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A comparative analysis of meta-heuristic methods for power management of a dual energy storage system for electric vehicles

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ABSTRACT

This work is focused on the performance evaluation of two meta-heuristic approaches, simulated annealing and particle swarm optimization, to deal with power management of a dual energy storage system for electric vehicles. The proposed strategy is based on a global energy management system with two layers: long-term (energy) and short-term (power) management. A rule-based system deals with the long-term (strategic) layer and for the short-term (action) layer meta-heuristic techniques are developed to define optimized online energy sharing mechanisms. Simulations have been made for several driving cycles to validate the proposed strategy. A comparative analysis for ARTEMIS driving cycle is presented evaluating three performance indicators (computation time, final value of battery state of charge, and minimum value of supercapacitors state of charge) as a function of input parameters. The results show the effectiveness of an implementation based on a double-layer management system using meta-heuristic methods for online power management supported by a rule set that restricts the search space.

1. Introduction

Green power generation technologies utilizing renewable energy sources, such as wind, solar, and biomass, have become popular and technologically feasible with significantly reduced greenhouse gas and harmful emissions [1–3]. The combination of zero-emission Electric Vehicles (EVs) and green power-generation can offer a great alternative opportunity to contribute for a more rational use of energy, environmental protection, and climate change mitigation, compared to the conventional approaches mostly depending on fossil fuels [4–6]. The penetration and expansion of EVs in the marketplace has been hindered by issues such as high purchase costs, short vehicle driving range, some safety concerns, limited number of recharging stations, time consumed recharging the batteries, and electricity infrastructure and policy challenges [1–11]. Presently, there is no single energy storage element meeting all the desired features to supply EVs and thereby the hybridization concept using commercially available energy storage devices has been gaining increased relevance [1,6–10].

Research in the energy storage field presently indicates that batteries, Fuel Cells (FCs), SuperCapacitores (SCs) and flywheels are the most suitable storage elements in EVs [3,4,6,8–12]. FCs and flywheels are promising technologies but not yet sufficiently mature, and FCs have no capacity to accept regenerative energy. Batteries are by far the most used storage elements in present EVs, being known by their high specific energy (HSE) and portability. Due to important technical advances, batteries have reached high efficiency and already offer an acceptable number of cycles over their lifetime [12]. Nevertheless, batteries do not meet all the requirements to be the only storage system of an EV as, in addition to having low power density, they have their weak point in the dynamical behavior when compared to SCs. Unlike batteries, SCs have high specific power (HSP), very high number of lifetime cycles, high efficiency and a good dynamical behavior, supporting high transient power [6–9,12–14].

The hybridization of two or more energy storage elements coupled using power electronics converters enables more degrees of freedom and improves both the vehicle driving range and the lifecycle of those storage elements by combining their advantages [6–15]. In recent literature, the most frequent combinations are: batteries/SCs [9,16–18]; FC/SCs [19,20]; FC/batteries [10,21] and FC/batteries/SCs [22]. SCs are used as a fast power regulator to limit the battery's current and regulate the DC-link voltage in a standalone application in [23]. The use of these combinations in

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Nomenclature

$\{Bat, SC\}$	subscripts that relate the variables to batteries or supercapacitores
Ref	subscript specifying the reference of the variable
OC	superscript specifying the open circuit value of the storage elements voltage
$\{min, max\}$	superscripts specifying the minimum or the maximum value
P_i	power supplied/charged by the storage elements
C_i	power assignment by the storage elements
$\{LB_i, UB_i\}$	lower and upper bound for the power assignment
SoC_i	state of charge of the storage elements
Q_i	charge level of the storage elements (A h)
V_i	storage elements voltage (V)
I_i	storage elements current (A)
δ_i	state of the charge gain of the storage elements
N_i	number of element in series
n_i	number of element in parallel
Cap_{SC}	supercapacitors capacitance (F)
P_{dem}	required electrical power in EV's DC bus (W)
Δt	integration time step (s)
N_{cycles}	number of iterations at constant temperature (SA) or number of the maximum iterations (PSO)
T	annealing temperature in SA
ΔE	difference between the evaluation function value of the candidate and incumbent solutions in SA
p'	random value uniformly distributed over (0, 1)
α	cooling rate in SA
X	solution generated in the current iteration
X^*	best solution
N_{swarm}	number of swarm elements
w	value of the inertia weight in PSO
x_i	position of particle i in PSO
v_i	velocity of the particle i in PSO
c_1, c_2	positive constants that control the individual and social behavior of each particle in PSO
$pbest_i$	best historical position for each particle
$gbest$	best position already occupied by the swarm
τ	threshold (%)
f_o	objective function

vehicular technology should be associated with adequate energy and power management algorithms. These algorithms should define the amount of power and energy to be transferred from or to the energy storage elements in order to supply the vehicle with high efficiency. Special attention has been devoted to the design of optimal energy management strategies due to their importance to urban EVs. Essentially, the existing approaches may be categorized in rule-based control strategies (operation mode dependence) and optimization strategies [14,15].

Fuzzy rule-based methods are used in several applications. They can be easily implemented with online supervisory control to manage power flow between multiple energy storage elements [24,25]. The rules can be determined based on human expertise and/or intelligence (machine learning methods), heuristics, or mathematical programming models. For instance, in [25] an energy management fuzzy logic controller is designed using Particle Swarm Optimization (PSO).

For optimization strategies two main approaches can be considered. The most direct is based on obtaining global optimal solutions through optimization over a fixed driving cycle (non-causal models), using knowledge of future and past power demand. For known environments (e.g., tramway or bus journeys), some works provide studies of power management methods using computer simulation [21,22]. A key aspect of this problem is the maintenance of the defined conditions (road and traffic conditions, driver behavior, etc.) and the associated power demanded by the EV. Changes in traffic conditions (e.g. traffic jams, number of passengers, starts and stops, etc.) generally lead to non-optimal solutions to the multiple energy storage system management problem. Hence, online methods are mandatory for real-world applications, and even though many of these approaches do not guarantee optimal solutions they generally present good quality (sub-) optimal solutions in the scope of their practical purposes in suitable computation times [17].

In the literature, a limited number of works related to multiple energy storage systems has been focused on implementable methods in embedded systems enabling power-sharing decisions in real time [17,24,26]. Some authors [27–29] have dealt with the energy management problem in EVs with multiple storage elements essentially regarding the online control capacity using optimization approaches. In [27], an approach taking into account the stochastic influences of traffic and driver behavior is used to determine a management strategy for online energy control based on dynamic programming. In [28], an optimal energy management strategy for plug-in hybrid EV (HEV) is proposed using neural networks to obtain sub-optimal online control using previous results from a PSO approach. A strategy combining PSO and Simulated Annealing (SA) to reduce the emissions and fuel consumption of a parallel HEV is presented in [29].

Although several solutions to the energy and power management problem have been proposed, a global architecture for an improved energy management system using a double-layer management strategy was previously proposed by the authors in [16]. This consists of a high layer for energy management and a low layer for power management, taken into account the required expected response times for these two management layers. Considering this double-layer management architecture, in which the energy management is accomplished by a rule-based method and the power management is implemented by a meta-heuristic algorithm, the application of two meta-heuristic algorithms, namely SA and PSO, for the power management layer is investigated in this paper. The two algorithms are evaluated and their merits compared as alternative search and optimization techniques when dealing with the power management problem of a dual energy storage system for EVs. A comparative analysis for the ARTEMIS driving cycle is presented, by evaluating three performance indicators (computation time, final value of battery state of charge, and minimum value of SCs state of charge) as a function of input parameters. Due to the dependence on these parameters, this type of algorithms is not normally a first choice whenever convergence in a very short computation time is a critical requirement, as it is required by a vehicle. Then, this paper is specifically devoted to discuss and compare the suitability and performance of two meta-heuristic algorithms (SA based on single solution trajectory and PSO based on the movement of a population) for online implementation of the proposed energy management architecture in electric vehicle applications, including the parameters definition as a critical input of the overall approach previously presented in