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Hardware-In-the-Loop bench design for electrified working vehicles simulation

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Summary

The increasing demand for more efficient working vehicles able to meet pollutant emissions regulations is currently pushing research teams both from the academia and from the industrial field towards hybrid and electric architectures as suitable solution. Despite the well consolidated position of this technology in the automotive field, several aspects prevent its widespread adoption in heavy-duty applications. The higher complexity of the energy management required can be explored with new testing and validation procedures which involve Hardware-In-the-Loop (HIL) technologies. With this simulation approach, complex system like architectures for hybrid electric working vehicles can be partially simulated and partially replicated in scaled version to deeply explore control strategies on real hardware and real mechanical layouts. In this work, the design of a HIL bench for simulation of a hybrid electric agricultural tractor will be presented. A control strategy for the proposed tractor architecture will be tested on the configured HIL bench to evaluate performance on two different working tasks derived from experimental measurements.

Keywords: Hardware-In-the-Loop (HIL), HEV (Hybrid Electric Vehicle), Control System, Off-Road

1 Introduction

Nowadays, air quality represents a real concern all around the world as demonstrated by the high number of specific regulations ratified by governments all around the world [1]-[3]. Among the different anthropogenic pollutant sources, the road and non-road transportation sectors play a big role in determining the total amount of emissions of substances like NO_x, Particulate Matter (PM) and Non-Methane Volatile Organic Compounds (NMVOCs) [4]. To limit the amount of substances emitted into the atmosphere as prescribe in the previously mentioned regulations, the automotive field considered the electrification process as a viable solution to improve the overall vehicle efficiency [5]. More efficient vehicles produce less pollutants per unit of work done. Recently, also the field of Non-Road Mobile Machineries (NRMM) has experienced an increasing involvement in vehicle electrification to meet the stringent emissions regulations for off-road machines [6]-[8]. However, if electrified vehicles represent now an established solution on the market Electric (ENRMM) or Hybrid Electric (HENRMM) off road machines are still not mature enough for the widespread adoption of the new technology. The construction field is the pioneer in the electrification process [9]. Hybrid excavators are a well consolidated technology already available on the market. The use of electric motors for the swing system allows for lower fuel consumption increasing the efficiency during acceleration and recovering the kinetic energy during deceleration of the swing movement. Several hybrid wheel loaders have been developed in the last decade with several architectural solutions [10]. In this case the most adopted topology is a series hybrid layout. In this configuration a traditional diesel engine coupled with an electric generator produces the electric energy required to propel one or more electric motors connected to the driveline. In other application fields like handling and agriculture several hybrid and electric prototype have been proposed in last decade [11]-[14]. Each field of application required architectural solution according to the specific working scenario the machine would face during its operating life. Most of the proposed architectures have hybrid configurations. Very few cases allow the successful adoption of full electric systems to propel the machine [12]. Although full electric configurations simplify system level design constraints and the manufacturing process, the actual state-of-the-art of energy storage systems prevents their adoption on a higher number of working machines categories. The energy density of today's battery-based solutions are not high enough to be considered if hard daily working cycles must be accomplished [15]-[16]. This is the main reason why hybrid electric solutions are today the most viable solution to improve the overall efficiency of NRMMs thus, to produce lower emissions.

Hybrid electric powertrains are the combination of a traditional thermal engines and one or more electric machines actuated as motor, generator or both depending on the specific working condition. In this scenario, the management of several complex subsystems requires dedicated control strategies which are strongly connected to the specific tasks the machine must accomplish. Several studies are available in the literature regarding performance optimization of hybrid electric powertrains for some working machines [17]-[19]. However, the control strategy must be validated by testing the hardware platform on which it will be deployed. Real signals as close as possible to the ones deriving from on-field working conditions should be provided to test the behaviour of the control strategy and its stability on the entire operating range. This concept is the foundation of the Model Based Design approach [20]-[21]. Simulating the system at various levels, it is possible to recreate the signals the Vehicle Control Unit (VCU) would receive as feedback from the real system as consequence of its actuation commands (analogue and/or digital). In particular, if the attention of the Verification and Validation (V&V) process is focused on the physical VCU it is common to talk of Hardware-In-the-Loop (HIL) simulation. As described in [22] and shown in Figure 1 there are different levels of HIL for hybrid electric architecture simulations. Depending on the definition of the Device Under Test (DUT) several HIL configuration can be considered. A HIL simulation focused only on the control unit, is a signal level HIL. If power converters are included in the simulation loop it is common to talk about power level HIL simulations. Finally, if the entire architecture is recreated both at the electrical, power and mechanical level the HIL simulation is said to be at mechanical/system level.

In this work, a mechanical level HIL bench will be shown. The main goal was to replicate a hybrid electric architecture for a small agricultural tractor. The Control Unit, on which a specific strategy for the application was implemented, was tested on the designed HIL bench with two main working scenarios, simulated from data collected on the field. The main goal was to prove the feasibility of the architecture in covering peak power demand during real working conditions splitting the power demand among the two power sources of the machine.

2 HIL bench setup

The HIL bench designed in this work was meant to replicate a parallel hybrid electric architecture for a small agricultural tractor. Many times, these machines come with oversized diesel engines to be able to satisfy the most demanding tasks the final user must accomplish. However, such tasks are usually not the ordinary routine for them thus, the oversized engine translates in higher fuel consumption and higher levels of emissions. Thus, a powertrain with a downsized diesel engine with an electric system able to provide the extra power required in these demanding tasks, would experience an overall higher efficiency and lower emissions. However, a specific control strategy must be developed to properly control the higher number of components in the new powertrain. The goal was to integrate the electric system with an off-the-shelf Internal Combustion Engine (ICE) with its own proprietary ECU obtaining the peak power capabilities of a traditional power unit with the joint work of the two new power sources.

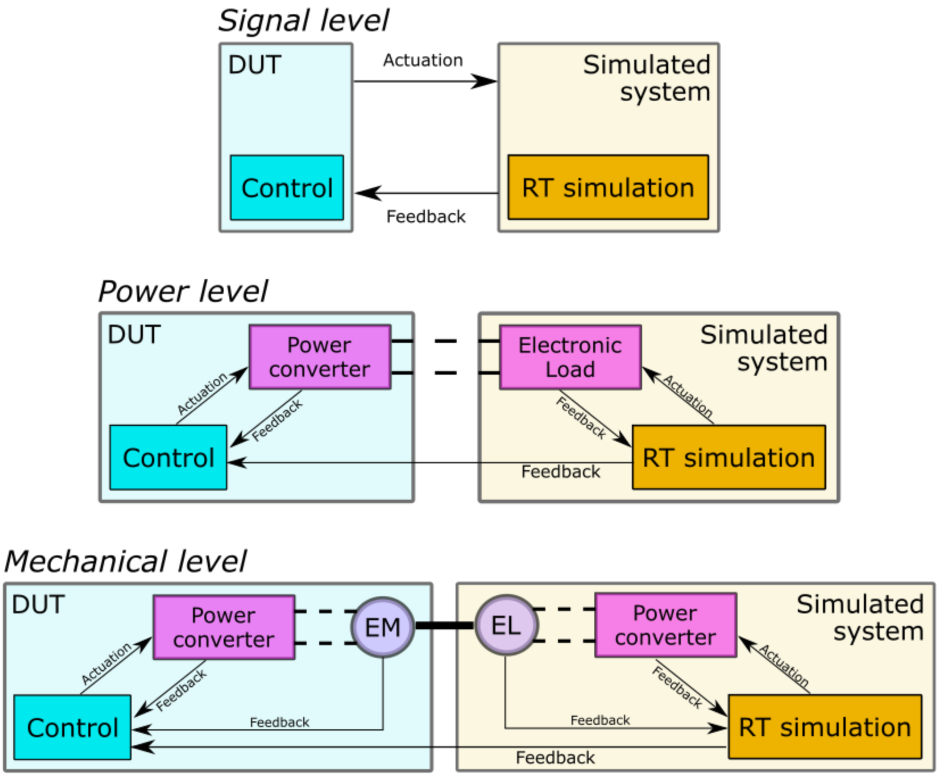

Figure 1 HIL configurations at different simulation levels

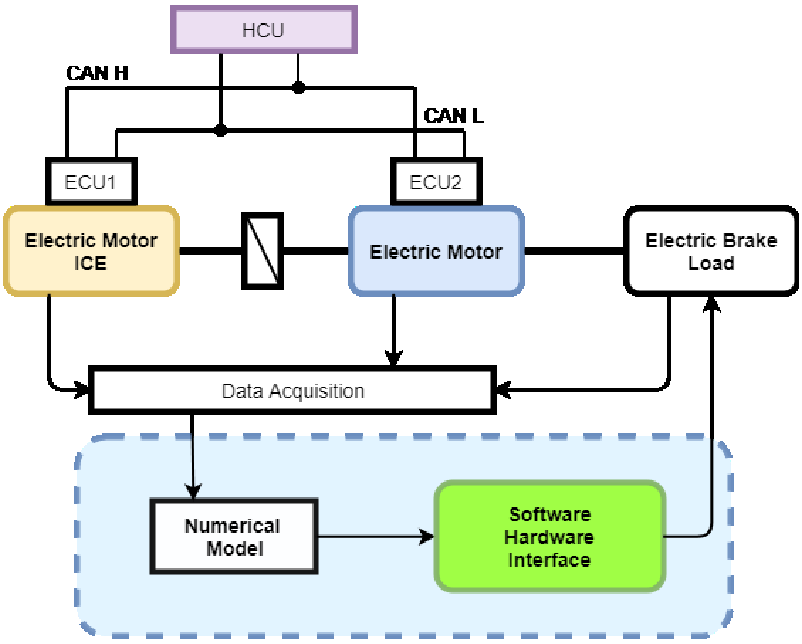

Figure 2 HIL bench layout

Figure 3 HIL mechanical bench overview

To test such a system the HIL bench shown in *Figure 2* and *Figure 3* was developed. As explained in the previous section, this setup wanted to simulate the system at the "mechanical level" replicating a scaled version of a real architecture. It consisted of:

- Two electric motors (Permanent Magnets Synchronous Motors -PMSM). One motor was actuated to simulate the ICE of the system, while the other simulated the Electric Motor (EM) in parallel on the same mechanical shaft to provide the extra power required during working conditions. Each motor was electrically powered by mean of a power electronic converter that took power from a DC source (a low voltage battery pack – 40V) and provided the required three phases sinusoidal current to the coils of the PMSM.
- Two Electronic Control Units (ECUs). Each power converter was controlled by a custom designed ECU. Each controller was in charge of reading the control commands sent by the supervisor control unit on the CAN BUS and sending the appropriate control (analogue) signals to the corresponding power converter. To simulate a real off-the-shelf diesel engine for off-road applications, ECU_1 custom firmware was developed to close a speed control loop using the ICE feedback speed and the speed reference sent by the supervisor unit to determine the correct actuation command for the power converter. EM was instead controlled in torque mode, thus ECU_2 was in charge of translating the torque reference from the corresponding control message sent by the supervisor control unit into physical actuation signals for the power converter.
- A supervisor Hybrid Control Unit (HCU). This was the controller of the system to be tested. The control strategy of the hybrid system was developed and deployed on this controller which was in charge of continuously monitoring the system feedbacks on the CAN BUS network determining the correct actuation commands both for ICE and EM in order to meet the driver need in terms of power and speed.
- An electromagnetic clutch. To engage or disengage the ICE motor from the rest of the powertrain, an electromagnetic clutch was considered. This element controlled by the HCU, allowed for simulations of full electric operations which would open the tractor to new fields of application in the so called Low Emissions Zones (LEZs).
- One electric brake (PMSM). To simulate the mechanical load closing the simulation loop at the mechanical level, a PMSM was used and actuated to apply a controlled braking torque. Its control signals were managed by a dedicated ECU, able to read the actuation commands from CAN BUS.

- *A driver/working conditions simulator*. A Linux based PC was in charge of simulating both the desired working speed of the power unit and the braking torque reference. The working speed of the power unit was obtained by experimental measurements during on field operations, recording the driver pedal signal. The braking torque was constantly evaluated by the software monitoring the actual power unit load in such a way that the load applied to the new power unit could be the same applied to the traditional one measured during on field operations. Each actuation command was sent over the CAN BUS network with a timing of 10 ms equal to the time period of the closed loop on the braking torque.

The role of the CAN BUS network in this bench setup was crucial. Not only was meant for developing a control system ready for vehicle implementation. It was used as communication protocol for the actuation commands, both from HCU to the ECUs and from the Simulator to the electric brake and the HCU itself. Thanks to the high level of customization of each control unit, a bench specific communication protocol was developed on top of the low-level CAN BUS protocol [23]-[24]. The custom protocol developed for the bench was inspired to the SAE J1939 standard [25]-[26]. A 250 kBit/s baudrate was considered as transmission speed of the network. Two custom frames were defined:

- A control frame for each ECU with a time period of 10 ms containing the reference speed, the normalized torque reference and the control mode (speed or torque mode)
- A monitoring frame from each ECU with a time period of 10 ms but with lower priority containing the current percentage load of the motor, the feedback speed and the currently activated control mode.

This structure was used to organize all the traffic on the network in terms of information and message priorities, defined within the message identifier of each frame.

2.1 HCU Control strategy

The proposed hybrid electric architecture for the orchard tractor was designed with a control strategy compliant with the initial goal of a Plug&Play configuration. The electric system should be able to provide the extra power needed by the smaller ICE in order to accomplish the same tasks of the traditional architecture, at least in terms of peak power capabilities. Since off-road engines usually are speed controlled, the electric system must follow the same reference speed providing power whenever the ICE reservoir is not sufficient to meet the desired set point. However, to optimize the use of the energy reservoir of the electric system a Load observer weighting function was considered. It is true that a smaller ICE would suffer the lack of power in some circumstances. However, as demonstrated by the on field experimental activity, most of the time these machines use just a fraction of the nominal installed power. Thus, the function of the Load observer must continuously watch over the actual engine load of the ICE, weighting the intervention of the electric system according to the actual effort of the engine. The more the engine is involved, the higher is the need of extra power to meet the driver demand.

The proposed control strategy is shown in *Figure 4*. The speed reference information derived from the pedal signal of the driver was used both by the ICE ECU_1 (as default) and by the HCU to evaluate the required action to meet the set point. The greater the speed error, the higher was the torque reference the two speed controllers would had generated. However, on the ICE branch, this torque reference was directly applied as actuation command to ICE. On the EM branch, inside the HCU, the torque reference was weighted by the Load observer function which monitored the actual engine load to understand if the EM intervention was really required or not. If the engine had enough power reservoir, the EM power boost was prevented to preserve the stored energy. The Load observer was designed according to a polynomial function of degree greater than one. Thus, EM intervention was set up to be effective above the 80% of the actual ICE engine load.

The Master-Slave control strategy with Load observer was just a part of the overall software architecture developed on the HCU supervisor. As shown in *Figure 5*, the overall software architecture developed with the EcoCoder Simulink libraries from ECOTRONS can be divided into the following steps:

- Target Hardware definition and setup. The specific hardware platform characteristics are provided in terms of input/output signals ports as well as power management settings.

- <u>CAN BUS protocol definition</u>. As stated before, the CAN BUS communication protocol played a big role in this architecture being the main communication channel between the different control units of the architecture. A custom .dbc file for the custom CAN BUS protocol was defined to provide the way to translate messages to and from the HCU. Moreover, a CCP (CAN Calbration Protocol) is defined to allow online parameters calibration.

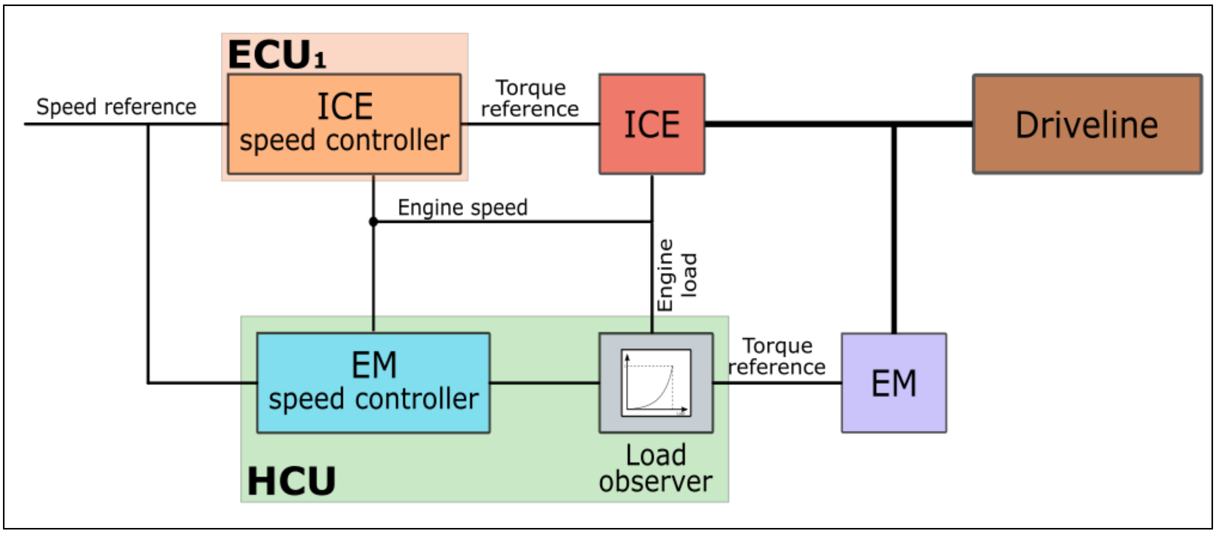

Figure 4 Master-Slave control strategy with Load observer

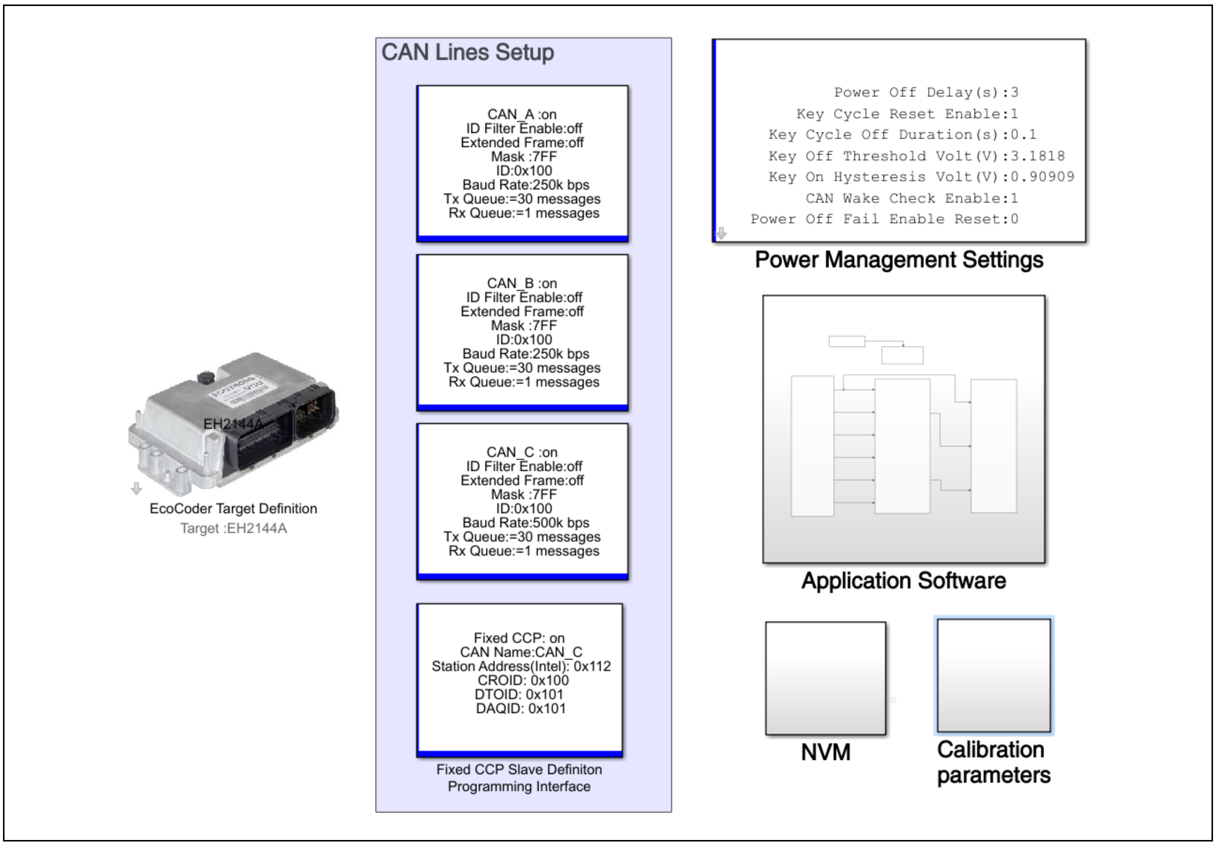

Figure 5 HCU software architecture

- Application software. Is the main core of the HCU software. It was divided into three sections: Input, Processing and Output. With a frequency of 5ms, the Input section was in charge of updating all the variable related to the input signals both in terms of analogue/digital signals or value read by specific CAN BUS messages. The Processing section took the values updated from the Input signals section and used them to run the Master-slave control strategy as well as other control logics and state machines. The Output section took the numerical actuation commands evaluated by the Processing section and implemented them as physical output signals or as control messages to be sent over the CAN BUS network with a certain timing.
- NVM and Calibration parameters definition. Developing the Application Software, it was crucial to identify in the code parameters which should be constant throughout the all life of the HCU and parameters that could require some set up or online calibration. The former are variables stored in the Non Volatile Memory (NVM) of the hardware platform and read every time the controller is turned on. The latter are parameters which can be updated on the RAM address though the CCP protocol defined in the CAN BUS section. It is worth to mention that these changes are available until the HCU is active. If it the controller is turned off, changes are lost because the RAM is not a permanent memory. Thus, it is common practice to flash again the software with the new calibrated variables as NVM values once the best configuration is found.

The software was developed for HIL bench architecture but with an architecture easily customizable on vehicles' CAN BUS network because of the custom communication protocol compliant with the SAE Standard J1939.

3 Experimental activity

To properly replicate the working scenario on the HIL bench, an extensive on field measurement campaign was done to characterize the tractor activities. Since the proposed parallel architecture must at least be able to replicate the same performance of a traditional power unit, the focus of the experimental activity was the engine performance. This component would be the one to be replaced by the proposed hybrid system which should perform as well as the predecessor. To characterize the engine performance, some parameters available on the CAN BUS network were recorded during tests. In particular, the attention was focused on four parameters:

- Engine speed reference (or equivalently the driver pedal signal)
- Current engine speed
- Actual engine percentage load
- Vehicle speed

In this work the attention was focused in particular on two specific working operations involving the Power-Take-Off (PTO) of the tractor: the use of the atomizer and of the shredding implements. Both tests were performed with the ICE at its thermal steady state conditions. Operations at cold start have slightly different behaviours which were not considered in this analysis. Most of the tractor operations are always started after the thermal engine reaches a good working temperature and oil recirculation.

4 HIL Testing

The HIL testing activity was voted at the HCU control strategy validation. From the on-field characterization of the tractor activities, two PTO working scenarios were considered: the use of the atomizer for fertilizer deposition and the use of the shredding tool for green maintenance. The two working scenarios have peculiar characteristics in terms of intensity variability of the working load. Simulations were performed according to the following procedure:

- The measured speed reference during the on-field activity was scaled according to the EM rotational speed range (800-2300 to 100-800)

- The ICE speed reference was sent on the CAN BUS by the Linux PC with a timing of 10 ms (+/-0.1 ms) to simulate the pedal controller actuated by the driver.
- The same software on the PC was in charge of constantly monitoring the actual power unit load to constantly adjust the brake torque command. In this way, the feedback loop allowed to apply the correct braking torque to have the power unit actual load as close as possible to the one measured on the traditional architecture.

To properly simulate the working scenario, both ICE and EM where set up to reach the same power output of the traditional architecture with the more powerful diesel engine. Of course, the power characteristics of the diesel engines both of the traditional and downsized architectures were properly scaled according to the actual power characteristics of the electric machines available on the bench.

In *Figure 6*, results from the Atomizer test are shown. The parameters showed were monitored from the CAN BUS network of the HIL bench itself. It is possible to see that in the Atomizer test the overall percentage load of the downsized equivalent ICE unit is almost at the same level of the percentage load measured on the tractor. Although the ICE equivalent power reservoir was lower, HCU actuated EM in order to provide the required amount of power to satisfy the applied load. Although EM was capable of providing higher power boost, the Load observer weighted properly the torque reference of the EM speed controller running on the HCU to use as much as possible the ICE as primary power source. It is worth to mention that the Load observer function was set up to allow the ICE to work in the 80% engine load range during heavy loads. The main reason is that continuous operations at higher engine loads usually affect negatively the overall lifespan of the engine. Thus, with the exception of peak power demands, it is better to help the engine to decrease as much as possible the overall load in continuous operations. Of course, the trade-off depends on the capacity of the energy storage system considered for the application. The bigger it is, the higher can be the influence of the electric system on the overall duty cycle. The mean load provided by EM was kept quite constant by the Load observer around the 20% of the overall capacity of the electric motor itself. The stability of the control strategy is confirmed by the good tracking of the speed reference given by the driver although the external applied load.

In *Figure 7* results from the Shredder test are shown. Also in this case, it is possible to appreciate the Load observer effect on the overall output of the system. The lower power demand related to this working task, was easily covered by the ICE unit. The slightly higher variability of the load compared to the previous case, involved a little bit more the EM unit although the overall contribution was lower than the previous case. The external load variability produces higher output from the EM speed controller which explain the EM contribution around 16% average although the relatively low ICE load. The joint effort of the two motors allowed to properly follow also in this case the speed reference given by the driver, which confirms the good stability of the system although a more dynamic load.

5 Conclusions

In this work the design of a Hardware-In-the-Loop bench for testing and validation of a hybrid electric architecture for an orchard tractor was shown. The system was developed to prove the feasibility of the hybridization of a specialized tractor and of the required control strategy. The combined use of a smaller diesel engine and of an electric motor in parallel can provide the same power capabilities of a traditional diesel architecture but reducing the overall emissions thanks to the use of a more optimized thermal unit. The HIL bench at mechanical level allowed to test the overall architecture in its scaled representation but with the same mechanical layout that would be involved in the final machine. The hybrid system must be controlled by a supervisor unit, the Hybrid Control Unit, in charge of monitoring the actual condition of each component and actuate them to meet the driver demand for the specific working task. To design a Plug&Play solution which could easily adapt to an existing tractor architecture, the control strategy was thought with a Master-Slave configuration where the Master element was the “off-the-shelf” Diesel engine, and the slave element was the electric system. The control strategy included a Load observer weighting function which was designed to modulate the EM power boost according to the actual effort of the ICE unit. The HIL bench activity was developed in order to replicate some working scenarios measured during on-field operations of an orchard tractor. Parameters were read from the vehicle CAN BUS network and then used as input or lookup tables for the HIL bench, which adapted the torque applied by the electric load in order to replicate the same type of working load felt by the tractor power unit. In this way, it was possible to test the hybrid architecture both in terms of layout and control logic with a realistic working scenario. Results showed a stable behaviour of the system and of the actuation logic as demonstrated by the good tracking of the desired speed from the driver pedal in the different working conditions. The Atomizer simulation allowed to test the power capabilities of the combined unit which was able to provide the same power output of an equivalent scaled configuration of the traditional (more powerful) Diesel engine. In this scenario, the EM power boost was modulated by the load observer in order to optimize both the operating range of the diesel engine and the amount of electric energy supplied, to wisely use the energy stored in the vehicle battery pack. Similar results were obtained on the simulation of a shredding operation where the lower overall ICE load allowed to have lower power boost from the electric unit. However, in future works more Load observer curves will be explored in order to provide the final user with the possibility to choose between several power unit control strategies which could address more the power boost or the charge optimization.

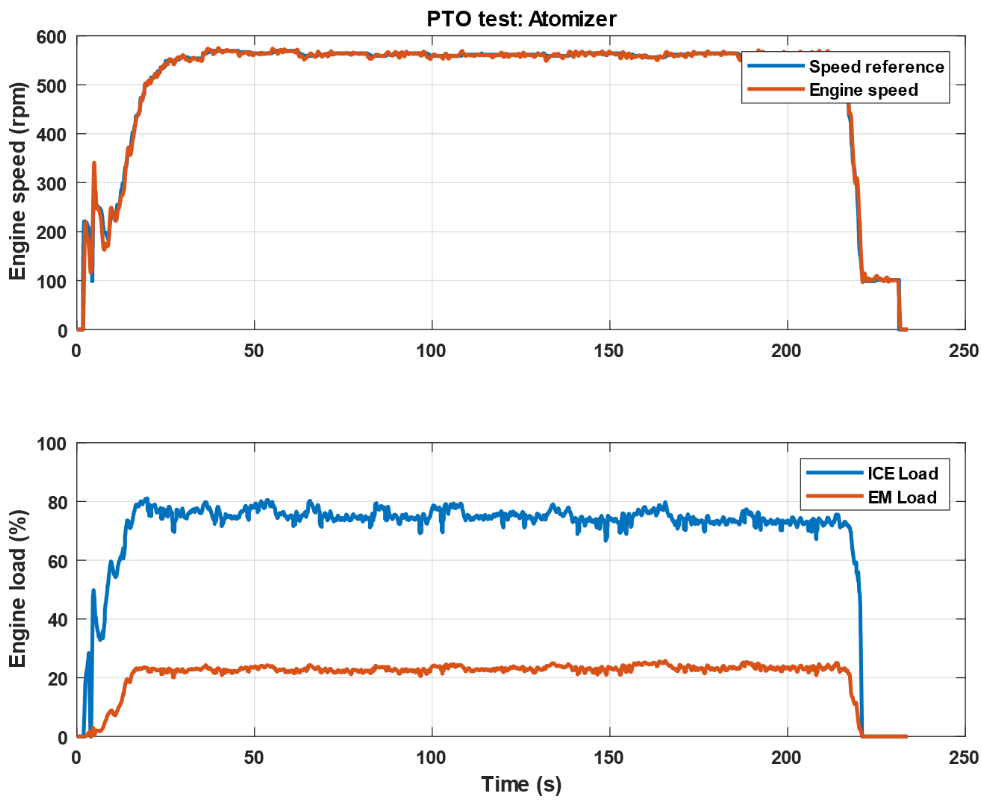

Figure 6 HIL simulation of the Atomizer test

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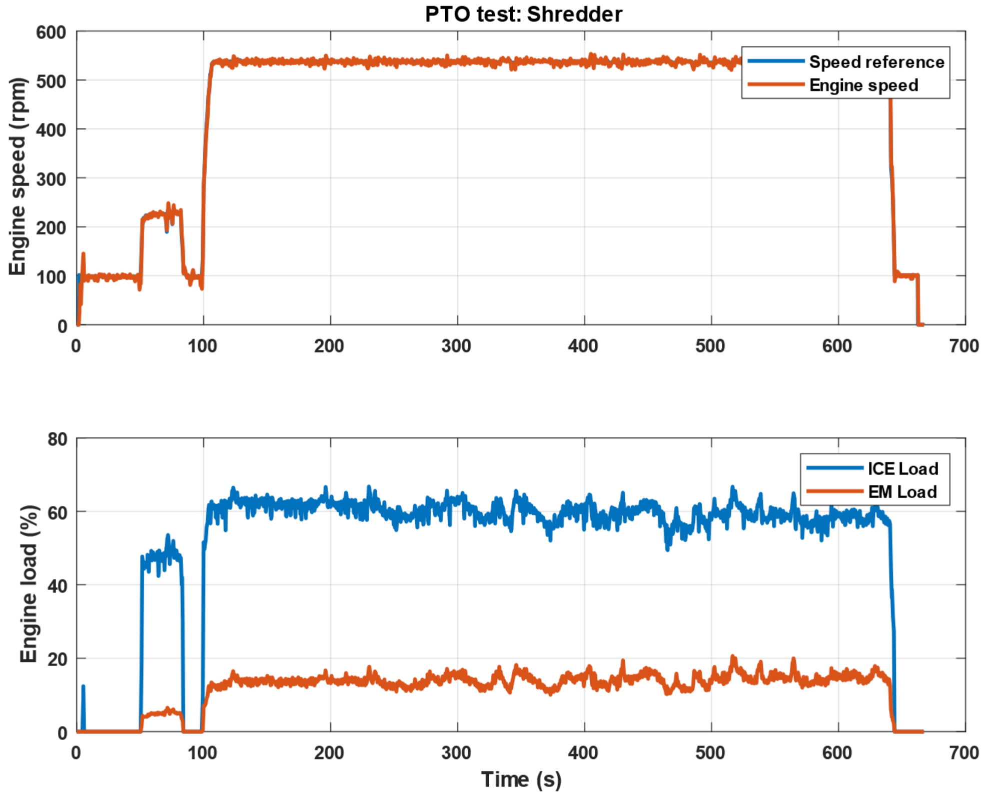

Figure 7 HIL simulation of the Shredder test

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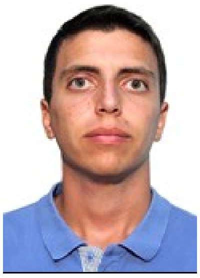

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