Applied Energy 169 (2016) 831–845

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Adaptive energy management strategy and optimal sizing applied on a battery-supercapacitor based tramway

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HIGHLIGHTS

- An adaptive EMS (based on fuzzy logic) for a tramway with hybrid ESS is proposed.
- A sizing approach and optimal battery-supercapacitor combination is presented.
- The cost model considers initial investment and degradation by cycling of the ESS.
- The hybrid ESS shows a clear operating cost reduction from the SC-based ESS.
- The adaptive EMS allows better harnessing of regenerative energy than the RB-EMS.

ARTICLE INFO

Article history:
Received 8 December 2015
Received in revised form 10 February 2016
Accepted 14 February 2016

Keywords:
Energy management strategy
Battery
Fuzzy logic
Hybrid energy storage system
Tramway
Supercapacitor

ABSTRACT

In this paper an adaptive energy management strategy (EMS) based on fuzzy logic and the optimal sizing for a tramway with a hybrid energy storage system (ESS) combining batteries (BT) and supercapacitors (SC) are presented. The EMS applies a sliding window to estimate the forward energy consumption and adapt the instantaneous power target for BT and SC. The hybrid ESS sizing is obtained by an optimization with multi-objective genetic algorithms (GA). The fitness functions are expressed in economic terms, and correspond to the costs of the energy absorbed from the catenary as well as the operation cost of the hybrid ESS (investment and cycling cost). The selected case study is the tramway of Seville, which operates in zones with and without catenary. The aim is to minimize the daily operating cost of the tramway taking into account the BT and SC degradation approach (cycling) and fulfilling the performance of the tramway in the catenary-less zone. The proposed approach (adaptive EMS and optimal sizing) is compared with the current solution in the tramway (SC-based) and with a hybrid ESS managed by a rule-based EMS (RB-EMS) in terms of daily operating cost and energy harnessing during regenerative braking phase. The proposed approach show cost reductions up to 25.5% (from SC-based), 6.2% (from hybrid ESS with RB-EMS) and a global efficiency around 84.4%.

1. Introduction

Currently, with the massive demand of mobility, and an increasing concern about the sustainable use of the energy resources as well as the new policies about emission reductions: efficient, economic and comfortable means of transportation are required [1]. Mainly in public transportation the current solutions in the market tend to the electrification of the energy source [1]. In this scope, it is worth to mention that the tramways have staged an impressive comeback over the past few years [2]. This way, several cities have addressed their massive transport solutions to a new generation of lighter, more efficient and safer tramways. These tramways are traditionally powered by an overhead catenary line, adding some negative consequences as: full overhead cables in city centers, power peaks injected/absorbed from the grid and low energy efficiency as result of the braking energy recovered and injected in the catenary or lost as heat in the crowbar system [2]. Feasible solutions of overcoming these problems are: removing the overhead cables (catenary-less zones) and implementing onboard ESS as Supercapacitors (SC) [2,3], Batteries (BT) [4,5] or

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http://dx.doi.org/10.1016/j.apenergy.2016.02.079
0306-2619/

hybrid ESS combining BT and SC [6–9] to supply energy during the travel (partially or entirely) and to take advantage of the energy from the regenerative braking phase.

In the tramway the use of SC is shown as suitable solution to increase the energy efficiency by absorbing the power peaks during the regenerative braking phase and reducing the power peaks from the catenary during the acceleration phase [2,10]. Moreover, the hybrid solution (by including BT in the ESS) results suitable mainly to increase the autonomy of the vehicle allowing the operation in zones without catenary [11]. This way, the energy stored in the BT would allow traveling longer distances without catenary and/or facing unscheduled events (e.g. non-considered stops, pedestrian crossing, etc.) during this autonomous zone.

When considering onboard hybrid ESS for vehicle applications, the sizing problem is closely coupled with the energy management and the application constraints. Therefore, the energy analysis results an important start point in order to determine the most suitable ESS sizing depending on the application requirements [3]. The configuration of the ESS pack results from the combination of several storage units in series and parallel connections. These storages units can be single cells [12] or modules combining several individual cells in a predefined configuration [13]. Basically, the series/parallel configuration allows reaching the specific voltage and energy required for the proper ESS pack operation. This way, the amount of storage units and the arrangement of these elements in the pack is a common problem addressed in the sizing process [14,15].

Besides, the selected energy management strategy (EMS) plays a key factor to ensure the correct vehicle performance, fulfilling the application requirements and operations constraints. In the transportation scope, several strategies have been proposed to manage the power split in hybrid ESS. The most common are the rule-based energy management strategies (RB-EMS) [3,4,6,16,17]. However, focusing on the tramway case, if the vehicle has to operate on different zones (with and without catenary) and the EMS considers further information about the ESS (available energy, degradation approach, power/energy demand, etc.) the rules development becomes in a complex problem due to the increase of variables and cases to evaluate. This way, the fuzzy logic appears as a promising tool due to the possibility to avoid most of the mathematical stiffness and complexity in the problem formulation and representing it based on the human reasoning [18]. Fuzzy logic has been widely applied for power sharing in hybrid vehicles with BT [5,12,19], SC [20] and hybrid ESS [8,9,21]. Torreglosa et al. [5] proposed a fuzzy strategy to manage the fuel-cell and battery operation in a tramway application. The aim was to allow the fuel-cell operation around its maximum efficiency and maintaining the BT state of charge in a desired level. Kisacikoglu et al. [20] presented a fuzzy strategy to control the dc voltage of the SC around its nominal value by supplying propulsion power and recuperating braking energy in a hybrid vehicle. García et al. [8] proposed a fuzzy control to define the power reference for a fuel-cell and the energy variation in the BT, while the SC controls the power peaks to maintain constant the dc bus voltage in a hybrid tramway. Li et al. [9] applied a power sharing strategy combining fuzzy logic and Haar wavelet transform in a hybrid tramway. The strategy filtered the low frequency components of power demand for the BT operation; while the high frequency components are managed by the SC. Gao et al. [21] presented a fuzzy strategy to determine the desired output power for BT and SC according to the propulsion power and recuperated braking power in a fuel-cell hybrid bus.

Nevertheless, all the aforementioned papers present EMSs based on fuzzy logic, which obtain the target for the system operation considering only the instantaneous state of their inputs. These EMSs satisfy the current power demand for the vehicle operation but the information about the future energy demand on the ESS is disregarded. Considering a wider scope (whole vehicle operation), this approach does not allow the suitable energy harnessing in the vehicle and it results in a non-optimal EMS. The proper energy harnessing becomes in a more important issue in the operation of hybrid ESS, which have different characteristics as in the case of BT (energy density) and SC (power density) [15].

However, with two storage systems operating simultaneously the power split ratio between these ones during the operation will have a strong impact mainly on their degradation cost and lifespan. Therefore, during the sizing stage of a hybrid ESS results important to take into account the economic analysis about the storage implementation [12,13] as well as the degradation approach of the ESS [14]; especially for onboard solutions where the investment and replacement costs are critical factors [15].

Both of the previously explained issues are addressed in this paper. On the one hand, a novel adaptive EMS based on fuzzy logic to manage the power split in a hybrid ESS (combining BT and SC) for tramway applications is proposed. This adaptive approach considers, in addition of the instantaneous conditions of the system (available energy in the ESS, power demand from the tramway), information about the future energy demand of the vehicle by applying a sliding forward window strategy. This strategy allows estimating the forward energy consumed/absorbed from/in the BT and SC pack. This way, the operation targets for the BT and SC pack are adapted (power split) to fully supply the instantaneous energy consumption but considering the future energy demand (increasing/decreasing the instantaneous consumption from the BT and/or SC pack). The aim is to increase the energy efficiency of the hybrid ESS with a proper harnessing of the onboard sources and the available energy from the vehicle (mainly in the regenerative braking phase).

On the other hand, a methodology for the optimal BT and SC pack sizing is defined (considering the proposed adaptive EMS). The sizing optimization is carried out through multi-objective genetic algorithms (GA). The multi-objective approach considers an economic model in order to evaluate the influence of the BT and SC sizing on the operating cost of the tramway in a long term view (whole lifetime of the vehicle). Besides the economic model considers the replacement cost defined by the degradation approach of the ESS. In this case, a degradation model based on the cycling counting Rainflow algorithm for lifespan estimation is applied. The aim is to minimize the daily operating cost of the tramway.

Finally, in order to validate the proposed approach (adaptive EMS and optimal hybrid ESS sizing) a comparative analysis in terms of operating cost reduction and energy harnessing during the regenerative braking phase is done. The selected case study is the tramway of Seville, considering the energy and power requirements of a specific city route section (including several stops and catenary-less operation). The results from the proposed approach are compared with: the current ESS in the tramway of Seville (SC-based) and with a hybrid ESS (with a non-adaptive RB-EMS) proposed in [11] for the same scenario.

2. Scenario overview

The scenario of this paper is based on experimental data and drive cycle of the tramway of Seville (Fig. 1(a)) designed and developed in collaboration between the traction equipment manufacturer CAF Power & Automation and IK4-IKERLAN Technology Research Centre. The energy and power requirements correspond to a section of the city route with several stops and a pedestrian zone with a catenary-less operation (500 m) and speed limit of 15 km/h (in the catenary-less zone). Fig. 1(b)–(c) shows the tramway speed/power profile provided by the manufacturer (CAF P&A)