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Efficient start–up energy management via nonlinear control for eco–traction systems

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HIGHLIGHTS

- Renewable HPS for the train start-up within *feeding* durations.
- Dynamic modelling of the modern HPS applied to traction systems.
- Port-Controlled Hamiltonian (PCH) design for supercapacitors' charge/discharge operation.
- Experimental validation and applicability of HPSs for energy management in eco-tractions.

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ABSTRACT

Electrochemical capacitors, called supercapacitors (SCs) or ultracapacitors, are devices conveniently used for embedded electrical energy management owing to their huge capacitance, low internal resistance and flexible control through power electronic conversion. This paper proposes a main power supply of hybrid Wind Generator (WG)–SC within the train station for feeding the traction onboard SC through specified limited feeding transit durations. Onboard SCs provide the train with the requested start–up self–energy. The hybrid WG–SCs system is an environmental–friendly source that enables the independency on national grid and guarantees an efficient bidirectional power transfer for energy management with enhanced dynamic performance. Therefore, the dynamic modelling and the experimental analysis of the modern hybrid WG–SCs used for managing the charge/discharge operation of SCs at Unity Power Factor (UPF) mode are presented. For this purpose, the Port–Controlled Hamiltonian (PCH) methodology is deduced and explicitly presented. Simulation results, via MATLAB™, reveal that the proposed PCH control methodology can be successfully implemented to ensure acceptable system dynamic behavior. Numerical results are validated with experimental measurements to investigate the significance of the PCH approach for the energy management operation in eco-tractions.

1. Introduction

Transport is currently one of the most energy–consuming and polluting sectors in both developing and developed countries. In the European Union (EU), for instance, it causes approximately 31% of total Green House Gas (GHG) emissions [1,2]. Therefore, the implementation of efficient, reliable and environmental–friendly transport systems becomes globally imperative both to meet the international agreements on GHG emissions reduction and to guarantee livable conditions in urban areas [1,2]. To curb emissions of carbon dioxide in the transportation sector, electric traction systems powered by renewable energies (wind, solar, and geothermal, etc.) offer a viable solution compared to their petroleum–based counterparts [3–17].

Renewable Energy (RE) systems are growing not only due to the obvious environmental considerations, but also in favor of the social, economic, and political interests. The variable nature of these systems particularly Photovoltaic (PV) and Wind Energy (WE) systems is attributed to the natural presence of the sun or the wind respectively. Consequently, it is difficult to predict and to program exactly the power generated by these primary sources. The power demand peaks do not coincide necessarily with the power generation. For this purpose, different Energy Storage Sys-

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tems (ESSs) can be used such as: batteries, hydrogen and Fuel Cells (FCs), flywheels, Supercapacitors (SCs), superconductor inductors, or compressed air devices [1,4,5,18]. Other strategies for energy storage aim at increasing the potential of power to gas and power to heat technologies, which may produce synthetic natural gas or increase the production of compressed and liquefied natural gas. These strategies are of considerable interest in transportation. Batteries have been successfully used in light-duty vehicles, hybrid battery-SC platforms for scooters, trucks, buses, tramway and trains. These latter systems may require more stored energy than that readily accommodated by batteries. González et al. (2016) have presented a comprehensive state of the art of supercapacitor material and technology. Owing to its high power capacity and long cycle-life, SCs can be conveniently used for hybrid ESSs applications. The authors recommended the use of hybridized battery-SC system in favor of their better energy density, cycle life and power rating [13].

Studies about buses using FCs and SCs have shown that the hybrid electrochemical/SC concept can be extremely interesting for high power Electric Vehicles (EVs) [10,13,14]. Zhu and Tatarchuk have designed a hybrid asymmetric ultracapacitor using both a double-layer capacitor electrode and a battery electrode to enhance of energy conservation and capacitance [16]. Therefore, new electrochemical capacitor technology can both operate at high charge/discharge rates over almost unlimited number of cycles and enable energy recovery in heavier duty systems. The SCs are of higher power density and lower energy density compared to other ESSs [4]. SCs or ultracapacitors, of very high capacitances, are superior to batteries in favor of their relative longer life cycle and higher charge/discharge rate. Owing to the lack of chemical reactions on the electrodes (ideally), SCs present relatively low internal resistance which means lower heat loss, higher efficiency (approximately 90%) and adequate reversibility [4,19,20]. Furthermore, SCs are considered suitable energy storage options in both railway and power applications and can be effectively used for peak load supply and for voltage stabilization purposes [3,4,19–21]. The comparison between various ESSs in terms of power and energy density have been introduced in [4]. Another detailed study about this application are presented by Sun and Zhang (2015) [15]. In [15], the authors have introduced an innovative bi-directional energy conversion system using SC as an energy source to drive an electric scooter for recovering the braking energy. Borowik and Cywinski (2016) have introduced the positive effects resulting from the modernization of an existing trolleybus transport system in Tychy, Poland. The modern vehicles equipped with traction batteries and generation systems have been studied particularly for environment protection, energy savings and limitation of GHG emissions [11]. Kühne has highlighted how electric buses achieve an energy solving in modern urban traffic. Insights into technical developments of EV equipment, catenary with fast driving handling characteristics and the use of plain electric and hybrid powertrains have been presented [12]. When a risky high starting current is drawn from the national grid for charging the train onboard SC (OB_{SC}), it increases the harmonic voltage drop proportionally to the source impedance at the point of common coupling. The non–linear sudden charging current harmonics may result in voltage ones and Power Quality (PQ) problems for the power network. Accordingly, filters and unbalance compensators are required to ensure proper system operation and to overcome PQ inconveniences [21,22].

This paper proposes a novel solution for the energy flow problem between storage components of different own characteristics for each. The energy is generated using RE sources stored slowly in the stationary SC. Then, the energy should be transferred rapidly to the embedded SC at the train arrival for a short duration limited by the train stop-period. This amount of energy/power is used for the train start-up.

The rest of the paper is organized as follows: the literature review is summarized in Section 2. In Section 3, the traction system under study and the idea behind the research are presented. The motor modelling, the multi–source charger topology and sizing, the corresponding electric circuit are discussed. Towards illustrating the energy management operation, the system state space model is deduced and the problem formulation is demonstrated in Section 4. In Section 5, the nonlinear PCH approach is explicitly developed. The stability proof of the proposed control methodology is introduced. Then, the analytical and the experimental simulation results are exhibited in Sections 6 and 7 respectively. Finally, the conclusions and perspectives of this research are drawn in Section 8.

2. Literature review

Although the use of Hybrid Power Systems (HPSs) based on both RE sources and ESSs has attracted researchers in both power system and vehicular applications, only very few studies have been concerned with the integration of hybrid systems for energy management purposes in traction systems. For EVs, Trovão and Antunes (2015) have studied the energy management of a dual ESS for EVs. Energy management for hybrid battery-SC systems have been thoroughly described with different approaches and different applications [8,9,16,17]. Torreglosa et al. (2016) have developed a predictive controller for an efficient decentralized energy management strategy employed into an EV charging station supplied by PV solar panels, batteries with grid [8]. Castaings et al. (2016) have studied different energy management strategies for battery-SC systems to define the best power flow sharing for the battery lifetime improvement using different optimization approaches considering EV real and random driving cycles [9]. García et al. (2013) have compared different control strategies for high-power EVs powered by FC, battery and SC taking into account real driving cycles [10].

A comparative analysis of meta-heuristic approaches, based on both the Simulated Annealing (SA) and the Particle Swarm Optimization (PSO) techniques, for power management have been considered in terms of different performance factors such as the computation time, the battery's final State of Charge (SoC), and the SC's minimum value of SoC [23]. Li et al. (2015) have developed a hybrid powertrain configuration based on a Proton Exchange Membrane (PEM), a battery and a supercapacitor without grid integration. The power sharing strategy has been illustrated based on a combined Fuzzy Logic Control (FLC) and Haar wavelet transform. Therefore, the proposed energy management system of the high–power hybrid tramway will be able to guarantee safe operating conditions with transient-free performance, extend the lifetime of each power source and enhance the energy efficiency of the overall system [24]. Wang et al. (2015) have suggested a new topology of multimode hybrid ESS. For this purpose, both rule–based and power–balancing control strategies have been introduced for mode selection and power distribution. The overall efficiency enhancement of the proposed hybrid ESS over the conventional ones has been verified [25]. Hung and Wu (2015) have proposed the use of hybridization for integrating dual motors to enhance EV system dynamics. An innovative combined sizing/control concept for the hybrid in–wheel motors of the EV has been demonstrated. Thanks to the enhanced energy of the combined optimal controllers, real light–duty EVs may be implementable [26]. For power system purposes, Bizon et al. (2015) have addressed efficient energy control strategies for the standalone

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