Modular approach to energy management and hybrid control strategy

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ABSTRACT

The article presents an overview of the vehicle simulation platform and how it was designed to optimize the energy management of virtually all kinds of series and parallel hybrid architectures. The article discusses the importance of optimizing strategies to correctly use the functions of electrical machines in hybrid powertrains and how the simulation tool is designed to accurately simulate virtually all hybrid powertrains. And also explore the mechanics of these simulation tools, highlighting their ability to accurately model various aspects of hybrid powertrains, including energy usage and emissions, and their role in improving the efficiency and sustainability of modern vehicles. Overall, this article provides a comprehensive introduction to this vehicle simulation platform and its potential to improve the way we approach hybrid vehicle design and optimization.

Kew words: simulator, hybrid vehicle.

1. INTRODUCTION

Concern for the environment has been relevant to several sectors, including the automotive sector. The growth in vehicle electrification is notable in some countries and regions, such as Europe and China, which have seen a high increase in pure electric car sales in recent years. However, in Brazil, electrification has come through hybridization, which is the combination of a combustion engine with an electric machine. There are several factors that justify this reality, such as the widespread use of biofuels such as ethanol, the ease of adaptation of vehicle platforms present in the market and also the fact that it is not necessary to adapt the infrastructure of electric service stations, which demands high investment.

Conceptually, the main hybridization platforms are P0, P1, P2, P3, P4, where there is variation in the position of the electric machine in the vehicle architecture.

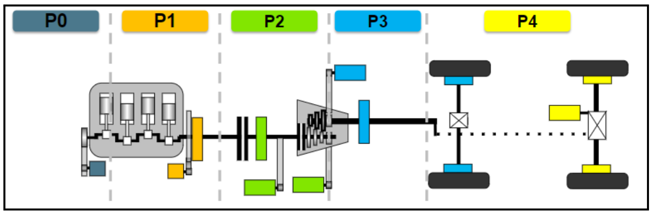

Figure 1. Hybridization platforms

The mild hybrid configurations P0 and P1 have the electrical machines coupled to the internal combustion engine, without the possibility of mechanical disconnection. This makes torque boost and energy recovery less efficient due to system torque losses.

The mild hybrid architectures P2, P3 and P4 are better in terms of efficiency, mainly due to the positioning of the electric machine. In these types of configurations, the electrical machine is positioned after the driveline connecting device (clutch), on the transmission input shaft (P2), on the transmission output shaft (P3) or on the rear differential (P4).

In a P2 configuration, the electrical machine can be attached laterally to the transmission, connected by a belt, or integrated into the transmission, connected by a gear. The main advantage of this architecture is the increased energy recovery potential and the availability of additional hybrid control functions.

In the P3 mild hybrid architecture, the electric motor is coupled to the transmission on the output shaft. In the P4 architecture, the electric motor is mounted on the rear axle drive or on the wheel hubs. The main advantage of these topologies is the greater potential for energy recovery. Compared to P0, P1 and P2 settings, engine and transmission losses, when the driveline is disconnected, are not considered during energy regeneration.

The P3 and P4 architectures also have the potential for electric driving mode if equipped with a high-torque electric machine. The P4's architecture gives the vehicle all-wheel drive capabilities, with the front axle powered by an internal combustion engine and the rear axle powered by an electric motor.

In line with this evolution in hybrid vehicle architectures, the analysis and simulation of their characteristics has become increasingly complex, as each platform has certain influences on the initial structure (only with the combustion engine). The objective of this work is to present a tool for the simulation of hybrid architectures, its functions, demonstrate examples of its use and a comparison with the results of a real application.

2. SIMULATOR AND ITS FUNCTIONS

The Hybrid Vehicle Simulator (HEVSim) is a tool developed by Valeo based on MATLAB, Simulink and AMESim. It has the vehicle architecture divided into modules, each with its own characteristics:

- **Internal Combustion Engine (ICE):** displacement, inertia, idle speed as a function of temperature, BMEP table as a function of engine speed, idle fuel consumption, fuel density and lower calorific value; engine maps: BMEP max prior of turbo activation as a function of engine speed, turbo lag as a function of engine speed, fuel mass flow as a function of engine speed and torque, FMEP as a function of speed and temperature, wall heat losses coefficient as a function of speed and BMEP;
- **Gearbox:** type, inertia, number of gears, gears ratio, gearbox efficiency map as a function of gear, speed, torque and temperature, torque losses map as a function of gear, speed, torque and temperature, and maximum clutch torque;
- **Electric machines (it can be one or two):** position (P0, P1, P2, P3, P4), torque limits map as a function of speed and voltage, power losses map as a function of speed, torque and voltage, rotor inertia, speed limit, reducer type, reducer ratio, reducer drag torque, wire resistance between machine and traction battery;
- **Vehicle informations:** mass, coefficient of static friction, coefficient of rolling resistance, air penetration coefficient, active area in aerodynamic drag, air density;
- **Wheel informations:** inertia and diameter;
- **12V Battery:** type and capacity;
- **Secondary Battery (if applicable):** type, number of cells in serial and parallel, total capacity, max charge and discharge current, max and min voltage, open circuit voltage as a function of battery state of charge, internal resistance as a function of battery state of charge, useful capacity, connectors resistance;
- **Network separator (DCDC convertor, switch, wire):** type, efficiency, mass power, wire resistance;
- Conduction cycle for the simulation (WLPT, FTP-75, HWFET, and others);
- **Starter / Alternator:** torque profile, pulley ratio;

- **On board charger (if applicable):** efficiency, as it'll be used to define the AC electrical consumption;

Each module is arranged in blocks by the simulator and are related to each other, and their parameters are adjusted as required.

The simulator's main objective is to analyze the benefits that hybridization can bring to the vehicle, which are the reduction of emissions, fuel economy, and energy regeneration. These advantages are guaranteed through the functionalities of the electric machine. Some of these functions are:

- **Generator:** high efficiency alternator functions and regenerative braking;
- **Starter assist:** First start and restart, reflex start, dual shoot and torque control;
- **Torque assist:** torque control and constant current;
- **Stalling assist.**

The use of these functions depends on the initial strategy of each case and on the considered architecture and may or may not be applied.

3. HYBRIDIZATION STRATEGY

With two sources, the car's traction formula is as follows:

$$P_{traction} = P_{ICE} + P_{EM} \tag{1}$$

Traction ($P_{traction}$) is no longer exclusive to the energy of the combustion engine (P_{ICE}), but also to the energy of the electric machine (P_{EM}), where the energy to be supplied is defined by the state of charge of the battery (SoC). The control strategy of this system must select the power to be produced by each ratio, charge the battery when the SoC is low and discharge the battery when the SoC is high.

The hybridization strategy can be defined during the simulation or as required and will depend on the assigned functions and characteristics. Some generic examples:

- **Regenerative braking in 12V :** negative torque demand and voltage regulation with max 15V;
- **Torque assist:** it has a positive torque demand and battery SOC must be above certain level;
- **Generation mode:** it has a negative torque demand and battery SoC must below certain level;
- **Gear shifting:** use an optimal gear shifting strategy
- **Hybrid control unit (HCU):** use optimal command strategy based on Hamiltonian Pontryagin minimization principle.

4. PONTRYAGIN'S MAXIMUM PRINCIPLE

The idea of Pontryagin's maximum principle is to find the minimum value for hamiltonian during a cycle, which means, in this application, to find the minimum amount of energy needed to move the vehicle as requested by the pilot. Follow equation:

$$H = P_{fuel} + \lambda * P_{battery} \tag{2}$$

Where:

- H is the hamiltonian, which represents the total energy of the system;
- P_{fuel} is the fuel power, equivalent to a fuel mass flow;
- $P_{battery}$ is the useful battery power, equivalent to a SoC variation;
- λ is the lagrangian factor. It gives an equivalence between fuel consumption and SoC variation.

The first step in applying the equation is to calculate all possible torque splits between ICE and EM, and also the fuel and electric consumption in each of these possibilities. Then, the value of λ must be calculated, which directly impacts the SoC, and must be chosen so that the battery does not charge and discharge excessively during the cycle, affecting its useful life. In other words, when λ is low, we tend to maximize the electrical energy coming out of the battery, and when λ is high, we tend to maximize the electrical energy going into the battery.

A limitation of the value of λ is that the initial state of charge of the battery must be equal to the final one, so as not to affect the performance, for example, if the vehicle comes to a stop, the battery must have the necessary charge for the EM to act as starter assistant .

$$\int P_{battery} = 0 \tag{3}$$

There are three ways to calculate the value of λ:

- **Offline;**
- **Online;**
- **Online with prediction.**

Offline is calculated before any cycle, and it is the simplest way to calculate λ, as there is no change in any system variable. From an initial value of λ, speed and requested torque, the final SoC is verified, and this system continues simulating until it finds an optimized value.

In Online, the vehicle is in the driving cycle and the value of λ must be calculated continuously, whenever the required torque and the SoC change. However, assuming that the torque and SoC are changing all the time, it is necessary to update the value of λ every few seconds. One way to improve the calculation time is to use a λ map, where the energy variation is presented as a function of torque demand, vehicle speed and the value of λ.

Even with λ being updated all the time to meet the vehicle's needs, there are some transients that make finding the minimum H difficult. These transients can be, for example, gear shifting and engine starting. At these instants, there is no way to predict what energy will be used in changing the speed and state of the components or even the exact loss of energy.

Thus, the most accurate λ calculation method is Online with prediction, which uses external data to predict and anticipate the behavior of the cycle. This prediction can be made using GPS and map data, as well as real-time traffic data.

5. SIMULATION EXAMPLES

In the table below, it is possible to compare the reduction in the level of CO2 emission between different examples of hybridization simulation, separated by vehicle segment and architecture.

HEV CO2 emissions - Reduction vs conventional [%]			
Architecture EM	**P0**	**P0P4**	**P4**
Seg B	-5.50%	-17.20%	
Seg C	-4.20%	-14.30%	-13.40%
Seg D	-5.80%	-17.20%	-16.40%
Seg E	-4.80%	-17.40%	-16.90%

Table 1. HEV CO_2 emissions

In a real application, some configurations were simulated and applied in a vehicle for comparison of the results considering the Brazilian market and regulations. The vehicle is a B-segment car, tested with E100 fuel, with the aim of studying the implementation of the P0 platform. In the simulation, the predicted fuel economy was -6.5% and in the real application, the observed economy was -5.7% in consumption.

6. CONCLUSION

The hybrid vehicle simulator is a key tool for the development of new technologies. Through this, automotive market manufacturers can take the first step to evolve systems and machines, ensuring that the settings will bring the due benefit sought, and that they will be in accordance with the new emissions laws. Through examples, it was observed that the results presented by the simulator are similar to a real application, and its use is relevant for the sector.

7. REFERENCES

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Figure 1 - Hybridization platforms. Valeo Intellectual property.

Table 1 - HEV CO_2 emissions. Valeo Intellectual property.