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Development of a regenerative braking control strategy for hybridized solar vehicle

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Abstract: This paper focuses on the development of a braking control strategy that allows the best trade-off between mechanical and regenerative braking on a hybridized vehicle. The research work is part of a project for the development of an automotive hybridization kit aimed at converting conventional cars into Through The Road hybrid solar vehicles. The main aspect of the project is the integration of state-of-the-art components (i.e. in-wheel motors, photovoltaic panels, batteries) with the development of an optimal controller for power management. A mild parallel hybrid structure is obtained by substituting/integrating the rear wheels with in-wheel motors and adding photovoltaic panels and a lithium-ion battery. A hybridizing equipment prototype, patented by the University of Salerno, is installed on a FIAT Grande Punto. A model useful for real-time braking control has been developed, starting from vehicle longitudinal model and considering dynamic weight distribution in front and rear axles and related wheel slipping effects. Different braking strategies have then been investigated, in order to maximize the benefits of regenerative braking.

Keywords: automotive hybridization kit; hybrid solar vehicles (HSV); vehicle electrification; HSV prototype; control strategy; regenerative braking; in-wheel motors.

1. INTRODUCTION

In recent times, hybrid vehicles (HEVs) have received an increasing attention as an alternative to traditional vehicles powered by internal combustion engines using fossil fuels.

Considering recent advances in battery technology and motor efficiency, HEVs are a valid and feasible way to reduce emissions and fuel consumption, and represent an effective bridge solution toward the vehicle electrification. Recently, some solutions for converting conventional vehicles into hybrid vehicles have also been proposed (Arsie et al., 2013; Marano et al., 2013, Hall et al., 2016), and optimal energy management strategies suitable for such kind of vehicles have been studied (Pisanti et al, 2014).

An important advantage of HEVs compared to conventional vehicles is the possibility to save energy during braking phases. When a conventional vehicle applies its brakes, kinetic energy is converted to heat due to friction between the brake pads and wheels. This heat is carried away in the airstream and kinetic energy is wasted. The total amount of energy lost in this way depends on how often, how hard and how long brakes are applied. A regenerative brake is a system that allows a vehicle to recover part of the kinetic energy dissipated during braking phases. Recovered energy can be stored in a battery in form of electricity and used during vehicle acceleration phases, increasing efficiency and fuel economy.

The energy available for storage depends on drive train efficiency, drive cycle and vehicle weight (Guzzella and Sciarretta, 2013). The impact of regenerative braking on energy saving is much more significant in urban driving because of relevant number of braking events representing a big energy loss with a great saving potential.

Obviously, in order to be cost effective, in a regenerative braking system the primary energy saved over a specified lifetime must offset the initial cost, size and weight penalties of the system. The energy storage unit must be compact, durable and capable of handling high power levels efficiently, and any auxiliary energy transfer or energy conversion equipment must be efficient, compact and of reasonable cost.

However, mechanical braking is still required in HEVs to keep braking phases more safe and, for example, to avoid problems in case of electrical failure.

Several studies on regenerative braking control strategies are available in literature (Rizzoni, et al., 2009; Maia, et al., 2015; Kumar, et al., 2016). They are mostly carried out on classical HEV's or EV's, and cannot be simply transposed to hybridized vehicles, where wheel motors are added in rear wheels in an existing conventional vehicle. Comparing to classical native HEVs, hybridized vehicles are characterized by the impossibility to modify/adapt the original engine control strategy (i.e. original ECU) in order to account for the electrical parts and their control (i.e., battery pack, electrical engine and solar panels). Moreover, for the specific vehicle developed, all the information needed to control the vehicle are derived from a limited number of variables measured by the OBD port (Arsie et al., 2013; Marano et al., 2013), estimating the missing data with suitable mathematical models (Naddeo et al., 2014). Such models have been implemented in the braking control strategy presented in this work.

In the following chapters, a study on the energy recovery potentialities by means of regenerative braking in a hybridized

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vehicle is presented, and control strategy are described. Moreover, the case with mechanical braking on rear axle coupled with regenerative one is also considered with the objective to define the best distribution of mechanical braking torque between front and rear axle to maximize regenerative effect, and guarantee a suitable and safe braking control.

2. A KIT FOR SOLAR HYBRIDIZATION

A solar-hybridized vehicle has been developed at the University of Salerno through the installation of an additional battery (Lithium-Ion) and two electrically driven in-wheel motors on the rear wheels on a conventional vehicle. Moreover, solar cells on vehicle bonnet and roof have been installed so that it is possible to charge battery pack taking advantage of solar energy. In that way, the vehicle can operate in pure electric mode (when ICE is switched off or disconnected by the front wheels) or in hybrid mode (when the ICE drives the front wheels and the rear in-wheel motors operate in traction mode or in generation mode, corresponding to a positive or negative torque). The battery can be recharged by both rear wheels, when operating in generation mode, and photovoltaic panels. Furthermore, it is possible to charge battery from electric grid. A Vehicle Management Unit (VMU) receives data from OBD gate, from battery (SOC estimation) and drives in-wheel motors by properly acting on the electric node EN. A display on the dashboard may advice the driver about the actual operation of the system (Fig. 1).

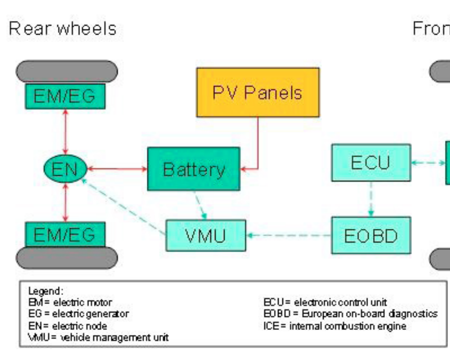

Fig. 1. Scheme of a system to upgrade a conventional car into a Mild Hybrid Solar Vehicle

The kit has been installed on a FIAT Punto, at the laboratories of the University of Salerno (Fig. 2).

Nominal ICE power [kW]	75
Fuel	Diesel
Coefficient of drag (C_d)	0.325
Frontal area [m^2]	2.05
Rolling radius [m]	0.295
Rolling resistance coefficient [/]	0.02
Base vehicle mass [kg]	1105
Driver mass [kg]	70
PV installed power [kW]	0.280
PV mass [kg]	4.7
Li-Ion Battery Capacity [kWh]	4.2
Li-Ion Battery Voltage [V]	96
Li-Ion Battery Mass [kg]	45
In-wheel motors power [kW]	14

Tab. 1. Vehicle and Hybridization Kit Characteristics

Fig. 2. Hybrid Solar Vehicle by University of Salerno

A study on the technical and economic feasibility of the hybridization kit confirms that significant reduction of fuel consumption and CO_2 emissions (18- 22%), comparable with HEVs benefits, but at lower investment cost, can be achieved. The results show that driving distance and type (urban vs. highway) and the availability of charging infrastructure play an important role in fuel economy, CO_2 emissions savings and pay-back time. Moreover, in spite of high cost of the flexible PV panels, the solution with PV panels result in lower pay-back time with respect to solutions with in-wheel motors only.

3. IN-WHEEL MOTORS

One of the most interesting aspects of the solar hybridization kit is represented by the partial recovery of kinetic energy allowed by wheel motors during braking. The optimization and the control of such feature represent the object of this paper.

Use of in wheel motors (IWM) allows to electrify the vehicle with no impact on mechanical transmission. A significant amount of space is therefore saved in the vehicle, compared to other hybrid solutions where electric motor is placed out of vehicle chassis. A hub motor typically may be designed in three main configurations. The least practical is an axial-flux motor, where stator windings are typically sandwiched between sets of magnets. The other two configurations are both radial designed with the motor magnets bonded to the rotor. In one of them, the rotor sits inside the stator, as in a conventional motor while in the other one, the rotor sits outside the stator and rotates around it. A typical IWM scheme is shown Fig. 3.