

## Conference Paper

# Development of a Modular Controller to Minimize Current Ripple in Low Inductance Coreless Permanent Magnet Motor

Jorge Miguel Guedes Rebelo and Miguel Ângelo Rodrigues Silvestre

Universidade da Beira Interior

## Abstract

In this paper, a development of a modular controller to minimize current ripple in a low inductance coreless permanent magnet synchronous motor (CPMSM) is described. Based on individual modules, the controller uses a 60 degree commutation scheme instead of the conventional 120 degree. The neutral point of the motor's windings is connected to an intermediate voltage level provided by a capacitor bank relative to the DC power bus. This feature allows the utilization of a single current sensing point that is used to regulate the motor's torque by hysteretic current level control. With this simplification of the control strategy it was possible to use a single Programmable Logic Device (PLD) to implement all the processing in the controller. The controller was built and tested, and the results showed efficient and smooth operation of the motor.

**Keywords:** Current ripple, Permanent magnet motor, Low inductance

Corresponding Author:

Jorge Miguel Guedes Rebelo  
jorge.rebelo@ubi.pt

Received: 26 November 2019

Accepted: 13 May 2020

Published: 2 June 2020

Publishing services provided by  
Knowledge E

© Jorge Miguel Guedes Rebelo and Miguel Ângelo Rodrigues Silvestre. This article is distributed under the terms of the [Creative Commons Attribution License](#), which permits unrestricted use and redistribution provided that the original author and source are credited.

Selection and Peer-review under the responsibility of the ICEUBI2019 Conference Committee.

## 1. Introduction

For the Aero@UBI battery electric prototype vehicle the coreless permanent magnet synchronous motor (CPMSM) was considered to be the most promising motor [1] since in this type of electrical machine the iron hysteresis and induced currents are absent, thus offering the best scenario of reaching a top efficiency, however CPMSM tend to have very small inductance compared to an iron cored Permanent Magnet Synchronous Motor (PMSM). Therefore, the motor efficiency is highly dependent on the controller ability to correctly supply the appropriate phase current waveform that maximizes the working motor efficiency. In [2] calls attention to the current ripple problem where a CPMSM can be suffer from a significant current ripple and thus produce additional  $I^2R$  losses in the windings, these losses are dependent from the controller switching frequency and the difference between the input voltage and the motor Back Electromotive Force (BEMF). The author describes a current ripple reduction strategy by adjusting the voltage supplied to the motor controller in accordance with the motor's BEMF using a DC-to-DC buck-boost converter. As shown in [3] the efficiency of such DC-to-DC converter

### OPEN ACCESS

topology showing that even for conventional PMSM high inductance motors the current ripple can be very detrimental, particularly in low speed and high motor loads conditions. As shown in [4] the low inductance of a coreless motor was taken into consideration by using external inductors of  $100\mu\text{H}$  per phase in order to limit the current ripple resulting from the switching action of the controller. On the other hand, in a low inductance motor the controller itself could suffer from excessive switching losses if all effort would be put into supplying the correct waveform to the motor. In an electric propulsion system, the controller may have the same importance as the motor itself to the whole system efficiency, in the motor controller lies the capability of managing when and how much current is applied to the motor's phase terminals. Being the development and construction of the motor controller a mandatory rule for battery electric prototypes in Shell Eco-marathon (SEM) regulations, after the motor was built, most of the efforts of the team went to its development in the SEM 2015 participation.

The development of motor controllers and inverters has been extensive in later years. This is due to the expansion of grid tied solar roofs in the case of inverters and due to the advent of electric plug-in cars. Motor controllers and inverters are very similar. Since the beginning of our SEM project, it was found that sinusoidal Field Oriented Control (FOC) concept offers the greatest potential for the Permanent Magnet Synchronous Motor (PMSM). To first try this control strategy, a development kit from Texas Instruments composed by the LAUNCHXL-F28027F and the BOOSTXL-DRV8301 was bought and tested. With this solution, the complexity of implementing the FOC concept on a developed and fabricated board was realized. Despite an effort to implement Colton's work [5] regarding a sinusoidal FOC on low-cost hardware another simpler solution was pursued. The merit of the multilevel inverter concept was recognized, as a modern trend in inverters heading towards increased efficiency. In multilevel inverters,  $n$  voltage levels are used to synthesize a sinusoidal voltage from a DC bus. In [6], a comprehensive summary of multilevel inverter circuit topologies and their control strategies is presented as well as their evolution. Compared with the two-level motor controller inverter, the multilevel inverter improves the output voltage quality but adds even more complexity, as shown in Figure 1.

In the present case, in the quest for the simpler yet efficient solution, a controller that could somehow take advantage of the multilevel inverter concept without its inherent complexity was thought of.

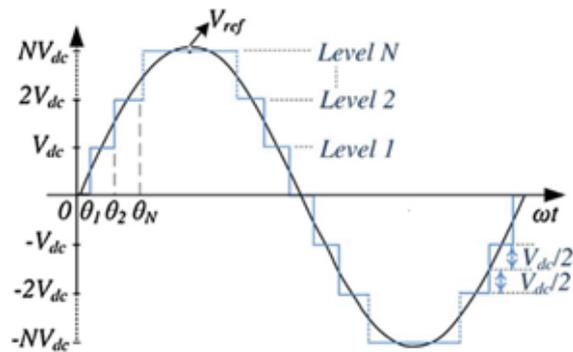


Figure 1: N-level output voltage waveform. Source: [7]

## 2. Methodology

The new controller was achieved through the use of a 60 degree commutation scheme, instead of the conventional 120 degree used in Brushless DC (BLDC) motor controllers, and by connecting the neutral point of the motor's windings to an intermediate voltage level provided by a capacitor bank. This feature allows the utilization of a single current sensing point that is used to regulate the motor's torque by hysteretic current level control. With this simplification of the control strategy it was possible to use a single Programmable Logic Device (PLD) to implement all the processing in the controller, like the solution presented in [8], where the author describes the development of a three-phase BLDC motor controller to fit in a small Electrical Vehicle. Using only combinatory tasks, such as AND, OR, Enable and with some additional analogic and digital electronics, a complex microcontroller is not needed.

## 3. Conceptual Design

The conceptual design of the present controller results from the implementation of various concepts and some features present in other controllers. Here is a list of the implemented concepts:

- **Modular** -- divide the controller in subparts so they can be replaced in case of damage or improved versions of each module are developed later;
- **Shoot through Protection** -- a short-circuit called shoot-through occurs when both switches of a half-bridge are on. Despite this being not an intended condition, it can happen due to logic propagation delay or due to the time that the MOSFETs require to charge or discharge the gates capacitance and change their state. If

this shoot-through condition is verified, the current flows directly from VCC to GND wasting energy and burning the circuit.

- **Programmable Logic Device** – the commutation scheme can be easily implemented into a Programmable Logic Device (PLD) because the signals from hall effect sensors can be read as a digital word of 3 bits that can be “computed” through logic gates and generate a corresponding logic output to control the three phase half bridges;
- **Hysteretic Control** – due to that the vehicle driving strategy was to keep constant velocity, one simple solution was to keep the motor operating at a constant torque which means that the current should be kept at a constant value as well.
- **N-Channel MOSFETs** -- despite being more difficult to drive, N-Channel MOSFETs are used in both sides of the half-bridges, they have a lower internal resistance and thus can deal with a higher current;
- **60 Degree Commutation Scheme** – the presence of the BEMF is very important to limit the current in the phase. So, it was thought that by switching the phase in a 60 degree commutation, rather than the typical 120 degree commutation used in BLDC motor controllers it would be easier to control the phase current level. By turning the phase on only 30 degree before its BEMF peak, the current gradient is smaller and thus the hysteretic switching frequency is also smaller. In Figure 2 the switching sequence and the current applied to the motor phase terminals are shown.

The final concept architecture is shown in Figure 3. A torque command signal is set by the driver in a form of a reference voltage level that is proportional to the desired motor torque. In the current sensor and comparator module, the current that is measured is compared to the torque command signal using a comparator that will generate a PWM signal. Two comparators are used in a way that if the current measurement signal voltage is lower than the torque command signal voltage the comparator will send a 1 to an AND gate that put a 1 on the current level control PWM signal. If, by the other hand, the sensed current voltage is higher than the torque command voltage signal the comparator will send 0 to the AND gate that, independently of the current sensed by the other sensor will set the PWM to 0. This will generate a phase current level control PWM signal that is logically multiplied with the phase commutation signal that goes to the half-bridge module to limit the current that is supplied to the motor in accordance with the torque command signal. The best point to measure the current in this controller

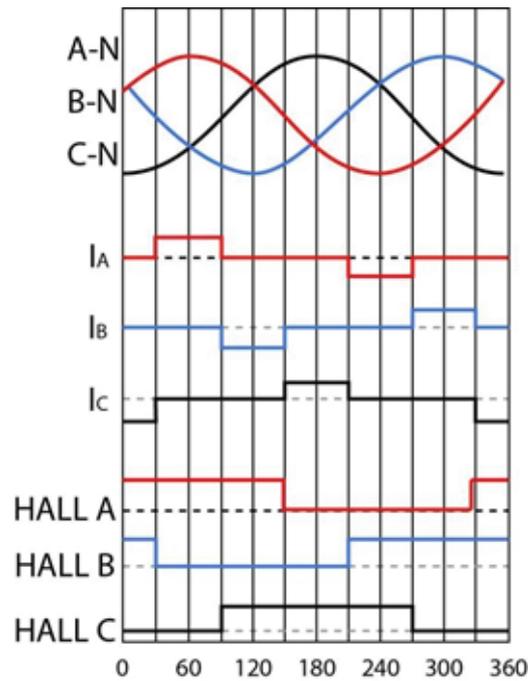


Figure 2: Graphical representation of the 60-degree commutation scheme.

configuration is between the capacitor bank module and the center of star of the motor where all the current supplied to the motor windings is passing through.

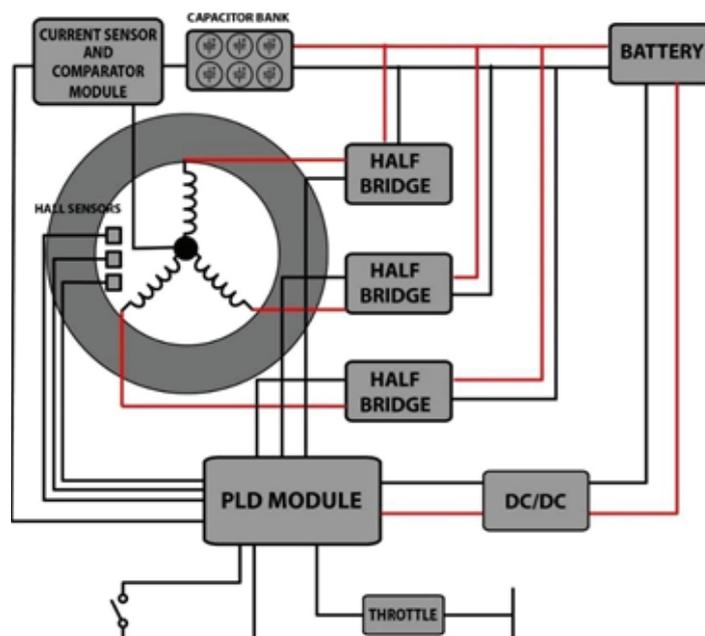


Figure 3: Controller concept design

## 4. Circuit Design and Implementation

### 4.1. Half-bridge

The inverter is composed by three half-bridge modules. Each of these modules are driven by the corresponding 2 bit logic control signals, one to control the high side MOSFET of the half bridge and the other controls the low side, the control signals must be complementary, otherwise any of the two MOSFETs is kept open to accomplish the shoot-through protection. The N-channel MOSFET type was chosen because of the low-voltage application and the constant low resistance when the fully on. MOSFET gate current limiting and pulldown resistors were used. Also, a bootstrap circuit was used to drive the high side of the half-bridge. A high capacitance bus capacitor was used to source and sink currents to and from the half-bridges. Figure 4 shows the implemented circuit for the half-bridge module.

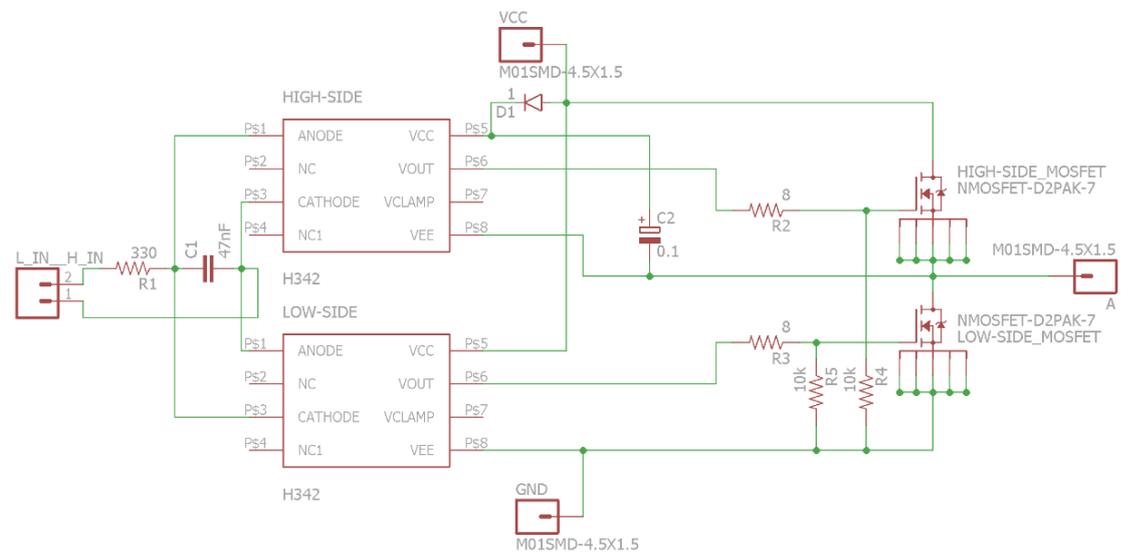


Figure 4: Half Bridge Module Schematic

### 5. Current Sensor and Comparator Module

For the current sensing two unidirectional current sensors were used, one measuring the positive current and the other the negative current. With this current sensing configuration, it was possible to have a sensed current voltage output that was proportional to the phase current independent of the current flow. A differential comparator was used to compare the current signal with the torque command signal. Figure 5 shows the implemented circuit for the current sensor and comparator module.

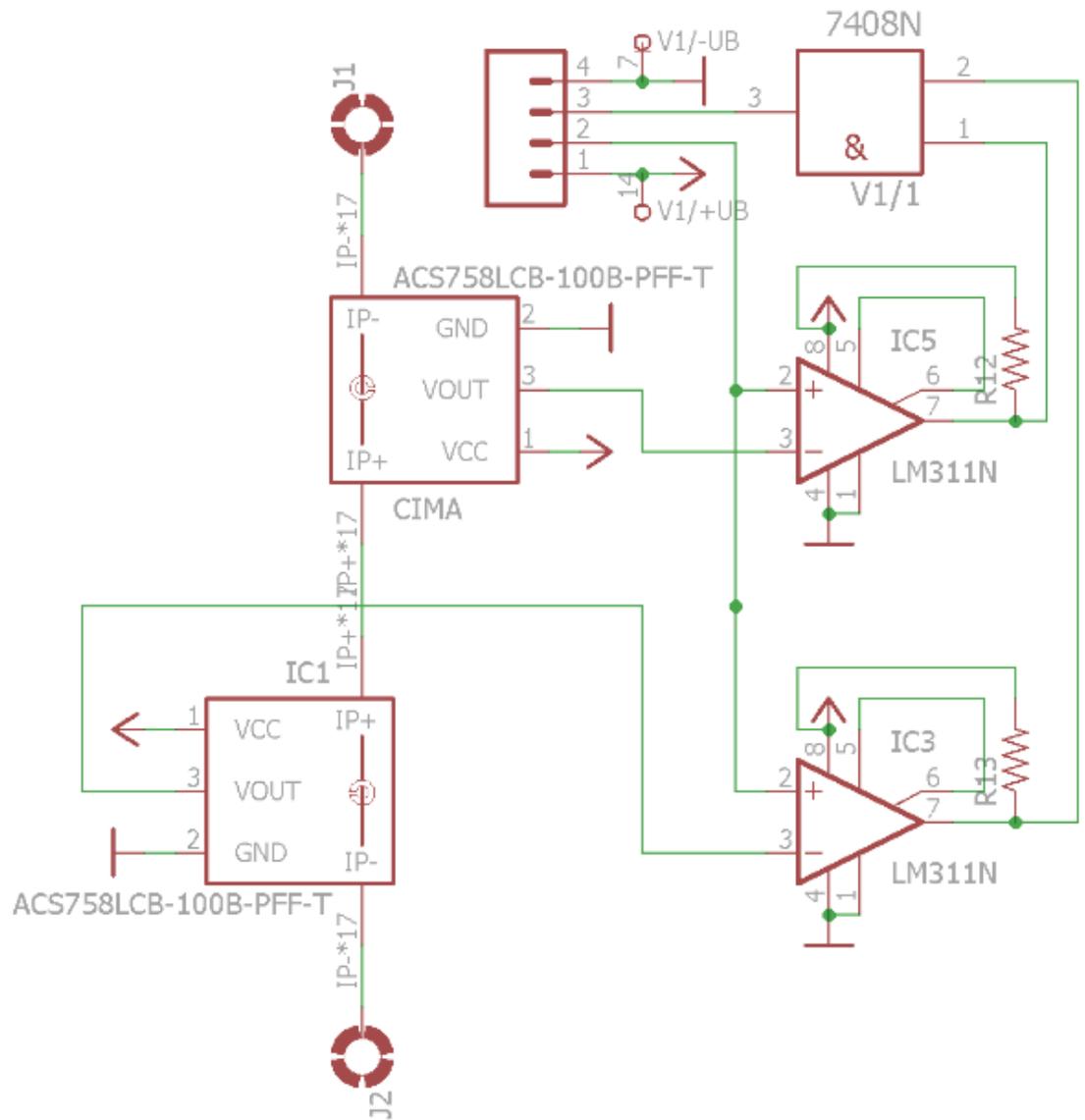


Figure 5: Current Sensor and Comparator Module Schematic

## 5.1. PLD Module

In the PLD module the motor's position was determined using three hall effect sensors mounted in the motor's stator and the switching scheme was implemented in the form of the Boolean expressions:

- AH=A&!B&!C&PWM;
- AL=!A&B&C&PWM;
- BH=!A&B&C&PWM;
- BL=A&!B&C&PWM;
- CH=!A&B&C&PWM;

CL=A&B&!C&PWM;

Figure 6 shows the implemented circuit for the PLD module.

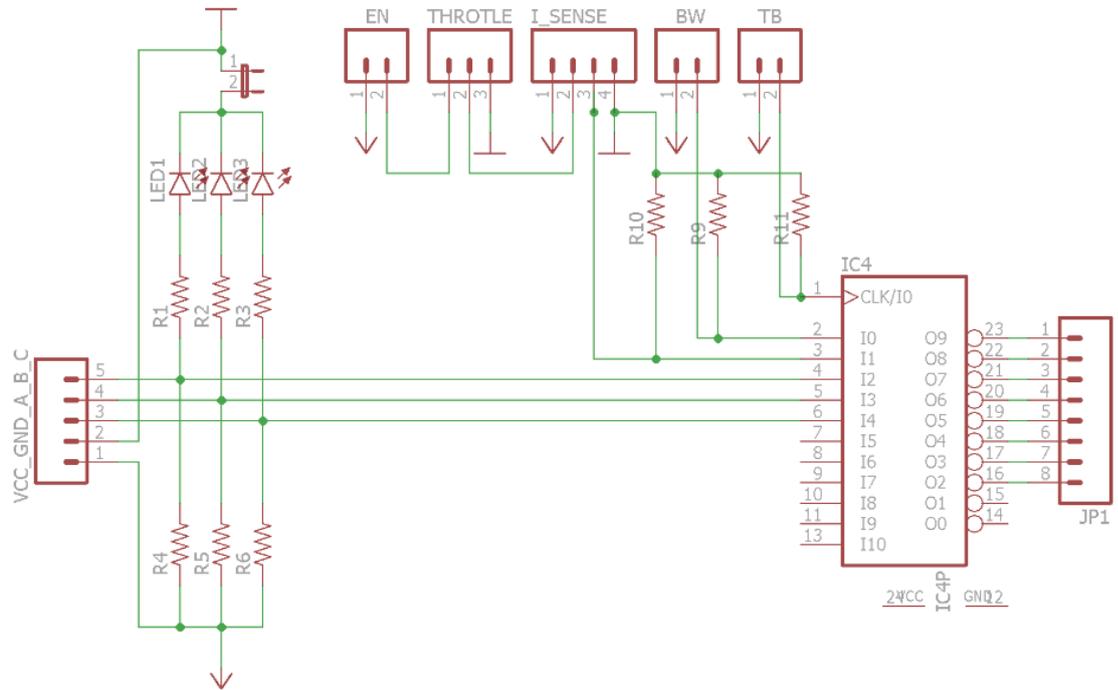


Figure 6: PLD Module Schematic

### 5.2. Capacitor Bank Module

In the capacitor bank module capacitors are connected in three parallel groups of two capacitors in series. The Capacitor bank module is responsible for creating an average zero potential voltage as the intermediate value between  $V_{DC+}$  and  $V_{DC-}$  of the DC bus.

### 5.3. Controller Testing

After the fabrication of all the controller modules, they were tested. The experiments and the results are described in the following subsections. The controller was tested together with the CPMSM developed for the SEM vehicle, as a system, to evaluate its performance. For these tests, the motor and controller were mounted on a test rig to collect data in the working conditions like they will be operated on the vehicle. For these tests, the energy was supplied from a regulated bench power supply that shows the voltage and current sourced to the motor and controller. The motor speed was calculated from the frequency of the BEMF signal monitored on an oscilloscope.

## 6. Current Limiting Function

To evaluate the controller's current level limiting function operation, the motor and the controller were connected. Using the controller to make the rotor spin and braking it by hand, an oscilloscope was used for phase voltage and the current measurements, it was possible to see how the controller regulates the current. Figure 7 shows the test rig for the current limiting function operation check.

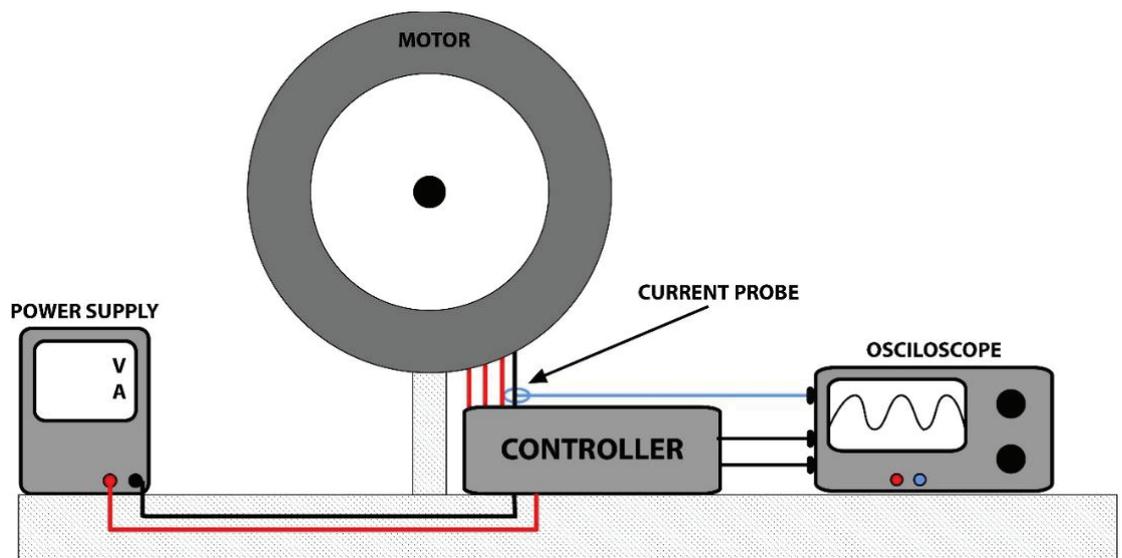


Figure 7: Motor-Controller System test rig schematic.

In Figure 8 shows how the current is limited, the hysteric control limits the current within an upper and a lower hysteresis band. It is, also, possible to observe that the 60 degree commutation is symmetric with the BEMF peak and the commutation frequency is smaller near the BEMF peak.

### 6.1. No Load Measurements

A test with no load applied to the motor was done to compare the power needed to keep the motor spinning at 277 rpm. This was the vehicle's design speed and the motor had been previously measured for the mechanical and stator windings induced current losses. In this condition, the power consumed is only used to keep the motor running. In Figure 9, the test rig for the no load current test is shown. In this test the current probe wasn't used and the current was measured with the power supply. The total power required to spin the motor is about 5.99 W. Please note that this value includes: the power consumption of by the controller, motor mechanical losses and stator windings induced current losses.

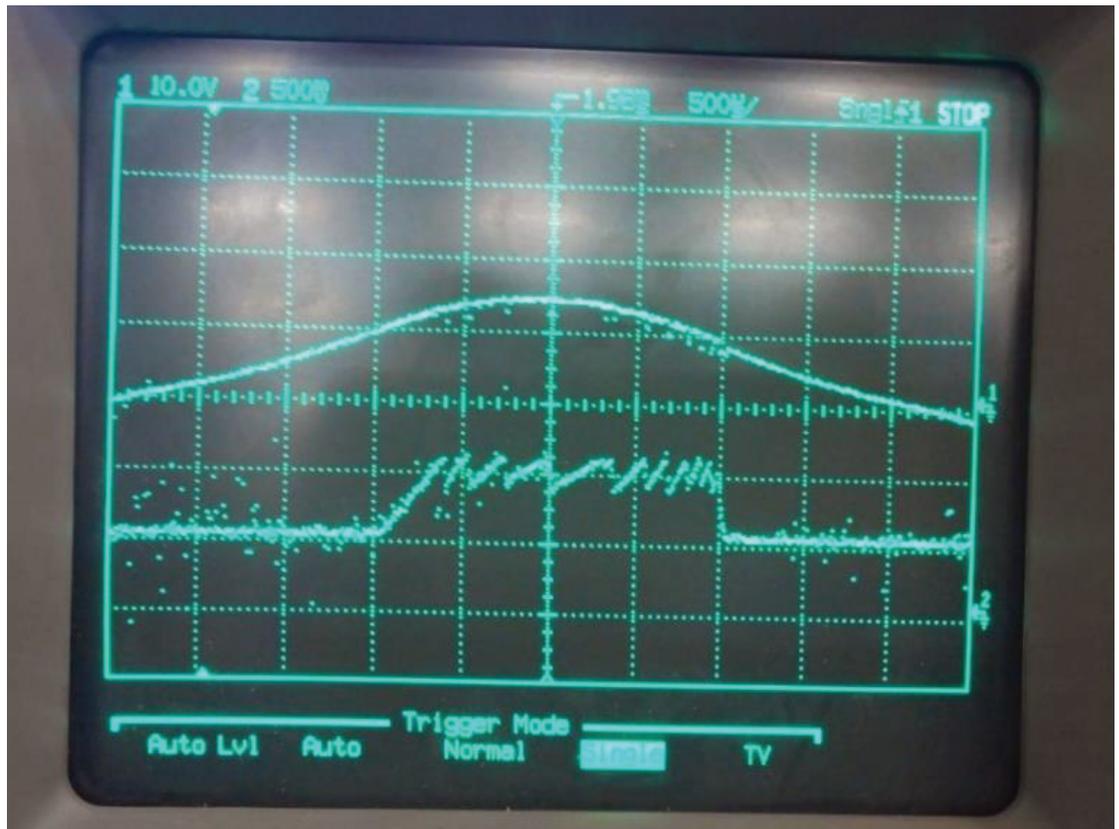


Figure 8: Current limiting function measurement.

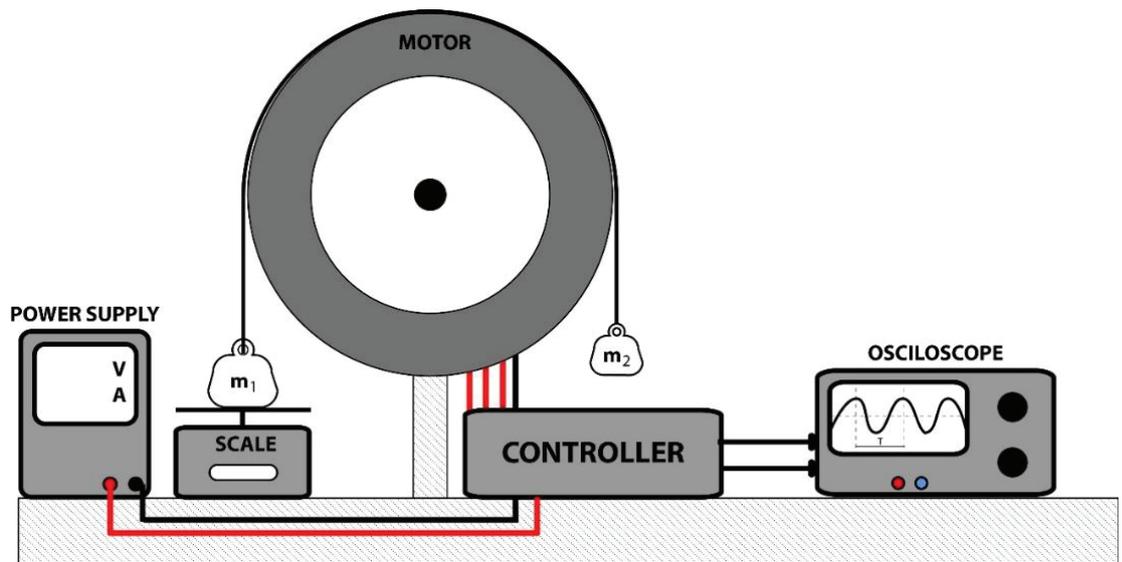


Figure 9: Schematic of the test bench used for load measurements.

## 6.2. Load Testing

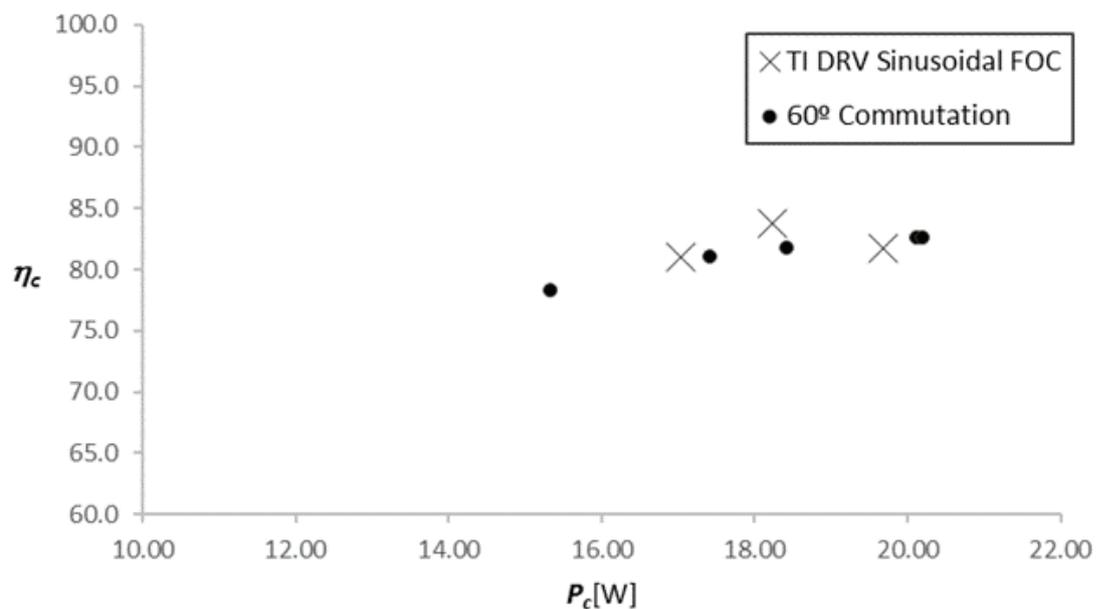
The motor rotation speed and power were kept close to the design 277 rpm and 18W, respectively. Figure 10 shows the tests data of the motor-controller system efficiency for the current 60° commutation scheme controller. The designed system has an efficiency

over 80% through the design point. The efficiency increases with the load at the tested condition of constant motor speed.

### 6.3. Load Testing with TI C2000 and DRV8301Controller

The previous test was repeated, this time the designed controller shown in Figure 9 was replaced by the TI commercial solution, the C2000 processor and the DRV8301 inverter controller. The experimental procedure as de same as used in the load testing.

The motor rotation speed was kept close to the design 277rpm. Figure 10 shows the experimental data corresponding to the use of Texas Instruments DRV sinusoidal FOC controller. When using the TI controller, 90mH choke inductors were connected in series with the motor phase terminals to limit the current ripple and improve the sensorless TI controller sensing. It is seen that the peak efficiency of the developed 60° commutation controller is quite near the efficiency of the state-of-the-art commercial FOC controller.



**Figure 10:** Motor-Controller system efficiency experimental results comparison between TI DRV and the designed controller.

## 7. Conclusions

In this paper, the development of simple but innovative modular controller to minimize current ripple in a low inductance CPMSM for a SEM prototype vehicle and the controller was described. Despite its simplified design and being only a proof of concept, it proved

to be capable of driving such peculiar motor as efficiently as the state-of-the-art industry FOC controller.

## Acknowledgment

This work has been supported by the project Centro-01-0145-FEDER-000017 - EMaDeS - Energy, Materials and Sustainable Development, co-financed by the Portugal 2020 Program (PT 2020), within the Regional Operational Program of the Center (CENTRO 2020) and the European Union through the European Regional Development Fund (ERDF). The authors wish to thank the opportunity and financial support that permitted to carry on this project.

## References

- [1] J. M. G. Rebelo and M. Â. R. Silvestre, "Development of a Coreless Permanent Magnet Synchronous Motor for a Battery Electric Shell Eco Marathon Prototype Vehicle," pp. 1– 9, 2018.
- [2] F. Caricchi, F. Crescimbinì, A. Di Napoli, and M. Marcheggiani, "Prototype of electric vehicle drive with twin water-cooled wheel direct drive motors," *PESC Record - IEEE Annual Power Electronics Specialists Conference*, vol. 2. pp. 1926–1932, 1996.
- [3] J. O. Estima, A. J. M. Cardoso, and S. Member, "Efficiency\_Analysis\_of\_Drive\_Train\_Topol," 2012.
- [4] H. C. Lovatt, V. S. Ramsden, and B. C. Mecrow, "Design of an in-wheel motor for a solar- powered electric vehicle," *IEE Proc. - Electr. Power Appl.*, vol. 145, no. 5, p. 402, 1998.
- [5] S. W. Colton, "Design and prototyping methods for brushless motors and motor control," Massachusetts Institute of Technology, 2010.
- [6] J. Rodríguez, S. Member, J.-S. Lai, and F. Zheng Peng, "Multilevel Inverters: A Survey of Topologies, Controls, and Applications," *IEEE Trans. Ind. Electron.*, vol. 49, no. 4, 2002.
- [7] S. J. Mesquita, F. L. M. Antunes, and S. Daher, "A new bidirectional hybrid multilevel inverter with 49-level output voltage using a single dc voltage source and reduced number of on components," *Electr. Power Syst. Res.*, vol. 143, pp. 703–714, Feb. 2017.
- [8] A. Van Den Bossche, D. V. Bozalakov, T. Vyncke, and V. Cerkov, "Programmable Logic Device Based Brushless DC Motor Control," *Power Electron. Appl. (EPE 2011)*, pp. 1–10, 2011.