A Supervisory Control Strategy for Series Hybrid Electric Vehicles with Two Energy Storage Systems

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Abstract- **Regardless of the topology of the hybrid electric vehicle, the essence of the HEV control problem is the instantaneous management of the power flows from the various energy storage devices to achieve the overall control objectives. In this paper we consider the case of energy management for a series hybrid powertrain configuration with two energy storage systems, i.e. batteries and ultracapacitors. The proposed power split algorithm is based on a modified instantaneous Equivalent Consumption Minimization Strategy (ECMS). The methodology could easily be applied to any kind of powertrain subject to the charge-sustaining constraint, and can readily be adapted to the specific characteristics of the components used in the powertrain.**

I. INTRODUCTION

Hybrid electric vehicles constitute an emerging class of alternative vehicles whose benefits include reduced emissions and enhanced fuel economy. In the last five years, research focus has shifted from applications for passenger vehicle to buses and trucks. Because of the introduction of new electrical energy storage systems like ultracapacitors and high performance batteries, the number of possible architecture configurations has increased considerably together with the need of more sophisticated and efficient energy management strategies. In the literature, while a lot of work can be found related to energy management in passenger vehicle [1]–[12], very little can be found regarding architectures with multiple energy storage systems [13], [14] that are more typical for trucks or buses. In this paper an energy management strategy for series hybrid vehicles with two different electric storage systems is presented.

Control strategies for hybrid-electric vehicles generally target several simultaneous objectives [2], [3], [5]-[14]. The primary one is the minimization of the vehicle fuel consumption, while also attempting to minimize emissions and to maintain or enhance drivability. Most typically, the architecture of a hybrid-electric vehicle includes an ICE with an associated fuel tank, an EM, and some type of electric storage system. Regardless of the topology of these components, the essence of the HEV control problem is the instantaneous management of the power flows from the various energy storage devices to achieve the overall control objectives. One important characteristic of this generic problem is that the control objectives are mostly integral in nature (fuel consumption per mile of travel), or semi-local in time like drivability, while the control actions are local in time. Furthermore, the control objectives are often subject to integral constraints, such as nominally maintaining the battery state-of-charge (SOC) in charge-sustaining hybrids. The global nature of both the objectives and the constraints does not lend itself to traditional optimization techniques, as the future is unknown in common driving circumstances. Much can be learned from global optimization exercises over a priori known driving cycles. However, these solutions do not directly lend themselves to practical implementations. An alternative approach involves instantaneous optimization of the power split between the energy converters, while accounting for the global constraints. The proposed power split algorithm is based on a generalization of the instantaneous Equivalent Consumption Minimization Strategy (ECMS) [8]–[10]. This approach is generic in nature, i.e. independent from the powertrain configuration (parallel, series, power split, etc.) and also independent from the particular powertrain components (engines or fuel cells, batteries or supercapacitors, etc.). This means that the methodology could easily be applied to any kind of powertrain subject to the charge-sustaining constraint, and can readily be adapted to the specific characteristics of the components used in the powertrain.

The paper is organized as follows. In the next section different series hybrid configurations with batteries and ultracapacitors are illustrated. In Section III the energy management control problem with two electric storage units is introduced, and a solution using the equivalent consumption minimization method is presented in Section IV. Finally simulation results to prove the effectiveness of the proposed approach are reported in Section V.

II. SERIES HYBRID ELECTRIC VEHICLE

A schematic picture for a series hybrid configuration is shown in Fig. 1. The power summation node, is an electrical summation node, i.e. power summation is obtained by addition of the electric power from generator and the electric storage.

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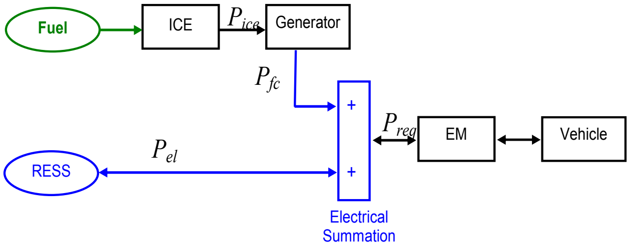


Fig. 1 Schematic representation of a series hybrid configuration.

In addition to the topology illustrated, we have at least two different RESS architectures [13]. The first architecture is depicted in Fig. 2a where there is a dedicated DC/DC converter for each power source. The second one instead, Fig. 2b, has only one DC/DC converter for one of the two sources (Supercaps) while the other one is directly connected to the electric bus.

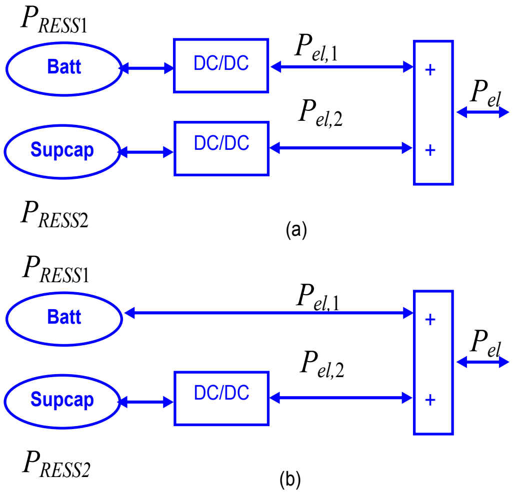


Fig. 2. Schematic representation of a connection of two electrical power sources- configuration.

The double-headed arrows in the bi-directional power path in Fig. 1 and Fig. 2 signify that it is possible for the power to flow in both directions in the path. This does not mean that the power can flow in both directions at the same time. The power flow path from the chemical storage (fuel tank) is unidirectional because it represents the irreversible engine process. The power flow path from the electrical storage is bi-directional because power can flow either from or to it. However, efficiencies in both directions are not necessarily the same.

III. ENERGY MANAGEMENT CONTROL PROBLEM

The basic challenge of energy management in a hybrid electric vehicle is to assure optimal use and regeneration of the total energy in the vehicle. In the case of series hybrids, at any time and for any vehicle speed, the control strategy has to determine the power distribution between primary energy converter (FC) and renewable electrical storage system (RESS) [8]–[10]. When multiple storage systems are available an additional power distribution among the RESSs has to be determined. These decisions are constrained by two factors. First of all, the motive power requested by the driver must always be satisfied up to a known limit (maximum power demand). Secondly, the state of charge of the RESS must be maintained within preferred limits, allowing the vehicle to be charge sustaining. Within these constraints, the first objective is to operate the powertrain in order to achieve the maximum fuel economy. Ideally the motive power must be split at each time to minimize the overall fuel consumption over a given trip, such as:

$$\min_{\{P_{fc}(t),P_{el,i}(t):i=1,2\}} \int_0^T \dot m_f(\tau)\,d\tau \tag{1}$$

with the constraints

$$\begin{aligned}
&P_{req}(t)=P_{fc}(t)+P_{el}(t)=P_{fc}(t)+P_{el,1}(t)+P_{el,2}(t) \quad \forall t\\
&0<SOE_{i,\min}\le SOE_i\le SOE_{i,\max}\le 1 \quad i=1,2\\
&0\le P_{fc}(t)\le P_{fc_{MAX}}\\
&P_{el,i_{MIN}}\le P_{el,i}(t)\le P_{el,i_{MAX}} \quad i=1,2
\end{aligned}$$

where T is the duration of the trip, $\dot m_f(t)$ is the fuel flow rate at time t, $P_{el,i}(t)$ is the power provided by the i^{th} electrical accumulator at time t, $P_{fc}(t)$ is the power provided by the fuel converter (engine only or engine plus generator depending on the configuration) at time *t*, P_{req} is the power requested but the driver and SOE_i is the state of energy of the RESS$_i$ and it is related to the energy or charge accumulated in the RESS$_i$ (i.e. SOE_i is an indicator of how much energy can be stored or withdraw from the RESS$_i$).

The main problem with this approach is that in order to solve such an optimization problem the whole driving schedule has to be known a priori, thus real-time control cannot be readily implemented. To avoid this drawback, one can replace the global criterion by a local one, reducing the problem to a minimization of the equivalent fuel consumption at each time [8]–[10]. The local criteria becomes at all times

$$\min_{\{P_{fc}(t),P_{el,i}(t):i=1,2\}} \dot m_{f,eq}(t) \quad \forall\ t \tag{2}$$

where $\dot m_{f,eq}(t)$ is the equivalent fuel flow rate at time t and with the same constraints as before. Note that in a charge-sustaining hybrid any present discharge or charge of the battery must ultimately be balanced by a corresponding future charge or discharge (respectively). This future charge or discharge will result in the fuel converter producing more or less power, thereby consuming more or less fuel than needed to meet the desired power. Thus, some equivalent (future) fuel use can be equated with the present use of the batteries. The equivalent fuel cost $\dot m_{f,eq}(t)$ is the sum of the actual fuel consumption rate of the fuel converter, $\dot m_{fc}(t)$, and the equivalent fuel use of the RESS, $\dot m_{f,RESS,eq}(t)$. The global minimization problem represented in (1) and the local minimization shown in (2) are not strictly equivalent. However, local minimization results in a formulation amenable to real-time control, while the use of the equivalent fuel flow rate indirectly accounts for the non-local nature of the problem.

IV. EQUIVALENT FUEL CONSUMPTION MINIMIZATION STRATEGY

A. Physical Viewpoint

The equivalent fuel consumption minimization strategy is based on the assumption of quasi-static behavior of the system. In general, for a normal vehicle, this behavior is characterized by capturing phenomena that are in the order of 0.5-1 sec, while faster dynamics are neglected.

The main idea consists in assigning future fuel savings and costs to the actual use of electric energy, and in particular:

- a present discharge of the RESS corresponds to a future fuel consumption that will be necessary to recharge the RESS;
- a present RESS charge corresponds to a future fuel savings because this energy will be available in the future to be used at a lower cost.

The strategy is charge sustaining because balances the costs in the future with the savings in the future. A schematic representation of this concept is depicted in Fig. 3.

During a discharge of the RESS (Fig. 3a), positive electric power flows along the electric path to the electric bus adding additional power to the amount produced by the fuel converter. This electric power is used by the electric motor as it provides mechanical power to the wheels. In order to maintain the state of charge of the RESS, this electric energy extracted from the RESS needs to be replenished in the future (Fig. 3a, highlighted). As with the parallel hybrid case, at some point in the future, the fuel converter will have to produce more power than is required by the vehicle, with the additional power being used to recharge the electric storage system through the electric bus. This additional power represents the equivalent future power and has associated with it some equivalent (future) fuel consumption. If power is currently flowing into the RESS (i.e. the RESS is currently charging), then the fuel converter is presently producing more power than required by the vehicle (Fig. 3b). This additional power is diverted into the RESS and will be available for future use. Using this extra power (presently being stored in the RESS) will reduce the amount of power the fuel converter will have to provide and thus the future fuel consumption (Fig. 3b, highlighted). Hence, a future equivalent fuel saving can be associated with a present charging of the RESS.

According to this interpretation, the problem of minimizing the fuel consumption given by (1) can be reformulated as an instantaneous minimization problem as in (2), where $m_{f,eq}\ t$ contains information regarding actual fuel consumption and future fuel saving/cost as described before. In particular, $m_{f,eq}\ t$ can be expressed as

$$m_{f,eq}\qquad m_{f,ICE}\qquad m_{f,RESS,eq}$$

where $m_{ICE}\ t$ is the fuel flow rate at time t, while $m_{f,RESS,eq}\ t$ is the equivalent fuel cost/saving associated to the RESS.

B. Mathematical Formulation: Discharging Mode for a Single Component RESS$_i$

In the case of two energy storage systems, we can write

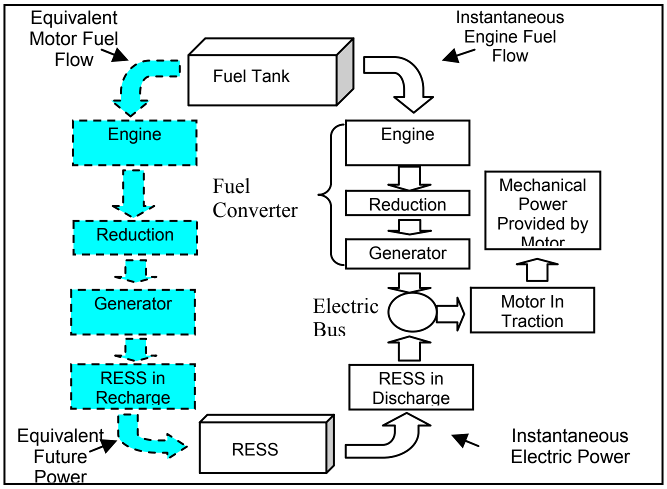
$$m_{f,eq}\qquad m_{f,ICE}\qquad m_{f,RESS_{1,eq}}\qquad m_{f,RESS_{2,eq}} \tag{3}$$

The amount of energy removed from the RESS$_i$ at a given power $P_{el,i}$ during an interval t is

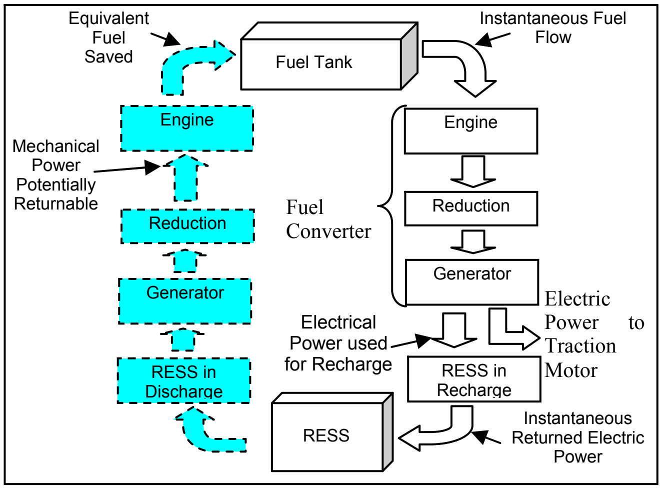
$$E_{RESS,i,dis}\qquad t\,P_{RESS,i,dis}\qquad t\,\frac{P_{el,i}(t)}{_{el,i,dis}(t)} \tag{4}$$

where

$$_{el,i,dis}(P_{el,i})\qquad _{pe,i,dis}(P_{el,i})\quad _{RESS,i,dis}(P_{el,i}) \tag{5}$$



(a)



(b)

Fig. 3. Energy path for equivalent fuel: (a) consumption during RESS discharge; (b) consumption during RESS recharge.

with $\eta_{pe,i,dis}$ efficiency of the power electronics that connects the electric storage to the electric bus during discharging, and $\eta_{,RESS,i,dis}$ efficiency of the electric storage RESS$_i$ at discharging. The future cost of $\Delta E_{RESS,i,dis}$ is

$$c_{\Delta E,i,dis} = C_{i,tot,chg} \frac{\Delta E_{RESS,i,dis}}{E_{i,tot,chg}} \quad [g] \qquad (6)$$

where $E_{i,tot,chg}$ is the total energy recharged in the future to RESS$_i$, $C_{i,tot,chg}$ is the cost of $E_{i,tot,chg}$. This condition is depicted in Fig. 4. The cost $c_{\Delta E,i,dis}$ is a fraction of the cost of the total energy recharged into the RESS$_i$. The total energy recharged in the future is

$$E_{i,tot,chg} = \int_{\substack{all\ future\\ rechg\ cond.}} | P_{RESS,i,chg}(t) | \, dt + \int_{\substack{all\ future\\ recov.\ cond.}} | P_{RESS,i,chg}(t) | \, dt + \int_{\substack{all\ future\\ rechg\ exchange\ cond.}} | P_{RESS,i,chg}(t) | \, dt$$

where the recharge exchange conditions are the condition of recharge when energy from RESS$_j$ is transferred to RESS$_i$. The cost of the total energy recharged in the future is

$$C_{i,tot,chg} = \frac{E_{tot,TANK-RESS_i}}{Q_{LHV}} \quad [g]$$

with

$$E_{tot,TANK-RESS_i} = \int_{\substack{all\ future\\ rechg.cond.}} \frac{P_{fc,RESS_i}(t)}{\eta_{fc}(t)} dt = \int_{\substack{all\ future\\ rechg.cond.}} \frac{| P_{RESS,i,chg}(t) |}{\eta_{fc}(t) \eta_{el,i}(t)} dt$$

$$\eta_{fc}(t) = \eta_{genset}(t)$$

$$\eta_{el,i}(t) = \eta_{pe,i}(t)\, \eta_{RESS,i}(t)$$

where $E_{tot,TANK-RESS_i}$ is the total energy flowing from the tank to the RESS$_i$, Q_{LHV} is the low heating value of the fuel, $P_{fc,RESS_i}$ is the power from the fuel converter to the RESS$_i$, and η_{genset} is the combined efficiency of ICE and generator.

By substituting the above expressions into (6), after some manipulations and approximating the efficiencies by their average values, it can be shown that during discharging

$$c_{\Delta E,i,dis} \approx \frac{1}{\overline{\eta}_{fc,rechg} \overline{\eta}_{el,i,rechg}} \cdot \frac{1}{1 + \overline{R}_{recov+exchg\,/\,rech,i}} \cdot \frac{1}{\eta_{el,i,dis}(P_{el,i})} \cdot \frac{P_{el,i}}{Q_{LHV}} \Delta t$$

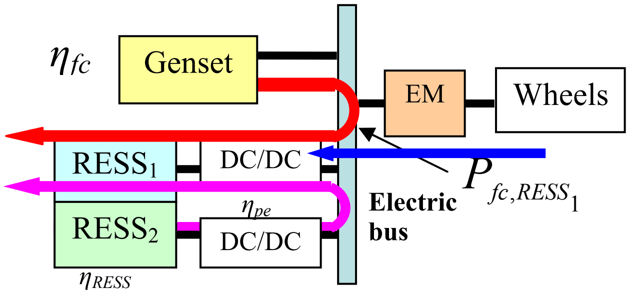


Fig. 4. Future recharging conditions.

where $\overline{\eta}_{fc,rechg}$ is the average efficiency of the fuel converter during recharge, $\overline{\eta}_{el,i,rechg}$ is the average efficiency of the electric path i during recharge, and $\overline{R}_{recov+exchg\,/\,rech,i}$ is the average value of

$$R_{recov+exchg\,/\,rech,i} = \frac{\displaystyle\int_{\substack{all\ future\\ recov.+rechg.exchg.cond.}} | P_{RESS,i,chg}(t) | \, dt}{\displaystyle\int_{\substack{all\ future\\ rechg.\ cond.}} | P_{RESS,i,chg}(t) | \, dt}$$

The cost in terms of fuel of discharging the RESS$_i$, i.e. the equivalent fuel consumption of the RESS$_i$ in discharging mode, is

$$\dot{m}_{f,RESS,i,eq} = \frac{c_{\Delta E,i,dis}}{\Delta t} \approx \frac{1}{\overline{\eta}_{rechg,i}} \cdot \frac{1}{\eta_{el,i,dis}(P_{el,i})} \cdot \frac{P_{el,i}}{Q_{LHV}} \qquad (7)$$

where $\overline{\eta}_{rechg,i}$ is some average recharging efficiency defined by

$$\overline{\eta}_{rechg,i} = \overline{\eta}_{fc,rechg} \overline{\eta}_{el,i,rechg} \cdot (1 + \overline{R}_{recov+exchg\,/\,rech,i})$$

$$\overline{\eta}_{x,rechg} = \frac{1}{T_{rechg}} \int_{\substack{all\ future\\ rechg.cond.}} \eta_x(t) dt$$

where T_{rechg} is the future time spent in recharge mode.

C. Mathematical Formulation: Charging Mode for a Single Component RESS$_i$

The amount of energy added to the RESS$_i$ at a given power $P_{el,i}$ during an interval Δt is

$$\Delta E_{RESS,i,chg} = \Delta t\, P_{RESS,i,chg} = \eta_{el,i,chg}(P_{el,i})\, P_{el,i}\, \Delta t \qquad (8)$$

where

$$\eta_{el,i,chg}(P_{el,i}) = \eta_{pe,i,chg}(P_{el,i})\, \eta_{RESS,i,chg}(P_{el,i}) \qquad (9)$$

with $\eta_{pe,i,chg}$ efficiency of the power electronics that connects the electric storage RESS$_i$ to the electric bus during charging and $\eta_{,RESS,i,chg}$ efficiency of the electric storage RESS$_i$ during

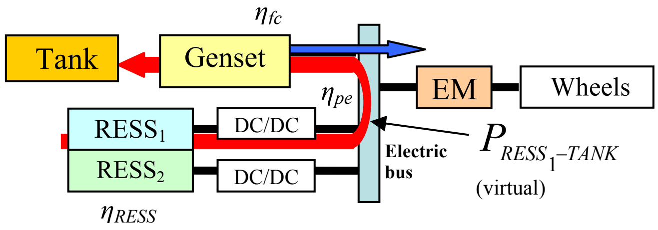


Fig. 5. Future discharging conditions.

charging. The future saving (negative cost) associated with $\Delta E_{RESS,i,chg}$ is

$$s_{\Delta E,i,chg} = S_{i,tot,dis} \frac{\Delta E_{RESS,i,chg}}{E_{i,tot,dis}} \quad [g] \qquad (10)$$

where $E_{i,tot,dis}$ is the total energy discharged in the future by RESS$_i$, $S_{i,tot,dis}$ is the saving due $E_{i,tot,dis}$. This condition is depicted in Fig. 5. The future saving $s_{\Delta E,i,chg}$ is a fraction of the savings due to the total energy discharged from the RESS$_i$. The total energy discharged in the future is

$$E_{i,tot,dis} = \int\limits_{\substack{all\ future\\ dis.cond.}} P_{RESS,i,dis}(t)\, dt + \int\limits_{\substack{all\ future\\ chg.exchg.cond.}} P_{RESS,i,dis}(t)\, dt$$

where discharge condition do not include energy transferred from one RESS to another. The exchange condition is when energy from the RESS$_i$ is transferred to another RESS$_j$ directly. The savings due to the total energy discharged in the future is

$$S_{i,tot,dis} = \frac{E_{tot,RESS_i-TANK}}{Q_{LHV}} \quad [g]$$

with

$$E_{tot,RESS_i-TANK} = \int\limits_{\substack{all\ future\\ dis.cond.}} \frac{\eta_{el,i}(t)\, P_{RESS,i,dis}(t)}{\eta_{fc}(t)} dt$$

where $E_{tot,RESS_i-TANK}$ is the total energy flowing from the RESS$_i$ to the tank (virtual). By substituting the above expressions into (10), after some manipulations and approximating the efficiencies by their average values, it can be shown that during charging

$$s_{\Delta E,i,dis} \approx \frac{\overline{\eta}_{el,i,dis}}{\overline{\eta}_{fc,dis}} \frac{1}{1+\alpha} \cdot \eta_{el,i,chg}(P_{el}) \cdot \frac{P_{el,i}}{Q_{LHV}} \Delta t$$

$$\alpha = \frac{\displaystyle\int\limits_{\substack{all\ future\\ chg.exchg.cond.}} P_{RESS,i,dis}(t)\, dt}{\displaystyle\int\limits_{\substack{all\ future\\ dis.cond.}} P_{RESS,i,dis}(t)\, dt}$$

where $\overline{\eta}_{fc,i,dis}$ is the average efficiency of the fuel converter during discharge, and $\overline{\eta}_{el,i,dis}$ is the average efficiency of the electric path during discharge. The cost in terms of fuel of charging the RESSi, i.e. the equivalent fuel consumption of the RESSi in charging mode, is

$$\dot{m}_{f,RESS,i,eq} = \frac{s_{\Delta E,i,dis}}{\Delta t} \approx \frac{1}{\overline{\eta}_{dis,i}} \cdot \eta_{el,i,chg}(P_{el,i}) \cdot \frac{P_{el,i}}{Q_{LHV}} \qquad (11)$$

where $\overline{\eta}_{dis,i}$ is some average discharging efficiency defined by

$$\overline{\eta}_{dis,i} = \frac{\overline{\eta}_{fc,dis}}{\overline{\eta}_{el,i,dis}} \frac{1}{1+\alpha}$$

$$\overline{\eta}_{x,dis,i} = \frac{1}{T_{dis}} \int\limits_{\substack{all\ future\\ dis.cond.}} \eta_{x,i}(t) dt$$

where T_{dis} is the future time spent in discharge mode.

Summarizing, we can write the expression for the equivalent fuel consumption of the RESS$_i$ as

$$\dot{m}_{f,RESS,i,eq} = \left(\gamma_i \frac{1}{\overline{\eta}_{rechg,i}} \cdot \frac{1}{\eta_{el,i,dis}(P_{el,i})} + (1-\gamma_i) \frac{1}{\overline{\eta}_{dis,i}} \cdot \eta_{el,i,chg}(P_{el,i}) \right) \cdot \frac{P_{el,i}}{Q_{LHV}}$$

where

$$\gamma_i = \begin{cases} 1 & if\ P_{el,i} \geq 0 \\ 0 & if\ P_{el,i} < 0 \end{cases}$$

It is worth to notice that the efficiencies $\overline{\eta}_{dis,i}$ and $\overline{\eta}_{rechg,i}$ are unknown because they depend on the future. In practical situations, the efficiencies $\overline{\eta}_{dis,i}$ and $\overline{\eta}_{rechg,i}$ are considered as unknown parameters to be tuned or estimated.

V. SIMULATION RESULTS

The proposed control strategy has been tested on a 20 tons heavy duty series hybrid electric truck equipped with a 225 kW Cummins engine and an electric generator of 150 kW rated power. The power train consists of two axles with one traction motor per axle having maximum torque of 3200 Nm and maximum speed of 7000 rev/min, a DC bus at 625V, two parallel branches constituted by 86 cells in series of 6.5 Ah NIMH batteries and 250 ultrapacitors in series with capacity of 2600 F. Different simulations have been conducted for different driving cycles. In Fig. 6 the velocity profile for a heavy duty urban driving cycle (HDUD) is reported. The equivalent fuel consumption obtained for this cycle is 5.1 gal/hr. This value takes into account not only the effective gasoline consumed but also the electric energy used thru an electric conversion efficiency factor of 0.25. The batteries SOE is presented in Fig. 7, while the battery current is reported in Fig. 8. Similarly, for the ultracapacitors the SOE is depicted in Fig. 9 and the current profile in Fig. 10. From the current plots it is clear that ultracapacitors and batteries are both exploited. The ultracapacitors are used first to absorb or release pick power while medium/low power is stored or released by the batteries.

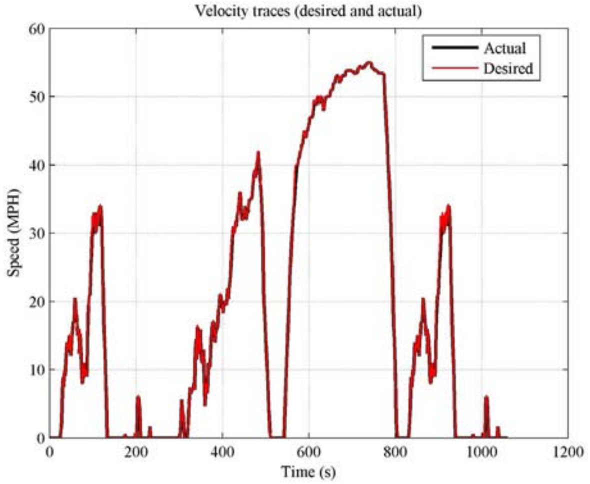


Fig. 6. HDUD driving cycle.

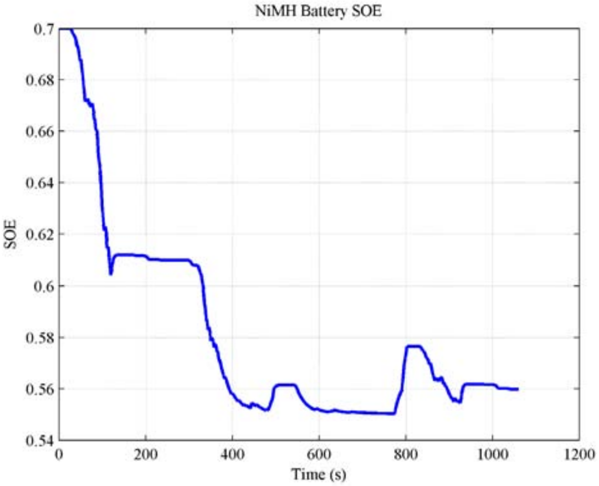


Fig. 7. Batteries State Of Energy for HDUD cycle.

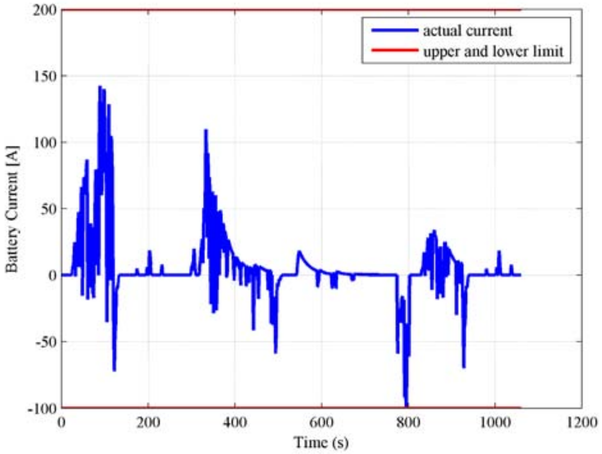


Fig. 8. Battery pack current for HDUD cycle.

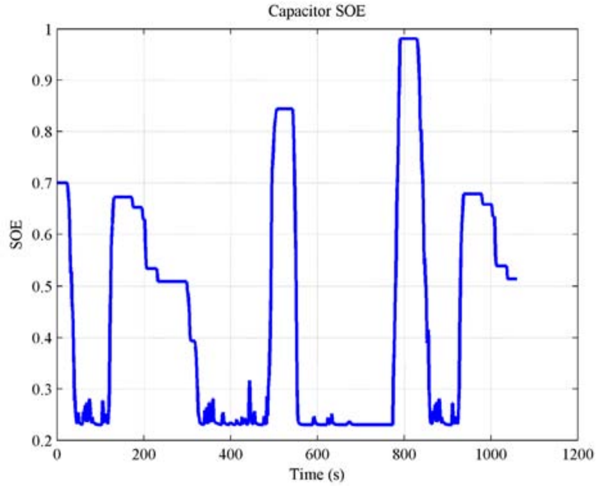


Fig. 9. Ultracapacitors State Of Energy for HDUD cycle.

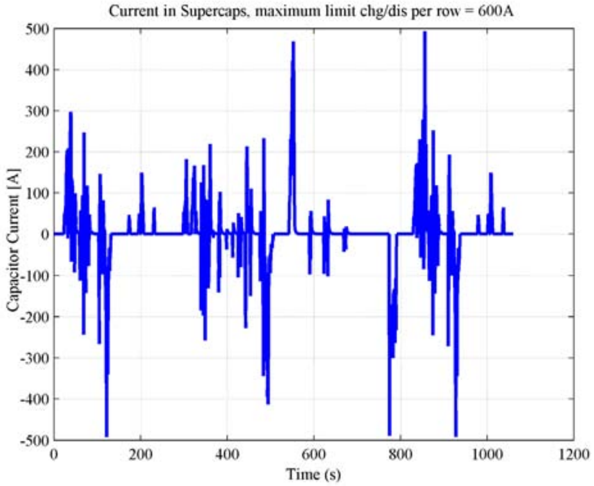


Fig. 10. Ultracapacitors current for HDUD cycle.

The Genset is forced to work along the maximum efficiency line as shown by the operating points in Fig. 11. Small deviations are due to various level of accessories load that can occur during the cycle. In Fig. 12 and 13 the operating points for the traction motors show essentially two low torque clusters characterized by low efficiency (less than 0.75) and high efficiency (higher than 0.88) .

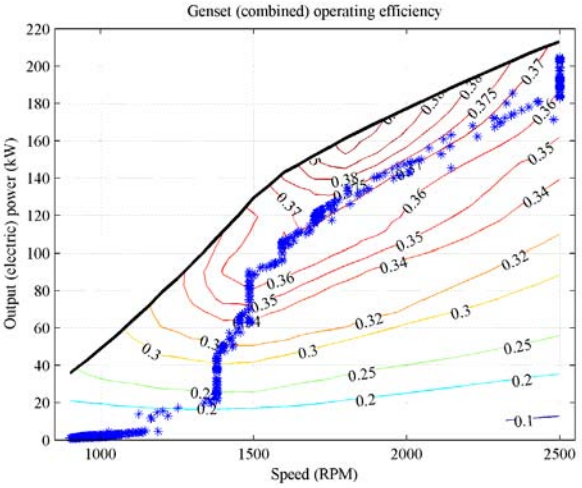


Fig. 11. Genset operating points for HDUD cycle.

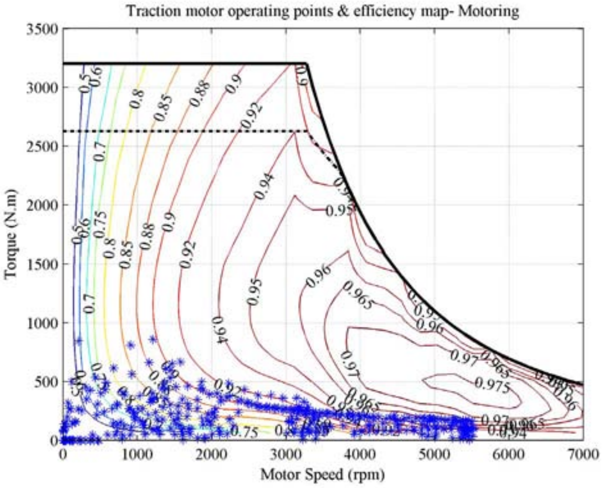


Fig. 12. Traction motor operating points during motoring for HDUD cycle.

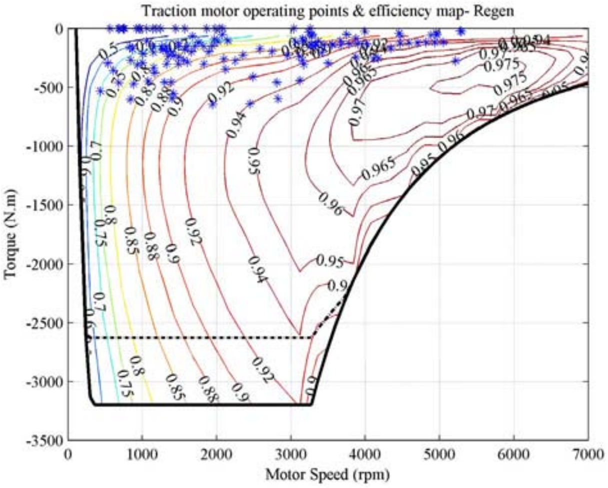


Fig. 13. Traction motor operating points during braking for HDUD cycle.

In Fig. 14 a driving cycle constituted by an on-road and off-road parts is presented. For this cycle, an equivalent fuel consumption of 5.0 gal/hr is obtained. The on-road portion of the cycle terminates at 668 s while an off-road portion constituted by dry packed dirt, mud, level cross country, and hilly cross country starts. The battery and ultracapacitors SOE is reported in Fig. 15 and 16. It is worth to notice a substantial change in the usage of the electric storage devices during off-road conditions. This change is obtained by modifying the values of the tunable average efficiency parameters in the control strategy so that the vehicle will operate at maximum performance. Finally, the power split for a particular portion of the cycle is shown in Fig. 17. This picture captures the transition from on-road to off-road where ultracapacitors and batteries are recharged during zero power requests at the bus in order to have them ready for the next power demand. Notice also how ultracapacitors are charged first while the batteries are charged only when the ultracapacitors reach the desired SOE level.

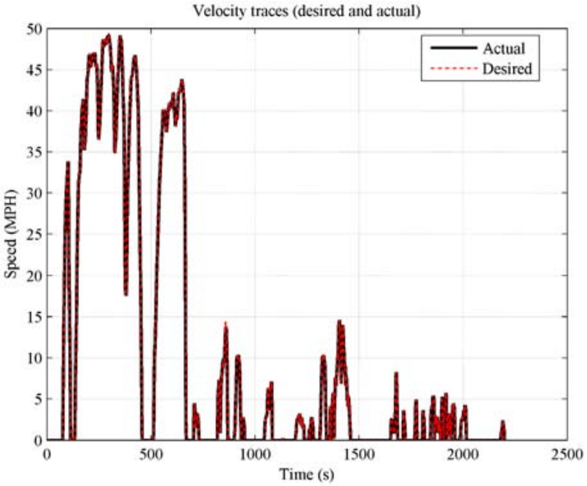


Fig. 14. Combined driving cycle with on-road and off-road portions.

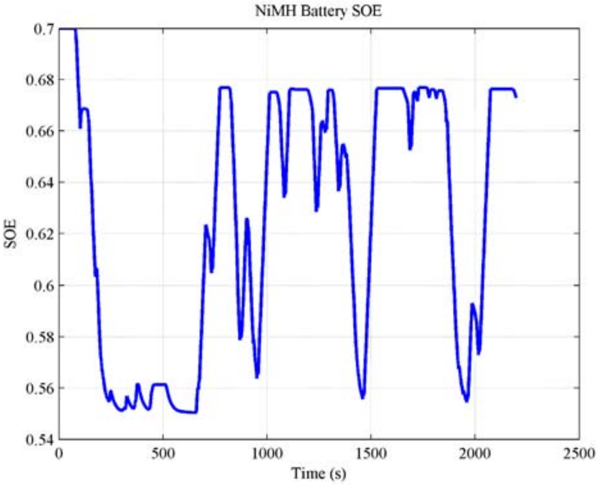


Fig. 15. Batteries SOE.

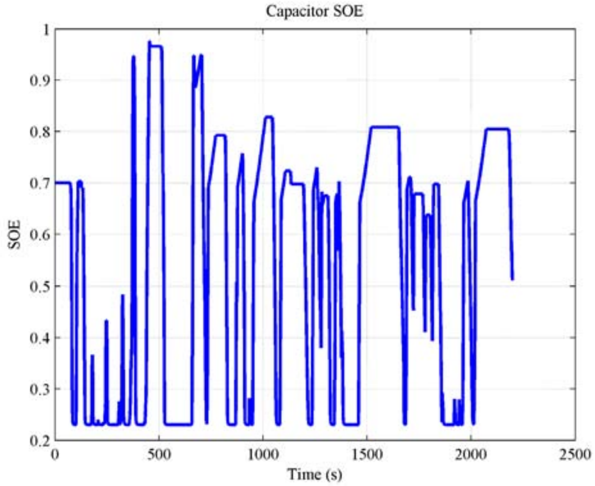


Fig. 16. Ultracapacitors SOE.

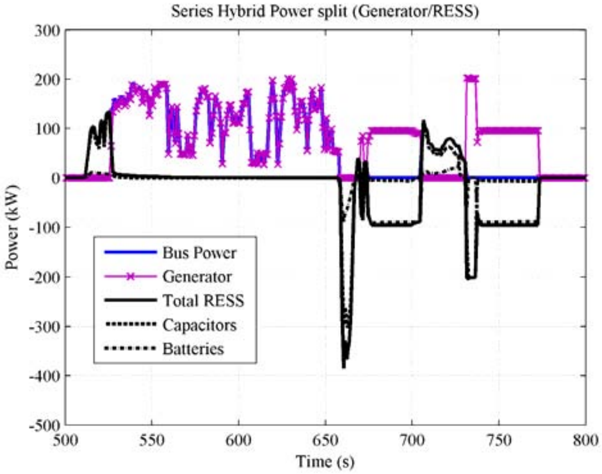


Fig. 17. Power split for a particular section of the driving cycle.

VI. CONCLUSIONS

In this paper, a modified ECMS strategy for a series hybrid vehicle configuration with two different energy storages is presented. The proposed ECMS strategy presents the following advantages:

- it requires the only knowledge of the efficiency maps for the various systems in the powertrain architecture, and their torque and power limits;
- it requires a limited number of inputs that include the SOE_i of the $RESS_i$ (i=1,2) and the torque requested at the wheels by the driver (this can be calculated from the accelerator and brake pedal position);
- it is easy to implement in real-time because the optimal power split can be determined by an easy and fast minimization of the function $\dot{m}_{f,eq}(t)$;
- in many cases, the optimal power split can be pre-calculated and saved in a multi-dimensional map as a function of the input variables, avoiding on-line minimization procedures and therefore, reducing the computational time;
- it is quite robust to estimation errors in the recharging and charging efficiencies and in the power split.
- It can be easily extended to any number of RESS in parallel.

Simulation results for a heavy duty truck with series hybrid powertrain and dual storage system show the effectiveness of the proposed supervisory control strategy.

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