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Study of a Hardware-In-the-Loop bench for an electrified working vehicle

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Abstract

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. The control architecture for proposed hybrid powerunit will be tested on the configured HIL bench to evaluate performance on three different working tasks derived from experimental measurements.

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

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1. Introduction

Air quality is one of the most critical topics discussed in the modern society. Governments have to continuously discuss to achieve international agreements whose goal is to tackle worldwide the problem of air pollution and climate change (Kuklinska (2015); Hooftman (2018); Yuan (2017)). Road and off-road transportation play a big role in the production of harmful substances like NOx, Particulate Matter (PM) and Non-Methane Volatile Organic Compounds (NMVOCs) Bourguignon (2018). In the automotive field, powertrain electrification demonstrated to be a real alternative to improve the overall vehicle efficiency Katrašnik (2007), limiting the total amount of emitted pollutants. Highly efficient vehicles produce a lower amount of pollutants per unit of work because less fuel needs to be burnt. The field of Non-Road Mobile Machineries (NRMM) is now experiencing the benefits of vehicle electrification as solution to meet the strict emissions regulations for off-road machines (Somà (2017); Wang (2016); Lajunen (2018)). However,

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although electric and hybrid electric powertrains represent now an established technological solution in the automotive field, Electric (ENRMM) or Hybrid Electric (HENRMM) off road machines are still at a not mature enough level for the widespread adoption and commercialization. Construction machines manufacturers were the first in investing resources for the development of electrified powertrains Wang (2016). Hybrid excavators, for example, are now a well consolidated technology already available on the market. Electric motors efficiently accelerate the swing system recovering kinetic energy during deceleration of the rotating cabin. Hybrid wheel loaders have been proposed by several manufacturers in the last decade with different powertrain topologies Filla (2008). The most adopted solution for this class of machines is the series hybrid configuration. A diesel engine and electric generator are responsible for the production of the electric energy required by the system to power one or more electric motors connected to the driveline and/or to the auxiliaries. In the handling and agriculture field, several hybrid and electric solutions have been recently proposed (Somà (2016); Mocera (2018); Immonen (2016); Moreda (2016)). Each field of application usually requires custom solution depending on the specific working scenario the machine could face during its operating life. Mostly, the proposed architectures have hybrid configurations. Very few cases allow the successful adoption of full electric systems to propel the machine Mocera (2018). Although full electric configurations simplify most of the design constraints required by traditional Diesel powertrains, the actual state-of-the-art of energy storage systems prevents the widespread adoption on a higher number of working machines categories. The energy densities of the available Li-Ion based solutions do not meet the requirements dictated by common hard daily working cycles (Mocera (2019, 2018); Vergori (2018)). This is the reason why hybrid solutions represent today the most realistic solution for commercial products in these categories. Hybrid electric powertrains consist of a thermal engine and one or more electric machines actuated as motor, generator or both depending on the specific topology and instantaneous working condition. However, to properly manage all these subsystems obtaining the best performance for the application dedicated control strategies must be developed. Several studies are available in the literature about performance optimization of hybrid electric powertrains used on working machines (Oh (2015); Kim (2016); You (2018)). However, the simulated control strategy must be always validated on the real hardware platform that will execute it. Signals as close as possible to those coming from field operations should be provided to test the behaviour of the control strategy and its stability. This is essentially the base concept of the Model Based Design approach (Gaviani (2004); Nibert (2012)). Simulating the system at different levels, it is possible to reproduce 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). If the attention is focused on the physical VCU it is common to talk of Hardware-In-the-Loop (HIL) simulation. As described in Bouscayrol (2008) there are different levels of HIL for hybrid electric architecture simulations depending on what is the Device Under Test (DUT). A HIL simulation which focuses the attention only on the control unit, is usually addressed as 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 was developed. The main goal was to replicate a hybrid electric architecture designed for a small orchard tractor. The VCU to which the powertrain management is demanded, was tested on the designed HIL bench. The working scenarios were derived from field measurements of the main engine parameters of the traditional Diesel powered tractor. The bench goal was to prove that a hybrid powertrain with a smaller thermal engine would be able to cover peak power demand during real working conditions, with the control unit properly splitting the power among the two power sources in a stable and safe way.

2. HIL bench setup

The HIL bench studied in this work aimed to replicate on a smaller scale a parallel hybrid powertrain designed for an orchard tractor. Tractors are usually designed with oversized Diesel engines to satisfy the most critical power demanding tasks a farmer could face. However, tractors are usually engaged for just a fraction of the installed power leading in those cases to an overall higher fuel consumption. Thus, powertrains with smaller Diesel engines but able to provide power boosts in certain operating conditions would lead to an average higher efficiency during the whole tractor life. However, more complex systems require proper control strategy to manage all the components in the best way possible. The proposed architecture aimed to integrate an electric system with off-the-shelf Diesel engines with their own ECU obtaining at least similar peak power capabilities when compared to the traditional propulsion system.

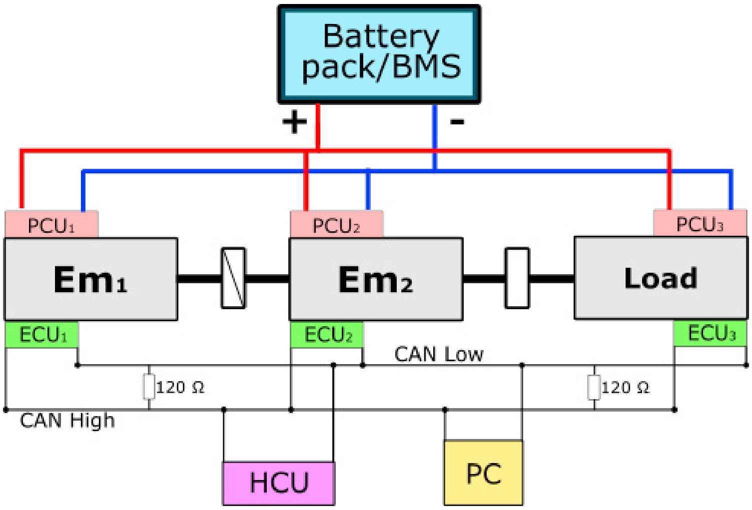
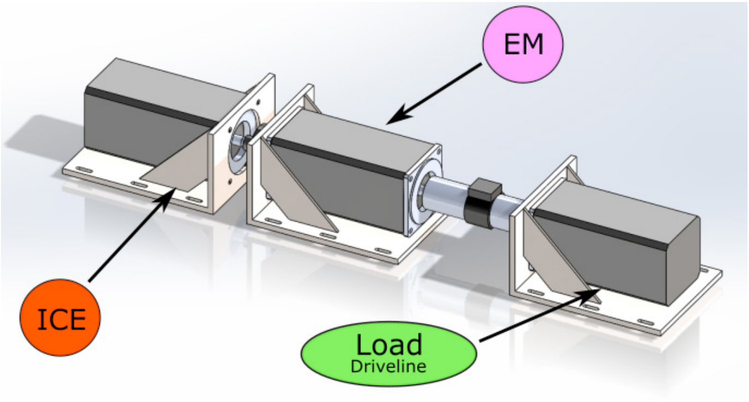
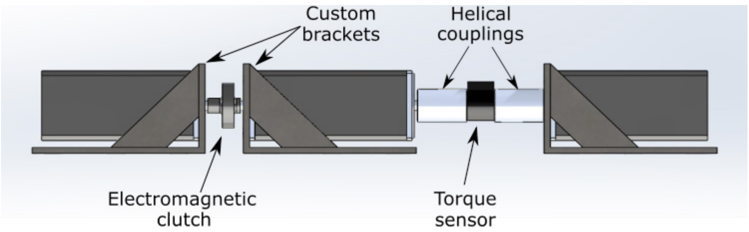


Fig. 1: HLI bench layout



(a) Flower one.



(b) Flower one.

Fig. 2: HIL Bench: mechanical couplings

To test the proposed powerunit, the HIL bench shown in Fig. 1, 2 and 3 was developed. The ”mechanical level” HIL bench aimed to replicate a scaled version of the entire powertrain consisting of:

- *Two Permanent Magnets Synchronous Motors (PMSM)*. The two motors were actuated by individual power electronic converters meant to convert the DC voltage of the system battery pack (40 V) to the required three

Fig. 3: HIL mechanical bench overview

phases sinusoidal current. One motor was controlled to simulate the Internal Combustion Engine (ICE) while the other to simulate the Electric Motor connected on the same shaft (parallel connection).

- *Two Electronic Control Units (ECUs)*. Each power converter (PCU in Fig. 1) was controlled by a local Electronic Control Unit (ECU) in charge of converting the control signals (either analogue or digital from the CAN BUS network) into actuation commands for the PCUs. ECU_1 firmware was developed to simulate the speed controller of the ICE, whereas ECU_2 firmware allowed both a speed and a torque control strategy.
- *A supervisor Hybrid Control Unit (HCU)*. The HCU was the supervisor controller to which the management of the whole powertrain was demanded. Its main tasks were related to the acquisition of the driver commands and feedback signals from the system components to elaborate the designed control strategy and send over the CAN BUS the proper actuation reference signals.
- *An electromagnetic clutch*. For the sake of completeness, an electromagnetic clutch was included in the powertrain between the ICE and the EM. Although not specifically included in the tests performed in this work, it allows to simulate the Full Electric mode. In this operating mode, only EM is actuated to propel the vehicle. However, the limited electric power installed on board should be sufficient to perform most of the tasks usually needed in Low Emissions Zones (LEZs) like close environments in the farm.
- *One electric brake (PMSM)*. To load the powertrain at mechanical level, a third PMSM machine was used and actuated in torque controlled mode. The ECU of this machine allowed to provide a mechanical load coming either from numerical model or from a set of data points sent over the CAN BUS network.
- *A driver/load simulator*. To complete the control architecture, a Personal Computer (PC) was in charge of simulating the driver control signals and the mechanical load to be applied by the Electric Load. For the specific case of this work, the pedal driver signal was assigned according to the field measurements. At the same time, the simulator was in charge of sending the correct Braking torque to be applied to ECU_3 according to a measured lookup table or according to a numerical model of the load. Each actuation command was sent over the CAN BUS network with a timing of 10 ms. To meet this timing requirement, the simulation software was developed on a Linux environment where the more stable and light task scheduling of the operating system allowed to achieve the desired timing performance.

Each ECU (Fig. 4) of the HIL bench was a node of a CAN BUS network (ISO 11898 (2014); Voss (2005)) where a custom communication protocol inspired to the SAE J1939 standard (SAE J1939 (2012); Voss (2008)) was developed. A 250 kBit/s baudrate was considered as transmission speed of the network. Two custom frames were defined:

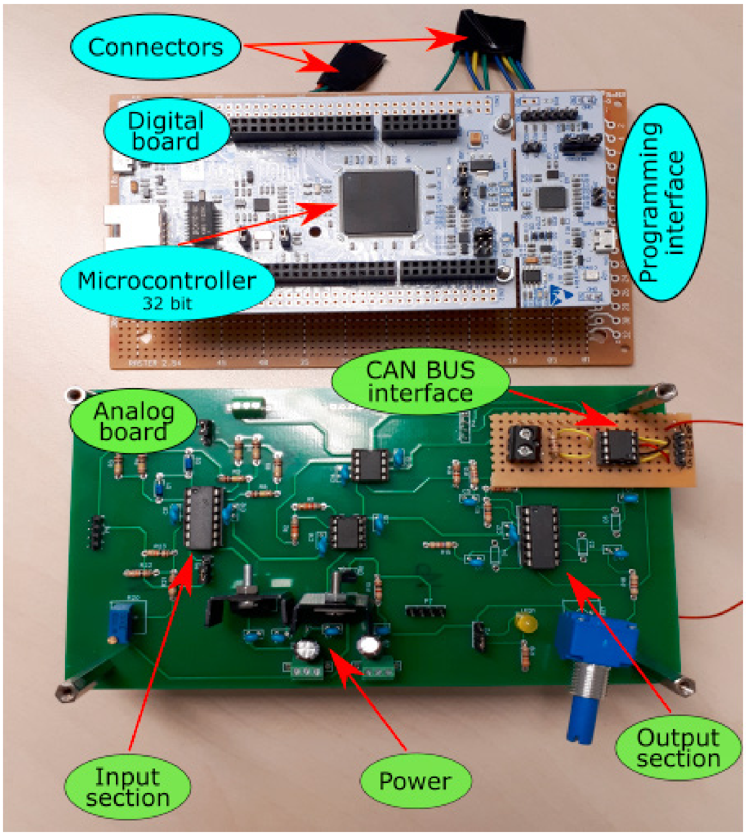


Fig. 4: Custom ECU architecture

- 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. The CAN BUS network implementation on the bench allowed to simulate performance of the control architecture also in terms of Real-Time capabilities of the proposed strategy.

3. HCU control strategy

The hybrid electric architecture proposed in this study for an orchard tractor was designed to be compatible with off-the-shelf Diesel engines and their local control logic. The electric system should provide power whenever the smaller Diesel engine of the new powertrain is not capable to satisfy the driver power demand. Since most of the modern off-road engines are speed controlled, a lack of power reservoir when performing a certain task would translate in a drop in the actual engine rpm and, in the most demanding cases, could result in a sudden engine shutdown. Thus, whenever the engine is not capable of following the speed set point because of an increase of the applied load, the HCU should control the electric motor to help it. Due to the faster response of the electric machine when requesting a certain amount of torque, the speed control loop running on the HCU must be managed in a master-slave configuration. Thus, to keep the diesel engine as the primary energy source, the EM control loop must run slower than the ICE one. Moreover, when actuating EM to provide a power boost, only positive torque (same direction of the diesel engine) must be provided. However, this simple master-slave configuration of the two control loops do not optimize the use of the electric energy stored in the battery pack. To be able to provide all the available power in the most demanding tasks, the loop parameters could provide electric power also in those cases where the smaller engine could be perfectly suitable. This is the reason why the Load Observer method shown in Fig. 5 was proposed for this control architecture. In some work case scenarios, a smaller ICE would suffer the lack of power reservoir. However, field measurements can easily show that most of the times these tractors use a fraction of the nominal power of their engines. The Load Observer function constantly looks at the actual ICE load transmitted over the CAN BUS network according to the J1939 standard. This parameter can be used to weight the actual EM torque reference according to the driver needs. If long work sessions are required, the battery energy have to be preserved to optimize as much as possible the overall efficiency of the working cycle. However, if the driver needs a boost to cover some heavy duty tasks, a Load Observer function with different weights would provide higher electric power at the cost of a more rapid discharge. In both cases the engine must remain the primary source of energy of the system: the higher the power demand, the higher will be the power output of the engine up to its saturation limits. For the purpose of this work, the Load Observer function was implemented in the form of a polynomial function of degree greater than one. The higher the polynomial order, the lower the EM boost at low engine loads. However, too high polynomial degrees can lead to more unstable behaviour, thus the best function must be calibrated also according to the vehicle characteristics. The polynomial function proposed in this work allowed a consistent EM intervention for ICE loads above 80%. 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 Fig. 6, the overall software architecture developed with the EcoCoder Simulink libraries from ECOTRONS can be divided into the following steps:

- *Hardware definition and setup.* The specific hardware platform characteristics were provided in terms of input/output signals ports as well as power management settings.
- *CAN BUS protocol definition.* 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) was defined to allow online parameters calibration.
- *Application software.* It was 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 the required 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 were variables stored in the Non Volatile Memory (NVM) of the hardware platform and read every time the controller was turned on. The latter were 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 were available until the HCU was active. If it the controller was turned off, changes were lost because 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.

4. Experimental activity

The goal of the proposed bench was to replicate a hybrid powertrain designed for an orchard tractor. Thus, to properly characterize the working scenarios an extensive set of field measurements were taken from a tractor of this

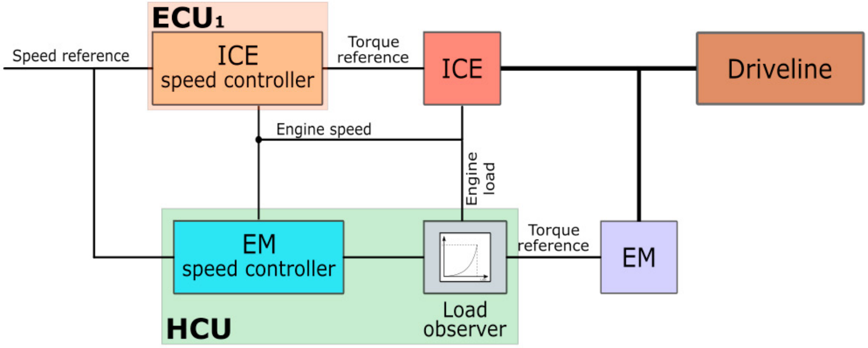
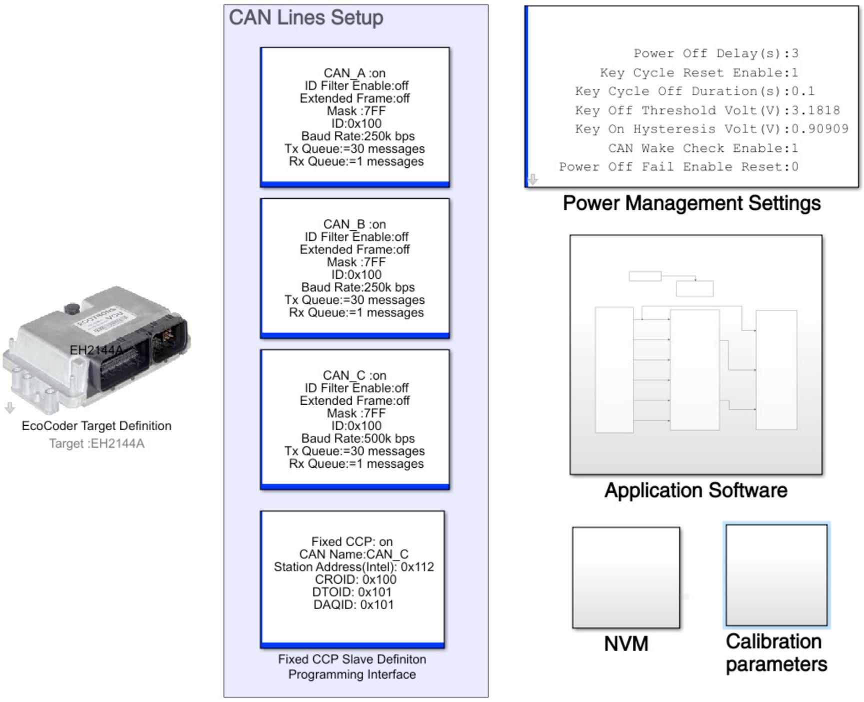


Fig. 5: Master-Slave control strategy with Load observer



```
CAN_A :on
ID Filter Enable:off
Extended Frame:off
Mask :7FF
ID:0x100
Baud Rate:250k bps
Tx Queue:=30 messages
Rx Queue:=1 messages
```

```
CAN_B :on
ID Filter Enable:off
Extended Frame:off
Mask :7FF
ID:0x100
Baud Rate:250k bps
Tx Queue:=30 messages
Rx Queue:=1 messages
```

```
CAN_C :on
ID Filter Enable:off
Extended Frame:off
Mask :7FF
ID:0x100
Baud Rate:500k bps
Tx Queue:=30 messages
Rx Queue:=1 messages
```

```
Fixed CCP: on
CAN Name:CAN_C
Station Address(Intel): 0x112
CROID: 0x100
DTOID: 0x101
DAQID: 0x101
```

```
Power Off Delay(s):3
Key Cycle Reset Enable:1
Key Cycle Off Duration(s):0.1
Key Off Threshold Volt(V):3.1818
Key On Hysteresis Volt(V):0.90909
CAN Wake Check Enable:1
Power Off Fail Enable Reset:0
```

Fig. 6: HCU software architecture

category during its daily working operations as well as simulating some of the most demanding tasks. The proposed parallel architecture must at least be able to provide the same power performance of the traditional architecture. Thus, the attention during the experimental activities focused on the performance parameters the engine published on the CAN BUS network of the vehicle. With the help of a CAN BUS analyser and of a personal computer (Fig. 7) the following parameters were monitored from the vehicle network:

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

Fig. 7: CAN BUS acquisition system

In this work the attention was focused on three specific working tasks involving the Power-Take-Off (PTO) of the tractor: the use of an atomizer, of a shredder and of a rotary harrow implement. All tests were performed with the ICE starting from its nominal operating temperature. 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.

5. HIL testing

In this work, the proposed parallel hybrid architecture for an orchard tractor and its control strategy architecture were tested on the designed HIL bench. The system was tested according to three working scenarios, derived from field characterization of the tractor activities. The chosen working scenarios consider the use of three different implements pulled to the tractor and taking power from it through its PTO system. In particular, the use of an atomizer for fertilizer deposition, the use of a shredding tool for green maintenance and the use of a rotary harrow superficial soil preparation were considered as case studies for this work. The proposed working scenarios had specific interesting characteristics in terms of average and peak power demand as shown in the summary reported in Tab. 1. The Atomizer load was characterized by a medium-high average power demand with almost a constant profile. The Shredding tool applied a medium-low load to the engine but with a higher difference between the mean and the maximum power request. Finally, the Rotary Harrow demonstrated to be the heaviest load among the all, with peaks in the power demands that can saturate the available installed power for few seconds. Thus, the proposed case studies had the correct ingredients to test: the stability of the control architecture in different operating conditions, from low loads up to full loading conditions; the overall performance of the powertrain understanding if the joint cooperation of the ICE and of the EM could at least perform as well as the traditional power unit.

Table 1: Statistics of the considered PTO working scenario – Power (kW).

	Atomizer	**Shredder**	**Rotary Harrow**
Min	34.5	12	35
Max	40	26	52
Mean	36	19	44

The testing session 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 (from 800-2300 rpm of the diesel engine down to 100-800 rpm of the electric motors)
- The ICE speed reference was sent over 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 on the bench the working scenarios, the power characteristics of the diesel engines both of the traditional and downsized architectures and of the EM of the electric system were scaled down according to the actual power characteristics of the electric machines available on the bench. In particular:

- the nominal power of the downsized diesel engine is 75% the nominal power of the traditional diesel engine
- the EM nominal power of the electric system is 40% the nominal power of the traditional diesel engine

Thus, the total installed power of the parallel hybrid power unit is greater then the nominal power. This would translate to overall better performance if the system is properly managed by the HCU. The same proportions were used when setting up the electric machines on the bench during the tests.

Fig. 8, shows results of the Atomizer test measured directly from the CAN BUS network of the bench. The plot shows the normalized percentage load of both the ICE and the EM while satisfying the power demand of the implement. It is worth to mention that the load applied to the hybrid power unit on the bench was the same measured during field measurements, just scaled to be compliant to the scaled size of the machines on the bench. The downsized ICE stabilized on a power output equal to the 80% of its total available power. The remaining power was correctly supplied by the EM that provided just 20% of its nominal power. Two considerations derived from this test. Although the lower nominal power of the diesel engine simulator, the power unit successfully satisfied the power demand without any instability as demonstrated by the good match between the reference set point of the speed controller and the actual rotational speed of the motors. Then, the use of just 20% of the electric power demonstrated the correct behaviour of the Load Observer which aimed to use the ICE as primary energy source, preserving the stored electric energy. As already mentioned, the Load Observer function was set up for these tests to increase the electric boost during heavy loading conditions. The 80% threshold identified was chosen also to preserve the overall lifespan of the engine which would suffer of higher fatigue if constantly load over this level. However, the trade-off strongly 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.

Fig. 9 shows results from the Shredder test. This working scenario was characterized by an overall light load, thus the goal of the HCU strategy was to minimize the amount of electric energy taken from the battery. The 60% average load on the ICE simulator and a mean 16% on the EM show the Load observer action in reducing as much as possible the amount of electric energy used. However, better results could have been achieved if a different weighting function would have been considered. In fact, the use of the same weights for the three working scenarios limited the degree of optimization achievable. The use of several calibrated Load Observer functions, for heavy and for light loads, would allow the driver to choose the best power unit management according to the daily activities.

This conclusion was highlighted also from the Rotary Harrow test, which results are shown in Fig. 10. This working scenario was the heaviest among the three case studies considered. The higher level of the power demand pushed the ICE at 90% of its power capability. These results are coherent with what was measured on the traditional power unit, which was highly stressed during this working task. During the most demanding moments, the EM was engaged at 40% of its maximum capabilities. A more aggressive Load Observer function would have led to a higher involvement of the electric system, but with a faster depletion of the stored energy. It is worth to mention that electric motors with lower nominal power could be taken into account if only these working scenarios are considered. However, the size of the electric machine proposed in this work was considered to allow also low power, full electric operations in LEZs. Smaller electric motors would not be able to perform minimal tasks, constraining the system to hybrid only operations.

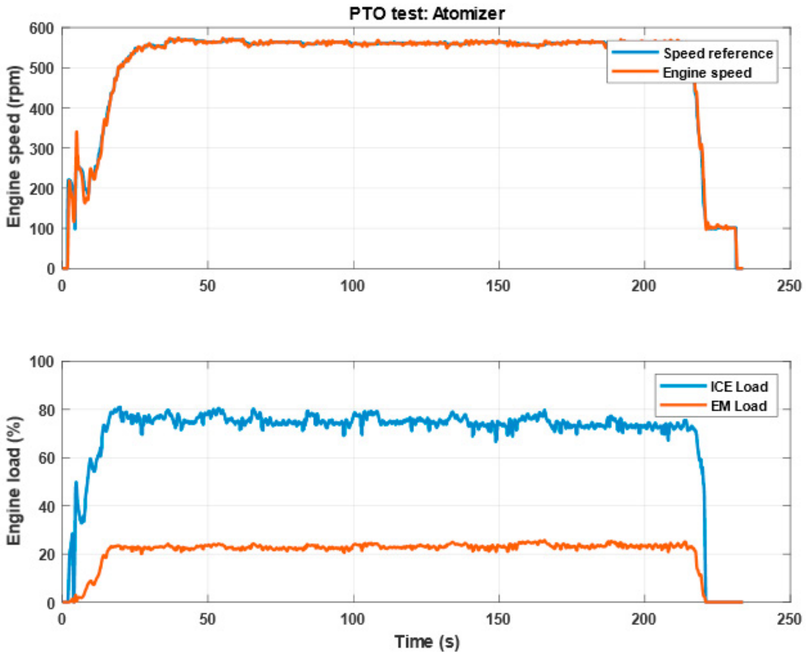


Fig. 8: HIL simulation of the Atomizer test

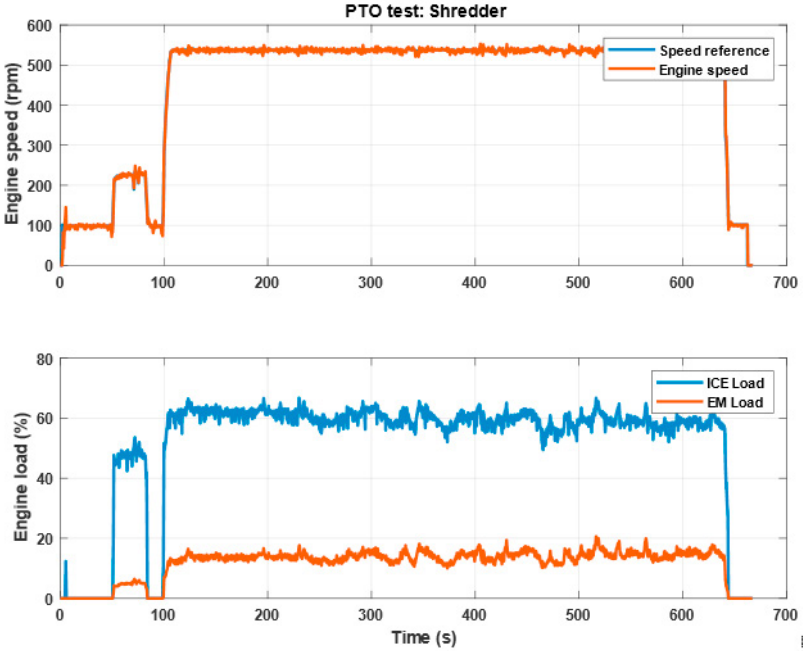


Fig. 9: HIL simulation of the Shredding tool

6. Conclusion

In this work, a Hardware-In-the-Loop bench was designed to replicate on a scaled size a parallel hybrid electric powertrain for an orchard tractor. The goal of the bench was to validate the proposed architecture in terms of sizing

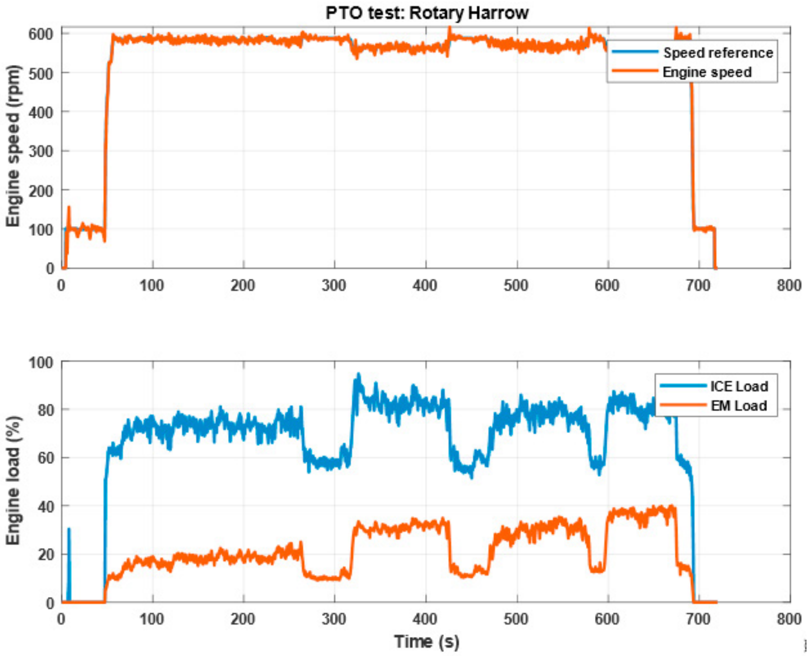


Fig. 10: HIL simulation of the Rotary Harrow tool

of the electro-mechanical components and of the control architecture. The proposed powertrain should have at least the same performance of the traditional power unit, providing power in the most stable way possible. The power unit on the HIL bench was controlled by a supervisor unit, the Hybrid Control Unit, in charge of executing the Master-Slave control strategy between the Internal Combustion Engine and the Electric Motor. The control architecture was designed to communicate through a CAN BUS communication protocol inspired to the SAE J1939 standard to be compatible with off-the-shelf Diesel power unit and their controllers. The algorithm included a Load Observer function aimed to optimize performance according to the needs of the driver. In this work, the proposed Load Observer function was calibrated to preserve the electric energy stored on the battery system in order to use as much as possible the thermal unit as the primary source of energy. However, several Load Observer function could be implemented giving the driver the freedom to choose according to the daily tasks to perform. On the HIL The scaled powertrain and its control architecture were tested both at software and hardware level with three working scenario derived from field measurements on a real orchard tractor. The three loading scenarios consisted of three working tasks involving different implements powered by the tractor Power-Take-Off. During these operations the tractor pulled and powered the implement at the same time. Measurements focused the attention on the monitoring parameters sent by the Diesel engine over the CAN BUS network to characterize the actual load experienced by the power unit during this operation. On the HIL bench, these loads were properly replicated to understand if the joint cooperation of the two motors could satisfy the instantaneous power demand. In all the three cases the power was provided by the hybrid power unit with stable output performance as demonstrated by the good match between the reference speed set point of the diesel speed controller and the actual speed of the shaft. Moreover, the Load Observer function managed well the power split in all three tests making sure that the thermal unit would always had been the primary energy source. This was demonstrated by the EM actual percentage load that was always below 40% of its maximum capabilities also in the most demanding scenarios of the Rotary Harrow test. The performed simulations confirmed that the use of different Load observer function would better fit to the need of the driver. In operations like shredding, the downsized engine would surely have enough power and the electric system could be preserved for more demanding tasks. Future works should investigate the differences in overall optimization if several Load Observer functions will be considered for the same working scenarios. Moreover, the real capabilities in full electric mode in terms of tasks that can be performed with the proposed sizes of the machines will be explored.

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