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Model based design and optimization of a fuel cell electric vehicle

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Abstract

Alternative vehicle powertrains (hybrid, hydrogen, electric) are a right answer to the emissions problem in very congested urban areas. The most effective alternative choice is surely represented by fuel cell vehicles. The design and optimization of this kind of powertrain can take a great benefit from mathematical models which include auxiliary management and control strategies of the energy fluxes: the use of a virtual platform limits the expensive and time-consuming experimental activity.
The Authors present a lumped parameter mathematical model of a hybrid vehicle fed by a fuel cell pack. The propulsion system (fuel cell and battery) is accurately designed according to energy balancing. The mechanical power is given by an electric machine, whose behavior as alternator allows the energy recovery during braking. This aspect is treated with particular care (inside the overall vehicle and powertrain modeling). Vehicle's stability and safety has been also verified before recovering energy, re-modulating the braking action.

Keywords: Hybrid; Electric vehicle; Fuel cell vehicle; Regenerative Braking System; Braking modelling.

1. Introduction

Passenger cars efficiency, in recent years, showed a strong improvement pushed by current international regulations on fuel efficiency and, principally, on pollutant and CO_2 emissions reduction [1]. These regulations imposed stringent targets that manufacturers have not reached yet [2]. So, very recently, economic crisis, oil price and GHG reduction polices pushed a radical change in the past trend, with a marked increase in fuel economy [3].

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Nomenclature

F_{bf}	front braking force	V	vehicle speed
F_{br}	rear breaking force	SOC	state of charge of the battery
M	vehicle weight	j	deceleration
F_{in}	force of inertia of the vehicle	ρ_{air}	air density
μ	road-tyre friction coefficient	F_{av}	propulsion force
F_{rot}	rolling resistance force	C_1	rolling resistance coefficient
F_{aero}	aerodynamic force	C_x	vehicle aerodynamic coefficient
S_{front}	vehicle frontal area	$\eta_{B,ch}$	battery charge efficiency
η_{mot}	electric traction motor efficiency	$\eta_{B,disch}$	battery discharge efficiency

There are more than a few technological options that show great potentiality in order to achieve this targets [4]: some of them are more simple to be installed on board and are already in the market, but have a low emission reduction potential. A significant step change will be reached thanks to the electrifications of the vehicle and, in particular, with alternative powertrains (like hybrid, electric, hydrogen, etc…). These new powertrains are particularly interesting in very congested urban areas, characterized by a high speed variations, where they represent the most effective and right answer. Powertrains based on pure electric propulsion or, even more, on fuel cells appears to be the most suitable candidates [5-7].

The interest on hybrid and electric vehicles is significantly growing because of their very low values of emissions and the wide diffusion of the electricity in cities. Several governments around the world, so, announced targets on sales on electric and plug-in vehicles: according to these national targets about 7 million of electric vehicles sales will reached by 2020 [8]. Also manufactures have to introduces a share of low emissions vehicles in their fleet in order to reach international targets and avoid penalties.

Hybrid vehicles can be classified in terms of degree of hybridization: micro-hybrids which have small electric motors coupled with the internal combustion engine (ICE) and low capacity batteries; full hybrids have higher capacity batteries and electric power flux, including energy recuperation pure electric traction; somehow intermediate are mild hybrids. In this classification, so, the higher degree of hybridization is reached by pure battery electric vehicles (BEV), but high degree of hybridization are displayed also by extended-range electric vehicles (EREV), which have an auxiliary power unit in order to sustain the battery charge, and plug-in electric vehicles (PHEV), in which pure battery electric phase is blended with a charge-sustaining phase [9].

From an energetic and environmental point of view, a significant step change is the use of fuel cells in vehicle propulsion: in fact, fuel cells deliver pure electrical energy, being not limited by Carnot efficiency and are suitable for propulsion in very congested urban areas being characterized by zero emissions.

Anyway actual market offer about HEV and BEV is still very limited and too costly to reach a relevant market penetration. Fuel Cell Electric Vehicles (FCEV) are also more far from the market. It is evident that a deep effort must be made in product development and standardization and that all the market sub-sectors must be considered.

The experimental research in this sector, at the same time, is expensive and really time-consuming, so needs the help of virtual platforms, which allow an easier results achievement and system management.

In this paper, the Authors present a wide modelling of a FCEV. The propulsion is therefore purely electrical and the energy storage section considers batteries (or ultra-capacitors) in order to recover energy or to give high power peaks occurring during braking or acceleration. The propulsion system is designed according to a method developed specifically. The fuel cell and the battery (primary power unit) are not chosen considering the mean propulsive power of the vehicle, but balancing the energy flows of the hybrid powertrain. Vehicle's weight is updated according to various component sizing and propulsion power recalculated in order to keep the same paying load. Fuel cell system (hydrogen fuelled) is represented according to their real operating characteristics as well as the electrical energy storage. The mechanical power is given by a reversible electric machine, whose behaviour as alternator allows the energy recovery during braking. The paper treats this aspect with particular care (inside the overall vehicle and powertrain modelling).

In fact, with reference to international approval drive cycle, the theoretical ratio between braking energy and overall propulsion energy can reach the 50% [10-12]. Braking energy recovery depends on several factors and, in particular, on the storage system capacity: state of charge (SOC) of the batteries, maximum acceptable input value of current and the power of the electrical machine [13]. Moreover, the braking system has to be managed with a defined ratio between rear and front braking, avoiding tyres slip and loss of directionality and granting vehicle's safety.

Finally, the effect of the vehicle management during the daily mission on component design (motor/alternator, fuel cell stack, batteries) has been evaluated; a simple control strategy (that preserves fuel cell life) for all the functions related to the vehicle's propulsion and braking has been implemented, defining energy fluxes among fuel cell, batteries and electric motor/generator.

2. The vehicle

During last years, Italian National Agency for New Technologies, Energy and Environment (ENEA) realized a series hybrid vehicle prototype, called Urb-E which made available a huge amount of experimental results, based on various control strategies used to optimize ICE utilization. A full description of the prototype is reported in previous papers by the Authors [14-15]. The rolling chassis has overall vehicle dimensions of 2.70 m length and 1.40 m width: it is a 2 seats vehicle with minimal size in order to solve urban traffic and parking problems. A series-hybrid architecture is chosen and consists of a motor-generator group composed itself by: a primary combustion engine (Piaggio QUASAR 250 cc) coupled with an electrical generator (brushless permanent magnet machine); an energy storage system based on ultra-capacitors (a series of 4 modules at 16 V and 550 F); an electric drive acting on front wheels (16 kW and 30 Nm); an electric node permitting mutual energy fluxes; three electrical converters and a power management system.

The management of thermal engine is realized by a torque control made by tuning the current supplied by the alternator and a closed loop speed control actuated by the throttle of ICE; the management of the hybrid propulsion system is realised by a supervision program.

A wide experimental activity has been done finalized to the obtainment of the motor-generator efficiency map and, so, fuel consumption in numerous steady working points. Several tests was also made in transient conditions, following different driving cycles [15].

The experimental results obtained on the series hybrid prototype were used to calibrate a comprehensive mathematical model of the vehicle, based on a Matlab-Simulink ® platform in a fully modular approach. This with the aim of evaluating the overall energetic performance of the vehicle and its main parts, as well as comparing the chosen power architecture with various possible different options. The model used is a lumped parameter one and is fully dynamical in most of its parts. So, several powertrain configuration can be simulated. Concerning fuel cell hybrid vehicle, data coming from MesDEA PEM cell are used (in terms of hydrogen consumption and efficiency): in the pure electric options, both ultra-capacitors and battery driven vehicles can be simulated. Lithium batteries were simulated according to a simple resistive model consolidated in literature [16-18]. Mixed storage systems with various control approaches can be, so, simulated considering all the aspects that influence fuel consumption.

3. The propulsion system design

The first issue in this kind of system is the design of the propulsion system of the vehicle. In particular, in this paper, it is considered a fuel cell series hybrid vehicle with a battery pack. Therefore, designing the propulsion system means to choose the energy strategy and, so, the fuel cell size and the battery capacity and power. This, obviously, influences the weight of the vehicle and so the propulsive power.

The method here proposed considers a propulsion strategy where the fuel cell can be completely switched on or off, in order to achieve the best efficiency of the fuel cell. The idea is to balance the propulsion energy coming from the fuel cell and that one coming from the batteries. In the initial conditions the fuel cell is powered and gives the design power. The reference driving cycle considered is the new World Harmonized Light-Duty Test Procedure Cycle (WLTP) considered for vehicles that have a very low ratio between power and kerb mass (Fig. 1), that can represent the typical driving cycle of a city (overall distance is 8 km in 1023 s with a maximum velocity of 64 km/h) [19]. This driving cycle was preferred to the actual urban homologation cycle (ECE) in order to have a more realistic test on urban behavior with higher velocity variations; moreover, the WLTP cycle has a higher maximum speed and a considerably greater distance, that are suitable during the designing phase of the propulsion system. The propulsive power of the vehicle P_{road} can be calculated according to eq. (1):

$$P_{road} = F_{av} \cdot V = (F_{in} + F_{rot} + F_{aero}) \cdot V = (Ma + MgC_1 + \frac{1}{2}\rho_{air} C_x S_{front} V^2) \cdot V \qquad (1)$$

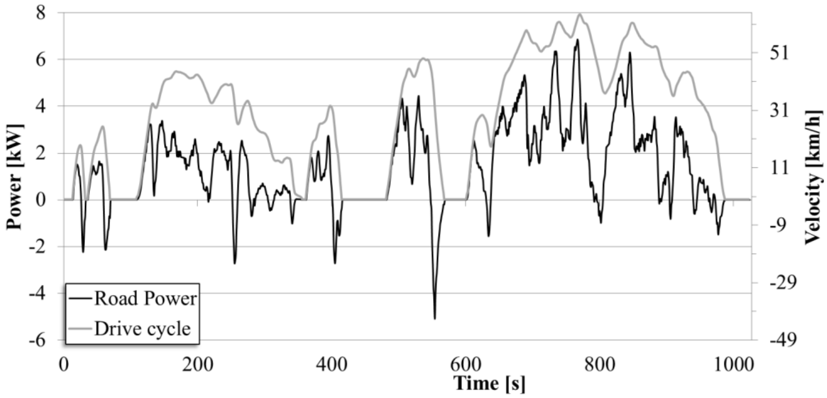

Fig. 1: Road power requested by the Urb-e vehicle to run the reference drive cycle (WLTP cycle)

The aim is to find an optimal level of fuel cell power (P_{FC}). This level must give enough energy (in the drive cycle considered) to fulfil the traction motor request, when the propulsive power is lower than the optimal fuel cell power, and to give to the battery the right amount of energy needed to fulfil the remained part of the drive cycle (when the power requested is higher than the optimal fuel cell power).

So, this calculation starts with a value of fuel cell given power. This, together with the battery, fixes the weight of the vehicle. Known this and all the geometrical characteristics of the vehicle, the propulsion power can be calculated according to Eq. (1). The energy given by the fuel cell directly to the traction motor $E_{FC,trac}$, being a parallel hybrid, is calculated as in Eq. (2):

$$E_{FC,trac} = \int_{WLTP} \frac{P}{\bar{\eta}_{mot}} dt \qquad \text{with} \begin{cases} P = P_{FC} & \forall P_{road} > P_{FC} \\ P = P_{road} & elsewhere \end{cases} \qquad (2)$$

The remaining energy required to run the reference cycle must be given by the battery. However, the battery is recharged by the fuel cell, so, by the portion of the energy of the fuel cell that is not used directly for the traction system. The energy that the battery have to provide $E_{B,trac}$ can be calculated as in Eq. (3):

$$E_{B,trac} = \int_{WLTP} \frac{P_{road} - P_{FC}}{\bar{\eta}_{mot} \bar{\eta}_{B,disch}} dt \qquad (3)$$

The extra energy given by the fuel cell (which is not used directly by the traction motor) is accumulated in the battery. Eq. (4) calculates the energy received by the battery from the fuel cell:

$$E_{FC,B} = \left(\int_{WLTP} P_{FC} dt - E_{FC,trac} \right) \bar{\eta}_{B,ch} \qquad (4)$$

At this point, in order to run the reference cycle with the fuel cell energy, the energy given by the fuel cell to the battery (Eq. 4) has to be equal or slightly higher than the battery energy supplied to the traction motor (Eq. 3). From a computational point of view, their difference must fall within a given tolerance (*toll*), Eq. (5):

$$E_{FC,B} - E_{B,trac} \leq toll \qquad (5)$$

$E_{FC,B}$ represents, also, the minimum capacity of the battery necessary to run a reference cycle. The real capacity must consider the possibility to have a higher mileage also in pure electric behaviour and, moreover, the lower limit recommended for the SOC of the battery, which is about 0.45 [20]. So, the battery chosen have a capacity three times higher than the evaluated energy needed.

If the Eq. (5) is not satisfied a different value of fuel cell power is tried and equations (1) to (5) are recalculated. The fuel cell and battery weights (and, so, vehicle weight) are updated according a linear relation. Finally, the battery power P_B must cover the propulsive power peak of the motor, so it can be calculated as in Eq. (6):

$$P_B = C\frac{(P_{road,max} - P_{FC})}{\bar{\eta}_{mot}\bar{\eta}_{B,disch}} \tag{6}$$

where C is an oversizing coefficient that consider the possibility to fulfil requested powers higher than those in reference cycle. The battery chosen is a LiFePO4 [21]: knowing its voltage, the maximum output current can be evaluated. Table 1 resumes the results of the propulsion system design process. Metal-hydride tank are considered as hydrogen storage: it contains 900 l of fuel at 12 bar with a weight of 6.2 kg.

Table 1: Propulsion component data

Fuel cell power	3400 W	Battery voltage	48 V
Fuel cell weight	21 kg	Battery max current	200 A
Battery power	10 kW	Battery weight	15 kg
Battery capacity	16 Ah	Vehicle weight (with a driver and one passenger)	676 kg

However, if the propulsion system was designed on the mean propulsive power, it would give back a smaller fuel cell power (3100 W), but a bigger battery (11 kW, 20 Ah). So, the weight saved thanks to the smaller fuel cell is compensated by the bigger battery, and the vehicle's weight does not suffer significant modifications.

4. The braking system model

Braking energy plays a crucial role in hybrid and electric vehicle. In fact, it can increase mileage of the vehicle sustaining the state of charge of the batteries during driving, in particular in urban missions, when the decelerations are very frequent. So, the Authors studied in deep the aspects related to braking force, determining limits linked to the wheels slip, which is responsible of loss of directionality and, so, braking time and space increase [22].

In these conditions, the maximum braking efficiency is reached (shorter stop distance) and a simple relation for the optimal distribution between front and rear braking forces can be find and is showed in Fig. 2, where optimal braking curve is drawn in the characteristic *Fbf-Fbr* plan, normalized to the vehicle weight; deceleration lines are also showed, with a constant deceleration j as a ratio of the gravitational acceleration g. For braking distributions which are different from the optimal one, front or rear axle reaches the locking condition before the maximum value of the allowed deceleration. So, for each value of road-tyres friction coefficient, front locking conditions and rear locking ones can be reached and represented in Fig. 2 by a bundle of parallel lines for different values of friction coefficient μ. All this considerations are to take into account within regenerative braking recovery system. If the braking distribution causes rear locking, the vehicle may become instable, also if directionality is not lost. If front wheels are the first that reach locking conditions, instead, stability are ensured, but with loss of directionality.

Another issue must be considered regarding the repartition between front and rear braking force. The deceleration is limited by the road-tyre friction coefficient. This constraint is subject of European Regulation (ECE R13-H) and it is also represented in Fig. 2 and shows the rear braking force limit.

Fig. 2 shows, also, for a fixed vehicle, a desired deceleration (dashed lines) can be reached by several constant braking distribution, represented in the graph by straight lines coming out from the origin. Only an optimal distribution can avoid that the locking conditions are reached. This is represented by the continuous line crossing the intersections between front and rear locking lines (for a fixed value of friction coefficient μ). Any other constant distribution can reach the desired deceleration value but locking an axle. Two locking possibility can be reached, depending on the pendency of the dashed bold line in Fig. 2. Locking conditions are represented in Fig. 3, considering μ=0.6 and j=0.6g. Initially, both axles participate to the braking according to the constant distribution. When locking conditions occur, one axle do not more participate and the braking proceed along the correspondent locking line till to the desired deceleration (Fig. 3). Obviously the locked axle do not participate anymore to the energy recovery.

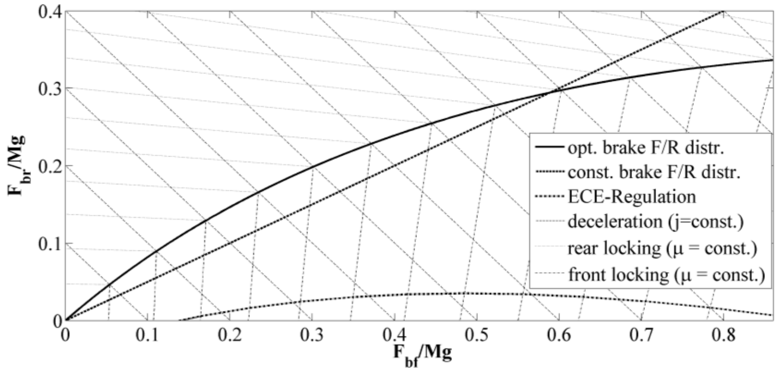

Fig. 2: braking characteristic graph. Optimal braking and constant distribution curves, rear and front locking line and ECE regulation limit

When the minimum stopping distance is considered, a non-linear distribution is required: so, it would require a smart on-board system which is able to determine, for a specific load, the correct front-rear distribution in order to achieve the desire deceleration value. However, in a hybrid or pure electric vehicle the braking is actuated by an electric motor and, so, it would be not so difficult to implement a model-based braking control.

So, three different braking strategies are considered: the constant front-rear braking force distribution is the reference case of a conventional vehicle, the optimal braking strategy has the aim to minimize the stopping distance and the maximum energy recovery strategy which considers all the braking force on the axle where is placed the traction motor (front axle in Urb-e vehicle).

In each strategy considered the dissipative braking system can act independently or cooperating with the regenerative one. In the first case, it starts working in order to reach the desired value of deceleration. In the second case, the control system adjusts the pressure within the dissipative braking hydraulic system in order to obtain the desired distribution curve, following the braking strategy and granting energy recovery.

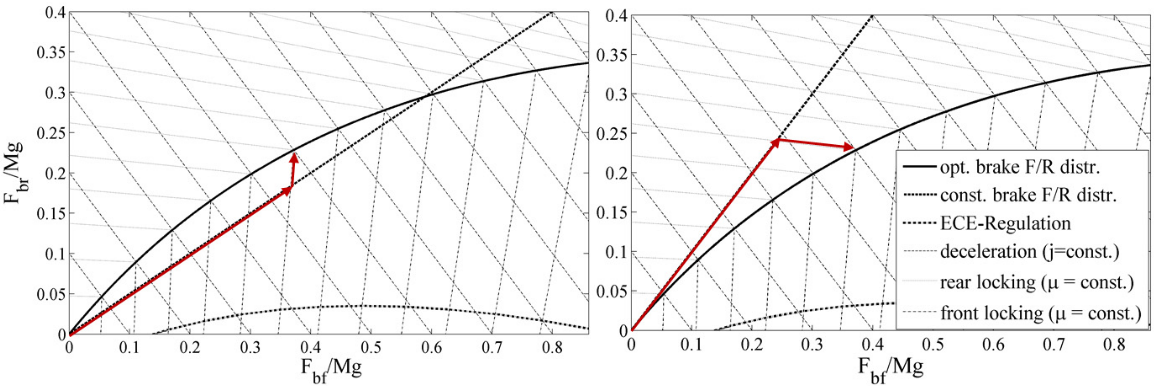

Fig. 3: front (left graph) and rear (right graph) locking conditions

So, the comprehensive model of the braking system with focus on the regenerative one has been considered and integrated in the vehicle model, in order to study the influence of the braking system on the vehicle behaviour. The model can manage the braking strategies considered and, so, the braking force distribution on the two axles and its limitations. The vehicle adhesion has, also, been considered, avoiding instability conditions and, finally, the braking force suitable to energy recovery can be evaluated. In particular, the energy recovered is limited by the SOC of the electric storage system (batteries and ultra-capacitors) and by the low efficiency of the electrical machine when it runs at low speed.

5. Results

The so-designed model of the vehicle Urb-e is performed on the reference urban cycle (Fig. 1), investigating the behavior of the propulsive system and the different braking strategies.

Fig. 4 shows the power balance at the electrical node before the traction motor. Being a parallel hybrid, the propulsive power is represented by the instantaneous sum between the fuel cell power and the battery power. The first is fixed at the designing value (dashed-dot line): this means that the SOC of the battery does not reach the maximum permitted value; battery power (dashed line) is negative when electrical current enters into the battery, positive when battery is giving power to the powertrain. Continuous line represents the power requested by the electrical traction motor: negative values indicate braking recovered power.

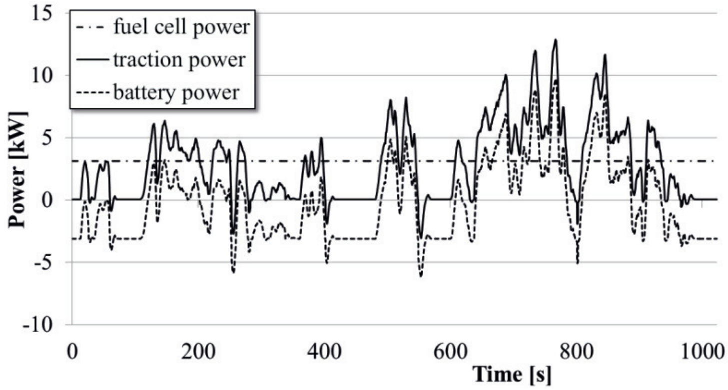

Fig. 4: power balance at traction motor node

In Fig. 4 is possible to track the energy flows: when the vehicle is stopped (traction power is null) all the fuel cell power recharge the battery, which is represented by a negative value of the battery power. Fuel cell has the priority as propulsion system, so when the traction power is lower than the fuel cell power, all the power requested by the powertrain is given by the fuel cell itself, while the extra-power provided by it (i.e. the difference between fuel cell power and traction power) goes into the battery (and the battery power has negative values). Finally, when the traction power is higher than the fuel cell power, this extra-power requested (i.e. the difference between the traction power and the fuel cell power) is given by the battery (who has power positive values).

Fig. 4 is referred to the conventional braking strategy with constant distribution of the braking force (67% on the front axle and 33% on the rear one) and shows, also, the good design of the fuel cell and the battery powers. However, the fuel cell needs a control strategy in order to do not overcharge the battery in low power urban missions. In fact, the fuel cell is designed to operate at constant output power (related to the its maximum efficiency), but in some cases this power could be too much to fulfill the traction requests and, at same time, cannot be stored into the battery (if the battery is almost fully charged). So, the strategy considered is a thermostatic one (Fig. 5): until the SOC of the battery is under a specific value, the fuel cell is powered on, when the SOC overcomes the upper limit (0.95), the fuel cell turns off until the SOC of the battery falls below the lower SOC limit. At this point the fuel cell turns on again. Fuel cell particularly takes benefit of this strategy, avoiding repeated on/off and low efficiency working conditions and, so, increasing its life [23].

Fig. 5 shows the SOC behavior for the reference WLTP cycle compared with a sequence of four ECE cycle. This second cycle, as known, has lower peak velocity and lower mean power (Fig. 6). In the WLTP cycle (Fig. 5a) the battery is well-designed: the SOC increases during the first lower phase of the cycle (600 s), but does not reach the upper limit, keeping turned on the fuel cell; in the second cycle phase (600-900 s) the requested power is higher and the battery must supply the extra-power needed by the vehicle, but the lower SOC limit is never reached. In the very final part of the cycle (900-1023 s) the power requested is lower and, then, the SOC increases reaching almost the initial value (0.6). Furthermore, if the propulsive system was sized on the mean propulsive power (fuel cell power: 3100 W; battery capacity 20 Ah), SOC behavior would not satisfy the operating limits of the battery itself.

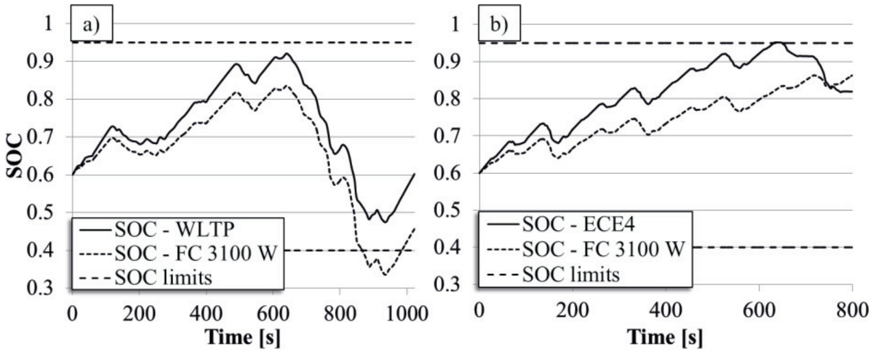

Fig. 5: comparison between SOC behaviour in WLTP cycle and 4 ECE cycles. Solid lines are referred to the optimal fuel cell power sizing, dashed lines to the mean propulsive fuel cell power sizing

In Fig. 5b is represented the SOC behaviour during a sequence of four ECE cycle. This cycle has lower power requested, so the fuel cell is over-dimensioned: in fact, SOC always increases and reaches the upper limit, turning off the fuel cell: from this point (600s, Fig. 6) to the end of the cycle the propulsion is purely electric and the propulsive power is given all by the battery (until the SOC would reach the lower limit). In this case, so, a lower hydrogen consumption is reached (cause of the shutdown of the fuel cell in the last part of the drive cycle): about 4 liters of hydrogen are needed to run 4 ECE cycles, while 6,3 liters for the WLTP one. However, WLTP cycle is twice longer than 4 ECE cycle and specific fuel consumption is about 13 km/l in WLTP case vs. 10 km/l in 4 ECE case. This confirm the importance of the choice of a real drive for the good sizing of the propulsion system.

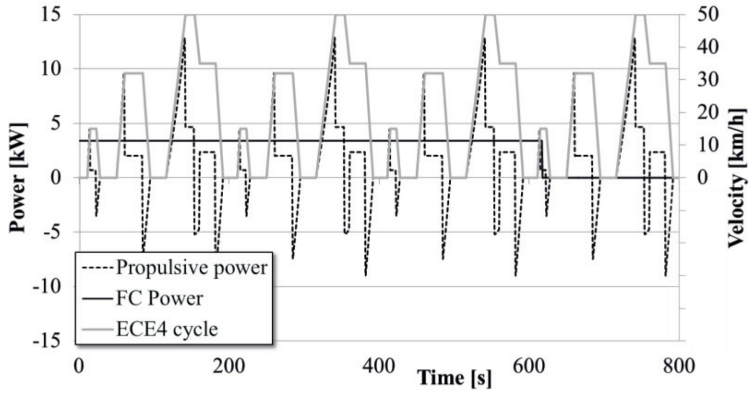

Fig. 6: Velocity, traction power requested and fuel cell power in 4 ECE cycles

Finally, the three braking strategy were compared. It is just the point to notice that the WLTP cycle has not high values of braking force, while in the ECE cycle the braking power is more than 35% of the propulsive one. However, high SOC values limit the energy recoverable from the braking, so, from this point of view, ECE cycle is penalized. Fig. 7 catches this aspect: WLTP cycle have braking higher braking efficiencies due to the lower SOC values, while ECE cycle has higher generator efficiencies due to the lower mean torque [24].

Fig. 7 shows, also, the great difference between the three braking strategies in terms of braking efficiency. The maximum recovery strategy (with braking only on the front axis) has efficiencies of about 80-90%. This means that the 90 % of the braking energy is recovered in electrical form. In this strategy, however, the generator shows the lower mean efficiency (about 80%). In the other strategies the braking efficiency is about 50-60% and the generator efficiency is about 90%. It is evident the trade-off between braking efficiency and generator efficiency. In particular, the optimal braking strategy (shorter stopping distance) has the lower braking efficiency. This can be expected looking at Fig. 2, where the optimal braking curve is over the constant distribution line: so, the front braking (the only one who participate to the recovery) is lower in this case.

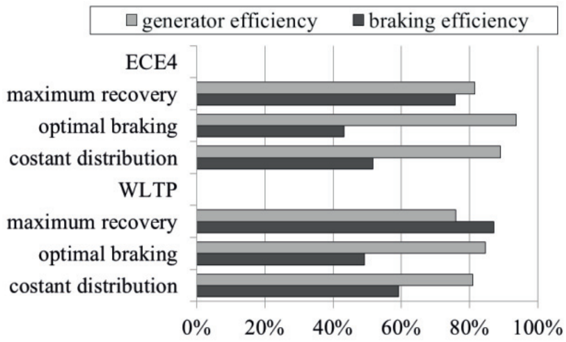

Fig. 7: braking strategies comparison

6. Conclusions

In this paper a comprehensive model-based design of a fuel cell electric vehicle is presented. The optimal choice of the fuel cell power, the battery power and capacity is done by an accurate balance of desired energy flows and power required on a urban test cycle (WLTP). Usually these choices are made simply considering the mean power or by experimental trials and are, so, not optimized, oversizing the components. With the proposed method (based on the energy flows through battery, fuel cell and powertrain) the optimal configuration can reduce power and weight components, saving fuel consumption and CO_2 emissions.

Once chosen the propulsion system, a mathematical model of a urban vehicle called Urb-e (previously calibrated and validated by several experimental campaign) has been used to perform the so-designed vehicle on different urban driving cycle. The software platform acts as a virtual vehicle and shows the energy flows through different components, confirming the results of the designing method. In particular, with a correct management of the propulsion system, great overall efficiency (fuel cell, charge/discharge of the battery, traction motor/generator) can be easily reached.

The model considers with particular care the braking system: locking and safety conditions are taken into account and three different braking strategies have been studied: optimal braking, constant braking distribution and maximum energy recovery. With the optimal braking strategy the shorter stopping distance is achieved, but has the lower energy recovery. The best recovery is obtained concentrating the braking action on the front axle, the only one where it is placed the electrical machine, but the generator efficiency is low. So, a good compromise must be find in order to solve this trade-off. Moreover, as in the ECE cycle the energy recoverable is huge (it is about the 38% of the ECE cycle), it is expected to recover more energy, but the braking efficiency is lower due to the higher SOC of the battery (which limits energy recovery).

In conclusion, the model presented has a wide range of applications and can reach furthers levels of optimization: motor/generator efficiency, braking modulation, fuel cell regulation till to consider different electrical machines on different axles and wheels. It opens to the possibility to downsize the propulsion system, allowing to reach better level of fuel consumption and to implement the best braking strategy, in order to privilege energy recovery or stopping distance.

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