

Management of Different Energy Storage Devices Using a Losses Minimization Algorithm

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Abstract—The paper presents a methodology for controlling different energy storage devices based on their efficiency curves and derived from their power losses functions. This control strategy was tested through simulations on a DC distribution system made up of two different energy storage devices (i.e., lead-acid battery and supercapacitors), and an active DC load. The effectiveness of the proposed algorithm was evaluated with different types of load cycles describing three benchmark driving cycles and was compared to different empiric strategies that set a constant share of the requested power between the storage devices.

Index Terms—energy storage, energy management, supercapacitors, DC distribution system, multi-source system.

I. NOMENCLATURE

SoC	(Battery) State of Charge
R_{0b}, R_{1b}, R_{2b}	Resistances of the battery model
R_{0sc}, R_{nsc}	Resistances of the supercapacitor model
C_{2b}, C_{2c}	Capacitances of the battery model
$C(v)$	Capacitance of the supercapacitor model
C_{nb}	Capacitances of the parallel R-C branches in the supercapacitor model
i_b, i_{sc}	Battery and supercapacitor currents
v_b, v_{sc}, v_{DC}	Battery, supercapacitor and DC bus voltages
$E_m(SoC)$	E.m.f of the battery, function of SoC
K_E	Thermal coefficient
P_{stg}	Algebraic sum of powers injected to or requested from storage devices
P_l, P_g	Power requested and generated by active loads
$\text{tr } \mathbf{A}$	Trace (i.e., sum of the diagonal elements) of the matrix \mathbf{A}
$\det \mathbf{A}$	Determinant of the matrix \mathbf{A}
∇f	Gradient vector of the scalar function f

II. INTRODUCTION

The growing global attention on sustainability, smart grids and renewable energy sources is leading to an increased concern on storage devices. In fact, one of the key feature of the next-generation distribution grids is the ability to store and manage energy by their own. This is mainly due to the presence of renewable energy sources and to the enhancements that these devices may offer towards the constitution of a flexible and dynamic distribution system where users are

thought not only as economically- and needs-driven energy customers but also, and even more significantly, as possible ancillary services providers.

Obviously the presence of storage systems implies a certain amount of initial investments, which make the energy supplied by these devices no costless and in some cases even more valuable than that supplied even by renewable energy sources, since that energy is intended to be used by customers for high-priority services (e.g., the energy coming from Plug-in Electric Vehicles). Moreover, the peculiar characteristics of different energy storage devices make the problem of finding the optimal management strategy a challenging task [1].

The aim of this paper is to describe a control strategy based on the maximization of an efficiency function for energy storage devices. This function is the sum of the different efficiency function of the storage devices that constitute the test system.

III. TEST SYSTEM

A. General Description

This control strategy is suited for a general DC bus distribution system to which different storage devices (e.g., batteries, supercapacitors, etc.), electrical AC and DC drives and power sources (e.g., conventional generators, renewable sources, an AC supply grid, etc.) are connected. The low voltage DC test system is shown in Fig. 1 [2].

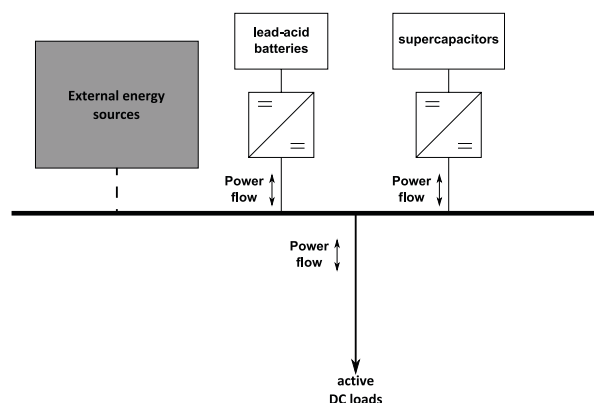


Figure 1. Layout of the low voltage DC test system analyzed [2]. The external source has a grey background because it can be excluded from the scheme.

The study of the overall feasibility of the proposed control strategy has been carried out on a DC distribution system implemented under MATLAB/Simulink environment made up of i) lead-acid batteries ii) supercapacitors and iii) a DC load with different power profiles.

B. Energy Storage Systems Models

The lead-acid battery has been modeled as a voltage source in series with the internal resistance, R_{0_b} and with two R-C branches that approximate the dynamic behavior of the battery (see Fig. 2) [3]–[5]. The values of the e.m.f E_m , generally, depend on the state of charge (SoC) of the battery according to the relationship $E_m = E_{m0} - K_E(273 + \vartheta)(1 - SoC)$, where ϑ is the electrolyte temperature measured in Celsius and K_E is a constant thermal coefficient [6]. Supercapacitor

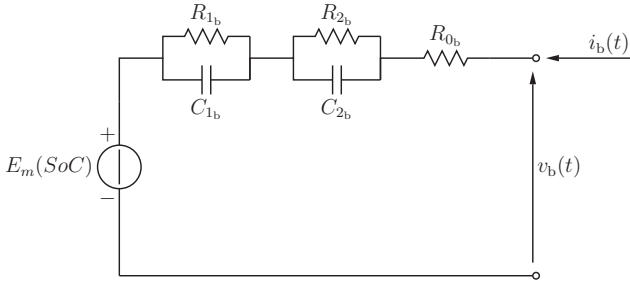


Figure 2. Lead-acid battery equivalent circuit.

have been modeled according to what described in [7] and shown in Fig. 3. It is made up of one branch which models the high frequency dynamics: $R_{0_{sc}}$ is the high frequency resistance; $C(v) = C_0 + k_v v$ is the capacitance—which depends on the two constants C_0 and k_v —estimated through a constant current charge [7], $C_{1_{sc}} = \dots = C_{n_{sc}} = \frac{C(v)}{2}$ and $\tau(v) = 3(R_{dc} - R_{0_{sc}})C(v)$, where R_{dc} is the DC resistance.

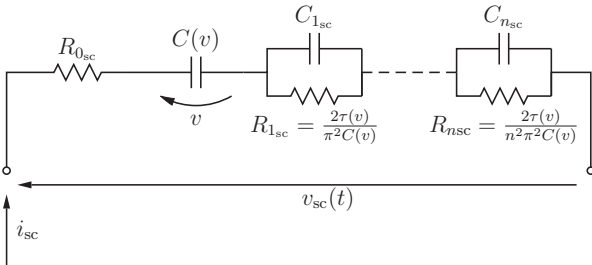


Figure 3. Supercapacitor equivalent circuit.

IV. CONTROL STRATEGY

A. General principle

The proposed control strategy is based on the idea of exploiting the different efficiency profiles which characterize the energy storage systems. These differences are based on the fact that some storage systems are suited for supplying power (i.e., power peaks for few seconds) while others are

suited for supplying energy (i.e., constant power for longer time intervals).

Let f be the general efficiency function

$$f := \eta(\mathbf{I}, \mathbf{S}, \mathbf{T}) \quad (1)$$

where $\mathbf{I} = [i_1 \ i_2 \ \dots \ i_N]^T$, $\mathbf{S} = [S_1 \ S_2 \ \dots \ S_N]^T$ and $\mathbf{T} = [T_1 \ T_2 \ \dots \ T_N]^T$ are respectively the vectors of currents, state of charge and temperature of each storage system. The strategy is based on finding the optimal value \mathbf{I}^* of supplied/requested current by each storage system so that f is maximized:

$$\eta^* = \max_{\mathbf{I}} f \quad (2)$$

subject to

$$P_{stg} = P_l - P_g \quad (3)$$

where the equality constraint (3) is the active power request balance.

The differences between the efficiency functions of the storage devices, together with the behavior of the load, can generally establish a trend of total depletion or recharge of the storage systems. Moreover, due to the intrinsic differences between the storage devices it may also happen that high-power- and low-energy-density devices are depleted faster than those with low power and high energy densities. In order to avoid these behaviors an additional term must be included in the expression of the optimal current value. This term takes into account the difference between the actual state of charge \mathbf{S}^{act} and the desired one \mathbf{S}^* :

$$\hat{\mathbf{I}} = \mathbf{I}^* + \mathbf{k}(\mathbf{S}^{act} - \mathbf{S}^*)^T \quad (4)$$

B. Formulation

The function describing the losses of the system can be addressed as a figure of the efficiency of the system itself. Assuming that the slow dynamics involving the parallel branches of the supercapacitor and the self-discharge branch of the battery can be neglected, the total losses of the coupled battery–supercapacitor system can be written as:

$$\begin{aligned} f(\mathbf{x}) = & (R_{0_b} + R_{1_b} + R_{2_b}) i_b^2 \\ & - 2(R_{1_b} C_{1_b} \dot{v}_{1_b} + R_{2_b} C_{2_b} \dot{v}_{2_b}) i_b \\ & + \left(R_{0_{sc}} + \sum_{n=1}^N R_{n_{sc}} \right) i_{sc}^2 \\ & - 2i_{sc} \left(\sum_{n=1}^N R_{n_{sc}} C_{n_{sc}} \dot{v}_{n_{sc}} \right) \\ & + R_{1_b} C_{1_b}^2 \dot{v}_{1_b}^2 + R_{2_b} C_{2_b}^2 \dot{v}_{2_b}^2 \\ & + \sum_{n=1}^N R_{n_{sc}} C_{n_{sc}}^2 \dot{v}_{n_{sc}}^2 \end{aligned} \quad (5)$$

where the terms containing the voltage derivatives (i.e., $C\dot{v}$) represent the current flowing in the resistances of the parallel R-C branches of both battery and supercapacitor. In this way

the efficiency maximization problem can be stated as a losses minimization problem. Let

$$\mathbf{x} = [i_b \quad i_{sc}]^T \quad (6a)$$

$$\mathbf{Q} = \begin{bmatrix} R_{0_b} + R_{1_b} + R_{2_b} & 0 \\ 0 & R_{0_{sc}} + \sum_{n=1}^N R_{n_{sc}} \end{bmatrix} \quad (6b)$$

$$\mathbf{b} = \begin{bmatrix} (R_{1_b} C_{1_b} \dot{v}_{1_b} + R_{2_b} C_{2_b} \dot{v}_{2_b}) \\ \left(\sum_{n=1}^N R_{n_{sc}} C_{n_{sc}} \dot{v}_{n_{sc}} \right) \end{bmatrix} \quad (6c)$$

$$\mathbf{A} = \begin{bmatrix} v_b & v_{sc} \\ v_{DC} & v_{DC} \end{bmatrix} \quad (6d)$$

the losses minimization problem can, thus, be written as

$$\min_{\mathbf{x}} f(\mathbf{x}) = \min_{\mathbf{x}} (\mathbf{x}^T \mathbf{Q} \mathbf{x} - 2\mathbf{x}^T \mathbf{b}) \quad (7a)$$

subject to

$$h(\mathbf{x}) := \mathbf{A} \mathbf{x} - u = 0 \quad (7b)$$

where u is the load current at the DC bus and $\mathbf{A} \mathbf{x}$ represents the sum of the currents supplied by the battery–supercapacitor system on the DC bus side (with the hypothesis of unitary efficiency of the converters), thus $h(\mathbf{x}) = 0$ being another way to write constraint (3). The transformation operated by \mathbf{A} takes into account that the two storage devices can have a different voltage levels with respect to each other and to be DC bus. From this formulation it follows that the Lagrangian function is

$$\mathcal{L} = \mathbf{x}^T \mathbf{Q} \mathbf{x} - 2\mathbf{x}^T \mathbf{b} + \lambda (\mathbf{A} \mathbf{x} - u) \quad (8)$$

and the minimum values can be obtained solving the system

$$\nabla \mathcal{L} = \mathbf{0} \quad (9)$$

that is, in this case,

$$\begin{cases} 2\mathbf{Q} \mathbf{x} - 2\mathbf{b} + \lambda \mathbf{A}^T = \mathbf{0} \\ \mathbf{A} \mathbf{x} - u = 0 \end{cases} \quad (10)$$

The solutions of (10) are shown in (11) where $\hat{\mathbf{Q}} = \begin{bmatrix} v_b & 0 \\ 0 & v_{sc} \end{bmatrix} \mathbf{Q}$. Moreover, since the second-order conditions are always satisfied—being the Hessian matrix of the Lagrangian function positive definite ($\mathbf{F} + \lambda \mathbf{H} = 2\mathbf{Q} > 0$)—the solutions of (10) identify the minimum value of f .

It is worth noting that this minimization is carried out on a continuous basis, i.e., for every value of u the algorithm sets the values of the currents of battery and supercapacitors in order to minimize losses while satisfying the active power constraint without any prior knowledge of u . Thus, the losses minimization is not designed to be an integral energy minimization because neither it explicitly takes into account the history of each storage device (i.e., the paths followed by each device to arrive to the current instant) nor it foresees the possible trend of u in order to perform some sort of predictive control. In fact, if the duty cycle set by load were known *a priori*, an optimal share between the power supplied by (or requested from) the storage devices could be found and this configuration could be even better than that found by the proposed algorithm, since the latter would be obtained through the summation of local minima whereas the former, taking advantage of the complete knowledge of the cycle, by minimization of the overall losses. This means that the proposed control strategy is particularly suited when the load behavior is unknown and randomly variable in time.

It is also important to notice that this control strategy exploits the knowledge or the estimate of the currents flowing through the resistances of the parallel R-C branches of both batteries and supercapacitors and of the state of charge. Generally it is not always true that one knows this information exactly. However, for what concerns the state of charge, there are some techniques that allow for its accurate estimation [8],

$$\begin{aligned} i_b &= -\frac{1}{\text{tr} \hat{\mathbf{Q}}} \left[-(R_{1_b} C_{1_b} \dot{v}_{1_b} + R_{2_b} C_{2_b} \dot{v}_{2_b}) v_{sc} + \left(\sum_{n=1}^N R_{n_{sc}} C_{n_{sc}} \dot{v}_{n_{sc}} \right) v_{sc} - \frac{u}{v_{DC}} \left(R_{0_{sc}} + \sum_{n=1}^N R_{n_{sc}} \right) \right] \\ i_{sc} &= -\frac{1}{\text{tr} \hat{\mathbf{Q}}} \left[(R_{1_b} C_{1_b} \dot{v}_{1_b} + R_{2_b} C_{2_b} \dot{v}_{2_b}) v_b - \left(\sum_{n=1}^N R_{n_{sc}} C_{n_{sc}} \dot{v}_{n_{sc}} \right) v_b - \frac{u}{v_{DC}} (R_{0_b} + R_{1_b} + R_{2_b}) \right] \\ \lambda &= -\frac{2}{v_{DC} \text{tr} \hat{\mathbf{Q}}} \left[u \det \mathbf{Q} - (R_{0_b} + R_{1_b} + R_{2_b}) \left(\sum_{n=1}^N R_{n_{sc}} C_{n_{sc}} \dot{v}_{n_{sc}} \right) v_{sc} \right. \\ &\quad \left. - \left(R_{0_{sc}} + \sum_{n=1}^N R_{n_{sc}} \right) (R_{1_b} C_{1_b} \dot{v}_{1_b} + R_{2_b} C_{2_b} \dot{v}_{2_b}) v_b \right] \end{aligned} \quad (11)$$

[9]. Moreover, the current flowing through the resistances can be estimated knowing the initial voltages of the capacitors and the current injected or drawn.

V. SIMULATIONS AND RESULTS

In order to test its effectiveness the proposed algorithm was tested on an automotive application. Three different benchmark load cycles have been used (see Fig. 4 for the plot of the speed with respect to time and Fig. 5 for the plot of power as seen by the shaft with respect to time). These three power profiles represent different benchmark driving cycles [10]:

- 1) New European Driving Cycle (NEDC);
- 2) USA Highway Fuel Economy (HWFET);
- 3) USA Federal Test Procedure 72 (FTP-72).

Since the simulations were meant to validate the proposed algorithm, no traditional internal combustion engine (ICE) has been considered, thus implying that no external power supply was used (batteries are charged when the vehicle ends its duty cycle). However, considering the efficiency of an opportunely suited ICE and of fuel costs, the algorithm can be easily extended to take into account also for external sources. Moreover it worth noting that no thermal dynamic behavior has been considered in this study. This means that the electrolyte temperature of the lead-acid battery, parameter that affects the dependency of e.m.f E_m on SoC, has been considered constant.

The main data of the three considered cycles are reported in Table I. The amounts of total energy supplied together with the cycles' lengths was used to select the battery size. In fact, a 9 kWh battery would allow for a cruising range of approximately 100 km for all the cycles [11]. For what concerns supercapacitors, they were dimensioned in order to be able to recover the 80% of the energy during the last braking phase of the NEDC cycle (approximately 130 Wh) which is, with respect to the three cycles, the one that involves the greater amount of recoverable energy.

TABLE I
LENGTHS AND ENERGIES FOR THE THREE CYCLES.

	NEDC	USA HWFET	USA FTP-72
length [km]	10.93	16.49	11.99
energy supplied [kWh]	0.92	1.193	1.045
recovered energy [kWh]	0.29	0.154	0.463

The values of the main parameters of the storage system devices are reported in Table II and Table III [12].

In this context of no external source the compensative action introduced in (4) was applied only to supercapacitors and was tuned in order to add a current of 30 A, in the DC reference system, when supercapacitors voltage reaches 60 V, the low threshold at which the protection are set to trigger. The initial state of charge of the batteries and the initial voltage of supercapacitors were set to 0.8 and 125 V respectively. In

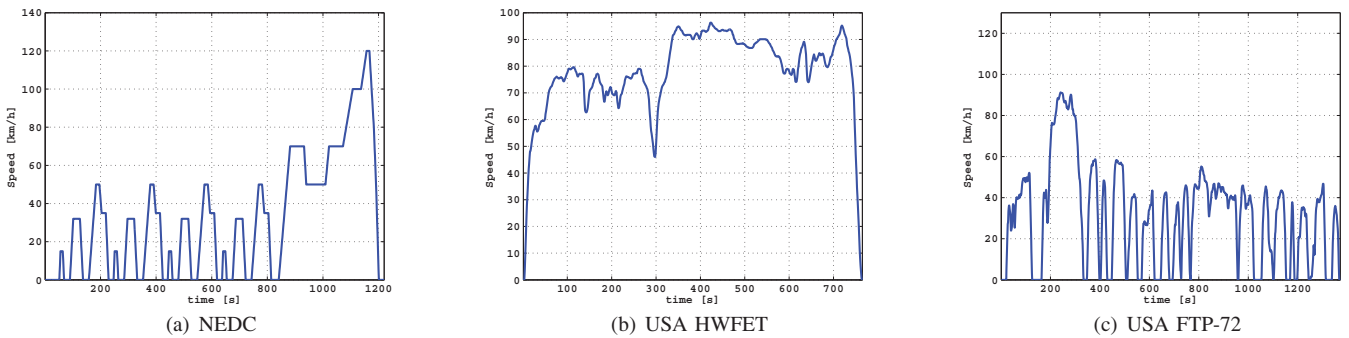


Figure 4. Standard driving cycles used to test the proposed algorithm.

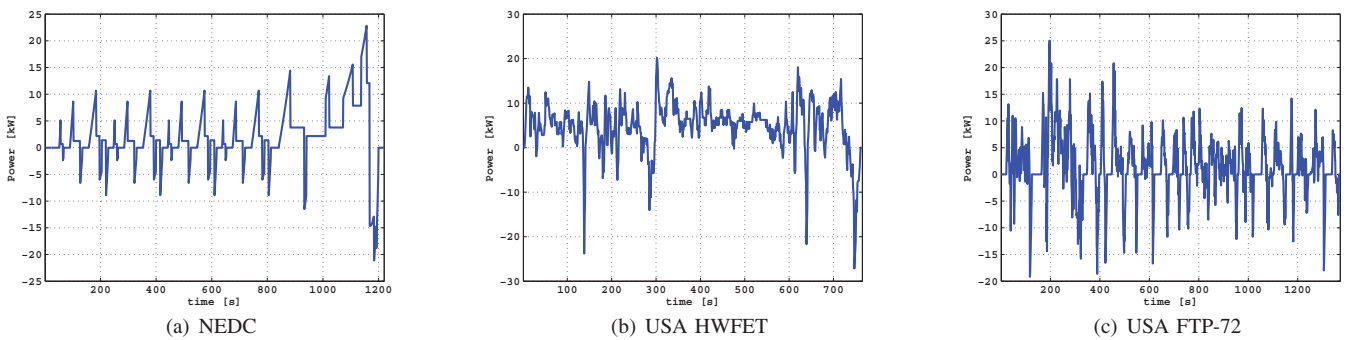


Figure 5. Profiles of the power as seen by the shaft for each driving cycles.

TABLE II
PARAMETERS OF THE LEAD-ACID BATTERY MODEL.

Battery module parameters 200 Ah — 48 V						
E_{m0} [V]	K_E [mV/°C]	R_0 [mΩ]	R_1 [mΩ]	R_2 [mΩ]	C_1 [F]	C_2 [F]
48	0.58	25	7	6	79	200

TABLE III
PARAMETERS OF THE SUPERCAPACITOR MODEL.

Supercapacitor module parameters 63 F — 125 V					
R_0 [mΩ]	R_{dc} [mΩ]	C_0 [F]	k_v [F/V]	R_2 [Ω]	C_2 [F]
12	18	42	0.168	90	5.55

order to validate the proposed algorithm, the obtained results were compared with two empiric control strategies which split the power requested or supplied by the active load according to a constant share (set *a priori*) between the two storage devices. One of these two empiric strategies has the same compensative action used in the proposed algorithm. A protection system was implemented in order to cut off requested supercapacitors current when their voltage reached the lower bound set to 60 V and the supplied current when their voltage reached the upper bound set to 130 V. When one of these protection triggered supercapacitors current was set to 0 (except for the compensative action) and the battery was the only storage device in charge of satisfying load requests.

Fig. 6 shows the values of power losses for the selected driving cycles and for the three different strategies. The solid lines represent power losses of the two empiric policies (with and without compensative action) while the dashed lines represent the level of power losses reached by the proposed algorithm where the share between the two storage devices is intrinsically regulated by the control strategy. Table IV reports the lowest power losses of the two empiric control strategy along with the respective supercapacitor share and the power

losses obtained by the presented strategy. It can be seen that it

TABLE IV
COMPARISON BETWEEN POWER LOSSES OF THE PROPOSED CONTROL STRATEGY AND THE LOWEST POWER LOSSES OBTAINED WITH CONSTANT SHARE CONTROL STRATEGY WITH AND WITHOUT COMPENSATION.

cycle	control strategy	losses [Wh]	sc share
NEDC	const share + comp	127.4	0.25
	const share no comp	139.5	0.70
	proposed algorithm	127.5	—
USA HWFET	const share + comp	143.1	0.35
	const share no comp	149.5	0.75
	proposed algorithm	150.1	—
USA FTP-72	const share + comp	58.6	0.80
	const share no comp	84.8	0.75
	proposed algorithm	60.9	—

displays the envisaged behavior. In fact for the three cycles it performs better than (or almost as good as) the constant share without compensation strategy. For NEDC cycle it also reaches power losses which are almost the same as those obtained by the two configurations of constant supercapacitor share of 0.25 and 0.8 respectively with the compensative action. This “constant” control strategy with compensation obtains lower figures in USA HWFET with a supercapacitor share from 0.25 to 0.4 and in USA HWFET with a supercapacitor share of 0.8. This is mainly due to the fact that these cycles are more biased with respect to NEDC, thus implying that some particular configurations (e.g., those with low or high supercapacitor usage) may manage the energy storage devices more efficiently. However it must be noted that power losses as obtained by the proposed algorithm are a 4–5% higher than the best case. Moreover it is also clear that the minimum can be found for the different cycles at different supercapacitors share. This means that, even though the proposed algorithm does not perform at best in USA HWFET and USA FTP-72 cycles, it is as well valuable since it allows to reach losses below—or at least very close to—the minimum values without any prior knowledge on the load requests. In fact, for the three cycles the minimum losses are obtained with significant variations of

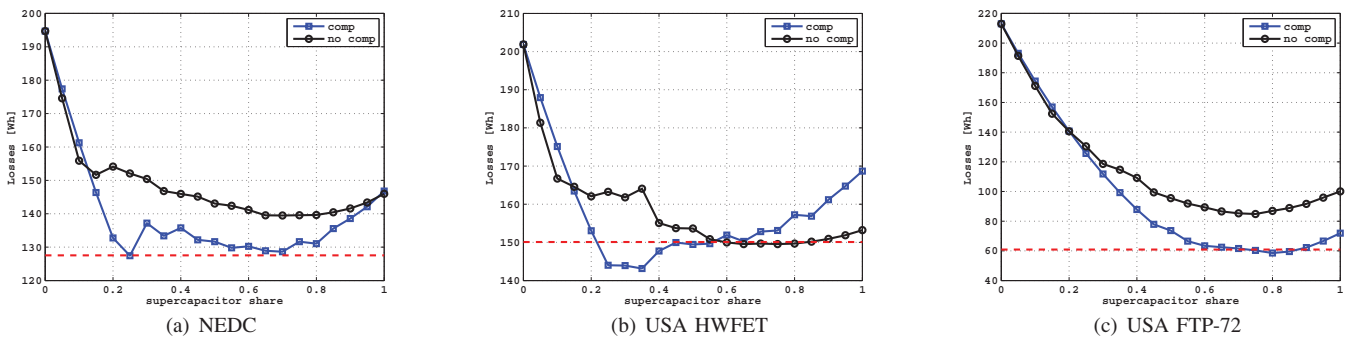


Figure 6. Power losses for obtained with the three control strategies for the tested driving cycles: solid lines represent the empiric strategies with (black square marker) and without (blue circle marker) compensative action; dashed lines represent the losses obtained using the losses minimization algorithm. In abscissa are reported the different percentage values of power share for supercapacitors. The dashed lines are reported to give a visual reference of the power losses obtained by the proposed algorithm.

the share between the two storage devices.

VI. CONCLUSIONS

The paper has presented a methodology for controlling different energy storage devices (i.e., lead-acid batteries and supercapacitors) based on a power losses minimization algorithm. This control strategy allows for instantaneous and continuous losses minimization without any prior knowledge of the load requests. A compensative action was added in order to take into account of the differences among the efficiency functions and avoid trends of total depletion or recharge of a single storage device. This additional term, which is function of the difference between the actual state of charge and the desired one, represents a weighting factor which can be tuned in order to privilege general availability of the storage devices with respect to strict losses minimization.

The control strategy was tested through simulations on a DC system made up of two different energy storage devices (i.e., lead-acid battery and supercapacitors), and a DC load reproducing three different benchmark driving cycles: i) New European Driving Cycle; ii) USA Highway Fuel Economy and iii) USA Federal Test procedure 72. The results were compared with an empiric strategy that set a constant share of the requested power between the storage devices. This strategy was also simulated with the additional compensative term for the sake of completeness.

The simulations have shown that the proposed algorithm performs in a way similar to—or even better than—the empiric strategies. Moreover while the best solutions for the empiric strategies were found at different shares between the two storage devices, the proposed algorithm finds a good approximation of the best solution in an independent way.

ACKNOWLEDGMENTS

This work has been partially financed by the Research Fund for the Italian Electrical System under the Contract Agreement between RSE and the Ministry of Economic Development – General Directorate for Nuclear, Renewable Energies and Electrical Efficiency, stipulated on July 29, 2009 in compliance with the Decree of March 19, 2009.

REFERENCES

- [1] M. B. Camara, H. Gualous, F. Gustin, and A. Berthon, "Design and new control of DC/DC converters to share energy between supercapacitors and batteries in hybrid vehicles," *IEEE Trans. Veh. Technol.*, vol. 57, no. 5, pp. 2721–2735, Sep. 2008.
- [2] M. Brenna, C. Bulac, G. C. Lazaroiu, G. Superti-Furga, and E. Tironi, "DC power delivery in distributed generation systems," in *Harmonics and Quality of Power, 2008. ICHQP 2008. 13th International Conference on*, Sep. 28–Oct. 1, 2008, pp. 1–6.
- [3] P. Mauracher and E. Karden, "Dynamic modelling of lead/acid batteries using impedance spectroscopy for parameter identification," *Journal of Power Sources*, vol. 67, no. 1-2, pp. 69–84, 1997, proceedings of the Fifth European Lead Battery Conference.
- [4] H. Andersson, I. Petersson, and E. Ahlberg, "Modelling electrochemical impedance data for semi-bipolar lead acid batteries," *Journal of Applied Electrochemistry*, vol. 31, pp. 1–11, Jan. 2001.
- [5] N. Moubayed, J. Kouta, A. El-Ali, H. Dernayka, and R. Outbib, "Parameter identification of the lead-acid battery model," in *Photovoltaic Specialists Conference, 2008. PVSC '08. 33rd IEEE*, May 2008, pp. 1–6.
- [6] M. Ceraolo, "New dynamical models of lead-acid batteries," *IEEE Trans. Power Syst.*, vol. 15, no. 4, pp. 1184–1190, Nov. 2000.
- [7] E. Tironi and V. Musolino, "Supercapacitor characterization in power electronic applications: Proposal of a new model," in *Clean Electrical Power, 2009 International Conference on*, Jun. 2009, pp. 376–382.
- [8] F. Codecà, S. M. Savaresi, and G. Rizzoni, "On battery state of charge estimation: A new mixed algorithm," in *Control Applications, 2008. CCA 2008. IEEE International Conference on*, Sep. 2008, pp. 102–107.
- [9] C. R. Gould, C. M. Bingham, D. A. Stone, and P. Bentley, "New battery model and state-of-health determination through subspace parameter estimation and state-observer techniques," *IEEE Trans. Veh. Technol.*, vol. 58, no. 8, pp. 3905–3916, Oct. 2009.
- [10] L. Guzzella and A. Sciarretta, *Vehicle Propulsion System – Introduction to Modeling and Optimization*. Springer Verlag, 2007.
- [11] M. De Nigris, I. Gianinoni, S. Grillo, S. Massucco, and F. Silvestro, "Impact evaluation of plug-in electric vehicles (pev) on electric distribution networks," in *Harmonics and Quality of Power (ICHQP), 2010 14th International Conference on*, Sep. 2010, pp. 1–6.
- [12] S. Buller, "Impedance-based simulation models for energy storage devices in advanced automotive power systems," Ph.D. dissertation, RWTH Aachen University, 2003.