Renewable and Sustainable Energy Reviews 41 (2015) 225–236

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

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

Review of electrical energy storage system for vehicular applications

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ARTICLE INFO

Article history:
Received 2 March 2014
Received in revised form
15 June 2014
Accepted 4 August 2014

Keywords:
Electrical energy storage system (EESS)
New energy vehicle (NEV)
Linear engine
Regenerative braking
Series-parallel switchover of ultra-capacitor (UC)
Hybrid power source

ABSTRACT

Recently, automotive original equipment manufacturers have focused their efforts on developing greener propulsion solutions in order to meet the societal demand and ecological need for clean transportation, so the development of new energy vehicle (NEV) has become a consensus among governments and automotive enterprises. Efficient electrical energy storage system (EESS) appears to be very promising for meeting the rapidly increased requirements of vehicular applications. It is necessary to understand performances of electrical energy storage technologies. Therefore, this paper reviews the various electrical energy storage technologies and their latest applications in vehicle, such as battery energy storage (BES), superconducting magnetic energy storage (SMES), flywheel energy storage (FES), ultra-capacitor (UC) energy storage (UCES) and hybrid energy storage (HES). The research priorities and difficulties of each electrical energy storage technology are also presented and compared. Afterwards, the key technologies of EESS design for vehicles are presented. In addition, several conventional EESSs for vehicle applications are also analyzed; the comparison on advantages and disadvantages of various conventional EESSs is highlighted. From the rigorous review, it is observed that almost all current conventional EESSs for vehicles cannot meet a high-efficiency of power flow over the full operation range; optimization of EESS and improved control strategies will become an important research topic. Finally, this paper especially focuses on a type of linear engine, a brand new automotive propulsion system used for NEV; the guiding principle of EESS design for the new type of linear engine is proposed, an overview of a novel hybrid EESS based on hybrid power source and series–parallel switchover of UC with high efficiency under wide power flow range for the type of linear engine is presented, and advanced features of the novel hybrid EESS are highlighted.

Contents

Abbreviations: AC, alternate current; BDPC, bi-directional DC–DC power converter; BES, battery energy storage; DC, direct current; EDLC, electric double-layer capacitor; EESS, electrical energy storage system; EMF, electromotive force; FCV, fuel cell vehicle; FC, fuel cell; FES, flywheel energy storage; FSMC, fuzzy sliding mode control; HES, hybrid energy storage; HEV, hybrid electric vehicle; ICE, internal combustion engine; kg, kilogram; kJ, kilojoule; kmh^{-1}, kilometer per hour; kW, kilowatt; kWh, kilowatt hour; LIB, lithium-ion battery; LIC, lithium-ion capacitor; Li-Ion, lithium-ion; NEV, new energy vehicle; PEV, pure electric vehicle; PSO, particle swarm optimization; PWM, pulse width modulation; rpm, revolutions per minute; SMC, sliding mode control; SMES, superconducting magnetic energy storage; SOC, state of charge; THS, Toyota hybrid system; UC, ultra-capacitor; UCES, ultra-capacitor energy storage; VSS, variable structure system

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http://dx.doi.org/10.1016/j.rser.2014.08.003
1364-0321/

1. Introduction

In recent years, projections of energy use and greenhouse gas emissions for industrialized countries typically show continued growth in car ownership and vehicle use. The International Energy Agency (IEA, 2009b) projects an average annual increase in global transport energy demand of 1.6% between 2007 and 2030 [1]. In response, automobiles shift significant portions of their required energy from petroleum to other sources. Automotive original equipment manufacturers focus their efforts on developing greener propulsion solutions in order to meet the societal demand and ecological need for clean transportation. So the development of new energy vehicle (NEV) has become a consensus among governments and automotive enterprises.

NEV is defined as a vehicle which uses alternative fuel technologies and electrification technologies [2]. It refers to vehicle using unconventional vehicle fuel as a power source, or vehicle using conventional fuel with new automotive propulsion system, advanced integrated vehicle dynamics control and driving technologies.

The development and emergence of NEV can solve the problems such as the pressure and need to significantly reduce automotive gas emissions, the rising concerns about balance in the economy and energy security related to oil import and the excessive growth of the automotive industry. So the NEV industry with huge market potential has shown the development trend of competing.

NEV has gradually formed a “three vertical and three horizontal” technical route pattern (“three vertical” for hybrid electric vehicle (HEV), pure electric vehicle (PEV), fuel cell vehicle (FCV); “three horizontal” means multi-energy driving force for the total into the motor and its control system and power management system). As one of the key technologies of NEV, electrical energy storage technology through three vertical and three horizontal technology systems is seeking a new breakthrough and researched deeply.

Numerous private companies and national laboratories, many with federal support, are engaged in the related technology research for vehicle powerful electrical energy storage system (EESS) and development efforts across a very wide range of technologies and applications. In Ref. [3], a comprehensive overview of HEV with a focus on hybrid configurations, energy management strategies and electronic control units was studied, through discussion of several related technologies; they concluded that HEV was a hot subject today that had some advantages such as lower fuel consumption, lower operating costs, lower noise pollution, low emissions, smaller engine size and long operating life. HEVs and their challenges were reviewed in Ref. [4]; comprehensive survey of HEV on sources, models, energy management system developed by some researchers was provided in this study; they thought that HEV was the promising future transport option for the next generation, and this paper also presented many factors, challenges and problems sustainable to the next generation HEV. In Ref. [5], a regenerative braking system involves the installation of an additional motor/generator in parallel to the internal combustion engine (ICE) and was used in conjunction with a power converter and ultra-capacitor (UC); the experiments results showed that energy consumption was significantly reduced by adding regenerative braking to the vehicles. Omar et al. presented assessment of lithium-ion capacitor (LIC) for using in battery electric vehicle and HEV applications [6]; in this study the general characteristics of LIC were analyzed and compared with electric double-layer capacitor (EDLC) and lithium-ion battery (LIB). Various battery models for various simulation studies and applications were reviewed in Ref. [7], and advantages and disadvantages of each model were presented; this study has a great help for understanding the battery behavior and performance during charge and discharge. A review of battery–UC hybrid power source performance for pulsed current loads was presented and passive, semi-active and fully active hybrids were explained [8]; they concluded that hybridization of high energy battery and high power UC would solve the drawbacks of battery-only supply. A review of energy sources and energy management system in electric vehicles was presented by the researchers in [9]; they discussed the available energy source, energy generator for electric vehicle, power converter, low-level control energy management strategy and control algorithm use in HEV and PEV; they thought that the optimized efficiency and smart grid control strategy were the keys for the growth of electric vehicles.

However, most of the review studies published were focused on electrical energy storage technologies for conventional automotive propulsion systems and their applications; there is a lack of review studies which systematically focus on detailed design approach of EESS for new automotive propulsion system; this study is the first review study which investigates the EESS used in a new type of linear engine applications. The findings of this study contribute to literature for a broader understanding of EESS for NEV.

The aim of this paper is to review various electrical energy storage technologies and typical EESSs for vehicular applications that have been reported in recent years. Besides, EESS design methodology of linear engine for HEV is discussed. The paper is therefore organized as follows. After the introduction section, various electrical energy storage technologies and their main developing trends are described in Section 2. Key technologies of EESS design for vehicles are presented in Section 3. Several typical conventional EESSs for vehicle applications are discussed in Section 4. An overview of a novel hybrid EESS for a type of linear engine is presented in Section 5. Conclusions are summarized in Section 6 and the recommendations are given in Section 7.

2. Electrical energy storage technologies

The most common electrical energy storage technologies used in vehicles include battery energy storage (BES), superconducting