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SCUOLA DI INGEGNERIA INDUSTRIALE
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Executive Summary of the Thesis

Hardware in Loop Simulation & Testing of Series Hybrid Architectures

Laurea Magistrale in Electrical Engineering - Ingegneria Elettrical

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Academic year: 2022-2023

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1. Introduction

The farming machinery industry is undergoing a steady transition in hybridized and electrified powertrains, and the relevance of hybrid technology in becoming increasingly relevant in terms of fuel economy, improved performance and reduced carbon footprint. With the introduction of a Battery Pack working in tandem with an Internal Combustion Engine, it is necessary to engineer and employ a suitably designed Energy Management System (EMS) that manages the energy exchange and power delivery between both the power sources. It is therefore important to ensure that the intervention of the Battery Pack ensures a reduction in the powertrain's reliance on the Engine, while making sure that all the power requirements are met. This thesis aims to model and simulate a series-hybrid tractor powertrain using Typhoon-HIL. An attempt has been made to design and test an EMS with the objective of optimizing the power delivered by the Battery Pack, and reducing the dependence on the Internal Combustion Engine.

2. Problem Statement

The objective of the thesis is to develop an energy management system that can accurately map the power requested from the electro-mechanical loads, and make adjustments to the power output of the engine and the Battery Pack in order to reduce the involvement of the I.C. Engine, while ensuring that the battery pack remains optimally charged [3]. In order to achieve this objective, this thesis adopts the following stages of progression:

1. Development of the basic Architectural Layout of the Electric Powertrain.
2. Selection and Modeling of PTO loads, and understanding Duty Cycles.
3. Testing and Validation of modeled loads, and ensuring all Power Quality criteria are met.
4. Designing a suitable Power Metering system, and running simulations on all load combinations to understand long-term loading scenarios.
5. Developing and deploying an Energy Management System that can successfully gauge power requirements, and govern the output of the Engine as well as the Battery Pack.

3. System Modeling

The modeling of the hybrid powertrain [4] architecture has been approached as shown in Figure 1. The architecture includes a generator, which represents the electrical power produced

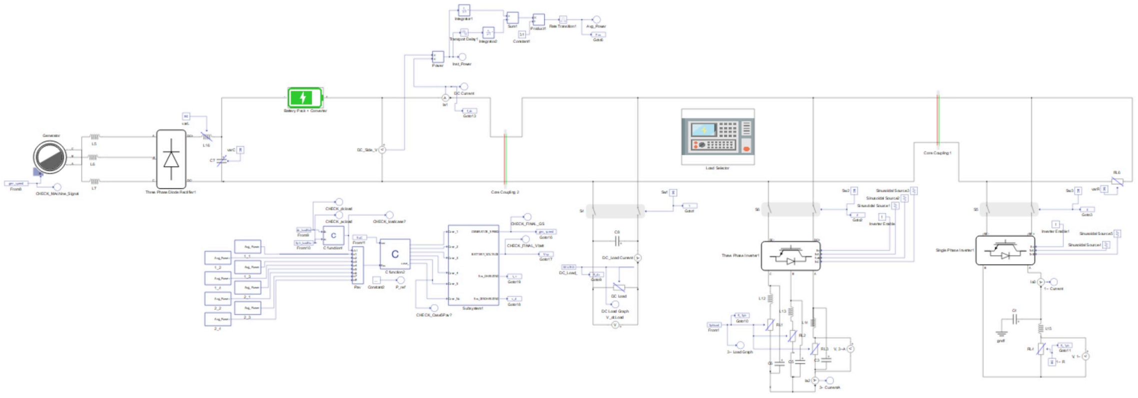


Figure 1: Overview of the Powertrain Architecture Model

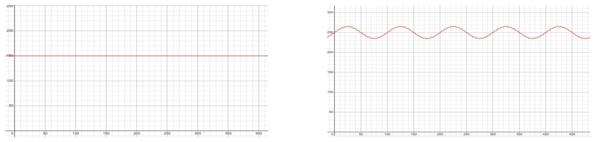
after the I.C. Engine. A Battery Pack has been modeled and installed, which supports the Engine in supplying power to the loads. A total of 7 different kinds of Agricultural Implements have been modeled into the system, and can be classified as DC [2], 1-phase AC [1] or 3-phase AC Loads.

In addition, the architecture is also equipped with a custom measurement system, designed for approximating Average Power consumed by the loads in time intervals of 0.1s. Finally, an EMS has been designed an employed, which takes charge of distributing power delivery between the Engine and the Battery Pack.

3.1. Duty Cycle Modeling

For simulating various kinds of agricultural implements, the following electrical loads have been modeled:

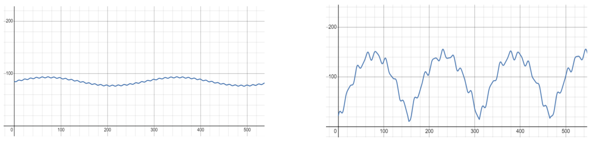
- **DC Loads:** Snowblower, Battery Heater.
- **1-phase AC Loads:** PLC Unit.
- **3-phase AC Loads:** Manure Spreader, Cultivator, Atomizer, Seed Spreader.



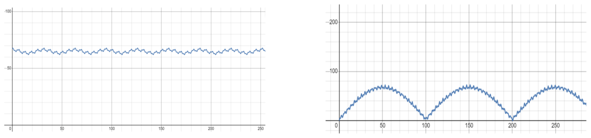
(a) Snowblower (b) Battery Heater

Figure 2: Duty Cycle Modeling of DC Loads.

The electrical loads have been modeled based on their real-world duty cycles, taking reference from literature [5] data. These have essentially been represented as time-varying resistance values, aimed to mimic the actual power behaviour of the implement. Equations 1 to 7 illustrate the mathematical functions developed to describe these load functions.



(a) Manure Spreader (b) Cultivator



(c) Atomizer (d) Seed Spreader

Figure 3: Duty Cycle Modeling of 3-phase AC Loads.

Snowblower:

$$R(t) = 150 \tag{1}$$

Battery Heater:

$$R(t) = 250 + 15[sin(\frac{2\pi}{100})t] + sin(t) \tag{2}$$

PLC Unit:

$$R(t) = 100 \tag{3}$$

Manure Spreader:

$$R(t) = 85 + 8sin(\frac{2\pi}{280}t) - sin(0.5t) \tag{4}$$

Cultivator:

$$R(t) = 15 + 130|sin(\frac{2\pi}{310})t| + 3sin(0.5t) + 8cos(0.3t) \tag{5}$$

Atomizer:

$$R(t) = 65 + 1.5cos(0.2t) + cos(t) + 0.5sin(3t) \tag{6}$$

Seed Spreader:

$$R(t) = 15 + 65|sin(\frac{2\pi}{200}t)| + 2sin(3t) - 5|cos(0.8t)| \tag{7}$$

3.2. Battery Pack

In this thesis, a custom Battery Pack has been designed and modeled, along with the converter. This has been carried out to suit the requirements of the model better, and reduce computational costs and system complexities.

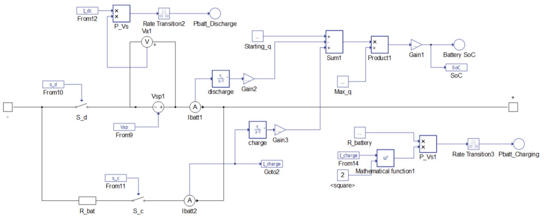


Figure 4: Battery Pack + Converter Model.

Furthermore, the Battery Pack is designed to supply a voltage of up to 225V at the DC Bus whenever required, in order to meet power demands without having to rely on the I.C. Engine. Additionally, the Battery Schematic has been designed to accommodate Battery charging and State of Charge (SoC) monitoring [3] using Coulomb Counting technique.

4. Energy Management System

The Energy Management System (EMS) is an important system which takes charge of managing power distribution duties between the Engine and the Battery Pack.

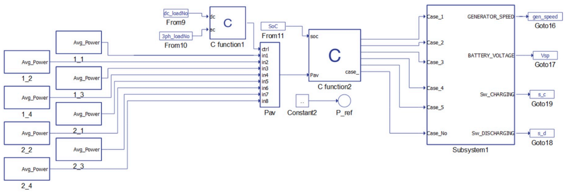
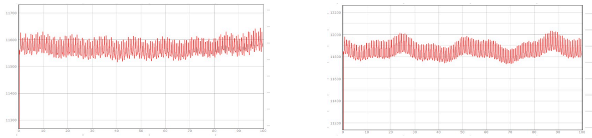


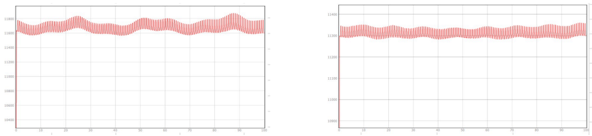
Figure 5: Energy Management System Model.

Figure 5 illustrates the model of the EMS deployed in the powertrain architecture. The system consists of a set of Dynamic Tables which provide the real-time Average Power values of all 8 load combinations (Four 3-phase AC Loads × Two DC Loads), along with two C-Functions which identify the implements selected by the user, and read the SoC of the Battery Pack. It should be highlighted that the Dynamic Tables contain pre-fed Average Power consumption data for all load cases, collected through independent load simulations without the intervention of the Energy Management System. These data-points have been simulated and collected for a time period of 100s, and have been illustrated in Figure 6.



(a) Snowblower + Manure Spreader

(b) Snowblower + Cultivator



(c) Battery Heater + Atomizer

(d) Battery Heater + Seed Spreader

Figure 6: Exemplary Average Power curves for some Load Cases.

It is essential that the EMS takes reference of power values from the ideal expected data available in the Dynamic Tables, as referencing Power values from the system itself may potentially lead to instabilities. Based on the SoC of the Battery, the EMS decides a "Case Number", which essentially dictates the involvement of the Battery Pack in power delivery to the electrical loads.

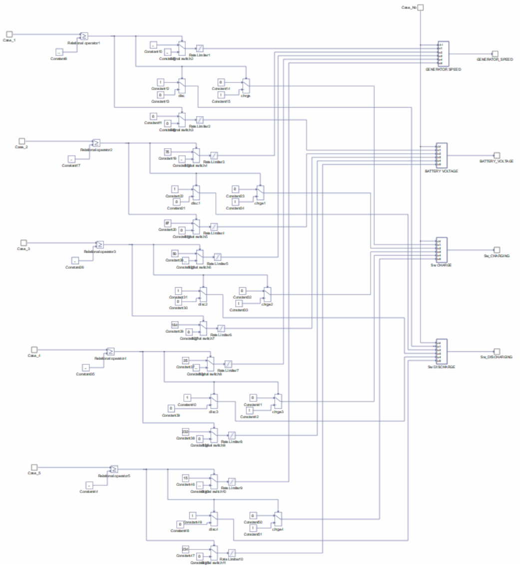


Figure 7: Signal Processing Network inside the Energy Management Controller.

The signals processed and pass through the various blocks of the EMS are finally fed into the Energy Management Controller, illustrated in Figure 7. Depending on the Case Number assigned in the previous stages, the Energy Management Controller decides the switching patterns and output values of the Engine and the Battery Pack. The overall EMS is essentially guided by the logic that when the power demand, or Average Power drawn by the loads exceeds a set threshold, does the Battery Pack come into play. Otherwise, the Engine supplies the lower power demands, while also charging the Battery Pack.

5. Simulation Results

The objective of running system-level simulations is to verify whether the EMS is working and managing energy distributions properly between the I.C. Engine and the Battery Pack. This can be verified only if all of the following conditions are met:

1. Battery and Engine Parameters change when $P_{av} > P_{ref}$, and according to SoC variation.
2. Battery charges when $P_{av} < P_{ref}$, and delivers power to the loads when $P_{av} > P_{ref}$.
3. SoC follows appropriate cycles based on Power Demand.

In this section, a total of 5 load cases have been simulated, all with different starting SoC values to get a better sense of the energy management being carried out by the EMS.

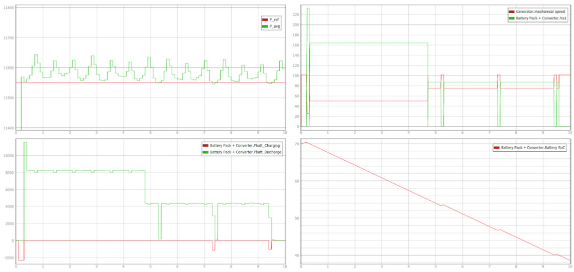


Figure 8: Powertrain Parameters with Battery Heater and Cultivator, Starting SoC = 70.0%.

The graphs illustrated in this section show clear indications of how the system parameters change, based on the real-time power demands of the loads. It can be observed that whenever the Average Power values exceed the threshold reference value, i.e. 11.55 kW, the EMS controls the power delivery to the loads, which can be seen as the green curves in the bottom-left graphs.

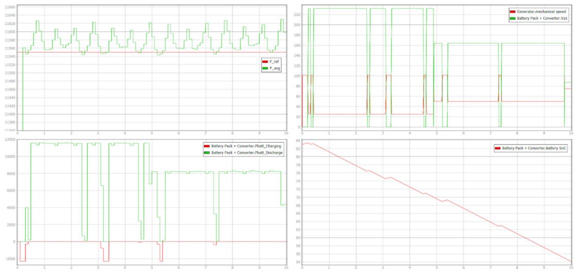


Figure 9: Powertrain Parameters with Battery Heater and Manure Spreader, Starting SoC = 83.0%.

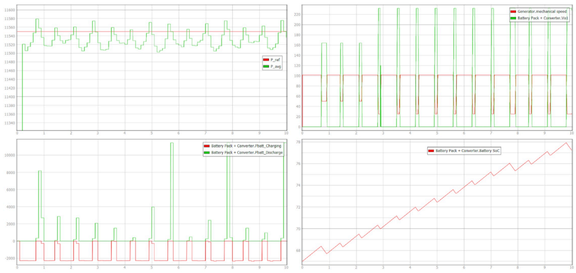


Figure 10: Powertrain Parameters with Battery Heater and Seed Spreader, Starting SoC = 67.0%.

Similarly, the bottom-left graphs also illustrate how much power the Battery Pack draws from the engine, which are shown in red. The EMS controls the Engine power to ensure that it supplies the loads, while also charging the Battery Pack when the power demand is not high. Also worth paying attention to are the top-right graphs, which indicate the real-time values of Battery Voltage and Generator Speed.

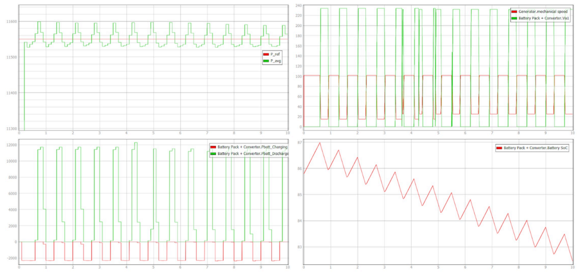


Figure 11: Powertrain Parameters with Snowblower and Cultivator, Starting SoC = 85.8%.

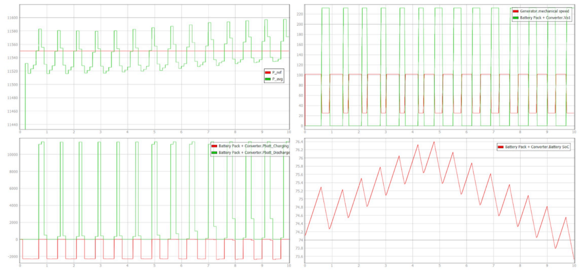


Figure 12: Powertrain Parameters with Snowblower and Manure Spreader, Starting SoC = 74.1%.

The Generator Speed goes down whenever power demand is high, thereby decreasing the power output from the Engine side. During this time, the Battery Voltage rises to compensate for the power. These changes take place whenever P_{av} crosses P_{ref}, and magnitudes of these parameters depends on the SoC of the Battery Pack. Finally, the bottom-right curves illustrated in red highlight the variation in Battery Pack SoC. Depending on when and for how long the Battery charges and discharges, the SoC goes up or down, and indicates an overall trend in power consumption.

6. Conclusions

From the tests and simulation data, it can be clearly observed that installing an effectively designed Energy Management System plays a key role in reducing the Hybrid powertrain's reliance on the Internal Combustion Engine. The impact played by the Battery's State of Charge is also critical in determining the contribution of power delivery from the Battery Pack. Maintaining the SoC of the Battery Pack must therefore be optimized in order to ensure the longevity of the electrical system and consistent power delivery by the Battery Pack. By incorporating hybridized architectures in agricultural powertrains, the need for designing and installing high-displacement Engines can be reduced. Not only do efficiently managed Hybrid powertrains offer high functionality to the user, they play a significant impact in bringing down the vehicle's carbon footprint. Additionally, the design and deployment of superior Energy Management Strategies can serve to improve powertrain performance even to a further degree. By employing more sophisticated control schemes, as well as using advanced tools such as Neural Networks and Reinforced Learning models, it is possible to predict the power demand of the loads, and make necessary corrections in the electrical network beforehand. This can not only lead to improved powertrain efficiencies, but can also help in bringing down system complexities, number of controllers and even power converter devices. The overall result could potentially be a far more compact and energy-efficient hybrid powertrain.

7. Acknowledgements

I extend my utmost gratitude to my esteemed supervisor, Professor Giambattista Gruosso and co-supervisor, Professor Giancarlo Storti Gajani for their guidance, invaluable support, and immense knowledge. I am extremely grateful for the instrumental role played by my other co-supervisor, Marziyeh Hemmati, whose deep technical insights and impeccable software skills have brought this thesis to life. I am also indebted to the faculty members of Politecnico di Milano, whose wisdom, expertise, and passion for their respective fields have enriched my academic experience. Their commitment to fostering an environment of learning and intellectual curiosity has been a constant source of inspiration throughout my journey.

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