POLITECNICO DI TORINO

Department of Mechanical and Aerospace Engineering

Automotive Engineering Course:

Propulsion System Development

MASTER OF SCIENCE THESIS

ICE TEST BENCH UPGRADING
FOR HYBRID AND ELECTRIC POWERTRAIN

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Abstract

ICE Test Bench Upgrading for Hybrid and Electric Powertrain
By Michelangelo Fratino

In the context of Electrified vehicles, BEV or HEV, testing phases, before building up final vehicle, are of crucial importance. To speed them up, and reduce their cost too, it is possible to create a *virtual vehicle model,* made – up of all its subcomponents, separately defined. This virtual model is then used to design real vehicle, not vice – versa, but to do that, all its subcomponents must be experimentally characterized and validated, in order to have a reliable virtual model. In fact, it is no coincidence that, most important simulation software, having at your disposal complete vehicle models, are all based on experimental validated subcomponents. One of the most important components of a vehicle is the powertrain, whose principal subcomponents, in case of BEV, are Batteries, Converter, Electric Motor. In these thesis activities, the goal is to build – up an Electric Motor model, validated through experimental activities in a Test Bench, in order to build a complete BEV virtual model in which all its subcomponents are characterized and experimentally validated. To accomplish this goal, thesis activities are focused on the upgrading of an ICE Test Bench, aimed at having at disposal a suitable bench for Electric Motor testing. Most important activities, in the upgrading phase, are related to studying best sensors to be used in the Test Bench, to fulfill measurement accuracy and ensure the highest possible reliable Motor model and Test Bench layout arrangement, to study safest and most efficient layout to speed up and increase test easiness. Final thesis activities are related to post – processing data, to correctly elaborate experimental results and obtain complete and reliable Motor model.

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List of Symbols

Name	Unit of Measure	Mathematical Symbol	Informatic Symbol	Location
DC Current	[A]	I_{DC}	I_DC	Inverter Input
DC Voltage	[V]	V_{DC}	V_DC	Inverter Input
Phase Current	[A$_{rms}$]	I_{rms}	I_rms	Inverter Output
Torque	[Nm]	T_m	T_m	Motor Shaft
Rotational Speed	[RPM]	ω	w	Motor Shaft
Mechanical Power	[W]	P_m	P_m	Motor Shaft
Electrical Power	[W]	P_{El}	P_el	Inverter Input
Efficiency	-	η_m	eta_m	-
Motor Temperature	[°C]	Θ_m	Temp_m	Motor windings

Chapter 1

1 Introduction

A motor test bench is a complex of machinery, instrumentation and support services needed to test it.

Motor testing is generally required to evaluate performance, characterize the effect of design parameters and working conditions on various parameters and, finally, homologate motor according to regulation procedures.

Tested performance classically includes:

- Electrical and Mechanical Powers;
- Motor efficiency;
- Motor Temperature.

The test bench must be designed in order to allow motor operation in each possible working point and it must be able to provide some measurements needed to characterize the motor in the tested working conditions.

The essential components of the test rig are:

- A *dynamometer* to absorb and measure the motor torque;
- Several *sensors* to measure the physical quantities of interest, such as:
    - Motor shaft angular velocity;
    - Battery current and voltage;
    - Motor windings Temperature;
    - Motor phase current;
    - Atmospheric conditions inside the test rig.
- A data acquisition system to store the measured variables;
- A control unit with a user interface, through which the testbed operator can monitor and control the engine, the dyno and the various sub – system of the test bed.

Testing of electric motors is generally done to determine characteristic curve points or entire characteristic curves. In this case, being a passive test bench, a single point at time is analyzed, in order to measure, in each point, all the characteristic physical quantities of interest.

Upgrading activities include all procedures to design Test Bench to correctly accomplish test results, especially measurements accuracy.

Therefore, ICE Test Bench upgrading leads to be able to carry out different type of tests, that are:

a. **UNECE Regulation No. 85**: homologation test needed to correctly characterize Electric Powertrain;

b. **Drive Setup and Development**: it is needed to correctly configurate all Drive System functions, that are:
   - Flux – Weakening;
   - Torque Ripple: for this purpose, specific instrumentation is needed, aimed at collecting Phase Current – Voltages, potentially synchronized with Motor revolution per minute and Torque measurement, to correctly studying Drive Setup with respect to Torque Ripple.

c. **Cooling System Development**: thermal analyses aimed at characterizing different Motor Torque levels, that are:
   - *Base Torque*: it is Torque level that ensures overcurrent use in Motor Control Strategy, avoiding saturation at *Rated Torque* only;
   - *Rated or Nominal Torque*: it is Torque level that ensures Thermal Equilibrium between Motor and Environment, at a suitable Temperature, defined as the maximum one; it depends on Cooling System type only.
   - *Maximum Torque*: it is maximum Torque level reached, that depends on Motor electrical characteristics only.

   Furthermore, thermal analyses are useful to study and obtain:
   - Motor Thermal Time Constant;
   - Assess most suitable Base Torque level on different type of tested Motors, considering also type of vehicle on which it will be mounted;
   - Cooling System dimensioning.

Moreover, once different Torque levels are obtained, it is possible to study a dynamic experimental test, in which all levels can be experienced cyclically, to asses results obtained in previous phases.

Therefore, Cooling System development allows to characterize Motor dynamic behavior, thus leading to study different strategies that can be used inside Powertrain system.

Different Motors type are tested, from Air to Liquid Cooled, having same Electrical Characteristics, thus same Maximum Torque, but different cooling systems, thus thermal analyses to characterize different Rated Torque of the two motors.

In following Chapters, Test Bench Hardware and Software will be explained, including also Regulation procedures followed to homologate Electric Motors tested.

Then, a User Manual and a brief Tutorial are reported, needed to understand main functions and experimental tests that can be carried out in the described Test Rig.

Chapter 2

2 Test Bench Architecture

Test Bench is of the Passive type, thus meaning that testing conditions are stable.

This means that experimental sessions are carried out in steady – state conditions, thus when all quantities to measure reached a constant value.

These quantities are:

- Mechanical Torque;
- Rotational Motor Speed;
- Direct Current and Voltage;
- Mechanical Efficiency;
- Motor Temperature.

Once they are determined, it's possible to obtain entire characteristic motor curves, containing all the fundamental data of the motor.

It is worth underline that, the ultimate test bench goal is to determine the *mechanical efficiency* with a maximum uncertainty of $\pm\,1\,\%$.

In this Chapter, all instrumentations and Test Bench layout are analyzed, and their choice is explained.

2.1 Architecture Layout

In FIGURE *2.1*, Test Bench Architecture Layout is reported, including:

A. Test Bench: mechanical and electrical components, all sensors, with their acquisition system layout;

B. Human Machine Interface: User Interface where Test Bench parameters setting and control system are performed.
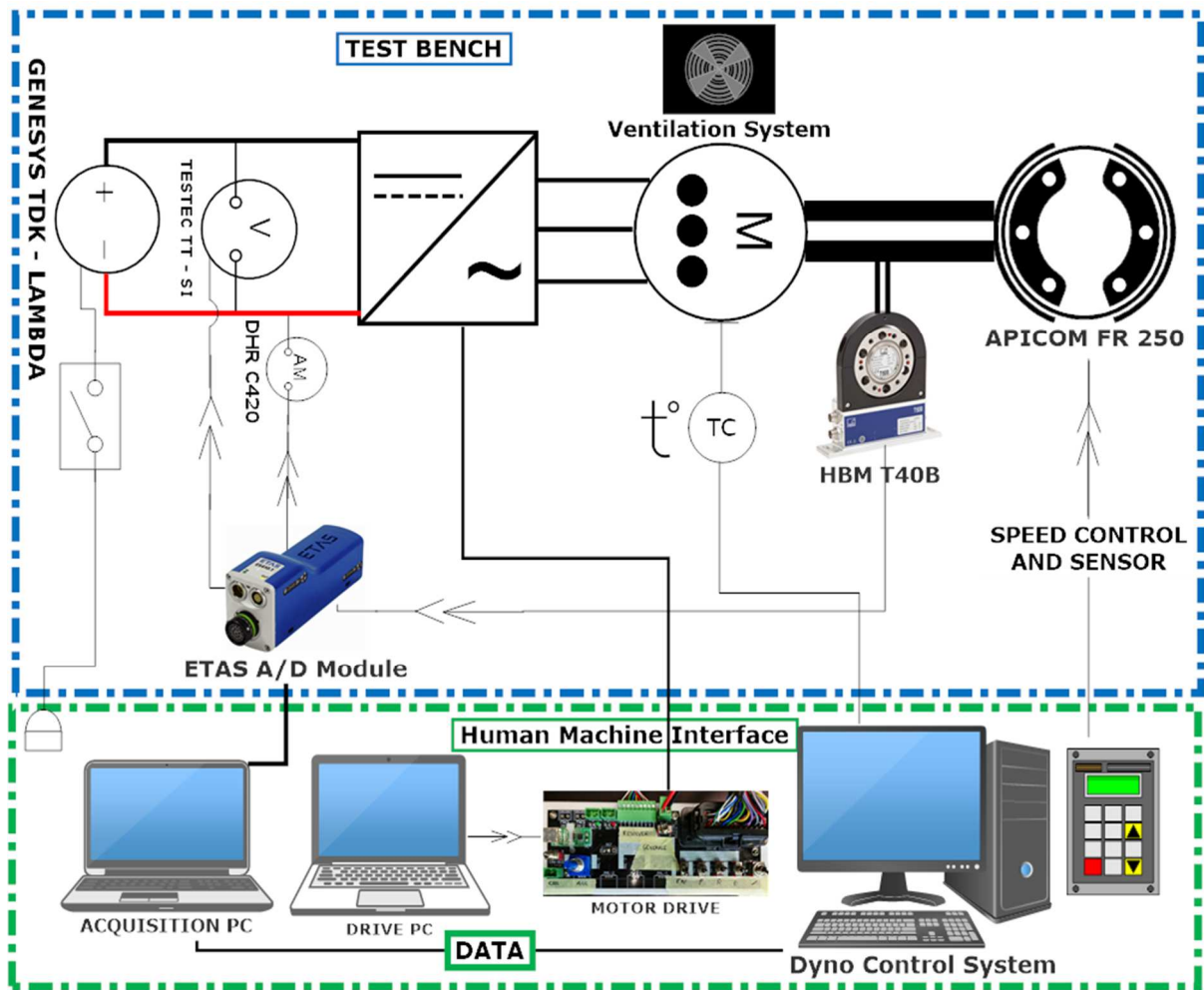
FIGURE 2.1 – Test Bench Architecture Layout

In following Sections, all components represented in above figure are detailed described.

2.2 Power Supply System

Power Supply is used to provide Electric Power to components needed to correctly ensure Motor Functioning.

To ensure proper operations, and to ease and improve acquisition operation, a Voltage Controlled and Stabilized Power Supply System is chosen, thus providing a single parameter to investigate during experimental session, i.e. DC Current. Its characteristics are summarized as follow.

- **Voltage Stabilized:** this means that, once output voltage is set, this will remain constant during all test session.

   It is worth underline it because it is a huge advantage with respect using Battery only as Power Supply, since its internal resistance leads to a Voltage and Current drop during test;

- **Current Limited:** output current can be set to a maximum value, that depends on Power Supply technical specifications, that will be ensured during all test session. Therefore, two important advantages are obtained:
   - Safety: it is possible to set up a maximum Output Current value, for safety reason, avoiding any instrumentation damage;
   - Testing Strategy: limiting and controlling Output Current leads to the possibility of studying limited Motor operating points, thus allowing studying fixed parameters points.

   Moreover, Output Current can also be set as the maximum allowed one by Power Supply System, ensuring the possibility of Motor testing in a wider operating range. In this case, during experimental session, Voltage value will be controlled, thus measurement focus will be on Output Current.

Chosen Power Supply components are of the Genesys^{TM} series, a product coming from the TDK – Lambda Americas Inc, a New Jersey company.

These series components operate from specified AC voltage range continuously; output current and Voltages are continuously displayed, and LED indicators show the complete operating status of the Power Supply. Front panel controls allow the user to set the output parameters, protection (Over – Voltage and Over – Current) and preview the settings.

Instead, the rear one includes the necessary connectors to control and monitor the Power Supply operation by remote analog signals or by the built – in serial communication.

A front – detailed view photo show one of them in FIGURE *2.2.*
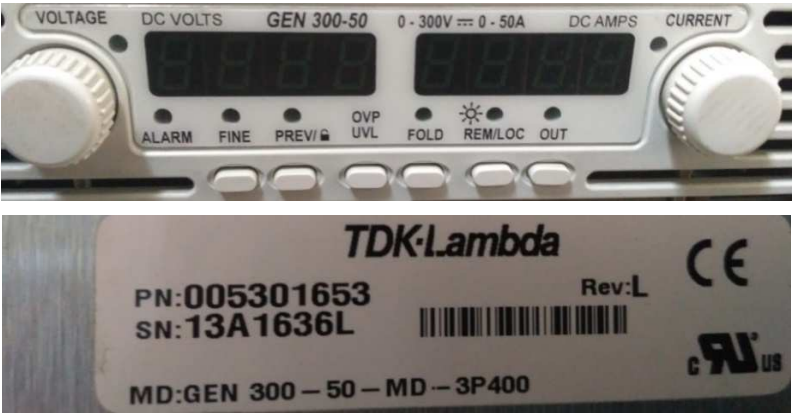
FIGURE 2.2 – Power Supply Detailed Front – View

In the top part, the two LED indicators are shown, while in the bottom one, the serial codes appear, that specify the technical characteristic of the Power Supply.

In TABLE *2.1*, the technical characteristics of the three 15 kW Power Supply present in the test bench are reported.

	Power Supply 1	Power Supply 2	Power Supply 3
Max. Voltage [V]	300	400	600
Max. Current [A]	50	37.5	25

TABLE 2.1 – Power Supply System Technical Specifications
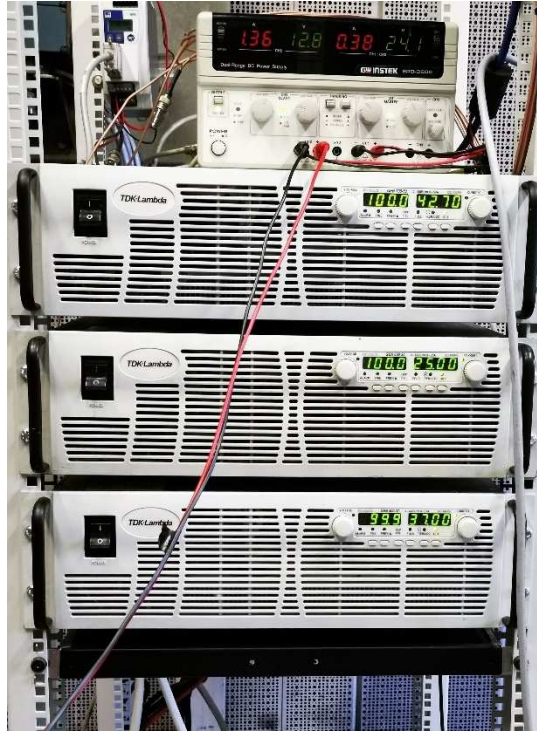
FIGURE 2.3 – Power Supply System Front − View

To increase the Power, it's possible to parallel connect the three Power Supplies; this modality is called Master/Slave operation with Active current sharing and it uses the rear panel connectors. The constraint for this modality is the equality of the three Power Supplies (equal Max. Voltage and Max. Current).

To overcome this problem, a second procedure is performed, by connecting together the three + and − poles of the different Power Supplies; in FIGURE *2.4,* connection layout is shown.
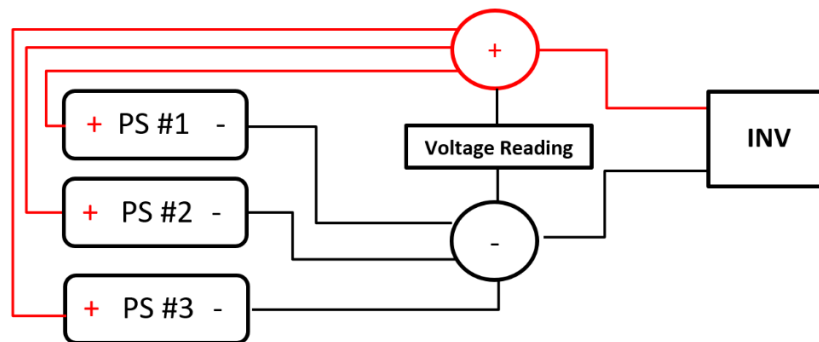
FIGURE 2.4 – Power Supply System Connection Layout

This connection limit is that the maximum achievable voltage is 300 V, that is the lowest maximum voltage between the three Power Supplies. A higher Voltage cannot be set, since the TDK Genesys^{TM} current sharing is not available for this connection type.

This means that the maximum achievable Power is equal to the maximum voltage times the sum of the three maximum currents, i.e. **33.6 kW**.

Using this configuration, it's still possible to further parallel connect a battery, with the advantage, from a measurement point of view, of having a *constant Direct Voltage.*

Second step for Power Supplies is the Remote Control, also called as *Independent Remote ON/OFF* or *Remote Enable/Disable.* To accomplish it, rear connector terminals are used, following the procedure explained in the TDK Genesys[TM] user manual.

DIP – Switches and J1 connectors are used, shown respectively in FIGURE *2.5* and FIGURE *2.6.*
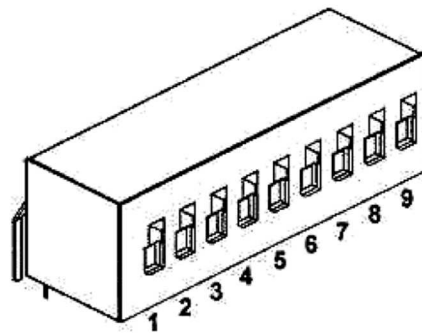
FIGURE 2.5 – Power Supply System DIP – Switches *[1, p. 51]*

Concerning DIP – Switches function, the #9 is the one that enables/disables the Remote Control, by setting it in the UP Position.
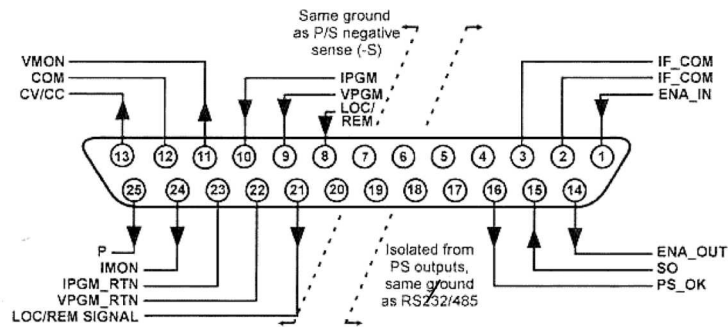
FIGURE 2.6 – Power Supply System J1 Connectors *[1, p. 53]*

Instead, regarding J1 connectors, the ones enabling the Power Supply output, by dry contact, are '*ENA_IN'* and '*ENA_OUT',* i.e. connectors #1 and #14, shown in FIGURE *2.6.*

By applying a short/open contact between them, the output of the Power supply is enabled or disabled, respectively.

A rear – view of the two connectors is shown in FIGURE *2.7*.

FIGURE 2.7 – Power Supply System J1 and DIP Switches Detail (Rear – View)

Final layout for J1 connectors is shown in FIGURE *2.8* and FIGURE *2.9.*
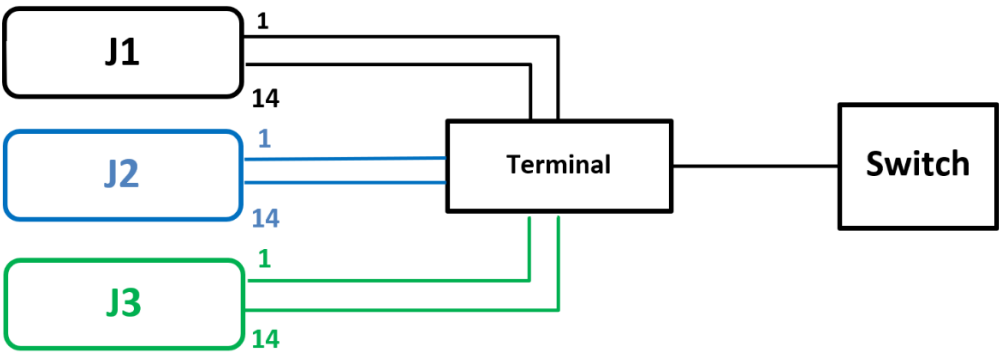
FIGURE 2.8 – Power Supply System J1 Connectors Layout Scheme
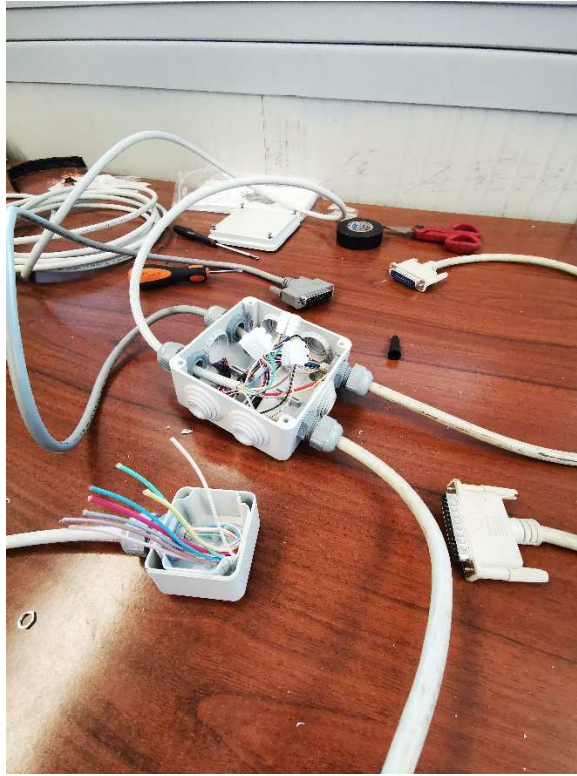
FIGURE 2.9 - Power Supply System J1 Connectors Layout

Thus, combining the parallel connection, and the DIP – Switches – J1 connectors one, the completely Power Supply unit is *Remote Controllable.*

2.3 Dynamometer

Most important component of an engine test rig is the dynamometer, which has three main functions:

- Generate a resistant (braking) torque to be applied to the motor output shaft, to reproduce some real motor working conditions, by simulating the applied load on the motor once it will be installed on the vehicle;

- Absorb the motor power, therefore it is also named *absorbing dynamometer;*

- Measure the output torque; in this case it is not used, since, as it will be shown in TABLE *2.2*, the characteristics of the used dyno are not suited to correctly measure the motor torque, therefore a *torque transducer* is used, described in *Sec. 2.4.*

In FIGURE *2.10,* APICOM FR 250 Eddy Current Dynamometer is shown, that is the Dyno used during all the experimental tests.
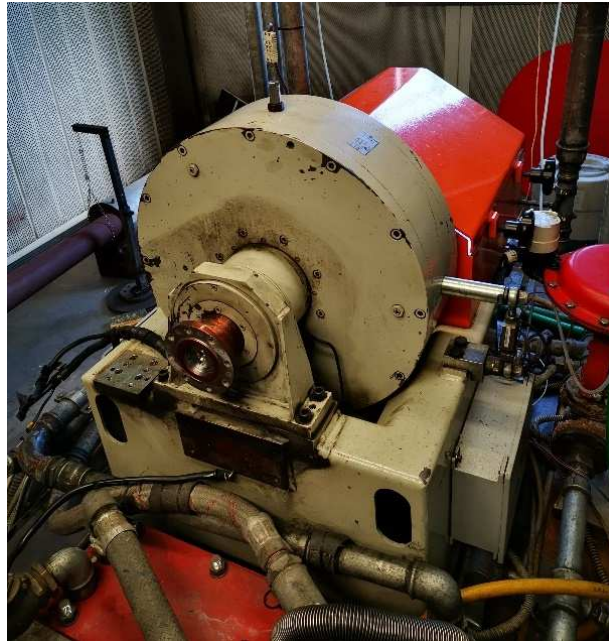
FIGURE 2.10 – APICOM FR 250

The eddy current brakes are equipments which allow the check of the mechanical behaviour of different types of engine, allowing the user to obtain the requested results operating them on the acquired variable. The generated resistant torque, between the dynamometer rotor and the stator, is provided by the magnetic field produced by eddy currents, which are opposing to the rotor rotation.

The absorbed power is transformed into heat, withdrawn from the brake using a cooling water circuit, which is performing no braking action.

APICOM FR 250 components are shown in FIGURE *2.11*, that are:

A. Braking body;
B. Torque Transducer;
C. Brake Basement;
D. Setting and System Display Tools;
E. Round per minute measurement system.
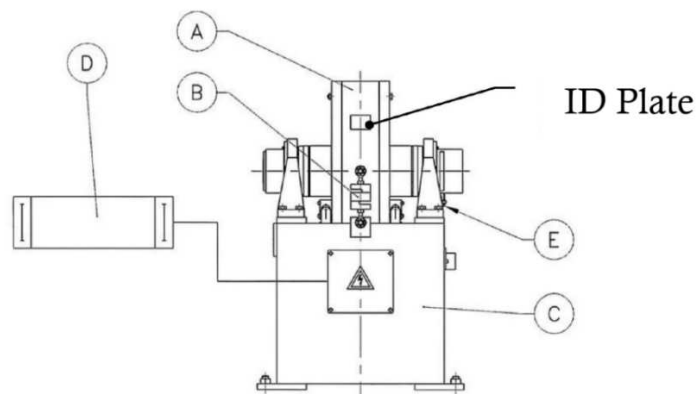
FIGURE 2.11 – APICOM FR 250 Components *[2, p. 16]*

The round per minute measurement system is composed by a 60 cogs wheel and a rpm detector, which sends its impulses to the system dysplay. Its physical characteristics are displayed in the FIGURE *2.12*.
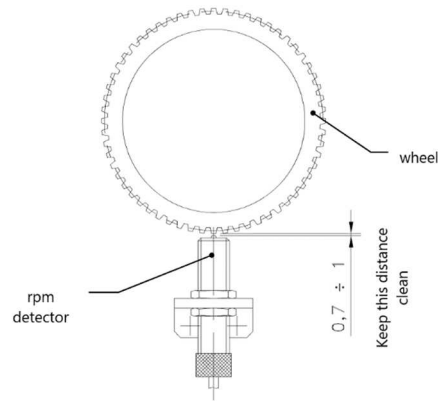
FIGURE 2.12 – APICOM FR 250 RPM Measurement System *[2, p. 18]*

The round per minute measurement system, together with the dynamometer angular velocity stabilization system, ensures an rpm precision reading of $\pm\, \mathbf{1}\, \boldsymbol{rpm}$.

In FIGURE *2.13,* torque measurement system is explained.
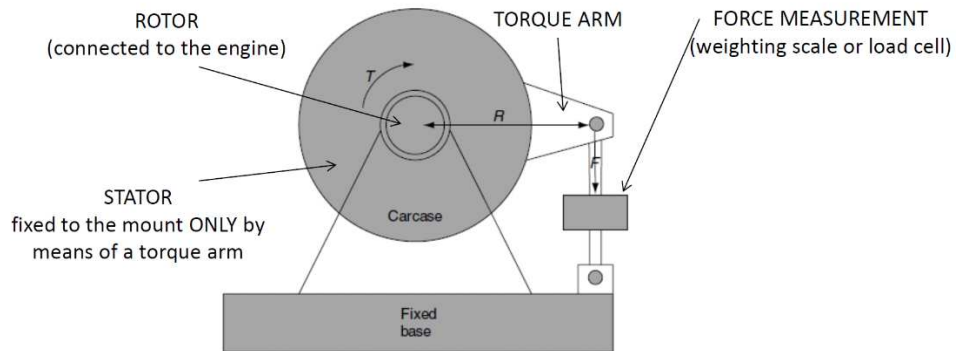
FIGURE 2.13 – Dynamometer Torque Measurement System

Whether the dynamometer is absorbing or providing power, a reaction torque is applied to it. Thus, if the Force applied to the transducer is F and the arm radius is R, then the torque applied to the motor shaft is shown in *Eq. 1*:

$$T = F \cdot R \tag{1.1}$$

This braking torque is provided by the magnetic field produced by eddy currents, which are opposing to the rotor rotation.

In APICOM FR 250, Torque measurement is performed through a load cell, on which Braking Torque is perceived as a Force times a certain lever arm. In FIGURE *2.14,* Torque measurement scheme is reported.
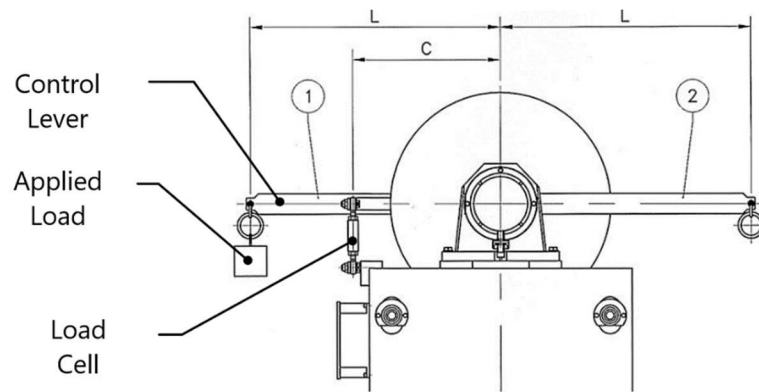
FIGURE 2.14 – APICOM FR 250 Torque Measurement System *[2, p. 39]*

In TABLE *2.2*, Torque Measurement system technical characteristics are reported.

	L [mm]	Load Cell [kg]	C [mm]	Cell Capacity [kg]	Full Scale [Nm]	Full Scale Maximum Error
FR 250	1019.7	1	375	250	800	± 2 %

TABLE 2.2 – Dynamometer Torque Measurement Characteristics *[2, p. 9]*

Full scale maximum error, i.e. ± 1.6 Nm, is too high, considering Torque values that are going to be measured. This leads to a different instrumentation choice.

To understand the dynamometer torque and power limits, its torque – power capacity curves are shown and explained in the following.

Capacity curves are composed by two axes:

- Rotational speed (rpm) on the abscissa axis;
- Torque and Power on the ordinate axis, with two different logarithmic scales.

In the exemple diagram of FIGURE *2.15,* five different segments are present, each of that used to determine, depending on the rotational speed, a different dynamometer information, explained in the following:

A. Maximum *Braking Power* at low rotational speed (maximum dyno excitational current);

B. Maximum *Torque,* determined by maximum *Dyno Braking Torque;*

C. *Nominal Power,* i.e. maximum dyno power, dependent on the maximum thermal dissipation capacity;

D. *Maximum Rotational Speed,* depending on bearing mechanical characteristics;

E. *No Load Power,* i.e. the minimum dyno power absorption, used to overcome internal friction (zero excitation current).
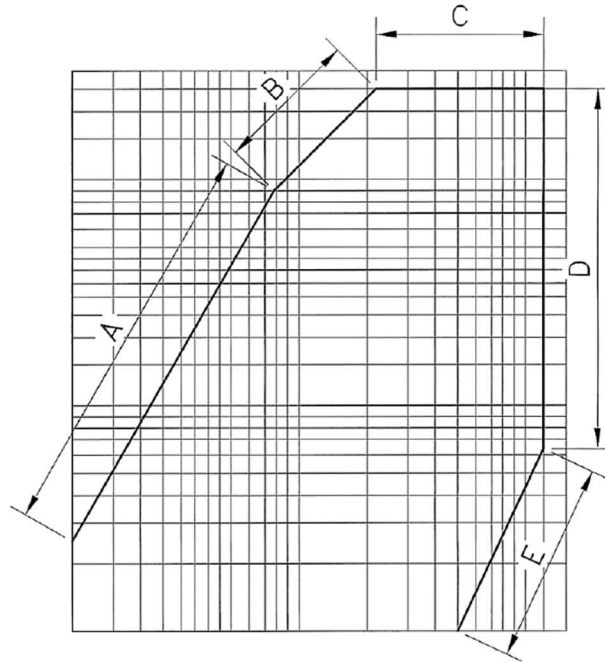
FIGURE 2.15 – Dynamometer Capacity Curve Example *[2, p. 11]*
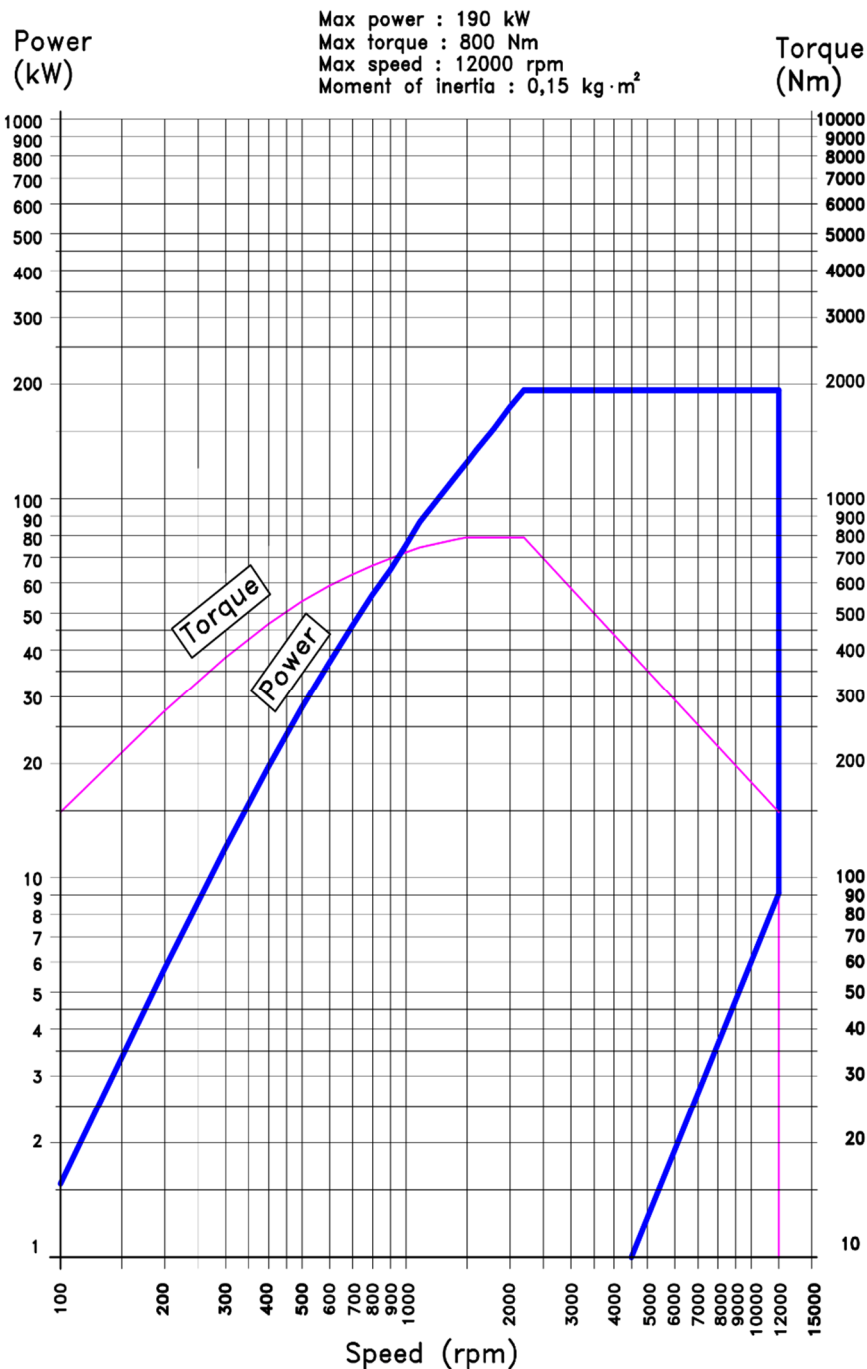
In FIGURE *2.16*, APICOM FR 250 Torque – Power Capacity curve is attached.

In TABLE *2.3* , Dyno most important characteristics are summarized.

	Apicom FR 250
Minimum Power [kW]	1.6
Minimum Torque [Nm]	15
Minimum Rotational Speed [rpm]	100
Maximum Power [kW]	190
Maximum Torque [Nm]	800
Maximum Rotational Speed [rpm]	12000
Maximum Current [A]	7
Moment of Inertia [kg m²]	0.15

TABLE 2.3 – APICOM FR 250 Capacity Curve Summary

FIGURE 2.16 – APICOM FR 250 Torque – Power Capacity Curves *[3]*

Dynamometer – Motor Coupling

To correctly couple Motor and Dynamometer, transmission joints capable of ensuring axis movements and allowing to decrease Torque fluctuations must be used, since they can lead to high vibration noise and coupling mechanical damages.

To ensure this behavior, precise and strictly technical characteristics are requested reported in TABLE 2.4.

Technical Characteristic	Request
Balancing Degree	2.5 mm/sec
Coaxial and Radial Oscillation Error	< 0.01 % of External Diameter
Screws Quality Class	> 10.9
Bolt Quality Class	> 8.8

TABLE 2.4 – Motor – Dyno Connection Technical Constraints [2, p. 25]

Transmission joints must operate with protection casing, whose technical drawing is shown in FIGURE 2.17. Quotas are reported in TABLE 2.5.
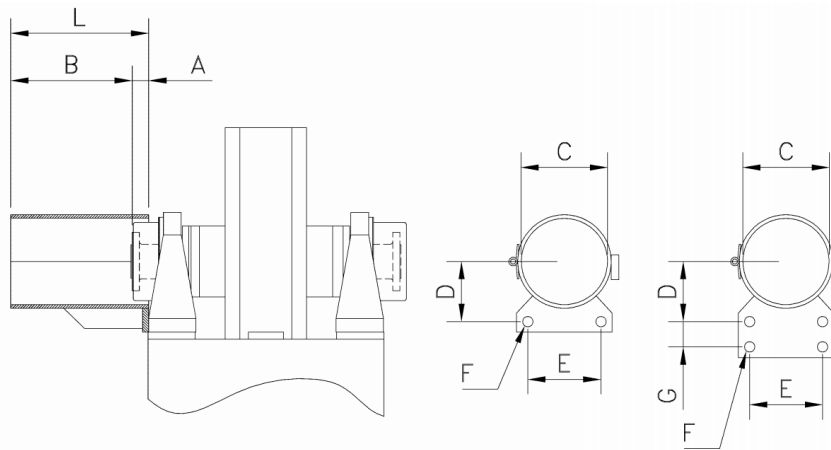
FIGURE 2.17 – Transmission Joints Casing Specifications [2, p. 27]

	A	B	C	D	E	F	G	L
FR 250	33	337	200	178	160	13	60	370

TABLE 2.5 – APICOM FR 250 Transmission Joints Quotas [2, p. 27]

Screws tightening moment depends on their threads, as reported in TABLE *2.6*.

Thread	M8	M10	M12	M14	M18	M24
Tighten Moment [kgm]	2.5	4.9	8.6	13.5	29	71

TABLE 2.6 – Transmission Joint Screws Technical Requests *[2, p. 25]*

Basing on these constraints, transmission joints is designed, together with a protection casing. In the following, CAD views and its technical drawing are reported in **Errore. L'origine riferimento non è stata trovata.** and **Errore. L'origine riferimento non è stata trovata.**.
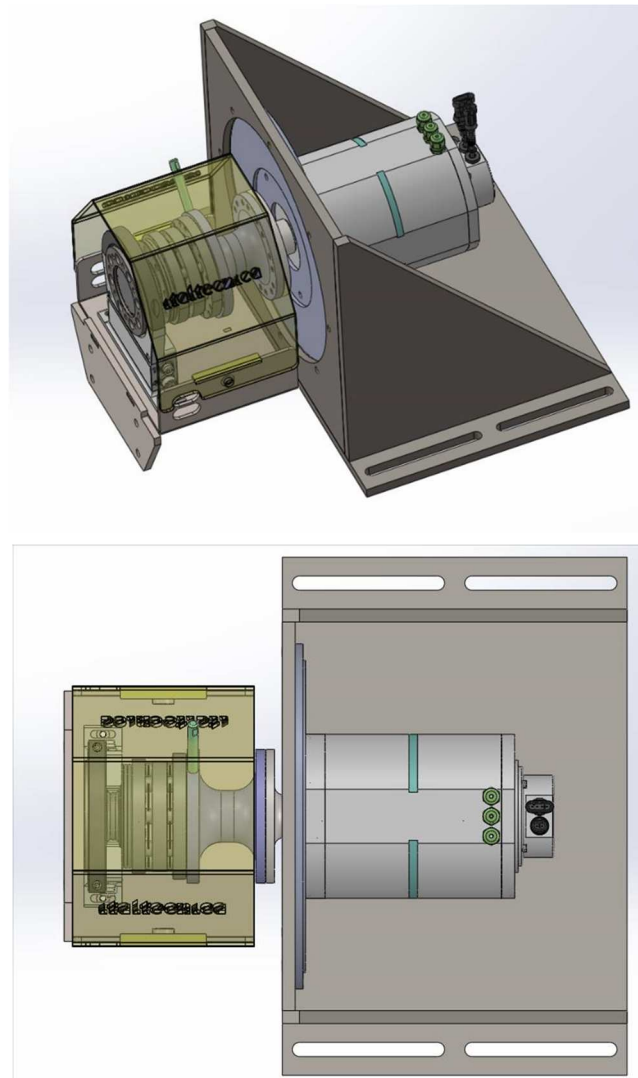
FIGURE 2.18 – Transmission Joint CAD Views

Num. articolo	Num. parte	Descrizione	Quantità
1	all_sala_188	_Flangia adattamento Moog or Sitem - flangia L supporto	1
2	all_sala_185_REV01	_Mozzetto di interfaccia freno-giunto Mayr ROBA DS64	1
3	all_sala_186	_Supporto comparatore per controllo allineamento	1
4	all_sala_187_REV02	_Mozzo dentato per interfaccia Sitem MTRI 180.120-giunto Mayr	1
5	all_sala_184.1	_base supporto motore elettrico	1
6	all_sala_184.2	_Flangia base supp motore elettrico	1
7	all_sala_184.3	_controvento motore elettrico	2
8	Giunto Mayr ROBA DS I_4411_0111		1
9	K_T408_500Q_MF_S_M_DU2_0_U		1
10	all_sala_190	_Adattatore freno-torsiometro	1
11	CS_all_sala_192	_assieme staffa supporto torsiometro	1

FIGURE 2.19 – Transmission Joint Technical Drawing

2.4 Torque Transducer

Dynamometer Torque Measurement System Full – Scale error is too high with respect to the expected Torque values of the tested motor, as it is shown in TABLE *2.2*, thus, a torque transducer is needed to fullfil the measurement precision goal on the efficiency.

To this purpose, HBM T40B torque transducer is used, shown in FIGURE *2.20*.

FIGURE 2.20 – HBM T40B Torque Transducer *[4]*

This choice is performed due to its Nominal (Rated) Torques from 50 Nm to 10 kNm and because of it is well suited for *static and dynamic torque measurement.*

It features a 0.03 % accuracy in terms of linearity, including hysteresis, as well as Temperature stability.

Instead, its *accuracy class* is equal to 0.1, meaning that the maximum single deviation, expressed in percentage, is equal or lower than the declared value of *accuracy class.* It must not be confused with all other deviations present in the Test Rig.

In TABLE *2.7,* most important T40B technical characteristics are reported.

	HBM T40B
Rated Torque [Nm]	50 – 500 Nm
Rated Rotational Speed [rpm]	20000
Accuracy Class	0.1

TABLE 2.7 – HBM T40B Technical Characteristics *[4, p. 56]*

Torque transducer is then coupled with the HBM PME measurement system, an amplifier modules used for recording measured quantities for internal digital processing. As the transducer itself, its *accuracy class* is 0.1.

This Torque transducer is chosen considering also Drive Setup and Torque Ripple measurement purposes, explained in *Ch. 1.* As it has been explained, to improve driveability and Motor performance, Torque ripple measurement is of fundamental importance.

2.5 DC Current Transducer and DC Voltage Probe

DC Current and Voltage are main electrical parameters to measure during experimental session.

As it is explained in *Sec.2.2,* Power Supply System is characterized by a stabilized Voltage Control and by a Maximum Current that can be set – up. This means that most important parameters to measure is DC Current.

Therefore, AC/DC Current Transducer DHR 300 C420 and the TESTEC TT – SI 9001 Active Differential Probe are chosen.

In FIGURE *2.21*, both sensors are shown and in TABLE *2.8,* main technical characteristics are reported.

FIGURE 2.21 – TESTEC TT SI – 9001 and DHR 300 C420

	DHR 300 C420	TESTEC TT-SI
Rated Current/Voltage [A/V]	300 A	700 V
Accuracy [%]	$< \pm 1\%$ of rated current	$\pm 2\%$
Linearity Error [%]	$< \pm 1\%$ of rated current	-

[7] [8]   TABLE 2.8 – DC Current and Voltage Probe Technical Characteristics *[5, p. 6] [6, p. 1]*

It is worth underline that, as a first approach, DC Voltage accuracy may seem too low, considering final accuracy goals.

This probe choice is performed considering Power Supply System technical characteristics that, together with a Testing Acquisition Strategy, that is explained in *Sec. 3.6.1*, leads to minimize DC Voltage measurements error.

Instead, considering DC Current probe, its choice comes from a trade – off between accurracy requested and instrumentation costs, further explained in *Sec. 3.3.*

2.6 Human Machine Interface Layout

Human Machine Interface Layout is useful to understand how the equipments and all sensors are managed and how the acquisition data systems work.

In FIGURE *2.22*, this layout is shown.

It was designed to have all system outside of Test Bench, to improve usability and parameters setting readiness.
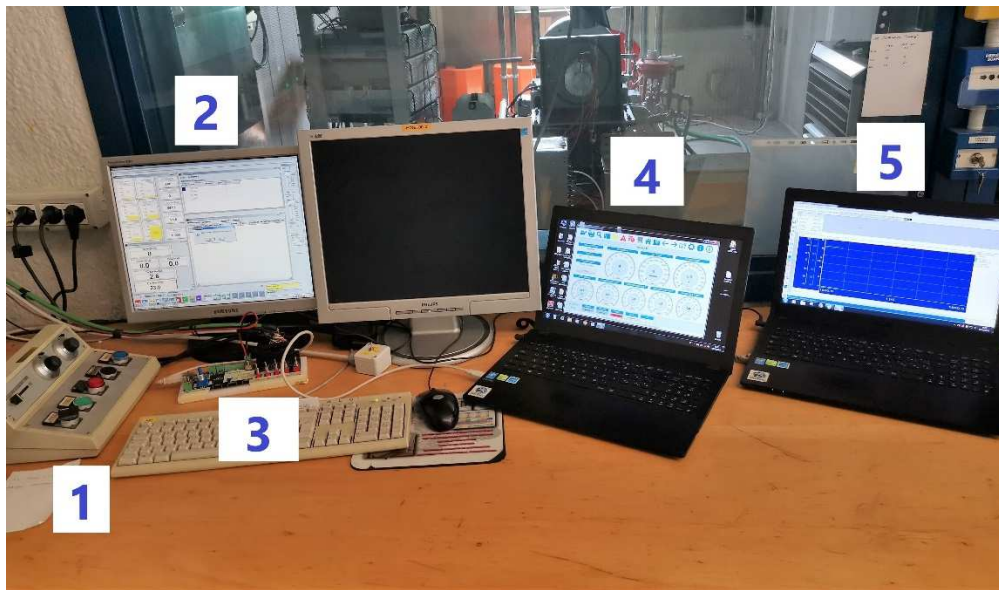
FIGURE 2.22 – Test Bench Control System Layout

Test Bench Control System Layout is composed by five elements, that are:

1. Dynamometer Setting Tools, with RPM setting rotational lever;
2. Dynamometer Control PC, through which it is possible to set Acquisition Frequency and Number of Measurements performed in each working point, as explained in *Sec.;* this PC contains sensors for:

   a. Round per Minute;
   b. Ambient Temperature;
   c. Motor Temperature (thermocouple, indicated with symbol *'t°'* in FIGURE *2.1*).

3. Electric Motor Drive System, needed to control Motor during experimental tests, explained in *Sec. 4.1.C and 4.1.D;*

4. Electric Motor Drive System Control PC, needed to control and set Motor parameters, before each experimental test. It is worth underline that this PC is not a predefined Test Bench component, since it is associated to Motor Drive and Inverter thus, in case in which another Motor will be tested, Drive PC will change too with its Control System Interface;

5. Acquisition PC, that includes:

- DC Current/Voltage sensors;
- Torque Transducer;
- ETAS ES400 Acquisition Unity, shown in **Errore. L'origine riferimento non è stata trovata..,** that is an A/D Module, capable of acquiring analog voltages at eight input channels, needed to acquiring and transfer to the final computer data coming from sensors connected to it.
  Its layout is shown in FIGURE *2.1.*

Acquisition PC is then connected to Dyno one, to generate a single output file containing all measurements collected by both PCs.

In FIGURE *2.23* and FIGURE *2.24*, Test Bench photos are reported.
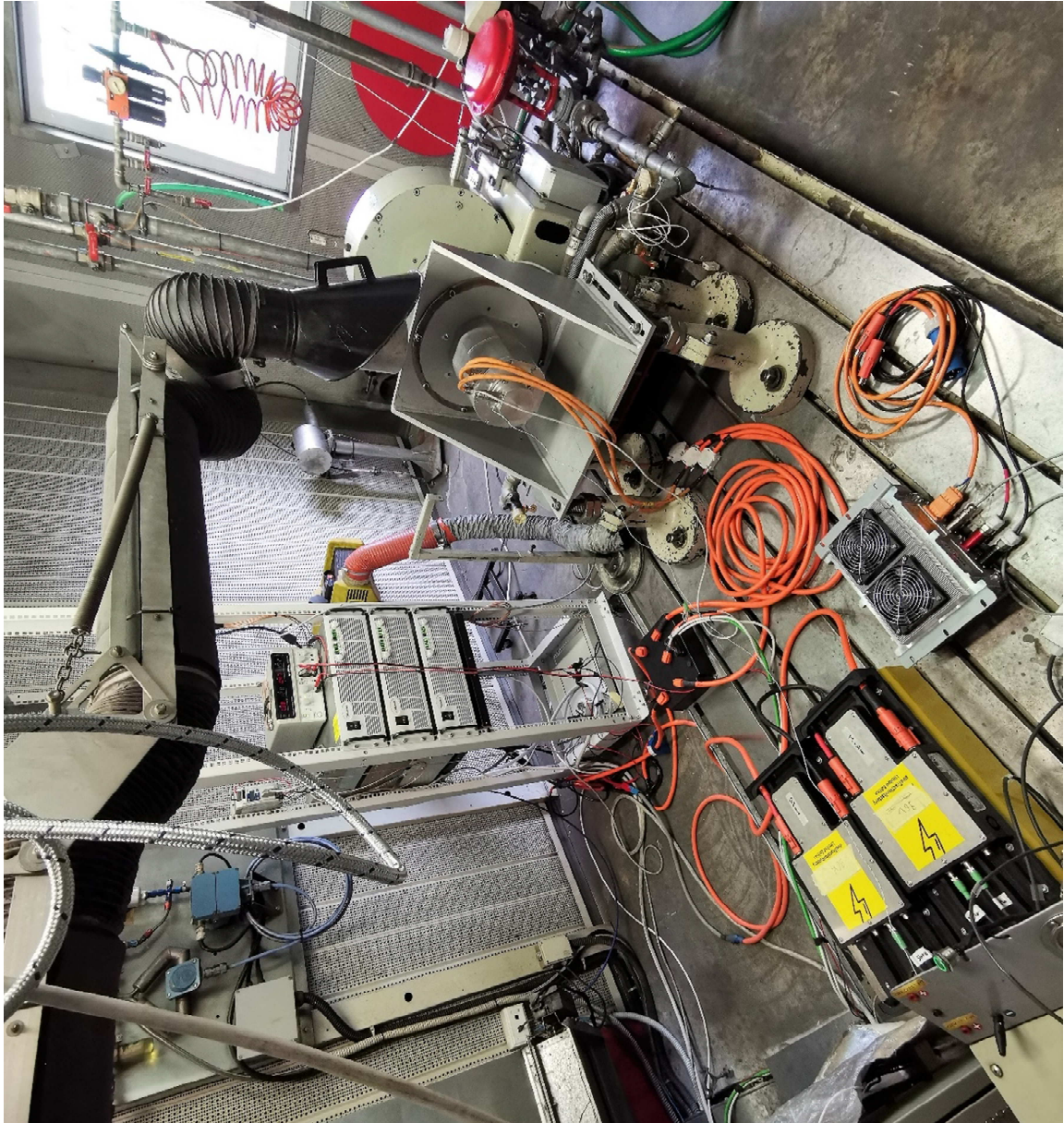
FIGURE 2.23 – Test Bench Photo 1
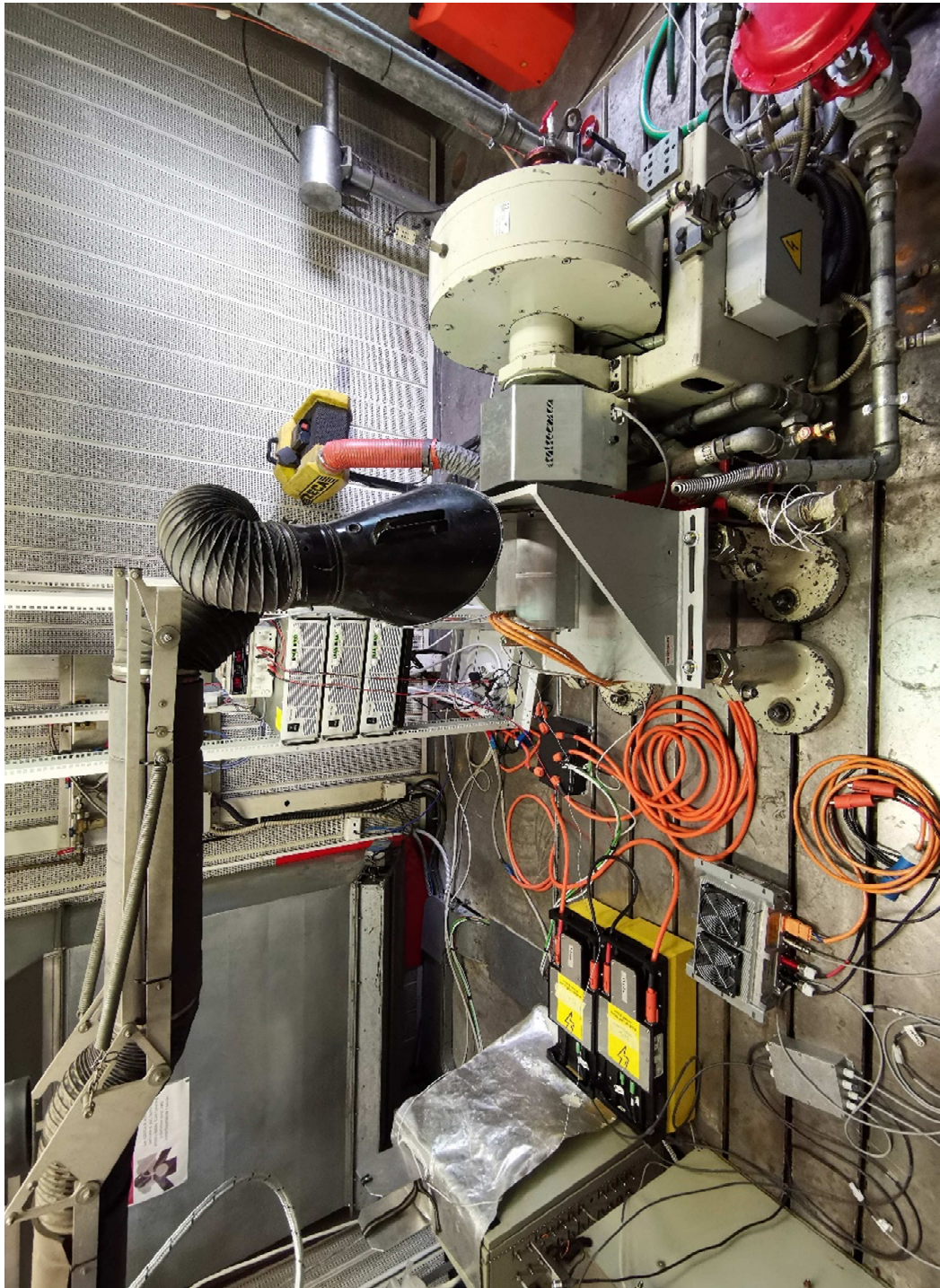
FIGURE 2.24 – Test Bench Photo 2

2.7 Data Processing: Raw Output File

In this Section, Test Bench Raw Output Files examples are reported

Raw Output File is directly generated from the Bench System as soon as test session is over. It contains all measured quantities, with data number depending on the session performed, the acquisition frequency selected and, of course, on time duration of the test.

It is of a .txt type, and an example for Regulation No. 85 is shown in FIGURE *2.25.*

```
Ora     Ciclo   Contaore        Test Step       Peso_fuel       Speed   Smoke   Torque Nm       Power   Power CV        PME     Fuel_Cons
T_O_Sump        P_Oil_Suct      T_O_PmpIn       P_O_PmpIn       T_O_PmpOut      P_O_PmpOut      T_O_ClrIn       P_O_ClrIn       T_O_ClrOut
a       h       NC      h       s       gr      Rpm     FSN     Nm      kW      cv      bar     kg/h    g/kWh   %       °C      bar     °C
9,5623 0,0000 0,0000 0,0000 0,0000 0,0000 0,0000 3,7384 0,0000 0,0000 0,0000 0,0000 0,0000 0,0000 22,5542 989,1049         0,0000
0,0000 -45,0871        -45,0871        -45,0871        -45,0871        0,0000 0,0000 0,0000 0,0000 0,0000 0,0000 0,0000 0,0000 0,0000 0,0000
9,5626 0,0000 0,0000 0,0000 0,0000 0,0000 0,0000 3,7767 0,0000 0,0000 0,0000 0,0000 0,0000 0,0000 22,4458 989,1049         0,0000
0,0000 -45,1024        -45,1024        -45,1024        -45,1024        0,0000 0,0000 0,0000 0,0000 0,0000 0,0000 0,0000 0,0000 0,0000 0,0000
9,5629 0,0000 0,0000 0,0000 0,0000 0,0000 0,0000 3,7143 0,0000 0,0000 0,0000 0,0000 0,0000 0,0000 22,4690 989,1204         0,0000
0,0000 -45,0909        -45,0909        -45,0909        -45,0909        0,0000 0,0000 0,0000 0,0000 0,0000 0,0000 0,0000 0,0000 0,0000 0,0000
9,5632 0,0000 0,0000 0,0000 0,0000 0,0000 0,0000 3,8247 0,0000 0,0000 0,0000 0,0000 0,0000 0,0000 22,4845 988,9655         0,0000
0,0000 -45,0871        -45,0871        -45,0871        -45,0871        0,0000 0,0000 0,0000 0,0000 0,0000 0,0000 0,0000 0,0000 0,0000 0,0000
9,5635 0,0000 0,0000 0,0000 0,0000 0,0000 0,0000 3,5180 0,0000 0,0000 0,0000 0,0000 0,0000 0,0000 22,5310 989,0275         0,0000
0,0000 -45,0871        -45,0871        -45,0871        -45,0871        0,0000 0,0000 0,0000 0,0000 0,0000 0,0000 0,0000 0,0000 0,0000 0,0000
9,5637 0,0000 0,0000 0,0000 0,0000 0,0000 0,0000 3,4445 0,0000 0,0000 0,0000 0,0000 0,0000 0,0000 22,5620 989,1359         0,0000
0,0000 -45,0909        -45,0909        -45,0909        -45,0909        0,0000 0,0000 0,0000 0,0000 0,0000 0,0000 0,0000 0,0000 0,0000 0,0000
9,5640 0,0000 0,0000 0,0000 0,0000 0,0000 0,0000 3,5796 0,0000 0,0000 0,0000 0,0000 0,0000 0,0000 22,5387 989,1204         0,0000
0,0000 -45,0871        -45,0871        -45,0871        -45,0871        0,0000 0,0000 0,0000 0,0000 0,0000 0,0000 0,0000 0,0000 0,0000 0,0000
9,5643 0,0000 0,0000 0,0000 0,0000 0,0000 0,0000 3,3697 0,0000 0,0000 0,0000 0,0000 0,0000 0,0000 22,5697 989,0894         0,0000
```

FIGURE 2.25 – Test Bench Raw Output File Example

Raw Output file does not depend on type of test session performed. It is always a .txt file containing in each column the corresponding measured quantities and, in each row, number corresponding to the quantity.

Number of rows depends on the test session duration, averaging time considered and acquisition frequency set at the start of the test.

Most important included parameters are reported in the following:

- Hour: time measurement is performed using hour as measurement reference; thus, a conversion is needed if time expressed in *second* is needed;
- Speed: it contains RPM measured by Dynamometer angular velocity measurement sensor;
- Ambient Temperature: it includes Test Rig ambient Temperature, important especially during thermal analysis;
- Transducer Torque: it should be noticed that, right measured Torque comes from transducer and it must not be confused with Dynamometer Load Cell measured Torque, that is included in the file too, simply named as *'Torque';*
- Current FS 300: it is DC Current measured by DHR 300 C420 Current probe;
- Voltage: it is DC Voltage measured by TESTEC probe.

Chapter 3

3 Test Classification

In this Chapter, all type of experimental tests that can be carried out inside Test Rig are described.

As a first approach, measurements layout is presented, to understand their real accuracy and the strategy that can be chosen depending on the tests type.

Finally, different aspects of the Test Bench are explained, including all phases of a test that can be encountered during experimental activities.

3.1 Testing Target

The tested motor is controlled using a *Constant Speed Strategy,* meaning that the dynamometer applies whatever load is required to maintain the requested speed, while different torque levels are requested to the motor.

In FIGURE *3.1*, a layout scheme of the test bench is proposed.
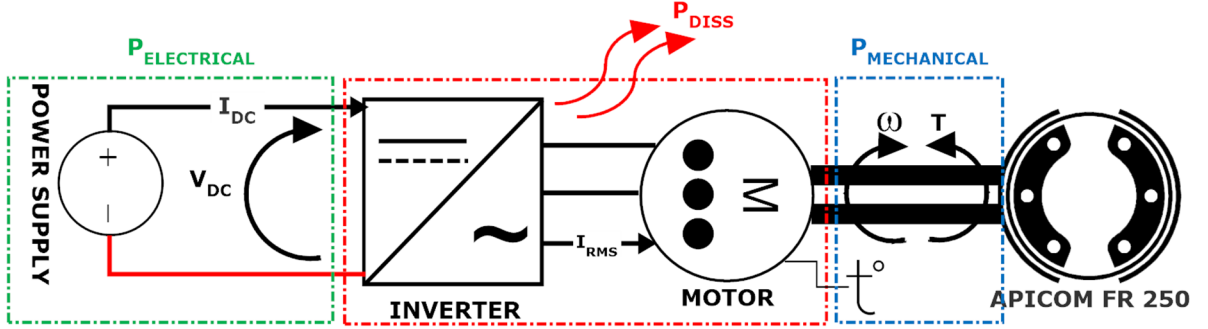
FIGURE 3.1 – Test Bench Measurements Scheme

It is now worth underline, considering layout shown in *Fig,* which is the logic behind first experimental sessions, and which are goals:

A. First experimental session includes a *'closed box'* mechanical efficiency evaluation, since it considers together Inverter + Motor.
Therefore, <u>evaluated efficiency quantifies thermal dissipation occurring in the two electrical components thus, Cooling System Development is performed</u> considering these results;

B. Moreover, evaluating efficiency in all Motor map points ensures requested Motor performance in all operating field.
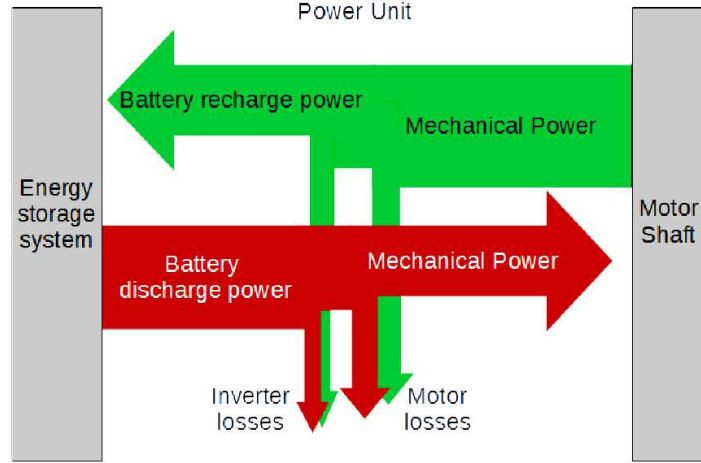
FIGURE 3.2 – Losses Flow *[8]*

Referring to FIGURE *3.1,* all measured quantities are reported and, considering '*k*' as each operating point, they are:

- Motor Mechanical Torque;

- Motor Rotational Speed;

- Motor Mechanical Power: $P_m(k) = T_m(k) \cdot \omega(k)$;

- Direct Current in Inverter Input;

- Direct Voltage in Inverter Input;

- Electrical Power, measured in Inverter Input: $P_e(k) = I_{DC}(k) \cdot V_{DC}(k)$;

- Mechanical Efficiency: $\eta_m(k) = \frac{P_m(k)}{P_{el}(k)}$.

- Efficiency as a function of Temperature: $\eta_k(T)$, depending on the equilibrium Temperature reached.

In TABLE *3.1,* all measured quantities are summarized, distinguishing them based on direct sensor measuring or indirect one.

Direct Measure	Indirect Measure	Final Measure
Mechanical Torque T_m	Mechanical Power P_m	Mechanical Efficiency η_m
Rotational Speed ω_m		
Direct Current I_{DC}	Electrical Power P_{El}	
Direct Voltage V_{DC}		

TABLE 3.1 – Test Bench Measurements Summary

This means that, to fulfill the $\pm 1\%$ *mechanical efficiency uncertainty,* the focus for measurement precision will be on all the direct measures shown in TABLE *3.1.*

Then, goal of the test is studying motor curves, characterizing all points that give information about:

- Minimum Rotational Speed at which motor delivers Mechanical Torque;
- Maximum Motor Rotational Speed;
- Minimum – Maximum Mechanical Torque;
- Minimum – Maximum Power.

In *Sec. 3.2,* testing strategy is explained, to understand logic behind experimental session and how Motor analyses are carried out.

3.2 Testing Strategy

Test strategy defines procedure to follow during all experimental tests having the goals of determining mechanical efficiency in Motor Map, thus securing Motor performances in all operating field.

To obtain these results, it's important to understand which part of the Torque – RPM diagram is analyzed during the tests, that is shown in FIGURE 3.3.
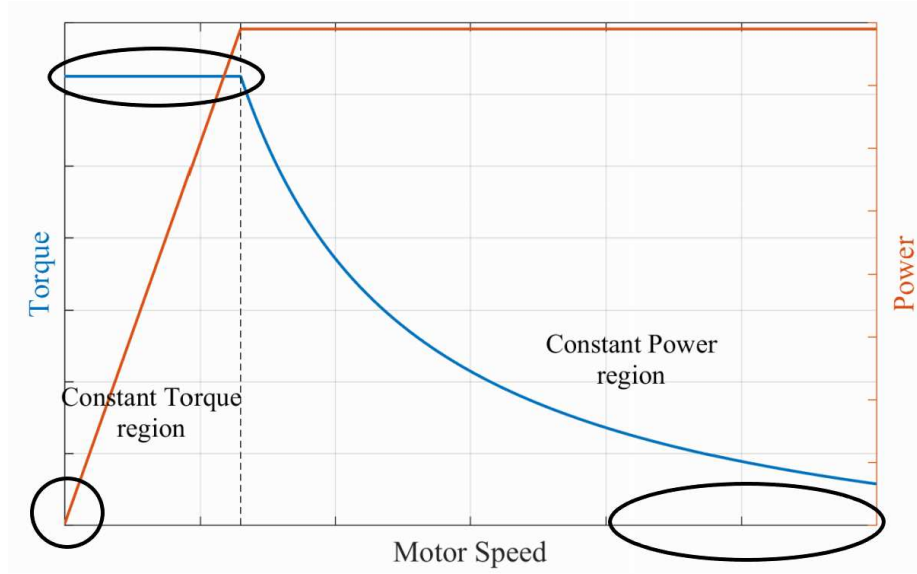
FIGURE 3.3 – T – RPM Curve Analysis Zone [8]

Top – left and bottom – right parts of the diagram are studied to determine the maximum and minimum Torque – Power of the motor, with the respective efficiency. Instead, the top – center part, is studied to characterize the *Nominal Torque* of the motor. At this point, it's important to define and underline the differences between Maximum – Minimum and Nominal Torque/Power and to define a third curve, important for testing strategy:

- **Base Torque/Power Curve:** set of operating conditions at which the thermal stability of the motor winding is reached for an indefinite time, at a Temperature value lower than *maximum one,* typically close to its half;

- **Nominal Torque/Power Curve:** set of operating conditions at which the thermal stability of the motor winding is reached for an indefinite time (*Steady – State or Continuous Operating Condition*); it depends on Cooling System only;

- **Maximum Torque/Power Curve:** set of operating conditions at which the motor can work for a limited time, since the thermal equilibrium of the motor winding is not reached (*Transient or Discontinuous Operating Condition*); it depends on Motor Electrical Characteristics only.
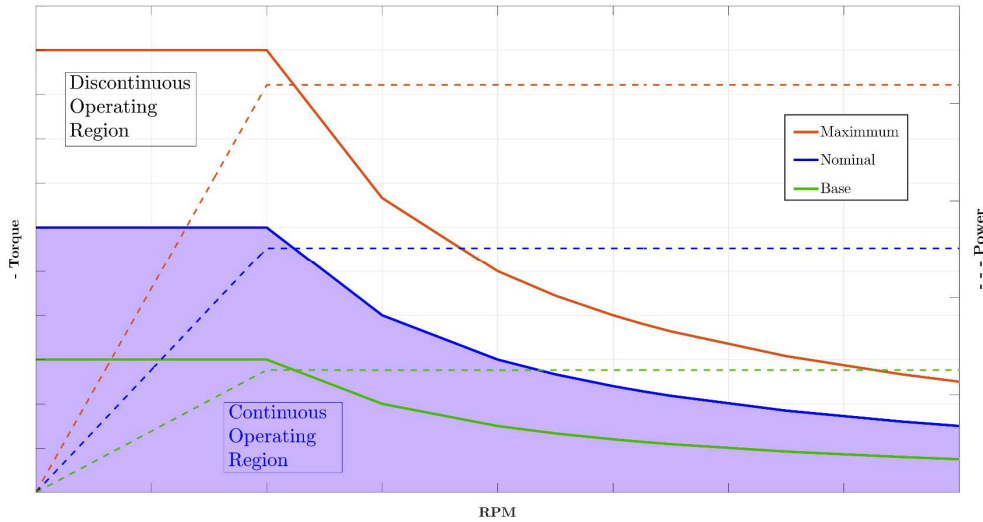
FIGURE 3.4 – Continuous and Discontinuous Motor Operating Regions

Since there are not names universally shared, *Maximum Torque/Power* can also be found as *Peak – Intermittent – Overload Torque/Power,* while *Nominal Torque/Power* can be found as *Continuous or Rated.*

It should be noticed that, *Maximum Torque* curve characterization

Considering this difference between the *Nominal – Maximum* curves, the testing typologies will be divided in two categories, depending on the characteristic point analyzed.

For instance:

- **T < T_nom:** in every point that satisfies this condition, being possible the reaching of the thermal equilibrium, all the measurements will be determined, including the *efficiency as a function of the Temperature,* by analyzing the Temperature evolution in the point, until the equilibrium condition is reached;

- **T > T_nom:** in these points the thermal equilibrium won't be reached, thus the *efficiency as a function of the Temperature* won't be determined; in this case, the Temperature evolution is studied until the *maximum Temperature* is reached.

Referring now to FIGURE *3.3,* strategy considerations are reported:

1) First analyzed points are the ones close to the *minimum measurable rotational speed*, dependent on the *dynamometer* characteristics*:* from this point, the requested Torque value is increased, keeping the rotational speed constant, until the *nominal torque* is reached. The difference of requested Torque between two points is set considering the minimum measurable torque value, depending on the sensor used in the test bench;

2) Working in a *Static Test Bench,* the goal is to analyze the points only once they are stabilized. Most important quantity to monitor is *Temperature,* to compute the *efficiency.* Thus, in each point in which the thermal equilibrium can be reached, the goal is studying the *Temperature Evolution,* to compute the *Thermal Time Constant* of the system, useful to understand, in each operating condition, which will be the time needed to the motor for reaching the thermal equilibrium.

To correctly accomplish this strategy, two fundamental test bench characteristics must be specified, that are:

- **Bench Resolution:** it specifies the resolution of the direct measured quantities. Once the rotational speed is fixed, it's fundamental to be able to correctly measure all the points while the requested Torque is increased, from the *minimum Torque* value to the *maximum one,* considering that its expected value is between **70 − 75 Nm**. The same applies to the *rotational speed, Direct current and voltage.*

- **Acquisition Time:** it's the time needed to acquire, in each working point, the physical quantities of interest.

Acquisition strategy is then carried out with an **Average Measurement Strategy**, meaning that, in all working point, results are obtained by averaging a number of samples that can be set with two parameters in Dyno Setting tools, explained in *Sec. 3.6.1.*
These parameters are:

- **Acquisition Frequency:** it sets frequency at which direct measured parameters are acquired (max. value 10 Hz);
- **Number of Measurements:** it sets number of samples on which average is performed.

Ratio between them gives the **Acquisition Time,** thus to have a trade – off between accuracy and time needed to characterize each working point, a strategy with a 10 number of measurement is set, with an acquisition frequency of 1 Hz; this means that, the obtained measured value comes from the average of 10 measurements, with a total acquisition time for a working point of 10 s.

In FIGURE 3.5, Bench Resolution and First Analyzed Point are shown superimposed to a typical Motor Torque – Power Curve.
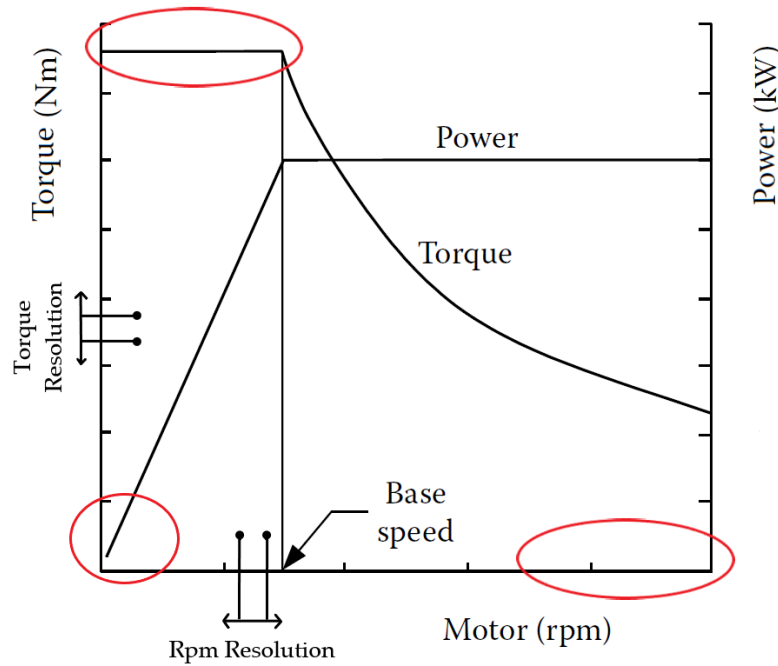
FIGURE 3.5 – Test Bench Resolution and First Analyzed Points on T – RPM Curve *[9, p. 57]*

Strategy performed depends on Test Bench instrumentations technical characteristics, whose manufacturer declared ones are reported in *Chapter 2.*

It is now important to study real measurement accuracy, to ensure that strategy performed is in accordance with real instrumentation properties; therefore, in *Sec. 3.3,* DC Current

probe Sensitivity Analysis is reported and in *Sec. 3.4,* mechanical efficiency real accuracy analysis.

3.3 DC Current Probe Sensitivity Analysis

Sensitivity analysis on measured DC Current is performed to understand the minimum necessary resolution or the maximum accepted error for the DC Current Probe to use during the testing activities.

The target of the analysis is having, in all measured points, a **maximum mechanical efficiency uncertainty of $\pm$ 1** %.

The analysis is performed considering two measured points, one on the *Nominal Torque – Power Curve* and the other on the *Maximum Torque – Power curve.*

The error considered in this analysis is referred to a specific current probe, the AGILENT N2780A, that is:

- 1% rdg (reading value);
- $\pm$ 500 mA FS (Full Scale 500 A).

The DC Voltage error is considered in the analysis, as a first assumption, referring to the technical specifications of the TESTEC TT – SI 9001, reported in TABLE *2.8,* equal to $\pm$ 2 % but, it can be considered negligible, since, using the Power Supply System during the tests, the DC voltage is kept constant during the steady – state tests. In the following, numerical analyses and results are reported.

3.3.1 Nominal Curve Point Analysis

Operating point 1 data are reported in TABLE *3.2.*

Quantity	Value
I_DC [A]	59.70
V_DC [V]	102
P_el [W]	6089.40
T_m [Nm]	26.18
RPM	2000
P_m [W]	5483.13
Eta [%]	90.04 %

TABLE 3.2 – Operating Point 1 Data

Considering now the error characteristics of AGILENT N2780A, reported in *Sec. 3.3,* the analysis is performed in two cases:

- DC Voltage error present;
- DC Voltage error negligible.

With a DC Voltage error not negligible, the analysis results are reported in TABLE *3.3*:

eta_rif		DC_Current						
	90.04%	58.603	58.7821	58.9612	59.7	60.3791	60.5582	60.797
	100.164	93.41%	93.13%	92.84%	91.69%	90.66%	90.39%	90.04%
	100.776	92.84%	92.56%	92.28%	91.14%	90.11%	89.85%	89.49%
	101.388	92.28%	92.00%	91.72%	90.59%	89.57%	89.30%	88.95%
DC_Voltage	102	91.73%	91.45%	91.17%	90.04%	89.03%	88.77%	88.42%
	102.612	91.18%	90.90%	90.63%	89.51%	88.50%	88.24%	87.89%
	103.224	90.64%	90.37%	90.09%	88.98%	87.98%	87.72%	87.37%
	103.836	90.11%	89.83%	89.56%	88.45%	87.46%	87.20%	86.86%

TABLE 3.3 – Point 1 Results, Considered DC Voltage Error

The efficiency range is equal to $\pm\, \mathbf{3.26}$ %.

Instead, if the DC Voltage is constant, assuming this due to the precision of the Power Supply System, obtained results are reported in TABLE *3.4*.

eta_rif		DC_Current						
	90.04%	58.603	58.7821	58.9612	59.7	60.3791	60.5582	60.797
DC_Voltage	102	91.73%	91.45%	91.17%	90.04%	89.03%	88.77%	88.42%

TABLE 3.4 – Point 1 Results, Negligible DC Voltage Error

Thus, obtaining an efficiency range equal to $\pm\, \mathbf{1.66}$ %.

In *Sec. 3.3.2,* analysis related to the *Maximum Torque – Power Curve* is reported.

3.3.3 Maximum Curve Point Analysis

Operating point 2 data are reported in TABLE *3.5.*

Quantity	Value
I_DC [A]	216
V_DC [V]	101.5
P_El [W]	21924
T_m [Nm]	32.5
RPM	6000
P_m [W]	20420.35
Eta [%]	93.14

TABLE 3.5 – Operating Point 2 Data

Considering now the DC Voltage error, results are reported in TABLE *3.6.*

eta_rif		DC_Current						
93.14%		213.34	213.988	214.636	216	217.148	217.796	218.66
	99.673	96.03%	95.74%	95.45%	94.85%	94.35%	94.07%	93.69%
	100.282	95.45%	95.16%	94.87%	94.27%	93.77%	93.50%	93.13%
	100.891	94.87%	94.58%	94.30%	93.70%	93.21%	92.93%	92.56%
DC_Voltage	101.5	94.30%	94.02%	93.73%	93.14%	92.65%	92.37%	92.01%
	102.109	93.74%	93.46%	93.17%	92.59%	92.10%	91.82%	91.46%
	102.718	93.18%	92.90%	92.62%	92.04%	91.55%	91.28%	90.92%
	103.327	92.64%	92.35%	92.08%	91.49%	91.01%	90.74%	90.38%

TABLE 3.6 – Point 2 Results, Considered DC Voltage Error

Thus, obtaining an efficiency range equal to $\pm\,\mathbf{2.82}$ %.

Instead, considering the DC Voltage error negligible, obtained results are:

eta_rif		DC_Current						
93.14%		213.34	213.988	214.636	216	217.148	217.796	218.66
DC_Voltage	101.5	94.30%	94.02%	93.73%	93.14%	92.65%	92.37%	92.01%

TABLE 3.7 – Point 2 Results, Negligible DC Voltage Error

Results obtained in TABLE *3.7* are considered acceptable, with an efficiency range equal to $\pm\,\mathbf{1.15}$ %.

3.3.4 Final Remark

In TABLE *3.8,* results summary is reported.

	Efficiency Range	
	DC Voltage Error	**NO DC Voltage Error**
Point 1	$\pm$ 3.26 %	$\pm$ 2.82 %
Point 2	$\pm$ 1.66 %	$\pm$ 1.15 %

TABLE 3.8 – Sensitivity Analysis Results Summary

Considering DC Voltage constant during tests, leads to accept a Current Probe having a *reading error* lower than $\pm$ 1 %, characteristic of the DHR 300 C420, and a Full – Scale Error close to 500 mA.

Instead, if the DC Voltage is not constant during tests, a more precise Current Probe is needed.

Finally, considering the technical characteristics of the TDK Lambda Power Supply system and the DHR 300 C420, a trade – off between precision and sensors cost is performed, leading to an acceptable efficiency range in all measured points.

Final requests for the Current Probe are:

- Reading error (%rdg) lower than 1%;
- Full – Scale error (%FS) close to 500 mA.

Considering now all the technical specifications of sensors and components of the test bench, an analysis on the efficiency range and precision in most important point is performed in *Sec.3.4.*

3.4 Mechanical Efficiency Real Accuracy Analysis

In this Section, an Analysis on the Efficiency Inaccuracy is performed, to understand if the goal of the Test Bench is reached or not, i.e. an inaccuracy interval on the efficiency equal to $\pm$ 1 %.

To this purpose, two thermal analyses are used to carry out the Inaccuracy Analysis, whose data are reported in TABLE *3.10.* Before that, it is useful to recall which are the measurements performed during the experiments, shown in TABLE *3.9,* since the analysis is performed considering relative errors related to them.

Thermal Analyses are used because they are performed in a *steady – state test,* during which, all requested quantities are theoretically constant since, the working point is the same. The goal of these analysis is to measure the Temperature evolution in the motor, in a point lower or close to the *Nominal Torque – Power Curve,* until the Temperature Equilibrium with the environment is reached.

Direct Measure	Indirect Measure	Final Measure
Mechanical Torque T_m	Mechanical Power P_m	Mechanical Efficiency η_m
Rotational Speed ω		
Direct Current I_{DC}	Electrical Power P_{El}	
Direct Voltage V_{DC}		

TABLE 3.9 – Test Bench Measurements Summary

	Thermal Analysis 1	Thermal Analysis 2
Avg Mechanical Torque [Nm]	13.97	26.79
Avg Rotational Speed [rpm]	3498	3503
Avg Direct Current [A]	50.20	100.94
Avg Direct Voltage [V]	108.23	100.03
Number of Samples	2500	2500

TABLE 3.10 – Thermal Analyses Data Summary

In both analyses, Power Supply System only is used, thus ensuring a quasi – constant Direct Voltage. Next step is computing *absolute* and *relative errors* related to all direct measured quantities and, finally, obtain *relative error* of mechanical efficiency.

In TABLE *3.11,* all declared sensors accuracies, related to their measured quantities, are reported.

Direct Measure	Sensor Accuracy
Mechanical Torque T_m	0.1 – 0.5 %
Rotational Speed ω_m	± 1 rpm
Direct Current I_{DC}	$< \pm1$ % rdg $\pm\, 1$ % FS
Direct Voltage V_{DC}	± 2 % rdg

TABLE 3.11 – Direct Measures Sensor Accuracy Summary

Absolute and relative errors are defined as following:

- *Absolute Error:* absolute value of the difference between an observed value of a quantity and its true value, computed as the difference between the maximum and minimum value of the measured quantity;

- *Relative Error*: measure of the uncertainty of measurement compared to the size of measurement, computed as the ratio between the *absolute error* and the sample *mean*.

In TABLE *3.12, absolute and relative errors* related both to direct and indirect measures are reported.

	Thermal Analysis 1		Thermal Analysis 2	
Quantity	**Absolute Error**	**Relative Error**	**Absolute Error**	**Relative Error**
Rotational Speed	1	0.029 %	4.5	0.129 %
Mech. Torque	0.095	0.682 %	0.0702	0.262 %
Cont. Voltage	0.034	0.032 %	0.145	0.145 %
Cont. Current	0.691	1.378%	1.132	1.119 %
Mech. Efficiency	-	**1.538 %**	-	**1.165 %**

TABLE 3.12 – Thermal Analyses Results Summary

Direct Voltage and RPM relative errors are the lowest, due to high rpm reading accuracy and almost constant Power Supply System output voltage.

Instead, considering Direct current, its lower value of analysis 1, with respect to the 300 A Full – Scale sensor, highly affects overall efficiency relative error, but its overall value is not so far from the 1 % goal.

3.5   Technical Specifications

Technical Specifications are needed to completely understand which are all possible types of motors that can be tested, having as output results, points and curves where the maximum uncertainty on the mechanical efficiency equal to $\pm\ 1\ \%$.

In TABLE *3.13,* a detailed recap of Test Bench Technical Specifications is reported.

Test Bench Technical Specifications	
Testing Power Range [kW]	$0.8 - 33.6$
Direct Voltage Range [V]	$1 - 300$
Direct Current Range [A]	$1 - 300$
Mechanical Torque Range [Nm]	$1 - 100$
Rotational Speed Range [rpm]	$100 - 12000$
Direct Voltage Error	$< 1\ \%$
Direct Current Error	$< 2\ \%$
Mechanical Torque Error	$< 1\ \%$
Mechanical Speed Error	$< 0.5\ \%$
Mechanical Efficiency Error	$< 1.5\ \%$
Direct Voltage Resolution [V]	< 0.1
Direct Current Resolution [A]	< 0.1
Mechanical Torque Resolution [Nm]	< 0.5
Rotational Speed Resolution [rpm]	1

TABLE 3.13 – Test Bench Technical Specifications Summary

3.6 Test Typology

Experimental test phase can start only once Start – Up procedure is over; it contains all instructions and procedures needed to correctly perform and obtain exact experimental results.

It is strongly advisable, before starting an experimental session, to perform a Test example, needed to asses correct functioning of all Test Bench, including sensors measurements, dyno functioning and so on. A good test example can be a reasonable low value for Electric Motor Rotational Speed and Torque, to asses all Test Rig measurements.

Once correct functioning has been assessed, experimental test can start.

Test Session can be of different types, that are:

- Electric Motor *Torque – Power Curve* exploration, measuring Torque at different RPM values. This test can be performed in two ways:

  - *Constant Speed Control:* by setting an RPM value to Dyno Setting Tool and increasing Torque level by acting on Drive System potentiometer, as explained in *Sec. 4.1.D;*
  - *Constant Torque Control:* by setting a certain value of the Drive System potentiometer and increasing RPM value with Dyno Setting Tool.

  In this way, all *Torque – Power Curve* can be explored, acquiring Torque and RPM value in each working point, thus obtaining different type of Motor Curves.

- Electric Motor *Steady – State Thermal Analysis,* by setting a fixed RPM and Torque value and evaluating the thermal equilibrium after a time equal to 30 minutes, as explained in UNECE Regulation No. 85 in *oA.*

- Drive Setup and Development: it is needed to correctly configure all Drive System functions, including *Flux Weakening* and *Torque Ripple;* in this Section, *Flux Weakening* only is explained, since specific instrumentation is needed to perform Torque Ripple measurement.

3.6.1 Data Acquisition

Before reporting different test procedures, it is important to explain Data Acquisition Strategy, that is different depending on the test running.

Two strategies are explained in the following

1. *Step – by – step strategy*: in this case, data are acquired in each time instant set by Dyno Control System;

2. *Average Acquisition Strategy*: data are acquired by averaging a number of measurements that is set before test running, explained below referring to FIGURE *3.6*. Parameters to set are:

   ▪ Acquisition Frequency, whose max. value is 10 Hz;
   ▪ Number of Measurements.

Ratio between them gives Acquisition duration, thus their tuning is performed to have most suitable test duration in each typology.

To open setting window, press F6 – F2.
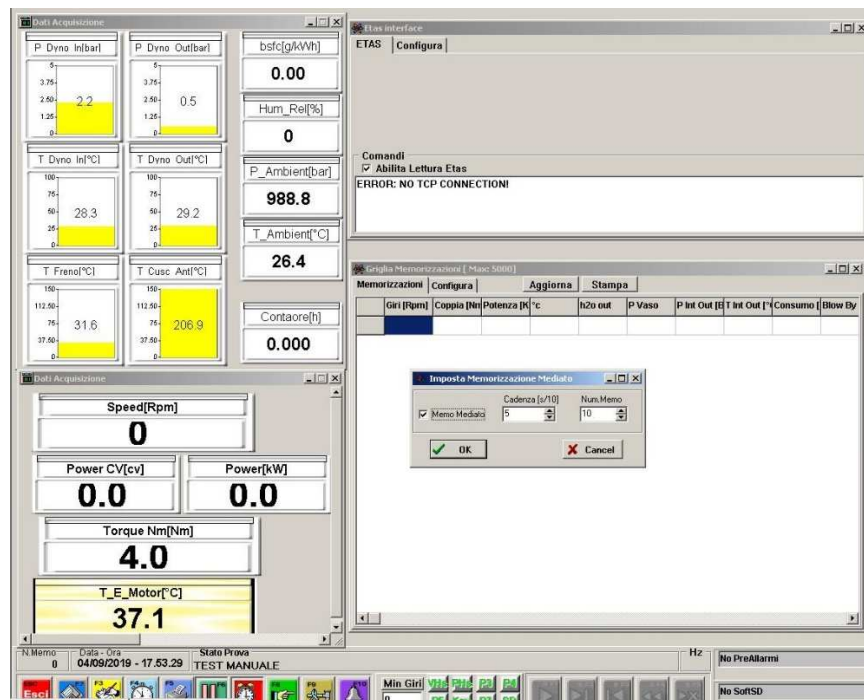
FIGURE 3.6 – Acquisition Parameters Setting

Procedure to follow depends on type of test to be carried out, and it is explained in the following.

3.6.2 Steady – State Thermal Analysis

In this Experimental Test, goal is to evaluate Electric Motor Steady – State Thermal Equilibrium, in a stationary working point.

Most important constraints in these tests are:

A. Air Cooled Motor:
- Motor must be in Thermal Equilibrium with Ambient, i.e. at Temperature equal of Ambient one, at Experimental test start;
- Ambient Air Temperature, at which Motor is been tested, must be set and kept constant during all test duration, in order to correctly measure all other parameters;

B. Liquid Cooled Motor:
- Motor must be in Thermal Equilibrium with Ambient, i.e. at Temperature equal of Ambient one, at Experimental test start;
- Liquid Cooling Temperature, at which Motor is been tested, must be set and kept constant during all test duration, in order to correctly measure all other parameters;

These analyses have several goals, since it can be obtained:

a. Thermal analyses aimed at characterizing different Motor Torque levels, that are:
   - *Base Torque*: it is Torque level that ensures overcurrent use in Motor Control Strategy, avoiding saturation at *Rated Torque* only;
   - *Rated or Nominal Torque*: it is Torque level that ensures Thermal Equilibrium between Motor and Environment, at a suitable Temperature, defined as the maximum one; it depends on Cooling System type only.
   - *Maximum Torque*: it is maximum Torque level reached, that depends on Motor electrical characteristics only.

b. Cooling System Development: by using different Torque levels obtained before, understanding most suitable base Torque in cooperation with vehicle cooling system that ensure overcurrent using in real vehicle operating conditions;

c. Motor Thermal Time Constant, once *Nominal Torque* level is characterized;

d. Iterative Cycles between Base Torque and Maximum Torque: dynamic test in which different current levels are requested, to assess possible overcurrent values to be performed in the electric powertrain;

Therefore, Thermal Analyses and Cooling System development allow to characterize Motor dynamic behavior, thus leading to study different strategies that can be used inside Powertrain system.

Procedure to follow is aimed at set working point in which evaluate Thermal Equilibrium and Acquisition Frequency only since, in this Experimental Test, no Average Acquisition is needed.
Acquisition Strategy used in this test is *Step – by – Step* type, explained in *Sec. 3.6.1*
Once all Start – Up procedures are completed, test can start, following procedure explained below.

I.   Turn ON Test Rig Ventilation System;
II.   RPM Setting through Dyno Set Tools;
III.   Enable Electric Motor rotation by acting on Drive Lever, as explained in *Sec. 4.1.D;*
IV.   Set Accelerator Percentage depending on Torque level requested;
V.   Check all working point values;
VI.   If point V. is satisfied, acquisition can start through Dyno PC.

Test can be considered completed only once Electric Motor Temperature reaches a steady – value. Results are accepted considering also Ambient Temperature evolution during test session.

3.6.3 Torque – Power Curve Exploration

In this section, a typical procedure to follow in all type of Torque – Power Curve Exploration is explained. Acquisition Strategy used is *Averaging Acquisition,* explained in *Sec. 3.6.1.*

It is important underline these tests goals, that are:

a. Assess Powertrain performance in all operating conditions;
b. Evaluate Efficiency, thus Dissipated Power, to assess performance and to sizing Cooling System.

These tests are divided in two categories, that are:

1. Constant RPM Control Exploration Strategy

In this procedure, a Constant RPM strategy is explored, meaning that RPM set by Dyno Tools is kept constant until all points in the Electric Motor Curve, at the set RPM value, are characterized.

Procedure to follow depends on working point position in the curve, if it is above of *Nominal or Maximum Torque – Power* curve, as explained in *Sec.*

To start test, main parameters to set are:

o RPM and Torque, by changing accelerator percentage in Drive System;
o Second important parameters to set, in all points not above *Maximum Torque – Power Curve,* are the **Number of Measurements** and **Acquisition Frequency**, that can be done by acting on Dyno Setting Tool.

Being in a Constant Speed Control, RPM is kept constant until all working points are characterized, while changing Torque value. Procedure to follow is:

I. RPM Setting by acting on Rotational Lever in Dyno Tools;
II. Activate Electric Motor rotation by acting on Drive Lever, as explained in *Sec. 4.1.D;*
III. Change accelerator percentage depending on requested Torque level;
IV. Once RPM and Torque values are stabilized, acquisition can start, by acting on Dyno acquisition PC;
V. After that first point is acquired, test can proceed by increasing Torque value of the requested quantity, considering Test Rig technical specifications shown in TABLE *3.13.*

Once *Maximum Torque – Power Curve* is reached, acquisition procedure changes, since Electric Motor Thermal Equilibrium is not experienced.

Therefore, it is advisable to set again Number of Measurements and Acquisition Frequency, to avoid an excessive duration of the test and a risk of reaching too high Temperature values, that will cause a stop in the experimental test.

2. Constant Torque Control Exploration Strategy

In this procedure, a Constant Torque strategy is explored, meaning that Torque Level request, set by Drive Potentiometer, is kept constant until all points in the Electric Motor Curve, at the set Torque value, are characterized.

In Constant Torque Control, procedure to follow is the same of the one explained in *point 1,* a part of sub – points V, explained below.

    V.   After that first point is acquired, test can proceed by increasing RPM value of the requested quantity, considering Test Rig technical specifications shown in *Sec. 0.*

The only difference, considering Constant RPM Control Strategy is the exploration direction in the Electric Motor *Torque – Power Curve,* as it is shown in FIGURE *3.7.*
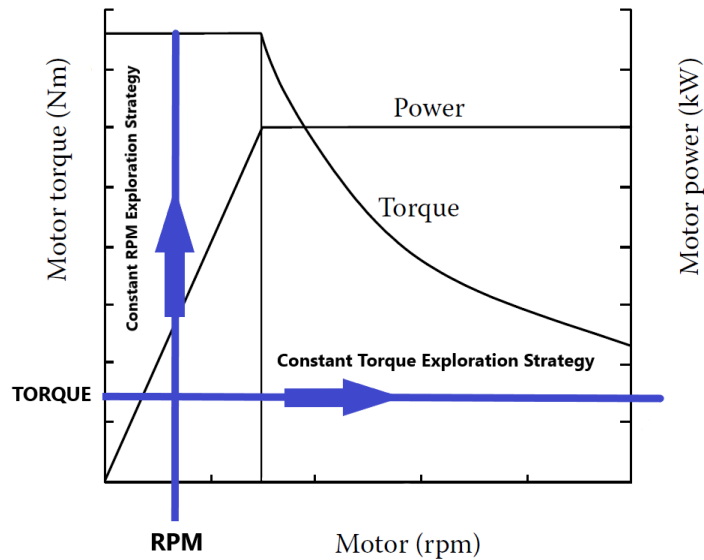
FIGURE 3.7 – Exploration Strategy on Torque – RPM Diagram *[9, p. 57]*

3.6.4 Drive Setup

Drive Setup includes following experimental tests, that are:

a.   Flux Weakening Check;
b.   Torque Ripple minimization;
c.   Motor Acoustic characteristics improvement.

In this section, Flux Weakening Check only is explained, since it is the only test carried out between the three listed above.

Flux Weakening Check tests type include procedure to verify and assess Flux Weakening effects. It is worth underline that, these tests are carried out verifying an '*overall*' effect, i.e. Flux Weakening is analyzed from Battery or Power Supply System output to Motor Mechanical output.

In fact, to correctly assess and verify Flux Weakening effects, particular instrumentation is needed, aimed at measuring DC Current and Voltages phases vectors with respect to angular position, that is not implemented in the Test Bench.

Therefore, a Flux Weakening behavior check is carried out, on complete Motor operating field, and obtained results can only be seen as a '*overall system results*', as an input – output only. In fact, as it is shown in *Sec. 3.7.3,* by using dotted lines representing ideal Flux Weakening Motor behavior, it is possible to understand, from system outside, if it is working or not, with a certain approximation.

It is worth underline that, in all plots representing Torque – Power curve with dotted lines, goal is to compare ideal Flux Weakening characteristics with the ones tested, to understand an overall correctness of the phenomenon. Dotted lines representing ideal Flux Weakening behavior are used also as a *Flux Weakening Check curves tag.* Thus, in every curve containing them, Flux Weakening Check is performed.

Concerning Test, Acquisition Strategy followed, usually, is *Average Acquisition,* with tuned parameters to speed up test, thus decreasing its duration.

Typical *Flux Weakening Check* Test includes three phases, that are:

I.   Flux Weakening Parameters Setting, that can be modified by opening Drive System Parameters Window, as the one reported in FIGURE *4.8.*

It is worth underline that, all Drive System parameters setting must be performed before testing start, with Drive System general switch in OFF position. After that, *'parameters saving'* must be done;

II. Torque Level Setting on which Flux Weakening is studied, by changing Maximum Current in Drive System Parameters Window, as shown in *Sec. 4.1.D;*

III. Test Run, starting from *base speed,* i.e. speed at which Flux – Weakening region starts, in order to decrease Test duration and Post – Processing complexity, also considering that Flux – Weakening does not affect constant Torque region;

Therefore, Dynamometer RPM lever must be set at base speed value, then acquisition can start, whose strategy depends on User choice (with or without Average Acquisition Method);

IV. RPM distance between two consecutive points to characterize is chosen equal to 500 RPM, to have a suitable correctness of Flux Weakening control characterization.

Test is considered over once all chosen working points are characterized.

In *Sec. 3.7.3*, Flux Weakening post – processed data and results are shown.

3.6.5   Efficiency Map without Flux Weakening

In this Section, a typical procedure to follow in case Efficiency Map, in different Motor operating points, is requested. Acquisition Strategy to use depends on time duration requested; of course, also in this case a trade – off between duration and accuracy must be considered. Nevertheless, *Average Acquisition Strategy,* explained in *Sec. 3.6.1*, is suggested. It is important underline test goals, that are:

    a. Evaluate Motor Efficiency, thus Dissipated Power, in all operating conditions;
    b. Using Efficiency and Dissipated Power to obtain *Iso – line curves,* needed to obtain *Mapped Motor.*

To accomplish these goals, Motor operating fields are explored in different ways, to assess performance in all points. To do that, Torque – Power Curve must be fully explored, thus different strategies can be carried out, that are:

    I.   Constant RPM Exploration Strategy;
    II.   Constant Torque Exploration Strategy.

These two strategies are fully explained in *Sec. 3.6.3*, and their logic is represented with respect to FIGURE *3.7*, thus they will not be detailed explained.

The important difference, in this case, is the Motor Map partition in intervals that allow the correct characterization of Efficiency and Dissipated Power at different levels between minimum and maximum Speed and minimum and maximum Torque.

Once these parameters are defined, Motor Mapping can start.

Efficiency Map results are reported in *Sec. 5.5.*

3.7 Post – Processed File

Post – Processed File is final Excel or Matlab file, containing all results of the considered test session. It is worth underline that these results are reported without filtering procedures, thus they can be considered as *Post – Processed Raw Files.*

Examples reported below are related to the two Regulation No. 85 tests and one *Flux Weakening Check* test.

3.7.1 Thermal Analysis

Considering *Max 30 minutes Power,* Post – Processed file highly differs due to increased test duration. In this file, Ambient Temperature evolution, DC Voltage during test and Delta Temperature between ambient and motor are reported, as shown in FIGURE *3.9*, FIGURE *3.10* and *FIGURE 3.11.*

FIGURE *3.8* shows typical layout for Post – Processed file.

Data	Ora	Ciclo	Contaore	Speed	T_Ambient	P_Ambient	T_E_Motor	coppia_tors\1	corrente\1	tensione\1	time	delta_T
0	9,2424	0	58,969	3505	24,9089	986,1306	27,2547	26,9338	101,0254	100,2329	106,92	2,3342
0	9,2427	0	60	3503	24,8701	986,2236	27,2547	26,9297	101,7411	100,2319	108	2,3342
0	9,243	0	60,844	3493	24,7694	986,0532	27,4846	27,0789	101,491	100,2255	109,08	2,5641
0	9,2433	0	61,969	3503	24,7617	986,2081	27,3697	26,93105	101,1284	100,1534	110,16	2,4492
0	9,2436	0	63	3496	24,9321	986,1461	27,9063	26,98735	101,5172	100,1501	111,24	2,9858
0	9,2438	0	63,937	3500	24,754	986,1771	28,2513	26,90495	101,2553	100,149	111,96	3,3308
0	9,2441	0	64,969	3498	24,7849	986,1306	28,1363	26,9086	101,3027	100,2207	113,04	3,2158
0	9,2444	0	66	3499	24,6997	986,0377	27,9063	26,9234	101,2598	100,2205	114,12	2,9858
0	9,2447	0	66,937	3498	24,7617	985,9757	27,7913	26,911	101,2242	100,2243	115,2	2,8708
0	9,2449	0	67,875	3497	24,6765	985,9602	27,3697	26,93615	101,5112	100,2185	115,92	2,4492
0	9,2452	0	69	3502	24,8701	985,9138	28,7879	26,97095	101,4427	100,1448	117	3,8674
0	9,2455	0	69,937	3496	24,8392	985,9912	28,3662	26,98	101,3724	100,1359	118,08	3,4457
0	9,2458	0	70,969	3498	24,8082	985,9448	28,2513	26,9809	101,4768	100,205	119,16	3,3308
0	9,2461	0	72	3499	24,8082	986,0222	28,4812	26,8928	101,4952	100,2051	120,24	3,5607
0	9,2463	0	72,937	3496	24,723	985,8053	30,0145	26,9524	101,2714	100,1564	120,96	5,094
0	9,2466	0	73,969	3503	24,7927	985,9138	28,5196	26,9847	101,4056	100,1292	122,04	3,5991
0	9,2469	0	74,906	3497	24,8004	985,8983	28,5579	26,9459	101,6018	100,1261	123,12	3,6374
0	9,2472	0	75,937	3496	24,7694	985,8673	28,0979	26,98455	101,332	100,1271	124,2	3,1774

FIGURE *3.8* – Max 30 Minutes Power Post Processed File

Ambient Temperature Evolution During Motor Thermal Analysis: Ventilation ON

rpm $= 3500$ $I_{DC, avg} = 100{,}9$ A $T_{AVG} = 26{,}7$ Nm
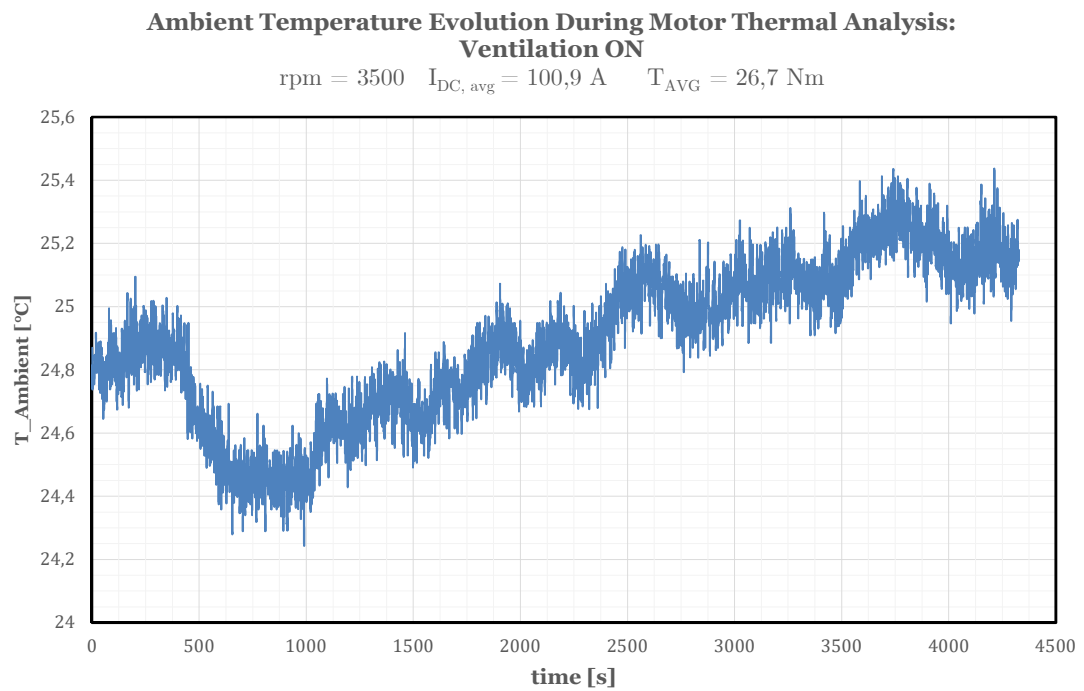
FIGURE 3.9 – Ambient Temperature Evolution during Max 30 Minutes Power Test

DC Voltage During Nominal Thermal Analysis

rpm $= 3500$ $I_{DC, avg} = 100.9$ A $T_{AVG} = 26.7$ Nm $T_0 = 24.7$ °C
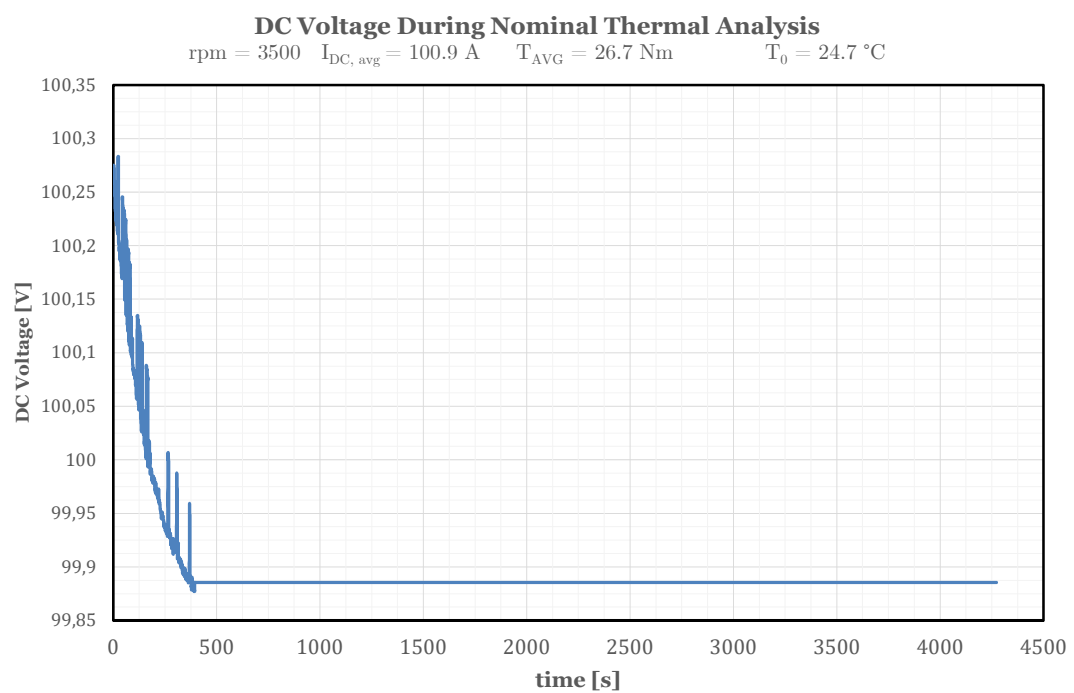
FIGURE 3.10 – DC Voltage during Max 30 Minutes Power Test

Delta Temperature Evolution During Thermal Analysis: Ventilation ON

rpm = 3500 $I_{DC, avg}$ = 100.9 A T_{AVG} = 26.7 Nm T_0 = 24.7 °C
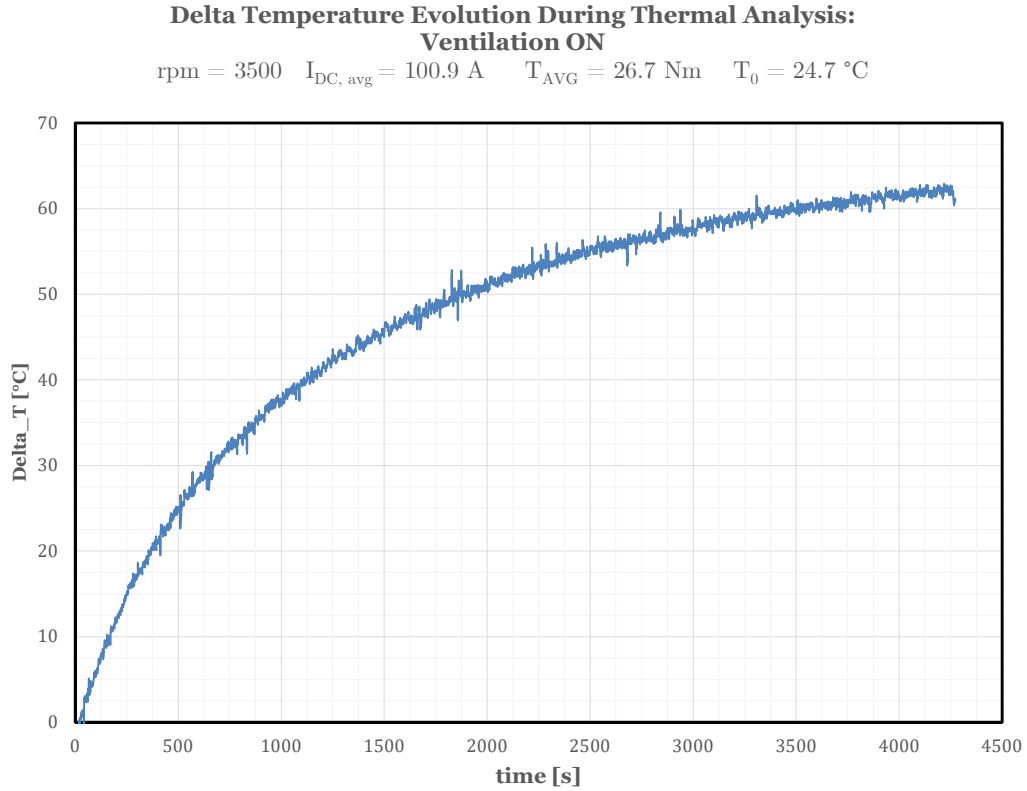
FIGURE 3.11 – Delta Temperature Evolution in 30 Minutes Power Test

3.7.2 Torque – Power Curve with Efficiency

Considering *Net Power Curve*, in each measured point direct and indirect measurements are reported, useful to compute mechanical efficiency, as reported in *Fig.* Each column contains the corresponding measured quantity, direct or indirect one and, the number of rows depends on test session duration and stabilization time for average acquisition method.

Final outputs for *Net Power Curve* are *Torque – Power* plots and *mechanical efficiency* table, shown in FIGURE *3.12, FIGURE 3.13* and *TABLE 3.14*.

It is worth underline that these results are obtained without active Flux Weakening.

T_E_Moto	P_Dyno_Ir	P_Dyno_C	T_Dyno_Ir	T_Dyno_O	T_Cusc_Ar	T_Freno	coppia_to	tensione\1	corrente_FS_100A\1	corrente_FS_300A\1	eta_pinza_300	Speed
°C	bar	bar	°C	°C	°C	°C						Rpm
67,7718	2,2239	0,5393	29,8975	30,6887	206,935	32,2508	26,8261	101,97308	19,57853	18,56477	74,58%	502,6
72,4558	2,2244	0,5396	29,9115	30,8724	206,935	32,3248	26,7496	101,97459	33,35377	32,54217	84,13%	996,65
76,2563	2,2264	0,5383	29,9408	30,946	206,935	32,3631	26,6613	101,90816	46,9782	46,67943	88,01%	1499,55
79,1406	2,2257	0,5387	29,934	31,0685	206,935	32,4079	26,5001	101,87828	60,14968	60,80698	89,82%	2005,05
82,0653	2,2251	0,5401	30,012	31,2094	206,935	32,4818	26,323	99,88979	73,91853	75,83535	91,04%	2501,95
84,5931	2,2261	0,5394	30,0798	31,3136	206,935	32,5752	26,1569	99,83736	86,04652	89,68112	91,74%	2998,75
86,8566	2,2244	0,5396	30,114	31,4667	206,935	32,62	26,2207	99,7541	98,54976	104,40814	92,50%	3508,7
86,8681	2,2264	0,5373	30,1795	31,4116	206,935	32,6185	16,3028	99,82938	78,83286	81,33146	94,63%	4500,35
85,0167	2,2251	0,5395	30,2301	31,3564	206,935	32,648	11,58	100,981	62,00313	62,84358	95,65%	5005,3
83,403	2,2215	0,538	30,2777	31,3687	206,935	32,7116	8,61168	101,93167	50,79916	50,67266	96,14%	5506,5
82,4256	2,2239	0,5397	30,3169	31,2768	206,935	32,7422	5,84696	101,97435	38,3222	37,57475	95,89%	6000,8

FIGURE 3.12 – Net Power Curve Post – Processed Output File
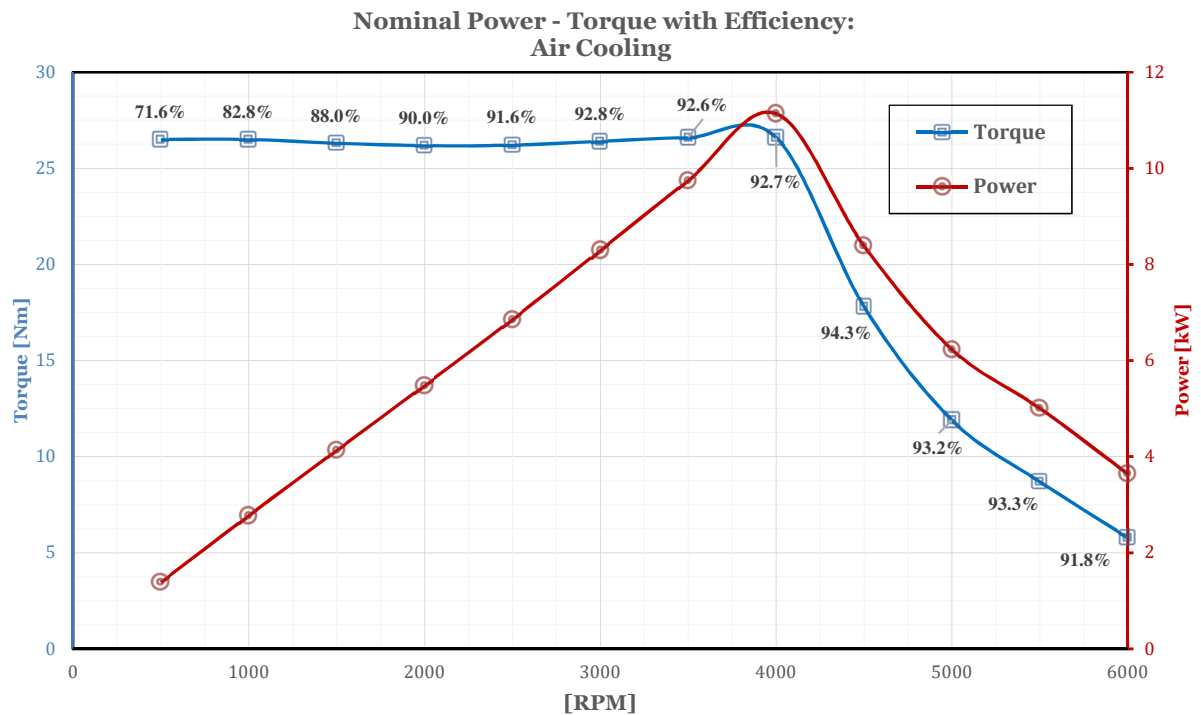
FIGURE 3.13 – Net Torque – Power Curve

[Nm]	500	1000	1500	2000	2500	3000	3500	4000	4500	5000	5500	6000
26,5	71,6%	82,8%	88,0%	90,0%	91,6%	92,8%	92,6%	92,7%				
17,8									94,3%			
11,9										93,2%		
8,7											93,3%	
5,8												91,8%

TABLE 3.14 – Net Torque – Power Curve Efficiency Table

3.7.3 Flux Weakening Check

Most common Flux Weakening Setup post – processed file includes typical excel file, with all performed measurement values, and Torque – Power Curves showing both experimental results and Ideal Motor curves, to correctly asses Flux Weakening functioning or, in negative case, to understand which operation perform to improving control system.

In FIGURE *3.14*, excel file is reported.

T_E_Motor	Speed	coppia_tors\1	FS_300A\1	tensione\1	P_el	P_mcn	eta	T_id	P_mcn_id
[°C]	[RPM]	[Nm]	[A]	[V]	[W]	[W]	[%]	[Nm]	[W]
46,9987	496,3	52,63229	45,70814	102,80482	4699,02	2735,43	58,21%	52,63229	2735,43
53,7525	1001,2	52,23015	74,62829	102,0862	7618,52	5476,09	71,88%	52,63229	5518,25
60,2457	1505,1	52,1691	104,90975	100,75355	10570	8222,57	77,79%	52,63229	8295,57
65,9684	2000,9	52,2721	134,01548	100,6045	13482,6	10952,8	81,24%	52,63229	11028,2
72,2086	2508,1	52,53502	166,05957	99,45456	16515,4	13798,2	83,55%	52,63229	13823,7
77,9811	3006,2	52,7336	200,13927	97,50552	19514,7	16601	85,07%	52,63229	16569,1
82,9986	3503,9	44,18287	189,0918	97,58651	18452,8	16211,9	87,86%	52,63229	19312,2
84,7925	4002,4	27,69058	126,64295	100,52036	12730,2	11606	91,17%	52,63229	22059,8
83,2937	4505,5	27,03156	137,37646	100,30165	13779,1	12753,9	92,56%	46,75518	22059,8
82,2627	5000,6	29,36268	169,23035	98,72096	16706,6	15376,1	92,04%	42,12604	22059,8
81,8717	5508,7	29,49546	190,962	97,39031	18597,8	17015	91,49%	38,24051	22059,8
82,255	6006,9	28,9797	208,97944	96,18254	20100,2	18229,4	90,69%	35,06892	22059,8
82,9334	6501,6	28,06302	222,08435	95,3514	21176,1	19106,6	90,23%	32,40056	22059,8
84,8155	7006,2	25,73748	224,16208	94,90287	21273,6	18883,3	88,76%	30,06701	22059,8
86,0075	7497,1	23,6627	222,59968	94,67084	21073,7	18577,5	88,15%	28,09826	22059,8
87,2878	7995,3	22,25839	228,88121	94,23383	21568,4	18636,2	86,41%	26,34741	22059,8

FIGURE 3.14 – Flux Weakening Setup Post – Processed File

In FIGURE *3.15*, a first Flux Weakening check is shown, in which it is appreciable that behavior is not correct, by comparing actual curves with ideal ones.

FIGURE 3.15 – Flux Weakening Check 1
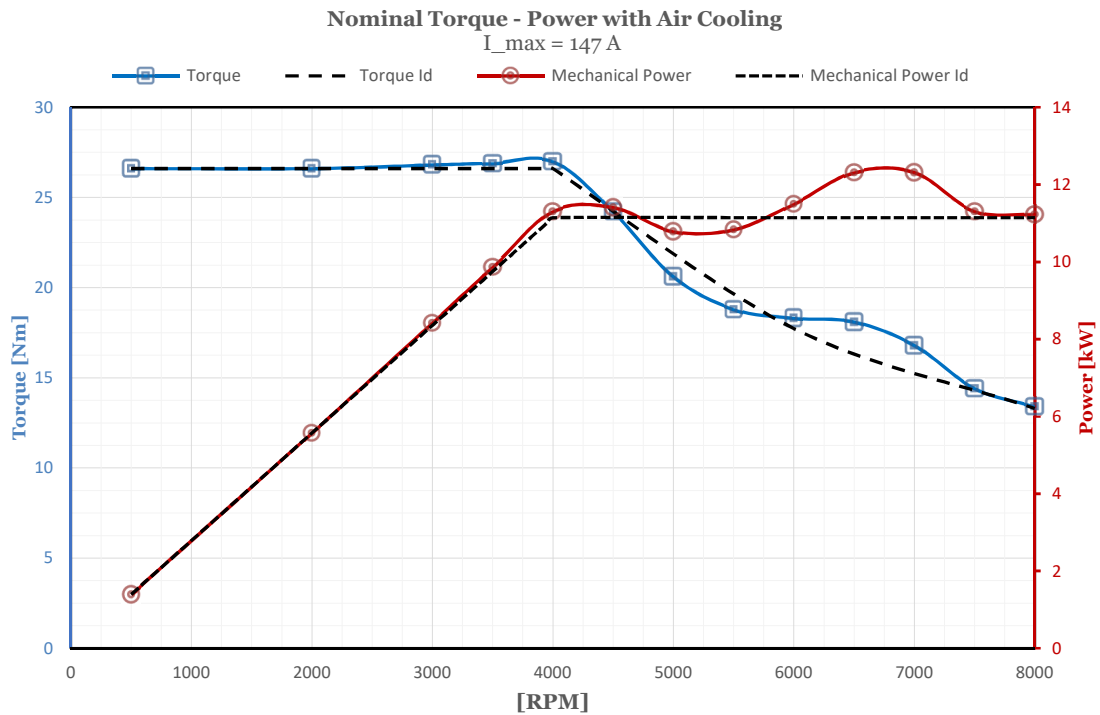
In FIGURE *3.16* and FIGURE *3.17*, a comparison between Nominal Curves is presented, showing differences in case in which Flux Weakening is active or not. It is worth underline how improvements are obtained between *Fig. 3.15* and *Fig. 3.17*.
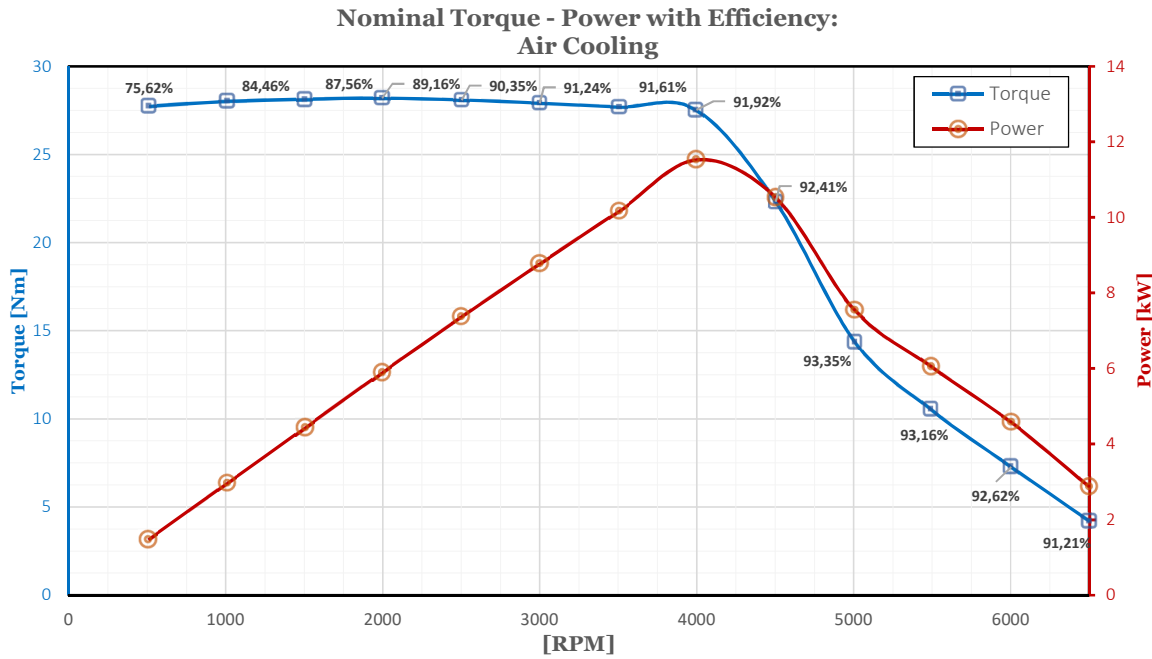
FIGURE 3.16 – Nominal Torque – Power Curve without Flux Weakening
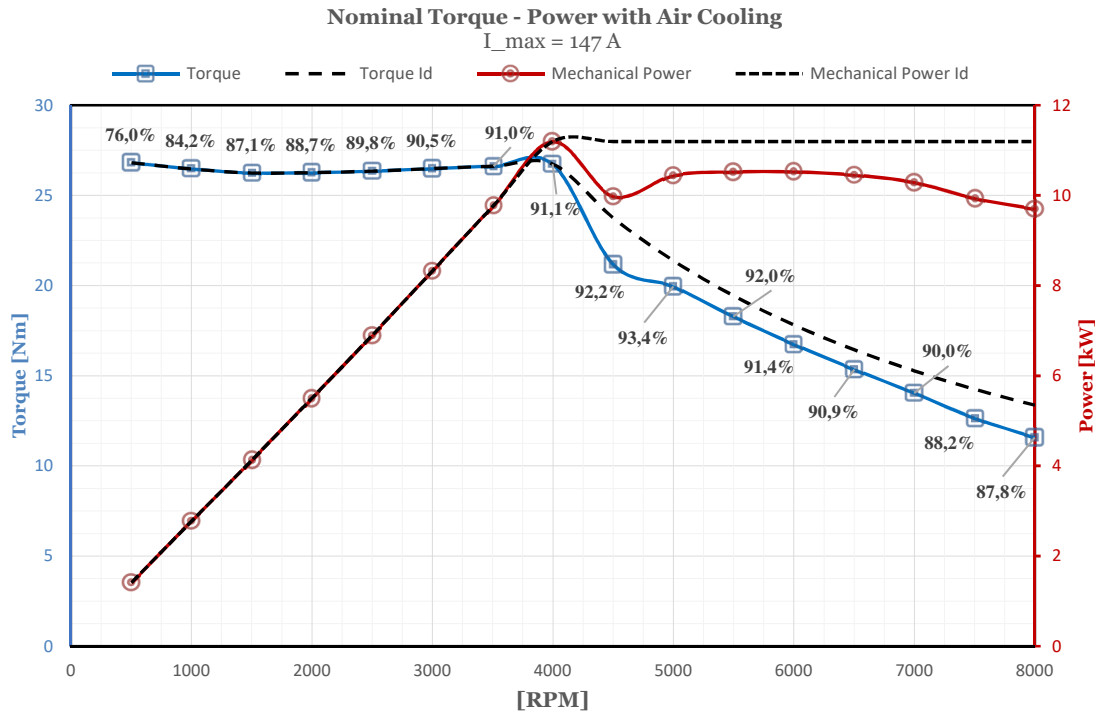
FIGURE 3.17 – Maximum Torque – Power Curve with Flux Weakening

Chapter 4

4 Experimental Test Run

In this chapter, detailed procedures explanation for UNECE Regulation No. 85 and Flux Weakening Check tests are reported.

These step – by – step explanations follow all actions that Test Bench User must perform to correctly set – up Test Rig and obtain acceptable results.

Moreover, before encountering Tests steps explanation, all detailed procedures to perform to correctly setup Test Bench, before starting experimental session, are explained.

Finally, steps to perform to conclude session are reported, including emergency cases too.

It is worth underline that, all procedures explained are referred to this Motor type only, thus they can be considered as an example on how to initialize Test Bench, since they are specifically referred to all instrumentation given.

4.1 Instrumentation Remoting

In this Section, Instrumentation Remoting procedures performed are reported. There are two main reasons why they are done, that are:

a. **Test Easiness:** by remoting Motor Instrumentation, it is easier to control it, thus speeding up all experimental tests;

b. **Safety:** most important reason, since it is not possible carry out experimental tests with a human user inside Test Bench, due to all possible cause of human damage that can happen.

To understand all procedures performed, Motor functioning instrumentation overview is reported, thus including only instrumentation that is used during these tests but that will be substituted once another Motor will be tested.

SITEM IPM Brushless Motor

FIGURE 4.1 – SITEM Motor

MAC Engineering Inverter and Drive
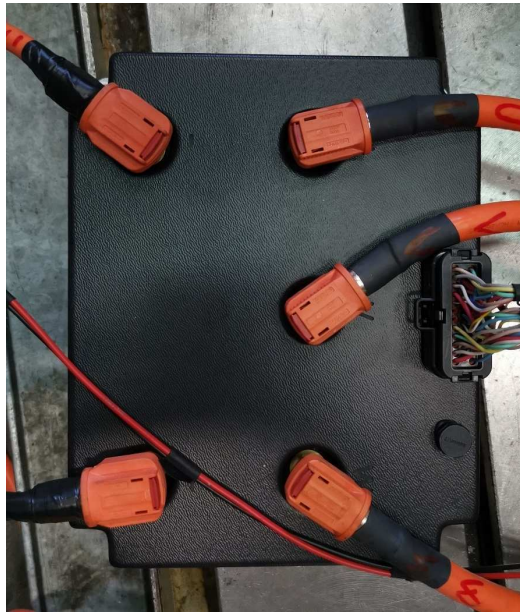
FIGURE 4.2 – MAC Engineering Inverter
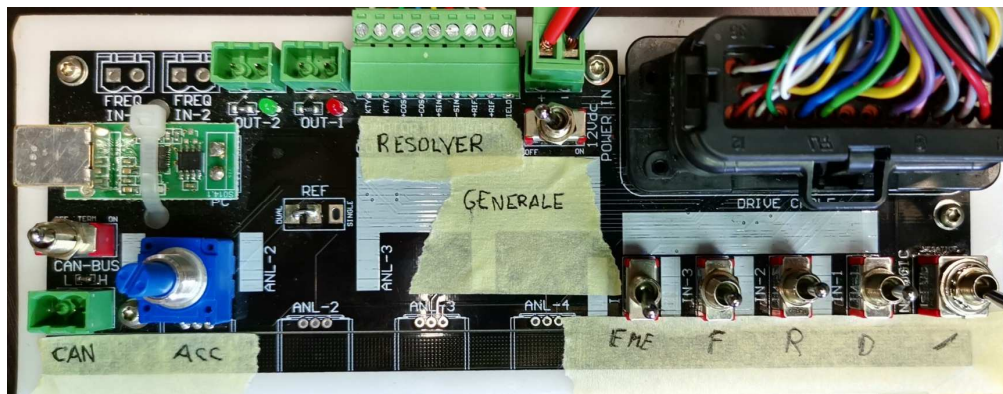
FIGURE 4.3 – MAC Engineering Drive System

Drive System is then connected to a PC that is used to run MAC Engineering Control Software, needed to setup different Motor parameters, explained in *Sec. 4.2.C* and *4.2.D*. Since Drive System is directly connected to the Inverter, in turn connected to Electric Motor, instrumentation remoting procedures include:

    I.   Drive – Inverter Cable remoting;
   II.   PC – Drive Cable remoting.

In this way, Drive System and its Control Software will be located outside Test Bench, thus inside Human Machine Interface, allowing tests easiness.

In *Fig. 4.4,* an old Test Bench layout, without remoted instrumentation is reported, while in *Fig. 4.5,* an actual one is shown, without instrumentation inside Test Bench.

FIGURE 4.4 – Old Test Bench Layout

FIGURE 4.5 – Remoted Test Bench Layout

Completing Instrumentation Remoting, final layout obtained is the one shown in FIGURE *2.1* and FIGURE *2.22,* including both Test Bench and Human Machine Interface.

4.2 Start – Up

Start – up contains all information and procedures to correctly initiate an experimental session inside Test Rig, including set – up for all instrumentations.

    A. Instrumentation Connection to Power Supply Circuit
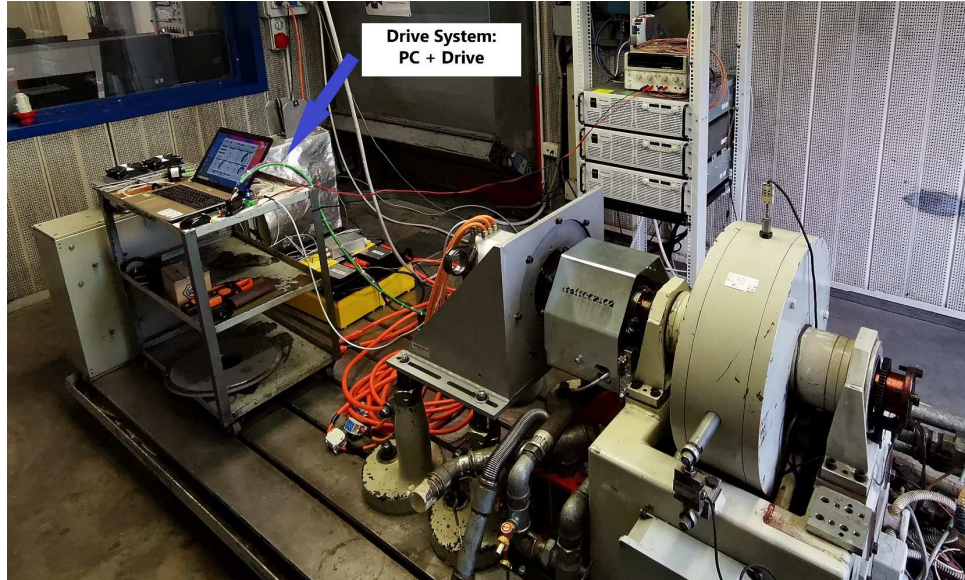
        a. Power Supply System: connect to Three – Phase Alternate Current Red Plug;

        b. Verify correct connection of Dynamometer to Power Supply System and to Cooling water circuit;

        c. Verify correct connection of Acquisition Data System to proper plug, i.e. PCs of *FIGURE 2.22.*

    B. Power Supply System Setting.

Referring to *FIGURE 2.2,* each set – up parameter, in Power Supply System front part, is explained.

        a. **Prev:** it shows current and voltage value in respective LED displays, that can be set – up using circular regulator;

        b. **Fine:** pushing it, current and voltage values regulation becomes more precise;

        c. **OVP – UVL:** used to set – up, respectively, Over Voltage Protection and Under Voltage Limit, to have a safety range of working Voltage value. Maximum value reached by UVL is 95 % of the set one.

        d. **FOLD:** it activates FoldBack or Over Current Protection;

        e. **REM/LOC:** it activates *Independent Remote ON/OFF* or *Remote Enable/Disable* modality;

        f. **OUT:** it exits set – up modality and Current and Voltage values will be shown in respective LED indicators.

    C. Electric Motor Drive Setting

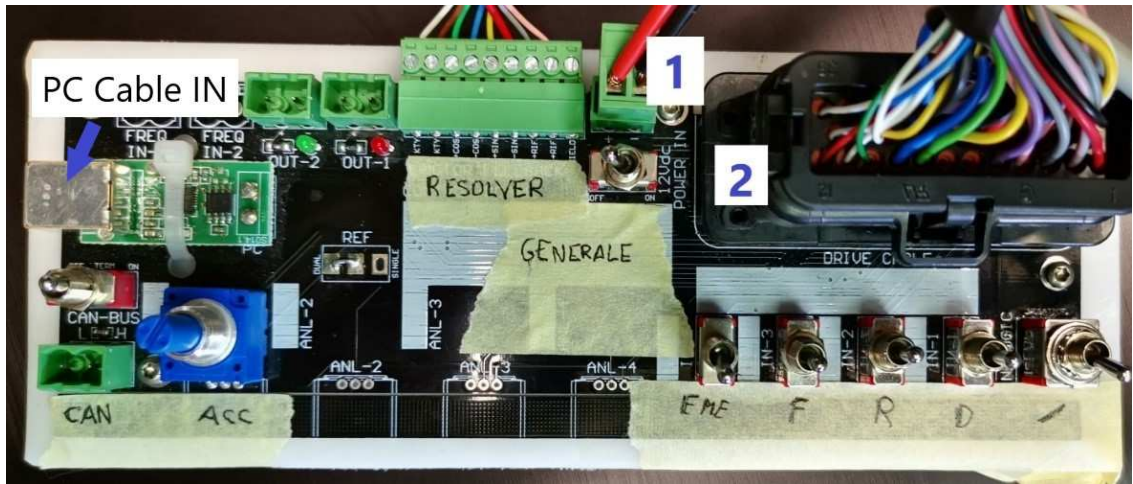In FIGURE *4.6,* a top – view of Drive System is shown, with all its components, whose function is explained below.

FIGURE 4.6 - Drive System Detailed Top View

a. **Cable 1:** Drive Supply Cable, to be connected to proper Supply System, shown on top of Power Supply System of FIGURE *2.3,* with a Supply Voltage equal to 12 V.

b. **Cable 2:** Drive Cable, to be connected to the Inverter;

c. **Resolver:** to be connected to Electric Motor, that sends, through it, information to the Drive System;

d. **General:** it is the ON – OFF Drive System Switch. <u>It is strongly recommended to turn it on only once the 12 V Power Supply System is already set – up</u>.

e. **Accelerator** a.k.a. **Acc:** blue potentiometer that increases the load of the electric motor, whose functioning is explained with respect to FIGURE *4.7.*

f. **Emergency** a.k.a. **Eme:** it is used to cause a free Electric Motor Rotation, thus disconnecting the Three – Phases Alternating Current supplied to it.

g. **Brake** a.k.a. **F:** brake pedals, not used to brake Electric Motor rotation but only to have an inversion of rotation direction of the Motor. It is not used in the experimental procedures, so its position must remain in the same of the ***Errore. L'origine riferimento non è stata trovata.*.**

h. **D – R** a.k.a. **Drive and Reverse:** they are used to select Electric Motor rotation direction. Last right – lever, indicated with symbol '/ ', is not used.

PC Cable IN represents the input for the PC – Drive Connection, needed to correctly ensure the functioning of Control Software.

D. Drive Control Software Set – Up

Pc is connected to Drive as explained in *point C* and, once verified the connection, it is possible to start MAC Engineering Drive System Control Software, whose Interface is shown in FIGURE *4.7*.
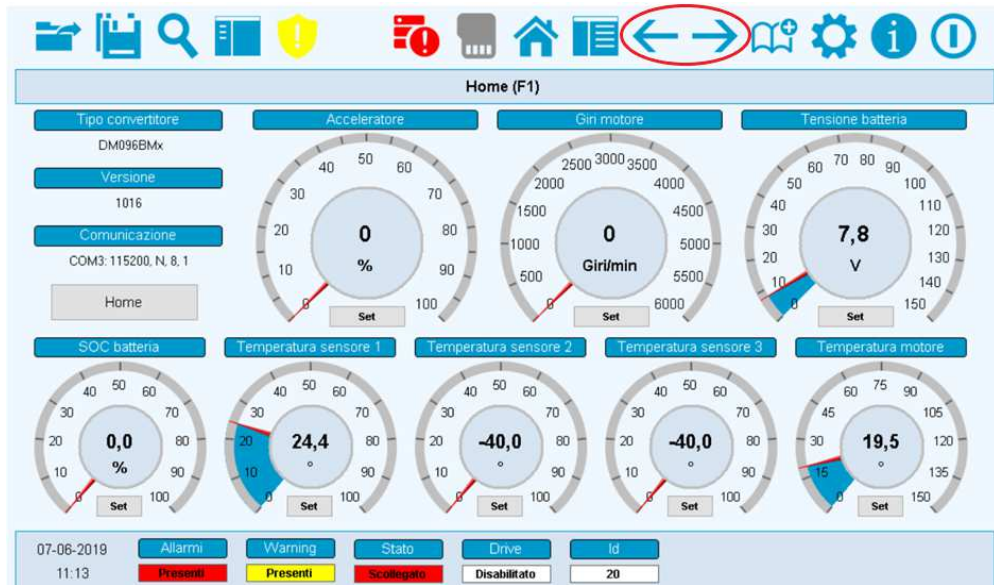
FIGURE 4.7 – MAC Engineering Drive System Control Software

a. **Accelerator:** it shows Electric Motor load percentage, that can be selected through the potentiometer. The logic behind the percentage variation is referred to an a – priori maximum current set and the load percentage refers to that maximum value.

   Ex: maximum set current 100 A, accelerator 10 % means a load current around 10 A. To ensure correct functioning of the load regulator, it is advisable to use a portable current probe and measure, at each 5 – 10 % step, both DC and Alternate Currents.

b. **Giri motore** a.k.a. **rpm:** it indicates Electric Motor rpm. It is advisable to use Dyno System to asses motor rpm, due to its higher accuracy.

c. **Tensione Batteria** a.k.a. **DC Voltage:** it indicates DC Voltage at Inverter Input, depending on the type of connection (Power – Supply or Battery). It can be useful to have a parallel check of DC Voltage measurement between sensor and Drive.

d. **Battery SOC:** not used. To know Battery SOC another display is used, shown in FIGURE 4.13.

e. **Temperature Sensor 1:** it indicates Drive Temperature, whose maximum allowable value is 70 °C. Other displayed Sensor Temperatures are not used.

f. **Motor Temperature:** it displays Electric Motor Temperature. It is advisable to use Dyno System Temperature sensor, due to higher accuracy with respect to Drive one.

Referring to *point e,* it is worth underline that, once Drive System reaches its maximum allowable Temperature, a de – rating procedure starts, meaning that current through it will decrease, thus Electric Motor Current and Torque will decrease too, allowing a Temperature control and avoiding any type of Drive damaging.

Using red highlighted arrows in FIGURE 4.7, it is possible to slide between all parameters that can be set – up by user. It is worth underline that, to correctly set – up a parameter, all Drive System Lever must be in 'idle' position and the General Switch 'ON – OFF' in OFF position, otherwise software will not save any parameter change; therefore, it is advisable to perform this operation at the start of each test session. To correctly save updated parameter, press grey symbol on top of FIGURE 4.7, then select '*memorize parameters*'.

Most important parameter to set is:

- **Max. Current**: it sets up Accelerator Full – Scale, therefore its percentage value will refer to Max. Current. It is the way to change Torque level, depending on the requested one.

In FIGURE 4.8, an example of parameters that can be set is reported. Parameter 37 is the current that must be changed at the start of each experimental session, depending on the type of test to be carried out.

FIGURE 4.8 – MAC Engineering Example Parameters

E. Sensors Start – Up

Referring to FIGURE *2.1,* all sensors position, and proper connection must be checked before test session start.

a. **DC Voltage Probe:** correct position must be checked and probe supply system, that can be done using battery or a proper supply cable. For further information, check the Probe User Manual.

Instead, considering FIGURE *2.21,* the attenuation ratio is chosen on User preferences; it's then advisable to have a remind on this choice and update acquisition system PC settings, i.e. Sensor Top and Bottom, that are shown in FIGURE *4.9.*

No.	Name	Units	Rate	AA-Filter	Digital Filter	Filter Frequency	Phys bottom	Phys top	Sensor bottom [v]	Sensor top [v]	Formula	Range min.	Range max.	Real range min.
1	tensione	V	0.1s	On	On	FIR auto	0.00	200.00	0.00	2.00	Sensor = 0.0 + (	0.00	200.00	-1000.00
2	FS_100A	A	0.1s	On	On	FIR auto	0.00	100.00	0.00	1.00	Sensor = 0.0 + (	0.00	200.00	-1000.00
3	coppia_tors	Nm	0.1s	On	On	FIR auto	-500.00	500.00	-10.00	10.00	Sensor = 0.0 + (	0.00	200.00	-500.00
4	FS_300A	A	0.1s	On	On	FIR auto	0.00	300.00	2.040	9.98	Sensor = 2.04 +	0.00	60.00	-454.91
5	ES410_AD1_CH5	V	10ms	On	On	FIR auto	0.00	60.00	0.00	60.00	Sensor = phys	0.00	60.00	-60.00
6	ES410_AD1_CH6	V	10ms	On	On	FIR auto	0.00	60.00	0.00	60.00	Sensor = phys	0.00	60.00	-60.00
7	ES410_AD1_CH7	V	10ms	On	On	FIR auto	0.00	60.00	0.00	60.00	Sensor = phys	0.00	60.00	-60.00
8	ES410_AD1_CH8	V	10ms	On	On	FIR auto	0.00	60.00	0.00	60.00	Sensor = phys	0.00	60.00	-60.00

FIGURE 4.9 – Sensor Setting

b. **DC Current Probe:** correct position must be checked and probe supply system.

c. **Torque Transducer:** check its proper functioning and correct measured value on Acquisition System PC display.

d. **ETAS Acquisition System:** it contains connections of previous sensors, thus it is fundamental to check its proper functioning, also checking its connection to Acquisition System PC.

F. Inverter Connection Set – Up

Inverter connection is fundamental to ensure proper connection of Drive System, DC Power Supply System and Electric Motor.

Referring to FIGURE *4.10,* Inverter Connection Set – Up is explained.
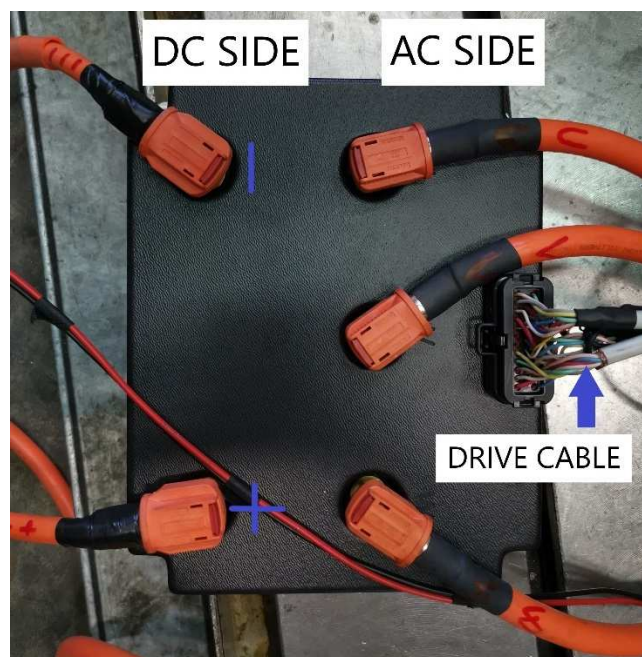
FIGURE 4.10 – Inverter Top – View

a. **Power Supply System – Inverter connection**: DC Power Supply System output cables must be correctly connected to the Inverter DC side, by respecting its + and – poles positioning. Referring to FIGURE *2.4,* red and black cables are useful to correctly distinguish them;

b. **Electric Motor – Inverter Connection:** on Inverter AC side, three different phases can be distinguished. They must match the indication on Electric Motor cables, to have a correct system functioning.

c. **Drive Cable – Inverter Connection**: Drive Cable shown in FIGURE *2.1* must be connected to Inverter as shown in FIGURE *4.10*.

G. Battery Connection Set – Up

Two Li - Ion Battery modules are at disposal for real – vehicle tests, shown in *Fig. 4.11*.

FIGURE 4.11 – ECO -Volta Traction Batteries

Single Module technical characteristics are reported in *Tab. 4.1*.

ECO – Volta Traction Battery Single Module

Quantity	Value
Open Circuit Voltage [V]	51.8
Capacity [kWh]	5
Weight [kg]	28

TABLE 4.1 – Battery Single Module Technical Data

Battery Connection Set – Up is fundamental in all cases in which real vehicle tests are performed, or in case in which Power Supply System combined Electrical Power is not enough to carry out experimental tests, by parallel connecting Battery – Power Supply System, as shown in FIGURE *4.12*.
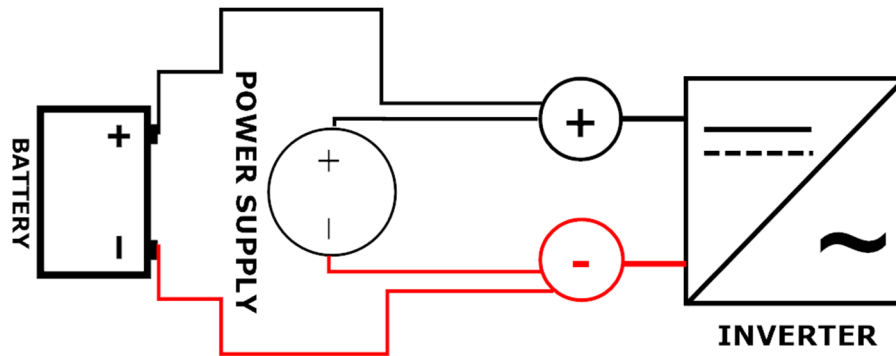
FIGURE 4.12 – Battery – Power Supply System Parallel Connection Layout

In the following, these two cases are distinguished.

a. **Battery Only – Inverter Connection:** in this case, follow instruction of Power Supply System – Inverter connection, explained at *point F*.

b. **Battery / Power Supply System Parallel Connection – Inverter Connection:** referring to FIGURE *4.12,* connection is possible once Voltage difference between Battery and Power Supply System is < 1 V, to avoid an excessive current flowing from Power Supply System to Battery, which could cause reading error to Current Probe Sensor.

   Thus, a correct Voltage measurement between the lowest Power Supply Voltage set and Battery positive poles must be performed and, once it is acquired, it can be decreased by regulating Power Supply System output Voltage by following procedure explained at point B.

   Connection can be performed only once Voltage difference value is checked, thus only once a value < 1 V is reached.

It is now fundamental to correctly distinguish Turn – On Battery procedures, since it is different between *point a – b,* by referring to FIGURE *4.12*.

a. In this case, Battery must be turned ON only after Inverter Connection is set – up.

b. Battery must be turned ON before reading Voltage difference and, once it is verified, connection can be performed.

FIGURE 4.13 – Battery SOC Led Indicator and ON – OFF Switch

4.3 Maximum 30 Minutes Power

In this section, all actions to be performed during a typical Maximum 30 Minutes Power, or Steady – State Thermal Analysis test are explained in detail.

Before starting, all operations reported in Start – Up procedure, in *Sec. 4.1,* must be followed, to correctly set – up all Test Bench hardware and software components.

Goal of Maximum 30 Minutes Power tutorial is to evaluate Electric Motor Thermal Equilibrium in a test during at least 30 minutes, with constraints related to accessories reported in *Appendix A.*

Once set – up phase is over, experimental test can start, following procedure explained below.

I.   Turn ON Test Rig Ventilation System;

II.   Set Maximum Current in Drive System, as explained in *Sec. 4.2.D,* depending on the requested Torque value;

III. Disable Average Acquisition Strategy tool, and set Acquisition Frequency to 1 Hz;

IV.   Set RPM value, using Dyno Setting Tool rotational lever;

V.   Enable Electric Motor Rotation, as explained in *Sec. 4.2.C*;

VI.   Set Drive System Accelerator Potentiometer to level corresponding to requested Torque;

VII. Check all measurements values;

VIII. Once measurements are validated, acquisition can start;

IX.   Test is over if Motor Temperature reaches a Steady – State value, considered acceptable from UNECE Regulation No. 85

X.   To validate results, a Post – Processed file containing DC Voltage, Motor Temperature and Ambient Temperature must be generated, as shown in *Sec.3.6.2.*

Test is considered over and accepted if all post – processed plots and results satisfy UNECE Regulation No. 85 requests.

In this way, *Nominal Torque* is evaluated, thus it will be used to characterize entire *Nominal Torque – Power Curve,* as it is explained in *Sec. 4.4.*

In FIGURE *4.14* FIGURE *4.15* and FIGURE *4.16*, an example result is proposed; as it is shown in *Fig. 4.14,* ambient temperature is not constant during test, leading to an impossibility of Motor at reaching thermal equilibrium with external environment.

To obtain these plots type, following procedures must be followed:

I.   Select time intervals in which plot all data, including Ambient Temperature, DC Voltage and Motor Temperature;
II. Once time interval is obtained, plot all data in that interval;
III. Compute average quantities in the time interval, such as DC Current, Torque and RPM, to correctly characterize experimental test.

An example of excel file used to characterize these tests is reported in FIGURE *3.8*.
Instead, a Maximum 30 Minutes Power results example is reported from FIGURE *4.14*, including:

a. Ambient Temperature Evolution;
b. DC Voltage during 30 Minutes;
c. Motor Temperature Evolution.

These results are considered failed, from Homologation perspectives, but they are considered relevant to characterize Maximum 30 Minutes Power tests type.

Ambient Temperature Evolution During Motor Thermal Analysis: Ventilation ON

rpm $= 3500$ $I_{DC, avg} = 97.2$ A $T_{AVG} = 25.5$ Nm
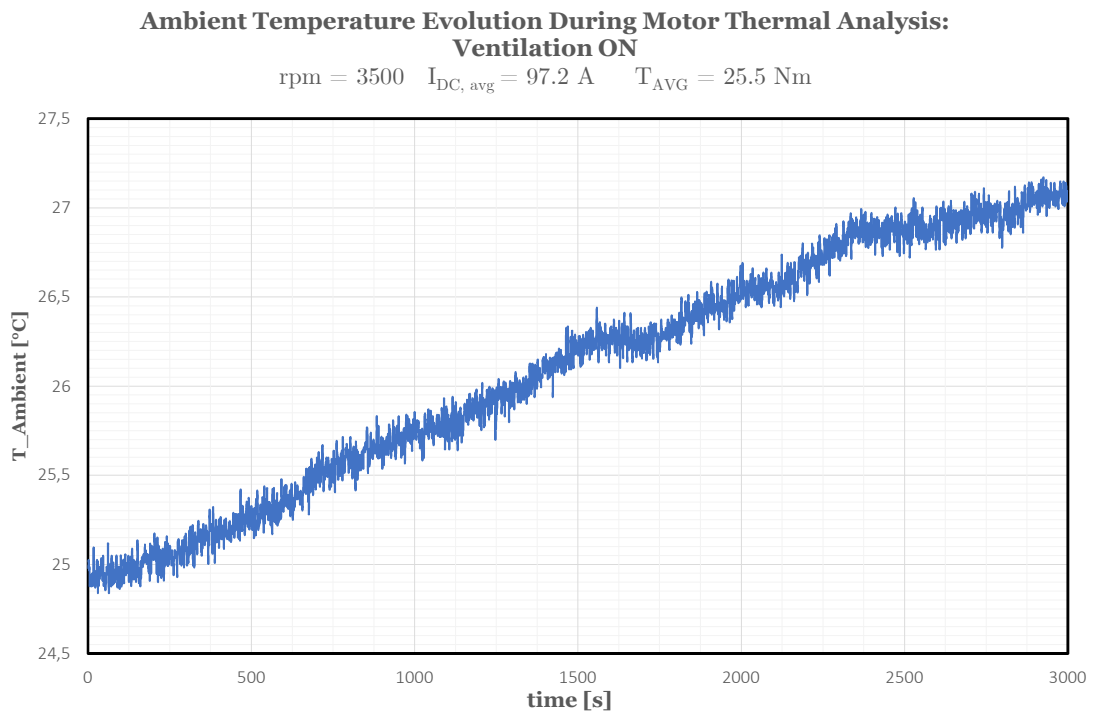
FIGURE 4.14 – Ambient Temperature Evolution: Failed Test

DC Voltage During Nominal Thermal Analysis

rpm = 3500 $I_{DC, avg}$ = 97.2 A T_{AVG} = 25.5 Nm
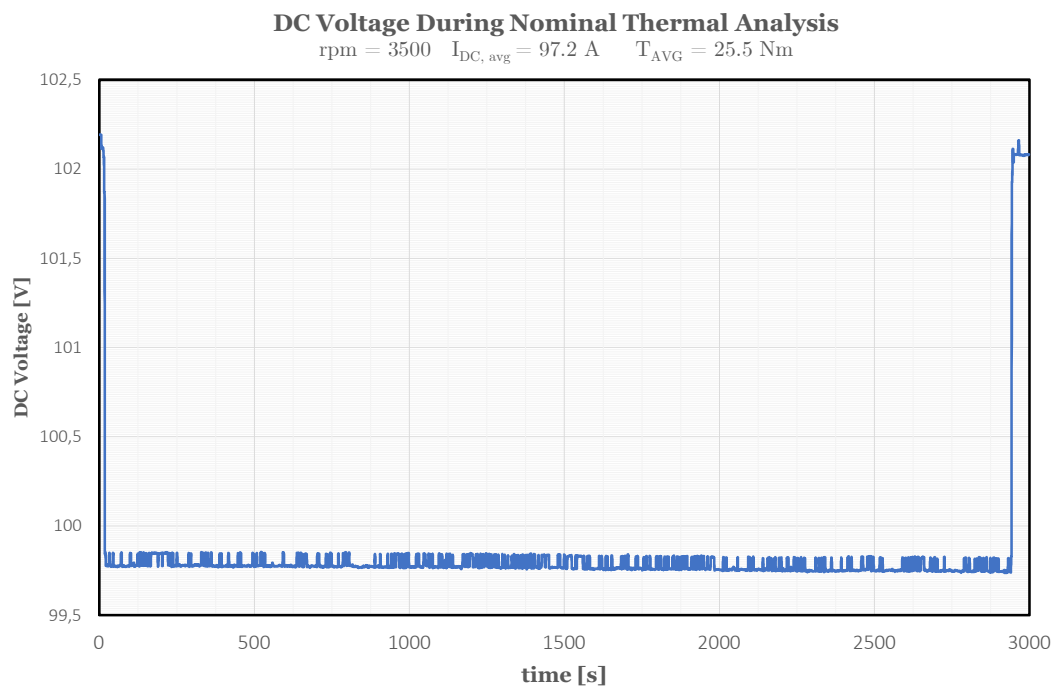
FIGURE 4.15 – DC Voltage Evolution: Failed Test

**Delta Temperature Evolution During Thermal Analysis:
Ventilation ON**

rpm = 3500 $I_{DC, avg}$ = 97.2 A T_{AVG} = 25.5 Nm T_0 = 24.8 °C

FIGURE 4.16 – Motor Temperature Evolution: Failed Test

4.4 Net Power Curve

Net Power Curve can be finally obtained once *Nominal Torque* is established.

To correctly characterize entire curve, it is advisable to acquire curve points, at a suitable RPM distance between them. A good trade – off between accuracy and test duration can be 500 RPM.

Goal in this curve characterization, is having a mechanical efficiency inaccuracy equal or lower to 1%. To accomplish that, Number of Measurements and Acquisition Frequency can be set to reduce inaccuracy interval related to direct measurements.
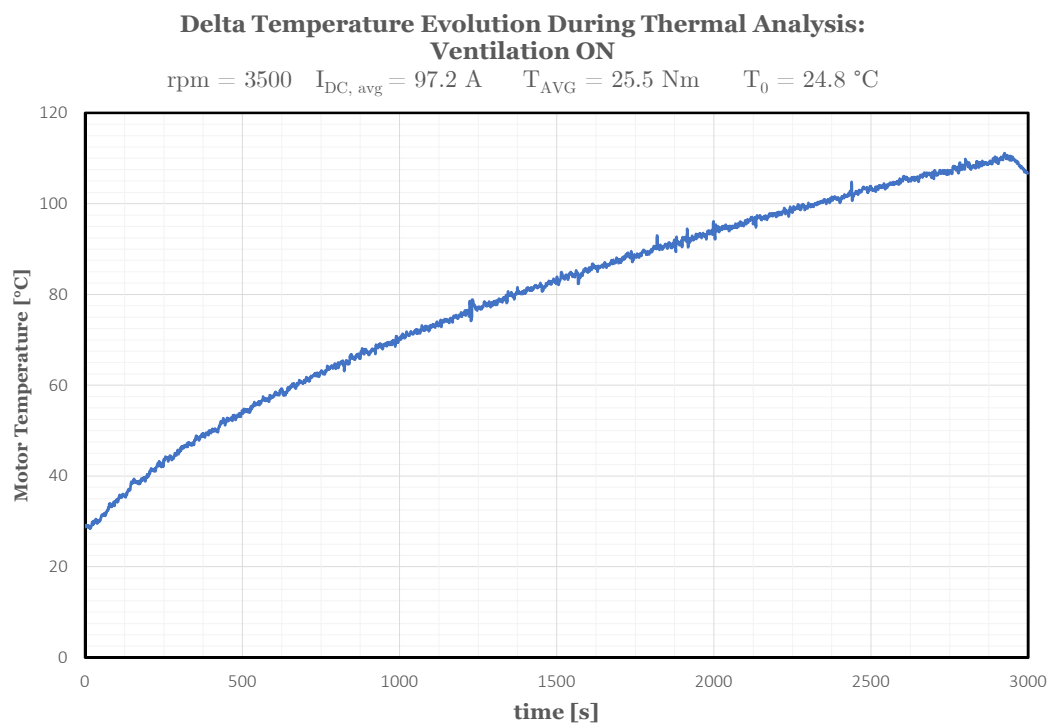
Therefore, before starting test, an accurate selection of these two parameters must be performed. Once their values are established, experimental test can start.

It is worth underline that, considering Test Bench Technical Specifications, reported in TABLE *3.13*, minimum RPM point is above 100 RPM.

Procedures to follow are explained below.

    I.   Set Number of Measurements and Acquisition Frequency in Dyno PC, as shown in FIGURE *3.6*;

    II.   Set Maximum Current Value related to *Nominal Torque*, evaluated through procedure explained in *Sec.4.3*, through Drive System Control Panel, shown in FIGURE *4.7*;

    III.   Set RPM through Dyno rotational lever, equal to the first point value to be analyzed;

    IV.   Enable Motor Rotation, using Drive Lever, as explained in *Sec. 4.1.D;*

    V.   Set Accelerator Potentiometer at percentage value related to *Nominal Torque.* It is advisable to set maximum current value to have requested Torque at an accelerator percentage value equal to 100%;

    VI.   Assess all measurements correctness;

    VII.   Start Acquisition;

    VIII.   Once Acquired point appears on Dyno PC, test can proceed by increasing RPM to the value corresponding to the second point to be characterized;

    IX.   Repeat from point VI.

Once complete test is performed, Post – Process file can be generated, by producing *Torque – Power Curve* plot and *Mechanical Efficiency Table*, as the ones shown in *FIGURE 3.13* and *TABLE 3.14*.

4.5 Drive Setup and Development

Drive Setup tests are performed to assess correct Motor performance, especially Flux Weakening. Other types of test can be focused on Torque Ripple or Acoustic analyses.
In this section, Flux Weakening Check procedures only are explained in detail, that are:

I. Set Number of Measurements and Acquisition Frequency in Dyno PC, as shown in *FIGURE 3.6*;

II. Set Maximum Current Value corresponding to Torque level on which Flux Weakening performance assessment is performed, through Drive System Control Panel, shown in FIGURE *4.7*;

III. Set Flux Weakening parameters in Drive System control panel, whose values depend on characteristics that are analyzed; after that, memorize edit performed;

IV. Set RPM through Dyno rotational lever, equal to the first point value to be analyzed; Two choices can be done in this case:

  a. To decrease test duration, first RPM point selected can be the one corresponding to base speed, to analyze Flux Weakening range only;

  b. If entire Torque – Power curve Flux Weakening performance assessment is performed, first RPM point selection corresponds to a suitable value, as the one discussed in *Sec 4.4.*

V. Enable Motor Rotation, using Drive Lever, as explained in *Sec. 3.6.D;*

VI. Set Accelerator Potentiometer at percentage value to 100 %;

VII. Assess all measurements correctness;

VIII. Start Acquisition;

IX. Once Acquired point appears on Dyno PC, test can proceed by increasing RPM to the value corresponding to the second point to be characterized;

X. Repeat from point VII.

Test can be considered completed once all points to characterize are correctly obtained and, to assess Flux Weakening function, they must be compared with Ideal Motor Torque – Power curves, as shown in FIGURE *3.15.*
As discussed in *Sec. 3.7.3*, Flux Weakening Check occurs in an '*overall system view'*, meaning that it is an input – output check, since Current and Voltages phases are not measured, because detailed instrumentation is needed to do that, and it is not present in the Test Bench.

To better understand all Flux Weakening Check phases, from beginning to actual development, different plots are reported in the following, including both types of RPM selection that can be performed, so that entire curve is characterized or Flux – Weakening range only.

In FIGURE 4.17 and FIGURE 4.18, wrong Flux Weakening behavior is apparent, simply comparing Nominal Torque and Power curves with ideal dotted ones. In this case, parameters are changed, and all curves are studied from base speed.

In FIGURE 4.19, a second Nominal Power Comparison is presented, and it is evident strong difference with the first one, only by comparing the gap between Actual and Ideal curves, proving an improvement in the development activities. In FIGURE 4.20 instead, a second Nominal Torque comparison is presented. All these figures are presented to show failure Flux Weakening Check experimental campaigns, needed to improve Drive System.

Finally, entire curves characterization is presented in FIGURE 4.21, by comparing Nominal Torque – Power Curve with ideal dotted ones, that represent latest and best result obtained in the Flux Weakening Check activities.
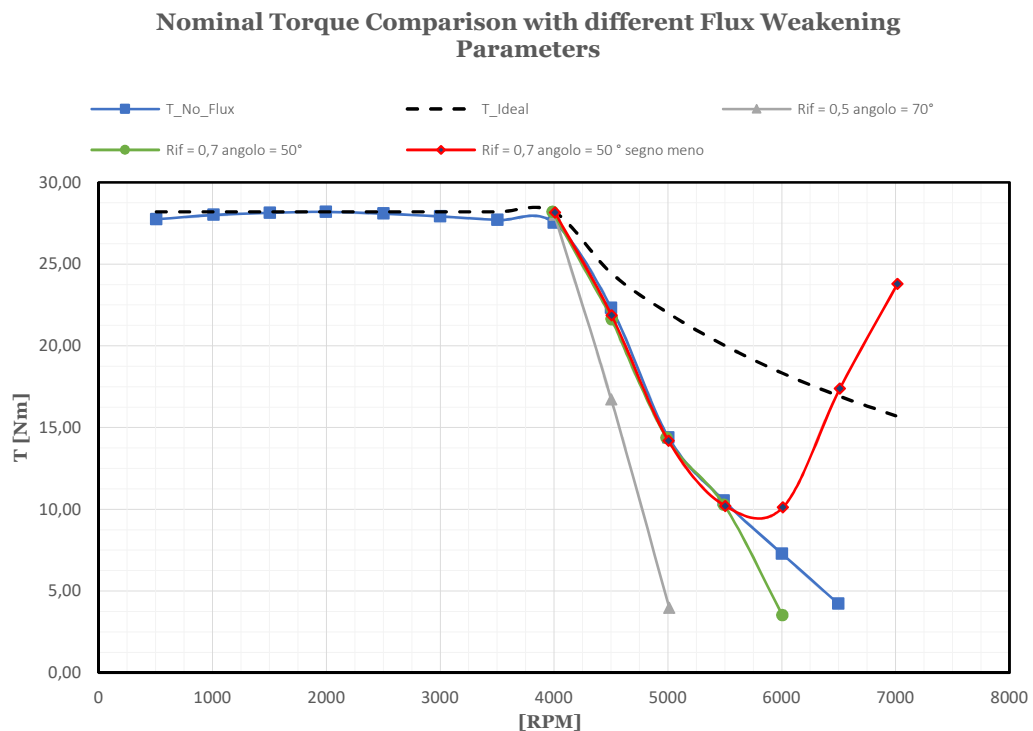
FIGURE 4.17 – Nominal Torque Flux Weakening Comparison #1

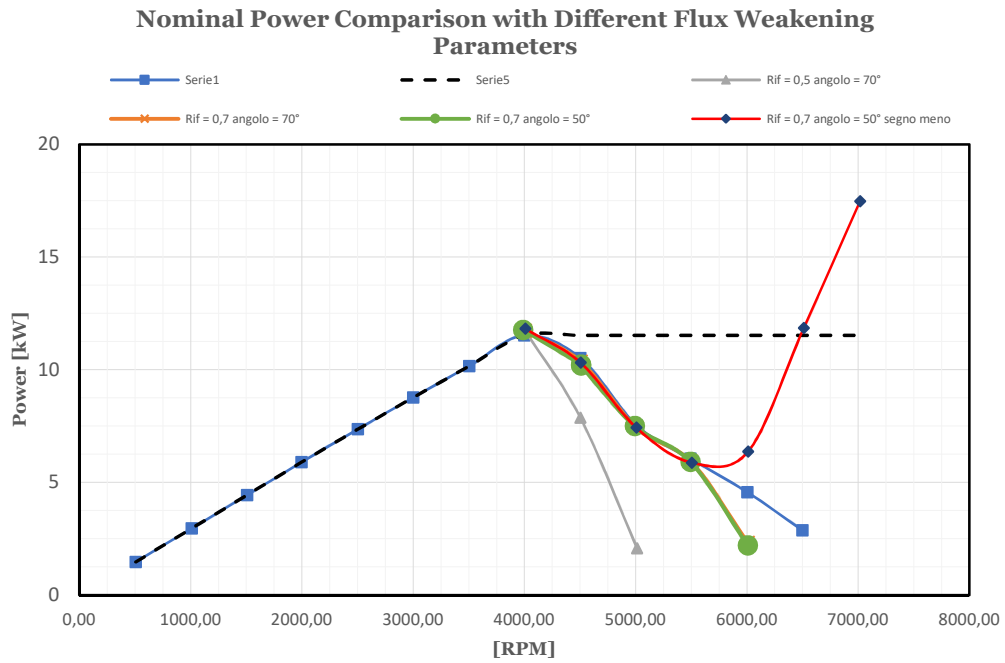FIGURE 4.18 – Nominal Power Flux Weakening Comparison #1
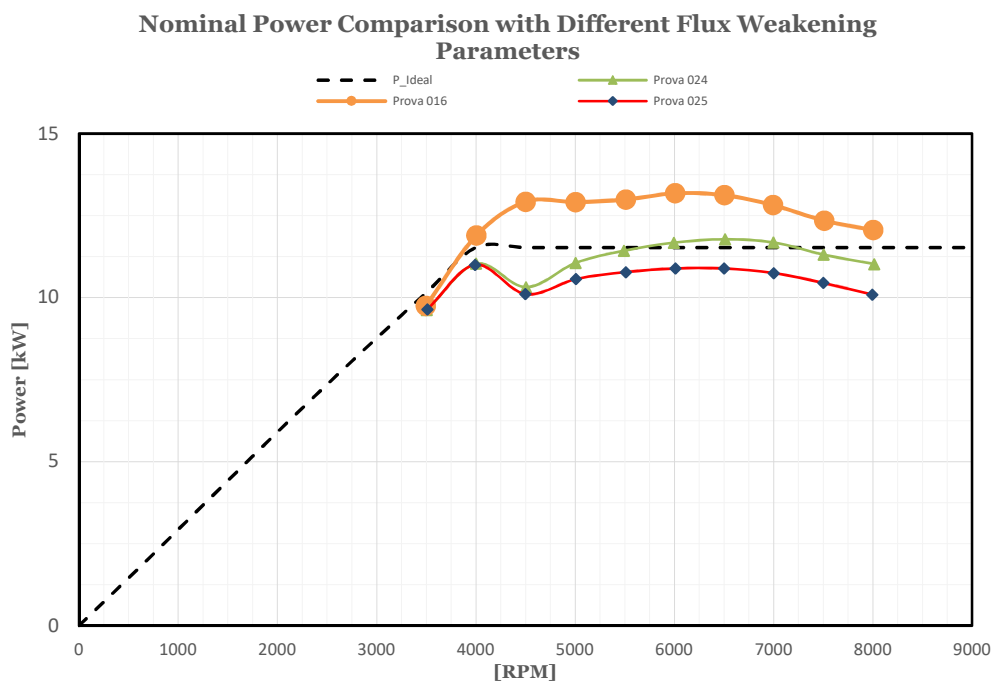
FIGURE 4.19 – Nominal Power Flux Weakening Comparison #2
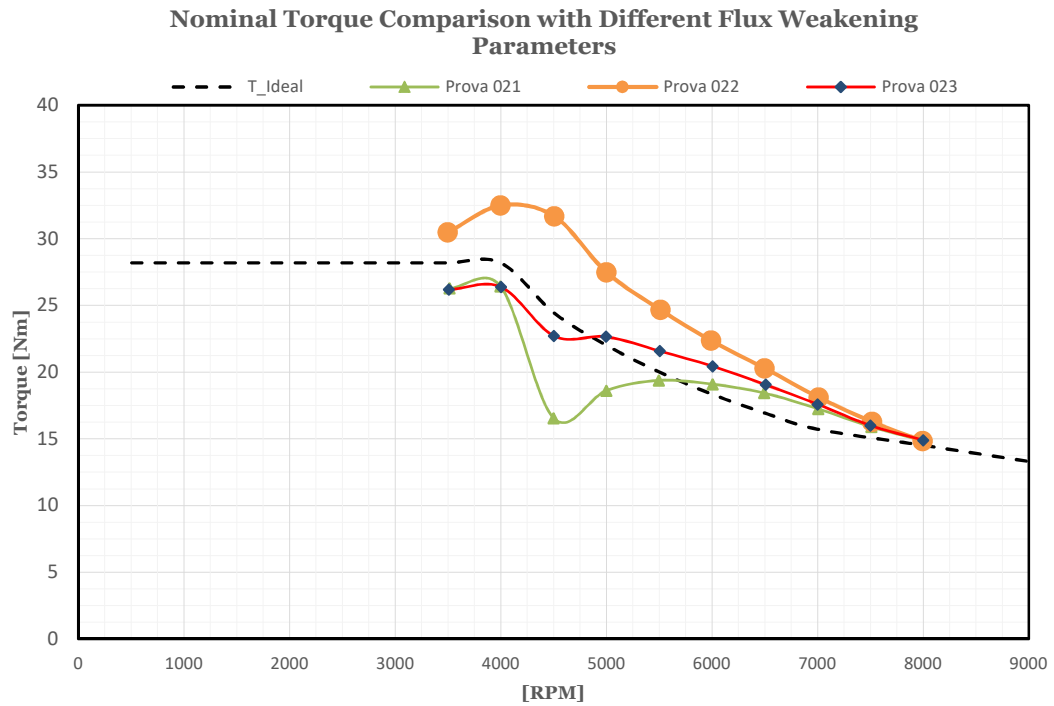
Nominal Torque Comparison with Different Flux Weakening Parameters

FIGURE 4.20 – Nominal Torque Flux Weakening Comparison #2

Nominal Torque - Power Curve Flux Weakening Comparison with Efficiency
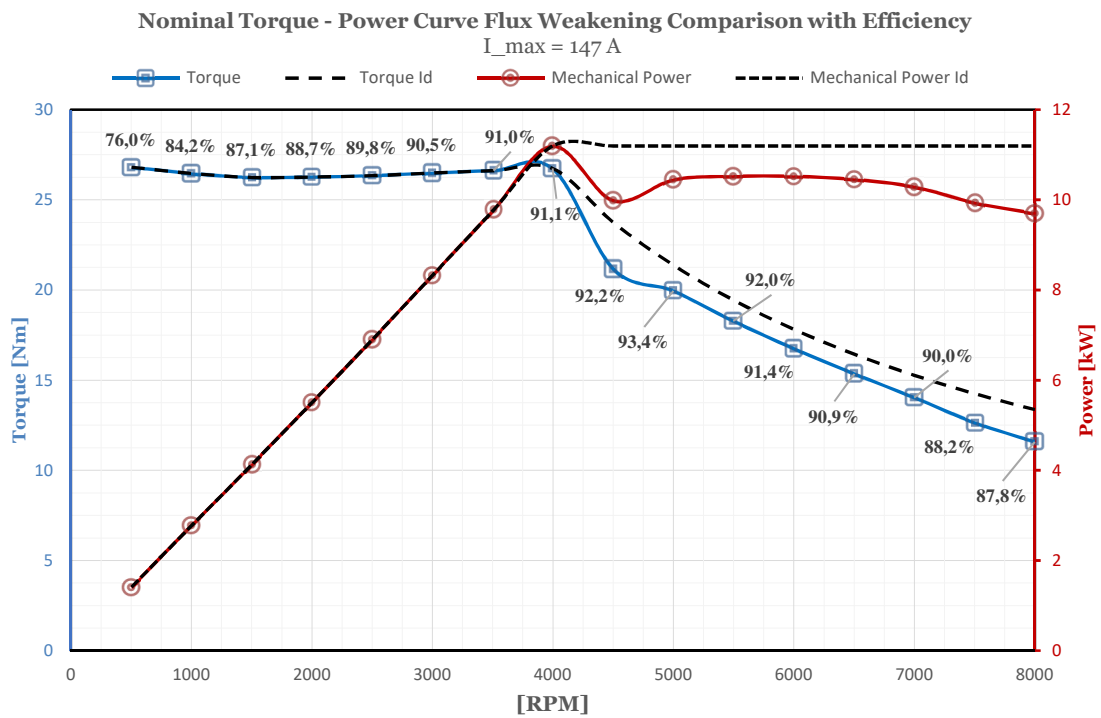I_max = 147 A

FIGURE 4.21 – Nominal Torque – Power Curve Flux Weakening Comparison

4.6 Shut − Down

In this Section, all procedures to follow when Test Bench experimental test is over, and activities are interrupted.

Most important constrained, as explained in Power Supply System Manual, in case it is active, is avoiding Regenerative Braking, since it could lead to Over Current damages of Power Supply System, causing an increase of DC Voltage on Inverter side and lead to its permanent damage.

Therefore, it is strongly advisable to follow procedure explained below, to avoid any kind of damage.

    I.   Set Accelerator Potentiometer to 0%;

    II.   Disable Electric Motor Rotation acting on Drive Lever;

    III.   Set RPM to its minimum value, to rapidly brake Electric Motor;

    IV.   Check if all direct measurements values reach 0 value, a part of DC Voltage;

At this point, it is possible to disable Supply Systems, as explained below:

    I.   Disable Power Supply System Output through Switch shown in FIGURE *2.9;*

    II.   Disable Battery Output, in case it is connected;

    III.   Turn − OFF Drive System, using ON − OFF switch shown in FIGURE *4.6;*

    IV.   Turn − OFF Drive System Power Supply;

    V.   Turn − OFF Power Supply System through Front − positioned general Switch, as shown in FIGURE *2.3;*

    VI.   Turn − OFF all sensors;

    VII. Turn − OFF Drive System PC, Acquisition System PC and Dyno PC.

4.7 Emergency

In this Section, procedures to follow in an Emergency situation are explained.

Emergency can arise due to different causes, malfunctioning or mechanical damage. Its first goal is to limit damage of any type of Test Bench components, thus avoiding problem to working personal.

Emergency causes can be:

- Electric Motor – Dyno Connection mechanical damage;
- Rotation shaft bearings mechanical damage;
- Electric Motor Temperature reaches maximum values;
- Power Supply System short circuit.

Emergency causes can be mechanical or electrical type.

In all emergency situations, first procedure to follow is the shut – down one, explained in *4.6.*

Instead, in exceptional dangerous situations, procedure to follow is explained below:

- Brake Motor till minimum rotational speed allowed by Dyno;
- Disable Motor rotation, through Drive System, as explained in *Sec. 4.1.C;*
- Once motor is stopped, disable all Power Supply System;
- Check instrumentations condition, to understand if any damage occurred;
- Understand cause of malfunction.

Chapter 5

5 Air Cooled Motor Results

In this Chapter, experimental results related to Air Cooled Motor are reported, including:

- Thermal Analyses;
- UNECE Regulation No.85 Results;
- Flux Weakening Results;

Moreover, before presenting results, a briefly Motor description is reported, including technical manufacturer declared data.

5.1 Motor Overview

Motor used during test is a SITEM IPM Brushless Motor. A front – section view is reported in FIGURE *5.1*, including both rotor and stator. It is possible to notice Permanent Magnets inside rotor.
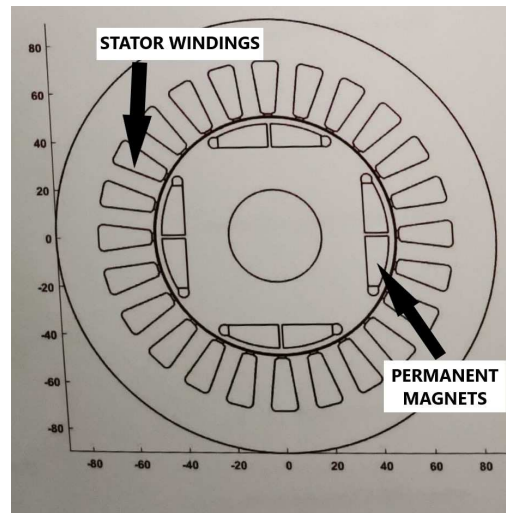
FIGURE 5.1 – SITEM IPM Section

In fact, IPM stands for Interior Permanent Magnet and it is an AC Motor that uses magnets embedded into Rotor's surface.

Magnets are used to generate a constant motor flux, instead of requiring the stator field to generate one by linking to the rotor, as in the case of induction motor. Its key characteristics are reported in *Tab. 5.1.*

Key IPM Motor Characteristics	
Interior Permanent Magnet Motor	Magnet are buried inside rotor
	More robust than SPM
	Good for high speed
	Reluctance and Magnetic Torque

TABLE 5.1 – IPM Key Characteristics

SITEM IPM Technical Data are reported in *Tab. 5.2.*

SITEM IPM Brushless Motor	
Quantity	**Value**
DC Voltage Supply [V]	96
Inverter Nominal Current [Arms]	150
Inverter Maximum Current [Arms]	300
Phase Constant [Vrms/rpm]	11.6
Weight [kg]	31

TABLE 5.2 – SITEM Technical Data

SITEM most important simulation results, regarding Motor performance, are reported in *Tab. 5.3.*

Quantity	Values		
Current Density [Arms/mm²]	4.5	5.5	11
RPM	4000	4000	3400
Torque [Nm]	23.1	28.4	55
Pmcn [kW]	9.7	11.9	19.4
AC Current [Arms]	121	147	300

TABLE 5.3 – SITEM IPM Simulation Results

In the following Sections, most important SITEM IPM Motor results are presented.

5.2 Motor Thermal Model

Electric Power that is dissipated in cables, due to Joule effect is converted into heat, giving rise to a Temperature increase. Temperature value should be kept below a maximum value T_{MAX}, to avoid windings damages thus reducing performance and components' lifetime.

Therefore, Thermal Model is needed to assess and describe concepts concerning heat propagation occurring inside Motor; it is worth underline that, the below described model, is based on strong simplifications and it has not the purpose to represent with fidelity the actual thermal behavior.

As previously shown in FIGURE *3.2*, power lost between the battery or power supply system and the motor shaft is caused by many factors. Losses in the inverter are mainly due to dissipation in the power modules, while in the motor they are divided in copper, iron and windage losses [8, pp. 28 - 30].

Stator windings insulation is the motor part most sensitive to thermal overheating. Exceeding the thermal limit of the insulation will result in acceleration of the oxidation process that will decrease the insulation life or even cause motor failure.

Copper Losses ($P_{loss,cu}$) are expressed in following equation:

$$P_{loss,cu}(\Theta_m) = R_w\,(\Theta_m)\,I^2 t \qquad (5.1)$$

Where:

- Θ_m is motor temperature;
- R_w is the total Ohmic Resistance of the windings, that is function of motor temperature;
- I^2 is rms current flowing in motor windings.

Thermal model presented below, is based on following assumptions:

- Copper Losses only, caused by Joule effect, are converted into heat;
- Heat transfer from windings to ambient takes into account only their temperatures, without considering other motor parts, like motor case.

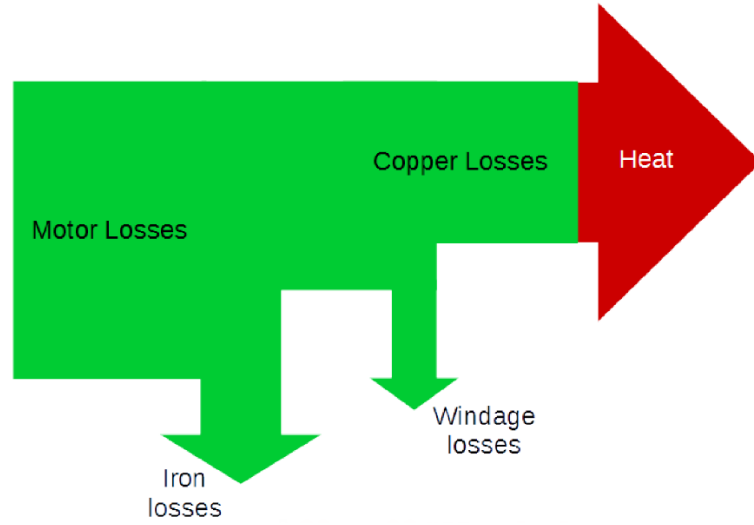In FIGURE *5.2*, heat power generation flow is presented.

FIGURE 5.2 – Power Loss Conversion to Heat Power Flow *[8]*

Heat propagation, on the basis of the second principle of Thermodynamics, occurs from one body at temperature Θ to the external environment at temperature Θ_A, provided that $\Theta > \Theta_A$.

Assuming, for sake of simplicity, a linear heat propagation model, the Thermal Power P_T, i.e. *heat flow (J/s)* corresponding to the electrical dissipated power, flows from the body at temperature Θ to the external environment at temperature $\Theta_A < \Theta$. It can be expressed with the *Fourier heat propagation law as:*

$$P = G_{ma}\left(\Theta_m - \Theta_A\right) = \frac{\Delta\Theta}{R_{ma}} \tag{5.2}$$

Where:

- G_{ma} is the Thermal Conductivity from the windings to the external environment. It is a global coefficient that incorporates thermal conductivity from windings to motor case and from case to external air;

- R_{ma} is defined as Thermal Resistance between windings and air.

As far as a body does not dissipate any thermal power, it tends to reach the thermal equilibrium with the surrounding environment, i.e. its temperature equals the ambient one thus $\Delta\Theta = 0$.

As soon as some thermal power is generated inside the motor windings, due to Joule effect, it cannot be immediately delivered to the external environment because the temperature

difference between the windings and the environment is initially zero and the heat cannot flow from two bodies at same temperature.
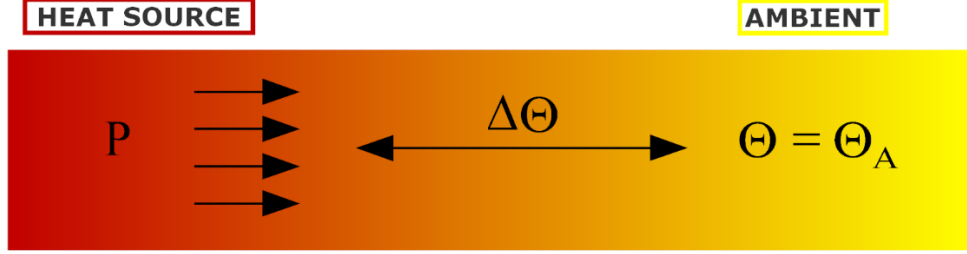
FIGURE 5.3 – Heat Flow Between Two Bodies

Thermal energy not delivered to the external environment, indicated in the following as Q, remains within the windings, and its temperature, assumed to be uniform inside windings, increases with respect to the ambient one proportionally to the amount of accumulated heat Q_m, i.e.

$$\Delta\Theta_m = (\Theta_m - \Theta_A) = \frac{Q_m}{C_m} \tag{5.3}$$

Where C_{TH} is the *thermal capacitance.*

Taking time derivative of (5.3), one gets:

$$\frac{d\Delta\Theta_m}{dt} = \frac{1}{C_m}\frac{dQ_m}{dt} \tag{5.4}$$

Where the l.h.s is the rate of change of the temperature difference between motor and external environment, while the heat flow accumulated in the body, i.e. the difference between generated power P_{th} and the one delivered to the environment P_A, appears in the r.h.s. of the equation, that is:

$$\frac{dQ_m}{dt} = P_{th} - P_A = P_{th} - G_{TH}\Delta\Theta_m \tag{5.5}$$

Where the relation (5.2) between temperature difference and the amount of heat delivered to the environment has been considered.

Replacing *Eq.* (5.4) in *Eq.* (5.3), one gets

$$\frac{d\Delta\Theta_m}{dt} = \frac{P_{th}}{C_m} - \frac{\Delta\Theta_m}{R_{ma}C_m} \tag{5.6}$$

It can be observed that this last equation is formally analogous to the one that describes the evolution of the voltage across the capacitor in the circuit of FIGURE 5.4.

In particular, it can be noticed that an analogy between temperature and voltage, between dissipated power and current, between thermal and electrical resistance and between thermal and electrical capacitance can be established [7] [8, pp. 30 - 32].

By solving *Eq.* (5.6), assuming P_{th} is constant over time and considering the initial condition as thermal equilibrium at $t = 0$, i.e. $\Delta\Theta_m = 0$, one gets:

$$\Delta\Theta_m(t) = P_{th}R_{ma}\left(1 - e^{-\frac{t}{\tau_{th}}}\right) \tag{5.7}$$

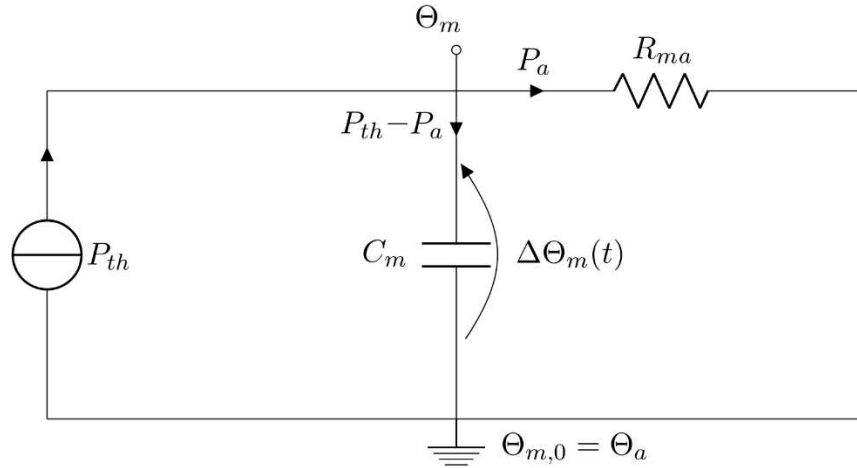Where $\tau_{th} = R_{ma}C_m$ is the *thermal time constant* of the system.

FIGURE 5.4 – Thermal Equivalent Circuit Of a Motor Dissipating a Thermal Power With Air *[7]*

The evolution over time of the temperature difference between the windings and the external environment in reported in FIGURE 5.5.
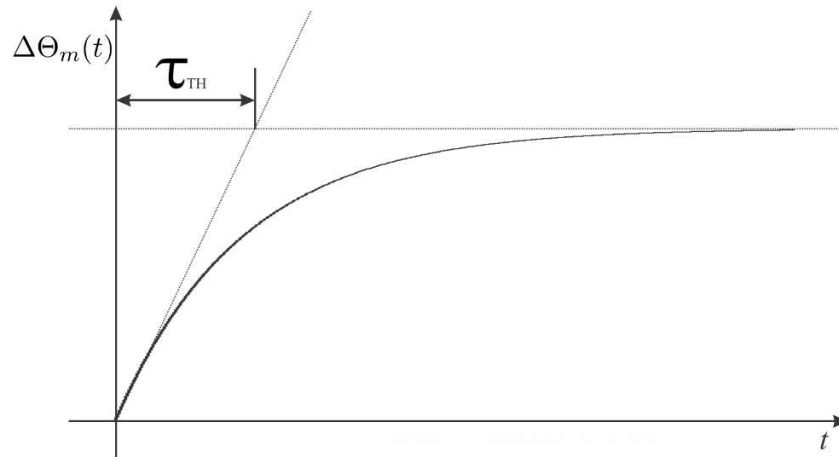
FIGURE 5.5 – Time Evolution Of Motor – Ambient Temperature Difference

5.3 Thermal Analyses Results

In this section, Air Cooled Motor thermal analyses results are presented. They include:

1. *Nominal Torque* definition, i.e. test aimed at finding set of working conditions that ensure thermal equilibrium between Ambient and Motor, explained in *Sec. 5.2;*

2. *Thermal Time Constant* evaluation, to compute Motor time response in different Torque levels, or between them.

While results of point 1 are presented as a homologation one, the latter are studied to characterize Motor dynamic parameters.

5.3.1 Nominal Torque Definition

As it has been shown in *Sec. 3.2*, Nominal Torque is defined as the set of operating conditions at which the thermal stability of the motor winding is reached for an indefinite time (*Steady – State or Continuous Operating Condition*) and it depends on Cooling System only.
Temperature at which equilibrium is reached is then defined as *Maximum Temperature.*
Therefore, *Nominal Torque* definition goal is defining Torque level that ensure thermal equilibrium between Motor and Ambient at *Maximum Temperature.*
Manufacturer windings maximum temperature is specified at 155 °C. To be conservative, a target value for maximum temperature is defined at 90 °C, thus the goal is finding Torque Level ensuring thermal equilibrium at this defined temperature.
It is worth underline that, to have acceptable results in this analysis, two conditions must be verified at the test start:

a. Motor and Ambient in thermal equilibrium, i.e. at test start Motor and Ambient temperatures are equal;
b. Ambient Temperature kept constant during test, to accurately replicate Thermal Model considerations done in *Sec. 5.2.*

In FIGURE *5.6* Test Bench Layout during test is reported; in FIGURE *5.7 Nominal Torque* steady – state thermal equilibrium results are shown, while in TABLE *5.4*, numerical results are summarized.
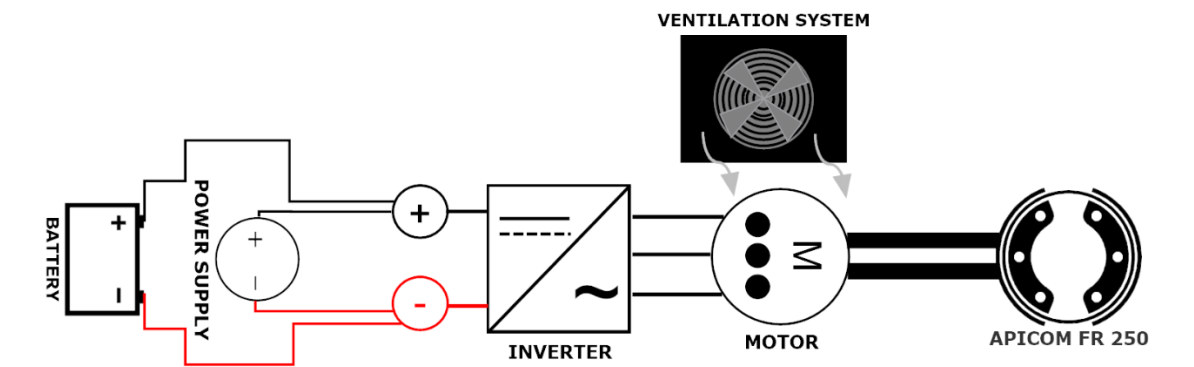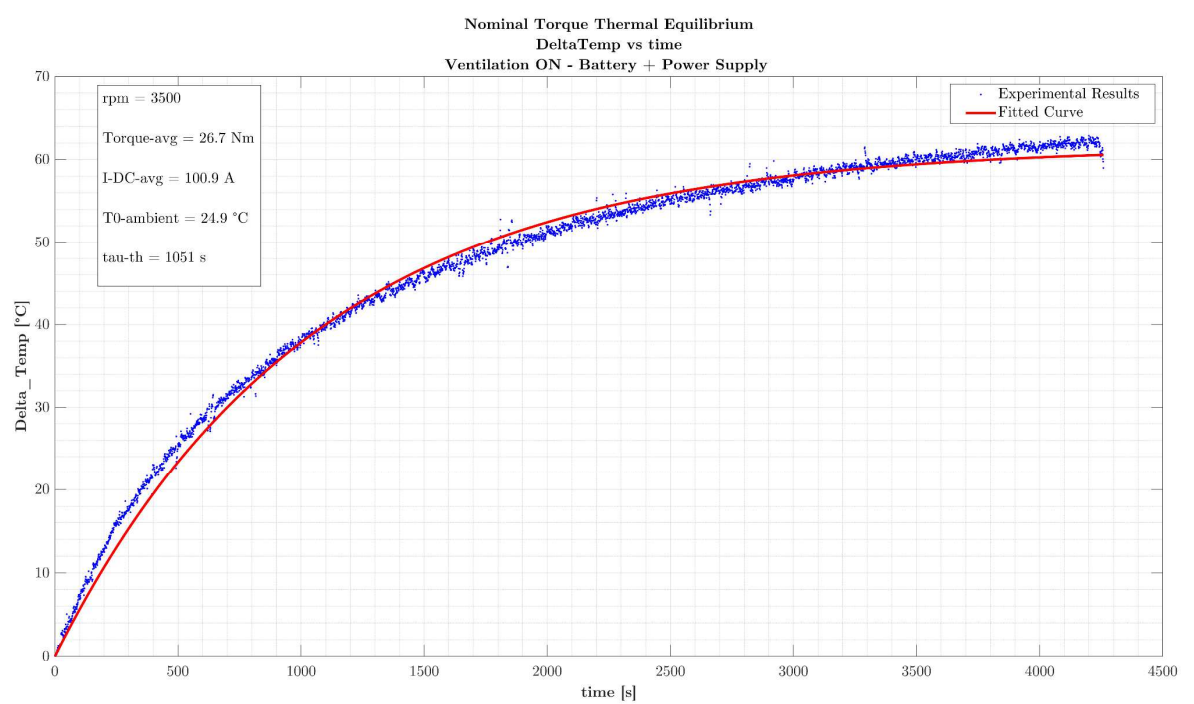

FIGURE 5.6 – Nominal Torque Definition Test Bench Layout

FIGURE 5.7 – Nominal Torque Steady – State Thermal Equilibrium

Results	Value
Average Torque [Nm]	26.7
RPM	3500
Average DC Current [A]	100.9
Average DC Voltage [V]	99.90
Ambient Temperature [°C]	24.9
Thermal Time Constant [s]	1051

TABLE 5.4 – Nominal Torque Curve Experimental Results

Fitted curve equation in *Fig. 5.6,* through which time constant is evaluated, comes from *'Matlab Curve Fitting Tool',* that uses *'least square methods'* to obtain best fitted curve for given experimental data.

In this case, since equation to fit the data is a – priori known, i.e. Eqn. 5.7, it is used in the Tool to obtain the unknowns parameters that best fits the experimental results.

Eqn. 5.8 shows '*Curve Fitting Tool'* results, with the two parameters value.

Instead, TABLE *5.5* , numerical information about fitted curve are reported.

$$\Delta\Theta_m(t) = 61.64\left(1 - e^{-\frac{t}{1051}}\right) \tag{5.8}$$

Results	Value
Coefficients Confidence Bounds	95 %
R – square	0.9933

TABLE 5.5 – Nominal Fitted Curve Data

5.3.2 Thermal Time Constant Evaluation

In this section, *Thermal Time Constant* is evaluated simulating the dynamic behavior that Motor experiences in a real vehicle. This means that, all three Torque levels are considered in this analysis. To this purpose, it is worth recall them:

a. *Base Torque*: it is Torque level that ensures overcurrent use in Motor Control Strategy, avoiding saturation at *Rated Torque* only;

b. *Rated or Nominal Torque*: it is Torque level that ensures Thermal Equilibrium between Motor and Environment, at a suitable Temperature, defined as the maximum one; it depends on Cooling System type only.

c. *Maximum Torque*: it is maximum Torque level reached, that depends on Motor electrical characteristics only.

At first two levels, temperature values, at which thermal equilibrium is reached, are associated, reported in TABLE *5.6*.

Torque Level	Thermal Equilibrium Temperature
Base	50 °C
Nominal	90 °C

TABLE 5.6 – Thermal Equilibrium Temperature vs Torque Level

Therefore, referring to Table., it is convenient to refer to Thermal Equilibrium Temperature reached with Base Torque level as *Base Temperature.*

As a first approach, it is useful evaluate and quantify Torque level that ensures a thermal equilibrium at *Base Temperature,* i.e. quantify Base Torque.

Test Bench Layout during this test is equal to the one reported in FIGURE *5.6*.

In FIGURE *5.8*, Base Torque Thermal Equilibrium is reported and in Eqn. 5.9, Delta Temperature equation versus time is shown.

Also in this case, *'Matlab Curve Fitting Tool'* is used to obtain Eqn. 5.9, whose parameters are reported in
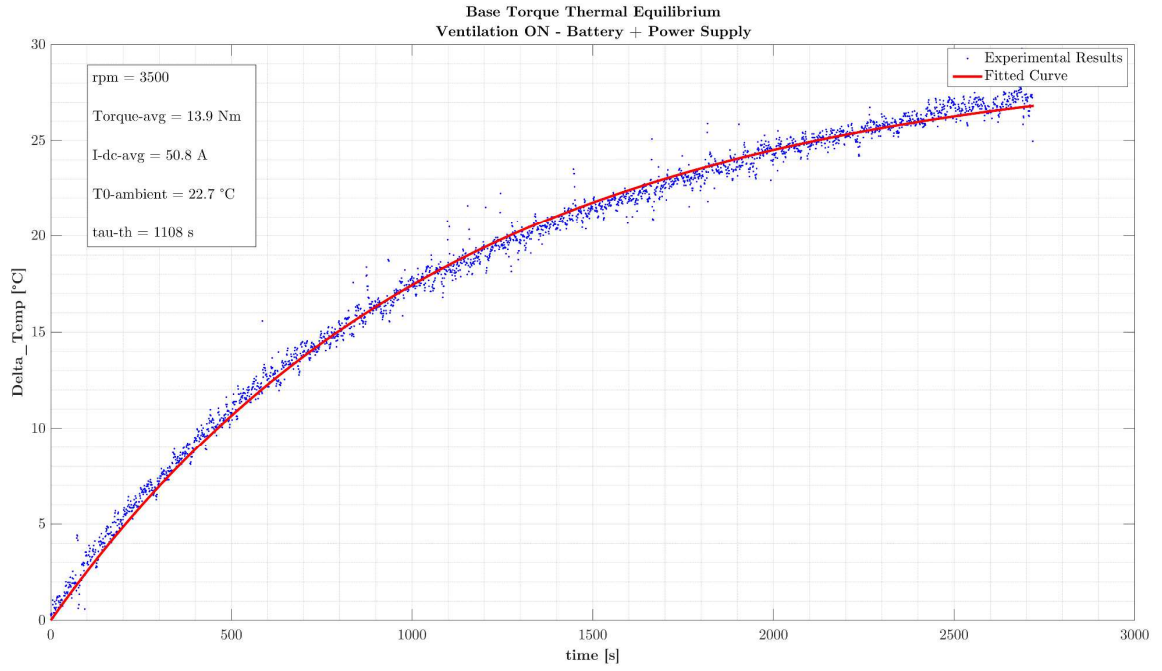
FIGURE 5.8 – Base Torque Steady – State Thermal Equilibrium

Results	Value
Average Torque [Nm]	13.9
RPM	3500
Average DC Current [A]	50.8
Average DC Voltage [V]	108.30
Ambient Temperature [°C]	22.7
Thermal Time Constant [s]	1108

TABLE 5.7 – Base Torque Curve Experimental Results

$$\Delta\Theta_m(t) = 29.33\left(1 - e^{-\frac{t}{1108}}\right) \tag{5.9}$$

Results	Value
Coefficients Confidence Bounds	95%
R – square	0.9964

TABLE 5.8 – Base Fitted Curve Data

Once Base Torque level is defined, it is possible to evaluate thermal time constants between the three levels, to understand thermal time response of the Motor in a real − vehicle case, e.g. when maximum acceleration is requested from low vehicle speed.

Therefore, three cases are analyzed:

a. Motor at maximum Temperature in free cooling evolution;

b. Motor in cooling evolution from maximum Temperature with Base Torque, to understand thermal time response in case in which low torque is requested after a strong acceleration, thus assessing how much time wait until another acceleration can be requested;

c. Motor with Maximum Torque request using Battery only, starting from Base Temperature, i.e. low load request, to assess thermal time response after a strong acceleration request that could cause a rapid increase of Temperature up to the maximum one.

In all three cases presented above, thermal time constant is computed graphically, recreating plot presented in FIGURE *5.5*.
Steps for the evaluations include:

a. Experimental Results Curve Fitting implementation, obtaining exponential equation best suiting data;

b. Tangent Line construction in experimental data origin;

c. Thermal Time Constant obtained through intersection between tangent line and horizontal asymptote.

In the following, three cases presented above results are shown.

Case a: Motor Cooling in free evolution

Test Bench layout in this test is the one reported in FIGURE 5.6.

In FIGURE 5.9, Free Evolution Cooling Experimental Data with Fitted Curve are reported, while in FIGURE 5.10 Thermal Time Constant is graphically obtained.
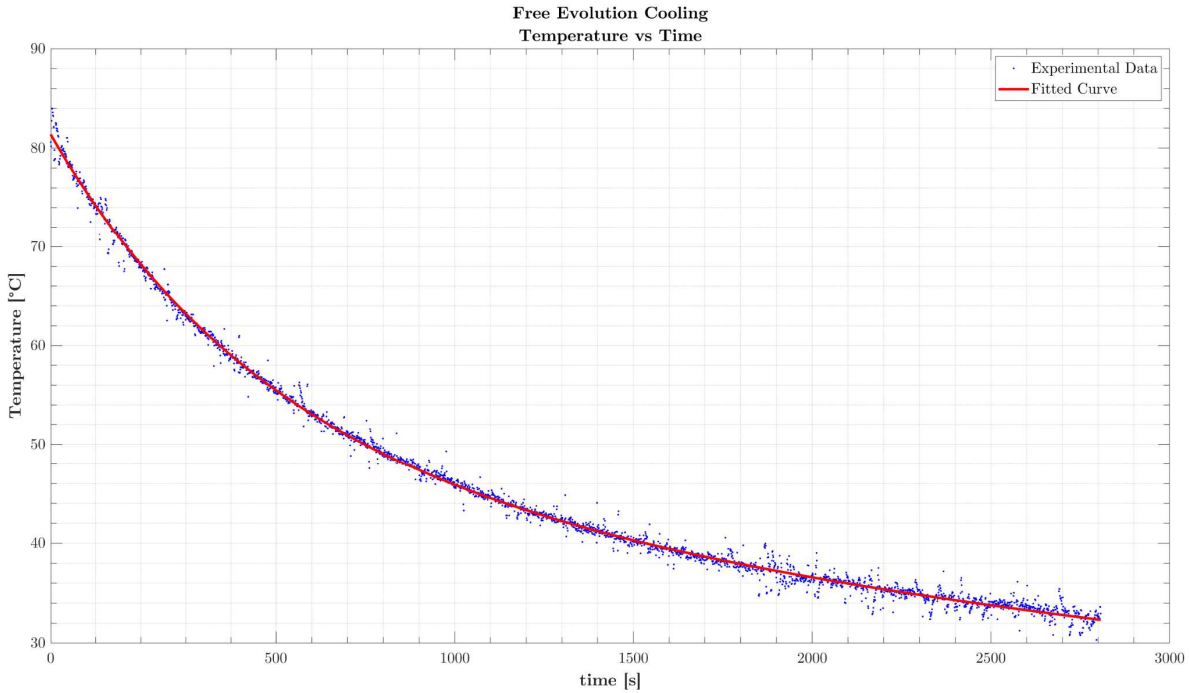

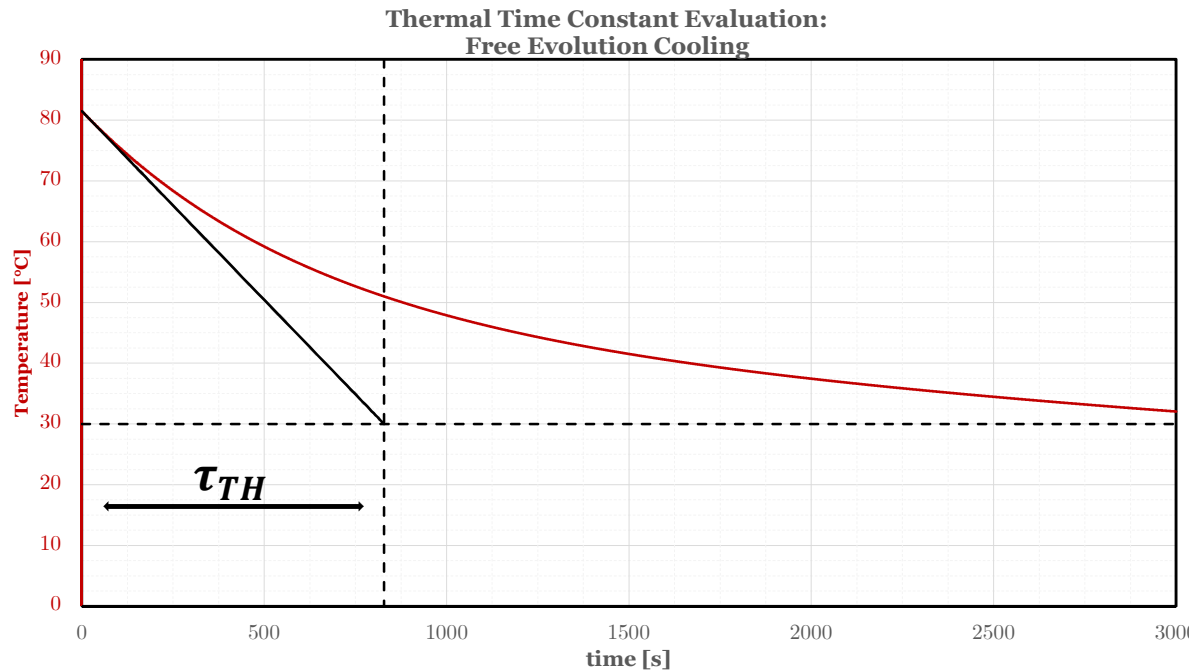FIGURE 5.9 – Free Evolution Cooling Temperature vs Time

FIGURE 5.10 – Free Evolution Cooling Thermal Time Constant

In TABLE *5.10*, Free Evolution Cooling Results are shown.

Results	Value
Average Torque [Nm]	-
RPM	-
Average DC Current [A]	-
Ambient Temperature [°C]	25.12
Thermal Time Constant [s]	827.26

TABLE 5.9 – Free Evolution Cooling Results

Case b: Cooling Evolution from Maximum Temperature with Base Torque

Test Bench layout in this test is the one reported in FIGURE *5.6*.

In FIGURE *5.11*, Free Evolution Cooling Experimental Data with Fitted Curve are reported, while in FIGURE *5.12* Thermal Time Constant is graphically obtained.
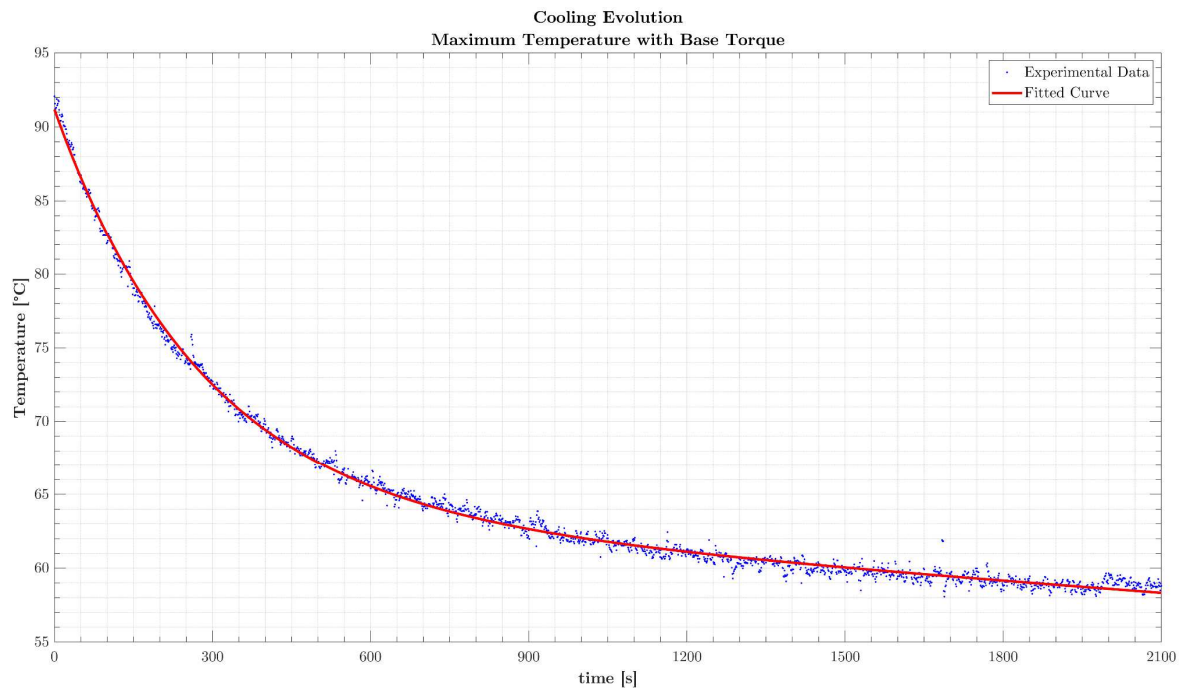

FIGURE 5.11 – Maximum Temperature with Base Torque Cooling Temperature vs Time
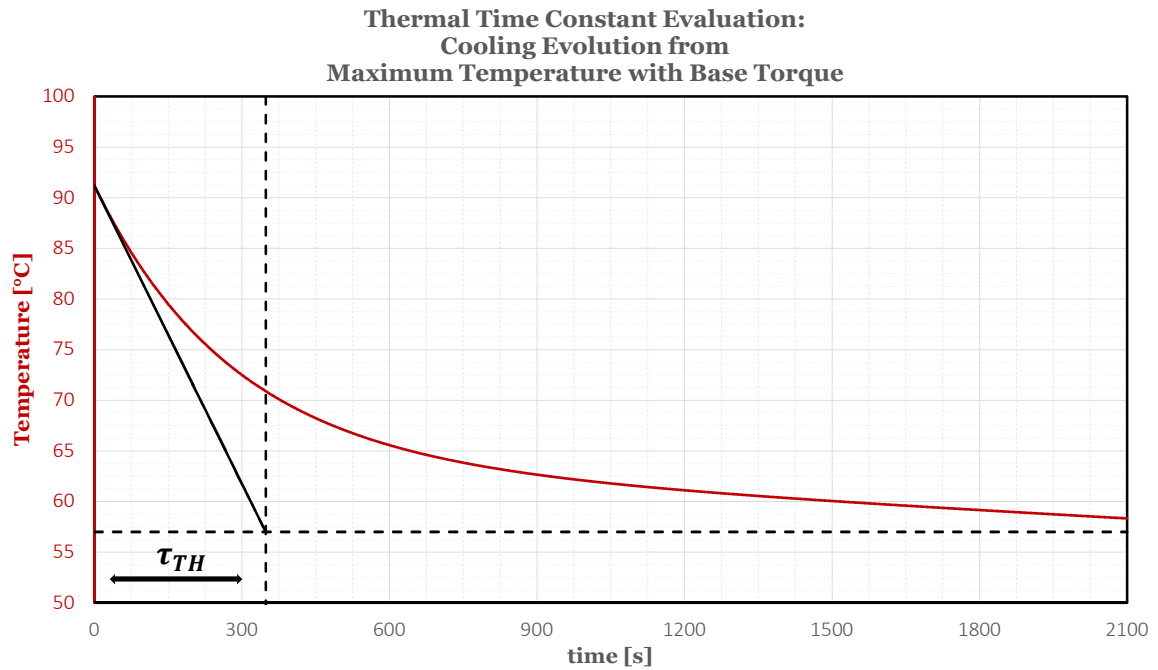
FIGURE 5.12 – Maximum Temperature with Base Torque Cooling Thermal Time Constant

In TABLE *5.10* Maximum Temperature with Base Torque Cooling results are shown.

Results	Value
Average Torque [Nm]	13.63
RPM	3500
Average DC Current [A]	49.31
Average DC Voltage [V]	107.57
Ambient Temperature [°C]	24.20
Thermal Time Constant [s]	348.25

TABLE 5.10 – Maximum Temperature with Base Torque Cooling Results

Case c: Evolution from Base to Maximum Temperature with Maximum Torque – Battery Only

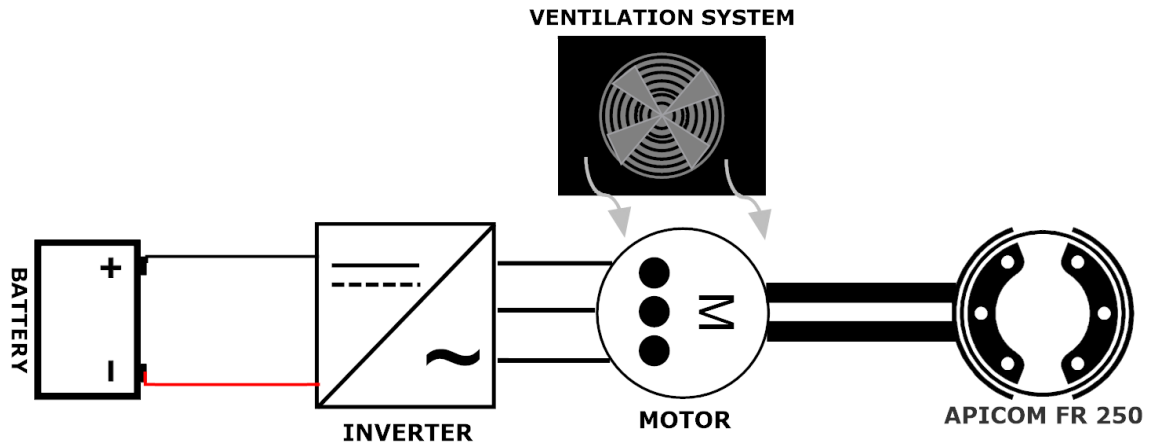Test Bench Layout used in this test is represented FIGURE *5.13*.

FIGURE 5.13 – Battery Only Test Bench Layout

In FIGURE *5.14* Base to Maximum Temperature evolution, with Battery only and Maximum Torque Requested, is shown. In FIGURE *5.15*, Thermal Time Constant is evaluated.
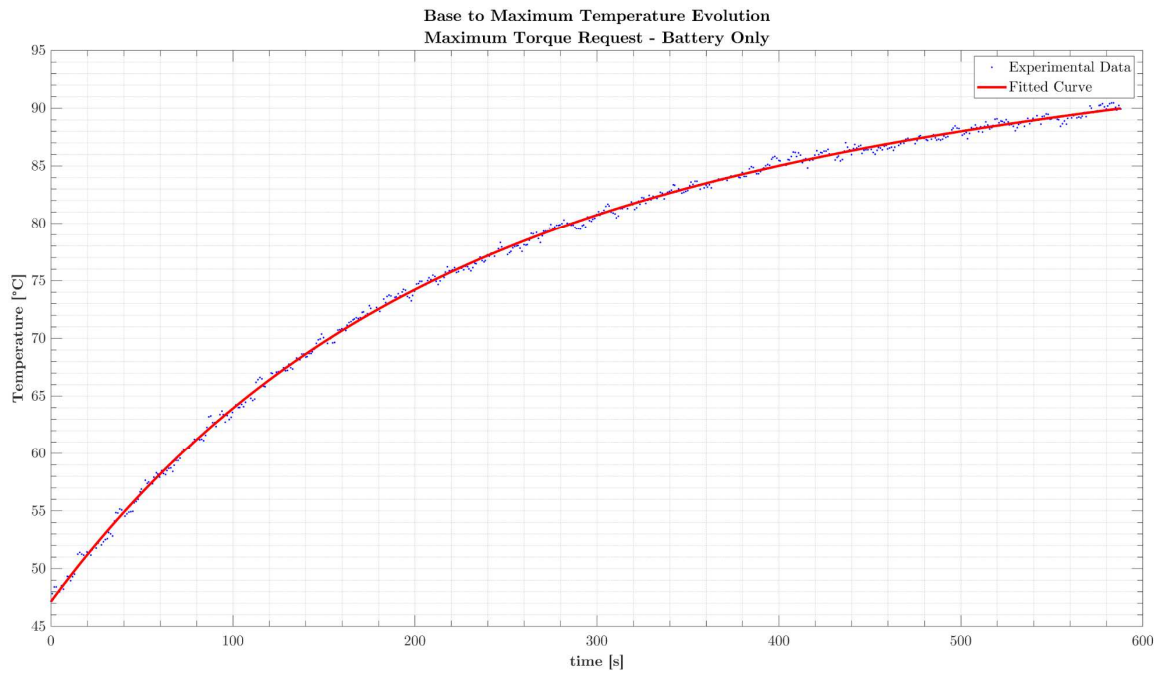

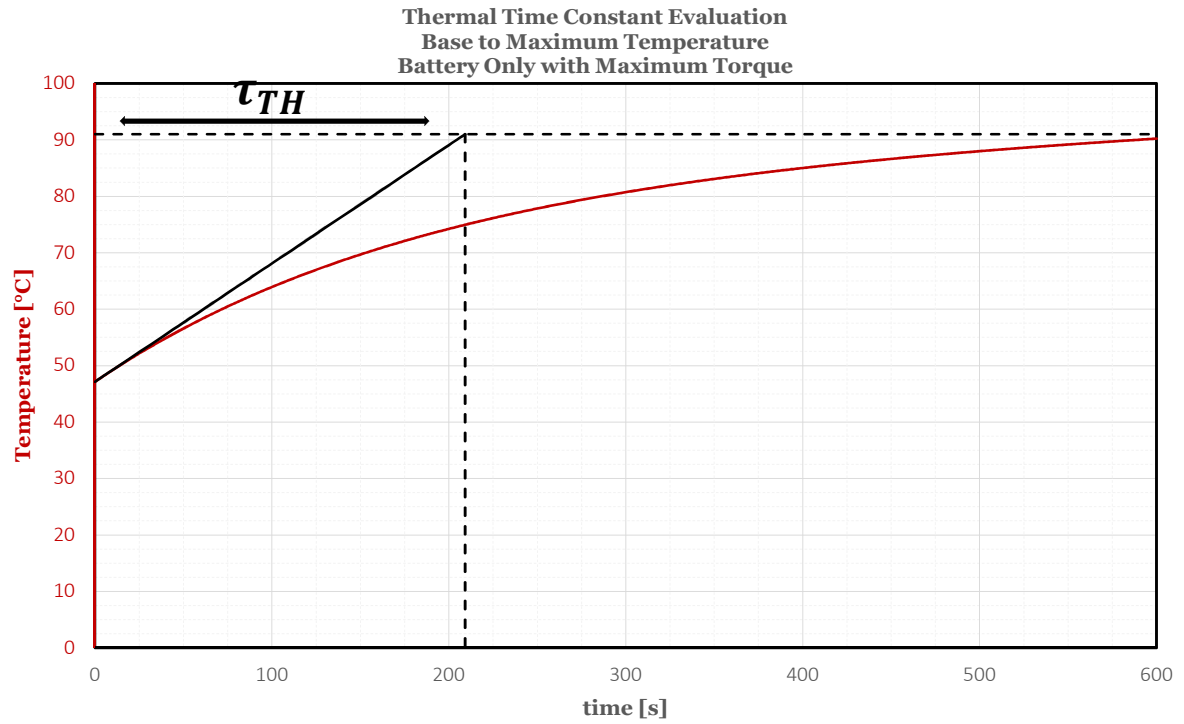FIGURE 5.14 – Base to Maximum Temperature Battery Only Evolution

FIGURE 5.15 – Base to Maximum Temperature Battery Only Thermal Time Constant

In TABLE *5.11* Base to Maximum Temperature Battery Only results are presented; due to battery intrinsic behavior, DC Voltage and DC Current are decreased during test, thus it is not correct reporting average values. Therefore, quantities intervals are reported.

Results	Value
Torque Interval [Nm]	32.76 – 46.10
RPM	3500
DC Current Interval [A]	148.01 – 195.74
DC Voltage Interval [V]	91.40 – 98.17
Ambient Temperature [°C]	24.65
Thermal Time Constant [s]	209.18

TABLE 5.11 – Base to Maximum Temperature Battery Only Results

In TABLE *5.12*, Thermal Time Constants evaluation summary is reported.

Thermal Time Constant Results Summary

Test	Value [s]
Base Torque Steady State Thermal Equilibrium	1108
Nominal Torque Steady State Thermal Equilibrium	1051
Free Evolution Cooling from Maximum Temperature	827.26
Cooling Evolution from Maximum Temperature with Base Torque	348.25
Base to Maximum Temperature Battery Only Evolution	209.18

TABLE 5.12 – Thermal Time Constant Results Summary

5.4 Nominal Torque – Power Curve with Efficiency

Once Nominal Torque is defined, as specified in *Sec. 5.3.1,* entire *Torque – Power Curve* is obtained.

Test Bench layout used is shown in *FIGURE 5.6,* while in FIGURE 5.16 Nominal Torque – Power Curve is presented.

In TABLE *5.13* Nominal Torque – Power Efficiency table is reported. It is worth underline that, these results are obtained using *Average Acquisition Strategy* explained in *Sec. 3.6.1,* by setting *Number of Measurements* equal to 10 and *Acquisition Frequency* to 1 Hz.
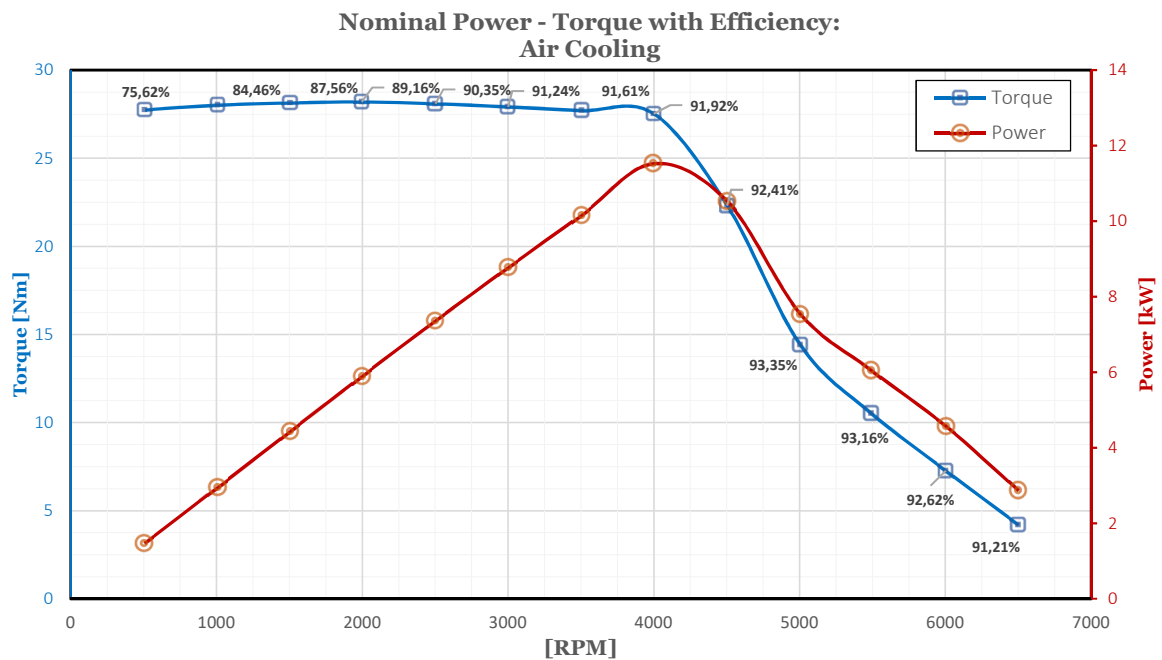

FIGURE 5.16 – Nominal Torque – Power Curve with Air Cooling

TABLE 5.13 – Nominal Torque – Power Efficiency Table

5.5 Efficiency Map without Flux Weakening

Torque – Power Curves exploration is aimed at determining Motor performance at different Torque levels. To assess them in all operating points, it is possible to create iso – lines through which experimental data are used to extend results to all Torque – rpm map.
Most important parameter to characterize is *Motor Efficiency*, thus *Dissipated Power* too.
In *Fig. 5.17,* Nominal and Base Torque Curves are shown, together with Experimental Data in which *Efficiency* and *Dissipated Power* are obtained.
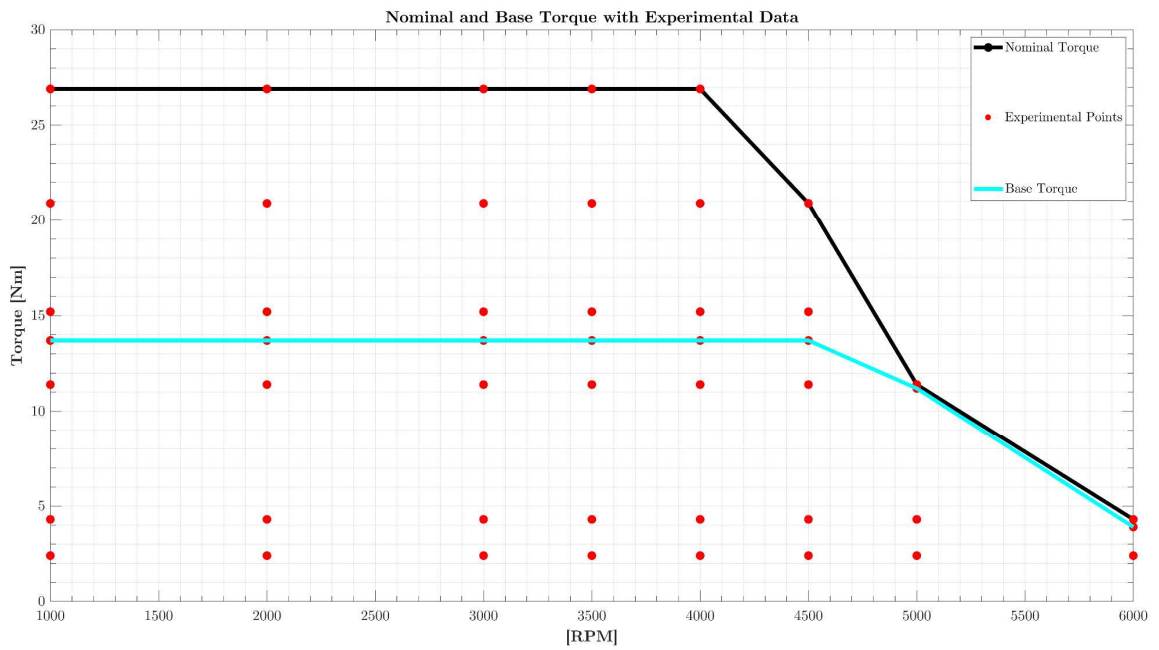

FIGURE 5.17 – Nominal and Base Torque with Experimental Data

In TABLE *5.14* and TABLE *5.15*, experimental data results are shown.

T [Nm]

	1000	2000	3000	3500	4000	4500	5000	6000
26.9	84.5 %	89.2 %	91.2 %	91.6 %	91.9 %			
20.9	82.6 %	86.2 %	86.7 %	87.8 %	88.1 %	92.4 %		
15.2	84.5 %	90.2 %	87.3 %	90.9 %	88.7 %	90.3 %		
13.8	91.9 %	92.2 %	93.3 %	93.5 %	93.5 %	93.2 %		
11.4	88.0 %	90.5 %	90.9 %	89.3 %	88.1 %	89.2 %	91.8 %	
4.3	85.8 %	88.4 %	93.1 %	87.4 %	88.8 %	88.1 %	87.1 %	85.2 %
2.4	82.8 %	79.6 %	80.2 %	80.3 %	80.2 %	78.9 %	79.5 %	78.7 %

[RPM]

TABLE 5.14 – Efficiency MAP Table

T [Nm]

	1000	2000	3000	3500	4000	4500	5000	6000
26.9	712.5	801.2	1299.9	1407.6	1013.4			
20.9	468.1	701.4	1005.9	1056.4	1204.9	864.7		
15.2	304.9	350.5	693.4	556.3	813.2	732.2		
13.8	126.8	223.6	311.4	351.7	395.7	458.9		
11.4	151.9	223.7	311.2	434.4	572.9	545.2	490.3	
4.3	85.1	133.4	104.8	240.7	244.1	342.5	466.8	432.3
2.4	52.4	115.1	155.1	175.3	200.1	224.1	240.1	260.3

[RPM]

TABLE 5.15 - Dissipated Power [W] MAP Table

Appendix

A. UNECE Regulation No. 85

Regulation No. 85 uniformly describe provisions concerning the approval of Electric Drive Trains, intended for the propulsion of motor vehicles of categories M and N, regarding the measurement of *Net Power* and the *Maximum 30 minutes Power* of electric drive trains. They are defined as:

- **Net Power:** power obtained on a test bench at the end of the crankshaft or its equivalent at the corresponding engine or motor speed, determined under reference atmospheric conditions;

- **Maximum 30 minutes Power:** maximum net power of an electric drive train which can deliver over a period of 30 minutes as an average.

The drive train shall have been run – in according to the manufacturer's recommendations. Auxiliaries necessary for the drive train operations, in the intended application, shall be installed in the same position as in the vehicle.
The electric drive train shall be equipped as specified in *Tab. A.1.*

Auxiliaries	Fitted for Test
DC Voltage Source	Voltage drop during test less than 5 %
Speed Variator and Control Device	Yes: Standard Production Equipment
Liquid Cooling: Radiator Fan – Fan Cowl Pump Thermostat	Yes: Standard Production Equipment
Air Cooling: Air Filter Cowl Blower Temperature Adjustment System	Yes: Standard Production Equipment
Electric Equipment	Yes: Standard Production Equipment
Bench Test Auxiliary Fan	Yes, if necessary

Table A.1 - Equipment Specification in UNECE Regulation No.85

Test for determining *Net Power* shall be carried out with the accelerator control set at the maximum position and the motor must have been run – in accordance with the recommendations of the applicant for the approval.

Data to be recorded are:

- **Torque** and **Speed**, to be simultaneously recorded;
- **Cooling Liquid Temperature**, at motor outlet;
- **Motor Inlet Air Temperature.**

Measurements accuracy requirements are reported in *Tab. A.2.*

Quantity	Required Accuracy
Mechanical Torque	$\pm$ 1% of measured Torque
Motor Speed	0.5 % of measured speed
Motor Inlet Air Temperature	$\pm$2K

Table A.2 Measurements Accuracy in UNECE Regulation No.85

Furthermore, due to Electric Drive trains characteristics, it is worth including *Peak Power* too, even if the Regulation is not requesting it.

Peak Power is important because is a fundamental quantity of Electric Drive Trains, usually not included in homologation; it is important to know since it strictly depends on Cooling System properties.

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