor Control Strategies for Washing Machines

In order for a washing machine to work properly and function well, some aspects can be considered, and some of them may take precedence over others.
First of all it should be analyzed how a washing machine works along its main characteristics. Secondly, considering that the electric motor and the electric drive are the ones that drive of the tub/basket in its main operation, the electric motor must be known in all its aspects and properties since the motor control strategies derive from a thorough study of it.

The aspects and characteristics of motor control and washing machine operation may depend on the priorities of the company and these may depend on the type of washing machine to be launched in the sales market.
These aspects to focus on include: the type of drum axis (horizontal or vertical axis), the type of drive (belt or direct), the type of used motor, the type of economic budget to be spent, the sensored strategy o sensorless for speed control and, last but not least, the type of motor control strategy used.

2.1 Washing machine operation

The operation of a washing machine can be resumed in 4 phases:

1. Pre-wash;
2. Tumbling/Washing;
3. Rinse;
4. Spinning.

- The **prewash** phase anticipates the washing cycle. During the pre-wash period, the tank is filled with water up to a certain level and then the cloths are soaked in water and then mixed with powder detergent. The system then drains the water from the tank. The reason why prewash is used is to remove stubborn dirt from clothes before the classic wash cycle. The pre-wash is not mandatory like the other 3 phases of the washing cycle.

- During the **washing** cycle, typically (below 50 rpm) **tumbling**, the tub is periodically moved back and forth at a low speed. After the rotational movements in both directions, the drum stops for a few seconds to resume the same cycle as before.

- **Rinse** means that a stream of cold water is inserted to rinse and then remove all the remaining detergent. Subsequently, the soapy water is removed from the washing machine. Eventually, it is common to have another rinse cycle where stirring with clean water is the final step.

- The **spinning** cycle aims to dry clothes by rotating the drum at high speed. Washing machines can have different spin speeds and this depends on each type of washing machine and program it presents.

In other terms and in a more practical way, these phases of an entire wash cycle can be divided into 2 main groups, based on the speed that the drum reaches during its operation.
The drum works at:

- about $30 \div 50$ rpm: speed for washing and rinsing;
- about $800 \div 1600$ rpm: as said before, it depends on the chosen program.

Depending on the low speed region ($400 \div 600$ rpm for motors) or high speed region ($8000 \div 18000$ rpm for motors), the electric motor behaves in different ways. It will be analyzed the behaviour of Permanent Magnet Synchronous Motor (PMSM), especially an Interior Permanent Magnet, motor and their control strategies. To understand the performance of a Interior Permanent Magnet motor in these 2-speed regions for a washing machine, the best is to perform the motor characterization.

2.2 IPM motor model

First of all, it should be borne in mind that all synchronous motors have serious difficulties at starting and at low speeds.
They are unable to self-starting due to the large inertia of the rotor plus the load, the rotor cannot follow the speed of the magnetic field which rotates at high speed values. The aim is to link the rotor speed to the electric field of the magnetic field thanks to a Variable-Frequency Drive (VFD). The process of changing the frequency of voltages and currents to power a AC motor is to straighten a AC current into a DC one and from there use a Pulse-Width modulation (PWM) voltage to recreate

the sine waveforms through the data gate commands to an inverter.
In addition, at high speeds, all synchronous motors that have a permanent magnet in their rotors must be careful of the demagnetization of their magnets as flux weakening occurs and therefore it would be perfect to know these types of limits as well.

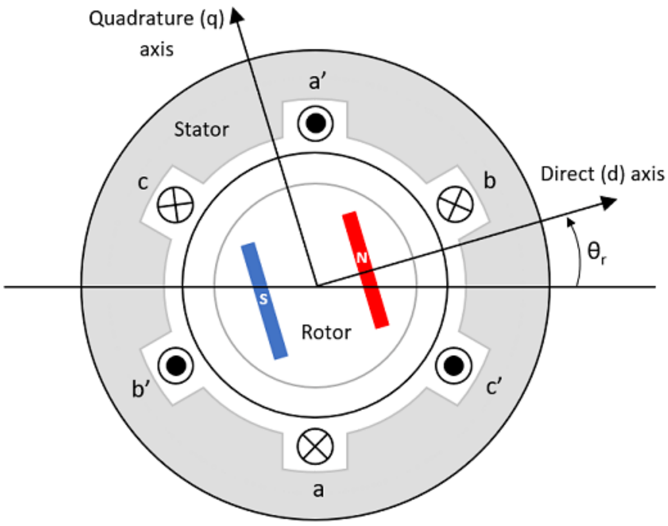


Figure 2.1: Interior Permanent Magnet (IPM) motor.[**45**]

In figure 2.1, a three-phase AC IPM motor with 1 pair of poles is shown for a simple case. When studying and analyzing an electric motor it is common to transform all the electrical variables in the frame d-q which rotates in the same way and the electrical speed of the rotor and the magnetic field of the stator. In general, the d axis coincides with the polar axis of the permanent magnets while the q axis is in quadrature with the d axis. But, depending on the type of motor control, the d-q axis can be referred to other electrical values.

$$\omega_{el} = pp * \omega_{mech}$$

The electrical speed ω_{el} or ω_e depends on the number of pair poles and on the mechanical speed required for that application. pp is the number of pole pairs and

it is always an even number, of course.
The ω_{mech} or ω_m depends on the working area of the washing machines and it generally varies between $0 \div 1600$ rpm referred to the drum movement. But considering that in a belt-driven washing machine there is the transmission ratio that goes from 10 up to 13 so the speeds reached by the motor are included in the range approximately of $0 \div 20000$.
In particular, for the sizes of electric motors used for washing machines maximum motor speed may reach, in general, about 18000 rpm motor.

The electromagnetic equations describing the motor in d-q frame are:

$$\begin{cases} \bar{v}_{dq} = R_s \bar{i}_{dq} + \dfrac{d\bar{\lambda}_{dq}}{dt} + j\omega_e \bar{\lambda}_{dq} \end{cases} \tag{2.1}$$

And the d-q components are:

$$\begin{cases} v_d = R_s i_d + \dfrac{d\lambda_d}{dt} - \omega_e \lambda_q \\ v_q = R_s i_q + \dfrac{d\lambda_q}{dt} + \omega_e \lambda_d \end{cases} \tag{2.2}$$

Where R_s is stator resistance, ω_e is the electric speed of electric quantities and v, i, λ are respectively voltage, current and flux quantities in d-axis and q-axis.

In particular, the two flux components are expressed as:

$$\begin{cases} \lambda_d = L_d i_d + \Lambda_{PM} \\ \lambda_q = L_q i_q \end{cases} \tag{2.3}$$

L_d, L_q are the autoinductance in the d-axis and q-axis and Λ_{PM} is the permanent magnets flux. These equation show the linear relationship between the dq currents i_{dq} with the dq stator flux λ_{dq}. In real situations these two expressions may not be true. The linearity between the two quantities may be respected when saturation of the ferromagnetic materials has not been reached yet.

The stator and the rotor tipically made with FeSi (Iron Silicon) laminations allow the maximum distribution of the magnetic flux field but the IPM motor, in particular, has anisotropy and also the air gap and iron lengths are very shorts. This means that the reluctance is very low and the inductances are greater than the ones of a SMPM motor. The short internal iron lengths of the machine are easy to saturate and even more so at the beginning for starting the washing machine because at the start-up the electric motor tries to give its maximum torque for that particular inertia with high currents. After saturation of the material, linearity no longer exists and inductances do not grow as the current gets higher and higher. This ferromagnetic behavior manifests itself in the magnetization characteristic of the material. Indeed, it is mandatory to find the magnetization aspects and the behavior of each electric motor used with the motor characterization procedure.

Beyond the limit of the linearity relationship, when the motor operated at high speed (flux weakening) it is necessary to find and use another relationship between the stator current and the flux solve the simulation and also to solve the problems motor control that a sensorless control strategy can show. As for the inductances and flux only, it is important to say that cross saturation occurs during motor operation because there is a close correlation between currents and fluxes. This means that i_d can affect λ_q and i_q can affect λ_d and these cross-coupling terms appear from equation 2.2:

$$\begin{cases} v_d = R_s i_d + \dfrac{d\lambda_d}{dt} - \omega_e L_q i_q \\ v_q = R_s i_q + \dfrac{d\lambda_q}{dt} + \omega_e \Lambda_{PM} + \omega_e L_d i_d \end{cases} \tag{2.4}$$

A better form to express this behavior of the magnetic flux is:

$$\begin{cases} \lambda_d = \lambda_d(i_d, i_q) \\ \lambda_q = \lambda_q(i_d, i_q) \end{cases} \tag{2.5}$$

Eventually, dq stator flux can be expressed in their component in a matricial way:

$$\bar{\lambda}_{dq} = \begin{bmatrix} L_{dd} & L_{dq} \\ L_{qd} & L_{qq} \end{bmatrix} \bar{i}_{dq} + \begin{bmatrix} \Lambda_{PM}(\theta_{temp}) \\ 0 \end{bmatrix} \tag{2.6}$$

L_{dd} and L_{qq} can be defined as L_d and L_q in order to maintain easy the writing and lecture too. L_{dq} and L_{qd} are generally assumed as equals between them and they can be neglected at high speed motor. θ_{temp} is the temperature of the magnets.

Indeed, as mentioned before, the d-axis is aligned with the PM flux.

According to this reference system the electromagnetic torque is expressed as:

$$T_{em} = \frac{3}{2} pp(\bar{\lambda}_{dq} \wedge \bar{i}_{dq}) \tag{2.7}$$

$$T_{em} = \frac{3}{2} pp\Big((L_d - L_q)i_d i_q + \Lambda_{PM} i_q\Big) \tag{2.8}$$

The two torque components are evident: one due to the reluctance of the machine, the other due to the permanent magnet flux. It all depends on the construction of the motor but in general PMASR motors have a high anisotropy and a good torque component produced by the permanent magnet inserted.
Permanent Magnet Assisted Synchronous Reluctance (PMASR) motor is different from IPM motor since the first has the rotor made up of laminations with a proper design of flux barriers in order to maximize the rotor anisotropy. Inside the flux barriers are inserted the magnets (but they don't fill totally the barrier). On the contrary of an IPM motor, the relevant component of torque is the one caused by anisotropy. They have the highest torque per volume at startup among all synchronous motors and also have the largest area of constant torque per speed.
While, the IPM motors have less anisotropy than those mentioned above because they don't present the flux barriers but only magnet in some specific shapes and disposition. But they perform well enough for the required application. It will all

be deepened more in this section soon.

Considering the mechanical aspect, the relation that must be satisfied is:

$$T_{em} = T_j + T_f + T_d \tag{2.9}$$

Where:

- T_{em} is the electromagnetic torque:

$$T_{em} = \frac{3}{2} pp \bigg((L_d - L_q) i_d i_q + \Lambda_{PM} i_q \bigg)$$

- T_l is the inertia torque and it depends on:

$$T_j = J \frac{d\omega_m}{dt} \tag{2.10}$$

  Where J is the moment of inertia [kg/m^2]. It means that this type of resistance torque appears only when the basket is accelerating or decelerating, not in steady-state conditions.

- T_f is the friction torque:

$$T_f = B\omega_m \tag{2.11}$$

  Where B is the friction coefficient [Nm · s]. This is the case of a friction torque that is always present during normal washing machines operation as it is directly proportional to the motor speed. In the event of a stopped motor, static friction will always be considered and a possible simplification is to keep it constant, especially at start-up.

- T_d is the disturbance torque tipically caused by the unbalance.

The motors, in fact, must produce a torque that can be able to move the load, overcoming not only the inertia of the basket and the heavier load basket (i.e. the clothes to be washed) but also the friction coming from the bearings, from the transmission band belt, by the viscous forces between the cloths and the water inside the tank. It is more difficult to predict and determine the load unbalance that is added as a resisting torque. The unbalance is unpredictable as the clothes are distributed randomly and its distribution always changes during the operation of the washing machines. But it is certainly an important contributor when it comes to resistance forces at the starting of washing machines. This is how many modern washing machines have algorithms in charge of measuring/estimating/predicting the load imbalance.

The advantage of considering the (d,q) reference system is that all the electrical quantities are no longer sinusoidal waveforms but are instead continuous quantities. This is because frame $d - q$ is rotating jointly with the synchronous speed ω_e of the electrical values. It should be remembered that obtaining the electromagnetic quantities in the $d - q$ framework occurs by first transforming the three-phase $a - b - c$ values into the $\alpha - \beta$ framework thanks to the Clarke transformation. Then, the quantities $\alpha - \beta$ are transformed into values $d - q$ thanks to the Park transformation.

Clarke's direct transformation:

$$\begin{bmatrix} I_\alpha \\ I_\beta \end{bmatrix} = \frac{2}{3} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix}$$

Park's direct transformation:

$$\begin{bmatrix} I_d \\ I_q \end{bmatrix} = \begin{bmatrix} \cos(\theta_{el}) & \sin(\theta_{el}) \\ -\sin(\theta_{el}) & \cos(\theta_{el}) \end{bmatrix} \begin{bmatrix} I_\alpha \\ I_\beta \end{bmatrix}$$

2.3 Characterization of electric motor

The main procedure that anticipates the choice of which and how a motor control strategy to use is the characterization of the motor.
Again, saturation and cross-saturation are critical mainly in Syr-R, PMASR, IPM motors. In fact, the characterization of the electric motor will be examined in all aspects. This procedure means finding the identification of the Magnetic Model Identification (MMI). In the simplest case, the analytical approach based on the equivalent magnetic circuit is taken into account. In general, the 2.3 equation is considered for this method and is mainly used by machine designers as they need all the specific information on engine design.

Experimental methods are used only when machine rated data are known. They can be divided into:

1. **Standstill methods**: they are known for wound field motors but cannot take into account saturation and cross saturation. This method can be applied with locked rotor by applying voltage pulses to the d axis while the constant current is controlled along the q axis. This takes into account all saturation effects but the voltages must be integrated and this can be critical for the tendency to drift due to offsets. Furthermore, the applied voltage is very low and therefore imprecise, particularly for motors with low per-unit resistance. In any case, the variations of the stator resistance are considered and compensated. Another aspect that this method does not include is the variation of the temperature of PM and thus regarding the core loss and its effect.[**46**]

2. **Constant-speed methods**: find flux linkage at constant speed measuring the d-q voltages when d-q current are impressed to the motor. The voltage is measured in motor terminals and, after that, it is low pass filtered. It is

compensated for the attenuation of module and phase because of the filter but also the fast Fourier transform scheme is used to extract the fundamental. This method doesn't consider the stator resistance variation and it becomes a problem in overload current conditions when high currents are circulating. Overmore, high speed of motor means high iron losses which aren't considered too.[**46**]
That's why the next method was proposed in 2013 in the paper [**46**].

3. **Comprehensive approach**: is perfect to use it for any synchronous motor. It solved some of the problems presented above.
   It takes into account the operating temperature and its variations, iron losses and how to avoid them for not interfering with the identification of the magnetic model, the variation of the stator resistance and its compensation, voltage harmonics (due to spatial harmonics) and inverter the dead times are averaged during the signal acquisition instead of doing other operations in post-processing. All these aspects ensure that this experimental method is the best and this will be adopted for this thesis work.

So, it will be defined the magnetic model so the functions of the flux:

$$\begin{cases} \lambda_d = f(i_d, i_q) \\ \lambda_q = f'(i_d, i_q) \end{cases} \tag{2.12}$$

Basically, the motor runs at stationary speed and current. The d-q currents are collected in a defined evaluation area. This area is bounded by $i_{d,min}$, $i_{q,min}$, $i_{d,max}$, $i_{q,max}$ and these limits are chosen in order to include all the operating conditions of interest of the Motor Under Test (MUT). A major limitation is not reaching the characteristic current I_{ch} which can demagnetize the rotor magnets. As for the current evaluation area, this is generally a regular spaced grid defined by equidistant matrices of currents [**46**]. The grid is evident in a d-q current mesh and depends on the type of motor to be analyzed. To have a better identification of the flux linkage it might also be better to consider a polar spaced grid that collects a piece of circumference where the limits are the maximum amplitude of the current and its load angle.

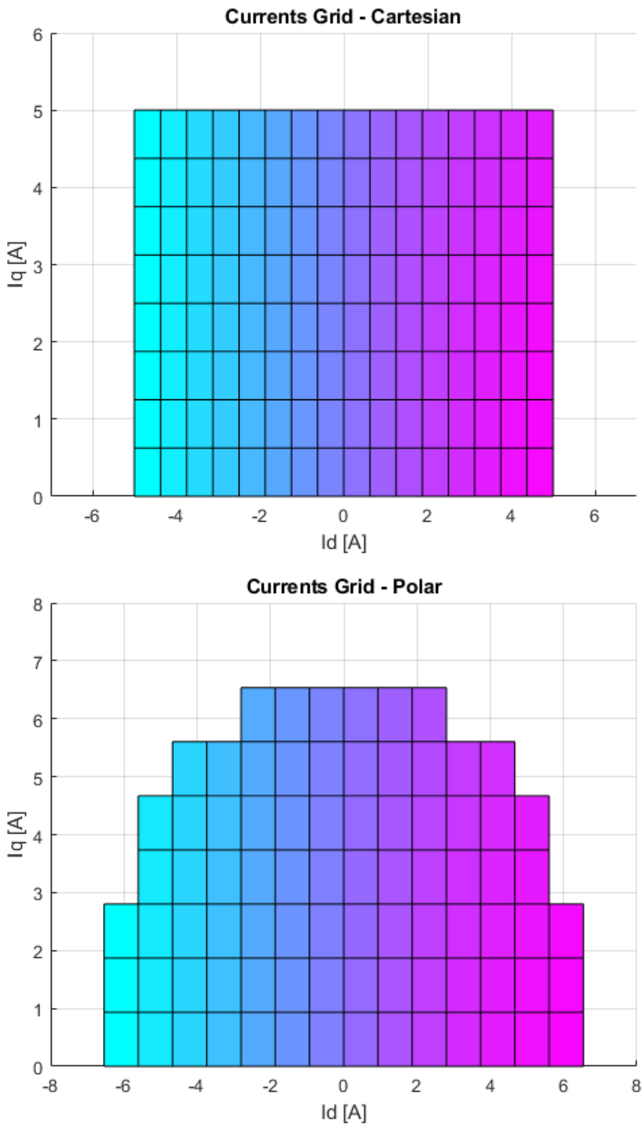


Figure 2.2: Types of current grids: (Up) Cartesian Grid (Down) Polar Grid.

In order to create a steady state condition for the MUT, the procedure must fulfill the following conditions:

1. The MUT driven ad constant speed by a servo-motor which is speed-controlled;
2. The MUT is vector current controlled;
3. The PWM voltages are measured or estimated;
4. The stator resistance drop are compensated;
5. The effect of iron losses must be negligible;
6. All test must be conducted at the same temperature.

For the 3^{rd} point, there are three ways to detect the d-q voltages. The best way is to analogically measure the voltages a-b-c, carry out analog rotational transformations, filter analogically to eliminate PWM components and, only afterwards, convert into digital values obtaining, in the end, d-q digital components. Another method is to reconstruct voltages from duty cycle and DC bus voltage but doing so it is mandatory to compensate with dead-time voltages error. At least, a-b-c voltages can be recontructed through the measurement of the three duty cycles.

For the 4^{th} point, the value of the stator resistance is difficult to find therefore the voltage drops caused by the stator resistance are compensated by giving currents $i_{d,k} + ji_{q,k}$ in motoring mode and after one mechanical revolution, giving the conjugate current $i_{d,k} - ji_{q,k}$ under braking conditions for one another mechanical revolution. The voltages are measured in the two modes and therefore the average between the two turns must be independent of the stator resistance.

In both modes, d-axis flux linkage doesn't change. Only q-axis flux changes.

$$\lambda_{d,mot} = \lambda_{d,gen}$$

$$\lambda_{q,mot} = -\lambda_{q,gen}$$

In fact, in motoring mode:

$$\begin{cases} v_{d,mot} = R_s i_{d,mot} - \omega_e \lambda_{q,mot} \\ v_{q,mot} = R_s i_{q,mot} + \omega_e \lambda_{d,mot} \end{cases} \tag{2.13}$$

In braking mode, that is the motor is working as a generator, only the i_q is inverted:

$$\begin{cases} v_{d,gen} = R_s i_{d,gen} + \omega_e \lambda_{q,mot} \\ v_{q,gen} = -R_s i_{q,gen} + \omega_e \lambda_{d,mot} \end{cases} \tag{2.14}$$

When averaging:

$$\frac{v_{d,mot} - v_{d,gen}}{2} = -\omega_e \lambda_q \tag{2.15}$$

$$\frac{v_{d,mot} + v_{d,gen}}{2} = \omega_e \lambda_d \tag{2.16}$$

Furthermore, all voltage drops, such as dead-time voltage errors and inverter voltage drops due to ON time, are already compensated for between the two operating modes. These voltage drops can be considered the same whether they occur in drive mode or braking mode.

It may happen that the resistance value varies as the temperature changes. Hence, the third mechanical revolution is also used to inject current in motor drive mode and measure the voltage again. Thanks to the d-q voltages in the motoring mode, it is now possible to evaluate a third average of the voltages to be inserted in the equations 2.15 and 2.16.

$$\lambda_d = \frac{1}{2 \cdot \omega_e} \left(\frac{v_{q,1} + v_{q,3}}{2} + v_{q,2} \right) \tag{2.17}$$

$$\lambda_q = -\frac{1}{2 \cdot \omega_e} \left(\frac{v_{d,1} + v_{d,3}}{2} + v_{d,2} \right) \tag{2.18}$$

For point 5^{th}, the motor speed must be high as v_d and v_q must be significant with a good signal/noise ratio. This means that it is better for the speed to be at its nominal value, but this contradicts the negligible iron losses.In fact, at high speeds the iron losses are no longer negligible as the conjugated current during braking is no longer opposite to the complex current in motion. Also, the $\lambda_{dq,1}$ is not equal to $\lambda_{dq,2}$ in amplitude and phase. The process done in the equations 2.15 and 2.16 can no longer be done.
The best compromise is to choose a speed that is one third of the base speed.

For point 6^{th} you have to choose at which temperature to start and carry out the whole procedure but it is simpler and more useful to do it in two precise conditions: when the motor is cold and when the motor is at operating temperature. The two situations can inform how the engine can be fully exploited at start-up when the engine is cold and when it is running normally and its temperature is at its steady-state value. This is why the Magnetic Model Identification procedure is divided into two different identifications:

- **Cold Motor procedure**: is the one that identifies the magnetic model when the motor is not warming up. To do so, every cycle (motoring mode, braking mode, motoring mode) of every point of the currents grid is separated to the next cycle by of a few seconds where Λ_{PM} is measured.
  The main objective is to control that Λ_{PM} is not changing its rated value and so that the motor is not warming up. After the cycle point, when no currents are circulating in the motor, Λ_{PM} can be measured too. The magnet flux that is calculated at the end of every cycle of the point follows this equation:

$$\Lambda_{PM} = \frac{V_q}{w_e}\bigg|_{I_d=I_q=0}$$

  While the stator resistance is monitored during the procedure. If the magnets flux is not reduced of more than 50% then the cold procedure is good and the hot motor procedure can be made. If not, the cold procedure has to be made again diminishing the duty cycle. Duty cycle regulates the active time of the cycle of every point. In order to keep temperature variations very low and under control, the active test time when current are sent to the motor should be as short as possible. But, the currents pulses should, at least, last more than speed regulation transient so it can be extinguished. Even because, all the measure can be done and logged in measurement devices. So every current pulse and electrical quantities can be sent for one mechanical period. So the duty cycle is determined as:

$$\Delta t_{point} = \Delta t_{cycle} + \Delta t_{pause}$$

Period of the cycle and the duty cycle are chosen, so the pause will be:

$$\Delta t_{pause} = \frac{\Delta t_{cycle}}{d_{cycle}}$$

If 5 minutes are chosen for the interval of time of the cycle and duty cycle is $d_{cycle} = 0.05$, then:

$$\Delta t_{pause} = 5/0.05 = 100s$$

Pause time has to last 100 s.

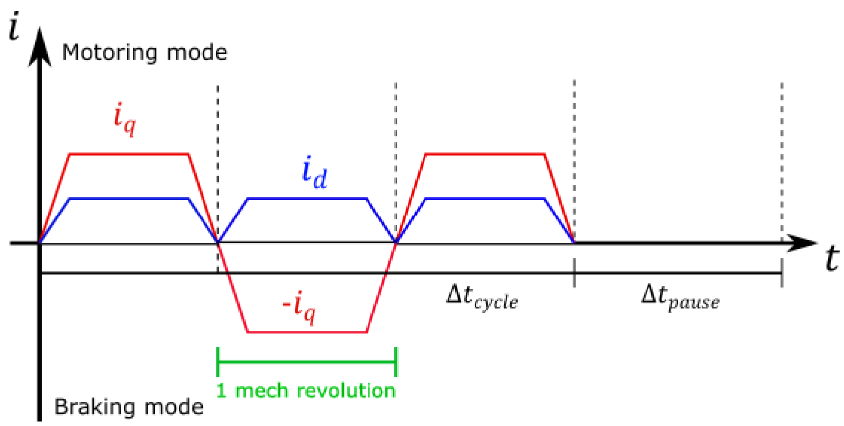


Figure 2.3: MMI cold motor procedure.

- **Hot Motor procedure**: requires warm-up procedure before to find out Hot motor magnetic model. For warming up the motor, the rated current, assumed as thermal current, is sent to the stator windings. The time lengths depends on the thermal constant of the motor and of course on the dimensions of it. It can last several hours from 2 hours up to 8 hours or more.
  During the warm-up procedure, the resistance and the magnet flux is monitored calculating them giving to the stator, first, only d-axis current and then, when currents are set to zero, magnet flux can be calculated.

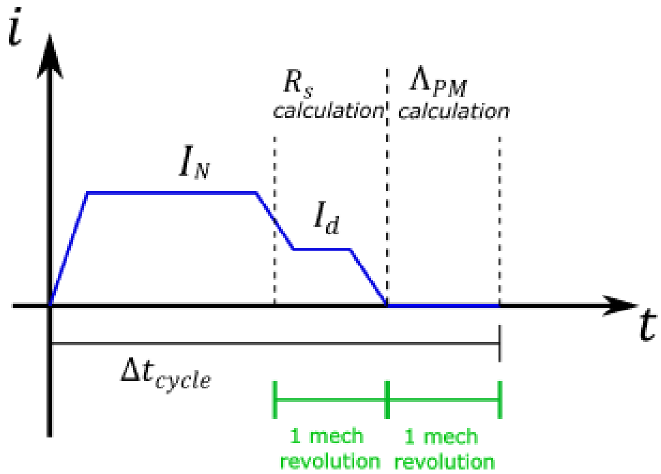


Figure 2.4: Motor Warm - Up procedure.

The d-axis current for resistance calculation, the pause in which flux of magnets is calculated last one mechanical revolution each of them. To do so, R_s and Λ_{PM} are calculated during 2 mechanical revolution like:

$$R_s = \frac{V_d}{I_d}\bigg|_{I_q=0}$$

$$\Lambda_{PM} = \frac{V_q}{w_e}\bigg|_{I_d=I_q=0}$$

When the motor is at its steady-state thermal condition the hot procedure for the identification of magnetic model can start. The hot procedure is the same as the cold one. There are so many currents points of the grid chosen to be tested. Every current point is tested with the same cycle of before (motoring mode, braking mode, motoring mode) with the exception that there's no pause between one point of measurement to another. The whole cycle for one point, including the time to measure Λ_{PM}, is about $6 \div 8$ seconds. At the end of every cycle (in M1 motoring mode, G in braking/generating mode/ in M2 in motoring mode again) this calculation is made up to test if motor is still in steady state thermal condition:

$$I_j = \sum (I_n^2 - I^2) \cdot t_{cycle}$$

Where I is the amplitude of the current of point j and t_{cycle} is the sample time.

During the cycle there is a counter that does the sum reported before. At the end of the cycle, if I_j is higher than zero/positive it means that the current is not high enough to keep warm the motor so heating is performed with a stator current which is higher than the thermal current ($I_d = \sqrt{2} I_n$) and the sum will decrease and when it goes to zero the next current point can be applied to the Motor Under Test (MUT). If I_j is negative then cooling is needed and no currents are injected, the sum will increase and when it goes to zero the procedure can go on with the next point. [**47**]

The main differences that can appear between the two procedure are that at steady-state thermal conditions flux drops of d-axis may be present due to the drop of the magnet flux linkage. All the performances concerning the electromagnetic torque, MTPA, MTPV, inductances get lower due to the high temperatures. Torque capability is reduced too for the hot motor. [**47**]

During the Magnetic Model Identification (MMI), the data detected can be post-processed thanks to numerical program as Matlab and so these data can be detected:

- **Direct Flux Maps** and **Inverse Flux Maps**: tipically Look-Up Table (LUT) are found and implemented for motor control methods. The usual relationship found is the relationship between d-q currents and d-q fluxes in self-excitation so that in saturation condition and in cross-saturation condition too.

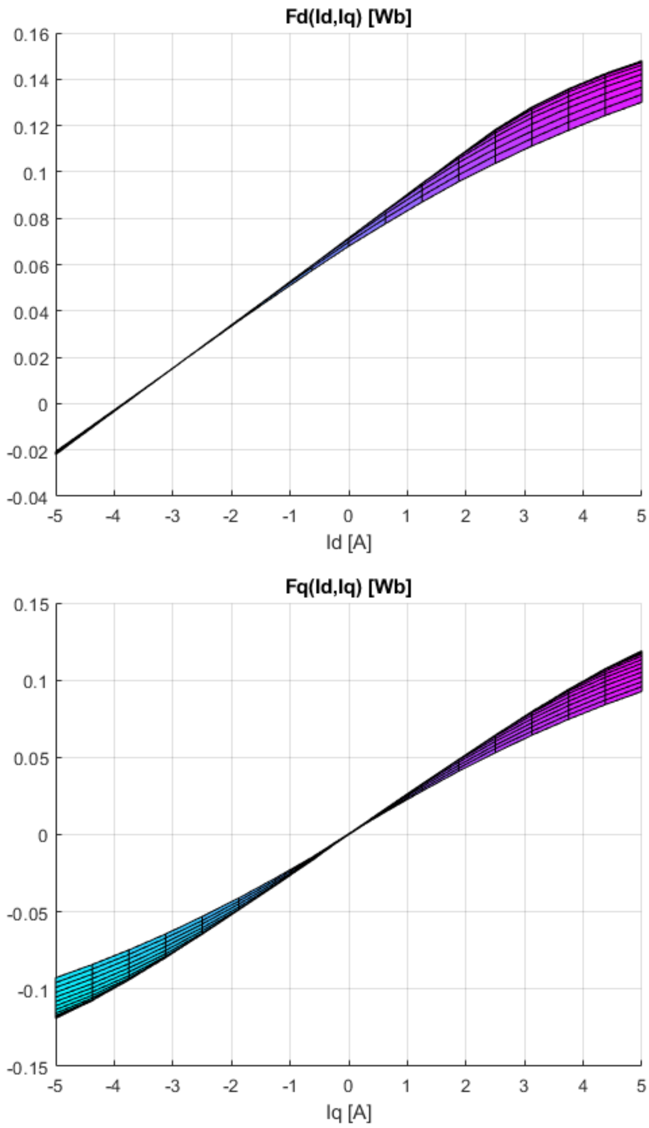


Figure 2.5: Relationship of equations 2.12: $F_d(i_d, i_q)$, (Down) $F_q(i_d, i_q)$.

- **MTPA - MTPV on I_d - I_q Plane**: Maximum Torque Per Ampère (MTPA) trajectories returns all minimum values of amplitude of the vector (so minimum values of i_d and i_q) current in order to give that exact torque. Every minimum value is the intersection between curves of isotorque and isocurrent.

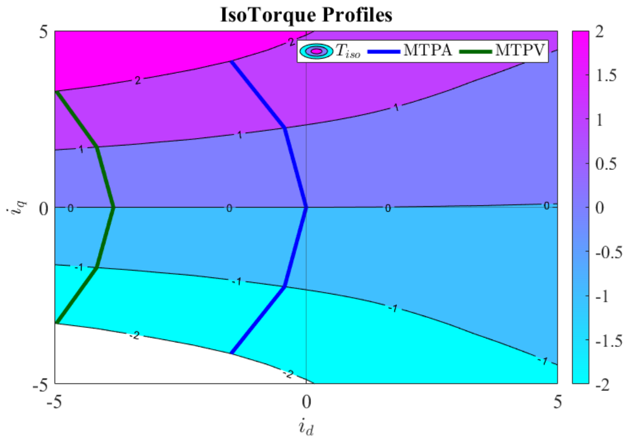


Figure 2.6: MTPA and MTPV trajectories on I_d - I_q plane.

- **MTPA - MTPV on λ_d - λ_q Plane**: Maximum Torque Per Ampère (MTPV) trajectories returns all values of amplitude of the vector flux in order to give that exact torque giving the fixed value of $V_{dq} = V_{max}$. Every value is the intersection between curves of isotorque and isoflux.

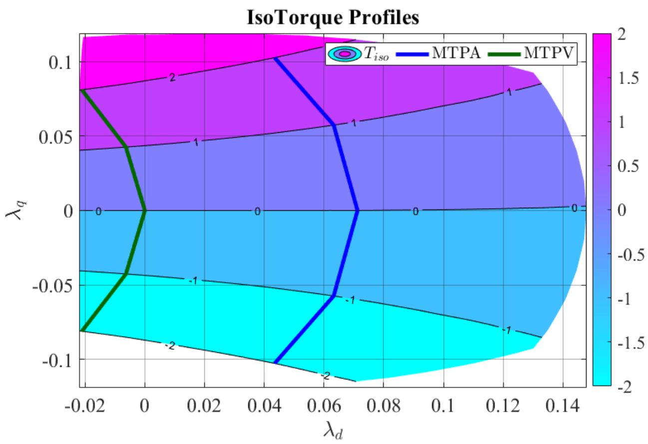


Figure 2.7: MTPA and MTPV trajectories on λ_d and λ_q plane.

The advantages of doing so are, above all, three. First, the motor performance can be decided offline following the previously found magnetic model. Secondly, the Maximum Torque Per Ampère (MTPA) and Maximum Torque Per Ampère (MTPV) trajectories are mandatory, so using them the motor is fully exploited. Third, no matter which manufacturers the engines come from, the identification procedure can provide a performance comparison. Therefore it is also useful to choose, among the manufacturers, from which motor suppliers to purchase motors that meet the needs of the application for which it will be used.
For sensorless control techniques, anisotropy factor or saliency ratio is required and it must be higher than unity for some kind of applications:

$$a_f = \frac{L_{qq}}{L_{dd}}$$

Since $L_{qq} > L_{dd}$ because the d-axis is directed on the polar axis of the permanent magnets and they have reluctance similar to the air one. While L_{qq} is directed on the ferromagnetic material of the rotor and so the reluctance is lower than air/PM reluctance. Many properties and characteristics of the motor performance depend on the saliency factor, in particular the Constant-Power Speed Ratio (CPSR) that gets bigger and bigger when saliency ratio increases. In particular, at high speeds, there is the problem of the Uncontrolled Generator (UCG) operating mode that is that Back-EMF becomes equal to or higher than DC-link voltage. At regime, equations, neglecting resistance voltage drops, become:

$$V_d = -\omega_e L_q I_q$$

$$V_q = \omega_m \Lambda_{PM} + \omega_e L_d I_d$$

In steady state conditions.

During the normal functioning of a motor, its performance can be described through Torque(Speed) curve and Power(Speed) curve. At the start-up the motor gives its highest starting torque depending on the inertia it has to overcome. After that, since the motor wants to gets higher ranges of speeds, if current is at its maximum value or rated one, supply voltage is increased until the maximum DC link voltage is available that is $V_{dc}/sqrt(3)$. When the highest currents and voltages are reached, if motor wants to high up its rotor speed flux-weakening has to happen. In fact,

$$\bar{V}_{dq} = j\omega_e\bar{\lambda}_{dq} \tag{2.19}$$

$$|V| = \omega_e|\lambda_s| \tag{2.20}$$

For the last equation 2.20, the maximum speed or base speed to reach before to enter in flux weakening region can be defined since V_{max} is know and λ_{max} is known too from MTPA trajectory.

$$\omega_{base} = \frac{V_{max}}{\lambda_{s,max}} \tag{2.21}$$

So, from the base speed of 2.21, the condition of flux-weakening can be defined and the amplitude of stator flux may be equal to or less than:

$$\lambda_{s,max} \leq \frac{V_{max}}{\omega_{base}} \tag{2.22}$$

At high speed, much higher than base speed, to maximize the performance, the motor goes in flux-weakening mode and the best technique after having followed MTPA trajectory is to follow MTPV trajectory.

In general, in order to reduce flux, currents must be set to lower value until i_q is set to zero while i_d can be decreased to negative values until it can and this can not provoke demagnetization of the permanent magnet.

Decreasing to negative values of i_d has limits. In the simple case, indeed, this is the vectorial form of the electromagnetic model of an IPM machine:

$$\bar{V}_d = 0 \tag{2.23}$$

$$\bar{V}_q = \omega_e \Lambda_{PM} - \omega_e L_d I_d \tag{2.24}$$

If ω_m gets higher and higher, the Back-EMF term can overcome DC-link voltage causing the UCG mode that is, of course, non-desirable. The fault may happen when this event occur and it causes the shut down of the inverter suddenly removing the gate excitation and so the gate commands from all the switches of the converter. It may not happen short-circuit between the switches but this event causes that the currents flow back up to the DC link until the rotor speed is reduced and so the Back-EMF too. It would be like the machine starts to work as a generator immediately after this shutdown of switches. The DC link may absorb all the current and power overloading the bus capacitor and submitting it to big stress. [**48**]

High anisotropy and saliency ratio may be play a huge role in this situation. In fact, the more saliency the motor presents the more the time the motor needs in UCG operation mode in order to extinguish the currents that flow back to the DC link [**48**]. On the other hand, high saliency ratio can be helpful.

In general, considering all maximum electric values admitted, the behavior of motor depends on speed that follows these scheme under reported. Constant-Power Speed Ratio (CPSR) is usually wider then the one reported thanks to the permanent magnet inserted and so thanks to the anisotropy. In fact, the higher the saliency ratio the wider the CPSR region. It is evident the maximum torque area goes from O to A, the CPSR are from A to B and the flux weakening region from B to C/D or E.

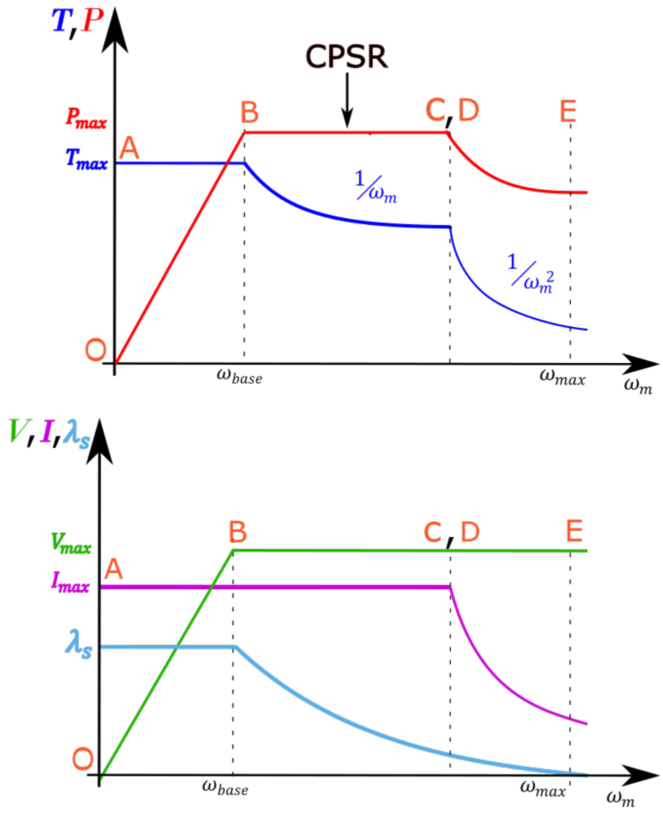


Figure 2.8: Power and Torque per speed.

These O,A,B,C,D points are reported in the next images in the $i_d - i_q$ plane where MTPA, MTPV are represented.

Resuming:

1. **O-A**: The first step to follow is at the start up, when motor currents follows the MTPA trajectory because maximum torque is required and the best exploitation of the motor working is required too;

2. **A-B**: the maximum torque is kept until the voltage that was increasing reaches its maximum value;

3. **B-C,D**: it is the CPSR region, flux weakening is occurring and the motor speed reaches higher values with maximum currents and voltages;

4. **D-E**: if the characteristic current is less than the maximum motor current and if a higher motor speed is required, the motor must travel along the MTPV path.

Ideally, the maximum speed is reached in the acrshort CPSR region if the characteristic current is equal to the maximum motor current. The maximum speed available for the motor depends actually on bearings which are always solicited by the rotating shaft and it happens that heat production is generated from internal friction. Moreover, i_{max} is determined by the maximum current of inverter and by the maximum current tolerated by the motor. Usually the former is higher than the latter, that's way the latter has to be considered. Overmore, other two main values have to be taken into account: i_{ch} and i_o.

- i_o: is the rated current of the motor;

- i_{ch}: is the current of short-circuit test or simply the characteristic current for which the flux of permanent magnets equals to zero, so it is the demagnetizing current.

The i_{ch} depends on the quantity and on the type of permanent magnets. And it is fundamental to relate both quantities:

- if $i_{ch} > i_{max}$: MTPV is outer the allowed area like figure 2.9 shows in point 'textbfD. So it means that the flux weakening stops before the ideal case.

- if $i_{ch} = i_{max}$: is the ideal case in which, at point **C** of figure 2.9, stator flux equals to zero and speed should reach infinite values.

- if $i_{ch} < i_{max}, i_o$: when permanent magnets give low contribute of flux, MTPV trajectory is taken into account to be followed during the functioning of motor to perform better in flux weakening region when CPSR ends. Reaching the point **E** means, as in the previous case, the ideal situation in which the speed reaches infinite values.

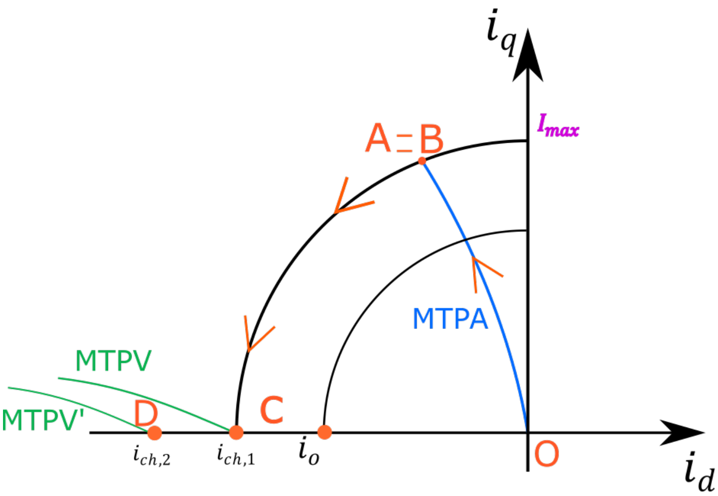


Figure 2.9: Behaviour of the motor through MTPA, CPSR, MTPV in $i_d - i_q$ plane.

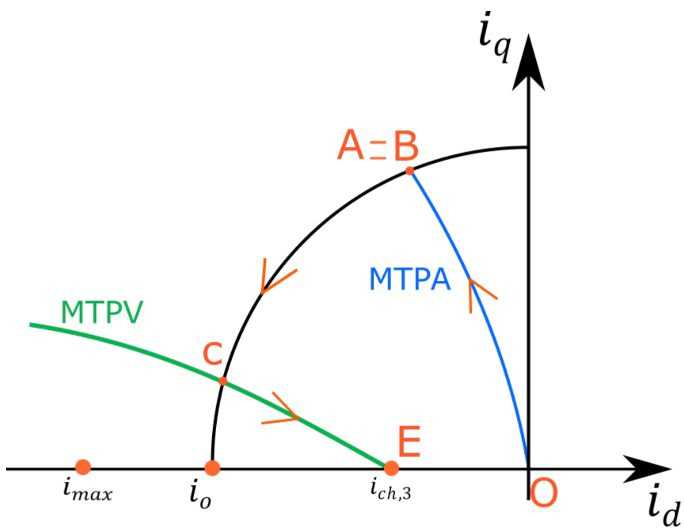


Figure 2.10: Same behaviour of the motor with different characteristics through MTPA, CPSR, MTPV in $i_d - i_q$ plane.

Considering $\lambda_d - \lambda_q$ plane, MTPV and MTPA trajectories are located, of course, like in the next figure.

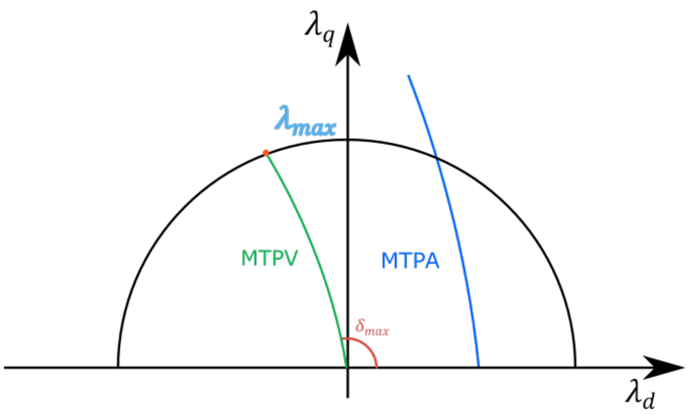


Figure 2.11: MTPA, MTPV in $\lambda_d - \lambda_q$ plane.

delta is the load angle and the maximum allowed is the one defined by MTPV. *delta* angle is the phase of stator flux. In a more detailed way, all the vectors are presented here:

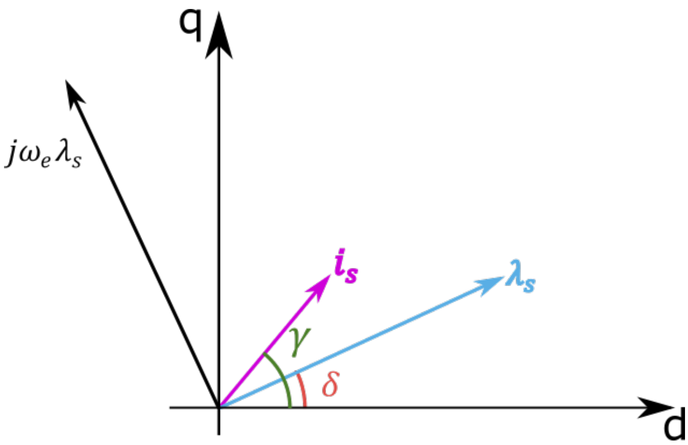


Figure 2.12: Vectorial diagram.

2.4 Control of AC Motor Drives

Motor control strategies are used to control the electric motor and cause it to behave in the way necessary for that type of application. They can be various and can be implemented with sensorless methods if the system to be controlled does not have a speed-position sensor.

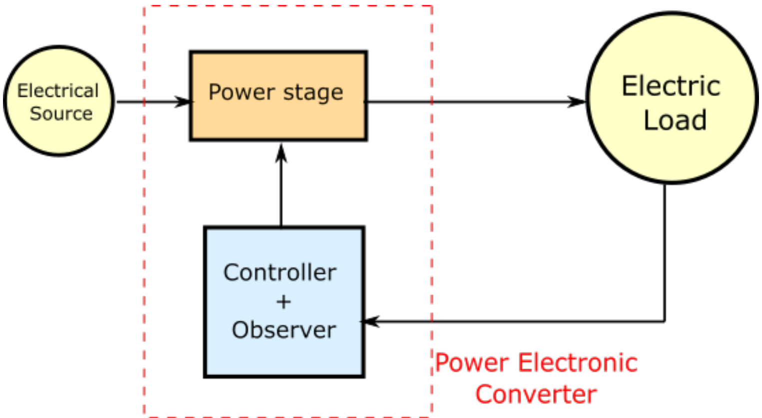


Figure 2.13: Block diagram.

The electrical drive includes the power stage which, as mentioned before, is characterized by two converters: AC/DC converter which rectifies the current coming from the electrical source which usually comes from the electrical network, DC/AC converter which creates through PWM provides the voltages to be supplied to the electric motor/load.
The controller is characterized by specific algorithms inserted inside an MCU which has the purpose of controlling the electromagnetic pair through codes that reproduce the equation of the electromagnetic model of the electrical model.
The observer is usually included when the motor control is sensorless. A main quantity is observed, which includes information on the position of the rotor, which means that an electrical quantity is estimated thanks to a closed loop.

The block diagrams that can represent the speed loop, the motor control loop and the sensored or sensorless method are presented in the following two figures:

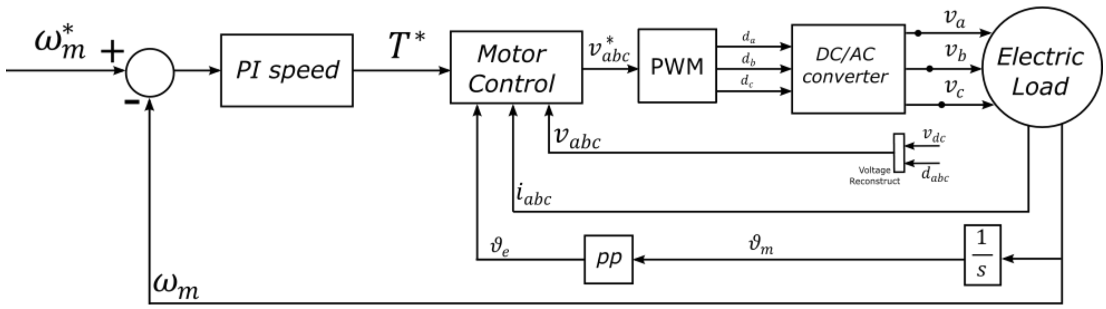


Figure 2.14: Block diagram of a sensored motor control.

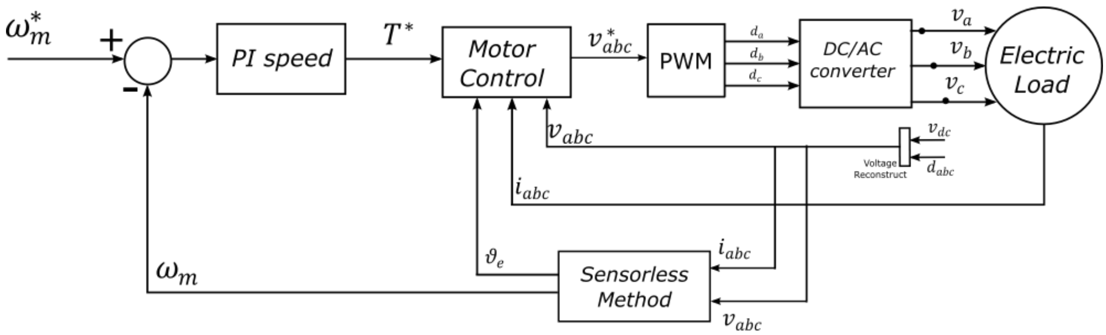


Figure 2.15: BLock diagram of a sensorless motor control.

When choosing the motor control strategy, it must be considered that the speed loop output is always the reference torque that enters the motor control implementation. Therefore, depending on the type of motor control, the reference torque can be reformulated to find d-q currents if using Current Vector Control (CVC), stator flux and q-current if using Direct Flux Vector Control (DFVC), stator flux and keep the value of reference torque when using Direct Torque Control (DTC). In the next few paragraphs, 2.4.1 and 2.5, we will only examine motor control first and sensorless methods second.

2.4.1 Scalar Motor Control Strategies

Considering only the motor control strategies, not taking into account whether it is sensored or sensorless, two types are used: Scalar control includes:

- V/f **control**:it is usually used for Induction Motor (IM) and not synchronous ones. The amplitude of the voltage is proportional to the reference frequency and this to maintain a constant flow. The reference value is only the frequency and the amplitude and phase angle of the voltage vector follow it. In this case, the direction of the d axis is the direction of the stator voltage. It is completely sensorless;

2.4.2 Vector Motor Control Strategies

Vector Control means that it controls a vector quantity through its two components in the $d-q$ or $\alpha-\beta$ frame. Vector controls are explained in the following paragraphs. The goal is always torque control, but this can happen in several ways:

- **Open Loop**:
  - $I-Hz$ **control**: it uses d-q components of the current vector to control the motor. The d-q frame is the same as V/Hz but now the control is vector and open loop. Only the current reference d is provided when the current reference q remains zero. It is a sensorless motor control and can be used for current loop calibration because it works very well in no-load conditions. When running with load, the torque capacity is reduced and it is difficult to use as there is no flow weakening capacity either. It is widely used for IM or as a parking space for Permanent Magnet Synchronous Motor (PMSM);

- **Closed Loop**:

  - **Current Vector Control (CVC)**: Current Vector Control (CVC) is a Field Oriented Control (FOC) type. It means that it is a Field Oriented Control therefore the components of the vector to be controlled refer to a direct reference frame on the flow vector. In the case of IM the d axis of the d-q frame is directed on the flux vector of the rotor, in the case of PMSM, the d axis of the reference frame d-q is directed on the flux vector of the magnet permanent.
    The controlled vector is the current vector. Generally the current components dq, i_d and i_q, go to two Proportional Integral regulator (PI) regulators, independent of each other if their band frequency is high enough to neglect the cross saturation, and they have the aim to reduce the difference (error) between the desired value and the real one that is usually measured. The PI controllers can be the same if the motor to be controlled is a SMPM motor. For IPM motors the regulators must be calibrated respecting the anisotropy of the machine. Also, the control used for synchronous machines is the Direct - Field Oriented Control (D-FOC) which means it uses an observer to estimate the theta angle used for the rotational transformation to return electrical values from α - β frame a $d - q$ frame or vice versa.

  - **Direct Torque Control (DTC)**: it is used in variable frequency drives. This control directly regulates, via PI regulators, the amplitude of the stator connection flux and the torque value.
    The actual torque can be found by measuring the currents and observing the stator flux. Considering the reference stator flux and the reference torque, they have been found thanks to Look-Up Table (LUT) that they respect the optimum efficiency of the motor. It means that this type of

dynamic control is faster than others.

- **Model-based Predictive Control (MPC)**: has the main objective of predicting, in each sampling time, the estimate of the currents that will occur in the subsequent sampling time. It is based on a mathematical model.

  Like the DeadBeat (DB) control which estimates the currents to be controlled with a sampling time in advance. This type of control, in particular, requires the exact parameters of the motor to correctly predict the electrical quantities. The DB control needs the compensation of the rotational transformation of the angle used to return the reference values to be given to PWM considering the delay in the execution of the digital control. This allows for a faster response than using the classic Proportional Integral regulator (PI) regulator.

- **Direct Flux Vector Control (DFVC)**: is called in this way because the d-q frame is directed in stator flux coordinates, the d-axis is directed in stator flux direction. This strategy control the stator flux through d-voltage component and the torque through the q-current component. It requires high accuracy when calibrating and setting motor parameters as it precisely controls the behavior of the motor. The main benefit is to achieve great performance with a complex implementation of the control code. It could work much better if integrated with an efficient observer to estimate the theta angle for the rotational transformation. This method will be presented in detail in the chapter 3.

2.5 Sensorless Methods

Sensorless methods are used when speed measurement is not present in the electric drive. Any type of motor control needs to know the electrical position of the electrical quantities to return the exact input to the inverter legs. Generally the practices of sensorless methods are divided into three main categories:

- **Open Loop Methods**: tipically used at the start-up;
- **Fundamental excitation signals techniques**;
- **High Frequency Injection (HFI)**.

2.5.1 Open Loop Methods

The open-loop estimators are those already known as **V / Hz** and **I-Hz**. The former dictate the frequency and voltage so that the electrical frequency is easy to know. The latter is used in FOC and usually for parking and starting an engine.

2.5.2 Fundamental excitation signals techniques

They usually use the Model Reference Adaptive System (MRAS) concept which means that the observer is a closed loop where the input goes to the reference model and the adaptive model and the difference of the outputs of both models is sent to a correction block and finally its output returns as feedback in the Adaptive Model.

- **Reduced order Observer**: can be an observer of current, of current with Inverse Magnetic Model, of stator flux. They work tipically in the α-β frame.

- *Reduced Order Observer of Current*:the currents of the reference model are the actual ones coming from the motor measurement and transformed in the α - β system, the currents of the adaptive model come from the voltage model of the machine also transformed in the α - β system. The error between the two currents is corrected with the use of the PI regulator and its output is the Back-EMF and through calculations between its components, amplitude and arctg, the electrical frequency and the mechanical speeds of the rotor can be found. The Extended Back-EMF concept can also be used for this type of observer.

$$\theta_e = arctg\left(\frac{e_\beta}{e_\alpha}\right) \tag{2.25}$$

- *Reduced Order Observer of Current with Inverse Magnetic Model*: the same as the previous one except that the adaptive model used the stator model to obtain the stator flux and now, through the reverse flux maps and the magnetic model, the d-q currents can be obtained. In this case the mechanical speed of the rotor and the electrical position can be obtained through the concept of active flux. It is more specific than the previous method and requires MMI;
- *Reduced Order Observer of Stator Flux*: the reference model is the real magnetic model obtained with MMI while the adaptive model is the stator model. The position of the rotor is always with the concept of active flow.

  For the concept of active flux the electrical position of the rotor is used, this expression:

$$\theta_e = arctg\left(\frac{\lambda_{act,\alpha}}{\lambda_{act,\beta}}\right) \tag{2.26}$$

- **Full order Observer**:also includes the mechanical model. The reference model is the real motor model (measured currents), the adaptive model is the stator model used to estimate the current and the mechanical model is also used to obtain the rotor position.

The main problem for this type of observer is that it behaves very badly at zero and low frequencies since the Back-EMF are very negligible and the model cannot find the exact value. It happens that the position of the rotor is not determined exactly. They work best with direct or reverse magnetic maps from MMI but the problems remain. The compensation of the error voltages due to the dead times of the inverter is also mandatory because they cause a reduction in the useful voltage to be sent to power the motor. For this reason, the real tensions must be sent to the observer. To overcome startup and low frequency problems, High Frequency Injection (HFI) is often used.

2.5.3 Extended Back-EMF

The concept of extended back-EMF is used in the reduced order observer of current when controlling electric motor that show anisotropy because this model enhances anisotropy and the difference between inductances L_d and L_q.
The disadvantage of using it is that the EMF is zero at zero frequency or at low frequenecies and it is difficult for the model obtain through integration the exact value. This is the main limit.
The model arises from:

$$\begin{cases} \lambda_d = L_d i_d + \Lambda_{PM} + \mathbf{L_q i_d} - \mathbf{L_q i_d} = L_q i_d + \lambda_{PM} + (L_d - L_q) i_d \\ \lambda_q = L_q i_q + \mathbf{L_d i_q} - \mathbf{L_d i_q} = L_d i_q - (L_d - L_q) i_q \end{cases} \tag{2.27}$$

It results that in the d-q reference frame, in the equation of the q direction the vector of the Extended Back-EMF E_{ext} has the expression:

$$E_{ext} = \omega_e \left[\lambda_{PM} + (L_d - L_q)i_q\right] - (L_d - L_q)\frac{di_q}{dt} \tag{2.28}$$

Reporting the d-q equations in the α - β system they result:

$$v_{\alpha\beta} = \begin{bmatrix} R_s + sL_d & \omega_e(L_d - L_q) \\ -\omega_e(L_d - L_q) & R_s + sL_d \end{bmatrix} \bar{i}_{\alpha\beta} + E_{ext} \begin{bmatrix} -sin(\theta_e) \\ cos(\theta_e) \end{bmatrix} \tag{2.29}$$

Where s is the variable in the Laplace domain and it is the derivative in time domain $\frac{d}{dt}$. Therefore, the electric rotor position can be estimated as:

$$\theta_e = arctg\left(\frac{e_{ext,\alpha}}{e_{ext,\beta}}\right) \tag{2.30}$$

2.5.4 Active Flux

The concept of active flux is used in the reduced order observer of current with MMI or with the observer of stator flux.
The concept of active flux permits to express α-β stator model in another way.
Active flux is:

$$\lambda_{act} = \Lambda_{PM} + (L_d - L_q)i_d \tag{2.31}$$

So the flux can be expressed:

$$\begin{cases} \lambda_d = L_d i_d + \lambda_{act} \\ \lambda_q = L_q i_q \end{cases} \tag{2.32}$$

Then, transforming the d-q equations into the α - β frame, they are expressed as:

$$\begin{cases} \lambda_\alpha = L_q i_\alpha + \lambda_{act} cos\theta \\ \lambda_\beta = L_q i_\beta + \lambda_{act} sin\theta \end{cases} \tag{2.33}$$

So the components in α - β systems are:

$$\begin{cases} \lambda_{act,\alpha} = \lambda_{\alpha} - L_q i_{\alpha} + \\ \lambda_{act,\beta} = \lambda_{\beta} - L_q i_{\beta} \end{cases} \tag{2.34}$$

Therefore, the electric rotor position can be find on:

$$\theta_e = arctg\left(\frac{\lambda_{act,\alpha}}{\lambda_{act,\beta}}\right) \tag{2.35}$$

It is evident that λ_{act} is directed on the d-axis and L_q has to be a known data. The great advantage of using this method in the observer is because it works even at zero frequency but it needs great accuracy of the motor parameters like stator resistance and inductance.

2.5.5 High Frequency Injection

The High Frequency Injection (HFI) methods are used when the motor to be controlled has a high anisotropy because they exploit this characteristic which manifests itself in the Magnetic Model Identification (MMI) and in the inductance values. There are two main types of HFI:

- **Sinusoidal HF Injection - continuous injection**:
  - *Revolving Carrier*;
  - *Alternating Carrier*;
- **Pulse HF Injection - discontinuous injection**.

The frequency chosen is high enough not to interfere with the frequency of the motor operating signals. Usually the chosen frequency is higher than 500 Hz, typically around 500 $\div$ 1000 Hz.

- **Sinusoidal HF Injection**: a high frequency signal is added to the fundamental signal when it is supplied before the signals go to the Pulse-Width modulation (PWM) to create duty cycles to supply them to the inverter. Furthermore, when measuring currents, it is necessary to use a demodulator to extract and obtain high frequency currents and fundamental currents.
High frequency currents can provide information about the position of the electric rotor and through some calculations and scaling factors the position can be estimated.
The advantage is that the method can be used at zero frequency. The disadvantage is that high accuracy is required when providing motor parameters and magnetic model.
For rotating carrier injection, rotor position information is included in the high frequency current in the α - β frame. But this method is not widely used to control the motor with permanent magnets. It can be useful for evaluating how anisotropic the motor is.
For the alternating carrier, the rotor position information is included in the high frequency d-current since the injection of the high frequency occurs only for d-voltage.
Usually, the chosen HFI frequency is a submultiple of the sample rate.

- **Pulse HF Injection**: it is also called the "INFORM" method in which high frequency voltages are applied for very short times in predefined directions. During the application of this method, the phase inductances and differential inductances can be estimated through the position of the rotor and the derivative of the currents. In fact, the position of the rotor can be obtained since the phase inductances depend on it. It can be difficult to use because PWM needs special algorithms to estimate the derivatives of the currents during operation. But it can be used with start pulses as a parking method.

A better scheme and an explanation of how it works will be shown later as HFI with alternating carrier is chosen in the method proposed in chapter 3.

Chapter 3

Proposed Sensorless Motor Control Strategy

The application for which a motor control type and sensorless method has been chosen is a washing machine in which a permanent magnet synchronous motor (type IPM) is used.
In the previous chapters, the operation of a Permanent Magnet Synchronous Motor and the operation of washing machines have been explained in detail considering many practical aspects.
In this chapter, after a general overview of the proposed method and its operation, the Direct Flux Vector Control (DFVC) with the integration of HFI will be well explained in every aspect.

3.1 Direct Flux Vector Control (DFVC)

The main reason a DFVC is chosen is because this type of control is really convenient for controlling the motor operating in the flux weakening region. Also, washing machines tend to run at high speeds, so the motor usually goes into the flux weakening region at maximum voltage and current.

Furthermore, the DFVC type allows you to take full advantage of the engine thanks to the use of maps obtained with Magnetic Model Identification (MMI). This motor control directly adjusts the amplitude of the stator flux and the magnitude of the quadrature current. In fact, the d axis is directed on the direction of the stator flux. In this way, regulating the stator flux means regulating the voltage d while regulating the quadrature current means regulating the voltage q. Also included in the Direct Flux Vector Control is Stator Flux Observer (SFO) with the use of the active flow concept. The following lines will show the block diagrams:

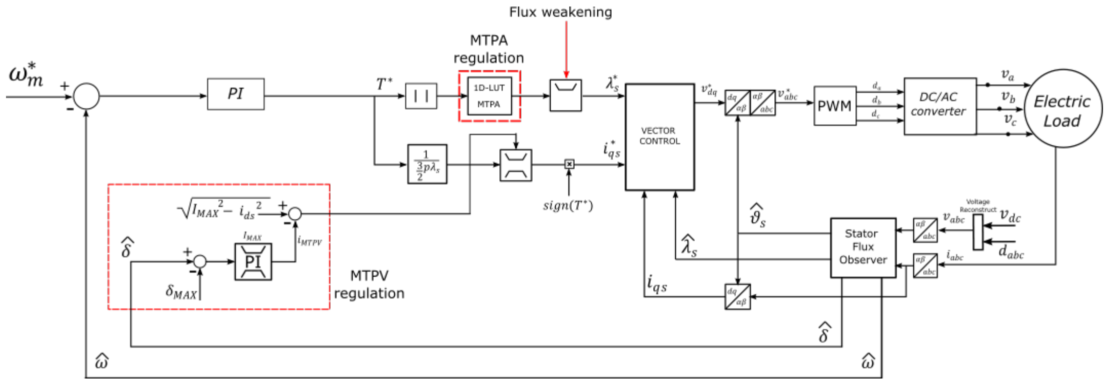


Figure 3.1: DFVC with SFO.

The main input is the motor speed and the main output is the voltage command in the stator flux frame given to the motor stator windings. Other inputs can be the currents measured during operation and the voltages reconstructed from the duty cycles, the currents in the stator frame, the voltage of the DC link, the estimated load angle. [**51**] In detail, each part of this method will be analyzed.

The equations of the starting model are:

$$\begin{cases} \bar{v}_{dq} = R_s \bar{i}_{dq} + \frac{d\bar{\lambda}_{dq}}{dt} + j\omega_e \bar{\lambda}_{dq} \end{cases} \tag{3.1}$$

In the stator flux frame, the equations become:

$$\begin{cases} \bar{v}_{dq,s} = R_s \bar{i}_{dq,s} + \dfrac{d\bar{\lambda}_{dq,s}}{dt} + j\omega_e \bar{\lambda}_{dq,s} \end{cases} \tag{3.2}$$

$$\begin{cases} v_d = R_s i_{d,s} + \dfrac{d\lambda_{d,s}}{dt} \\ v_q = R_s i_{q,s} + \omega_s \lambda_{d,s} \end{cases} \tag{3.3}$$

Because the stator flux is directed on the new d-axis, it is called the ds-axis.

$$\begin{cases} \lambda_{d,s} = \lambda_s \\ \lambda_{q,s} = 0 \end{cases} \tag{3.4}$$

All the model can be described with the two following equations:

$$\begin{cases} \bar{v}_{dq,s} = R_s \bar{i}_{dq,s} + \dfrac{d}{dt} \begin{bmatrix} \lambda_s \\ 0 \end{bmatrix} + \lambda \begin{bmatrix} 0 \\ \omega + \frac{d\delta}{dt} \end{bmatrix} \\ T_{em} = \dfrac{3}{2} pp \lambda_s i_{q,s} \end{cases} \tag{3.5}$$

3.1.1 Speed Loop

The speed loop is the outer loop because the main reference sent to the motor control is the drum speed translated with the motor speed. The output of the speed PI is the reference torque which must be translated with the amplitude of the stator flux and the current in quadrature. The error between target speed and actual speed goes to this PI.
The estimated actual value comes from the stator flux observer which returns the rotor speed at the output.

The Proportional Integral regulator (PI) regulator consists of a proportional part and an integral part and their parameters are chosen considering the value shown in the table in the next section.

3.1.2 Inner Loops: Stator Flux and Quadrature Current loops

Internal loops are more complex because they require more attention in calibrating the parameters of the PI s controllers and in limiting the output.
First of all, it is evident that the reference torque must be managed to obtain the amplitude of the corresponding stator flux while the quadrature current can be obtained from a scale factor, that is the torque factor k_t.
For the amplitude of the stator flux, this is obtained from the MTPA regulation obtained with the MMI. Then, the LUT was created and inserted into the algorithm code. The presence of the LUT may limit the use of the algorithm. Depending on the size of the LUT, it can take up so much memory in the microprocessor or it can take a long time to process and calculate the data during the motor control sample time. What follows from the study for using DFVC is that this LUT is needed.
Reference stator flux is limited when flux weakening occurs. In fact, during the weakening of the flux, the amplitude of the stator flux is reduced following the trajectory MTPV. There are several ways to limit the stator flux after MTPV. In this case it can be said, in general, that the stator flux must be:

$$\lambda^* \leq \frac{|V_{max} - R_s i_{qs} \cdot sign(w)|}{|w|} \tag{3.6}$$

Where V_{max} is the maximum voltage allowed to the inverter and obviously depends on the power supply voltage of the acrshort DC link.
Furthermore, the quadrature current is also limited and takes into account the

value of I_{max}, $i_{d,s}$, i_{MTPV}. For i_{MTPV}, the control tries to cancel the error between the maximum load angle and the estimated load angle via a PI regulator. The output is precisely the MTPV current of the quadrature axis.
The current must be limited with a maximum and minimum value that are: $i_{q,max} - i_{MTPV}$ and 0.

For the parameters of the acrshort PI controllers of both quantities, stability rules were followed for the open loop transfer function.

Parameters	value	Unit of Measure
k_{p_w}	0.15	[Nm]
k_{iw}	1.0	[Nm]
$k_{p_{flux}}$	5000	[V]
$k_{i_{flux}}$	500000	[V]
$k_{p_{current}}$	50	[V]
$k_{i_{current}}$	2600	[V]
$k_{p_{delta}}$	0.01	[A]
$k_{i_{delta}}$	20000	[A]

Table 3.1: PI parameters

For the q control, the reference equation of the model after some manipulation is:

$$L_d \frac{di_d}{dt} = -R_s i_{q,s} + k \cdot (v_{d,s} - R_s i_{d,s}) + b \cdot (v_{q,s} - \omega \lambda_s)$$

Where ω is the stator flux speed and:

$$k = \frac{1}{2} \left(1 - \frac{L_d}{L_q} \right) \cdot sin(2\delta)$$

$$b = -\left(1 - \frac{L_d}{L_q}\right) \cdot cos(2\delta) + \frac{\lambda_{PM}}{\lambda_s} \cdot cos(\delta)$$

After designing the PI of the q axis control, the torque response depends on the factor b. At low speed, therefore at nominal torque, the response is very fast while at high speed, therefore it means that in the region of flux weakening, the response becomes very slow as b decreases. It is as if a torque step disturbance is applied at high speeds.
Unlike the d-q rotor frame, the cross coupling between the two axes is not evident since in the transient *delta* the angle varies and appears in the equation ref eq3.5. The influence of $v_{d,s}$ in $i_{q,s}$ is visible through the factor $k($ *delta*$)$. [**50**]

This type of control is stable for values of torque under the pull-out torque limit or maximum-torque-per-flux limit represented by MTPV.
The control is stable for positive values of b:

$$b(\lambda, \delta) > 0$$

For $b = 0$ the pull-out torque condition coincides with δ_{max} belonging to MTPV trajectory.

Maximum load angle is fundamental for MTPV limitation and the maximum value is around: $90° < \delta_{max} < 135°$ for IPM motor. It is variable because it depends on the saliency ratio. [**50**] The block diagram that represents the delta limitation in order to respect the MTPV trajectory is reported here:

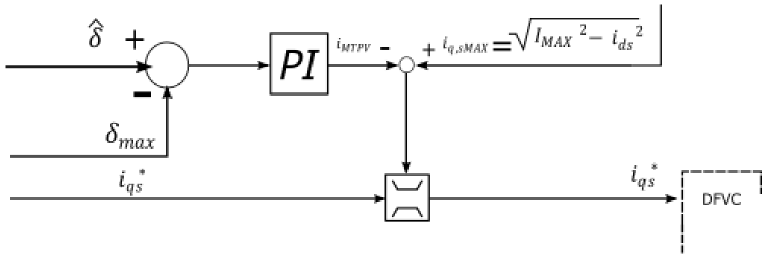


Figure 3.2: Block diagram of delta limitation

That figure shows that delta limiting and hence the production of i_{MTPV} occurs when the real delta exceeds the maximum delta and this means in the flow weakening region. There are many ways to limit the delta and this is one way to do it. The maximum delta could be selected in a 1D-LUT with the stator flux estimation as input. Or the delta regulator output could be limited by the maximum torque found thanks to 1D-LUT which provides it with the stator flux estimate as input.

3.1.3 Stator Flux Observer (SFO) and Phase-Locked Loop (PLL)

The stator flux observer is showed in the next figure:

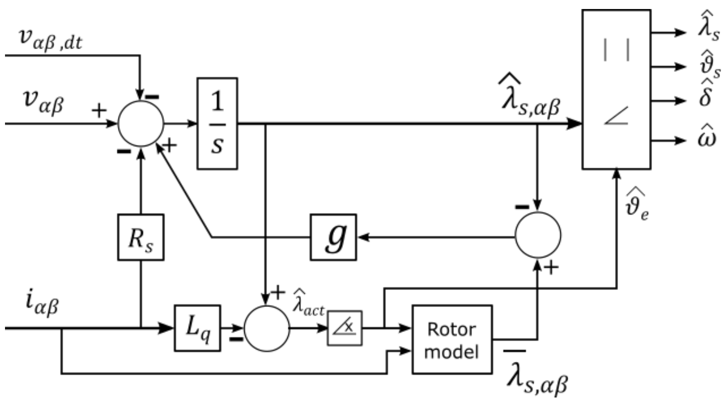


Figure 3.3: SFO with the use of Active Flux concept. [**51**]

This type of observer can operate at any frequency because g is the crossover frequency that determines which type of model estimates the stator flux. At zero frequency and at low frequencies up to frequency g the magnetic model is used. For frequencies greater than g one, the stator model estimates Back-EMF.
If the model does not respect the accuracy of the motor parameters, an estimation problem occurs only at low frequencies, at high speeds this cannot affect the dynamic response.
If low speeds are not required and/or the starting torque is not that high, MMI could be avoided and a mathematical magnetic model could be entered. [**50**]

With this Stator Flux Observer (SFO) these speeds can be estimated:

- **Stator flux vector**: $\theta_s = arctg\left(\frac{\lambda_{\beta,s}}{\lambda_{\alpha,s}}\right)$ from stator flux directed on the new d_s axis;

- **Electric Rotor Speed**: $\theta_e = arctg\left(\frac{\lambda_{\beta,act}}{\lambda_{\alpha,act}}\right)$ from active flux concept.

The estimation of the rotor speed can be derived from the manipulation of $theta_e$ obtained through the active flux. Phase-Locked Loop (PLL) is best for providing an accurate estimate of speed from low to high frequencies. It actually corrects the observed quantity through a closed loop and a PI to adjust the output. The output is a speed [rad/s] and specifically if the angle of the electric rotor is the input, the speed of the electric rotor frame is the output. If it is integrated, the correct electrical angle is obtained. But it happens that the integral part of the PI is already filtered; for this reason the best speed of the electric rotor frame to consider is that coming from the integral part. As shown in the next figure:

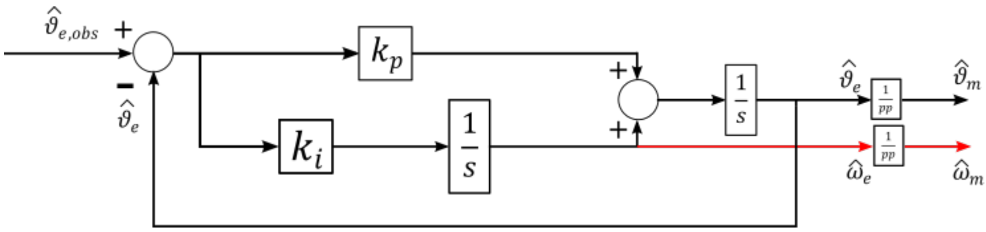


Figure 3.4: PLL.

The manipulation made in order to obtain the difference of the angles is:

$$\hat{\theta_{e,obs}} - \hat{\theta}_e \approx sin(\hat{\theta_{e,obs}} - \hat{\theta}_e)$$

That it becomes:

$$sin(\hat{\theta_{e,obs}} - \hat{\theta}_e) = sin(\hat{\theta_{e,obs}})cos(\hat{\theta}_e) - cos(\hat{\theta_{e,obs}})sin(\hat{\theta}_e)$$

The parameters used are:

Parameters	value	Unit of Measure
k_{pPLL}	150	[rad/s]
k_{iPLL}	4300	[rad/s]

Table 3.2: PI parameters

Eventually, the proper limitation are:

- Voltage Limitation: it occurs limitating the stator flux with the equation mentioned before in 3.6;
- Current Limitation: that happens like $i^*_{q,s} = \sqrt{I^2_{max} - i^2_{d,q}}$;
- Delta Limitation: it occurs in flux weakening that means correcting and limitate the stator flux phase since MTPV trajectory is followed.

The great advantage in using this type of control, DFVC, is that it is already calibrated for being used with any kind of motor because "the bandwidth of the λ

control is independent of magnetic saturation and the machine model" [**50**]. While the $i_{q,s}$ regulation is disturbed by the term $\omega_s \lambda_{PM}$ that is properly compensated as a feedforward in the current loop and other disturbances are compensated thanks to the integration part of the current loop. Only motor parameters and Look-Up Table (LUT)s must be changed in order to have good performance with the right motor but it works in every case. The main disadvantages have been already presented and this solution proposed presents a good dynamic response for such kind of application.

3.2 Adopted Sensorless strategy

High Frequency Injection (HFI) was chosen as the sensorless method. In general, as mentioned above, there are different types of HFI but they can be used in motor control in two ways:

- Parking: park the rotor in order to find the initial rotor position;
- Parking + sensorless method at low frequencies.

The second option is used when the observer used it doesn't work at low speed. At low speeds and frequencies, the back-EMF is too small to detect that the estimate can be affected by a certain percentage of error. If this happens, the control may fail because the rotor position is not estimated well enough.
High Frequency Injection may be one of the methods that can improve zero frequency performance.

In this case, the solutions adopted are both. In any case, the High Frequency Injection (HFI) consists in injecting pulses of high frequency sinusoidal voltages to the motor and in filtering the measured current obtaining the fundamental current signals and the high frequency ones thanks to which to find the position of the rotor. But the Stator Flux Observer (SFO) must include a flag depending on who uses the theta observed by the stator flux observer or uses the theta estimated with HFI.

The modified block diagram of the DFVC with HFI is:

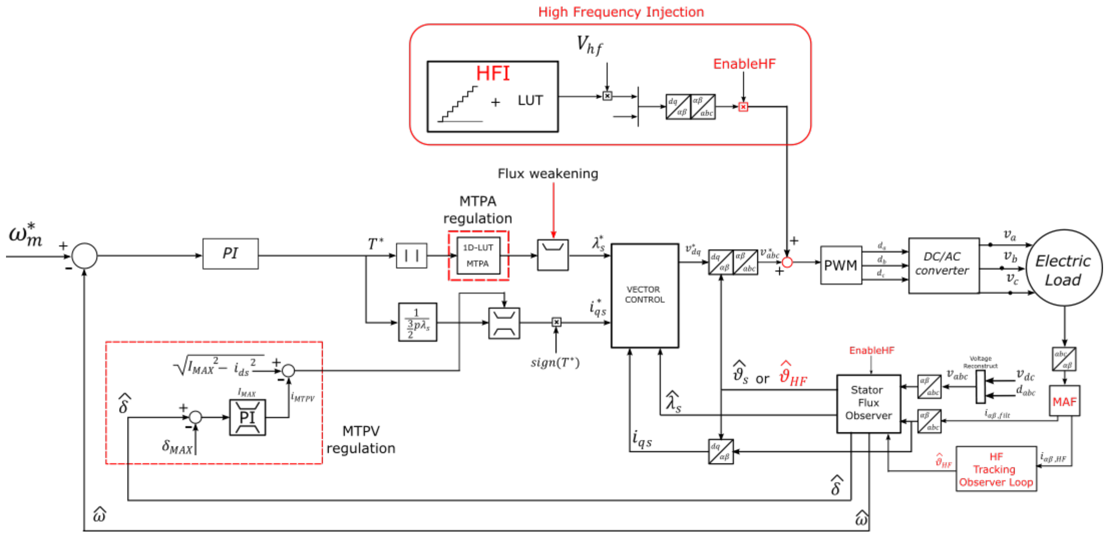


Figure 3.5: HFI in Direct Flux Vector Control.

The high frequency sinusoidal voltages are obtained thanks to a counter and for each count each $cos(\ theta_{HF}t)$ is read and taken from a LUT which stores each cosine value. The injection takes place only on the d axis, it is a pulsating signal, if only the HFI enable flag is active.

In the reading of the current measured by the shunts, on the other hand, Moving Average Filter (MAF) are used to obtain high frequency and filtered currents.

The high frequency q-axis current is that which contains the rotor position information. From this quantity the $theta_{HF}$ will be evaluated and after the detection of the initial position the estimated theta can be reset and therefore the motor will be ready for starting.

After the injection of high frequency signals, 2 pulses of V_d are applied. They are 2 equal impulses but one positive and one negative. During these pulses, the currents on the d axis are stored and compared. The larger current determines the polarity of the rotor magnets.

A main aspect to pay attention to is the use of the inductors L_d and L_q, because their nominal values cannot be used as they change during acrshort HFI. The adopted values should be: L_{dh} and L_{qh}. These inductances are the differential ones which are the ratio between the flux variation and the excitation current variation. The magnetic model, in fact, can be expressed as it follows:

$$\begin{bmatrix} \lambda_{dh} \\ \lambda_{qh} \end{bmatrix} = \begin{bmatrix} L_{dh} & L_{dqh} \\ L_{qdh} & L_{qh} \end{bmatrix} \begin{bmatrix} i_{dh} \\ i_{qh} \end{bmatrix} \tag{3.7}$$

Starting from these mathematic model, there is another way to express the magnetic model considering the Average and Difference Inductance:

$$L_{avgh} = \frac{L_{dh} + L_{qh}}{2}$$

$$L_{\Delta h} = \frac{L_{dh} - L_{qh}}{2}$$

They are used because emphasizes the contributions of positive and negative sequences of current components. These inductances are used in order to extract the theta rotor position.

The value of the amplitude of high frequency voltage is chosen depending on this expression:

$$i_{dh} \approx \frac{V_{HF}}{2pi f_h L_{dh}}$$

The range considered of i_{dh} is $0.3 \div 0.5$ A, so based on this, V_{HF} is determined. To extract the $theta_{HF}$ from the q-axis high frequency current, a demodulation function is created:

$$F_{demod} = \frac{\omega_h \Delta}{V_{HF} L_{dh}} sin(\omega_h t)$$

Where $\Delta = L_{dh}L_{qh} - L_{dqh}^2$. The L_{dh}, L_{qh}, L_{dqh} are differential inductances corresponding to the d-q operating point. They are not equal to rated values of inductances.

When demodulating the q-current, this happens:

$$\frac{i_{qh}}{F_{demod}} = \Delta\gamma_{HF}$$

This corresponds to the theta error. This can be introduced into the HF tracking loop which is actually very similar to the PLL block. The *Delta gamma* enters a PI regulator, the output is the estimated electric rotor speed and dividing by pp and integrating it gives the rotor position.

The values chosen for High Frequency Injection (HFI) method adopted are:

Parameters	value	Unit of Measure
f_h	500	[Hz]
V_{HF}	40	[V]
$k_{p_{HF}}$	150	[rad/s]
$k_{i_{HF}}$	4300	[rad/s]
L_{dh}	Ld	[H]
L_{qh}	Lq	[H]
$L_{dqh} = L_{qdh}$	0	[H]

Table 3.3: PI parameters

The high frequency q-axis current component contains the main information about the rotor position:

$$i_{qh} = \frac{V_{HF}}{\omega_h}\frac{L_{\Delta h}}{\Delta}sin(2\theta_{err})$$

This equation doesn't show the L_{dqh} term because it has been neglected since for this application the value of that differential inductance is zero.
$theta_{err}$ is the difference between the observed theta and that estimated by the

tracking observer's loop which is like a PLL and corrects the angle giving an estimate of the position of the theta rotor:

$$\theta_{err} = \theta - \hat{\theta}$$

The $\Delta\gamma$ found, as mentioned before, is perfectly equal to θ_{err}. In the following block diagram the tracking observer loop:

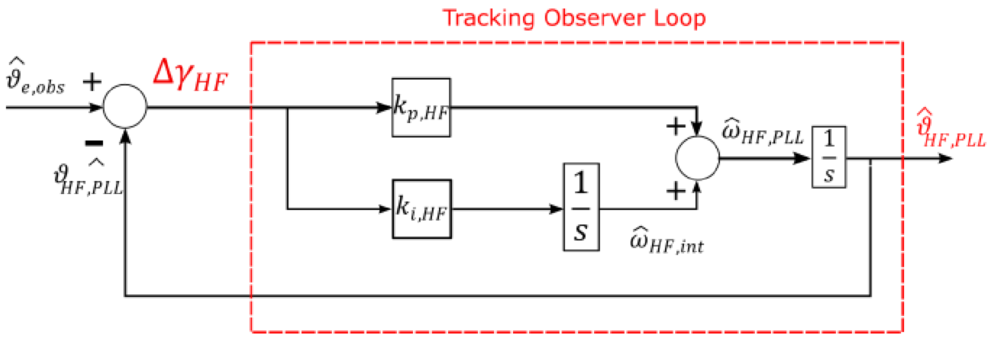


Figure 3.6: HF Tracking Observer Loop.

It is also important to put in evidence that compensation of dead-time error voltages is needed. The dead-time caused by the switch of enabling-disabling IGBTs of legs inverter cause also the error in voltages that supply the motor. This dead-time error voltages must be found through proper procedure and inserted in the motor control C-code. In this way, the motor should receive the exact values of variables and then respond better at dynamic solicitations.

Chapter 4

Simulation Results

The results of the simulations were obtained with the implementation of the sensorless C-code motor control in Matlab script and inserted in the simulink model through the use of the S function. The simulink model reproduces as faithfully as possible the entire system including the motor control, measuring devices such as shunt resistor, voltage source inverter PWM (VSI), electric motor and the load that the washing machines should represent.

The C code includes the Direct Flux Vector Control (DFVC) algorithm with the use of Stator Flux Observer (SFO) and the integration of High Frequency Injection (HFI) as a sensorless technique. First, low-pass filters (LPF) are used to filter the DC link voltage V_{DC}, the rotor speed, the electric rotor frame speed (frame dq), the voltage V_s reconstructed from the duty cycles from signal noises. The engine control code respects the block diagrams shown in the previous chapter 3. In the next section 4.1 the model will be discussed.

4.1 Simulink Model

The simulink model in block diagrams is represented here:

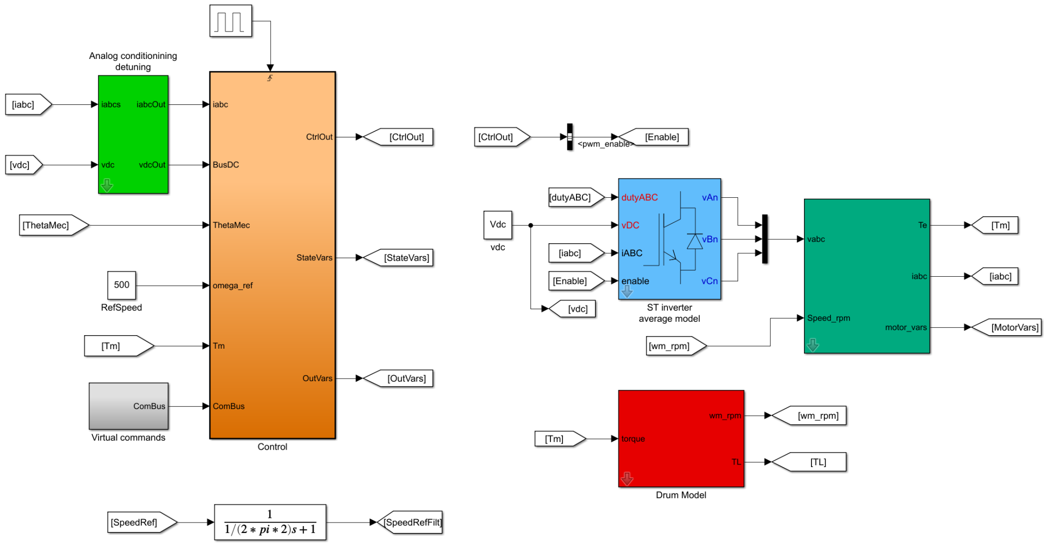


Figure 4.1: Simulink Model.

The blocks are:

- **Green Block**: represents shunt resistances of the legs of the inverters that measure the currents.

  The *inputs* are the real motor currents i_{abc} and the real DC link voltage V_{DC}. The *outputs* are the same of the inputs detuned with the conditioning of the analog measures;

- **Orange Block**: represents the motor control code with the internal S-function.

  The *inputs* are the currents measured i_{abc}, the DC link voltage measured V_{DC}, the real rotor position, the reference motor speed, the real electromagnetic torque, the virtual commands.

The *outputs* are the control variables, state variables and output variables that are all the quantities we want to plot in order take into account how the motor control code and simulations works and how it responds to this particular strategy. All these outputs could be like duty cycles and the enabling of PWM, the flags and enabling mode of interests such as SensorlessFlag, EnableHF, StateDrive of the state-based motor control, the dq currents, the rotor speed and angle estimated and so on.

- **Blue Block**: is the inverters model represents also with the S-function.

  The *inputs* are duty cycles, the currents i_{abc}, the enabling commands, the DC link voltage.

  The *outputs* are the three voltages to give to the motor v_{abc};

- **Dark Green Block**: is the electric motor model.

  The *inputs* are the three voltages and the real speed of the motor.

  The *outputs* are the real electromagnetic torque, the three real currents i_abc, all the variables we want to pick in order to plot them like dq currents, $\alpha - \beta$ current, stator flux, rotor position etc;

- **Red Block**: reproduces the load model with the frictions included.

  The *input* is the real electromagnetic torque.

  The *outputs* are the real rpm motor speed and the load torque.

The parameters of the Voltage Source Inverter (VSI) used are:

Parameters	value	Unit of Measure
f_{sw}	16000	[Hz]
T_{sw}	$62.5 \cdot 10^{-6}$	[s]
$v_{err,DT}$	$0 \div 3$	[V]

Table 4.1: VSI parameters.

The electric motor used is the MUT3 (Motor Under Test). The motor parameters and values of its rated and maximum variables are reported in the next table:

Parameters	value	Unit of Measure
pp	4	-
R_s	2.565	[Ω]
$\lambda_{PMrated}$	0.0813	[Wb]
L_d	0.0174	[H]
L_q	0.0216	[H]
L_{dq}	0	[H]
L_{dh}	0.0174	[H]
L_{qh}	0.0216	[H]
L_{dqh}	0	[H]
L_{dh}	0.0174	[H]
I_{max}	5	[A]
$I_{max,MTPA}$	7.06	[A]
V_{max}	173.2	[V]
T_{max}	2.5	[Nm]
$\lambda_{max}(T_{max})$	0.1334	[Wb]
$T_{max,HF}$	2.0	[Nm]
δ_{max}	173	[$°C$]

Table 4.2: MUT3 parameters.

The load has been reproduced with these data:

Parameters	value	Unit of Measure
Mass	2.6	[kg]
Pulley Ratio	12	-
friction	1.8	[Nm/(rad/s)]
Inertia	2.74	[$kg \cdot m^2$]

Table 4.3: Load Parameters.

4.2 Simulink Results

Starting a washing machine is the worst and most burdensome case because, at full load, it is difficult for the electric motor to overcome the inertia to set the drum in motion. The motor must provide the maximum electromagnetic torque to rotate the drum and it means that the required currents reach the highest values of the motor capacity.
That is why a thorough study was done for this application.
Three solutions were considered:

1. **HFI Start-up + No R_s Detection**;
2. **HFI Start-up + R_s Detection**;
3. **HFI Initial Position Detection + R_s Detection**.

4.2.1 01 - DFVC+HFI Start-Up + No R_s Detection

In this solution HFI is used to detect the initial rotor position but also at low speed and at 250 ÷ 300 rpm motor the HFI is switched with SFO. The following figures refer to a start-up of a cold motor with R_s used at $25°C$.

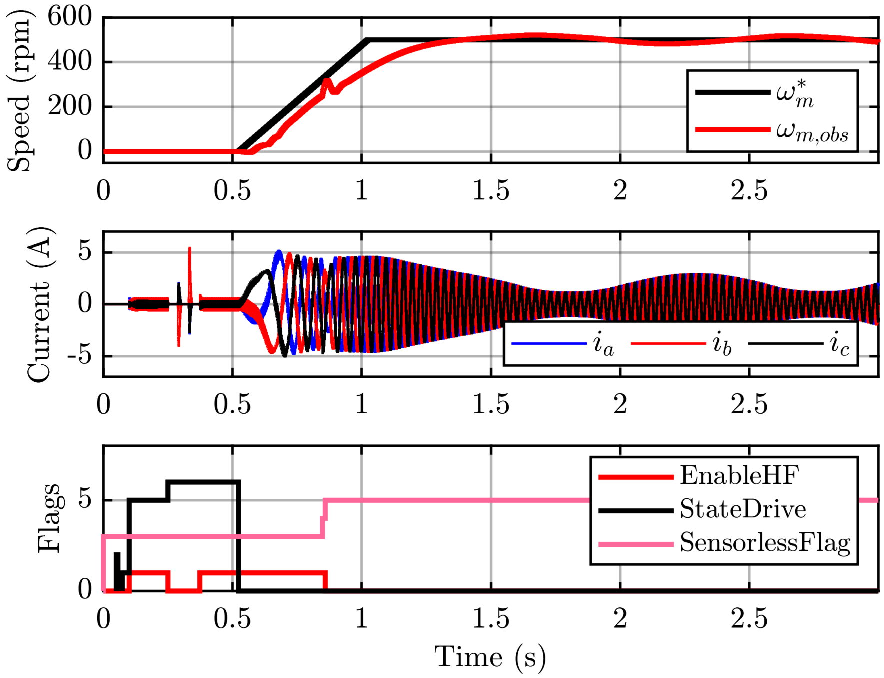


Figure 4.2: From top to bottom: reference and estimated rotor speed; motor currents; StateDrive variable flag, EnableHF flag variable, Sensorless Flag variable.

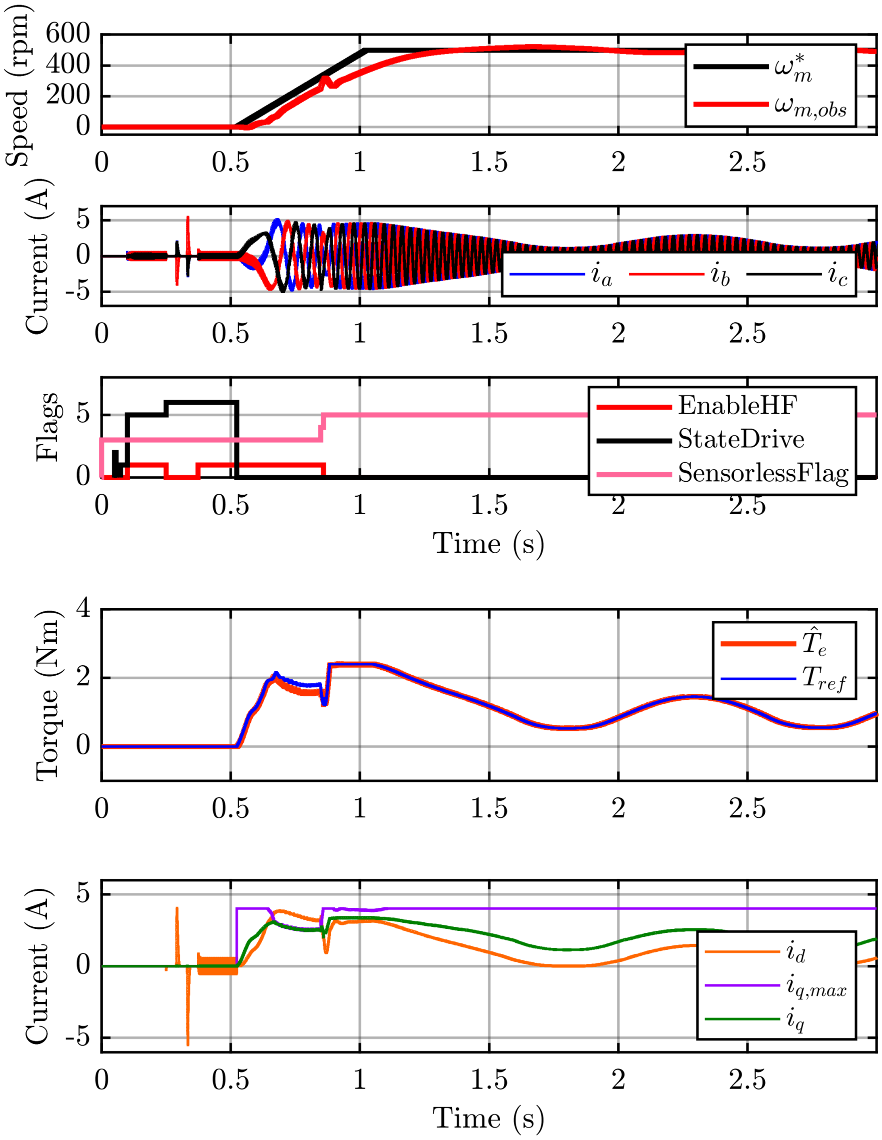


Figure 4.3: Top figure.From top to bottom: reference and estimated rotor speed; reference torque, maximum torque and estimated one. Bottom figure. From top to bottom: reference and estimated torque; bottom: $d - q$ currents and maximum q-current.

With the particular zoom in the switch from the HFI to the fundamental signal:

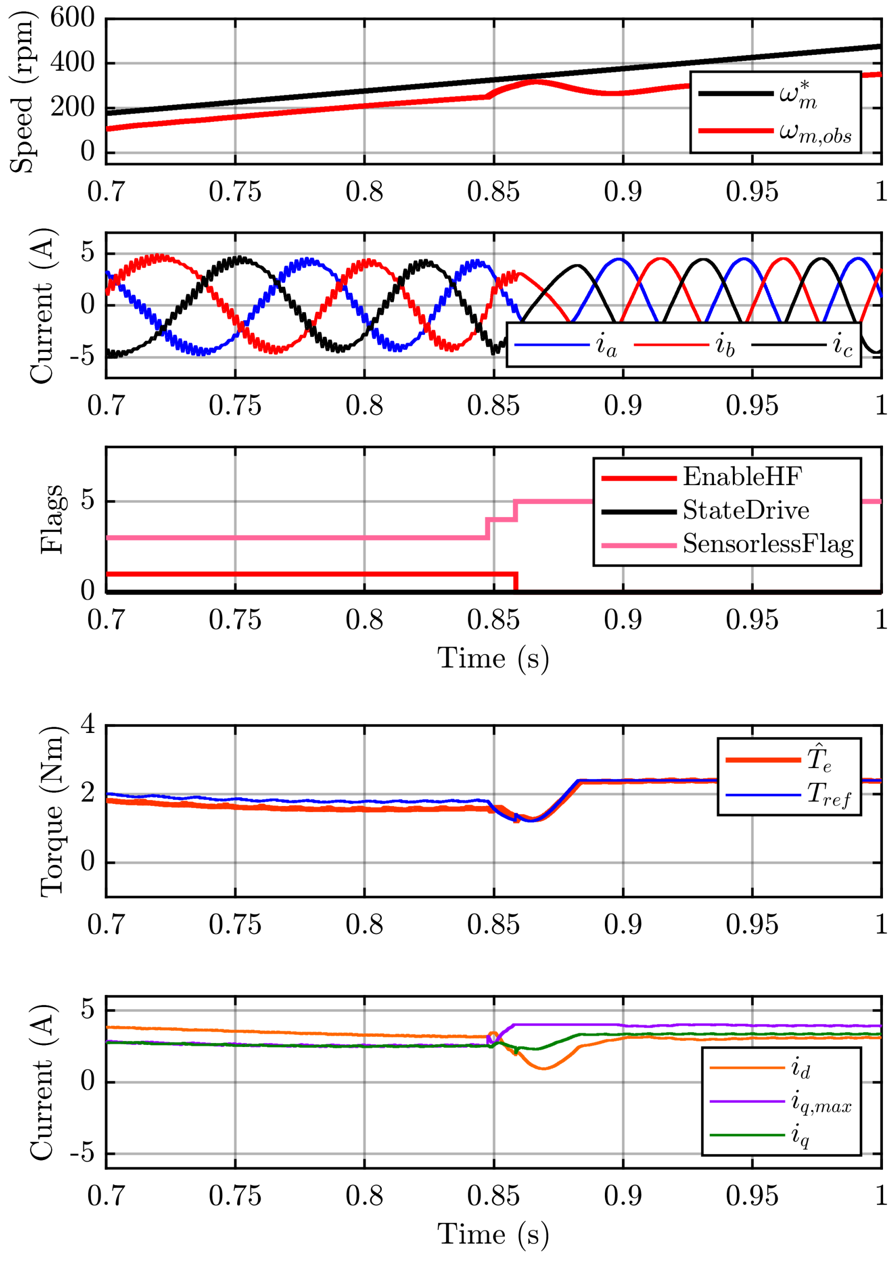


Figure 4.4: Top figure: zoom of figure 4.2 when HFI is switched with SFO at 300 rpm motor; Bottom figure: zoom of top figure of figure 4.3.

In the washing cycle, therefore at the beginning of the operation of a washing machine, the motor is subjected to a high number of starts and stops and to high currents. The electric motor reaches a high temperature and the stator resistance changes in value. This parameter is used for SFO. It can be dangerous not to estimate the value of the stator resistance because it can compromise every start of the washing machines. It is shown here how the motor responds to motor control if no resistance is detected and the following figures refers to R_s for an hot motor that respectively is $90°C$, $180°C$, $210°C$.

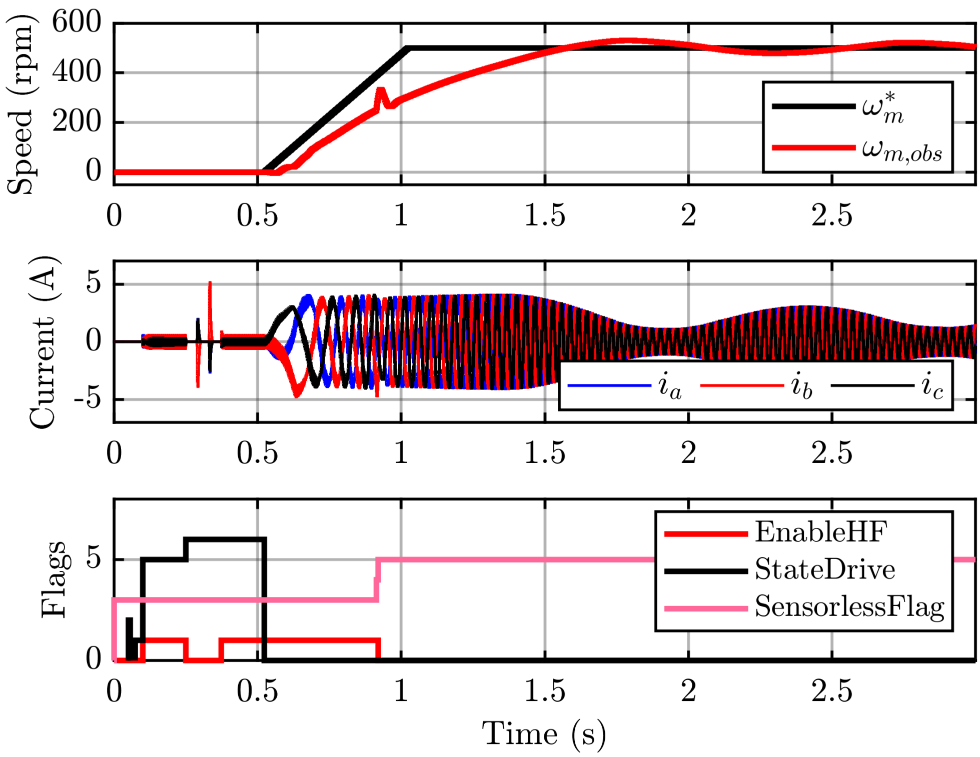


Figure 4.5: Same figure as 4.2 with R_s at 90°.

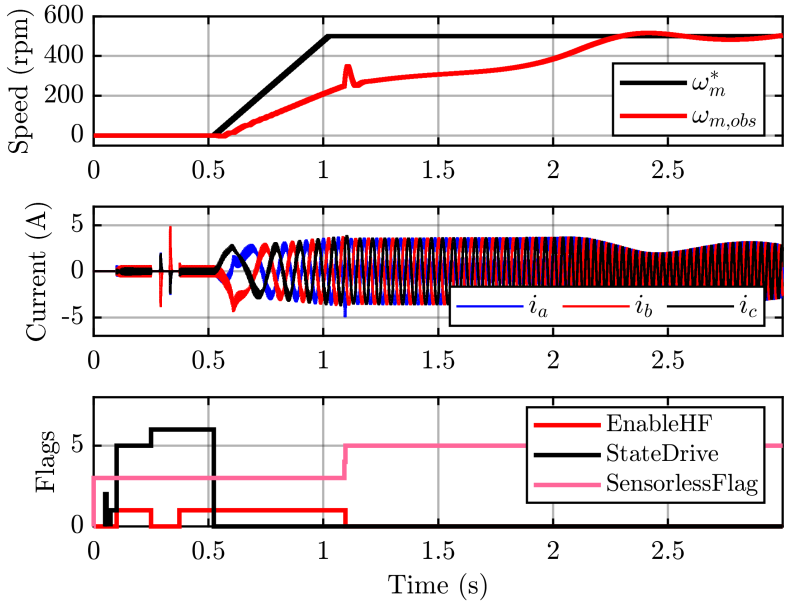


Figure 4.6: Same figure as 4.2 with R_s at 180°C.

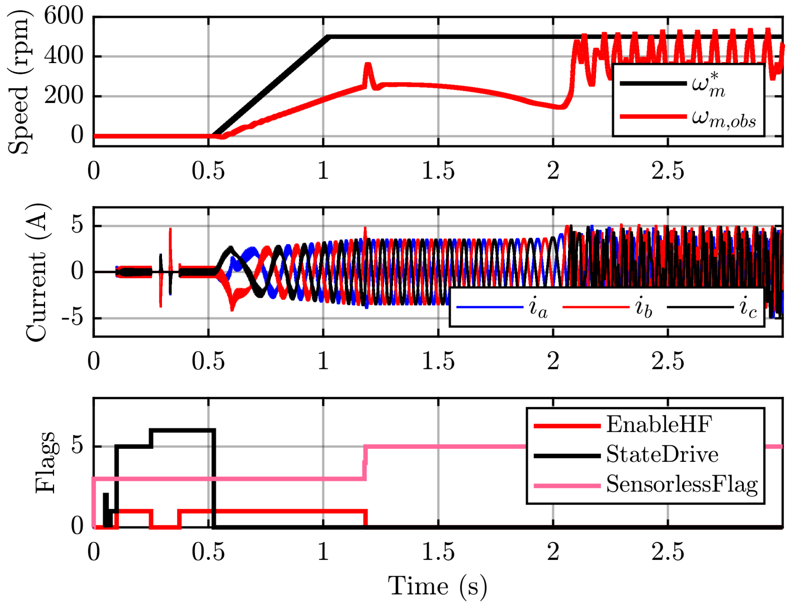


Figure 4.7: Same figure as 4.2 with R_s at 210°C

It is evident how the dynamic response gets worse than the case before when motor is hot, the resistance gets bigger. It results that it is better to do the estimation of the resistance before the start-up after the initial rotor detection and the check polarity.

4.2.2 02 - DFVC+HFI Start-Up + R_s Detection

In the next figures, it is presented how it is the sequence fo this type of motor control in which first there's HFI, then the check polarity, then HFI just to assure that the position estimated is right, the R_s detection before the starting.

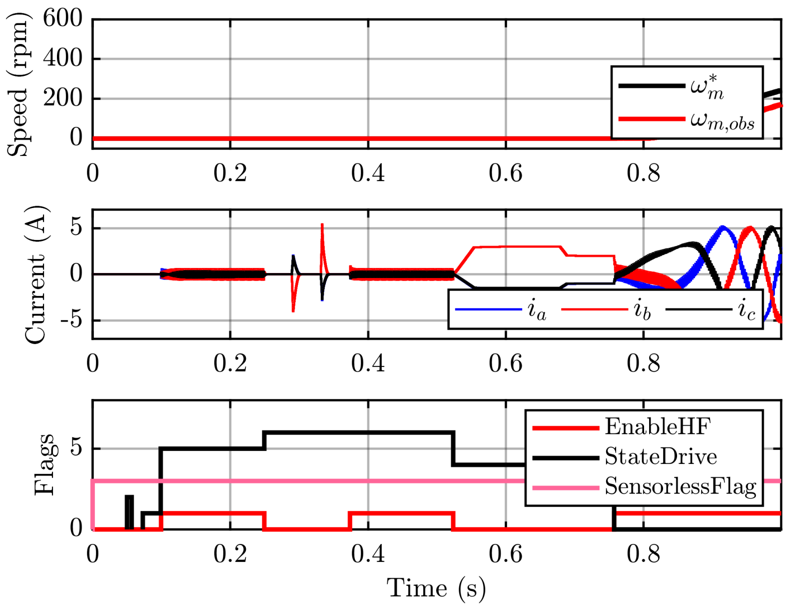


Figure 4.8: Zoom to see motor states. From top to bottom: reference and estimated rotor speed; motor currents; StateDrive variable flag, EnableHF flag variable, Sensorless Flag variable.

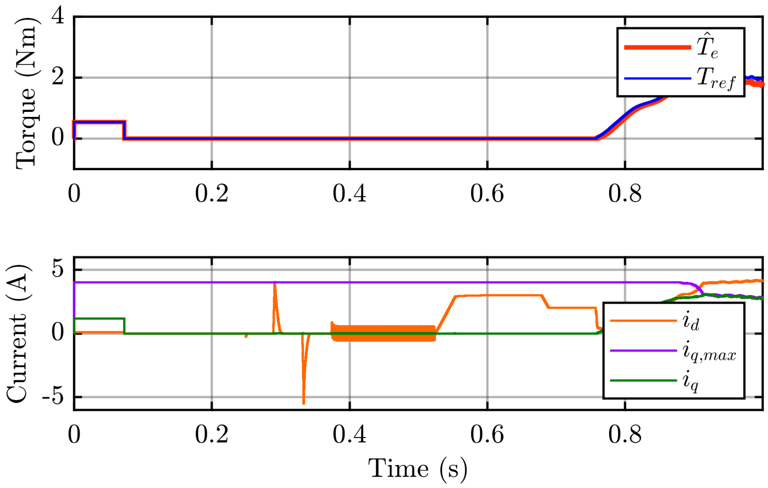


Figure 4.9: Zoom to see the current pulses of check polarity. From top to bottom: reference and estimated torque; $d-q$ currents, maximum q-current.

The performance with the stator resistance detection is much more better than before. With stator resistance R_s at $25°C$:

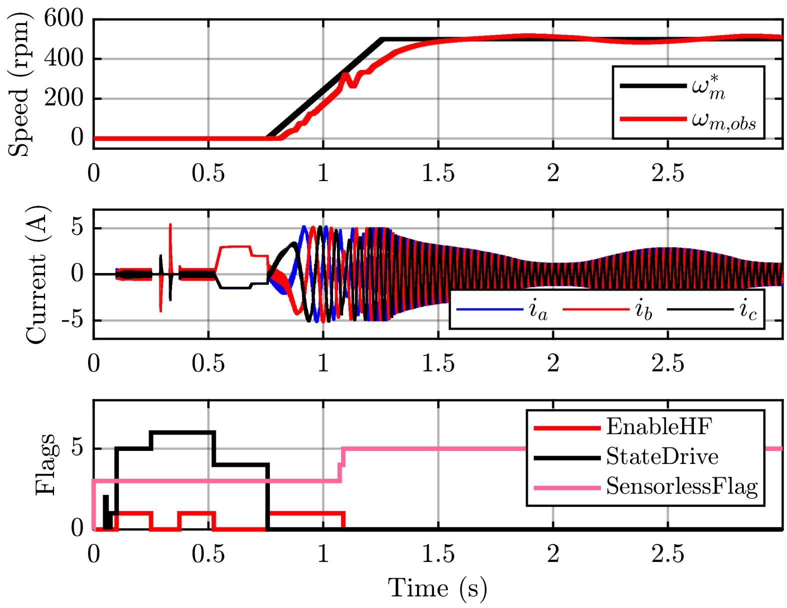


Figure 4.10: Top figure. From top to bottom: reference and estimated rotor speed; motor currents; StateDrive variable flag, EnableHF flag variable, Sensorless Flag variable.

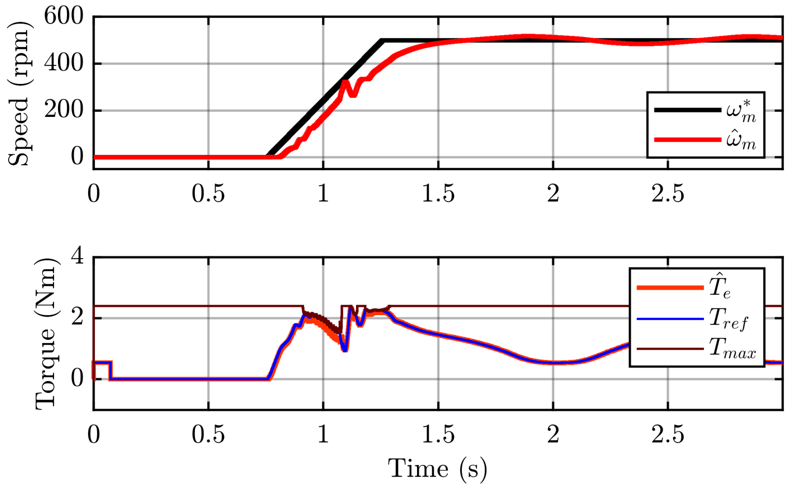


Figure 4.11: From top to bottom: reference and estimated rotor speed; reference torque, maximum torque and estimated one.

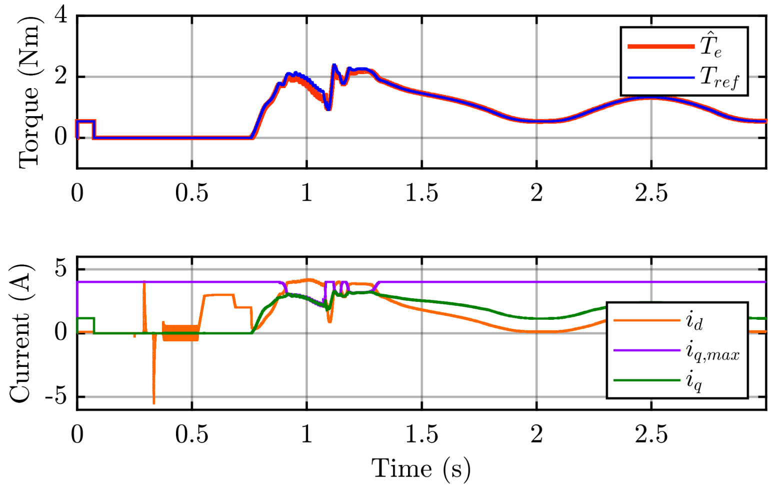


Figure 4.12: From top to bottom: reference and estimated torque; $d-q$ currents and maximum q-current.

It is also evident a better performances at starting when the motor is hot:

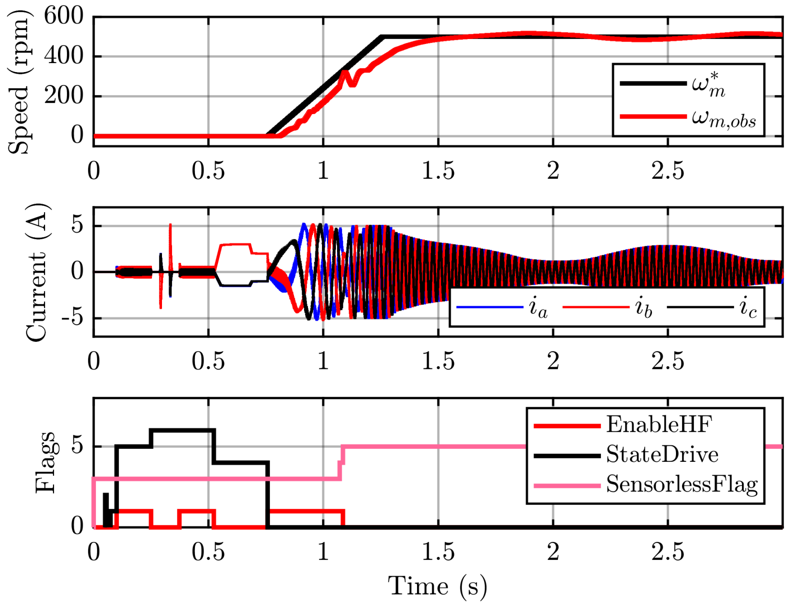


Figure 4.13: Same figure of top figure of 4.16 with R_s at 90°C.

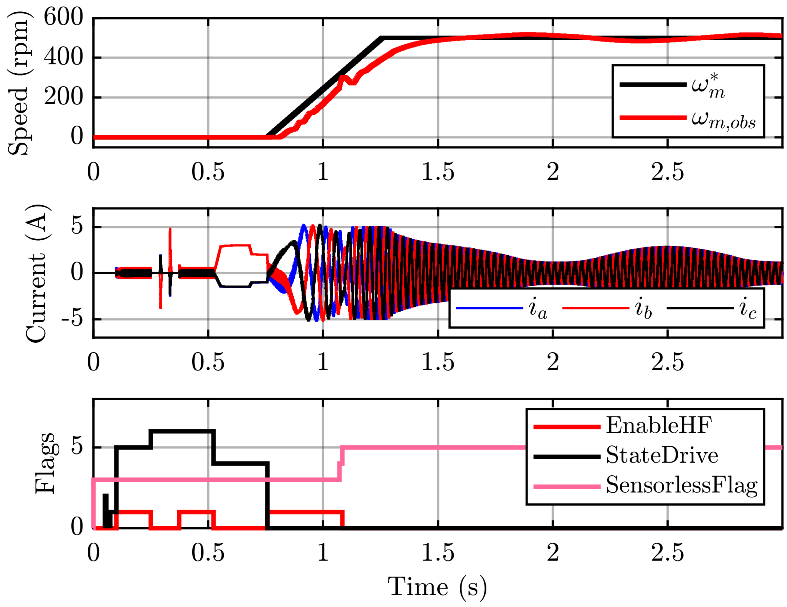


Figure 4.14: Same figure of top figure of 4.16 with R_s for 180°C.

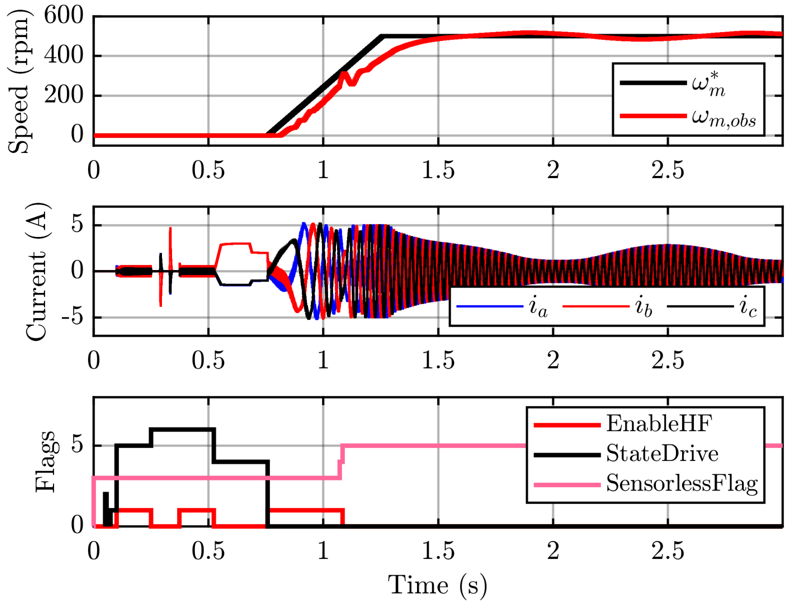


Figure 4.15: Same figure of top figure of 4.16 with R_s for 210°C.

4.2.3 03 - HFI Initial Position Detection + R_s Detection

The dynamic response with this solution is not performative as solution n° 02. The next figures refers to cold motor with value of R_s at 25°C.

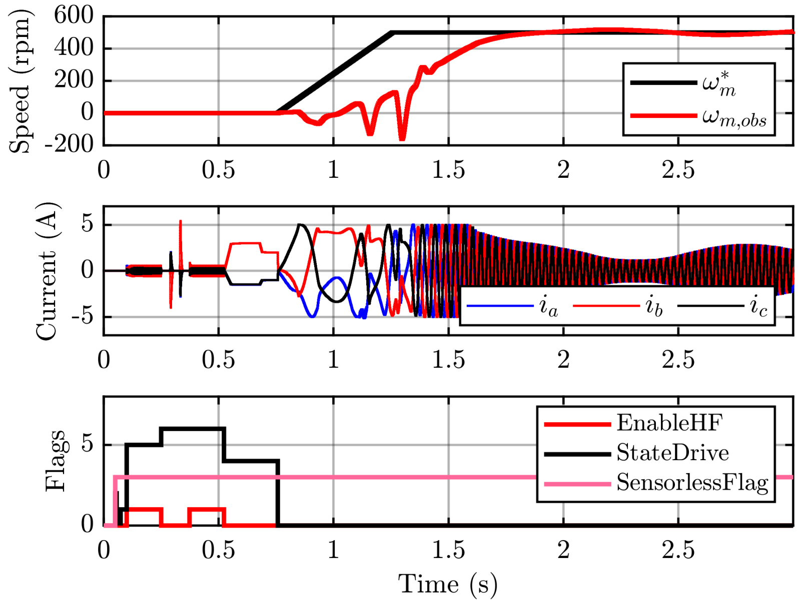


Figure 4.16: From top to bottom: reference and estimated rotor speed; motor currents; StateDrive variable flag, EnableHF flag variable, Sensorless Flag variable.

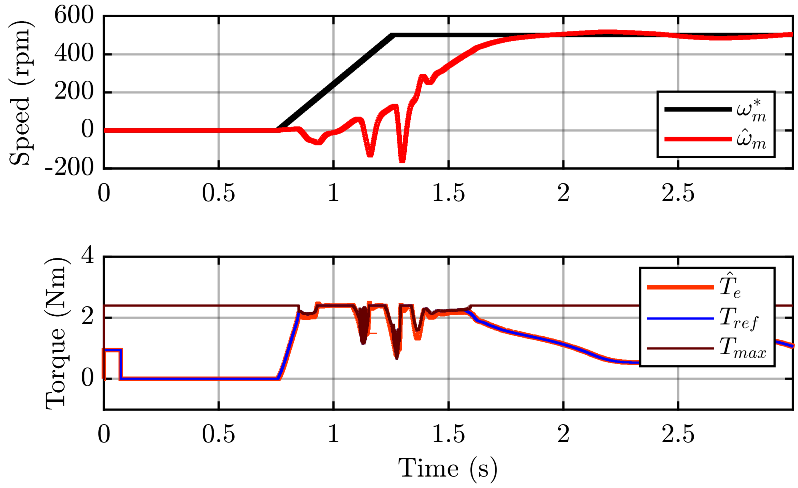


Figure 4.17: From top to bottom: reference and estimated rotor speed; reference torque, maximum torque and estimated one.

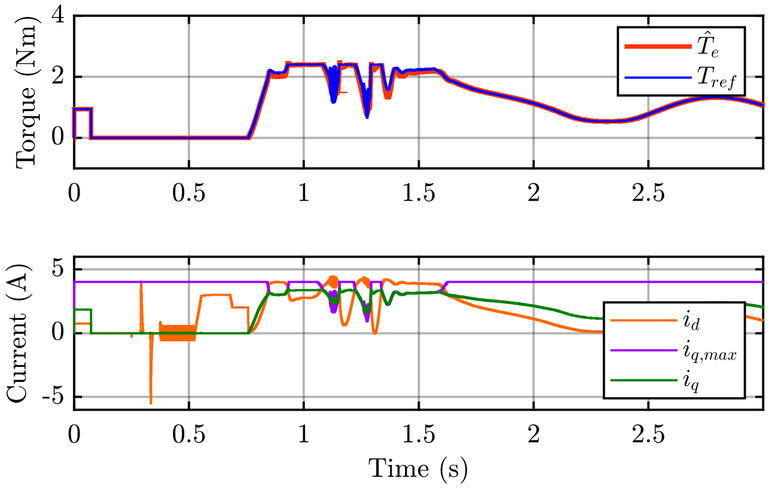


Figure 4.18: From top to bottom: reference and estimated torque; $d-q$ currents and maximum q-current.

The next figures refers to hot motor with value of R_s at $90°C$, $180°C$, $210°C$.

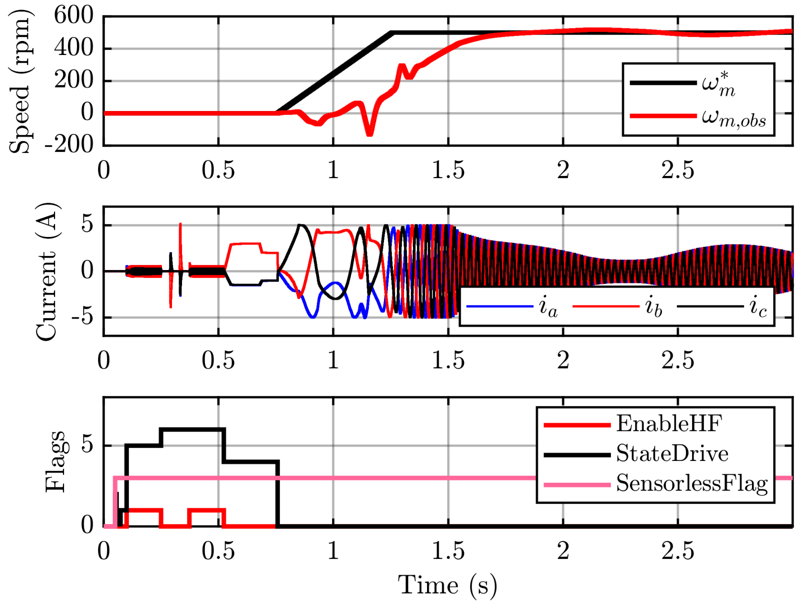


Figure 4.19: Same figure of top figure of 4.16 with R_s at 90°C.

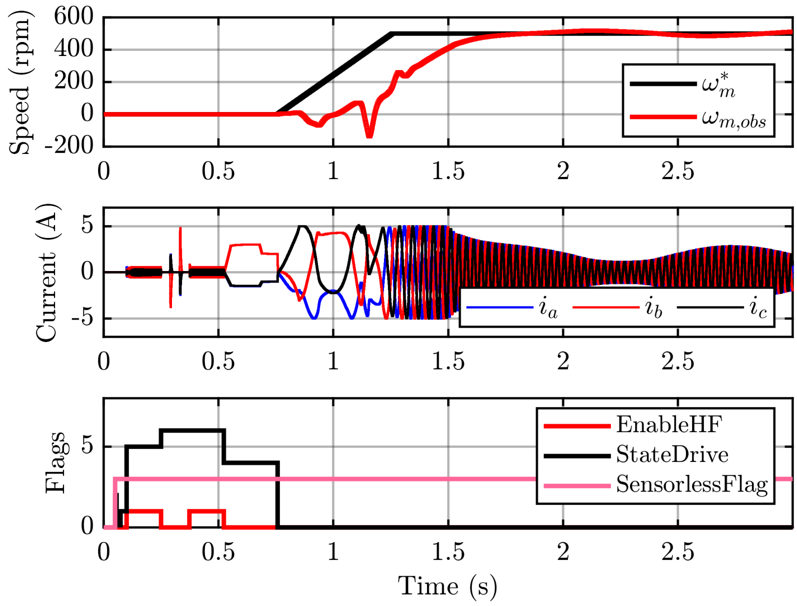


Figure 4.20: Same figure of top figure of 4.16 with R_s for 180°C (top) and 210°C (bottom).

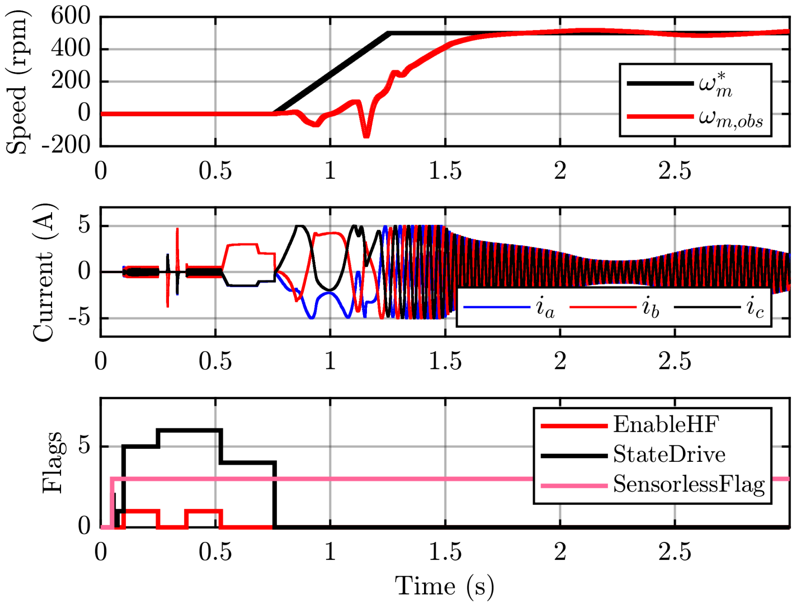


Figure 4.21: Same figure of top figure of 4.16 with R_s for 180°C (top) and 210°C (bottom).

Chapter 5

Experimental Results

5.1 Laboratory tests

Experimental tests have been in made in Polito Laboratories and the it has been used:

- **dSpace**: it is an hardware and with its Real-Time Interface software it permits to be an interface between models and C-code on Matlab/Simulink and the real inverter.

Figure 5.1: dSpace Hardware used.

- **Inverter**: it is made with IGBTs. It has a switching frequency of 16000 Hz and dead-time of 0.99 μs.

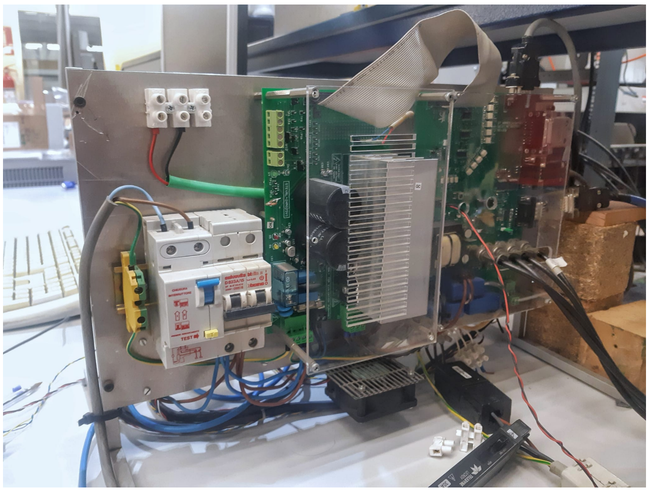


Figure 5.2: IGBTs Inverter used.

- **Electric Motor**: the one used is called MUT 3. It is an IPM motor.

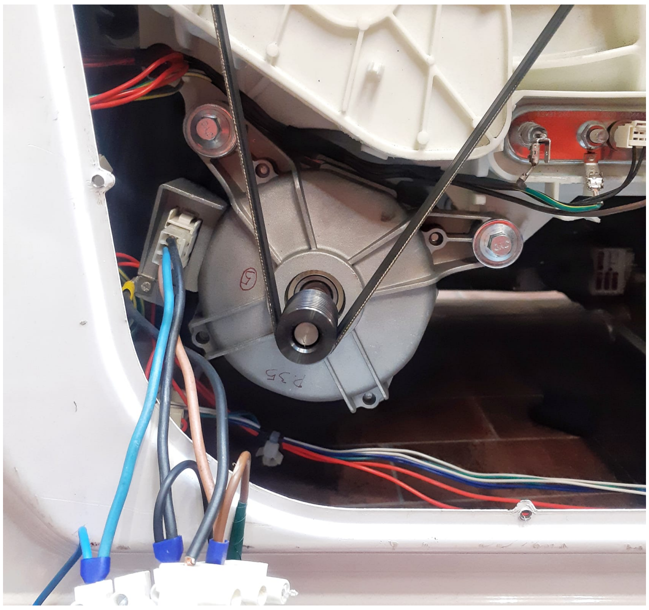


Figure 5.3: MUT3 Interior Permanent Magnet (IPM) motor used.

- **Washing Machine**: an Haier Group brand washing machines under the name of Candy. It is made for a full load of 14 kg and it could reach a maximum spin speed of 1400 rpm drum.

Figure 5.4: Candy Washing Machines.

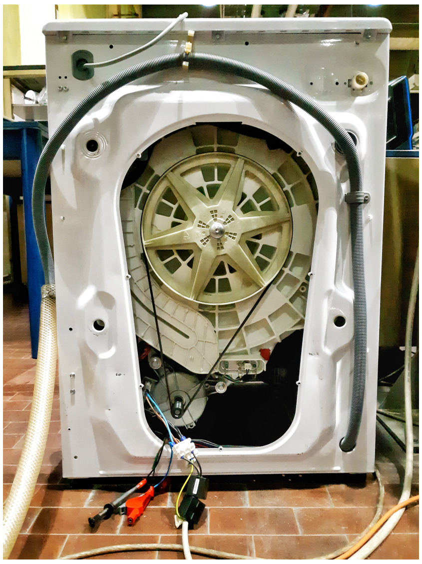


Figure 5.5: Candy Belt-Driven Washing Machine.

5.2 Experimental Results

Laboratory tests have been conducted at some specific conditions. The heaviest load tested was:

- 11 kg of clothes;
- 35 l of water;
- 500 g of unbalance.

Since a better performance has been showed by the HFI for initial position detection and with the R_s detection in laboratories tests, only this solution is inserted here.

5.2.1 START-UP: DFVC + HFI Initial Position Detection + R_s Detection

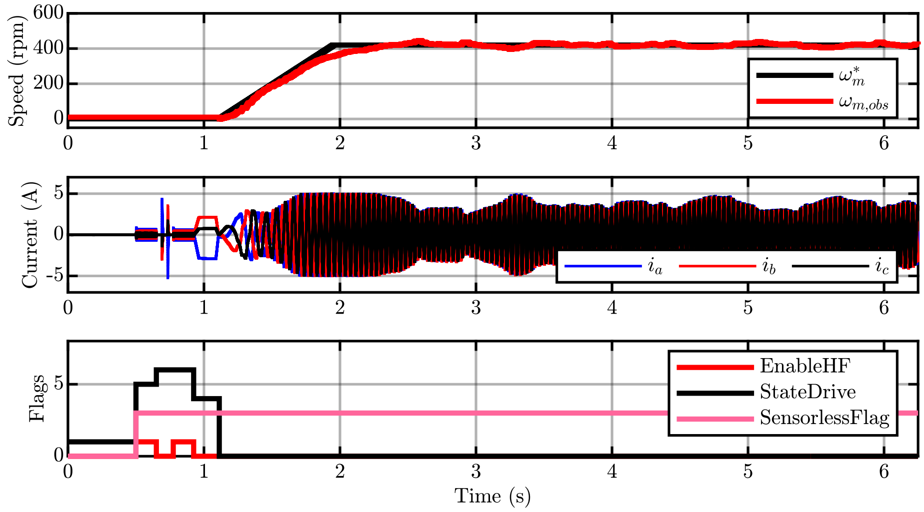


Figure 5.6: From top to bottom: reference and estimated rotor speed; motor currents; StateDrive variable flag, EnableHF flag variable, Sensorless Flag variable.

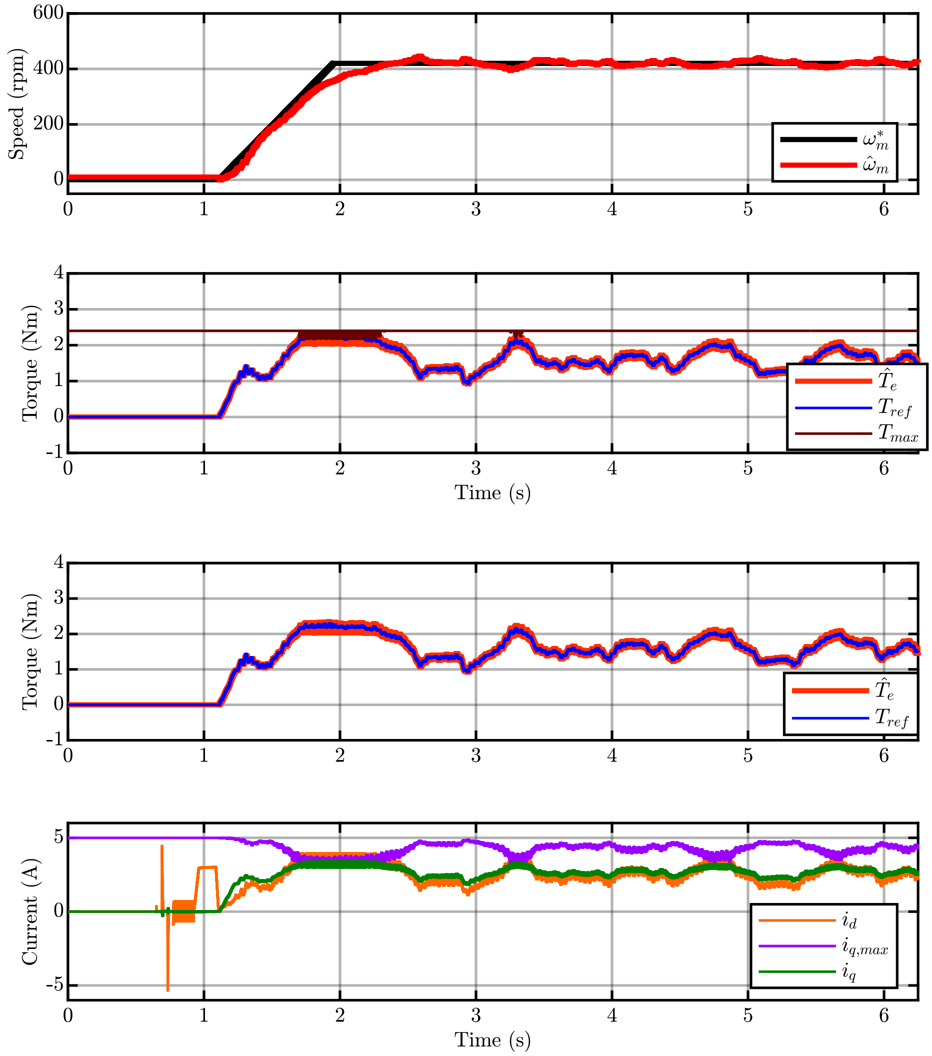


Figure 5.7: Top figure. From top to bottom: reference and estimated rotor speed; reference torque, maximum torque and estimated one. Bottom figure. From top to bottom: reference and estimated torque; $d - q$ currents and maximum q-current.

It is considered also the stopping motor:

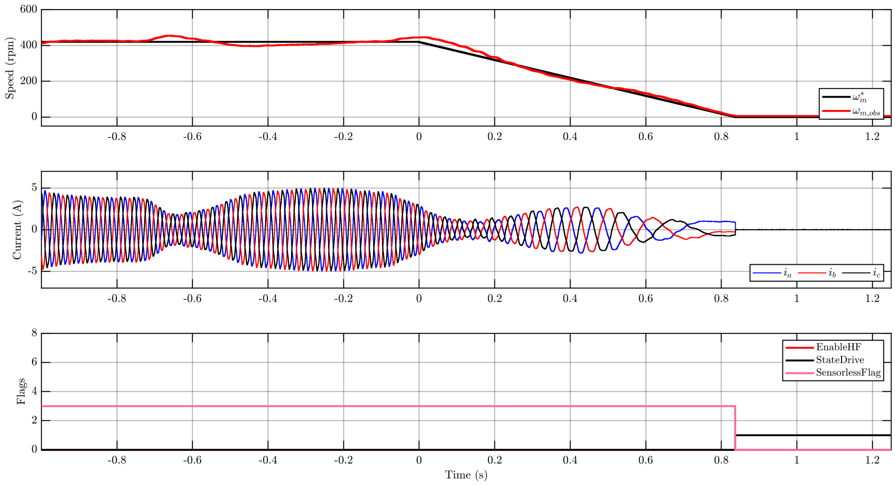


Figure 5.8: From top to bottom: reference and estimated rotor speed; motor currents; StateDrive variable flag, EnableHF flag variable, Sensorless Flag variable.

5.2.2 HIGH SPEED: DFVC + HFI Initial Position Detection + R_s Detection

At high speeds, the drum is filled only with wet clothes and they are satellite in the circumference of the basket. If they are not placed in a balanced way, they can cause imbalance and so the inertia gets bigger.

The next figures represent the acceleration from 16000 to 18000 rpm motor at no load, when drum is empty.

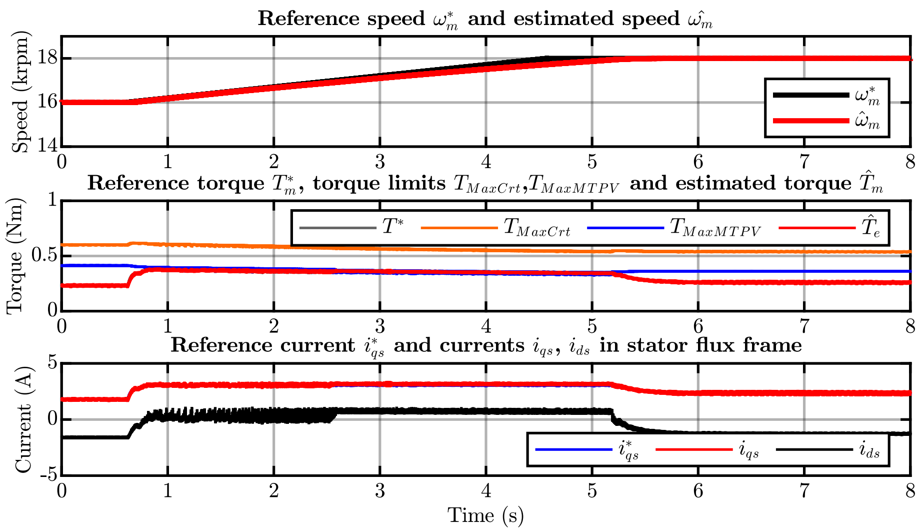


Figure 5.9: From top to bottom: reference and estimated speed; reference torque, maximum torque in MTPA and in MTPV, estimated torque; $d_s - q_s$ current and q_s reference current.

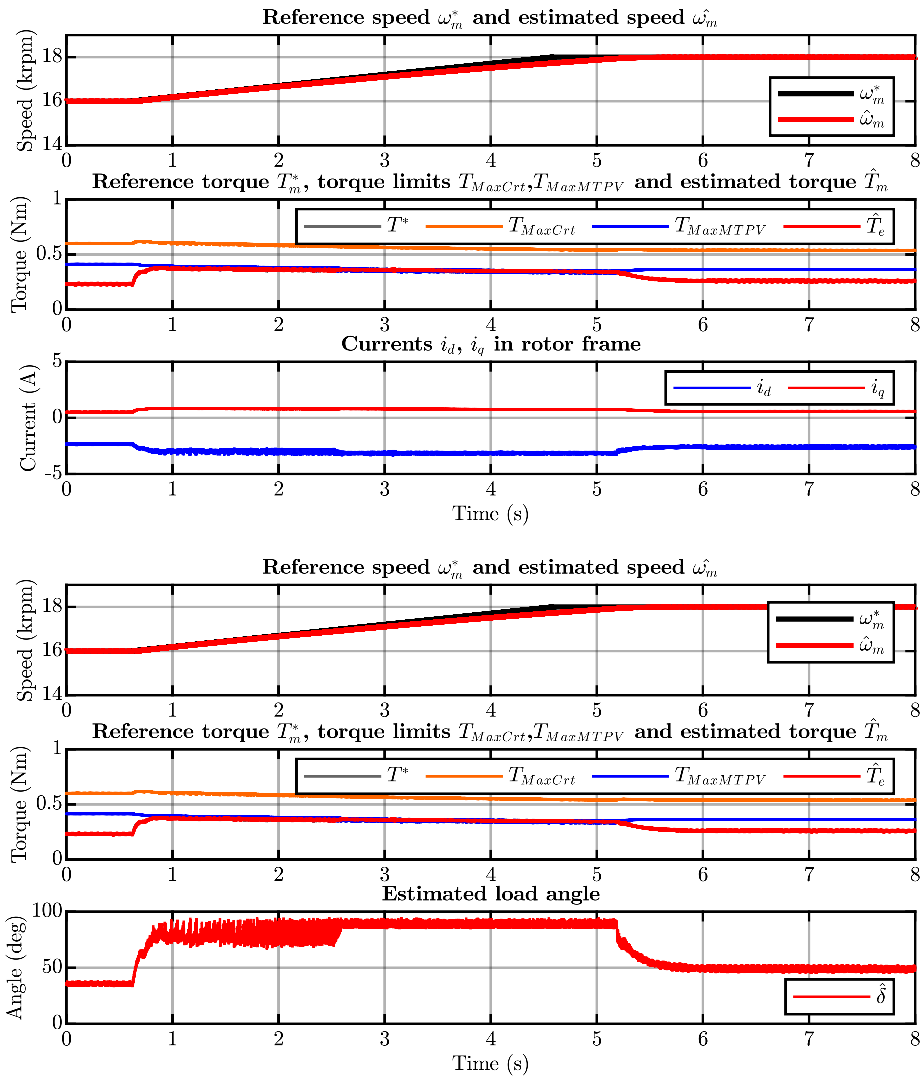
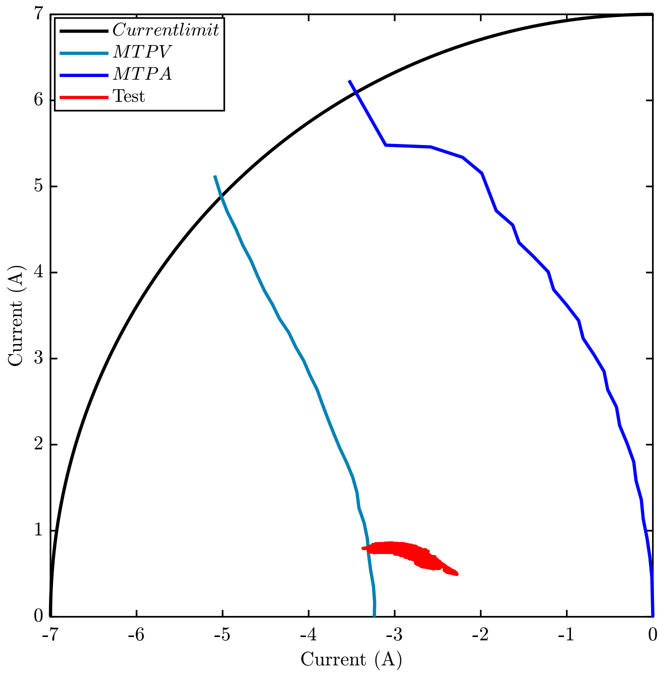


Figure 5.10: Top figure. From top to bottom: reference and estimated speed; reference torque, maximum torque in MTPA and in MTPV, estimated torque; $d-q$ currents. Bottom figure. From top to bottom: reference and estimated speed; reference torque, maximum torque in MTPA and in MTPV, estimated torque; estimated load angle δ.



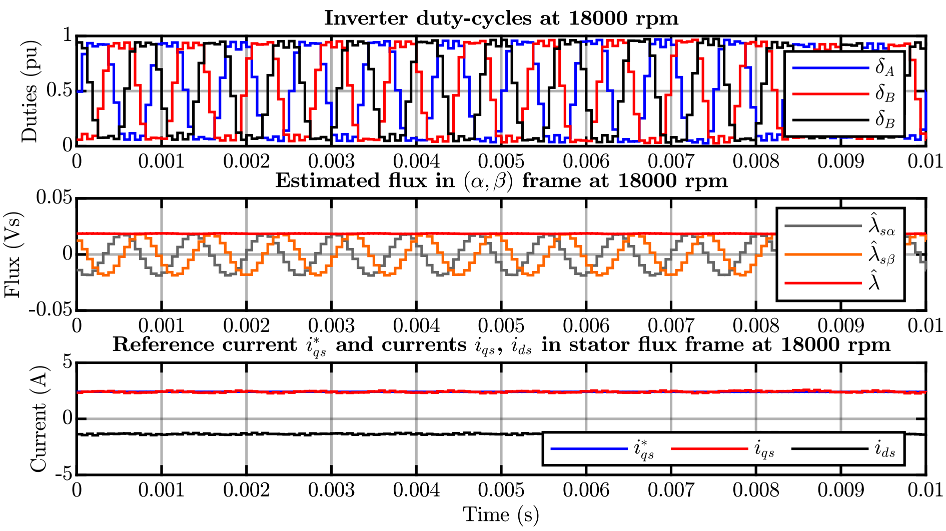


Figure 5.11: Top figure. From top to bottom: current limit, MTPA, MTPV during acceleration, current during accelerations during the test. Bottom figure. From top to bottom: inverter duty cycles; estimated $\alpha - \beta$ flux components and its estimated amplitude; $d - q$ currents and q_s reference current.

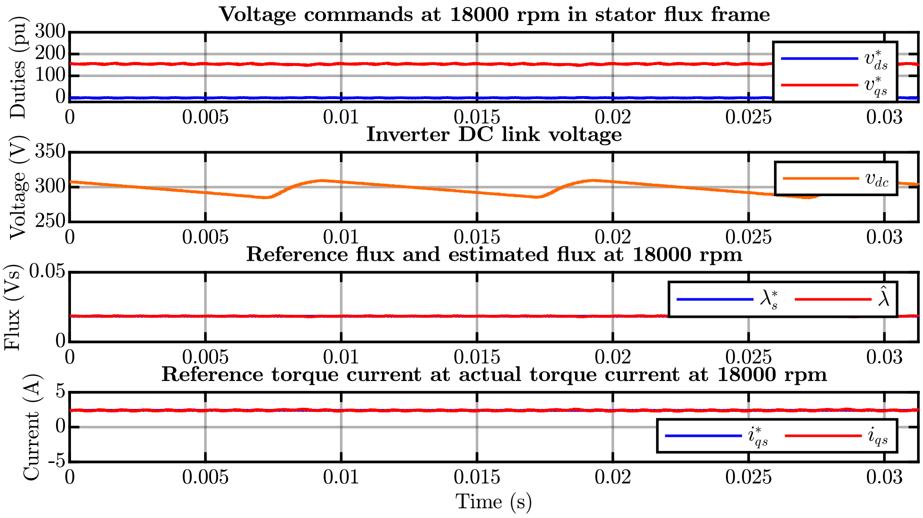


Figure 5.12: From top to bottom: reference $d_s - q_s$ voltages at 18000 rpm motor; DC link voltage at 18000 rpm motor; reference and actual q_s current at 18000 rpm motor.

5.3 Results and observations

Simulation results showed which solution was better to adopt above the other. After having chose the solution in which Direct Flux Vector Control (DFVC) is integrated with HFI for initial position detect with the preliminary R_s detection and SFO as sensorless strategy is used, the laboratories tests put in evidence that:

- The motor have responded very well at starting in the heaviest load and during all the tumbling (washing operation) procedure. The HFI could be implemented at start-up but this will add more complexity to the motor control C-code.

- The motor responded very well at no load at high speed and during acceleration respecting the motor control and so following the MTPV trajectory in order to exploit the motor at its best.

Conclusions

The experimental results have confirmed all the previsions made with the simulation model.
The observations show that:

- The characterization of the electric motor (Magnetic Model Identification) was fundamental because it permitted to design the best magnetic model to insert in the motor control. In this case, for a sensorless motor control, it was so important to implement Look-Up Tables in order to obtain exact values of stator flux amplitude for Direct Flux Vector Control (DFVC) and to regulate the load angle of MTPV region through the limitation of the torque current. This means that for every motor inserted in the washing machines the magnetic model should be known, but that is the price for having a good performance of a washing machine using Permanent Magnet Synchronous Motor (PMSM).

- DFVC is a high performance solution since it controls directly the stator flux directed on d_s axis and the torque current $i_{q,s}$ directed on q_s axis.
  The flux weakening results very easy to implement and limit $i_{q,s}$ current and the motor seems to responds very well following the MTPV trajectory at high speeds.

- The control method is quite sensitive at low speeds to the motor parameters and dead-time error voltages. Even if the SFO can estimated rotor position for the entire range of frequency, the DFVC + SFO use the value of stator resistance that changes with temperature variations and they use also the reconstruction of voltages that aren't correct since the dead-time of inverter legs causes error voltages. That's why it is so important to identify and compensate dead-time error voltages and also estimate R_s during the sensorless motor control. These procedure are necessary.

- The solution adopted DFVC + HFI for initial rotor position at a high frequency of 500 Hz results to be noiseless;

- Tests at full load for starting and at no load at high speed responded very well to the solicitation given to the washing machines as figures of chapter 5 show; the motor responds well to the dynamic of motor control loops.

- The motor control through regulation of stator flux - torque current responds very well considering the presence of oscillations of the DC link voltage with fundamental frequency that goes from 0 to 1200 Hz at 18000 rpm motor.

- To conclude the project, experimental validation made in the Haier Group company will be done in the future.

Bibliography

[1] *How washing machine is made - material, making, used, parts, components, structure, procedure, product.* [Online]. Available: http://www.madehow.com/Volume-1/Washing-Machine.html (visited on 09/15/2021).

[2] *Washing Machines*, en, Apr. 2011. [Online]. Available: https://clusterpile.wordpress.com/2011/04/20/washing-machines-2/ (visited on 09/15/2021).

[3] *Parts of a Washing Machine & How it Works*, en, Jun. 2009. [Online]. Available: https://www.brighthubengineering.com/consumer-appliances-electronics/38895-working-parts-of-a-washing-machine/ (visited on 09/18/2021).

[4] Unknown, *World of Physics: How Washing Machines Work*, Apr. 2017. [Online]. Available: http://physicsworld123.blogspot.com/2017/04/how-washing-machines-work.html (visited on 09/18/2021).

[5] T. t. p. g. i. S. a. n. l. f. t. i. g. b. c. o. c. D. t. v. u. cycles and S. C. D. M. D. D. T. R. i. t. Text, *Topic: Washing machines*, en. [Online]. Available: https://www.statista.com/topics/2186/washers-and-dryers/ (visited on 09/18/2021).

[6] W. Wilde, *3 Types of Washing Machines | Duerden's Appliance & Mattress | Salt Lake City, UT*, en, Apr. 2019. [Online]. Available: https://www.duerdensappliance.com/blog/3-types-of-washing-machines (visited on 09/18/2021).

[7] M. Z. U. January 4 and 2016, *When It Comes to Washers, There's No Place Like America*, en. [Online]. Available: https://www.reviewed.com/laundry/features/washer-space-race-spinning-out-of-control (visited on 09/18/2021).

[8] *Top-loading washers remain more popular with Americans*, en-US. [Online]. Available: https://www.consumerreports.org/cro/news/2010/04/top-loading-washers-remain-more-popular-with-americans/index.htm (visited on 09/18/2021).

[9] *Lavatrici Direct Drive*. [Online]. Available: https://www.riemelettrodomestici.it/lavatrici-direct-drive/ (visited on 09/19/2021).

[10] R. Bojoi, B. He, F. Rosa, and F. Pegoraro, «Sensorless Direct Flux and Torque Control for Direct Drive washing machine applications», in *2011 IEEE Energy Conversion Congress and Exposition*, ISSN: 2329-3748, Sep. 2011, pp. 347–354. DOI: 10.1109/ECCE.2011.6063790.

[11] *Lavatrici Direct Drive*. [Online]. Available: https://www.riemelettrodomestici.it/lavatrici-direct-drive/ (visited on 09/19/2021).

[12] *Agitator Washers vs. Impeller Washers | Whirlpool*. [Online]. Available: https://www.whirlpool.com/blog/washers-and-dryers/impeller-vs-agitator.html (visited on 09/19/2021).

[13] *Amana 3.5 Cu. Ft. Top Load Washer with Dual-Action Agitator White NTW4516FW*, en. [Online]. Available: https://www.bestbuy.com/site/amana-3-5-cu-ft-top-load-washer-with-dual-action-agitator-white/5369600.p?skuId=5369600 (visited on 09/19/2021).

[14] *Front Loader Washing Machine, 9.5kg | Haier New Zealand*. [Online]. Available: https://www.haier.co.nz/laundry/washing-machines/front-loader-washing-machine-9.5kg-hwf95an1-62354.html (visited on 09/19/2021).

[15] *CS149TE | Candy Washing Machine | White | ao.com*, en-GB. [Online]. Available: https://ao.com/product/cs149te-candy-washing-machine-white-80946-1.aspx (visited on 09/19/2021).

[16] *Pralka CANDY RO16106DWMCE/1-S 10kg 1600 obr A+++*, pl. [Online]. Available: https://www.mediaexpert.pl/agd/pralki-i-suszarki/pralki/pralka-candy-rapido-ro16106dwmce-1-s (visited on 09/19/2021).

[17] *Candy CSTG 48TE/1-S Felültöltős mosógép, 8 kg, 1400 ford/perc, Mix Power Systems, Easy Iron, Kg Detector, GentleTouch opening, F energiaosztály, Fehér - eMAG.hu*, hu. [Online]. Available: https://www.emag.hu/candy-felultoltos-mosogep-8-kg-1400-ford-perc-mix-power-systems-easy-iron-kg-detector-gentletouch-opening-f-energiaosztaly-feher-cstg-48te-1-s/pd/DS9W3DMBM/ (visited on 09/19/2021).

[18] *staber*. [Online]. Available: https://www.solardirect.com/archives/energy/staber/Copy%20of%20staber.htm (visited on 09/19/2021).

[19] *Drive (inverter) motor | DonanımHaber Forum*. [Online]. Available: https://forum.donanimhaber.com/drive-inverter-motor--125759571 (visited on 09/19/2021).

[20] *Appliances Online*. [Online]. Available: https://www.appliancesonline.com.au (visited on 09/24/2021).

[21] *Get the right size washer – washing machine capacity explained*, en-US. [Online]. Available: https://www.appliancesonline.com.au/academy/laundry/get-the-right-size-washer-washing-machine-capacity-expained/ (visited on 09/24/2021).

[22] *FAQ: What are servo pancake motors and how do they work?* [Online]. Available: https://www.motioncontroltips.com/faq-servo-pancake-motors-work/ (visited on 09/24/2021).

[23] *What is a direct drive motor?*, en-US, Sep. 2018. [Online]. Available: https://www.linearmotiontips.com/what-is-a-direct-drive-motor/ (visited on 09/24/2021).

[24] NoskillsrequiredN, *How to Use a Washing Machine Motor*, en. [Online]. Available: https://www.instructables.com/How-to-Use-a-Washing-Machine-Motor/ (visited on 09/25/2021).

[25] *How to Use a Washing Machine Motor : 6 Steps - Instructables*. [Online]. Available: https://www.instructables.com/How-to-Use-a-Washing-Machine-Motor/ (visited on 09/25/2021).

[26] Trybotics, *Washing Machine Motor Wiring Diagram*, en. [Online]. Available: https://trybotics.com/project/Washing-Machine-Motor-Wiring-Diagram-7500 (visited on 09/25/2021).

[27] P. Stekl, «Washing Machine Three-Phase AC Induction Motor Drive», en, p. 22,

[28] *Universal Motor*, en. [Online]. Available: https://www.indiamart.com/proddetail/universal-motor-7423433048.html (visited on 09/25/2021).

[29] *Washing machine motor speed control*. [Online]. Available: https://www.tehnomagazin.com/Motor/Washing-machine-motor-speed-control.htm (visited on 09/25/2021).

[30] *Which controller is used in washing machine? – ElectroAnswers.com*. [Online]. Available: https://electroanswers.com/appliance/which-controller-is-used-in-washing-machine/#How_does_triac_control_AC_motor_speed (visited on 09/25/2021).

[31] L. Xheladini, A. Tap, T. Aşan, M. Yılmaz, and L. T. Ergene, «Permanent Magnet Synhronous Motor and Universal Motor comparison for washing machine application», in *2017 11th IEEE International Conference on Compatibility, Power Electronics and Power Engineering (CPE-POWERENG)*, ISSN: 2166-9546, Apr. 2017, pp. 381–386. DOI: 10.1109/CPE.2017.7915201.

[32] *Universal Motor For Washing Machine-Wolong Electric Group Co., Ltd.* [Online]. Available: https://www.wolong-electric.com/product/details/118.html (visited on 09/29/2021).

[33] *PSC Motor For Washing Machine-Wolong Electric Group Co., Ltd.* [Online]. Available: https://www.wolong-electric.com/product/details/117.html (visited on 09/29/2021).

[34] *BPM Motor For Washing Machine-Wolong Electric Group Co., Ltd.* [Online]. Available: https://www.wolong-electric.com/product/details/119.html (visited on 09/29/2021).

[35] *AC Induction Motors vs. Permanent Magnet Synchronous Motors*, en, Jan. 2017. [Online]. Available: https://empoweringpumps.com/ac-induction-motors-versus-permanent-magnet-synchronous-motors-fuji/ (visited on 09/29/2021).

[36] *Brushless DC electric motor*, en, Page Version ID: 1046003216, Sep. 2021. [Online]. Available: https://en.wikipedia.org/w/index.php?title=Brushless_DC_electric_motor&oldid=1046003216 (visited on 09/29/2021).

[37] *PRODUCTS – Motor Appliances SRL*, en-GB. [Online]. Available: https://www.motorappliances.com/products/ (visited on 09/29/2021).

[38] W. Cheng, H. Zhiwei, and G. Jinian, «The application of a novel motor in washing machines», in *ICEMS'2001. Proceedings of the Fifth International Conference on Electrical Machines and Systems (IEEE Cat. No.01EX501)*, vol. 2, Aug. 2001, 1030–1033 vol.2. DOI: 10.1109/ICEMS.2001.971855.

[39] *LG washing machine direct drive motor*, en. [Online]. Available: https://www.huoltopalvelu.com/LG-washing-machine-direct-drive-motor (visited on 09/30/2021).

[40] [Online]. Available: https://www.printedmotorworks.com/brushed-pancake-motors/ (visited on 09/30/2021).

[41] *Direct drive motors*, en-US. [Online]. Available: https://www.elmeq.com/download/direct-drive-motors/ (visited on 09/30/2021).

[42] T. Win, «Speed Controller Design of Permanent Magnet Synchronous Motor used in Washing Machine», en, p. 6,

[43] *Permanent Magnet Synhronous Motor and Universal Motor comparison for washing machine application | IEEE Conference Publication | IEEE Xplore.* [Online]. Available: https://ieeexplore-ieee-org.ezproxy.biblio.polito.it/document/7915201 (visited on 10/11/2021).

[44] ChauGentelia, *Interior Permanent Magnet Synchronous Motor | Psoriasisguru.com*, en-US. [Online]. Available: https://psoriasisguru.com/interior-permanent-magnet-synchronous-motor/ (visited on 10/12/2021).

[45] *Three-phase interior permanent magnet synchronous motor with sinusoidal back electromotive force - Simulink - MathWorks Italia*. [Online]. Available: https://it.mathworks.com/help/autoblks/ref/interiorpmsm.html (visited on 10/13/2021).

[46] E. Armando, R. I. Bojoi, P. Guglielmi, G. Pellegrino, and M. Pastorelli, «Experimental Identification of the Magnetic Model of Synchronous Machines», *IEEE Transactions on Industry Applications*, vol. 49, no. 5, pp. 2116–2125, Sep. 2013, Conference Name: IEEE Transactions on Industry Applications, ISSN: 1939-9367. DOI: 10.1109/TIA.2013.2258876.

[47] E. Armando, P. Guglielmi, G. Pellegrino, and R. Bojoi, «Flux linkage maps identification of synchronous AC motors under controlled thermal conditions», in *2017 IEEE International Electric Machines and Drives Conference (IEMDC)*, May 2017, pp. 1–8. DOI: 10.1109/IEMDC.2017.8002334.

[48] T. Jahns and V. Caliskan, «Uncontrolled generator operation of interior PM synchronous machines following high-speed inverter shutdown», *IEEE Transactions on Industry Applications*, vol. 35, no. 6, pp. 1347–1357, Nov. 1999, Conference Name: IEEE Transactions on Industry Applications, ISSN: 1939-9367. DOI: 10.1109/28.806049.

[49] *What is a Direct Drive motor? - Magnetic Innovations*, en-US. [Online]. Available: https://www.magneticinnovations.com/faq/direct-drive-motor/ (visited on 11/06/2021).

[50] G. Pellegrino, R. I. Bojoi, and P. Guglielmi, «Unified Direct-Flux Vector Control for AC Motor Drives», *IEEE Transactions on Industry Applications*, vol. 47, no. 5, pp. 2093–2102, Sep. 2011, Conference Name: IEEE Transactions on Industry Applications, ISSN: 1939-9367. DOI: 10.1109/TIA.2011.2161532.

[51] *Sensorless Direct Flux and Torque Control for Direct Drive washing machine applications | IEEE Conference Publication | IEEE Xplore*. [Online]. Available: https://ieeexplore-ieee-org.ezproxy.biblio.polito.it/document/6063790 (visited on 11/15/2021).