POLITECNICO DI MILANO
School of Industrial and Information Engineering
Course of Master's Degree in Electrical Engineering

# Efficiency Characterization of Synchronous Reluctance vs Induction vs Permanent Magnet Assisted Synchronous Reluctance Motors.

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# *Acknowledgements*

What is experience? *"Experience is learning from your own mistakes"*. This sentence can be considered well known and also a bit expected, but if we stop and think about that it is an absolute truth, in my life I've made a lot of mistakes but the force of a person arises in bad moments and when you feel lost, this is the base of science, research & development and all the human progress.

I hope I'll never forget the importance of mistakes in all my life and my work career, learning from my faults and treasuring everything can increase my experience.

During these years, a lot of people leave a mark on me and my academic career, and it's thanks to each one of these people that I could become how I am; I can't say thanks to all of us, but I'll try to mention as many names as possible.

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Thanks to my family and my girlfriend Nadina, that everyday inspired me and sustain my state of mind during beautiful but also difficult periods.

Thanks to the ABB SMO Team members Maria, Pietro, Aida, Veronica, Giovanni, Marco and my internship fellow Hessam that gave me a great opportunity and made me feel good during all the internship and an integral part of the work team.

## Abstract

Energy efficiency has become more and more important in electric motors, due to their large use in Industrial and civil applications. Old DC motors are often going to be replaced with new AC Induction drive systems. ABB has recently developed two unique solutions, Synchronous Reluctance and Permanent Magnet Synchronous Reluctance to achieve higher energy efficiency levels. It is unfortunately not clear, in many cases, what can be the economic and environmental advantage of using such solutions in place of the old DC systems.

My work focus is an experimental level to characterize and compare the behaviour of these three systems in several working points, to provide a full picture of its uses advantages. All tests were carried out in the **ABB Advanced Motor Technology SMO-Team laboratory Vittuone, Italy.**

My work consisted in carrying out efficiency tests on different electric motors when fed with a frequency converter. The analysed motors were all **IEC-size 15kW 4-Pole motors namely an induction motor, a synchronous reluctance motor and a Permanent Magnet Synchronous Reluctance Motor and we also made a test on a DC motor which was not of the same specification as others but we did it to have a general overview of DC motors too.** These tests were based on a testing protocol that included many different working points for the selected motors to the aim of building an efficiency MAP for different loads and speeds considering all the IEC standards for every tests and following them properly. It is worth mentioning that I followed all the testing procedures with standards mentioned in IEC booklet.

The outcome of this work is very useful for the R&D team as well as to ABB sales department and after gaining a more thorough knowledge about behaviour of motors of different technologies when it comes to efficiency, and to ABB sales forces, that can use the obtained information from my work to build up proposal better targeted at improvement of applications efficiency.

# Chapter 1

# 1. Introduction

## 1.1 ABB

The experience that has conducted me to the study and the realization of electric motors efficiency characterization is based on the biannual internship that I did at *ABB Ltd., Discrete Automation and Motion Division*, situated in Vittuone (MI), Italy. A photo of the factory can be seen in Figure 1.

Figure 1: ABB factory in Vittuone (MI).


ABB Ltd., acronym of Asea Brown Boveri Ltd., is a Swiss multinational corporation based in Zurich, Switzerland; the company in its current form was created in 1988, but its history spans over 120 years. Worldwide leader, with 150.000 employees all over the world, it operates in approximately 100 countries and points its main production to energy and automation technologies. ABB has a long history and a rich heritage of technology innovation; it not only invented or pioneered many power and automation technologies that have shaped the world we know today, but has managed to maintain its technology leadership in these areas, often for decades.

Today, ABB stands as the largest supplier of industrial motors and drives, the largest provider of generators to the wind industry and the largest supplier of power grids worldwide.

## 1.2 Scope of Work

The internship with thesis that I carried out in this company took place, in particular, in the SMO R&D Team (acronym of *Special Motors for OEMs Research & Development Team*), that refers to Engg. Giulio Secondo and Engg. Alessandro Castagnini; the team works on “special” motors, new technological electric machines, studying and designing consistently new prototypes of motors that can be ordered by customers or realized for R&D aims.

Scope of my work was carrying out efficiency tests on different electric motors when fed with a frequency converter. The analysed motors were all IEC-size 15kW 4-Pole motors namely an induction motor, a synchronous reluctance motor and a Permanent Magnet Synchronous Reluctance Motor. These tests were based on a testing protocol that included many different working points for the selected motors to the aim of building an efficiency MAP for different loads and speeds considering all the IEC standards for every tests and following them properly.

The outcome of this work is very useful for the R&D team and after gaining a more thorough knowledge about behaviour of motors of different technologies when it comes to efficiency, and to ABB sales forces, that can use the obtained information from my work to build up proposal better targeted at improvement of applications efficiency.

## 1.3 Thesis Purpose

This thesis work aims to study and analyse the Induction, Synchronous Reluctance, Permanent Magnet Synchronous Reluctance and a DC Motor, focusing the attention on the efficiency characterization of all these motors at different level of usage. So there is a clear MAP of efficient motors available for the R&D and Sales Unit of ABB for their business in Motors.

I have made a comparison between all these three motors which were tested for their efficiency response, explaining which motor can be useful of the usage required by the customers.

Since the validation of IEC/EN 60034-30, a worldwide energy efficiency classification system has existed for low voltage three-phase asynchronous motors. This system increases the level of harmonization in efficiency regulations around the world and also covers motors for explosive atmospheres. IEC/ EN 60034-30:2008 defines International Efficiency (IE) classes for single speed, three phase, 50 and 60 Hz induction motors. The standard is part of an effort to unify motor testing procedures as well as efficiency and product labelling requirements to enable motor purchasers worldwide to easily recognize premium efficiency products. The efficiency levels defined in IEC/EN 60034-30 are based on test methods specified in IEC/ EN 60034-2-1:2007.

# Chapter 2 “INDUCTION MOTOR”

## 2.1 Description :-

Theoretically an induction or asynchronous motor is an AC electric motor in which the electric current in the rotor needed to produce torque is obtained by electromagnetic induction from the magnetic field of the stator winding. An induction motor therefore does not require mechanical commutation, separate-excitation or self-excitation for all or part of the energy transferred from stator to rotor, as in universal, DC and large synchronous motors.

Induction motors are the most commonly used electrical machines. They are cheaper, more rugged and easier to maintain compared to other alternatives.

## 2.2Construction:-

An induction motor has 2 main parts; the Stator and Rotor. The Stator is the stationary part and the rotor is the rotating part. The Rotor sits inside the Stator. There will be a small gap between rotor and stator, known as air-gap. The value of the radial air-gap may vary from 0.5 to 2 mm.

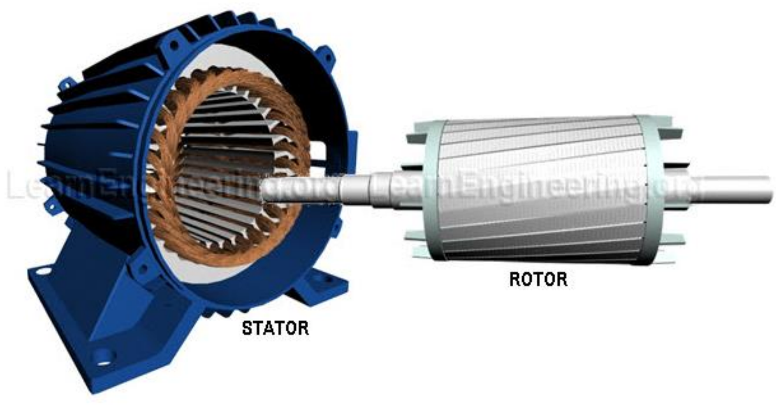



*Figure 1: Parts of an Induction Motor*

### 2.2.1 The stator:

The stator is the outer stationary part of the motor, which consists of:

- The outer cylindrical frame of the motor, which is made either of welded sheet steel, cast iron or cast aluminum alloy. This may include feet or a flange for mounting.
- The magnetic path, which comprises a set of slotted steel laminations pressed into the cylindrical space inside the outer frame. The magnetic path is laminated to reduce eddy currents, lower losses and lower heating.
- A set of insulated electrical windings, which are placed inside the slots of the laminated magnetic path. The cross-sectional area of these windings must be large enough for the power rating of the motor. For a 3-phase motor, 3 sets of windings are required, one for each phase.

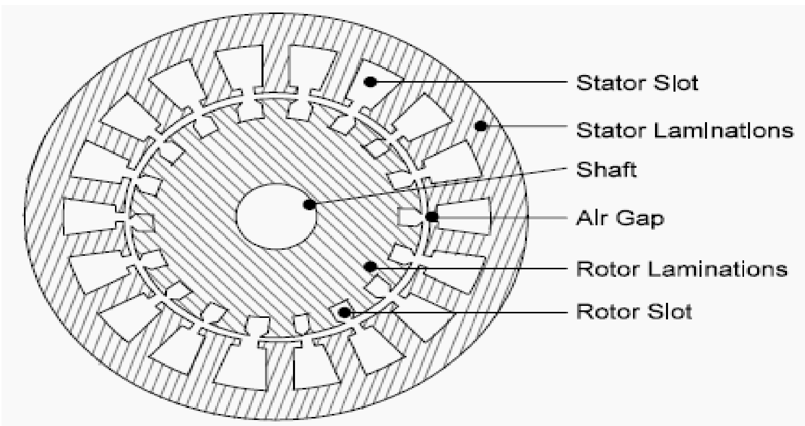



*Figure 2: Stator and Rotor Laminations*

A Stator is made by stacking thin-slotted highly permeable steel laminations inside a steel or cast iron frame. The way the steel laminations are arranged inside the frame is shown in the following figure. Here only few of the steel laminations are shown. Winding passes through slots of the stator.


*Figure 1: Construction Details of a Stator*

**Effect of 3 Phase Current Passing through a Stator Winding:**

When a 3 phase AC current passes through the winding something very interesting happens. It produces a rotating magnetic field (RMF). As shown in the figure below a magnetic field is produced which is rotating in nature. RMF is an important concept in electrical machines. We will see how this is produced in the next section.


*Figure 2: Rotating Magnetic Field Produced in an Induction Motor*

### 2.1.2 The Rotor:

This is the rotating part of the motor. As with the stator above, the rotor consists of a set of slotted steel laminations pressed together in the form of a cylindrical magnetic path and the electrical circuit. The electrical circuit of the rotor can be either:

- Wound rotor type, which comprises 3 sets of insulated windings with connections brought out to 3 sliprings mounted on the shaft. The external connections to the rotating part are made via brushes onto the sliprings. Consequently, this type of motor is often referred to as a slipring motor.

Squirrel cage rotor type, which comprises a set of copper or aluminium bars installed into the slots, which are connected to an end-ring at each end of the rotor. The construction of these rotor windings resembles a 'squirrel cage'. Aluminium rotor bars are usually die-cast into the rotor slots, which results in a very rugged construction. Even though the aluminium rotor bars are in direct contact with the steel laminations, practically all the rotor current flows through the aluminium bars and not in the laminations.

### 2.1.3 The Other parts:

The other parts, which are required to complete the induction motor are:

- Two end-flanges to support the two bearings, one at the drive-end (DE) and the other at the non-drive-end (NDE)

- Two bearings to support the rotating shaft, at DE and NDE
- Steel shaft for transmitting the torque to the load
- Cooling fan located at the NDE to provide forced cooling for the stator and rotor
- Terminal box on top or either side to receive the external electrical connections

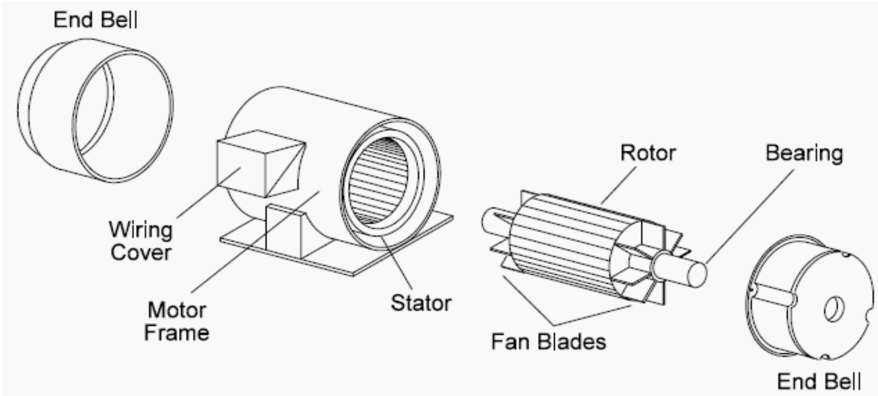



*Figure 3: Assembling Details of Typical AC Induction Motor*

## 2.3 Operating Principle :-

To understand the phenomenon of a rotating magnetic field, it is much better to consider a simplified 3 phase winding with just 3 coils. A wire carrying current produces a magnetic field around it. Now for this special arrangement, the magnetic field produced by 3 phase A.C current will be as shown at a particular instant.

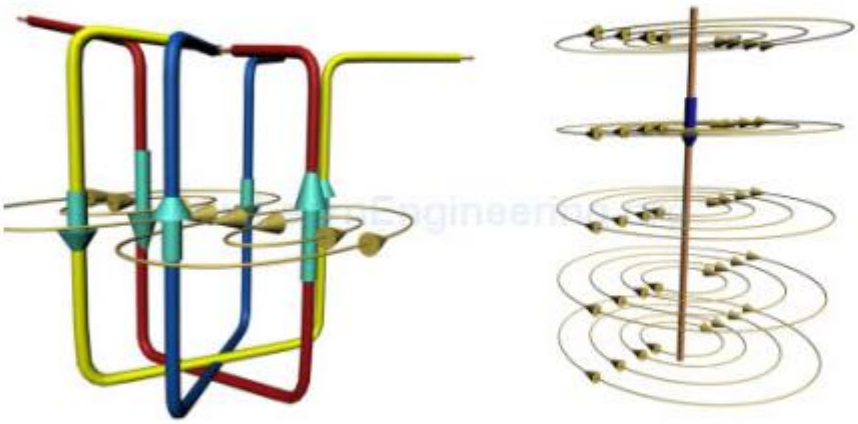


*Figure 4: Magnetic field produced around the simplified winding and a single wire*

The components of A.C current will vary with time. Two more instances are shown in the following figure, where due to the variation in the A.C current, the magnetic field also varies. It is clear that the magnetic field just takes a different orientation, but its magnitude remains the same. From these 3 positions it’s clear that it is like a magnetic field of uniform strength rotating. The speed of rotation of the magnetic field is known as synchronous speed.

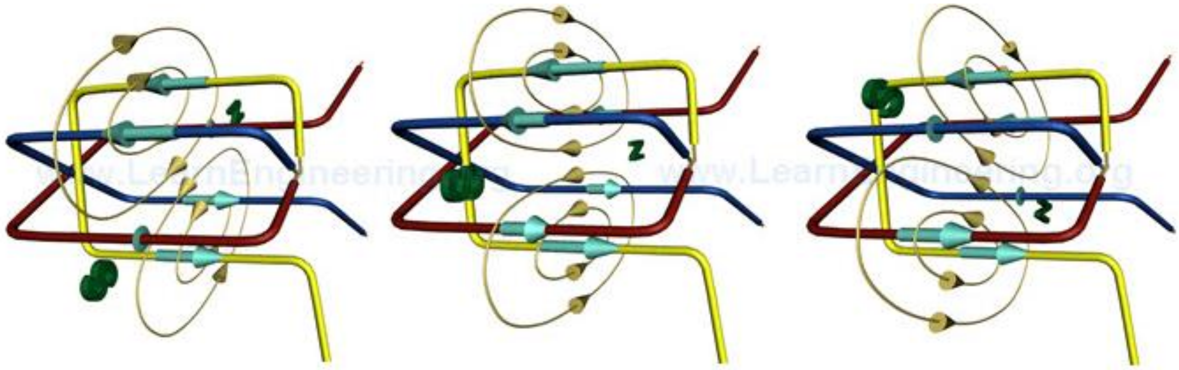


*Figure 5: Rotating Magnetic Field Produced Over Simplified Winding*

### 2.3.1 The Effect of RMF on a Closed Conductor:

Assume you are putting a closed conductor inside such a rotating magnetic field. Since the magnetic field is fluctuating an E.M.F will be induced in the loop according to Faraday’s law. The E.M.F will produce a current through the loop. So the situation has become as if a current carrying loop is situated in a magnetic field. This will produce a magnetic force in the loop according to Lorentz law, so the loop will start to rotate.

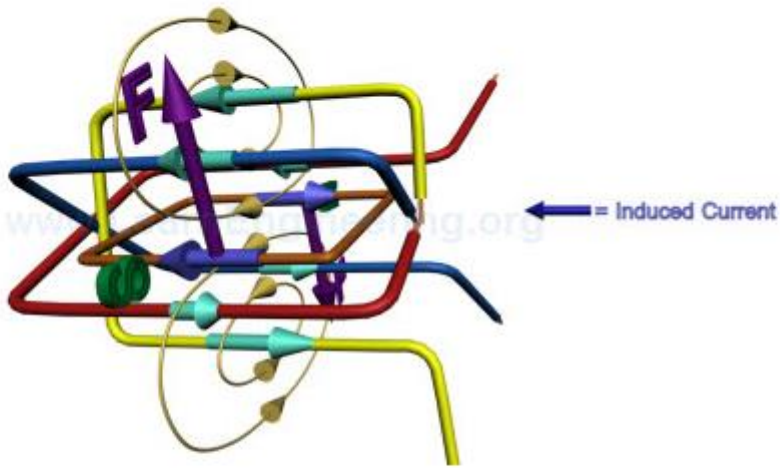



*Figure 6: Effect of RMF on a Closed Conductor*

### 2.3.2 Production of a rotating magnetic field:

The stator of an induction motor consists of a number of overlapping windings offset by an electrical angle of 120°. When the primary winding or stator is connected to a three phase alternating current supply, it establishes a rotating magnetic field which rotates at a synchronous speed.

The direction of rotation of the motor depends on the phase sequence of supply lines, and the order in which these lines are connected to the stator. Thus interchanging the connection of any two primary terminals to the supply will reverse the direction of rotation.

The number of poles and the frequency of the applied voltage determine the synchronous speed of rotation in the motor's stator. Motors are commonly configured to have 2, 4, 6 or 8 poles. The synchronous speed, a term given to the speed at which the field produced by primary currents will rotate, is determined by the following expression.

Synchronous speed of rotation = (120* supply frequency) / Number of poles on the stator.

### 2.3.3 Production of magnetic flux:

A rotating magnetic field in the stator is the first part of operation. To produce a torque and thus rotate, the rotors must be carrying some current. In induction motors, this current comes from the rotor conductors. The revolving magnetic field produced in the stator cuts across the conductive bars of the rotor and induces an e.m.f.

The rotor windings in an induction motor are either closed through an external resistance or directly shorted. Therefore, the e.m.f induced in the rotor causes current to flow in a direction opposite to that of the revolving magnetic field in the stator, and leads to a twisting motion or torque in the rotor.

As a consequence, the rotor speed will not reach the synchronous speed of the e.m.f in the stator. If the speeds match, there would be no e.m.f. induced in the rotor, no current would be flowing, and therefore no torque would be generated. The difference between the stator (synchronous speed) and rotor speeds is called the slip. The rotation of the magnetic field in an induction motor has the advantage that no electrical connections need to be made to the rotor.

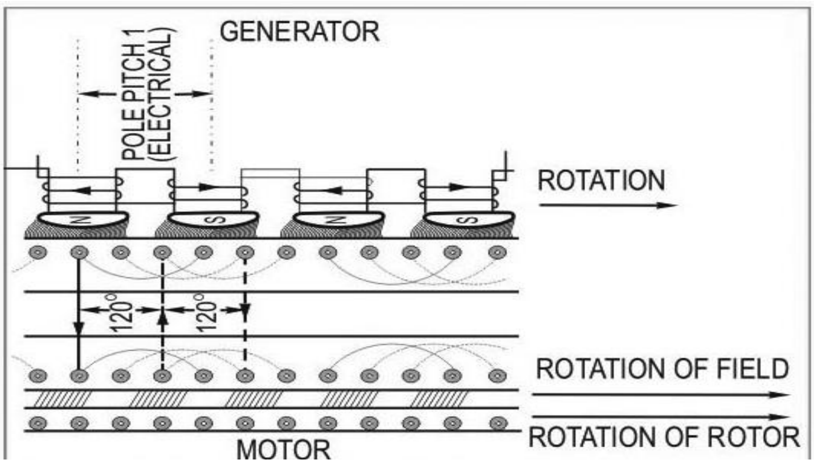



*Figure 7: Production of Rotating Magnetic field in a Three Phase Induction Motor*

## 2.4 Working Principle:-

A similar phenomenon also happens inside an induction motor. Here instead of a simple loop, something very similar to a squirrel cage is used. A squirrel cage has got bars which are shorted by end rings.

*Figure 8: Squirrel Cage Rotor which is the Most Commonly Used One in Induction Motors*

A 3 phase AC current passing through a Stator winding produces a rotating magnetic field. So as in the previous case, current will be induced in the bars of the squirrel cage and it will start to rotate. You can note variation of the induced current in squirrel cage bars. This is due to the rate of change of magnetic flux in one squirrel bar pair which is different from another, due to its different orientation. This variation of current in the bar will change over time.

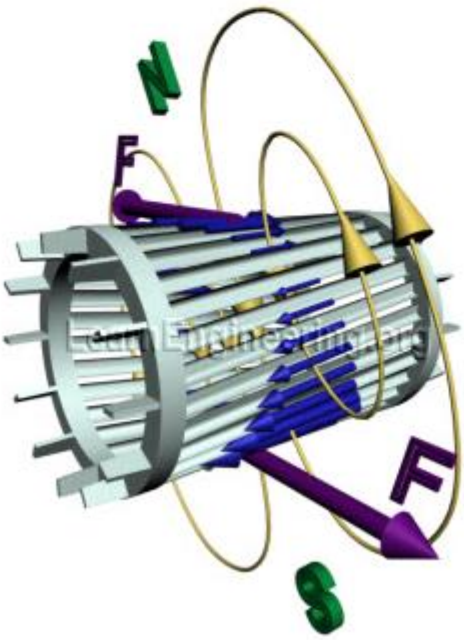



*Figure 9: RMF Produces a Torque on Rotor as in the Simple Winding Case*

That's why the name induction motor is used, electricity is induced in rotor by magnetic induction rather than direct electric connection. To aid such electromagnetic induction, insulated iron core lamina are packed inside the rotor.


*Figure 10: Thin Layers of Iron Lamina which are packed in Rotor*

Such small slices of iron layers make sure that eddy current losses are at a minimum. You can note one big advantage of 3 phase induction motors, as it is inherently self-starting.

You can also note that the bars of a squirrel cage are inclined to the axis of rotation, or it has got a skew. This is to prevent torque fluctuation. If the bars were straight there would have been a small time gap for the torque in the rotor bar pair to get transferred to the next pair. This will cause torque fluctuation and vibration in the rotor. By providing a skew in the rotor bars, before the torque in one bar pair dies out, the next pair comes into action. Thus it avoids torque fluctuation.

### 2.4.1 The Speed of Rotation of a Rotor & the Concept of Slip:

You can notice here that the both the magnetic field and rotor are rotating. But at what speed will the rotor rotate? To obtain an answer for this let's consider different cases.

Consider a case where the rotor speed is same as the magnetic field speed. The rotor experiences a magnetic field in a relative reference frame. Since both the magnetic field and the rotor are rotating at same speed, relative to the rotor, the magnetic field is stationary. The rotor will experience a constant magnetic field, so there won't be any induced e.m.f and current. This means zero force on the rotor bars, so the rotor will gradually slow down.

But as it slows down, the rotor loops will experience a varying magnetic field, so induced current and force will rise again and the rotor will speed up.

In short, the rotor will never be able to catch up with the speed of the magnetic field. It rotates at a specific speed which is slightly less than synchronous speed. The difference in synchronous and rotor speed is known as slip.

## 2.4.2 Energy Transfer in the Motor:

The rotational mechanical power obtained from the rotor is transferred through a power shaft. In short in an induction motor, electrical energy is enters via the Stator and output from the motor, the mechanical rotation is received from the rotor.


*Figure 11: Power Transfer in a Motor*

But between the power input and output, there will be numerous energy losses associated with the motor. Various components of these losses are friction loss, copper loss, eddy current and hysteresis loss. Such energy loss during the motor operation is dissipated as heat, so a fan at the other end helps in cooling down the motor.

## 2.4.3 Speed Control:

In synchronous AC motors, the rotor turns at exactly the same speed as the rotating magnetic field; in an induction motor, the rotor always turns at a lower speed than the field, making it an example of what's called an asynchronous AC motor. The theoretical speed of the rotor in an induction motor depends on the frequency of the AC supply and the number of coils that make up the stator and, with no load on the motor, comes close to the speed of the rotating magnetic field. In practice, the load on the motor (whatever it's driving) also plays a part—tending to slow the rotor down. The greater the load, the greater the "slip" between the speed of the rotating magnetic field and the actual speed of the rotor. To control the speed of an AC motor (make it go faster or slower), you have to increase or decrease the frequency of the AC supply using what's called a variable-frequency drive. So when you adjust the speed of something like a factory machine, powered by an AC induction motor, you're really controlling a circuit that's turning the frequency of the current that drives the motor either up or down.

## 2.5 Efficiency of Three Phase Induction Motor:

The main goal of my test was to perform detail tests on induction motor to plot its efficiency map.

Efficiency is defined as the ratio of the output to that of input,

$$Efficiency,\ \eta\ =\ \frac{output}{input}$$

Rotor efficiency of the three phase induction motor,

$$=\ \frac{rotor\ output}{rotor\ input}$$

= Gross mechanical power developed / rotor input

$$=\ \frac{P_m}{P_2}$$

Three phase induction motor efficiency,

$$=\ \frac{power\ developed\ at\ shaft}{electrical\ input\ to\ the\ motor}$$

Three phase induction motor efficiency

$$\eta\ =\ \frac{P_{out}}{P_{in}}$$

### 2.5.1 Efficiency Calculation Test:-

Specification of Motor Under test:

- Induction M3AA 160 MLB 4_IE2
- 4-Pole
- Rated Torque : 97.5Nm
- Rated Speed : 1470rpm
- Power : 15kW
- Voltage : 400V
- Current : 28.5 Ampere

## 2.5.2 Test Method for Determination of Efficiency :-

Following the test rules indicated in **IEC 60034-2-1** manual we opted the **Direct Method** for the determination of efficiency for this kind of motor.

The first step to start the efficiency test was to make a **heat run test** at selected motor nominal torque i.e. 97.5 and nominal speed and this heat run test usually last about 4 to 5 hours (Mandatory for Heat run test) until the temperature of motor gets stabilized.

The motor under test was fed with a supply and in opposite to the testing motor another motor was coupled and a torque meter was installed. The secondary motor was used as a load. So the primary test was to make the motor under test run for at least 4 hours or 5 hours to get stabilized. After the motor stabilization the motor was stopped immediately and we recorded some readings discussed below with more details.

Some interesting events can be seen using ABB personal designed software called as Interface used for testing of motors to make a record of all log files which later on we use for finding out the efficiency of a motor. In the above diagram like the start and stop time of the motor in the Measurement Control section. You can also have a look about the Temperature Measurement where you can see the stabilized temperature.

The following below are the important reading we made exactly after the immediate stoppage of motor at nominal values of motor.

## ➢ Motor tested at Nominal Speed and Torque

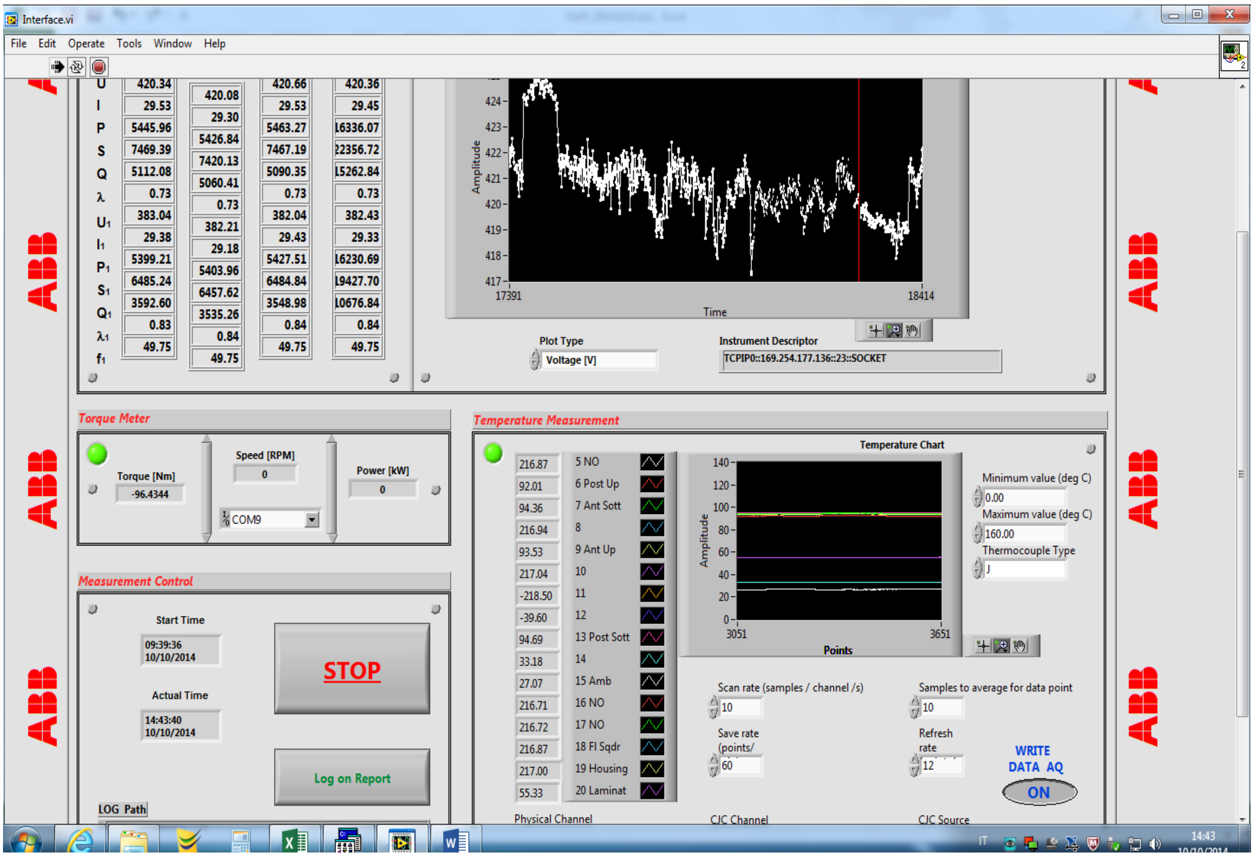



*Figure 14:- Induction M3AA 160 MLB 4 heat run nominal (100%) 1470 rpm, torque 200 Nm*

- ➢ Selimar in coppia analogica, 2380 mV (with 60 mV offset)

- ➢ ACS880-01-038A-3(Drive System) Speed 1470 rpm
- ➢ Offset Torque Meter :- 0.02 Nm

R Cold (22°C):
- ➢ Ruv = 352.70 mOhm
- ➢ Ruw = 351.20 mOhm
- ➢ Rvw = 350.00 mOhm
- ➢ R media = 351.30 mOhm

**Note: Ruv, Ruw, Rvw are all stator resistance**

After this test we supplied the motor again and started it to let it get stabilized again but with **Partial loads this time.**

## ➢ Motor tested at Speed (75%)

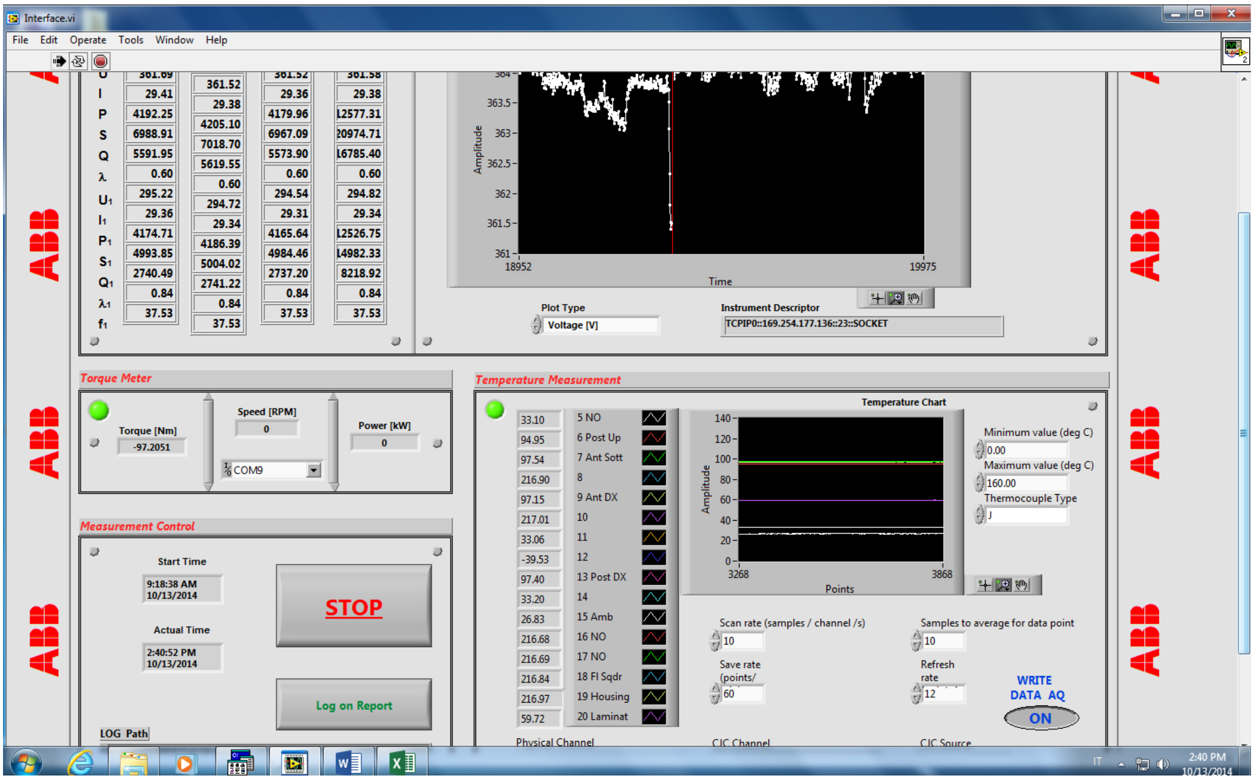



*Figure 15:- Induction M3AA 160 MLB 4 heat run nominal (75%) 1102.5 rpm, torque 200 Nm*

- ➢ Selimar in coppia analogica, 2380 mV (with 60 mV offset)
- ➢ ACS880-01-038A-3(Drive System) Speed 1102.5 rpm
- ➢ Offset Torque Meter :- 0.02 Nm

R Cold (22°C):

- ➢ Ruv = 352.70 mOhm
- ➢ Ruw = 351.20 mOhm
- ➢ Rvw = 350.00 mOhm
- ➢ R media = 351.30 mOhm

## ➢ Motor tested at Speed (50%)

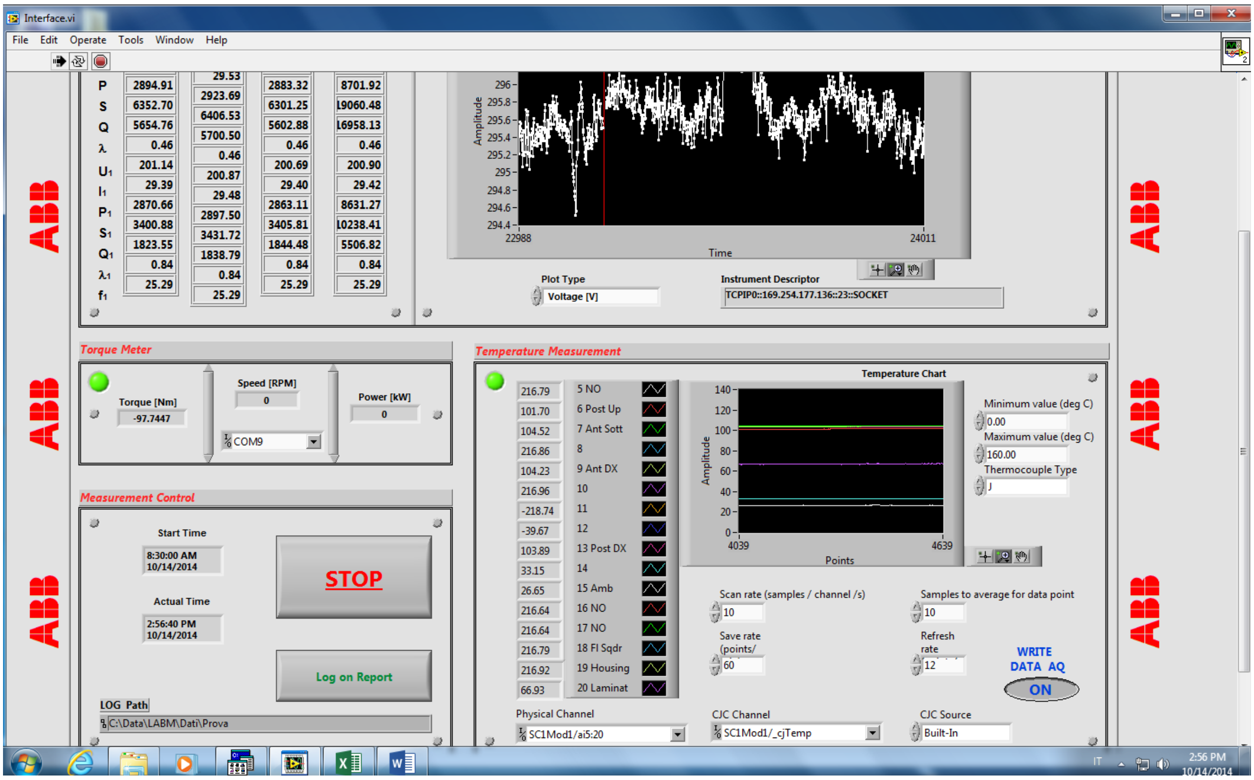


*Figure 16:- Induction M3AA 160 MLB 4 heat run nominal (100%) 1470 rpm, torque 200 Nm*

- Selimar in coppia analogica, 2380 mV (with 60 mV offset)
- ACS880-01-038A-3(Drive System) Speed 735 rpm
- Offset Torque Meter :- 0.02 Nm

R Cold (22°C):

- Ruv = 352.70 mOhm
- Ruw = 351.20 mOhm
- Rvw = 350.00 mOhm
- R media = 351.30 mOhm

## ➢ Motor tested at Speed (25%)

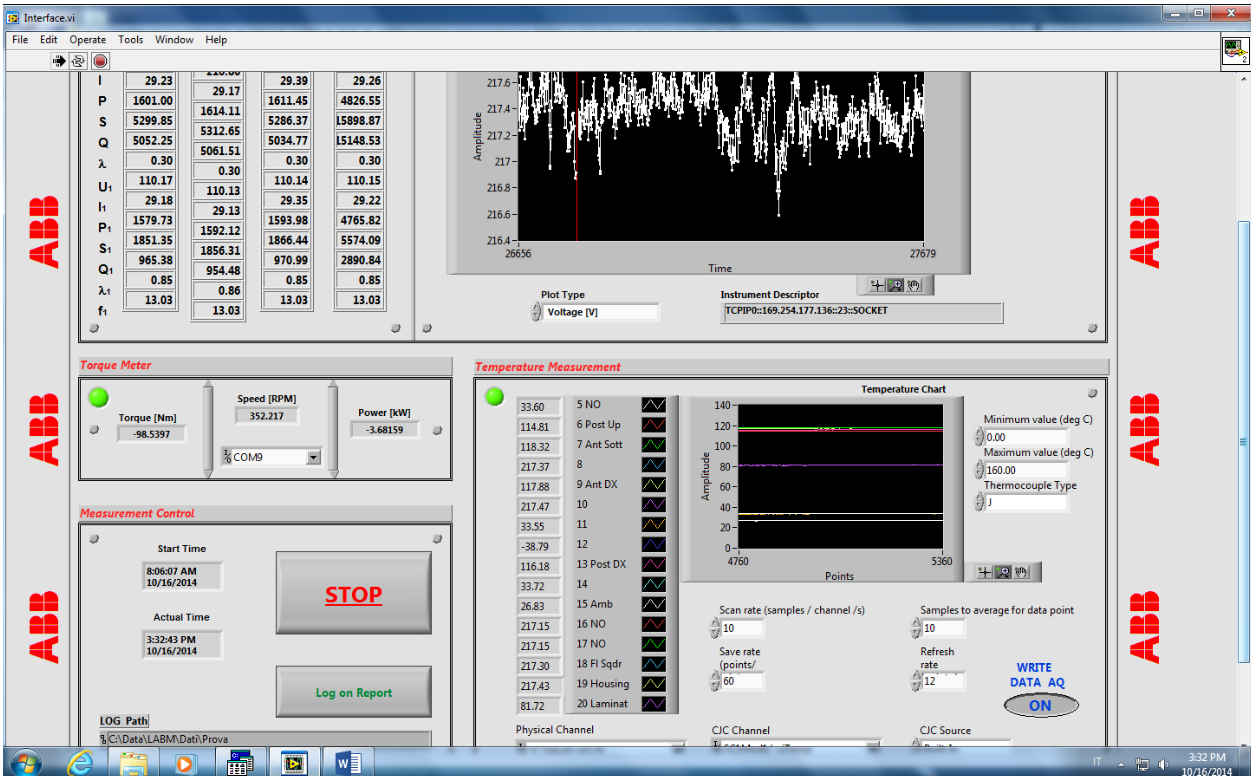



*Figure 17:- Induction M3AA 160 MLB 4 heat run nominal (100%) 1470 rpm, torque 200 Nm*

- ➢ Selimar in coppia analogica, 2380 mV (with 60 mV offset)
- ➢ ACS880-01-038A-3(Drive System) Speed 367.5 rpm
- ➢ Offset Torque Meter :- 0.02 Nm

R Cold (22°C):

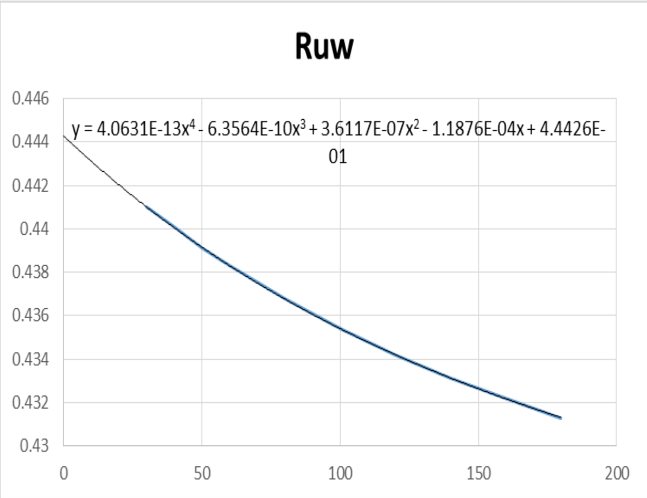
- ➢ Ruv = 352.70 mOhm
- ➢ Ruw = 351.20 mOhm
- ➢ Rvw = 350.00 mOhm
- ➢ R media = 351.30 mOhm

Fit with two exponentials (Matlab)

| | | | |
|---|---|---|---|
| A | 0.001 | alpha | -0.1 |
| B | 0.01 | beta | -1 |
| C | 0.34 | | |

**Cooling heat run 10/10/2014**

| Time(seconds) | Ruw |
|---|---|
| 30 | 0.441 |
| 40 | 0.4401 |
| 50 | 0.4391 |
| 60 | 0.4383 |
| 80 | 0.4368 |
| 100 | 0.4354 |
| 120 | 0.4342 |
| 140 | 0.4331 |
| 160 | 0.4322 |
| 180 | 0.4313 |
| | |

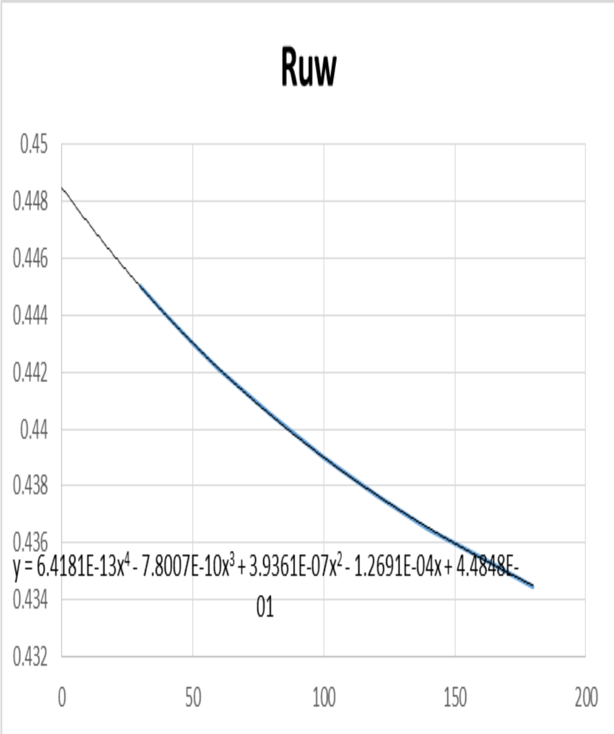



| Time | Fit |
|---|---|
| 0 | 0.34709 |
| 30 | 0.345478 |
| 40 | 0.345007 |
| 50 | 0.344567 |
| 60 | 0.344156 |
| 80 | 0.34341 |
| 100 | 0.342757 |
| 120 | 0.342184 |
| 140 | 0.341683 |
| 160 | 0.341245 |
| 180 | 0.34086 |

| Partial loads | | | | | |
|---|---|---|---|---|---|
| Load | Tref | Seli [mV] | speed | measured speed | |
| 150% | 146.3 | n.a. | | | |
| 125% | 121.9 | 2960 | 1470 | 1454 | |
| 100% | 97.5 | 2380 | 1470 | 1460 | |
| 90% | 87.8 | 2170 | 1470 | 1461 | |
| 75% | 73.1 | 1820 | 1470 | 1462 | |
| 50% | 48.8 | 1220 | 1470 | 1465 | |
| 25% | 24.4 | 650 | 1470 | 1467 | |
| 83% | 80.9 | 1990 | 1338 | 1327 | |
| 64% | 62.4 | 1570 | 1176 | 1170 | |
| 50% | 48.8 | 1230 | 1176 | 1171 | |
| Offset torsiometro | | 0.02 | | | |

**Cooling heat run 10/13/2014**

| Time | Ruw |
|---|---|
| 30 | 0.445 |
| 40 | 0.444 |
| 50 | 0.443 |
| 60 | 0.4421 |
| 80 | 0.4405 |
| 100 | 0.439 |
| 120 | 0.4377 |
| 140 | 0.4365 |
| 160 | 0.4355 |
| 180 | 0.4345 |

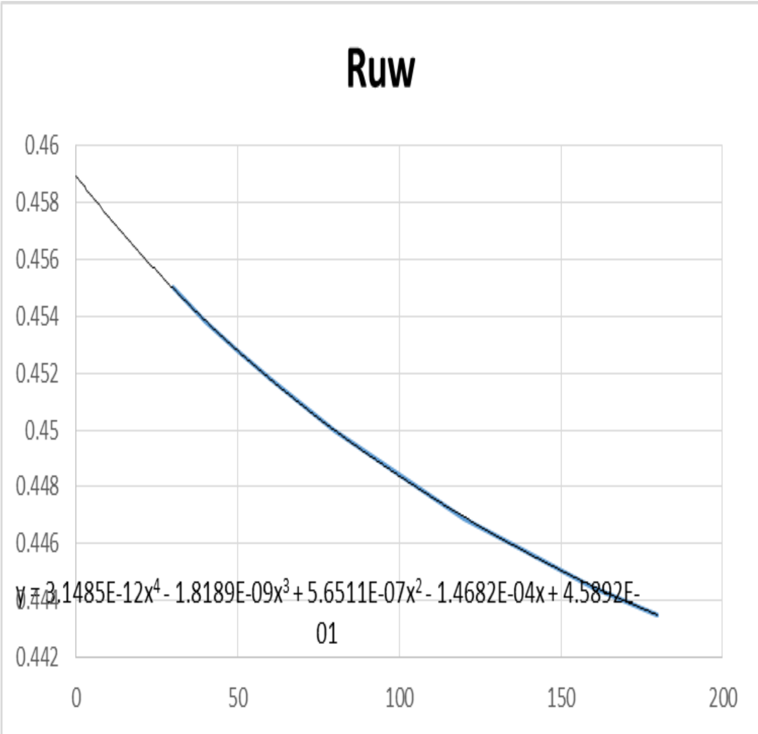



| Time | Fit |
|---|---|
| 0 | 0.34709 |
| 30 | 0.345478 |
| 40 | 0.345007 |
| 50 | 0.344567 |
| 60 | 0.344156 |
| 80 | 0.34341 |
| 100 | 0.342757 |
| 120 | 0.342184 |
| 140 | 0.341683 |
| 160 | 0.341245 |
| 180 | 0.34086 |

| Partial loads | | | | | |
|---|---|---|---|---|---|
| Load | Tref | Seli [mV] | speed | measured speed | |
| 150% | 146.3 | n.a. | | | |
| 125% | 121.9 | 2960 | 1102.5 | 1088 | |
| 100% | 97.5 | 2380 | 1102.5 | 1092 | |
| 75% | 73.1 | 1820 | 1102.5 | 1094 | |
| 56% | 54.6 | 1360 | 1102.5 | 1096 | |
| 50% | 48.8 | 1220 | 1102.5 | 1098 | |
| 38% | 36.6 | 940 | 1102.5 | 1100 | |
| 25% | 24.4 | 650 | 1102.5 | 1102 | |
| 40% | 39.0 | 990 | 926.1 | 922 | |
| Offset torsiometro | | 0.02 | | | |

**Cooling heat run 10/14/2014**

| Time | Ruw |
|---|---|
| 30 | 0.455 |
| 40 | 0.4538 |
| 50 | 0.4528 |
| 60 | 0.4518 |
| 80 | 0.45 |
| 100 | 0.4484 |
| 120 | 0.4469 |
| 140 | 0.4457 |
| 160 | 0.4445 |
| 180 | 0.4435 |

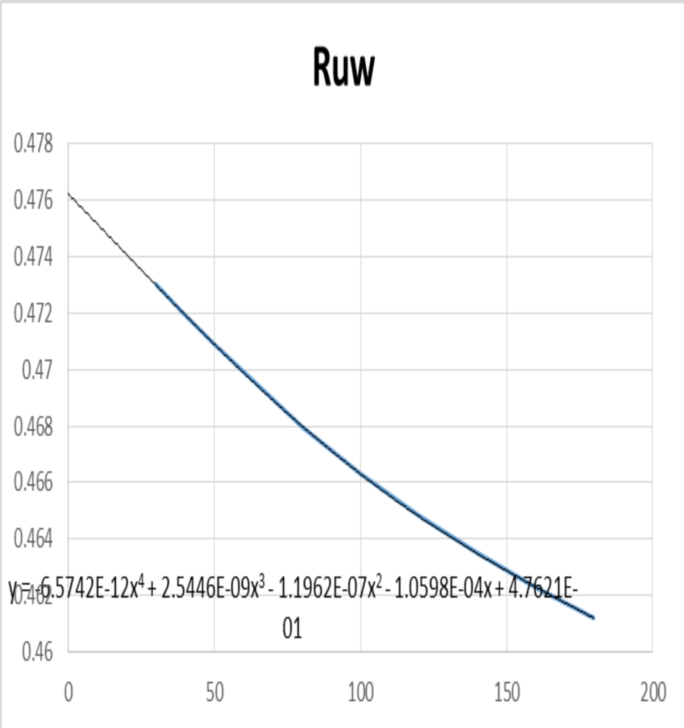



| Time | Fit |
|---|---|
| 0 | 0.34709 |
| 30 | 0.345478 |
| 40 | 0.345007 |
| 50 | 0.344567 |
| 60 | 0.344156 |
| 80 | 0.34341 |
| 100 | 0.342757 |
| 120 | 0.342184 |
| 140 | 0.341683 |
| 160 | 0.341245 |
| 180 | 0.34086 |

| Partial loads | | | | | |
|---|---|---|---|---|---|
| Load | Tref | Seli [mV] | speed | measured speed | |
| 150% | 146.3 | n.a. | | | |
| 125% | 121.9 | 2960 | 735 | 720 | |
| 100% | 97.5 | 2380 | 735 | 724 | |
| 75% | 73.1 | 1820 | 735 | 727 | |
| 50% | 48.8 | 1220 | 735 | 729 | |
| 25% | 24.4 | 650 | 735 | 733 | |
| | | | | | |
| Offset torsiometro | | 0.02 | | | |

**Cooling heat run 10/16/2014**

| Time | Ruw |
|---|---|
| 30 | 0.473 |
| 40 | 0.4719 |
| 50 | 0.4709 |
| 60 | 0.4699 |
| 80 | 0.468 |
| 100 | 0.4663 |
| 120 | 0.4648 |
| 140 | 0.4635 |
| 160 | 0.4623 |
| 180 | 0.4612 |




| Time | Fit |
|---|---|
| 0 | 0.34709 |
| 30 | 0.345478 |
| 40 | 0.345007 |
| 50 | 0.344567 |
| 60 | 0.344156 |
| 80 | 0.34341 |
| 100 | 0.342757 |
| 120 | 0.342184 |
| 140 | 0.341683 |
| 160 | 0.341245 |
| 180 | 0.34086 |

| Partial loads | | | | | |
|---|---|---|---|---|---|
| Load | Tref | Seli [mV] | speed | measured speed | |
| 150% | 146.3 | n.a. | | | |
| 125% | 121.9 | 2960 | 367.5 | 352 | |
| 100% | 97.5 | 2380 | 367.5 | 356 | |
| 75% | 73.1 | 1820 | 367.5 | 358 | |
| 50% | 48.8 | 1220 | 367.5 | 361 | |
| 25% | 24.4 | 650 | 367.5 | 364 | |
| | | | | | |
| Offset torsiometro | | 0.07 | | | |

# 2.5.3:- Motor Efficiency Class Test End Result:-

| Test date | 10/10/2014 | Motor type | Induction M3AA 160 MLB | | S/N | |
|---|---|---|---|---|---|---|
| | | Motor code | | | Int. Ref. | Rotor 2 |

**Nameplate data**

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Voltage | 400 | V | Power | 15 | kW | Eff 100% | |
| Frequency | 50 | Hz | Current | | A | Eff 75% | |
| Speed | 1470 | rpm | | | | Eff 50% | |
| Back-e.m.f. | 176.2 | V | | | | | |

IE2 limit 95.10% 50 Hz 4 poles

Traced from plate 97.44 Nm

**Stator resistance before testing**

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Ruv | 352.70 | mOhm | Ruw | 351.2 | mOhm | Rvw | 350 | mOhm |
| Rmean | 351.30 | mOhm | T ambient | 22 | deg C | | | |

| Heating test | U(H) | I | P1 | P.F.(H) | T | Act. Load | n | P2 |
|---|---|---|---|---|---|---|---|---|
| | 383.68 | 29.49 | 16390.01 | 0.84 | -96.63 | -99.2% | 1470 | 14874.81 |
| **Loss separation** | **Pfw** | **Pfe** | **Ps,t** | **Pr,t** | **PLL** | | | |
| | 48.95 | 0 | 575.58 | 0 | 0 | | | |

**Motor temperatures after testing**

| Stator | | | Rotor | | |
|---|---|---|---|---|---|
| Ruw | 444.26 | mOhm | Back-e.m.f. | 157 | V rms |
| Winding overtemp | 64.07 | K | Magnets overtemperature | 49.3 | K |
| Ambient | 27.14 | deg C | | | |

**Motor efficiency, direct method**

| | |
|---|---|
| **Efficiency** | 90.8% |
| **Eff. Class** | IE2 |

**Motor VSD efficiency, draft IEC 60034-30-2, 2/1741/CD**

| | |
|---|---|
| **Efficiency** | 86.0% |
| **Eff. Class** | IE2V |

| Partial Loads | U(H) | I | P1 | P.F.(H) | T | Act. Load | n | P2 | eta |
|---|---|---|---|---|---|---|---|---|---|
| 25% | 366.20 | 12.09 | 4334.3 | 0.561 | 24.5 | 25.1% | 1470 | 3764.2 | 86.85% |
| 50% | 372.76 | 17.04 | 8159.2 | 0.739 | 48.1 | 49.4% | 1470 | 7404.8 | 90.75% |
| 75% | 380.65 | 23.17 | 12350.3 | 0.807 | 73.3 | 75.2% | 1470 | 11281.3 | 91.34% |
| 100% | 383.58 | 29.51 | 16390.3 | 0.836 | 96.6 | 99.2% | 1470 | 14876.1 | 90.76% |
| 125% | 382.49 | 37.08 | 20795.4 | 0.847 | 121.0 | 124.2% | 1470 | 18629.8 | 89.59% |
| | | | | | | | | | |

## 2.6:- Advantages:-

The biggest advantage of AC induction motors is their sheer simplicity. They have only one moving part, the rotor, which makes them low-cost, quiet, long-lasting, and relatively trouble free. DC motors, by contrast, have a commutator and carbon brushes that wear out and need replacing from time to time. The friction between the brushes and the commutator also makes DC motors relatively noisy (and sometimes even quite smelly).

## 2.7:- Disadvantages:-

Since the speed of an induction motor depends on the frequency of the alternating current that drives it, it turns at a constant speed unless you use a variable-frequency drive; the speed of DC motors is much easier to control simply by turning the supply voltage up or down. Though relatively simple, induction motors can be fairly heavy and bulky because of their coil windings. Unlike DC motors, they can't be driven from batteries or any other source of DC power (solar panels, for example) without using an inverter (a device that turns DC into AC). That's because they need a changing magnetic field to turn the rotor.

Electric motors are extremely efficient, typically converting about 85 percent of the incoming electrical energy into useful, outgoing mechanical work. Even so, there is still quite a bit of energy wasted as heat inside the windings—which is why motors can get extremely hot. Most industrial-strength AC motors have built-in cooling systems. There's a fan inside the case attached to the rotor shaft (at the opposite end of the axle that's driving whatever machine the motor is attached to). The fan sucks air into the motor, blowing it around the outside of the case past the heat ventilating fins.

### 2.7.1 Losses in Induction Motor:

There are two types of losses occur in three phase induction motor. These losses are,

- Constant or fixed losses
- Variable losses

#### 1. Constant or Fixed Losses:

Constant losses are those losses which are considered to remain constant over normal working range of induction motor. The fixed losses can be easily obtained by performing no-load test on the three phase induction motor. These losses are further classified as:

- Iron or core losses
- Mechanical losses
- Brush friction losses

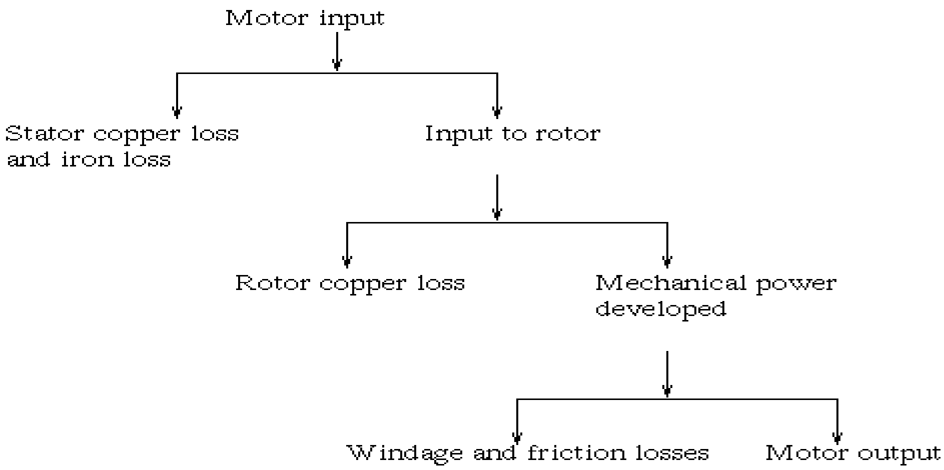
## 1. Iron or Core Losses:

Iron or core losses are further divided into hysteresis and eddy current losses. Eddy current losses are minimized by using lamination. Since by laminating the core, area decreases and hence resistance increases, which results in decrease in eddy currents. Hysteresis losses are minimized by using high grade silicon steel. The core losses depend upon frequency. The frequency of stator is always supply frequency, f and the frequency of rotor is slip times the supply frequency, (sf) which is always less than the stator frequency. Hence the rotor core loss is very small as compared to stator core loss and is usually neglected in running conditions.

## 2. Mechanical and Brush Friction Losses:

Mechanical losses occur at the bearing and brush friction loss occurs in wound rotor induction motor. These losses occurs with the change in speed. In three phase induction motor the speed usually remains constant. Hence these losses almost remains constant.

## 2. Variable Losses:




These losses are also called copper losses. These losses occur due to current flowing in stator and rotor windings. As the load changes, the current flowing in rotor and stator winding also changes and hence these losses also changes. Therefore these losses are called variable losses. The copper losses are obtained by performing blocked rotor test on three phase induction motor.

The main function of induction motor is to convert an electrical power into mechanical power. During this conversion of electrical energy into mechanical energy the power flows through different stages. This power flowing through different stages is shown by power flow diagram. As we all know the input to the three phase induction motor is three phase supply. So, the three phase supply is given to the stator of three phase induction motor.

# Chapter 3 “ABB Synchronous Reluctance Motor”

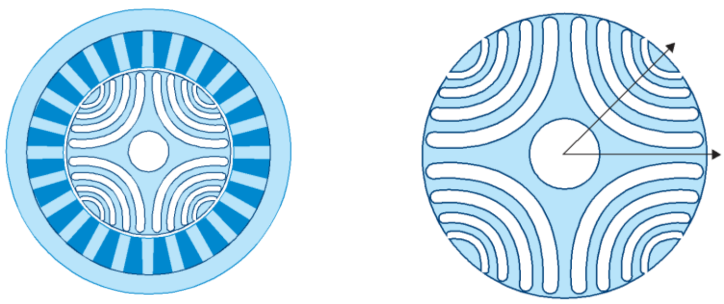
## 3.1 Description:-

The synchronous reluctance motor is a three-phase electric motor with a magnetically anisotropic rotor structure. In the four-pole version, the rotor has four high- and four low-permeance axes. High permeance means high magnetic conductivity and higher inductance, while low permeance means lower inductance.

Reluctance is the inverse of permeance and is, in practical terms, magnetic resistance; high reluctance results in low inductance. The axes with high permeance can be referred to as the direct or d-axis, while the axes with high reluctance can be referred to as the quadrature or q-axis.

**Reluctance motors** are the special type of motor, where the output mechanical power and the overall performance is quite good as compared to the maintanance and operating cost. Most commonly used stepper motor is a type of reluctance motor. In fact, there are many timing devices where small motors having constant speed characteristic are very advantageous. These motors operate from a single phase ac supply.

This is how single phase synchronous motor came into being. They do not require dc source of power supply for excitation nor they do they use permanent magnets. The most commonly used types of single phase synchronous motors are reluctance motor and hysteresis motor. The output of reluctance motors lies within a few kilowatts and they are used in several applications, especially in various industries. The theory of reluctance motor is slightly different from the conventional motoring theory. That is why they are treated as special motor. In this topic we are going to discuss about the construction and working principle of the reluctance motor.



Cross-sectional illustration of a four-pole synchronous reluctance motor (left), and the definition of the magnetic d- and q-axes of its rotor (right).

## 3.2 MOTOR HIGHLIGHTS

- **Today's technology makes it feasible**
- **Very high motor or system efficiency**
- **To be used where application already demands variable speed**
- **Competitive VSD package with very high efficiency, unobtainable–**
- **Motors meet IE4 efficiency levels according to IEC 60034-30-1 Ed 1.0.**
- **Unprecedented reliability through very low winding and bearing temperatures.**
- **Can replace standard induction motors: same power-size combinations.**
- **Variant codes and mechanical construction based on the proven M3BP cast iron process performance motors.**
- **Conventional yet innovative. Same parts, easy to source and change.**
- **No magnets, no cage – you cannot break what isn’t there.**

IE4 Synchronous reluctance motor – magnet-free

## 3.3 Construction:-

When a magnetic field is produced in the air gap by applying exciting currents to the stator windings, the rotor will strive to align its most magnetically conductive axis, the d-axis, with the applied field, in order to minimize the reluctance in the magnetic circuit. In other words, torque is produced in the air gap between the stator and rotor whenever the applied field vector and the d-axis of the rotor are not aligned.

The magnitude of the vector field and the speed of its rotation can be controlled by a frequency converter. The high saliency of the rotor means that its angular position can be simply detected by a sensorless control. Expensive absolute encoders, resolvers, and other rotational sensors are therefore not required.

The sensorless control system keeps track of the rotor's angular position in relation to the stator and creates a vector field with accurate magnitude and rotational speed in accordance with the control reference signals dictated by the load.

Since performance is dependent on the information about the rotor's position, the motor needs a frequency converter; it cannot be started with a direct-on-line supply. The rotor runs in synchronism with the applied vector field, striving to minimize reluctance in the magnetic circuit that is present.

This functional principle has given its name to the technology

– Synchronous reluctance.

Synchronous reluctance motors run smoothly due to the sinusoidal air gap field distribution and operation with sinusoidal current.

## Rotor design

The rotor design of a synchronous reluctance motor com- prises electric steel plates stacked together to form a rotor package. The electric steel plates have punched holes as flux barriers, the torque produced by the motor is proportional to the difference between the inductances on the d- and q-axes: the greater this difference, the greater the torque production. The synchronous reluctance motor is therefore designed with magnetically conductive material, iron, in the d-axis and magnetically insulating material, air, in the q-axis.

As the rotor has no windings and consequently no joule losses, it runs considerably cooler and with better efficiency than the rotor in an induction motor. The cool running of the rotor also means lower bearing temperatures, which in turn increase the reliability of the bearing system.

## Further considerations

Eliminating rotor joule losses in the synchronous reluctance motor has led to compact construction, good efficiency levels and cooler bearing temperatures. The main disadvantage of this technology is that the motor's power factor is generally not as good as with induction motors.

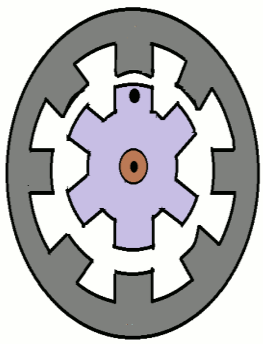
Since there is always a frequency converter between the motor and the grid, the lower power factor is not apparent on the grid side and consequently does not have an impact on the grid supply dimensioning. However, the lower power

Factor may sometimes mean that a frequency converter with a higher current rating is needed.

The stator and frame design are based on proven induction motor technology, and the rotor consists of only iron and air. The lack of windings and permanent magnets in the rotor eliminates potential faults associated with these components, resulting in robust motor technology optimized for industrial variable speed applications.

## 3.4 Operating Principle of Reluctance Motor: -

Let us discuss that how a **reluctance motor** works. When the stator of the reluctance motor is supplied with a single phase ac supply the motor starts as an induction motor (single phase). The starting / centrifugal switch disconnects the auxiliary winding of the motor at a speed of about 75% of synchronous speed. Now the motor operates with its main winding in operation. Gradually it accelerates and attains speed very close to synchronous speed. Now what happens?
When the **reluctance motor** starts to run at a speed close to synchronous speed, a reluctance torque is produced. The rotor aligns itself in minimum reluctance position. The rotor pulls into synchronism. After pulling into synchronism, the induction torque disappears but the rotor remains in synchronism due to synchronous reluctance torque alone. The motor adjusts its torque angle for change in load as in 3-ph synchronous motor. If load is excessive motor may not pull into synchronism and if already running it may pull out of synchronism.



## 3.5 Efficiency of Synchronous Reluctance Motor: -

Synchronous-reluctance designs work at high efficiency and high torque density without the need for permanent excitation or permanent magnets. However, they only offer a low power factor and limited high-speeds. Finally, switched reluctance designs offer high-speeds and high-torque density, along with no need for permanent excitation or permanent magnets. Their drawbacks include acoustic noise, torque ripple, rotor-core loss, high fundamental frequency, and the need for a six-lead connection.

Efficiency is defined as the ratio of the output to that of input,

$$Efficiency,\ \eta\ =\ \frac{output}{input}$$

Rotor efficiency of the three phase ,

$$=\ \frac{rotor\ output}{rotor\ input}$$

= Gross mechanical power developed / rotor input

$$=\ \frac{P_m}{P_2}$$

Three phase  motor efficiency,

$$=\ \frac{power\ developed\ at\ shaft}{electrical\ input\ to\ the\ motor}$$

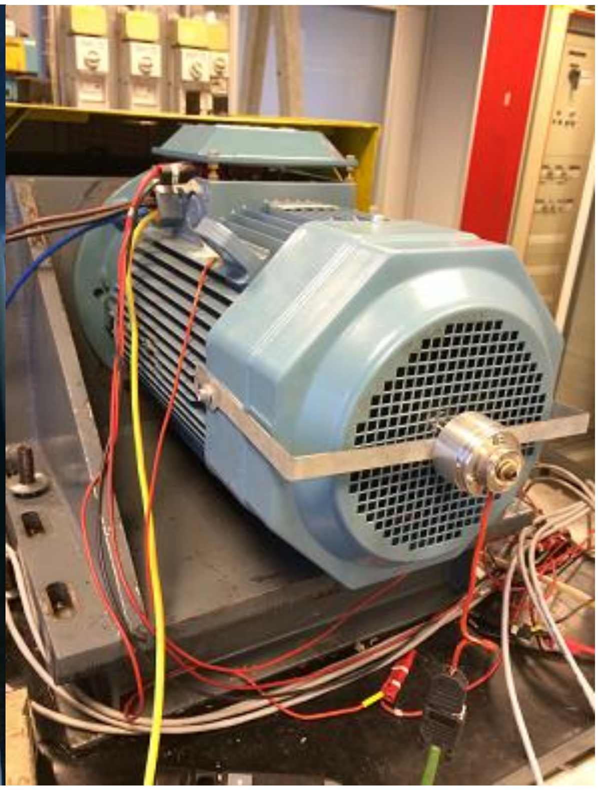
Three phase  motor efficiency

$$\eta\ =\ \frac{P_{out}}{P_{in}}$$

# Efficiency Calculation Test:-

**Specification of Motor Under test:**

- SRM M3BL 160 MLB
- 4-Pole
- ACS850 (Drive System) ABB
- Rated Torque : 95.5Nm
- Rated Speed : 1500 rpm
- Power : 15kW
- Voltage : 400V
- Current : 33.7 Ampere



## 3.5.1 Test Method for Determination of Efficiency :-

Following the test rules indicated in **IEC 60034-2-1** manual we opted the **Direct Method** for the determination of efficiency for this kind of motor.

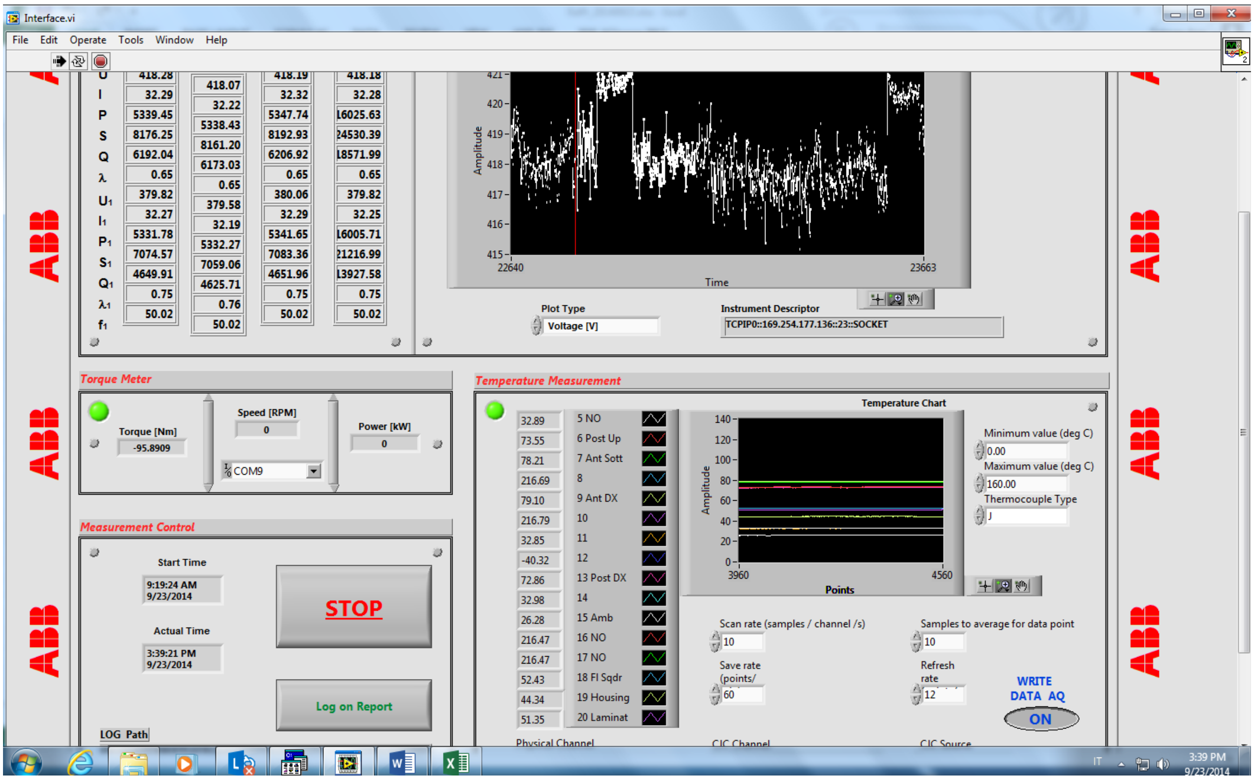
The first step to start the efficiency test was to make a **heat run test** at selected motor nominal torque i.e. 97.5 and nominal speed and this heat run test usually last about 4 to 5 hours (Mandatory for Heat run test) until the temperature of motor gets stabilized.

The motor under test was fed with a supply and in opposite to the testing motor another motor was coupled and a torque meter was installed. The secondary motor was used as a load. So the primary test was to make the motor under test run for at least 4 hours or 5 hours to get stabilized. After the motor stabilization the motor was stopped immediately and we recorded some readings discussed below with more details.

Some interesting events can be seen using ABB personal designed software called as Interface used for testing of motors to make a record of all log files which later on we use for finding out the efficiency of a motor. In the above diagram like the start and stop time of the motor in the Measurement Control section. You can also have a look about the Temperature Measurement where you can see the stabilized temperature.

The following below are the important reading we made exactly after the immediate stoppage of motor at nominal values of motor.

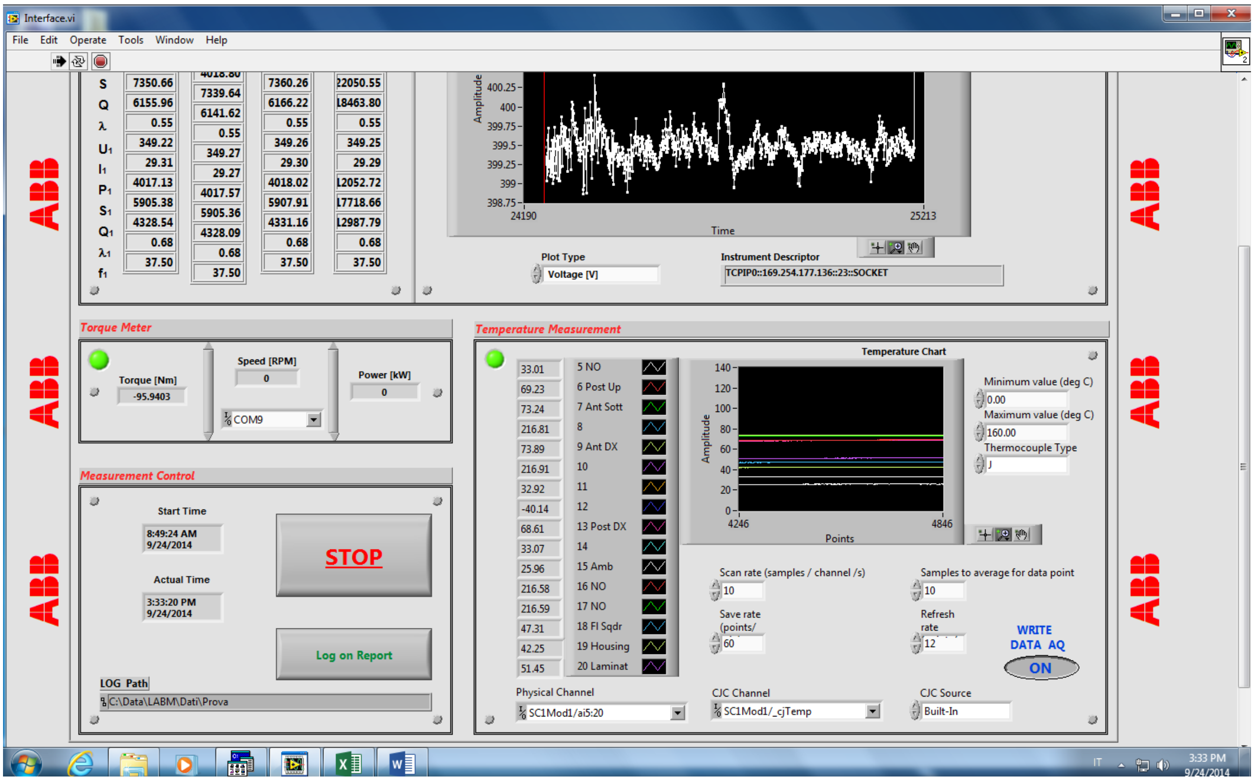
- **23/09/2014, SRM M3BL 160 MLB 4 3GBL162105-BSC heat run nominale, torsio 200 Nm**



Selimar in coppia analogica, 2310 mV (with 60 mV offset)
ACS850 (Drive System) velocita', 1500 rpm
Offset torsiometro: 0.02 Nm

R a freddo (25.5°C):
Ruv = 300.70 mOhm
Ruw = 300.63 mOhm
Rvw = 300.35 mOhm
R media = 300.56 mOhm

- **24/09/2014, SRM M3BL 160 MLB 4 3GBL162105-BSC heat run 1125 rpm, torsio 200 Nm**

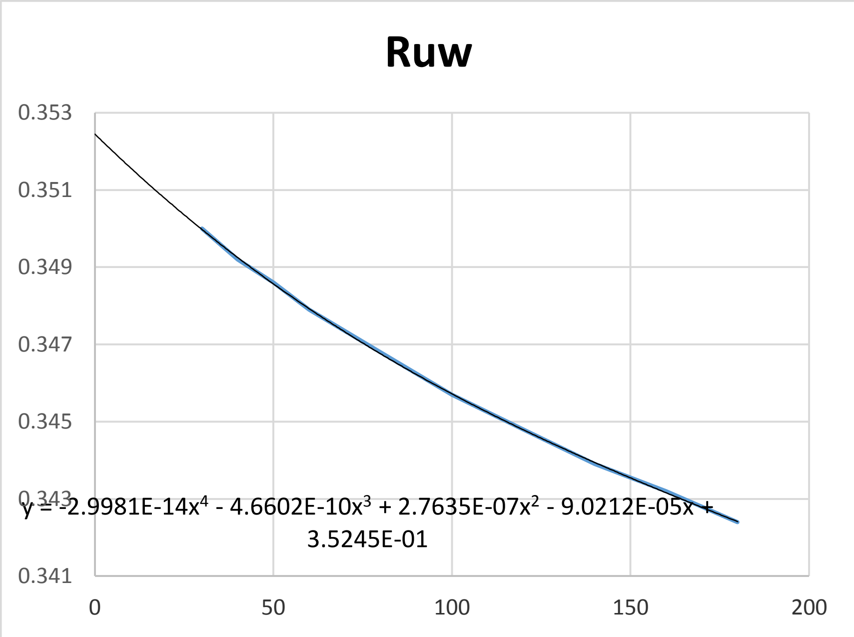



Selimar in coppia analogica, 2310 mV (with 60 mV offset)
ACS850 (Drive System) velocita', 1125 rpm
Offset torsiometro: 0.20 Nm

R a freddo (25.5°C):
Ruv = 300.70 mOhm
Ruw = 300.63 mOhm
Rvw = 300.35 mOhm
R media = 300.56 mOhm

- **Cooling heat run 23/09/2014**

| Time | Ruw |
|---|---|
| 30 | 0.35 |
| 40 | 0.3492 |
| 50 | 0.3486 |
| 60 | 0.3479 |
| 80 | 0.3468 |
| 100 | 0.3457 |
| 120 | 0.3448 |
| 140 | 0.3439 |
| 160 | 0.3432 |
| 180 | 0.3424 |

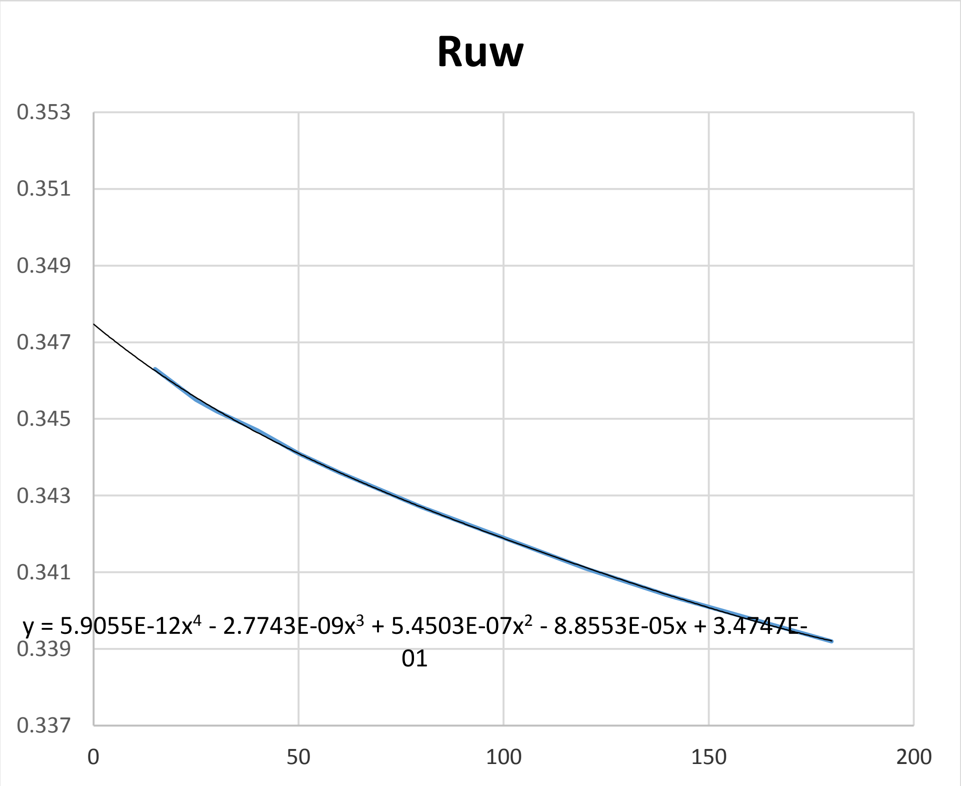



| Time | Fit |
|---|---|
| 0 | 0.34709 |
| 30 | 0.345478 |
| 40 | 0.345007 |
| 50 | 0.344567 |
| 60 | 0.344156 |
| 80 | 0.34341 |
| 100 | 0.342757 |
| 120 | 0.342184 |
| 140 | 0.341683 |
| 160 | 0.341245 |
| 180 | 0.34086 |

| Partial loads | | | |
|---|---|---|---|
| Load | Tref | Seli [mV] | speed |
| 150% | 143.2 | n.a. | |
| 125% | 119.4 | 2870 | 1500 |
| 100% | 95.5 | 2310 | 1500 |
| 90% | 85.9 | 2070 | 1500 |
| 75% | 71.6 | 1740 | 1500 |
| 50% | 47.7 | 1190 | 1500 |
| 25% | 23.9 | 620 | 1500 |
| 83% | 79.2 | 1930 | 1365 |
| 64% | 61.1 | 1500 | 1200 |
| 50% | 47.7 | 1190 | 1200 |
| Offset torsiometro | | -0.1 | |

- **Cooling heat run 24/09/2014**

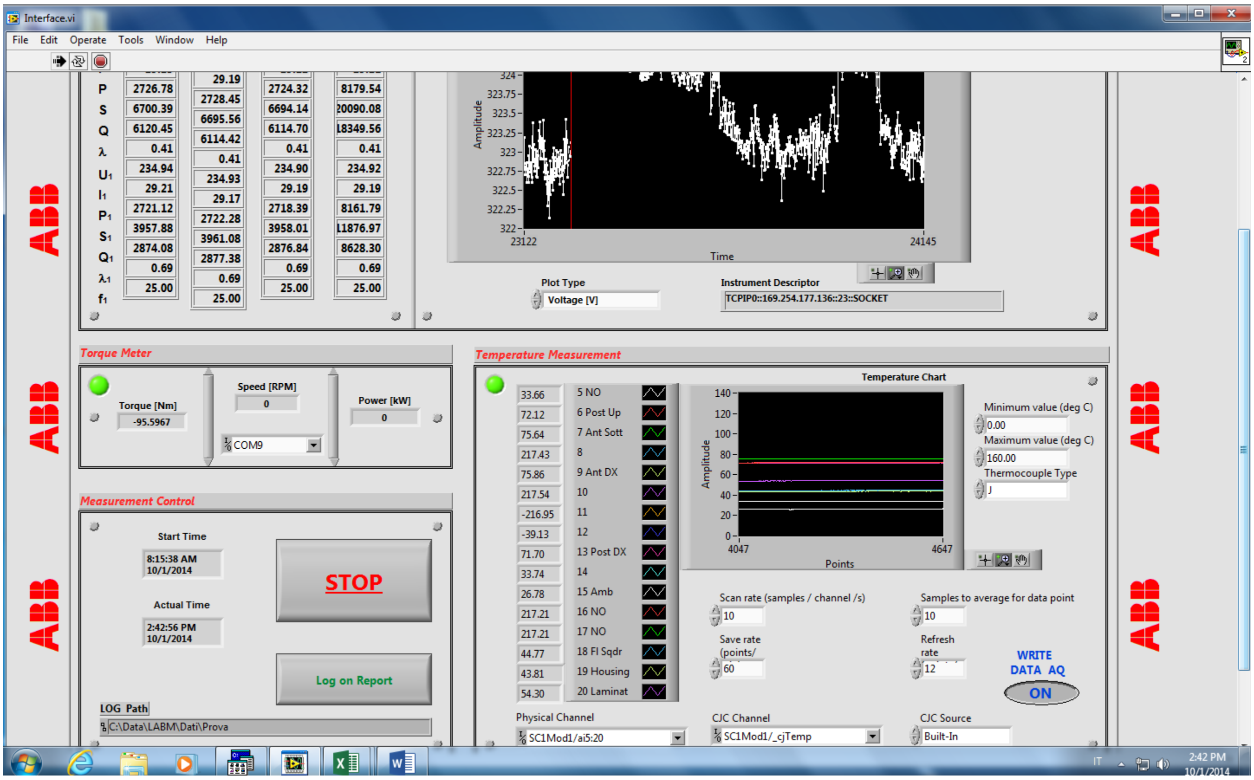
| Time | Ruw |
|---|---|
| 15 | 0.3463 |
| 25 | 0.3455 |
| 30 | 0.3452 |
| 40 | 0.3447 |
| 50 | 0.3441 |
| 60 | 0.3436 |
| 80 | 0.3427 |
| 100 | 0.3419 |
| 120 | 0.3411 |
| 140 | 0.3404 |
| 160 | 0.3398 |
| 180 | 0.3392 |




| Time | Fit |
|---|---|
| 0 | 0.34709 |
| 15 | 0.346244 |
| 25 | 0.345725 |
| 30 | 0.345478 |
| 40 | 0.345007 |
| 50 | 0.344567 |
| 60 | 0.344156 |
| 80 | 0.34341 |
| 100 | 0.342757 |
| 120 | 0.342184 |
| 140 | 0.341683 |
| 160 | 0.341245 |
| 180 | 0.34086 |

| Partial loads | | | |
|---|---|---|---|
| Load | Tref | Seli [mV] | speed |
| 150% | 143.3 | n.a. | |
| 125% | 119.4 | 2870 | 1125 |
| 100% | 95.5 | 2310 | 1125 |
| 75% | 71.6 | 1740 | 1125 |
| 56% | 53.5 | 1310 | 1125 |
| 50% | 47.8 | 1190 | 1125 |
| 37.5% | 35.8 | 900 | 1125 |
| 25% | 23.9 | 620 | 1125 |
| 40% | 38.2 | 950 | 945 |
| | | | |
| | | | |
| Offset torsiometro | | -0.18 | |

## ➢ 1/10/2014, SRM M3BL 160 MLB 4 3GBL162105-BSC heat run 750 rpm, torsio 200 Nm

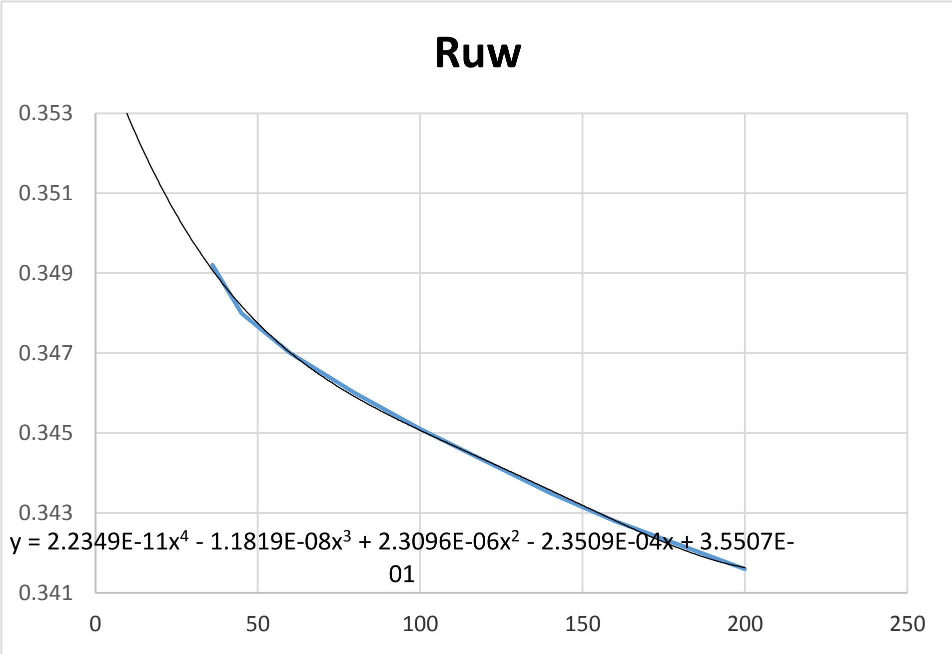



Selimar in coppia analogica, 2320 mV (with 60 mV offset)
ACS850 (Drive System)   velocita’, 750 rpm
Offset torsiometro: 0.10 Nm

R a freddo (25.5°C):
Ruv = 300.70 mOhm
Ruw = 300.63 mOhm
Rvw = 300.35 mOhm
R media = 300.56 mOhm

- **Cooling heat run 01/10/2014**

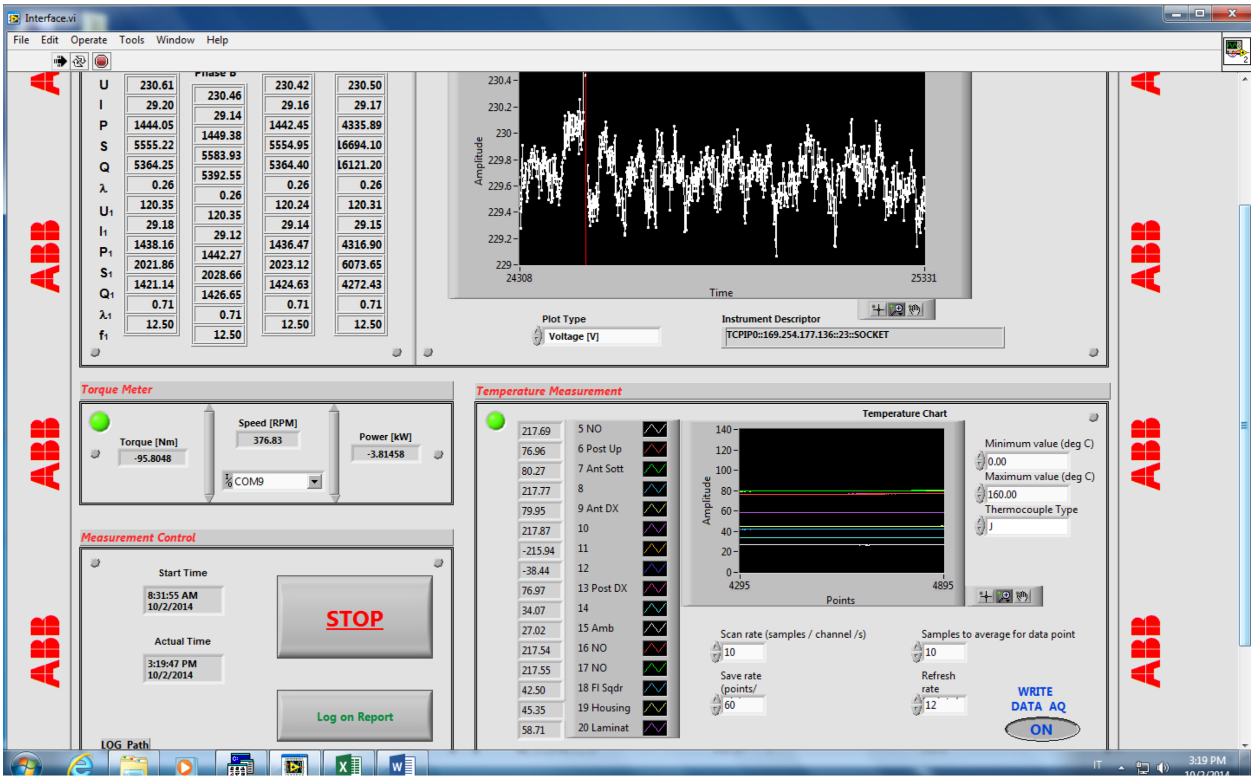
| Time | Ruw |
|---|---|
| 36 | 0.3492 |
| 45 | 0.348 |
| 60 | 0.347 |
| 80 | 0.346 |
| 100 | 0.3451 |
| 120 | 0.3443 |
| 140 | 0.3435 |
| 160 | 0.3428 |
| 180 | 0.3422 |
| 200 | 0.3416 |




| Time | Fit |
|---|---|
| 0 | 0.34709 |
| 36 | 0.345192 |
| 45 | 0.344784 |
| 60 | 0.344156 |
| 80 | 0.34341 |
| 100 | 0.342757 |
| 120 | 0.342184 |
| 140 | 0.341683 |
| 160 | 0.341245 |
| 180 | 0.34086 |
| 200 | 0.340524 |

| Partial loads | | | |
|---|---|---|---|
| Load | Tref | Seli [mV] | speed |
| 150% | 143.2 | n.a. | |
| 125% | 119.4 | 2870 | 750 |
| 100% | 95.5 | 2320 | 750 |
| 75% | 71.6 | 1740 | 750 |
| 50% | 47.7 | 1190 | 750 |
| 25% | 23.9 | 620 | 750 |

- **2/10/2014, SRM M3BL 160 MLB 4 3GBL162105-BSC heat run 375 rpm, torsio 200 Nm**

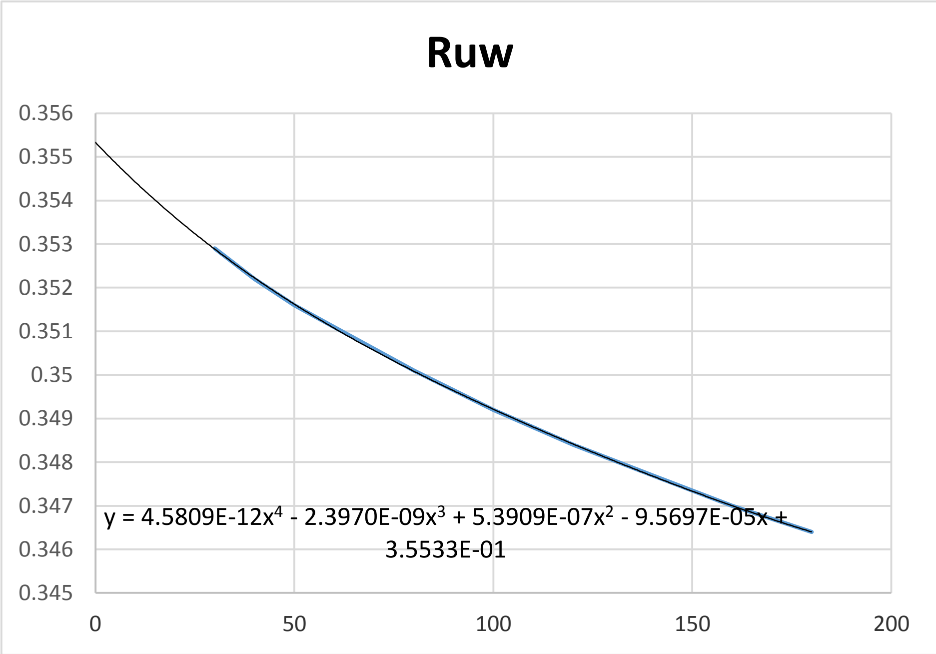


Selimar in coppia analogica, 2320 mV (with 60 mV offset)
ACS850 (Drive System) velocita', 375 rpm
Offset torsiometro: 0.12 Nm

R a freddo (25.5°C):
Ruv = 300.70 mOhm
Ruw = 300.63 mOhm
Rvw = 300.35 mOhm
R media = 300.56 mOhm

- **Cooling heat run 02/10/2014**

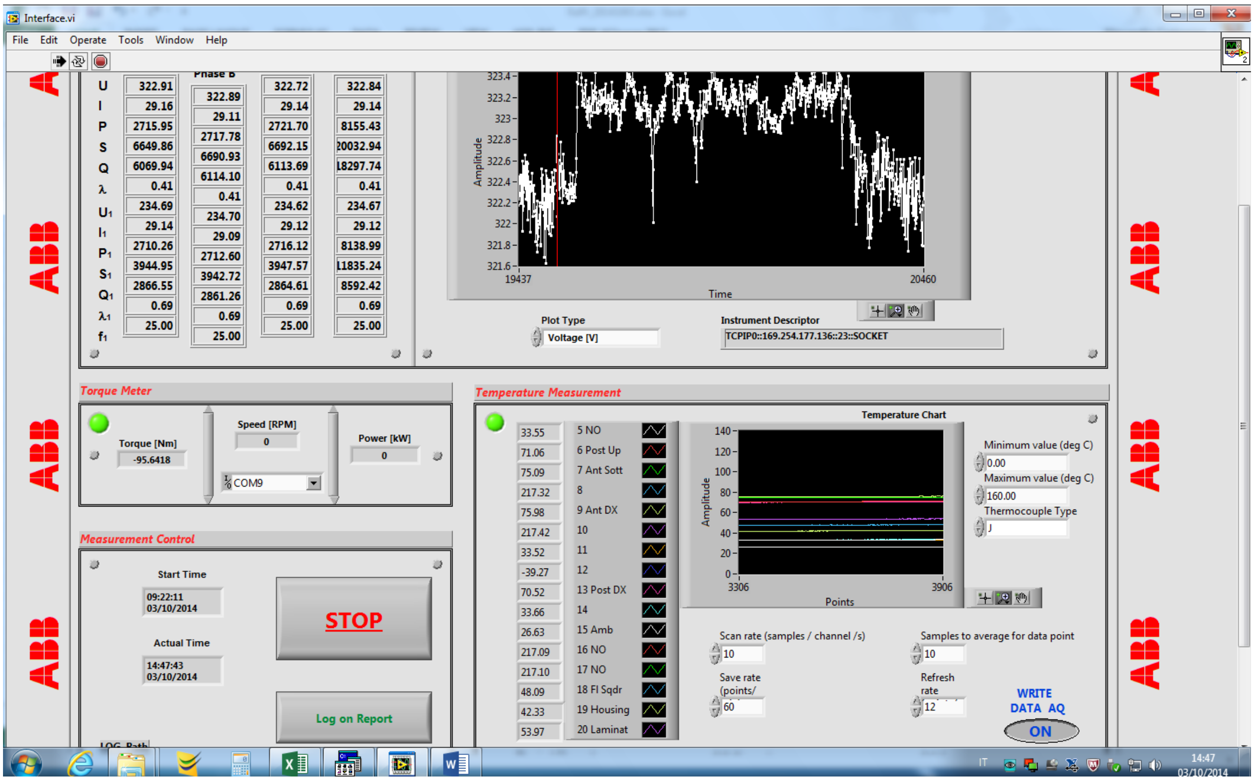
| Time | Ruw |
|---|---|
| 30 | 0.3529 |
| 40 | 0.3522 |
| 50 | 0.3516 |
| 60 | 0.3511 |
| 80 | 0.3501 |
| 100 | 0.3492 |
| 120 | 0.3484 |
| 140 | 0.3477 |
| 160 | 0.347 |
| 180 | 0.3464 |




| Time | Fit |
|---|---|
| 0 | 0.34709 |
| 30 | 0.345478 |
| 40 | 0.345007 |
| 50 | 0.344567 |
| 60 | 0.344156 |
| 80 | 0.34341 |
| 100 | 0.342757 |
| 120 | 0.342184 |
| 140 | 0.341683 |
| 160 | 0.341245 |
| 180 | 0.34086 |

| Partial loads | | | |
|---|---|---|---|
| Load | Tref | Seli [mV] | speed |
| 150% | 143.2 | n.a. | |
| 125% | 119.4 | 2870 | 375 |
| 100% | 95.5 | 2320 | 375 |
| 75% | 71.6 | 1740 | 375 |
| 50% | 47.7 | 1190 | 375 |
| 25% | 23.9 | 620 | 375 |

- **3/10/2014, SRM M3BL 160 MLB 4 3GBL162105-BSC heat run 750 rpm repeated, torsio 200 Nm**

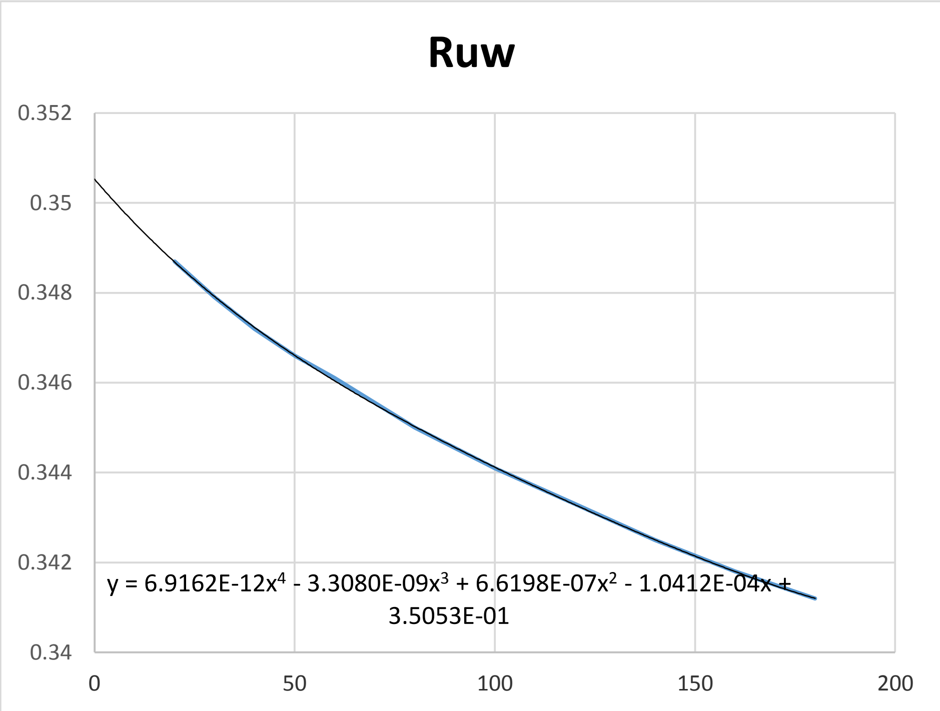



Selimar in coppia analogica, 2310 mV (with 60 mV offset)
ACS880-01-038A-3 velocita’, 750 rpm
Offset torsiometro: 0.1 Nm

R a freddo (25.5°C):
Ruv = 300.70 mOhm
Ruw = 300.63 mOhm
Rvw = 300.35 mOhm
R media = 300.56 mOhm

- **Cooling heat run 03/10/2014**

| Time | Ruw |
|---|---|
| 20 | 0.3487 |
| 30 | 0.3479 |
| 40 | 0.3472 |
| 50 | 0.3466 |
| 60 | 0.3461 |
| 80 | 0.345 |
| 100 | 0.3441 |
| 120 | 0.3433 |
| 140 | 0.3425 |
| 160 | 0.3418 |
| 180 | 0.3412 |




| Time | Fit |
|---|---|
| 0 | 0.34709 |
| 20 | 0.34598 |
| 30 | 0.345478 |
| 40 | 0.345007 |
| 50 | 0.344567 |
| 60 | 0.344156 |
| 80 | 0.34341 |
| 100 | 0.342757 |
| 120 | 0.342184 |
| 140 | 0.341683 |
| 160 | 0.341245 |
| 180 | 0.34086 |

| Partial loads | | | |
|---|---|---|---|
| Load | Tref | Seli [mV] | speed |
| 150% | 143.2 | n.a. | |
| 125% | 119.4 | 2870 | 750 |
| 100% | 95.5 | 2310 | 750 |
| 75% | 71.6 | 1740 | 750 |
| 50% | 47.7 | 1190 | 750 |
| 25% | 23.9 | 620 | 750 |

# 3.5.2:- Motor Efficiency Class Test End Result:-

| | | | | | |
|---|---|---|---|---|---|
| Test date | 23/09/2014 | Motor type | SRM M3BL 160 MLB | S/N | |
| | | Motor code | | Int. Ref. | Rotor 2 |

**Nameplate data**

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Voltage | 400 | V | Power | 15 | kW | Eff 100% | |
| Frequency | 50 | Hz | Current | | A | Eff 75% | |
| Speed | 1500 | rpm | | | | Eff 50% | |
| Back-e.m.f. | 0 | V | | | | | |

**IE5 limit** 95.10% 50 Hz 4 poles

**Trated from plate** 95.49 Nm

**Stator resistance before testing**

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Ruv | 300.70 | mOhm | Ruw | 300.63 | mOhm | Rvw | 300.35 | mOhm |
| Rmean | 300.56 | mOhm | T ambient | 25.5 | deg C | | | |

| Heating test | U(H) | I | P1 | P.F.(H) | T | Act. Load | n | P2 |
|---|---|---|---|---|---|---|---|---|
| | 378.39 | 32.35 | 16001.73 | 0.75 | 95.70 | 100.2% | 1500 | 15032.55 |
| Loss separation | Pfw | Pfe | Ps,t | Pr,t | PLL | | | |
| | 48.95 | 0 | 551.25 | 0 | 0 | | | |

**Motor temperatures after testing**

| Stator | | | Rotor | | |
|---|---|---|---|---|---|
| Ruw | 352.45 | mOhm | Back-e.m.f. | 0 | V rms |
| Winding overtemp | 44.48 | K | Magnets overtemperature | 0.0 | K |
| Ambient | 26.21 | deg C | | | |

**Motor efficiency, direct method**

| | |
|---|---|
| Efficiency | 93.9% |
| Eff. Class | IE5 |

**Motor VSD efficiency, draft IEC 60034-30-2, 2/1741/CD**

| | |
|---|---|
| Efficiency | 92.6% |
| Eff. Class | IE5V |

| Partial Loads | U(H) | I | P1 | P.F.(H) | T | Act. Load | n | P2 | eta |
|---|---|---|---|---|---|---|---|---|---|
| 25% | 325.26 | 12.18 | 4108.9 | 0.597 | 23.8 | 24.9% | 1500 | 3734.4 | 90.89% |
| 50% | 383.07 | 18.26 | 8063.5 | 0.666 | 48.0 | 50.3% | 1500 | 7546.6 | 93.59% |
| 75% | 380.84 | 24.65 | 11932.4 | 0.734 | 71.6 | 74.9% | 1500 | 11242.2 | 94.22% |
| 100% | 379.47 | 32.53 | 16146.8 | 0.755 | 96.1 | 100.6% | 1500 | 15096.1 | 93.49% |
| 125% | 380.02 | 39.93 | 19798.3 | 0.753 | 120.0 | 125.6% | 1500 | 18842.9 | 95.17% |
| 150% | 0.00 | 0.00 | 0.0 | 0.000 | 0.0 | 0.0% | 0 | 0.0 | 0.00% |

## 3.6 Advantages :-

- Reduction of losses means cooler motor
- Smaller motor for same application
- Up to two frame sizes smaller
- Enables more compact machinery
- Weight reduction
- More power from same size
- Improve process performance
- Jump to next output level without mechanical changes to existing machinery
- To be used where application already demands variable speed
- removes rotor iron losses
- reduction of total losses up to 40%
- less heat and higher efficiency
- Can replace most of the variable speed driven induction motors in quadratic torque (pumps, fans) and constant torque applications
- Reliable high efficient **"workhorse"** for general industrial applications.

# Chapter 4 "Permanent Magnet Assisted Synchronous Reluctance Motor"

## 4.1 Description: -

Permanent magnet motors have attracted a lot of attention recently for their potential for saving energy. However, they are only used for certain applications because the magnets are expensive. This paper discusses the optimum design of the low-cost, highly efficient magnet assisted reluctance motors with a minimum amount of magnets.

The PM assisted synchronous reluctance machine is mainly a type of synchronous reluctance motors (SynRM) which is a family member of brushless AC machines consisting of the conventional dc permanent magnet machine, the permanent magnet synchronous machine and the cage induction machine. The members of this family have a standard three phase stator of induction machine with spatial sine wave rotating field. Generated torque is relatively smooth and as a result, the operation is quiet. A conventional three phase inverter can be used to drive the motors of this family if electronically controlled drive is desired.

## 4.2 Construction: -

When PMs are inserted into the rotor flux barriers of a synchronous reluctance motor, it becomes a permanent magnet assisted synchronous reluctance motor (PMASR). PMs can be mounted in the rotor core of the axially or transversally laminated structure. Figure shows a transversally laminated PMASR. The polarity of magnets is chosen such that counteract the q-axis flux of the SynRM at rated load. Regardless of the different choice of d, q axes, in principle, the PMASR seems nothing more than a particular case of interior permanent magnet motor (IPM).

However, a substantial difference is the high anisotropy rotor structure of PMASR and as a result, low value of the PM flux. The amount of PM flux is quite lower than the amount of rated flux. In contrast, in the usual IPM the most flux comes from the magnets and the flux produced by stator currents is considered as an unwanted reaction flux. In practice, because of the above mentioned difference between PMASR and IPM machines, they have different suitability to the large flux-weakening ranges.

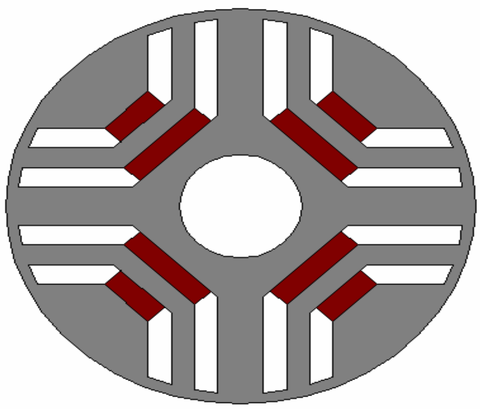


Figure: Four-pole transversally-laminated PM assisted rotor design.

## 4.3 Efficiency of PMASR: -

Efficiency is defined as the ratio of the output to that of input,

$$Efficiency,\ \eta = \frac{output}{input}$$

Rotor efficiency of the three phase,

$$= \frac{rotor\ output}{rotor\ input}$$

= Gross mechanical power developed / rotor input

$$= \frac{P_m}{P_2}$$

Three phase  motor efficiency,

$$= \frac{power\ developed\ at\ shaft}{electrical\ input\ to\ the\ motor}$$

Three phase  motor efficiency

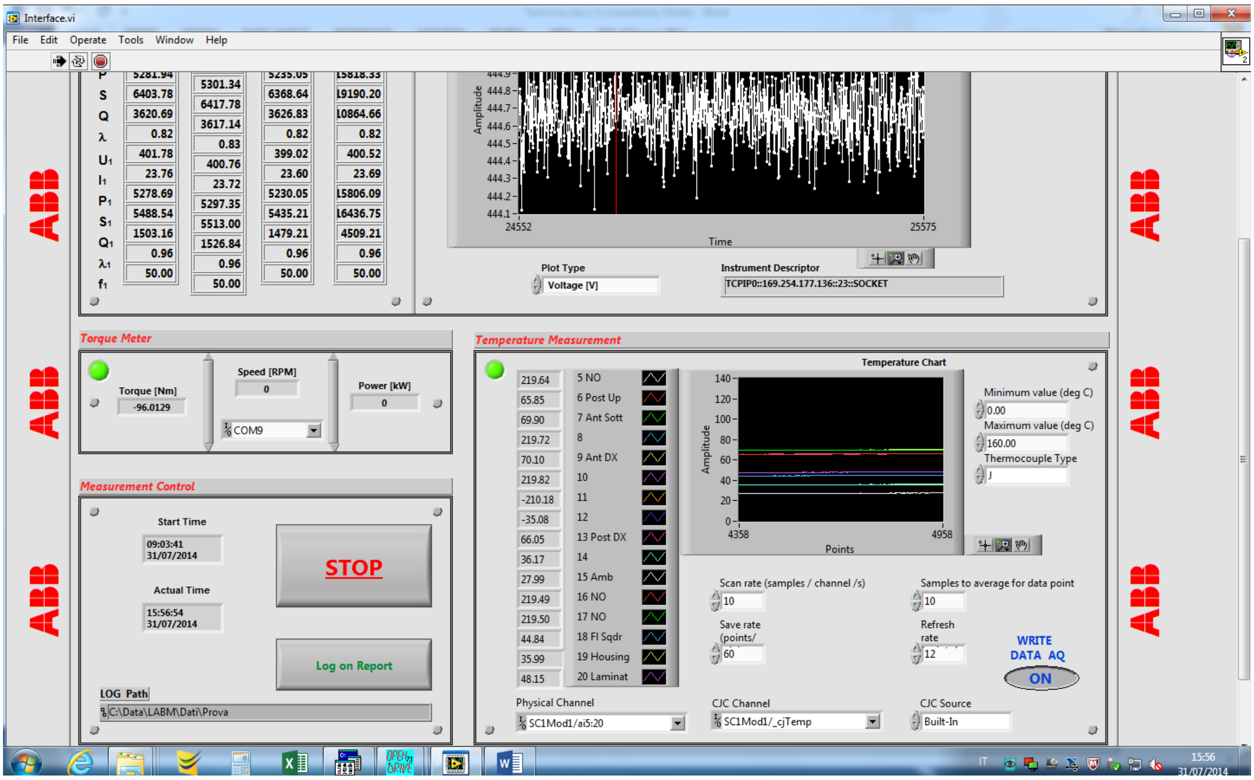
$$\eta = \frac{P_{out}}{P_{in}}$$

**Specification of Motor Under test:**

- M3AA160MLB-4 PMASR
- 4-Pole
- ACS880 (Drive System) ABB
- Rated Torque : 95.5Nm
- Rated Speed   : 1500 rpm
- Power            : 15kW
- Voltage          : 400V
- Current          : 24 Ampere

## 4.4 Efficiency Test of PMASR: -

- **31/7/2014, H160 PMASR rotor 2, heat run nominale, torsio 200 Nm**



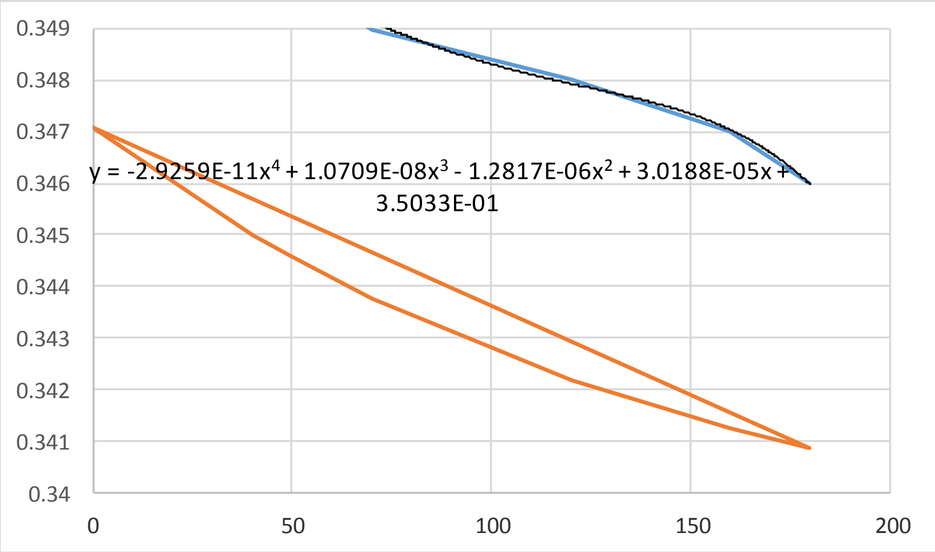

Selimar in coppia analogica, 2310 mV (with 60 mV offset)
OPD-R in velocita', 1500 rpm, Params_manualtuning2
Alim DC-link 618 Vdc (TDE) 618 Vdc (tester)
Offset torsiometro: 0.06 Nm ???

R a caldo: vedi dati raffreddamento

R a freddo (25.5°C):
Ruv = 300.70 mOhm
Ruw = 300.63 mOhm
Rvw = 300.35 mOhm
R media = 300.56 mOhm

- **Cooling heat run 31/7/2014**

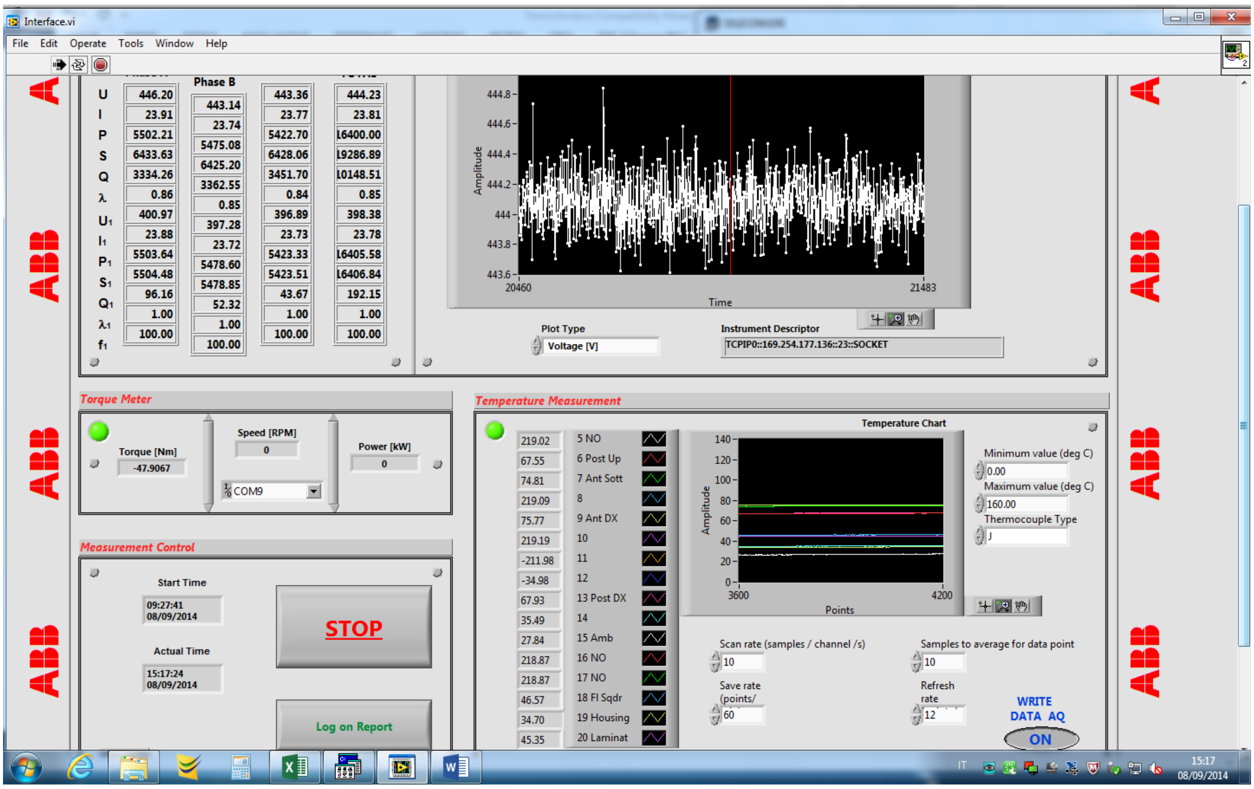
| Time | Ruw |
|---|---|
| 40 | 0.35 |
| 50 | 0.35 |
| 70 | 0.349 |
| 120 | 0.348 |
| 160 | 0.347 |
| 180 | 0.346 |




| Time | Fit |
|---|---|
| 0 | 0.34709 |
| 40 | 0.345007 |
| 50 | 0.344567 |
| 70 | 0.34377 |
| 120 | 0.342184 |
| 160 | 0.341245 |
| 180 | 0.34086 |

| Partial loads | | | |
|---|---|---|---|
| Load | Tref | Seli [mV] | speed |
| 150% | 143.2 | n.a. | |
| 125% | 119.4 | 2870 | 1500 |
| 100% | 95.5 | 2310 | 1500 |
| 75% | 71.6 | 1740 | 1500 |
| 50% | 47.7 | 1190 | 1500 |
| 25% | 23.9 | 620 | 1500 |
| Offset torsiometro | | -0.1 | |

- **08/09/2014, H160 PMASR rotor 2, heat run speed 200%, torsio 200 Nm**



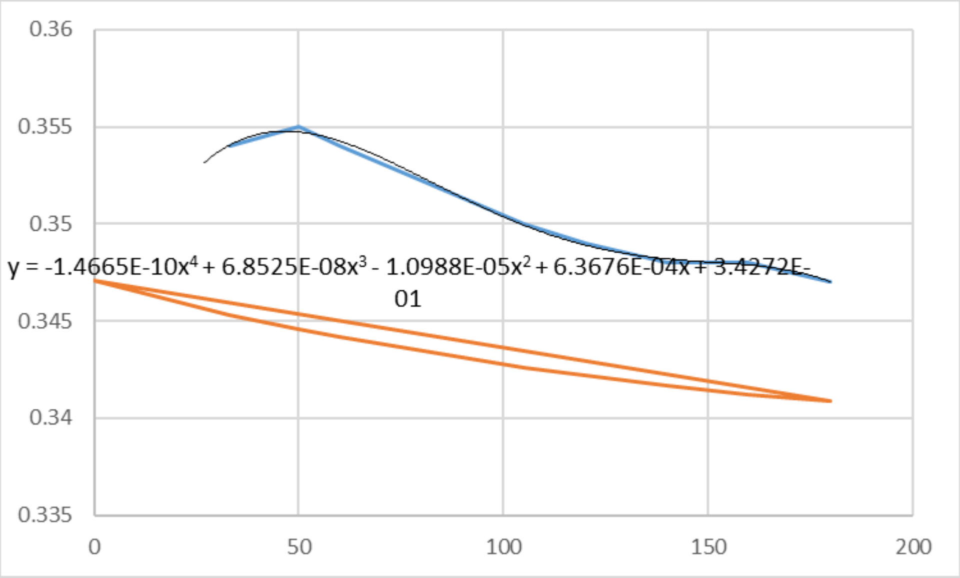

Selimar in coppia analogica, 1180 mV (with 60 mV offset)
OPD-R in velocita', 3000 rpm, Params_manualtuning2
Alim DC-link 621 Vdc (TDE) 619 Vdc (tester)
Offset torsiometro: 0.13 Nm ???

R a caldo: vedi dati raffreddamento

R a freddo (25.5°C):
Ruv = 300.70 mOhm
Ruw = 300.63 mOhm
Rvw = 300.35 mOhm
R media = 300.56 mOhm

- **Cooling heat run 09/08/2014**

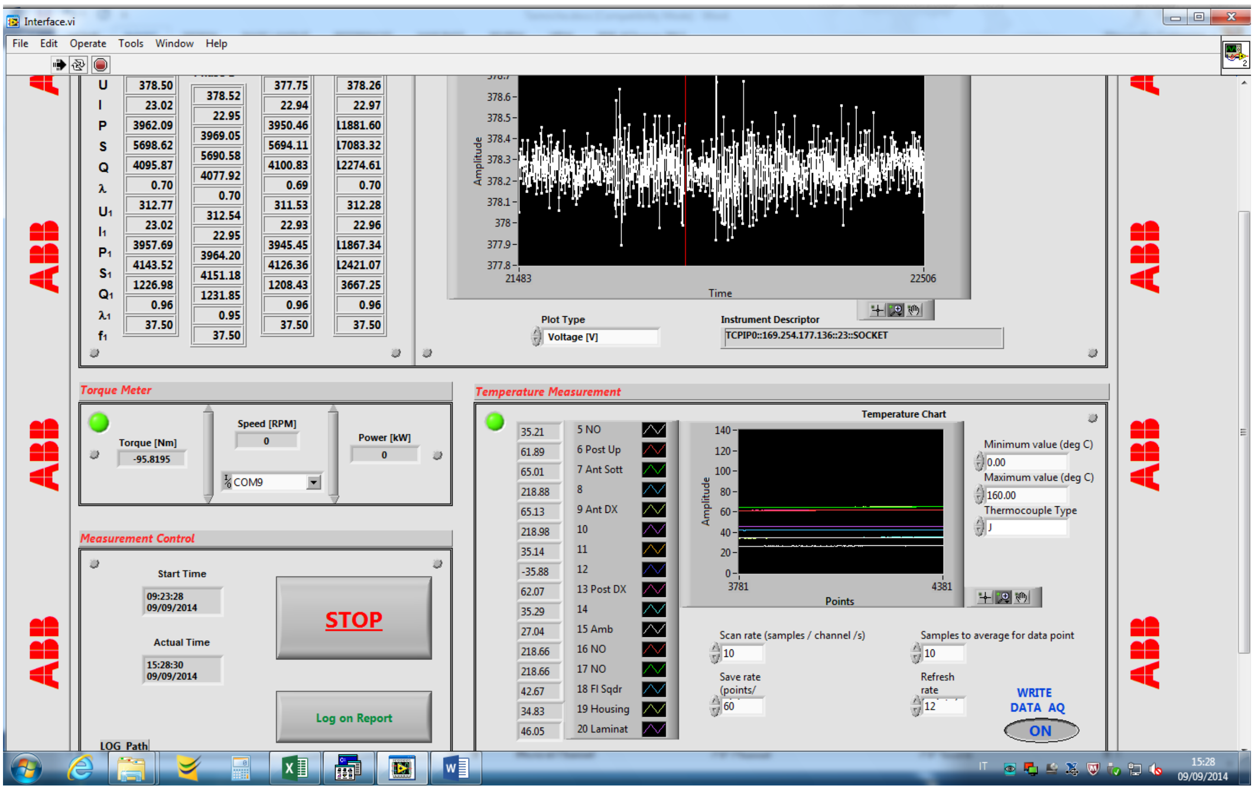
| Time | Ruw |
|---|---|
| 33 | 0.354 |
| 50 | 0.355 |
| 60 | 0.354 |
| 105 | 0.35 |
| 120 | 0.349 |
| 140 | 0.348 |
| 160 | 0.348 |
| 180 | 0.347 |




| Time | Fit |
|---|---|
| 0 | 0.34709 |
| 33 | 0.345333 |
| 50 | 0.344567 |
| 60 | 0.344156 |
| 105 | 0.342606 |
| 120 | 0.342184 |
| 140 | 0.341683 |
| 160 | 0.341245 |
| 180 | 0.34086 |

| Partial loads | | | |
|---|---|---|---|
| Load | Tref | Seli [mV] | speed |
| 150% | 71.6 | n.a. | |
| 125% | 59.6 | 1450 | 3000 |
| 100% | 47.7 | 1180 | 3000 |
| 75% | 35.8 | 890 | 3000 |
| 50% | 23.9 | 610 | 3000 |
| 25% | 8.9 | 250 | 3000 |
| Offset torsiometro | | -0.1 | |

09/09/2014, H160 PMASR rotor 2, heat run speed 75%, torsio 200 Nm




Selimar in coppia analogica, 2310 mV (with 60 mV offset)
OPD-R in velocita’, 1125 rpm, Params_manualtuning2
Alim DC-link 621 Vdc (TDE) 619 Vdc (tester)
Offset torsiometro:-0.075 Nm ???

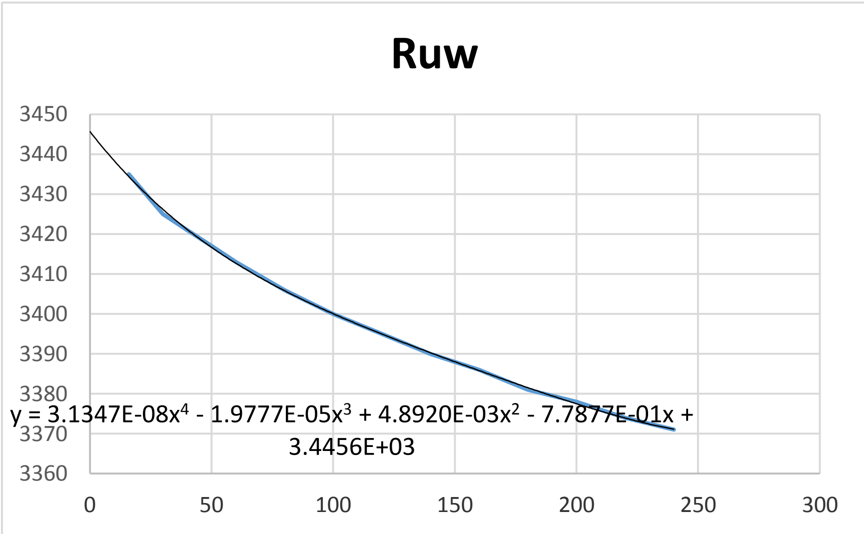
R a caldo: vedi dati raffreddamento

R a freddo (25.5°C):
Ruv = 300.70 mOhm
Ruw = 300.63 mOhm
Rvw = 300.35 mOhm
R media = 300.56 mOhm

- **Cooling heat run 09/09/2014**

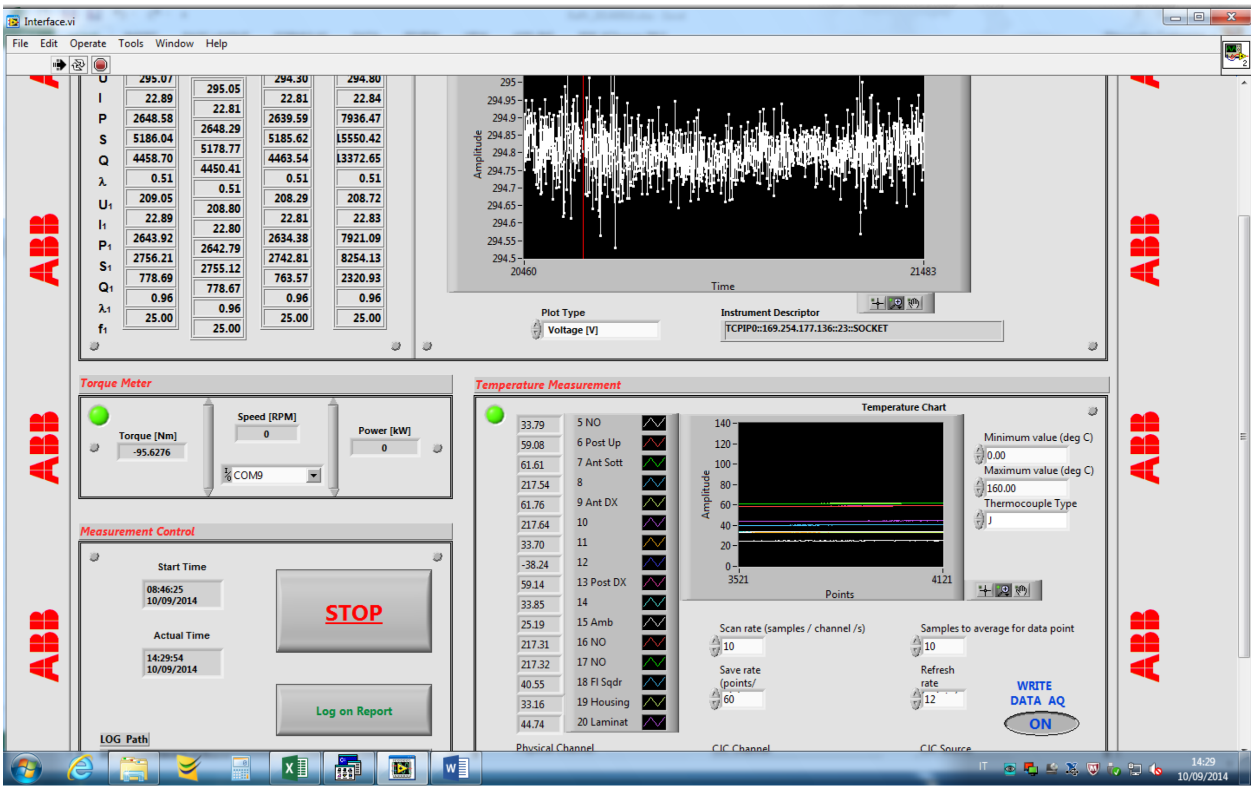
| Time | Ruw |
|---|---|
| 16 | 3435 |
| 30 | 3425 |
| 40 | 3421 |
| 50 | 3417 |
| 60 | 3413 |
| 80 | 3406 |
| 100 | 3400 |
| 120 | 3395 |
| 140 | 3390 |
| 160 | 3386 |
| 180 | 3381 |
| 200 | 3378 |
| 220 | 3374 |
| 240 | 3371 |

| Time | Fit |
|---|---|
| 0 | 0.34709 |
| 16 | 0.34619 |
| 30 | 0.345478 |
| 40 | 0.345007 |
| 50 | 0.344567 |
| 60 | 0.344156 |
| 80 | 0.34341 |
| 100 | 0.342757 |
| 120 | 0.342184 |
| 140 | 0.341683 |
| 160 | 0.341245 |
| 180 | 0.34086 |
| 200 | 0.340524 |
| 220 | 0.340229 |
| 240 | 0.339971 |




| Partial loads | | | |
|---|---|---|---|
| Load | Tref | Seli [mV] | speed |
| 150% | 143.2 | n.a. | |
| 125% | 119.4 | 2870 | 1125 |
| 100% | 95.5 | 2310 | 1125 |
| 75% | 71.6 | 1740 | 1125 |
| 56% | 53.5 | 1320 | 1125 |
| 50% | 47.7 | 1190 | 1125 |
| 37.5% | 35.8 | 890 | 1125 |
| 25% | 23.9 | 620 | 1125 |
| 40% | 38.2 | 960 | 745 |
| Offset torsiometro | | -0.13 | |

10/09/2014, H160 PMASR rotor 2, heat run speed 50%, torsio 200 Nm




Selimar in coppia analogica, 2310 mV (with 60 mV offset)
OPD-R in velocita', 750 rpm, Params_manualtuning2
Alim DC-link 621 Vdc (TDE) 619 Vdc (tester)
Offset torsiometro: 0.02 Nm ???

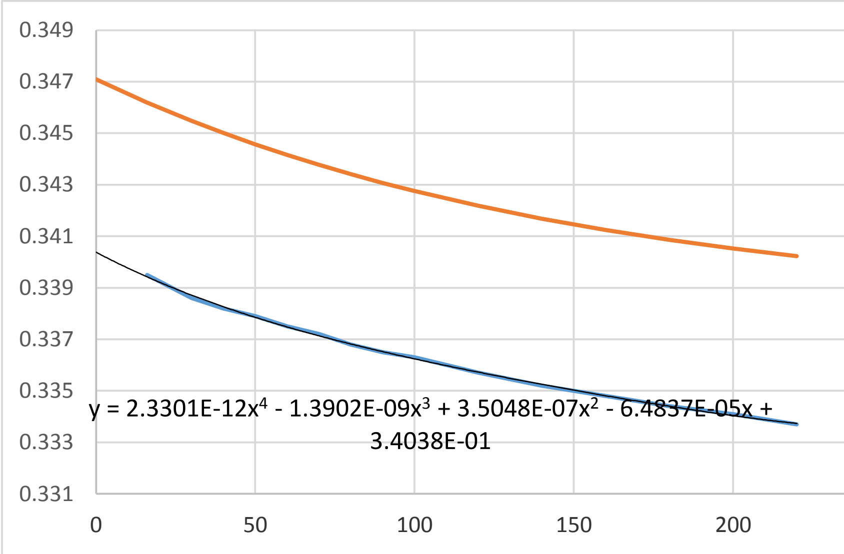
R a caldo: vedi dati raffreddamento

R a freddo (25.5°C):
Ruv = 300.70 mOhm
Ruw = 300.63 mOhm
Rvw = 300.35 mOhm
R media = 300.56 mOhm

- **Cooling heat run 09/10/2014**

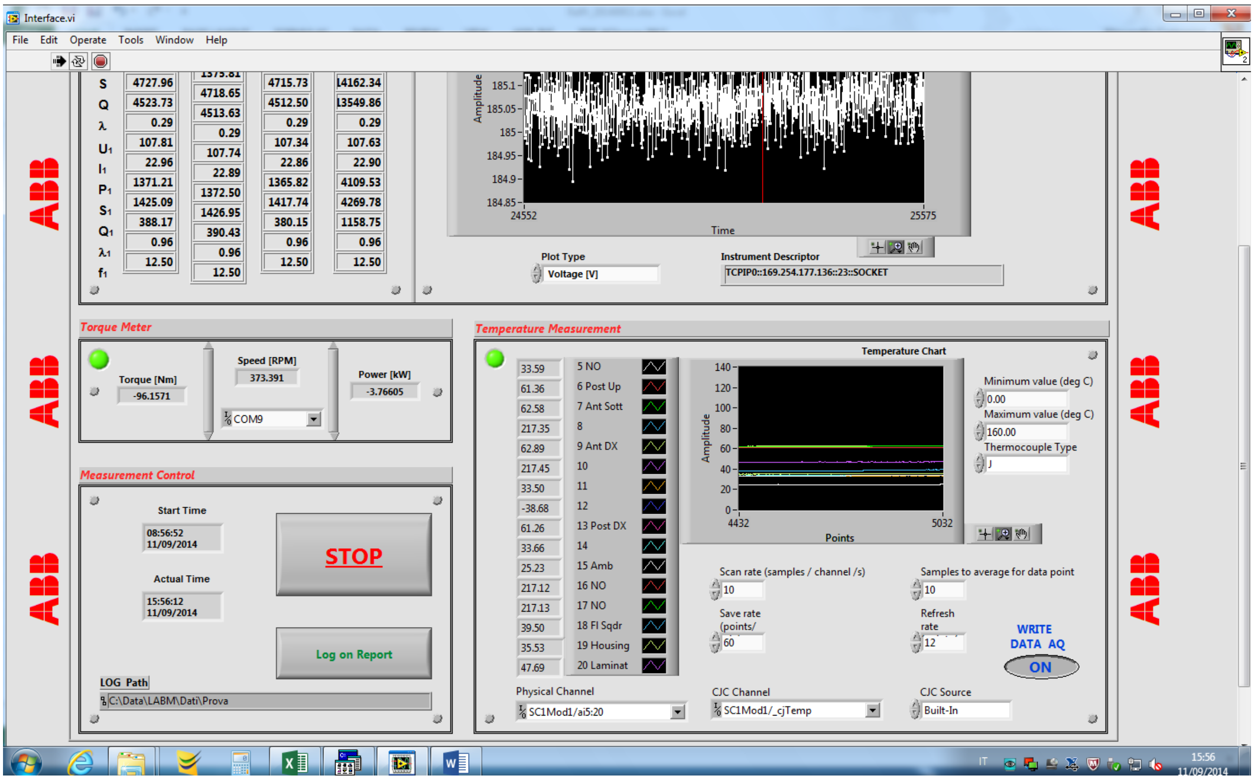
| Time | Ruw |
|---|---|
| 16 | 0.3395 |
| 30 | 0.3386 |
| 40 | 0.3382 |
| 50 | 0.3379 |
| 60 | 0.3375 |
| 70 | 0.3372 |
| 80 | 0.3368 |
| 90 | 0.3365 |
| 100 | 0.3363 |
| 120 | 0.3357 |
| 140 | 0.3352 |
| 160 | 0.3348 |
| 180 | 0.3344 |
| 200 | 0.3341 |
| 220 | 0.3337 |
| 240 | 0.3334 |

| Time | Fit |
|---|---|
| 0 | 0.34709 |
| 16 | 0.34619 |
| 30 | 0.345478 |
| 40 | 0.345007 |
| 50 | 0.344567 |
| 60 | 0.344156 |
| 70 | 0.34377 |
| 80 | 0.34341 |
| 90 | 0.343072 |
| 100 | 0.342757 |
| 120 | 0.342184 |
| 140 | 0.341683 |
| 160 | 0.341245 |
| 180 | 0.34086 |
| 200 | 0.340524 |
| 220 | 0.340229 |




| Partial loads | | | |
|---|---|---|---|
| Load | Tref | Seli [mV] | speed |
| 150% | 143.2 | n.a. | |
| 125% | 119.4 | 2870 | 750 |
| 100% | 95.5 | 2310 | 750 |
| 75% | 71.6 | 1740 | 750 |
| 50% | 47.7 | 1190 | 750 |
| 25% | 23.9 | 620 | 750 |
| | | | |
| Offset torsiometro | | 0.09 | |

11/09/2014, H160 PMASR rotor 2, heat run speed 25%, torsio 200 Nm




Selimar in coppia analogica, 2310 mV (with 60 mV offset)
OPD-R in velocita', 375 rpm, Params_manualtuning2
Alim DC-link 621 Vdc (TDE) 619 Vdc (tester)
Offset torsiometro: -0.08 Nm ???

R a caldo: vedi dati raffreddamento

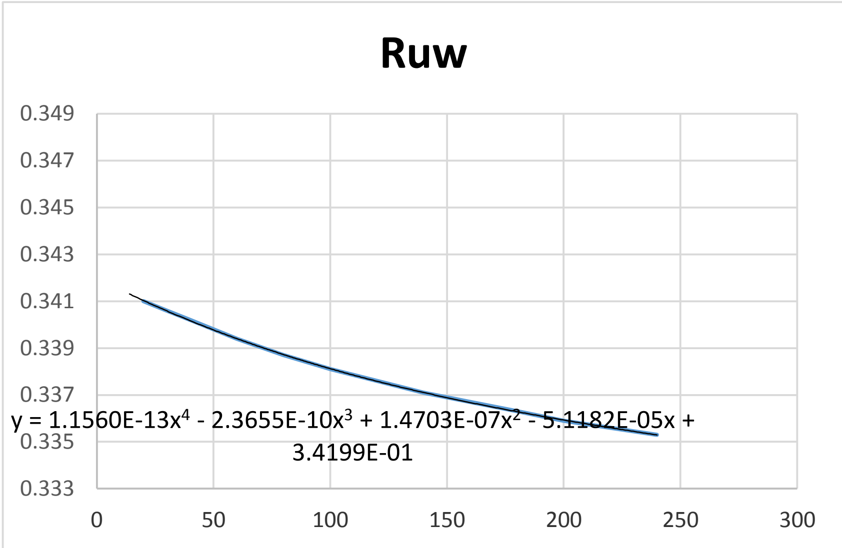
R a freddo (25.5°C):
Ruv = 300.70 mOhm
Ruw = 300.63 mOhm
Rvw = 300.35 mOhm
R media = 300.56 mOhm

- **Cooling heat run 09/10/2014**

| Time | Ruw |
|---|---|
| 20 | 0.341 |
| 30 | 0.3406 |
| 40 | 0.3402 |
| 60 | 0.3394 |
| 80 | 0.3387 |
| 100 | 0.3381 |
| 120 | 0.3376 |
| 140 | 0.3371 |
| 160 | 0.3367 |
| 180 | 0.3363 |
| 200 | 0.3359 |
| 220 | 0.3356 |
| 240 | 0.3353 |

| Time | Fit |
|---|---|
| 0 | 0.34709 |
| 20 | 0.34598 |
| 30 | 0.345478 |
| 40 | 0.345007 |
| 60 | 0.344156 |
| 80 | 0.34341 |
| 100 | 0.342757 |
| 120 | 0.342184 |
| 140 | 0.341683 |
| 160 | 0.341245 |
| 180 | 0.34086 |
| 200 | 0.340524 |
| 220 | 0.340229 |
| 240 | 0.339971 |

| Partial loads | | | |
|---|---|---|---|
| Load | Tref | Seli [mV] | speed |
| 150% | 143.2 | n.a. | |
| 125% | 119.4 | 2870 | 375 |
| 100% | 95.5 | 2310 | 375 |
| 75% | 71.6 | 1740 | 375 |
| 50% | 47.7 | 1190 | 375 |
| 25% | 23.9 | 610 | 375 |
| | | | |
| Offset torsiometro | | 0.02 | |



# 4.5 Efficiency Test PMSR End Result:-

## Motor efficiency class test

| | | | | | | |
|---|---|---|---|---|---|---|
| **Test date** | 31/07/2014 | **Motor type** | M3AA160MLB-4 PMASR | | **S/N** | |
| | | **Motor code** | | | **Int. Ref.** | Rotor 2 |

**Nameplate data**

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Voltage | 400 | V | Power | 15 | kW | Eff 100% | |
| Frequency | 50 | Hz | Current | | A | Eff 75% | |
| Speed | 1500 | rpm | cosphi | | | Eff 50% | |
| Back-e.m.f. | 176.2 | V | | | | | |

IE5 limit 95.10% 50 Hz 4 poles

Trated from plate 95.49 Nm

**Stator resistance before testing**

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Ruv | 300.70 | mOhm | Ruw | 300.63 | mOhm | Rvw | 300.35 | mOhm |
| Rmean | 300.56 | mOhm | T ambient | 25.5 | deg C | | | |

| **Heating test** | **U(H)** | **I** | **P1** | **P.F.(H)** | **T** | **Act. Load** | **n** | **P2** |
|---|---|---|---|---|---|---|---|---|
| | 400.58 | 23.73 | 15843.75 | 0.96 | 96.22 | 100.8% | 1500 | 15113.92 |
| **Loss separation** | **Pfw** | **Pfe** | **Ps,t** | **Pr,t** | **PLL** | | | |
| | 48.95 | 0 | 292.38 | 0 | 0 | | | |

**Motor temperatures after testing**

| **Stator** | | | **Rotor** | | |
|---|---|---|---|---|---|
| Ruw | 349.365396 | mOhm | Back-e.m.f. | 157 | V rms |
| Winding overtemp | 40.16 | K | Magnets overtemperature | 51.6 | K |
| Ambient | 27.85 | deg C | | | |

**Motor efficiency, direct method**

| | |
|---|---|
| **Efficiency** | 95.4% |
| **Eff. Class** | IE5 |

**Motor VSD efficiency, draft IEC 60034-30-2, 2/1741/CD**

| | |
|---|---|
| **Efficiency** | 94.1% |
| **Eff. Class** | IE5V |

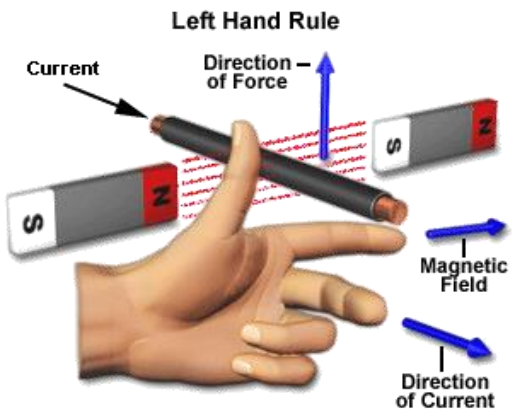
| **Partial Loads** | **U(H)** | **I** | **P1** | **P.F.(H)** | **T** | **Act. Load** | **n** | **P2** | **eta** |
|---|---|---|---|---|---|---|---|---|---|
| 25% | 171.28 | 14.36 | 4076.3 | 0.958 | 24.1 | 25.3% | 1500 | 3788.9 | 92.95% |
| 50% | 270.45 | 17.15 | 8024.8 | 0.999 | 48.3 | 50.6% | 1500 | 7588.9 | 94.57% |
| 75% | 350.86 | 19.94 | 11861.5 | 0.979 | 71.9 | 75.3% | 1500 | 11292.2 | 95.20% |
| 100% | 400.42 | 23.74 | 15853.0 | 0.962 | 96.2 | 100.7% | 1500 | 15112.3 | 95.33% |
| 125% | 398.80 | 29.71 | 19830.0 | 0.966 | 120.1 | 125.7% | 1500 | 18860.5 | 95.11% |
| 150% | 0.00 | 0.00 | 0.0 | 0.000 | 0.0 | 0.0% | 0 | 0.0 | 0.00% |

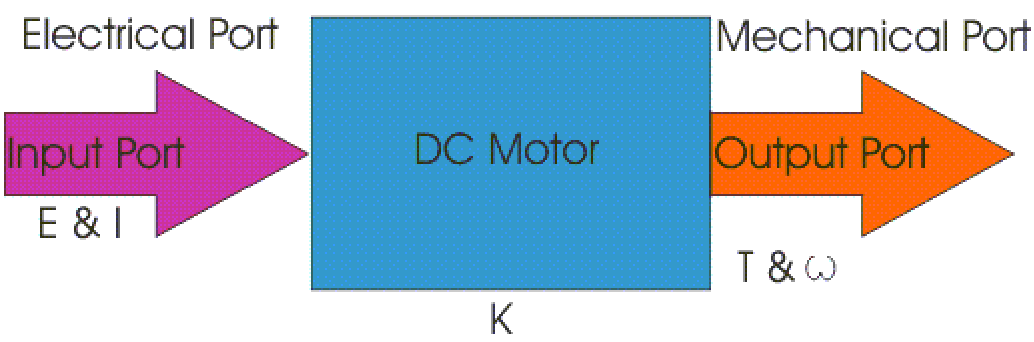
# Chapter 5 “DC Motor”

## 5.1 Description:-

This DC or direct current motor works on the principal, when a current carrying conductor is placed in a magnetic field, it experiences a torque and has a tendency to move. This is known as motoring action. If the direction of current in the wire is reversed, the direction of rotation also reverses. When magnetic field and electric field interact they produce a mechanical force, and based on that the working principle of dc motor established. The direction of rotation of a this motor is given by Fleming’s left hand rule, which states that if the index finger, middle finger and thumb of your left hand are extended mutually perpendicular to each other and if the index finger represents the direction of magnetic field, middle finger indicates the direction of current, then the thumb represents the direction in which force is experienced by the shaft of the dc motor.

Structurally and construction wise a direct current motor is exactly similar to a DC generator, but electrically it is just the opposite. Here we unlike a generator we supply electrical energy to the input port and derive mechanical energy from the output port. We can represent it by the block diagram shown below.



## 5.2 Construction:-

A DC motor like we all know is a device that deals in the conversion of electrical energy to mechanical energy and this is essentially brought about by two major parts required for the **construction of dc motor**, namely.

1) Stator – The static part that houses the field windings and receives the supply and,

2) Rotor – The rotating part that brings about the mechanical rotations.
3) Yoke of dc motor.

4) Poles of dc motor.

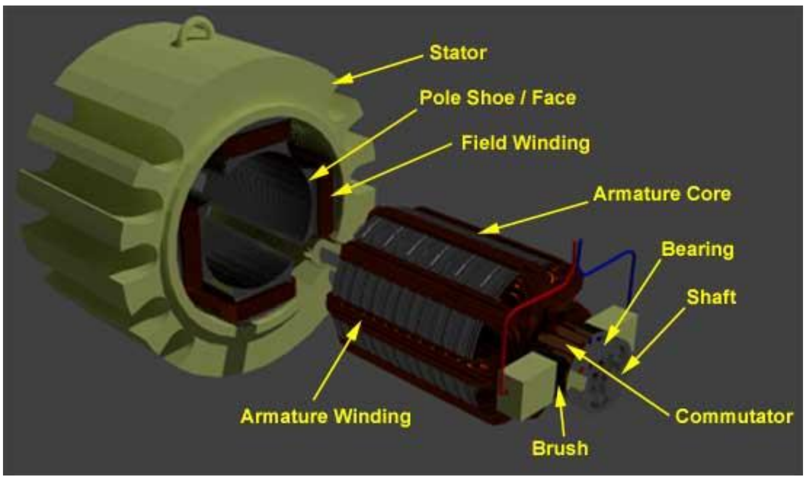
5) Field winding of dc motor.

6) Armature winding of dc motor.

7) Commutator of dc motor.

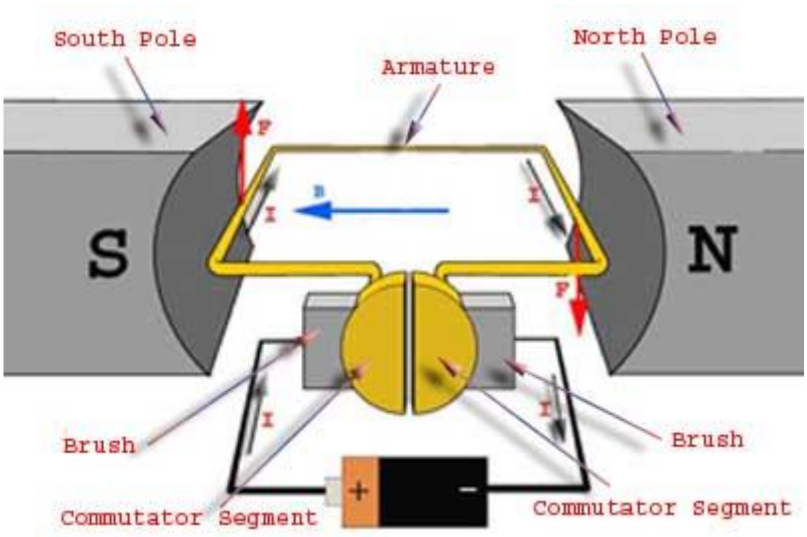
8) Brushes of dc motor.

All these parts put together configures the total construction of a dc motor.



## 5.3 Working Principle:-

A DC motor in simple words is a device that converts direct current (electrical energy) into mechanical energy. It's of vital importance for the industry today, and is equally important for engineers to look into the **working principle of DC motor** in details that has been discussed in this article. In order to understand the **operating principle of dc motor** we need to first look into its constructional feature




The very basic construction of a dc motor contains a current carrying armature which is connected to the supply end through commutator segments and brushes and placed within the north south poles of a permanent or an electro-magnet.

For the **operation of dc motor**, considering E = 0

$$dF = dq \times v \times B$$

I.e. it's the cross product of dq v and magnetic field B.

$$dF = dq\frac{dL}{dt} \times B \qquad \left[v = \frac{dL}{dt}\right]$$

Where dL is the length of the conductor carrying charge q.

$$dF = \frac{dq}{dt}dL \times B$$

$$or, dF = IdL \times B \quad \left[Since,\ current\ I\ =\ \frac{dq}{dt}\right]$$

$$or, F = IL \times B\ = ILB\sin\theta$$

$$or,\ F = BIL\sin\theta$$

From the 1st diagram we can see that the construction of a DC motor is such that the direction of current through the armature conductor at all instance is perpendicular to the field. Hence the force acts on the armature conductor in the direction perpendicular to the both uniform field and current is constant.

$$i.e. \theta =\ 90^\circ$$

So if we take the current in the left hand side of the armature conductor to be I, and current at right hand side of the armature conductor to be − I, because they are flowing in the opposite direction with respect to each other.

Then the force on the left hand side armature conductor,

$$F_l = BIL\sin 90^\circ = BIL$$

Similarly force on the right hand side conductor

$$F_r = B(-I)L\sin 90^\circ = -BIL$$

We can see that at that position the force on either side is equal in magnitude but opposite in direction. And since the two conductors are separated by some distance w = width of the armature turn, the two opposite forces produces a rotational force or a torque that results in the rotation of the armature conductor.

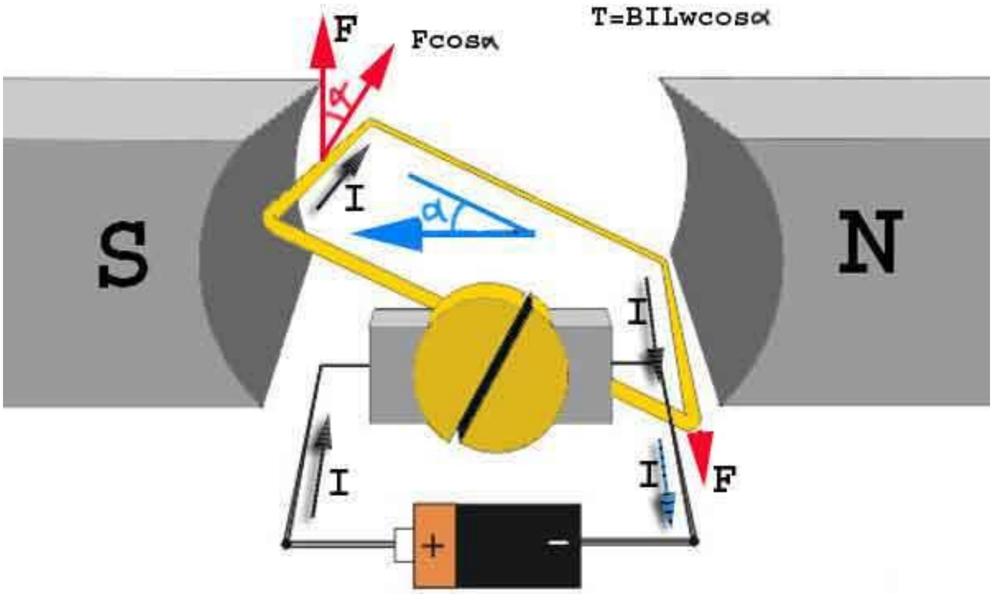
Now let’s examine the expression of torque when the armature turn crate an angle of α with its initial position.

The torque produced is given by,

$$Torque = (force,\ tangential\ to\ the\ direction\ of\ armature\ rotation\ ) \times (distance).$$
$$or,\ \tau = F\cos\alpha \times w$$
$$or,\ \tau = BILw\cos\alpha$$

Where α is the angle between the plane of the armature turn and the plane of reference or the initial position of the armature which is here along the direction of magnetic field.

The presence of the term cosα in the torque equation very well signifies that unlike force the torque at all position is not the same. It in fact varies with the variation of the angle α. To explain the variation of torque and the principle behind rotation of the motor let us do a step wise analysis.

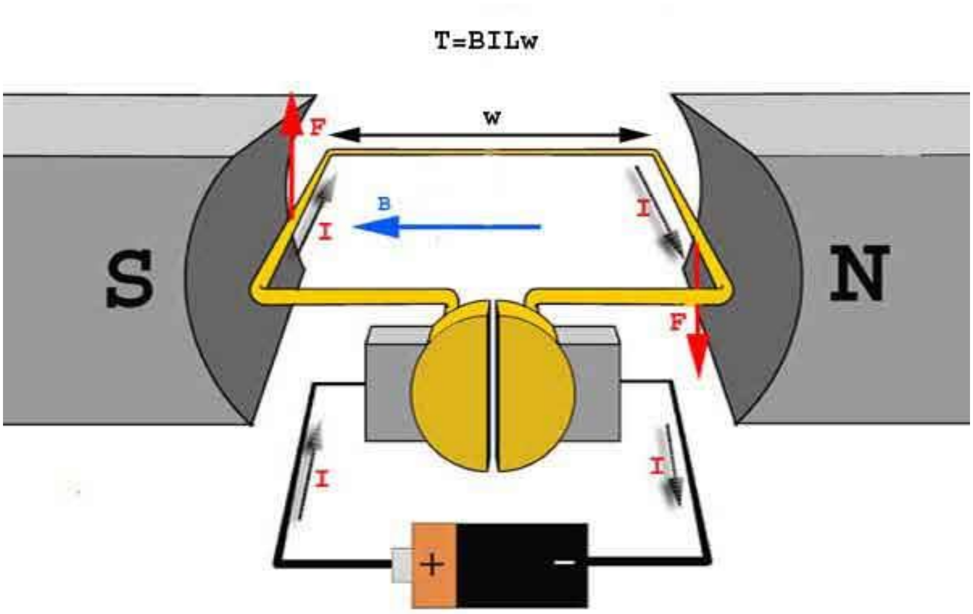



**Step 1:**

Initially considering the armature is in its starting point or reference position where the angle α = 0.

$$\therefore\ \tau = BILw \times \cos 0^\circ = BILw$$

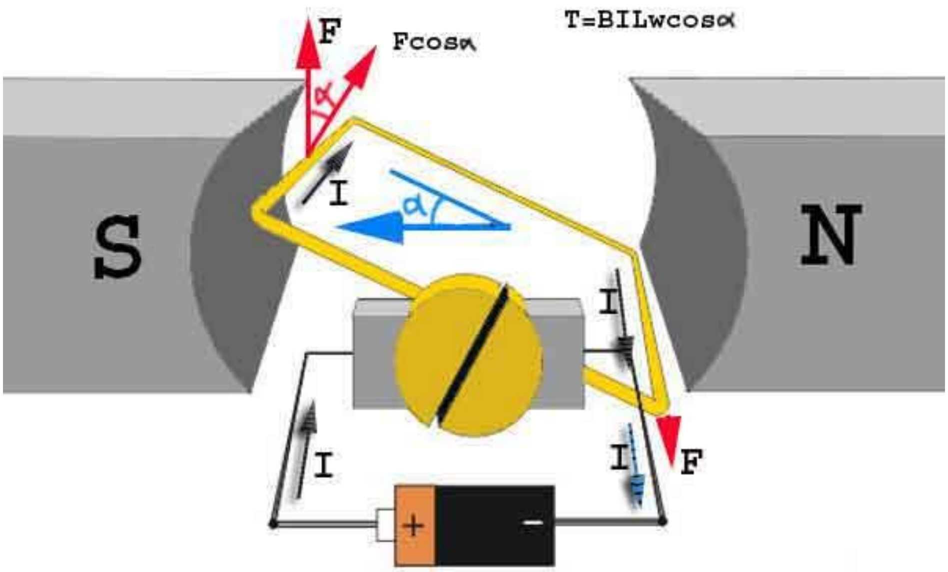
Since α = 0, the term cos α = 1, or the maximum value, hence torque at this position is maximum given by τ = BILw. This high starting torque helps in overcoming the initial inertia of rest of the armature and sets it into rotation.




**Step 2:**

Once the armature is set in motion, the angle α between the actual position of the armature and its reference initial position goes on increasing in the path of its rotation until it becomes 90° from its initial position. Consequently the term cosα decreases and also the value of torque.

The torque in this case is given by τ = BILwcosα which is less than BIL w when α is greater than 0°.

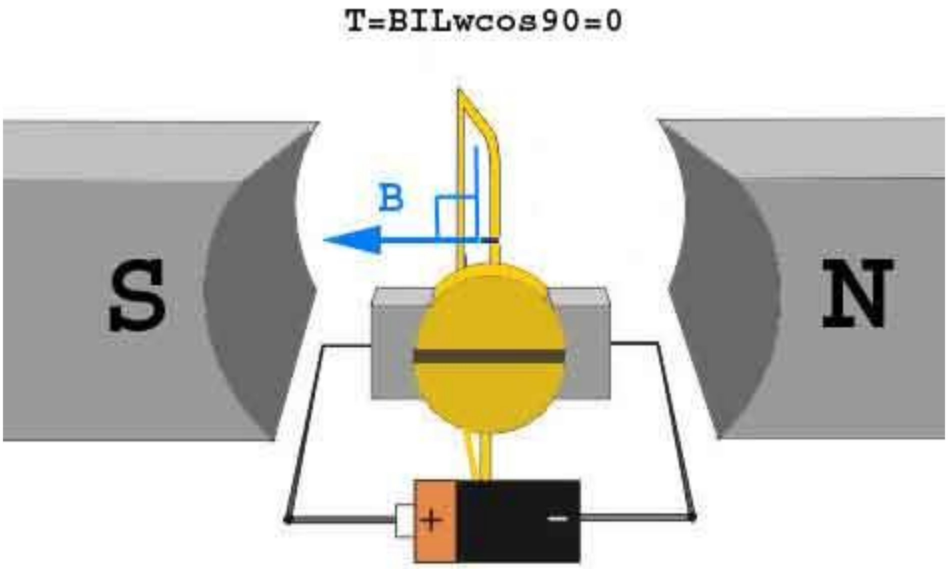



**Step 3:**

In the path of the rotation of the armature a point is reached where the actual position of the rotor is exactly perpendicular to its initial position, i.e. α = 90°, and as a result the term cosα = 0.

The torque acting on the conductor at this position is given by,

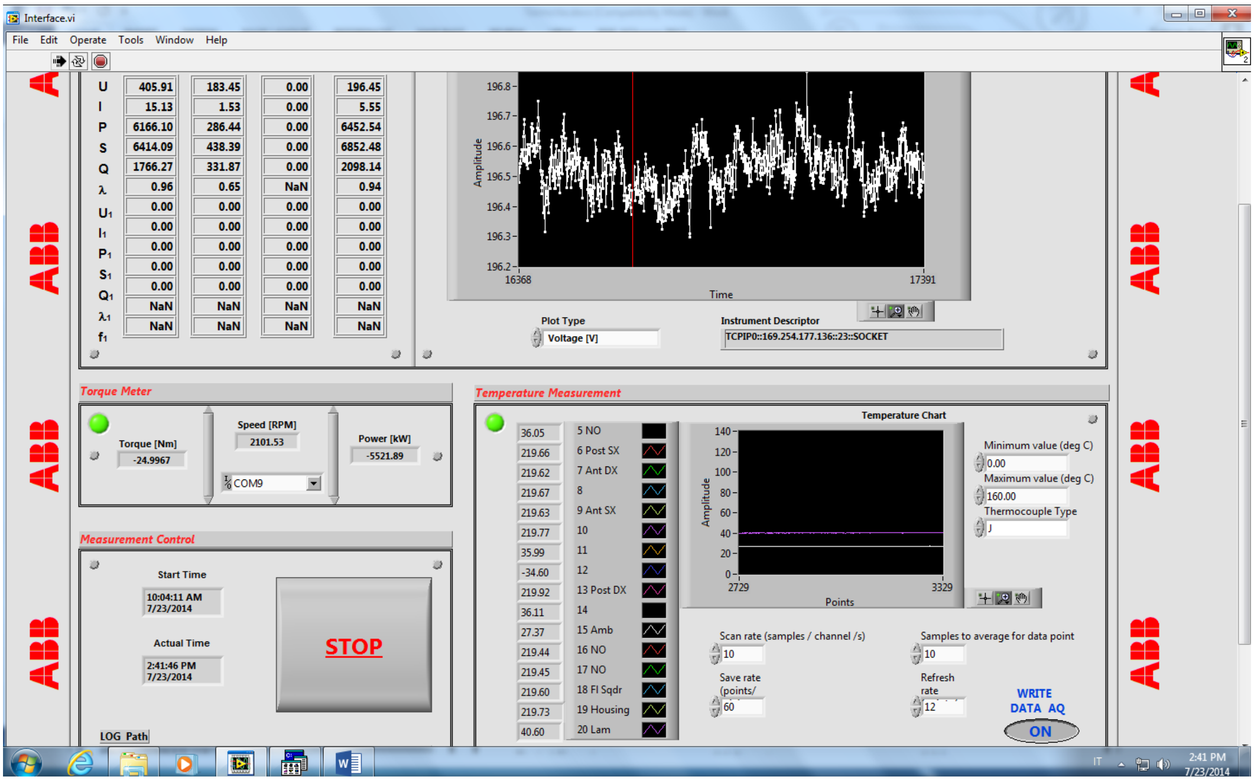
$$\therefore \ \tau = BILw \times \cos 90^\circ = 0$$




I.e. virtually no rotating torque acts on the armature at this instance. But still the armature does not come to a standstill, this is because of the fact that the operation of dc motor has been engineered in such a way that the inertia of motion at this point is just enough to overcome this point of null torque. Once the rotor crosses over this position the angle between the actual position of the armature and the initial plane again decreases and torque starts acting on it again.

## 5.4 Efficiency Calculation Tests: -

## 23/7/2014, DC motor 5.4 kW, heat run nominale, torsio 50 Nm




Selimar in coppia analogica, 620 mV (with 60 mV offset)
DC drive in velocita', 100%
Velocita' misurata 2102 rpm
Offset torsiometro: -0.03 Nm

R a caldo:
Rarm = 2.768 Ohm
Rfield = 117.4 Ohm

R a freddo (23°C):
Rarm = 2.255 Ohm
Rfield = 93.7 Ohm

| | Torque Calculations at | | | | |
|---|---|---|---|---|---|
| | 25% | 50% | 75% | 100% | No load |
| | 6.055 | 12.11 | 18.165 | 24.22 | |
| Speed at | 2246 | 2192 | 2144 | 2103 | 2294 |

Value of Temperature

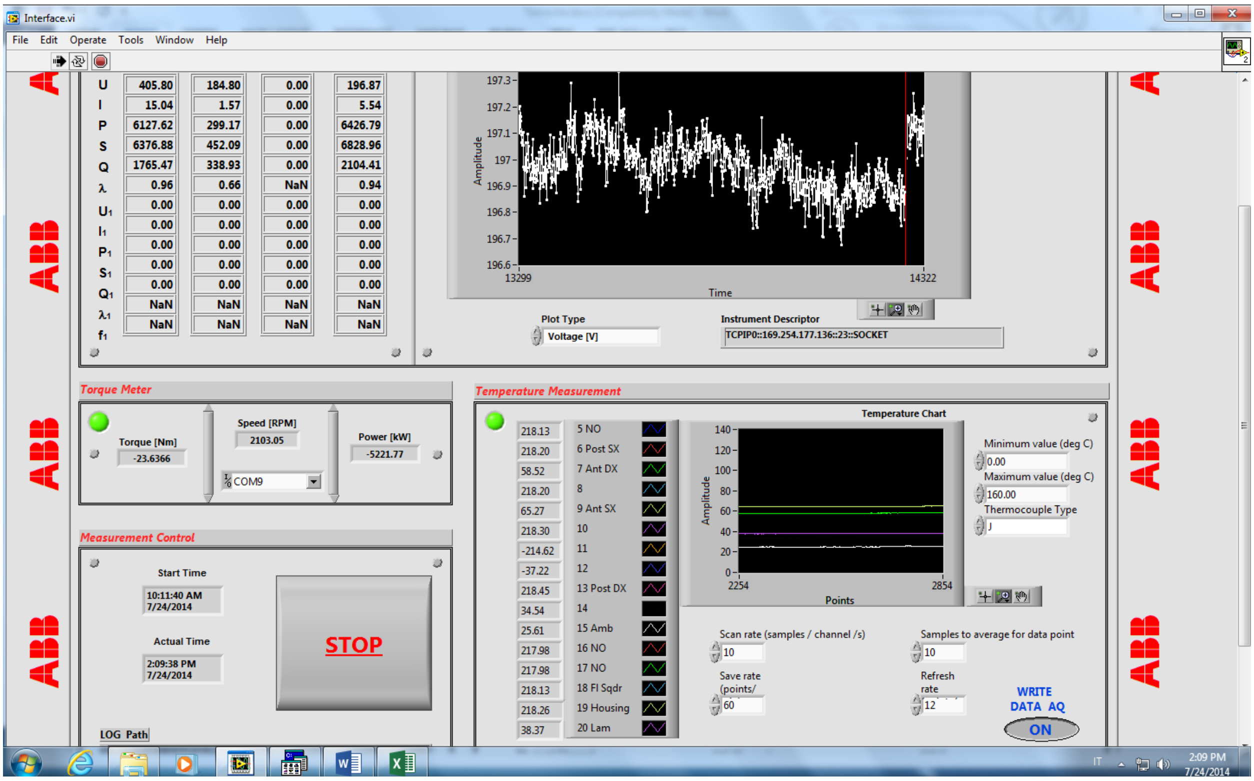
$$\theta 2 - \theta a = \left(\frac{R2 - R1}{R1}\right) * (K + \theta 1) + \theta 1 - \theta a$$

Where

- θ1 is the temperature © of the winding (cold) at the moment of the initial resistance measurement;
- θ2 is the temperature © of the winding at the end of the thermal test;
- θa is the temperature © of the coolant at the end of the thermal test;
- R1 is the resistance of the winding at temperature θ1 (cold);
- R1 is the resistance of the winding at the end of the thermal test;
- K is the reciprocal of the temperature coefficient of resistance at 0© of the conductor material, For Copper K=235;

| Armature Winding θ2 | Field Winding θ2 |
|---|---|
| 81.69357 | 88.2572 |

# 24/7/2014, DC motor 5.4 kW, heat run nominale, torsio 50 Nm




Selimar in coppia analogica, 620 mV (with 60 mV offset)
DC drive in velocita', 100%
Velocita' misurata 2098 rpm
Offset torsiometro: -0.12 Nm

R a caldo:
Rarm = 2.755 Ohm
Rfield = 116.0 Ohm

R a freddo (22.6°C):
Rarm = 2.255 Ohm
Rfield = 93.7 Ohm

| | Torque Calculations at | | | | |
|---|---|---|---|---|---|
| | 25% | 50% | 75% | 100% | No load |
| | 6.055 | 12.11 | 18.165 | 24.22 | |
| Speed at | 2246 | 2192 | 2144 | 2103 | 2294 |

Value of Temperature

$$\theta 2 - \theta a = \left(\frac{R2 - R1}{R1}\right) * (K + \theta 1) + \theta 1 - \theta a$$

Where

- θ1 is the temperature © of the winding (cold) at the moment of the initial resistance measurement;
- θ2 is the temperature © of the winding at the end of the thermal test;
- θa is the temperature © of the coolant at the end of the thermal test;
- R1 is the resistance of the winding at temperature θ1 (cold);
- R1 is the resistance of the winding at the end of the thermal test;
- K is the reciprocal of the temperature coefficient of resistance at 0© of the conductor material, For Copper K=235;

Armature Winding θ2
81.69357

Field Winding θ2
88.2572

**(Note: As you can see that the DC motor is not of the same specification like the others motors we tested in the lab, so there was no sense to make a comparison of DC motor with the other motors.**

**But it was important to discuss it here because I have worked out on it and I tested it like the other motors too).**

# Chapter 6 "Efficiency Comparisons b/w Motors Tested"

## 6.1 Comparison of Result Achieved:-

Here in this chapter I will show you the comparison of all the 3 motors with same specification tested in the ABB SMO Laboratory during my thesis work.

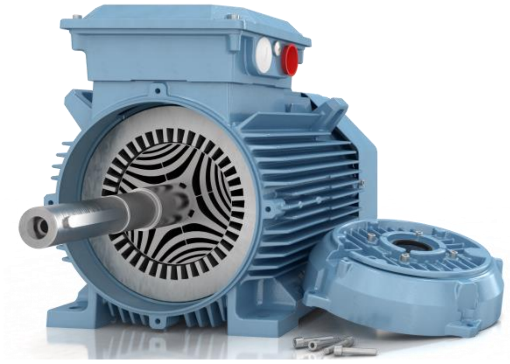
So I start with the result achieved from all the motors and represent it in a Tabular form to be interpreted easily.

| | **Induction M3AA 160 MLB 4_IE2** | **M3AA160MLB-4 PMASR** | **SRM M3BL 160 MLB** |
|---|---|---|---|
| **Efficiency (%)** | 90.8% | 95.4% | 93.9% |
| **Efficiency Class** | **IE2** | **IE5** | **IE5** |
| | | | |

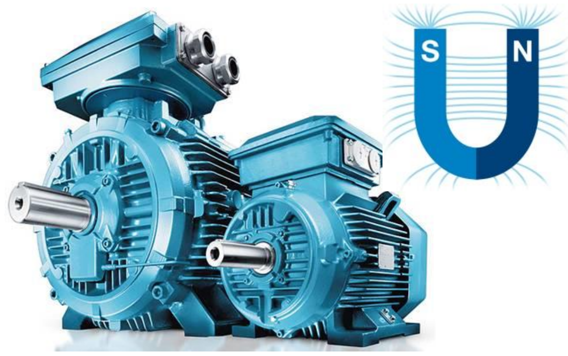
## 6.2 Discussion about the Efficiency of Motors under test:-

Higher efficiency requires new technology

IE2 Induction motor



IE4 Synchronous reluctance motor – magnet-free




IE4 Permanent magnet motor – rare earth

**Today's technology makes it feasible Very high motor or system efficiency**

Synchronous reluctance technology Design concept

Single sheet of punched electrical steel

- Synchronous reluctance motor needs a drive (ACS850)
- Can replace most of the variable speed driven induction motors in quadratic torque (pumps, fans) and constant torque applications
- Reliable high efficient **"workhorse"** for general industrial applications
- Energy losses reduced by up to 40% compared to IE2 efficiency class
- Energy savings
- Compactness and efficiency of permanent magnet motor
- Service friendliness of induction motor
- Magnet free design


- Higher reliability through lower bearing temperature
- Less heat in rotor
- Less heat transferred though shaft to bearings

- Grease will last longer and maintain better lubrication
- Less maintenance and down time

## 6.3 How much does a motor cost?

- 65 % of total electricity at industrial sites is consumed by electric motors
- Motor purchasing price corresponds to 8 to 12 weeks of its electricity consumption
- The capital cost will represent only 1% of the total life cycle operational costs of the motor
- Reliable motors with a high efficiency level ensure the lowest life cycle costs

One 75kW Motor cost ............25 years to run 24/7?

$90,000

Life time cost of power

$2,250,000............ Save............6% $135,000

# Chapter 7 “Devices Used for Tests”

As there were many devices used in the test but I will mention here the main big ones. I also want to mention I used ABB internal Softare developed for testing of such motors on a Computer PC. And there was also a software interface between all the hardware connected for the testing to control and change the torque and speed value from PC apart from the Drive systems control.

## 7.1 ACS880 (ABB Drive System for PMSR)

Built on our all-compatible drive architecture these inverter modules are designed to fit all your cabinet requirements. The modules come in eight frame sizes, including the R8i inverter module for building high power inverters in multidrives. The R8i has a speed-controlled fan, quick connectors and wheels for easy manoeuvring. Built-in capacitors smooth the voltage of the DC bus bars, while safety is key with safe torque off (STO) as standard.

Highlights

- Power range 1.5 to 3200 kW
- Built on common drives architecture
- Direct torque control (DTC) as standard
- Built into customer’s cabinets
- IP00 enclosure classes
- Integrated safety including STO as standard
- Intuitive control panel with USB port
- Supports a wide range of fieldbus protocols
- Flexible I/O and encoder options

## 7.2 ACS850 (ABB Drive System for SRM)

ACS850 drives are ideal for applications like cranes, extruders, conveyors, winders, pumps, fans and mixers in industries such as material handling, plastic and rubber, food and beverage, textile and metals. ACS850 drives offer a wide range of built-in options such as different I/O and communications. A wide selection of external accessories is also available. The flexibility and programmability of the drives make them suitable for many applications in different industries.

Mains connection

- Supply voltage 3-phase 380 to 500 V AC +10 /-15% 3-phase 200 to 240 V AC ± 10%
- Frequency 50 to 60 Hz ± 5%
- DC connection DC voltage level 485 to 675 V DC ± 10% (-5 types) 270 to 324 V DC ± 10% (-2 types)

- Charging circuit Internal in frames A to D External in frames E0 to G2 Motor connection
- Motor types AC induction motors, permanent magnet motors and synchronous reluctance motors
- Output frequency 0 to 500 Hz

**Operating conditions**

- Degree of protection

  IP20 according to EN 60529 (G frames IP00); Open type according to UL 508

- Ambient temperature -10 to +55 °C (14 to 131 °F), derating above 40 °C (104 °F) No frost allowed
- Installation altitude 0 to 4000 m (0 to 13000 ft) (IT network: 2000 m [6560 ft]), derating above 1000 m (3280 ft): 1%/100 m (328 ft)
- Relative humidity Max. 95%, no condensation allowed
- Climatic/ environmental conditions

  Class 3K3, 3C2 according to EN 60721-3-3. Oil mist, formation of ice, moisture condensation, water drops, water spray, water splashes and water jets are not permissible.

- Vibration Class 3M4 according to EN 60721-3-3
- EMC (According to EN 61800-3)

  Categories C2 and C3 with optional filter (according to EN 61800-3)

- Functional safety Safe torque off (STO according to EN 61800-5-2) IEC 61508: SIL 3 IEC 61511: SIL3 EN 62061: SILCL 3 EN ISO 13849-1: PL e Certified by TÜV
- Compliance Frames

  A to D: CE, GOST R, UL, cUL, CSA, C-Tick Frames E0 to G: CE, GOST R; pending: UL, cUL, CSA, C-Tick

## 7.3 ACS880-01-038A-3(ABB Drive System for Induction Motor)

The ACS880 series drives are part of ABB’s all-compatible drives portfolio. Compatible with virtually all types of processes, automation systems, users and business requirements they are designed to tackle any motor-driven application, in any industry, whatever the power range. The innovation behind all-compatibility is our new drives architecture that simplifies operation, optimizes energy efficiency and helps maximize process output. The ACS880 series consists of single drives, multidrives and drive modules

At the heart of the drive is direct torque control (DTC), ABB’s premier motor control technology. The extensive range of options include EMC filters, encoders, resolvers, du/dt filters, sine filters, chokes and brake resistors, as well as application specific software. Built-in safety features reduce the need for external safety components. Multiple drives can be daisy-chained for synchronized drive-to-drive communication. The drives offering includes enclosure classes IP21 and IP55 for dusty and wet environments. ABB provides an extensive selection of support documentation for planning including dimension drawings in different formats, EPLAN P8 macros and helping in line apparatus selection tool.

Main features include − Enclosure classes IP21 and IP55 for different environments − Compact design for easy installation, commissioning and maintenance − Incoming air temperature measurement for protecting the drive from different temperature related failure mechanisms − Integrated safety including safe torque off (STO) as standard (TÜV Nord certificate) with the optional safety functions module (FSO-11) − Supports various motor types including synchronous reluctance motors − Intuitive control panel with USB connection − Removable memory unit for easy maintenance − Drive composer PC tool for commissioning and configuration − Primary control program - common software used throughout the ACS880 drive series − Control unit supporting a wide range of fieldbuses, feedback devices and input/output options − Coated boards as standard − Controllable cooling fan − Built-in braking chopper option for frame sizes R5 to R9 − EMC filter option − du/dt filter option for motor protection − Built-in choke

## 7.4 Torque Meter

A torque sensor or torque transducer or torque meter is a device for measuring and recording the torque on a rotating system, such as an engine, crankshaft, gearbox, transmission, rotor, a bicycle crank or cap torque tester. Static torque is relatively easy to measure. Dynamic torque, on the other hand, is not easy to measure, since it generally requires transfer of some effect (electric or magnetic) from the shaft being measured to a static system.

I used a torque meter of 200 N.m. for my efficiency tests.

## 7.5 Current Clamp meter

Current clamp or current probe is an electrical device having two jaws which open to allow clamping around an electrical conductor. This allows properties of the electric current in the conductor to be measured, without having to make physical contact with it, or to disconnect it for insertion through the probe. Current clamps are usually used to read the magnitude of a sinusoidal current (as invariably used in alternating current (AC) power distribution systems), but in conjunction with more advanced instrumentation the phase and waveform are available. Very high alternating currents (1000 A and more) are easily read with an appropriate meter; direct currents, and very low AC currents (mill amperes) are more difficult to measure.

## 7.6 FLUKE Power Analyzer Norma 4000

The compact Fluke Norma Series Power Analysers provide the latest measurement technology to assist engineers with the development and testing of motors, inverters, lighting, power supplies, transformers and automotive components. Based on a patented, high-bandwidth architecture, the instruments deliver high-precision measurements of single or three-phase current and voltage, harmonics analysis, Fast Fourier Transformation (FFT) analysis, as well as calculations of power and other derived values.

The Series consists of the Fluke Norma 4000 4000 Three-Phase Power Analysers and the Fluke Norma 5000 Six-Phase Power Analysers. These rugged, high-precision analysers provide unmatched price performance for easy and reliable use in the field, or as a bench unit in laboratories and on test benches.

Electric motors and inverter drive systems – Through detailed spectrum analysis and dynamic torque calculation capabilities, switching losses caused by the inverter are accurately measured, and a thorough evaluation is made of torque transients and harmonics at higher frequencies.

| **General Specifications** | |
|---|---|
| **Number of Phases** | **Fluke Norma 4000:** 1 to 3<br>**Fluke Norma 5000:** 3, 4 or 6 |
| **Weight** | **Fluke Norma 4000:** Approx. 5 kg (11 lb.)<br>**Fluke Norma 5000:** Approx. 7 kg (15 lb.) |
| **Size** | **Fluke Norma 4000:** 150 mm x 237 mm x 315 mm (5.9 in x 9.3 in x 12.4 in)<br>**Fluke Norma 5000:** 150 mm x 447 mm x 315 mm (5.9 in x 17.6 in x 12.4 in) |
| **On-board Printer** | **Fluke Norma 4000:** No<br>**Fluke Norma 5000:** Yes (optional) |
| **Display** | Colour, 5.7“ / 144 mm - 320 x 240 pixel<br>User-selectable background lighting and contrast. |
| **Bandwidth** | dc to 3MHz or dc to 10MHz depending on input module |
| **Basic Accuracy** | 0.2%, 0.1% or 0.03% depending on input modules |
| **Sampling Rate** | 0.33 MHz or 1 MHz depending on input modules |
| **Voltage Input Range** | 0.3 V to 1000 V |
| **Current Input Range (direct, not via shunt)** | 0.03 mA to 20 A depending on input module |
| **Memory for Configurations** | 4 MB |
| **Memory for Settings** | 0.5 MB |
| **Fast Fourier Transformation (FFT)** | To the 40th harmonic |
| **RS232/USB Interface** | Standard |

| | |
|---|---|
| **PI1 Process interface (8 analog/impulse inputs and 4 analog outputs)** | Optional |
| **IEEE 488.2/GPIB interface (1 MBit/s Ethernet / 10 MBit/s or 100 MBit/s)** | Optional |
| **Fluke NormaView PC software (for data download, analysis & report writing)** | Standard |

## 7.7 Kistler torque como torque type 4700

The evaluation instrument CoMo Torque Type 4700B... is ideal for industrial use and for research and development applications. Torque sensors with strain gage technology and standardised voltage output or frequency output can be connected directly.

• Display with indication of exact measured data for torque, speed, angle of rotation, force and mechanical power

• 4x20 character display

• Multiple menu language operation

• High measuring accuracy

• High scan rate 10 kHz

• Low-pass filter (filter off, 0,1 Hz ... 1 kHz)

• Memory with up to 5 000 measured values, each channel

• Min/max capture and limit value monitoring

• Can be remote via USB or RS-232C

• Scaled analog outputs

Description The simple parameterisation allows it to be used in production when evaluating torque/revolution measurements or torque/ angle of rotation measurements. The intuitive menu of the Type 4700B... allows it to be quickly adapted to new measurements and inspection tasks. Settings can be made easily for all functions, such as tarring, saving peak values, average determination, setting limits, measurement duration, pre- and post-triggers, calibration, scope of display, units, and the interface. Up to 20 parameter records can be stored internally in the non-volatile flash memory.

Application The industrial usages are numerous and various: • Determination of the performance of powered equipment using torque input and revolution • Design of transfer components or systems by determining the efficiency factor (for example, for clutches, brakes, gear boxes, motors and turbines) • Process control when screwing or verifying the inflexion point for torque wrenches • Function control during assembly, if the torque is evaluated in dependence of the angle of rotation; for example, when checking seat adjustments and hinges. The result of the evaluation is shown on the digital display as an OK or NOK signal

## 7.8 Function generator YOKOGAWA FG200

Featuring versatile sweep and modulation functions. These instruments offer you the capability to sweep not only frequency, but also other parameters as well, such as phase, amplitude, offset voltage, or duty cycle, with linear, log, linear step, log step, or arbitrary (FG310/FG320) sweep patterns. You can even sweep frequency and amplitude at the same time. Offering up to 256 programmed sequence steps (FG310/FG320)

Features

**The powerful sweep and modulation capabilities of these instruments make them ideal for applications in mechatronics, and vehicle design and testing.**

- Frequencies from 1 μHz to 15 MHz
- Arbitrary sweep patterns (FG310/FG320)
- Load and modify waveforms from other instruments (FG310/FG320)
- Versatile sweep and modulation functions
- External sweep control (/R1 option)
- Amplitude and duty cycle
- Multichannel output via synchronized operation
- Up to 256 programmed sequence steps (FG310/FG320)

Frequency range:

- 1 μHz to 15 MHz (Sine, Square)
- 1 μHz to 200 kHz (Triangle, Pulse, Arbitrary waveform)
- High resolution:
- 1 μHz or 9 digits max