Università degli Studi di Padova
Dipartimento di Ingegneria Industriale
EDLab Padova


# Mild-Hybrid Motorcycle Vehicle

## MO.bi regional project 2010-2012

**Mattia Morandin**, Marco Ferrari, Silverio Bolognani, Mosè Castiello

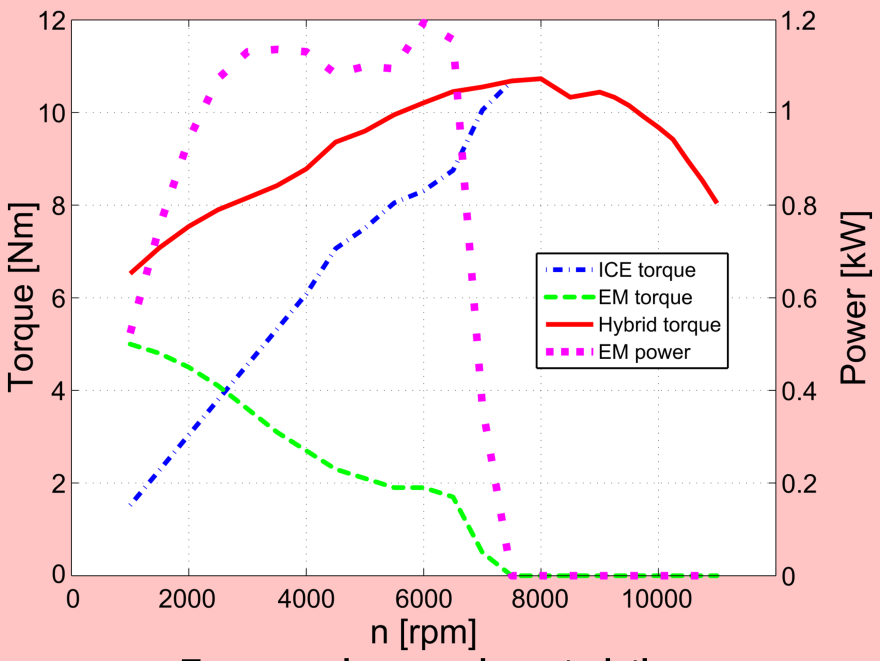
Department of Industrial Engineering, Electric Drive Laboratory (EDLab)
University of Padova, Padova, Italy

## Topic

In recent years, great developments have been obtained in the area of the electric and hybrid propulsion systems, as this technology allows emissions and fuel consumption to be reduced. In the **motorcycles** the transition from Internal Combustion Engine (ICE) vehicles to **hybrid electric vehicles** (HEVs) **is very attractive** but there are still open issues and possible optimizations to be investigated in order to optimize the size and the weight of the electric parts on-board. The principal requirements of energy storage systems in HEVs are: weight, volume, power and energy density, lifetime, cost, and maintenance. The combination of different types of energy sources (batteries, ultracapacitors, fuel cells, ect.) complements drawbacks of each single device.

## Target

The goal of this project is to **improve the performance** of a given motorcycle (in terms of torque) by replacing its conventional alternator with a **new electric machine (EM)** suited to improve the torque of the original ICE and to reduce emissions. In this way the new vehicle will be hybrid with parallel philosophy and with the term boost will be indicated an increase of torque with respect to the original one (only ICE).
The **hybrid torque** has been designed in order to satisfy the user's requirement and it could be different if the motorcycle is designed for race, long trip, or urban use.

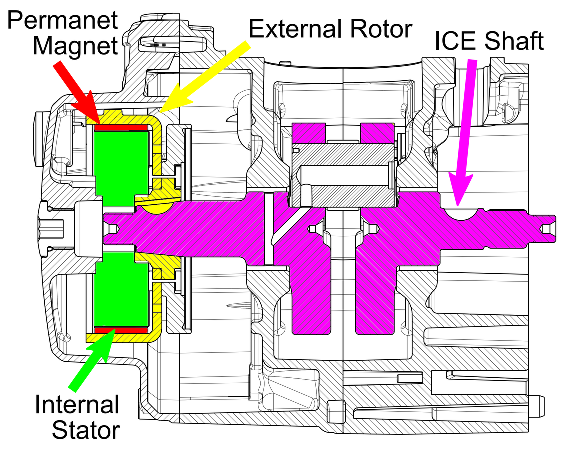



**Torque and power characteristics**

## Power-Train Overview

The motorcycle that has been chosen to realize the hybrid vehicle is **Aprilia RS4 125**.
The proposed power-train architecture is composed by an electric machine fed by a conventional 3-phase inverter direct connected to a energy storage, it commanded by the "*Vehicle Management & Control Unit*".

### Motorcycle ICE



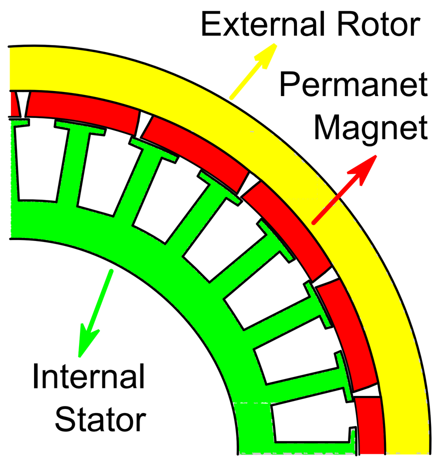

**Sketch of ICE connection with EM**

TABLE I
MOTORCYCLE PARAMETERS.

| Parameter | Value |
|---|---|
| Engine | single cylinder, 4 valves |
| Type of injection | electronic |
| Bore x Stroke | $58 \times 47\ mm$ |
| Total displacement | $124.8\ cc$ |
| Compression ratio | $12.5 \pm 0.5 : 1$ |
| Gear box | 6 Ratios: $1^{st}$ 11/33, $2^{nd}$ 15/30, $3^{rd}$ 18/27, $4^{th}$ 20/24, $5^{th}$ 25/27, $6^{th}$ 23/22 |
| Clutch | Multiple discs in oil bath |
| Primary drive | Gears, 69/29 |
| Final drive | Chain, 60/13 |
| Fuel tank capacity | $14.5\ l$ |
| Weight | $140\ kg$ |

- **Aprilia RS4 125** (milestone in the evolution of the 125cc sport bike).
- **Direct connection with EM** (simplest solution).
- **4 stroke engine** (low emission, Euro 3).

### Electric Machine



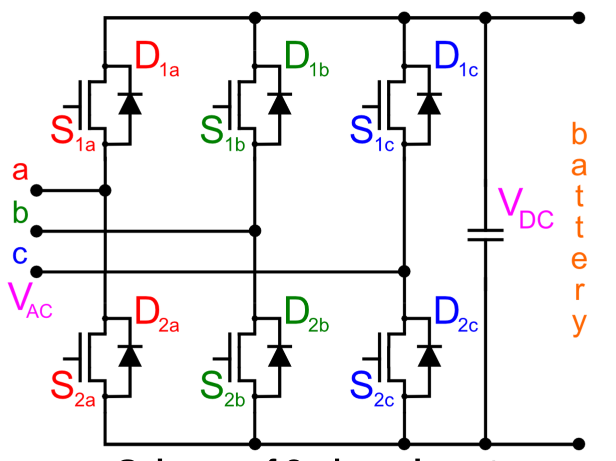

**Sketch of stator laminator**

TABLE II
ELECTRIC MACHINE PARAMETERS.

| Parameter | Value |
|---|---|
| Pole number | 18 |
| Slot number | 27 |
| External stator diameter | $156\ mm$ |
| Stack length | $35\ mm$ |
| Type of magnet | Ferrite |
| Rated torque | $10\ Nm$ |
| Rated phase current | $25\ A_{pk}$ |
| Rated phase voltage | $220\ V_{pk}$ |
| Phase resistance | $75\ m\Omega$ |
| Phase inductance | $230\ \mu H$ |
| External Phase inductance | $120\ \mu H$ |
| Magnet flux linkage | $0.024\ V_{pk}s$ |
| Rated speed | $9000\ rpm$ |
| Average efficiency | $90\ \%$ |
| Weight | $5\ kg$ |

- **External rotor** (space saving).
- **SPM synchronous machine** (high torque density).
- **Tooth-wound** (reduce the copper weight and also cost and Joule losses).

### Three-Phase Inverter



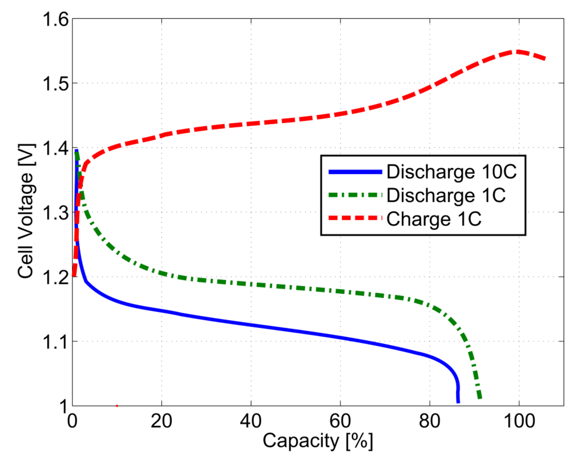

**Scheme of 3-phase inverter**

TABLE III
3-PHASE INVERTER PARAMETERS.

| Parameter | Value |
|---|---|
| Number of phases | 3 |
| Type of switch | IGBT |
| Switching frequency | $20\ kHz$ |
| Dead time | $2\ \mu s$ |
| Maximum DC bus voltage | $500\ V$ |
| Rated AC current | $25\ A_{pk}$ |
| Rated AC voltage | $220\ V_{pk}$ |
| Average efficiency | $90\ \%$ |
| Weight | $3\ kg$ |

- **3-phase inverter** (simple and economic solution).
- **Modulation** (Space Vector PWM).
- **Control** (d-q axis current control).

### Battery Pack



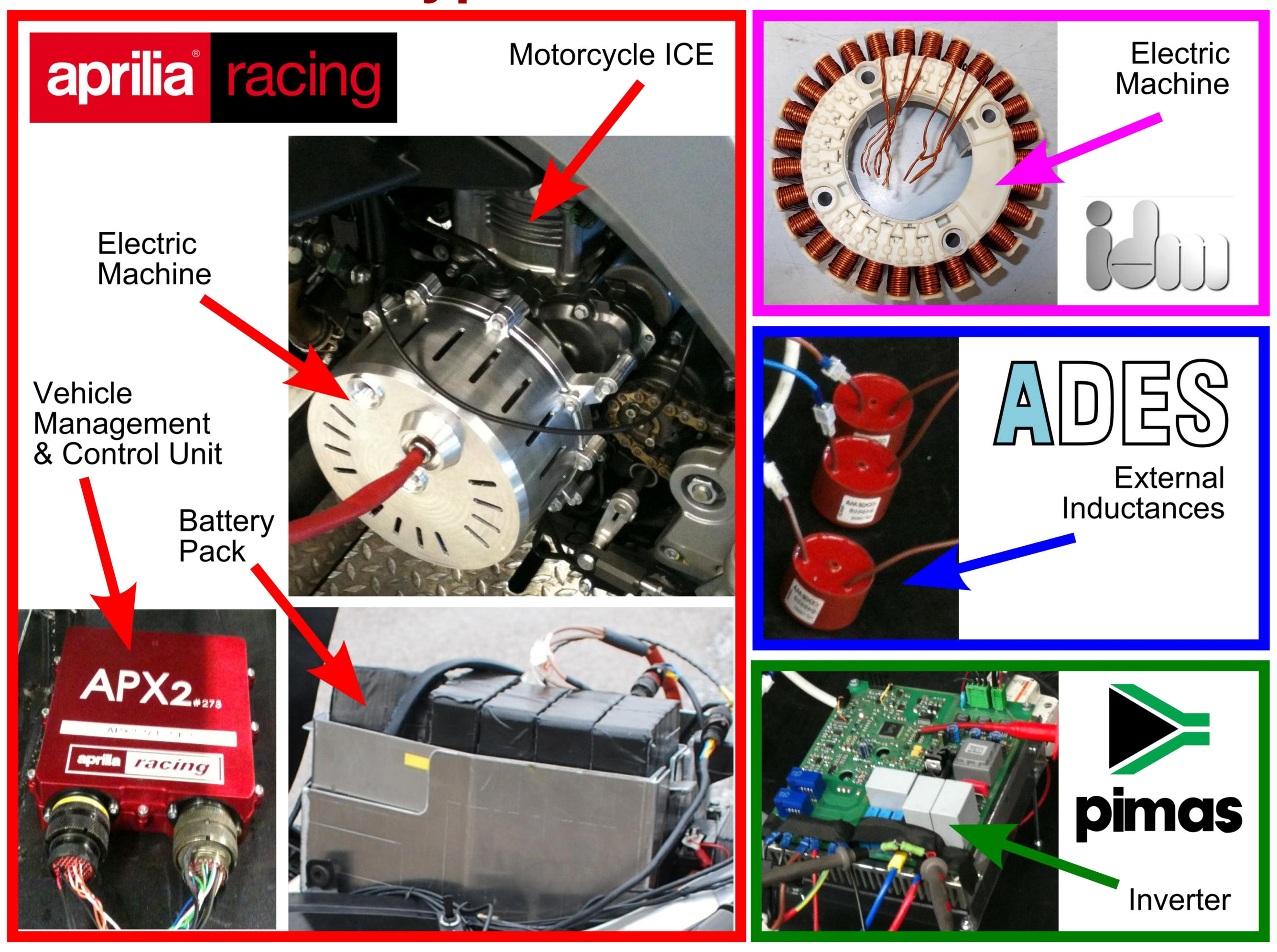

**Charge/discharge characteristics**

TABLE IV
BATTERY PACK PARAMETERS.

| Parameter | Value |
|---|---|
| Type of battery | Ni-Mh |
| Cell nominal voltage | $1.2\ V$ |
| Cell typical capacity | $1.8\ Ah$ |
| Cell internal impedance | $75\ m\Omega@1\ kHz$ |
| Cell diameter | $14\ mm$ |
| Cell height | $50\ mm$ |
| Number of cells in series | 350 |
| Maximum battery voltage | $450\ V$ |
| Maximum discharge current | $18\ A$ |
| Maximum charge current | $1.8\ A$ |
| Weight | $11\ kg$ |

- **Ni-Mh** (economic solution).
- **High voltage** (reduce the DC current in the battery).
- **Small cells** (easy to pack).

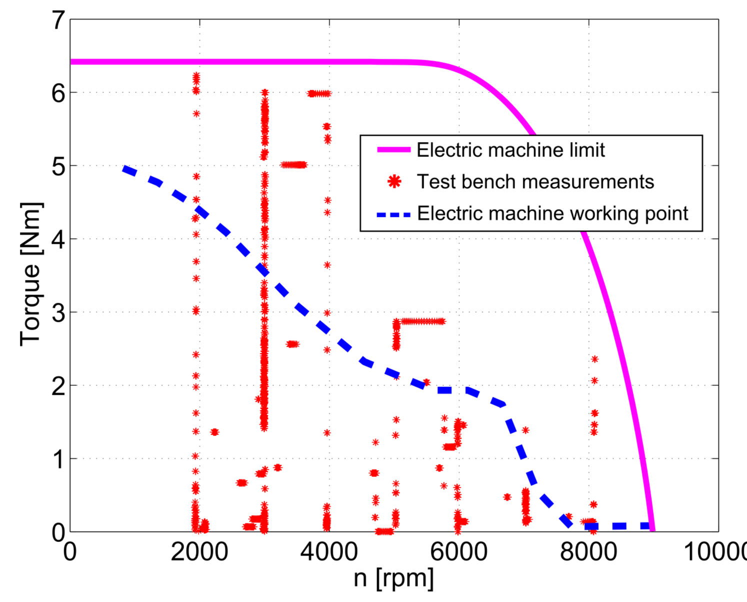
## Vehicle Prototype




## Test at Aprilia Test Bench

The performance of proposed HEV has been verified at Aprilia test bench in all regimes of operation.

**Motorcycle under preliminary test at Aprilia Test bench**




**Test bench performance measurements**

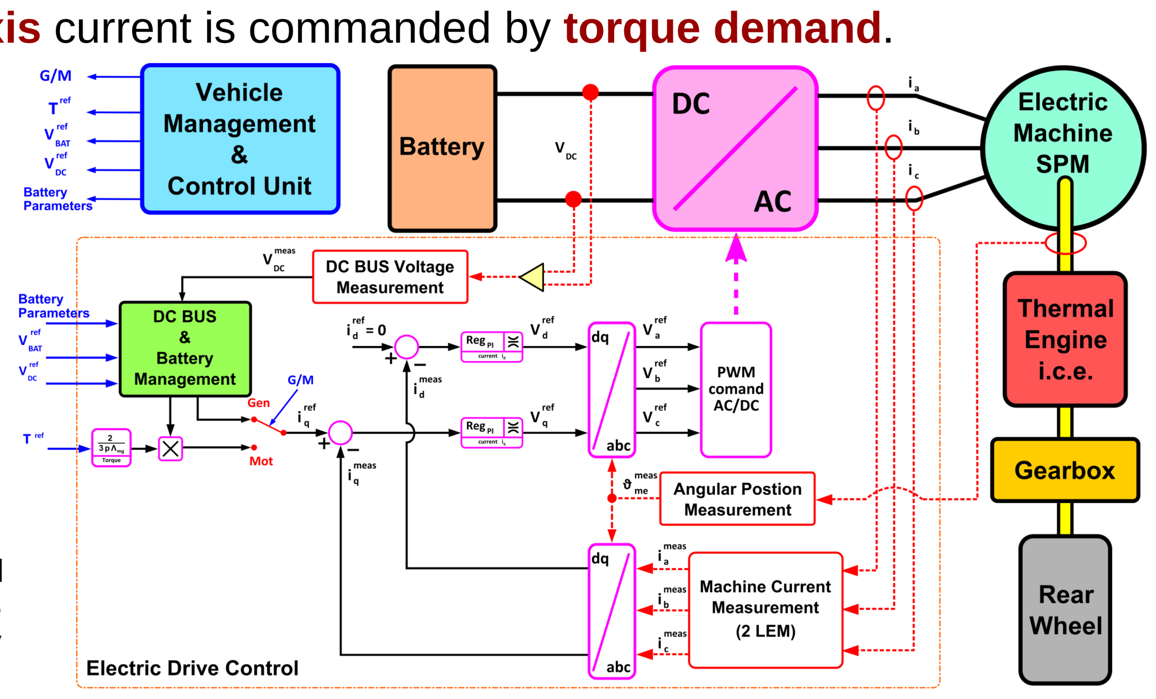
## Electric Machine Control Scheme

The control technique principle adopted for this HEV is a **torque control**. In order to generate a higher level of the torque:

- the stator current vector has to be synchronized with the rotor polar axis, d–axis (encoder or resolver is needed);
- the **machine is controlled to comply with the MTPA** (Maximum Torque Per Ampere) operation.

According to the MTPA control and the SPM configuration **two current loops** are implemented:

- the **d-axis** current is maintained to **zero**;
- the **q-axis** current is commanded by **torque demand**.




**Overall control diagram of the proposed HEV**

There are **two operating modes** ("G/M") controlled by a logical state provided by the "*Vehicle Management & Control Unit*" :

- **Motoring mode (M)**: power is transferred from the battery to the motor drive (during start-up or a torque boost to the ICE), the electric machine is torque controlled.
- **Generating mode (G)**: the (braking) torque of the electric machine is controlled in order to regulate battery current or voltage. Reference battery current calculation and control of battery voltage are performed inside the "*Battery Management*".

## Test in Pontedera racetrack

The performance of proposed HEV has also been verified in Pontedera racetrack, a small private circuit situated inside the headquarters of the Piaggio company.
**Two test sessions** have been done: a first session with only ICE and a second session with hybrid system in order to compare the performance of the two different vehicles.

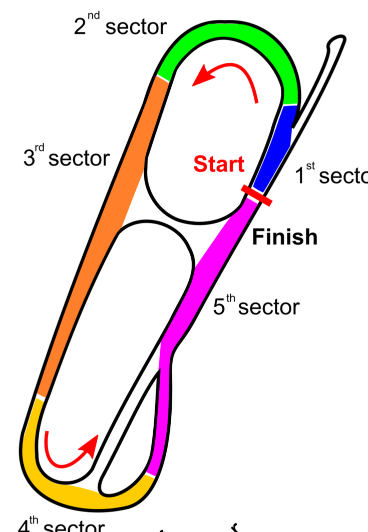
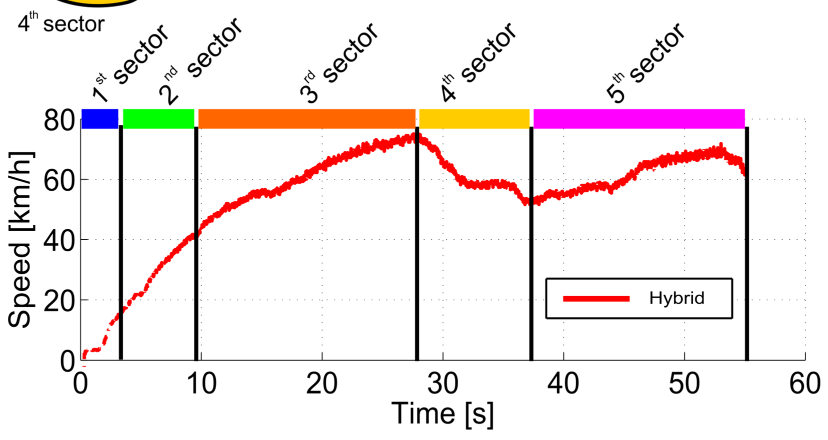
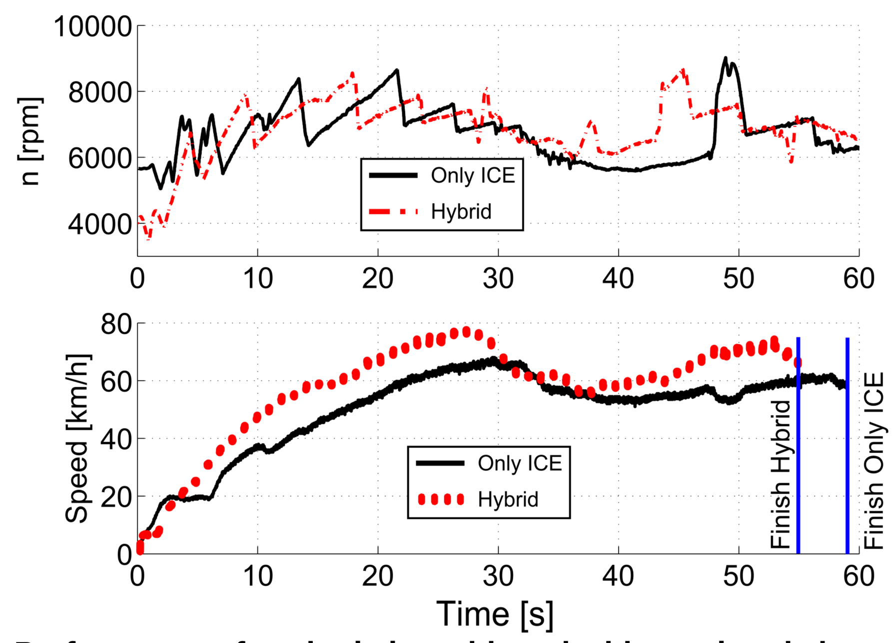



TABLE V
PONTEDERA RACETRACK PARAMETERS.

| Parameter | Value |
|---|---|
| $1^{st}$ $sector$ length | 50 m |
| $2^{nd}$ $sector$ length | 160 m |
| $3^{rd}$ $sector$ length | 260 m |
| $4^{th}$ $sector$ length | 130 m |
| $5^{th}$ $sector$ length | 210 m |
| Weather condition | cloudy |
| Ground condition | wet |
| Ground temperature | $15\ ^oC$ |

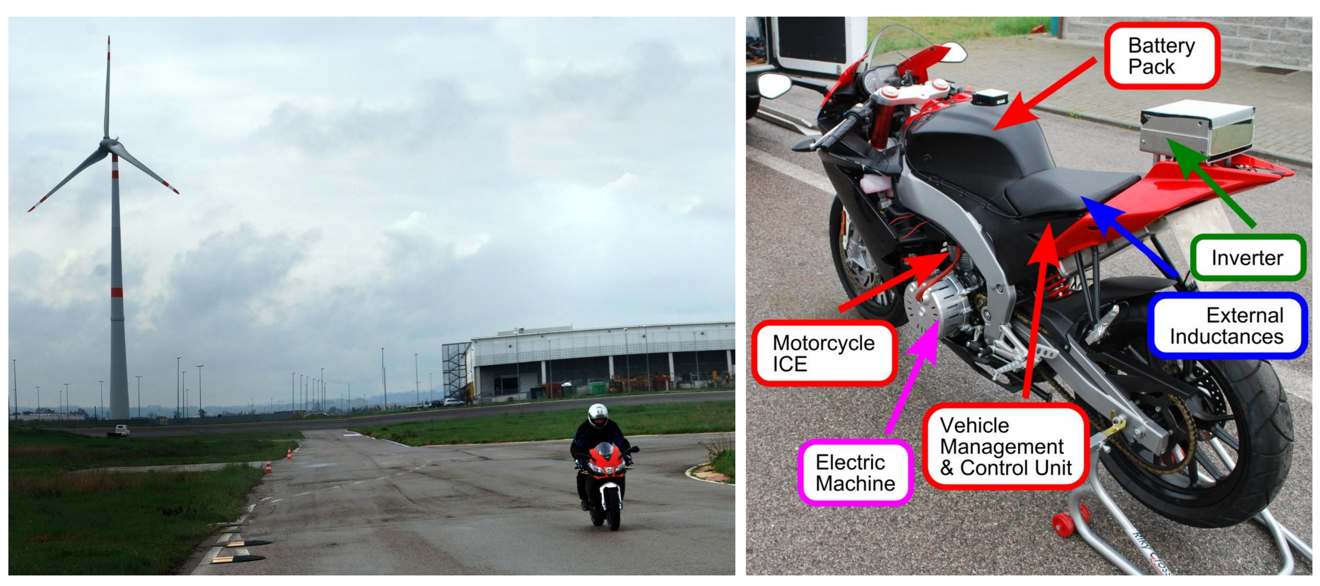



**Performance of a single lap with electric boost**




**Performance of a single lap with and without electric boost**

**Photos of prototype motorcycle during test in Pontedera racetrack**




## Conclusions and Future Works

- An energy conversion system suitable for hybrid electric vehicles is proposed in this project. It is based on a SPM synchronous machine, a 3-phase inverter direct connect to the battery pack.
- Optimization and advantages of the system architecture have been analyzed through simulations and experimental tests by a prototype motorcycle.
- Future work consists in improving the power-train efficiency of HEV.

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