Powertrain Energy Management for Hybrid Electric Scooter

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***Abstract*—This paper presents the structure and controls of an Hybrid Electric Scooter (HES). The vehicle manages also a regenerative breaking system. This work began with a currently marketed 125 cm^3 scooter with only heat engine. An electric motor has been placed in the wheel. To feed this electric motor, two electric storage are used : $LiFePO_4$ cells and supercapacity. Twenty-four cells are linked together in order to create a 80 V battery. Supercapacity replaces classic lead battery feeding auxiliary devices (sensors, dashboard ...) and absorbs eventual current peaks during accelerations. An energy management has been developed and tested on a fully functional scooter. Moreover, as the scooter has been developed in partnership with a trading company (Mazziotta Motors), whose purpose was to market a final product, we carried out the tests imposed by the standards on electromagnetic compatibility.**

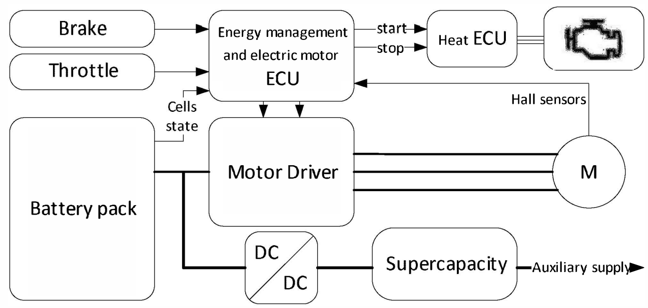

Figure 1. Overview of the system structure

I. Introduction

Hybrid electric vehicle are expected to be a major challenge in the coming years [1]–[3]. Powertrain architectures (discussed in section II) integrate complex electrical and electrochemical systems such as electric motor and heat engine, DC/DC converter and batteries [4]. The development of low-emission vehicle can help to increase air quality. As reduced air quality mainly affects large cities(Europe, Asia, USA), developing a light, smart and clean energy transportation for city seems really rational. Many products have been developed in the past year as [5]–[7]. Most movements in the city are achieved at a speed below 35 kilometers per hour. Based on this observation, the strategy of the HES consists of using only electric energy below this speed. At higher speed, heat engine is used to provide more thrust. This strategy is discussed in section III. The HES has took the advantage of many road tests and these experimental results are discussed in section refexp.

II. System configuration

The figure 1 illustrates an overview of the system architecture. Each part of this structure is describe below.

A. Heat engine

The original engine of $125cm^3$ was retained. Only Engine Control Unit (ECU) undergoes slight changes. Indeed ignition and thrust signals are derived toward an additional ECU controlling electric motor and therefore heat engine.

B. Electric motor

The HES is equipped of an electric motor, as we said in introduction placed in the rear wheel. This motor is a 6 kW 3-phases brushless motor. It is controlled by a motor driver on the shelve from Sevcon. Brake and throttle signals are provided by the electric motor ECU. This ECU is also a part on the shelve from Motohawk in which the energy management strategy has been implemented. In order to control the motor, it is obviously with hall sensors.

C. Battery, Battery Management System and regenerative braking

The HES contains a 80V - 15Ah battery, which can provide current peaks of 60A during accelerations. This battery is composed of 24 $LiFePO_4$ cells. Each cell is monitored using LTC6802 circuit from Linear technology. These monitors are managed by micro-controller. It sends information to the rest of the system through CAN bus protocol. Essentially, the electric motor ECU uses these information to calculate State of Charge (SoC) using method developed in [8]. SoC is estimated combining two measurements : at startup, voltage of the battery pack is measured and compared to a mean discharge curve and during operation current measure is done and soft coulometer is used to determine the battery capacity. Current is sampling each millisecond and is ingrated in order to estimate battery charged used When the HES is turned off, current SoC is stored in memory (ROM) and at the next startup this value is averaged with the SoC obtained measuring the battery voltage except when a fully or partial charge of the battery has been detected. Experimentaly, theses two values were very close but with the aging of the battery pack, it will certainly differ.

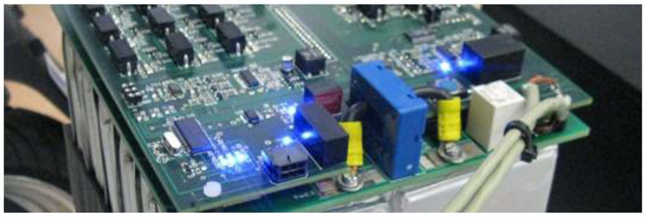

Figure 2. Photography of the Battery Management System Printed Circuit Board

Cells are monitoring during HES activity but also during charging. The Battery Management System is a dissipative one : in order to balance cells voltage, henceforth one cell reaches a voltage threshold, it's discharged through a passive resistance until its voltage decreases to the mean of the 24 cell voltage.

Contrary to [7], the battery pack (and the charger) is not integrated to the HES and so can be take off and charged at home. Battery chargers for Hybrid Electric Vehicle (HEV) have been the subject of much research [9]–[11]. The charger developed here is controlled by the BMS (Battery Management System) which can switch on or off the charger during cells balancing.

Regenerative braking system is presented on figure 4 and figure 3. Between the disc brake and the lever, an hydraulic controller is introduced. This controller send to the ECU information about pressure applied on the lever by the user. Until the brake lever reaches the mid-course, there is no mechanical braking but the ECU use progressively the electric motor as generator. A generator which feeds the battery pack with produced current. Then, in the second part of the lever course, the mechanical braking is still operating. The hydraulic circuit is so closed and applied pressure on the lever is transmitted to the disc brake. This is useful in case of emergency braking, electrical failure and simply to be in agreement with the law.

III. System control

The electric motor ECU deals also with energy management. Two modes are selectable by user : hybrid mode and zero-emission mode. In hybrid mode, four cases are considered :

- Battery is fully charged (between a SoC of 30% and 100%). In this case, below 35km/h, the scooter moves only with electric motor.
- Battery is low (between 10% and 30%). The same strategy than the first case is adopted but regenerative braking is used to recharge the battery during deceleration phases.
- Battery is very low (between 5% and 10%). In this case, electric motor is no more used. Regenerative braking is switched on again.
- Battery SoC is under 5%. At this level, ECU considers that there is a default in the battery pack as from 5%, no electric energy should be used by the HES.

Figure 3. Photography of the regenerative breaking system

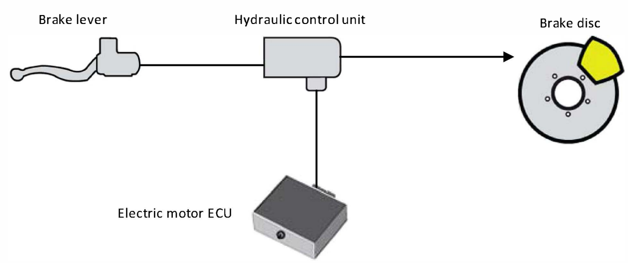

Figure 4. Regenerative braking system overview

In normal operation (first or second case), the scooter starts always in full electric mode. If the speed reaches 35km/h, the engine is started and thrust of the electric motor is decreased as the speed increases. The engine will stop only when the scooter is stopped by the user.

Regarding the zero-emission mode, only electric energy is used but the speed of the scooter is limited to 45km/h.

In order to control the electric brushless motor, an on the shelf controller from Sevcon has been choosen. It is controlled by the ECU in wich the strategy above is implemented. Signals to drive the motor controller (throttle and electrical break) are only analog. This driver can also communicate essentials informations to the ECU using a controller area network (CAN) bus : these are the wheel speed and the consumed current. Also using this CAN bus, the BMS communicate to the ECU some parameters in order to estimate the SoC as explained above and to monitoring the battery cells. Indeed, if a cell reach a low voltage level, the electric propulsion will be stopped and the user alerted of the dysfunction.

Experimental results of these strategies are discussed in the following section.

IV. Experimental results

When used only on zero-emission mode, with fully charged battery pack a path of 4,1 km can be traveled. The table

I show the experimental results, in hybrid mode in terms of gasoline consumption with different strategies or parameters, we obtained on a representative city path of 50 km. Measurements are made for heat engine only, hybrid mode using a threshold of 30km/h, 35km/h and finally 40km/h. The threshold corresponds to the speed at which the engine starts. Below this speed only electric motor propels the scooter. Each consumption result is given in liter per 100km. Consumption saving is given according the results using only the heat engine.

Table I
EXPERIMENTAL RESULTS IN HYBRID MODE

	Engine only	Hybrid mode (30km/h threshold)	Hybrid mode (35km/h thr.)	Hybrid mode (40km/h thr.)
Gasoline consumption	4.158 L	2.894 L	2.61 L	1.868 L
Consumption saving	0%	30.4%	37.2%	55%

In these tests, output battery current was limited to 40A. Another test has consists to increase this value to 60A. In the hybrid mode with a threshold of 35km/h, we notice a gasoline consumption of 2.8 l per 100km. As the battery is faster discharged, the consumption increases a little but the ease of use of the scooter is improved. It seems, after testing this configuration that it is a good tradeoff between consumption and comfortable use.

The choice of the 35km/h threshold can be discussed (and surely improved) because the consumption gain is higher when the threshold is higher but its again a good tradeoff to save gasoline using the scooter in different situation (city or highway road). Indeed, on long road without stop, the battery is faster discharged using a 40km/h threshold and the consumption increases.

V. ELECTROMAGNETIC COMPATIBILITY STUDY

Directive 97/24/EC imposes limitations on the levels of emission of electromagnetic noise. As the HES is intended to be sold, this directive should be respected in order to obtain a permit to travel from UTAC (French official standardization of vehicles). Figure 5 shows a photography of the scooter during the tests. In emission, 13 frequencies ranging from 45MHz to 900MHz are tested. As shown in figure 6, certain test frequencies, certain limits have been exceeded. The tests are performed for use only with the engine and for use in hybrid. These tests allowed for corrective actions to reduce the noise level of the product. All cables and the box containing the BMS were shielded. These changes were enough to reduce the level of disturbance of the scooter and the table II summarizes the results in comparison to the maximum level authorized by the directive.

Figure 7 show the final study : all emissions are below the maximum limits in order to pass the directive recommendations.

Immunity tests were also conducted in order to determine if the system could function in extrem condition of EMC

Figure 5. The HES in Faraday cage

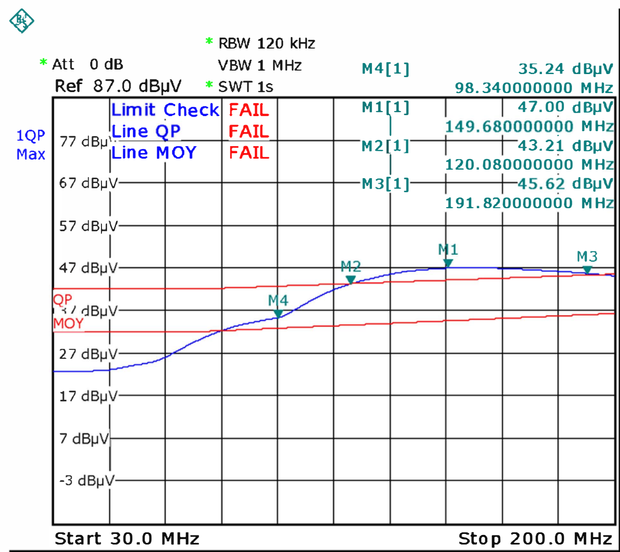

Figure 6. First EMC study

perturbation. The BMS was the first element to be disturbed from a frequency of 450 MHz and a level of 20V/m. The serial peripheral interface (SPI) used between electronics component was the first impacted sub-system. To avoid these problems, a new printed circuit board has been designed with inner ground layer. This improvement has made the system a little more reliable but without showing a significant gain.

VI. CONCLUSION AND PERSPECTIVES

In this paper, we have presented an overview of our hybrid electric scooter. We have implemented a simple but efficient power management strategy. After testing the vehicle, it turns out that the system seems to be very reliable. We have improved the consumption of a simple scooter with heat

Table II
EXPERIMENTAL RESULTS IN ELECTROMAGNETIC EMISSION

Frequencies (MHz)	45	65	90	120	150	190	230
Maximum Level ($dB\mu V/m$)	46	46	47.2	49.1	50.6	52.1	53.4
Engine only	31	29	27	37	26	26	23
Hybrid mode	33	31	27	37	26	25	24
Frequencies (MHz)	280	380	450	600	750	900	
Maximum Level ($dB\mu V/m$)	54.7	56.7	57	57	57	57	
Engine only	24	26	29	30	30	31	
Hybrid mode	29	26	29	33	30	30	

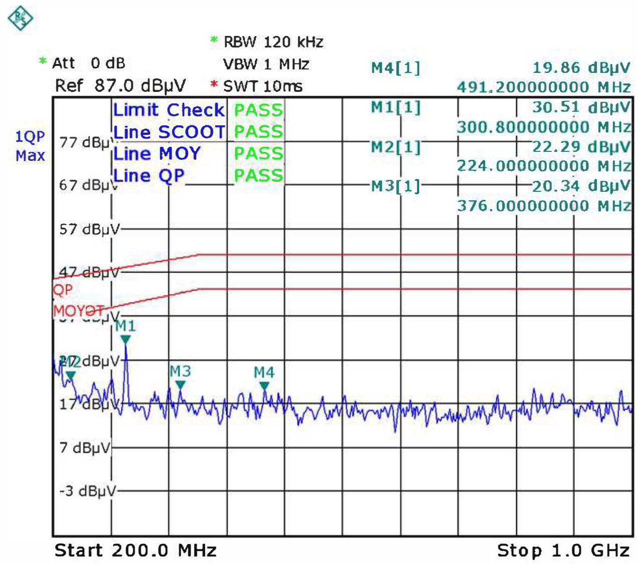

Figure 7. EMC study after corrective actions

engine adding an electric motor, its controller and its power storage. The adopted strategy is probably improvable and the scooter needs other tests in different real situations to establish the better tradeoff. The BMS can be improve in order to evaluate an important battery parameter that is the state of health (SoH) which takes into account the battery aging and can improve the SoC estimation. Furthermore, the EMC field has been studied in order to respect european directive. The scooter is currently studied by a private company in order to commercialize in a near future the entire product or some parts (BMS, regenerative braking system or ECU with the developed power management strategy).

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