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Reducing the Peak-to-average Power Ratio for Electric Vehicles using Hybrid Energy Storage Systems (HESS)

Li Sun, Nong Zhang

School of Electrical, Mechanical and Mechatronic Systems, University of Technology, Sydney, NSW, Australia,

clickler@gmail.com; nong.zhang@uts.edu.au

Abstract

In this paper, a simple but innovative algorithm is developed to effectively reduce peak-to-average power ratio for electric vehicles powered by battery pack (BP) alone under real-life load fluctuation. A converter-supercapacitor pack (SP) coupled Hybrid Energy Storage topology upon which such algorithm is deployed is proposed to divert excess power that would otherwise damage BP into SP via power converter (PC) in a regulated fashion. Along with the algorithm itself, a simplified HESS model is also developed in Matlab to validate such algorithm and simulation results prove its effectiveness across various real-life drive cycles with significantly extended battery lifecycle.

1 Introduction

Conventional electric vehicles employing rechargeable BP alone suffer from battery performance degradation i.e. aging, or output power throttling makes it difficult to cope with whole spectrum of load conditions without compromising durability and safety. To address these problems a converter-SP coupled Hybrid Energy Storage topology has been proposed whose aim is to divert excess power that would otherwise damage BP to SP via power converter in a regulated fashion. The algorithm kicks in every time the load changes so that relatively higher frequency portion of the load power profile gets channelled to the SP and the remaining less-varying power demand can be sourced from the BP.

Throughout literature survey, existing methods include either a rule-based approach [1],[2], or employing a low pass filter technique at a fixed or pre-determined cut-off frequency [3],[4],[5]. Our approach is different to all of the above, in which, an optimal energy management strategy can be possibly achieved by varying the location of such cut-off frequency dependent on load variation so that contribution of each power source is optimally allocated while constantly picking up ongoing trend of the load.

In this paper, a simplified HESS model is developed in Matlab to validate such algorithm and simulation results prove its effectiveness under typical real-life drive cycles.

The structure of this paper is arranged such that in section 2, the setup of the simulation circuit and test environment is introduced. Fundamental concept of the algorithm is briefly introduced in section 3, and due to constraints of possible patent application, only typical simulation results are shown in section 4.

2 Simulation setup and test environment

In this paper, the most popular converter topology as shown in Figure 1 is adopted for analysis due to its high controllability and efficiency [6]. Also can be realized is that, considering the output current of the SP I_{sp} is restricted and bundled with the PC, by actively controlling this current, we could simply achieve indirectly regulating the current from the BP I_{bp} simultaneously at any given load current I_{load} from the inverter motor

drive unit. Note this control approach is bi-directional so the arrows as shown in Fig. 1 can be reversed as well for example, when the EV is running under regenerative braking mode.

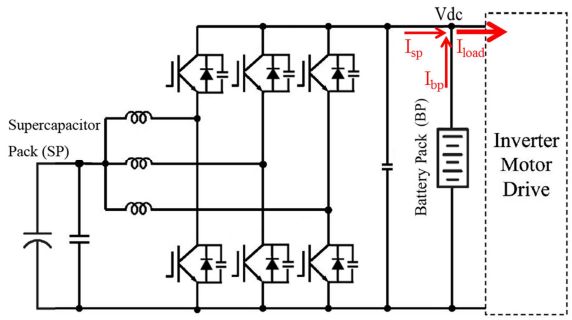

Figure 1. Circuit diagram of a ZVS three-phase interleaved half bridge converter topology

Having comprehended the above, a few parameters and assumptions of our simulation are set as the following with further simplification:

- *Vbp* or *Vdc* is fixed in our analysis at 400V.
- *Vsp* is varying between 150V and 300V.
- PC has an output current limitation at 400A. PC is treated as an ideal power conversion unit that has no power loss.
- Average efficiency for BP alone is assumed at 85%.
- The internal resistance of the SP is significantly smaller than that of the BP hence power loss on SP alone is neglected in this analysis.
- The inverter motor load and for a typical passenger vehicle, so the curb mass is sized at … the peak power rating for the inverter motor module is fixed at 130kW)
- The average efficiency for the motor efficiency is assumed at 90%, in both forward motoring mode and regenerative braking mode.

An analytical model can now be established (using Matlab), combined with any given drive cycle containing velocity-time series plot, to work out in backwards the exact I_{load}, upon which an intelligent split ratio between the BP and SP-PC modules can be decided by an adaptive algorithm, which is going to be explained in the next section.

3 Algorithm development

The idea of the power split algorithm can be self-explained in Figure 2, as well as can be briefly described here: Having understood that given any load power P_{load}, the purpose of the SP and PC is to source or sink the relatively higher frequency portion of P_{load}, a Discrete Fourier Transformation (DFT) is then applied to P_{load} so as to extract out its lower frequency portion as P_{filter}, by locating an cut-off frequency whose value varies depending on the nature of load vector. This is then being subtracted by the current value of P_{load}, and gets further divided by the current value of V_{dc} so that the reference current of the SP and PC as I_{sp_ref} is obtained and get precisely regulated in current mode control. Only simulation result is shown within this paper due to constraints of the possible patent application.

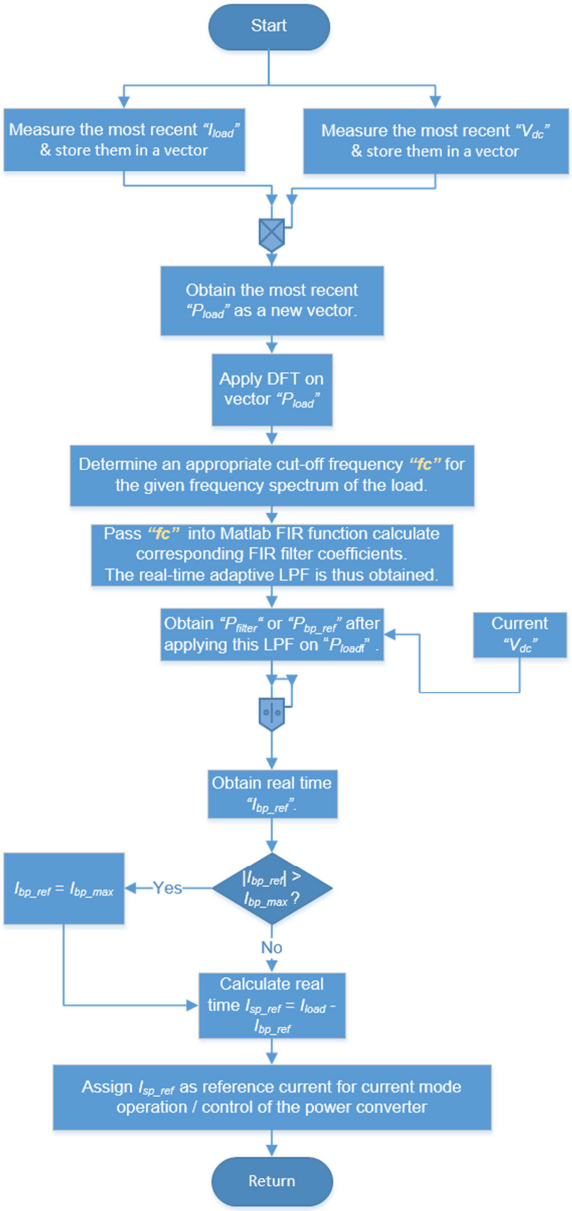

Figure 2. Flow chart of adaptive power split algorithm

4 Simulation results

To evaluate the effectiveness of this algorithm, two distinctive driving cycles are carefully chosen, namely NEDC (Fig. 3) and LA92 (Fig. 5) as testing targets.

Across all EPA stipulated driving cycles, the NEDC driving cycle is at odds with the LA92 driving cycle in terms of "aggressiveness", in other words, the NEDC driving cycle possesses the lowest acceleration or deceleration rate whilst the LA92 the highest at both rates. [7]

The intuitive idea is then to test and compare between these two extremes, and to expect anything else in between will fall within these two extremes. Bear in mind the whole rationale to reduce the peak-to-average power ratio is to somehow manipulate the level of "aggressiveness" battery faces in a way to avoid it from being abused.

Combined with practical EV characteristics listed in Table 1, various time-series load power waveforms for the aforementioned two driving cycles are plotted in Fig. 4 and Fig.6.

Table 1: Key characteristics of a practical EV

Vehicle type	Passenger car
Vehicle mass (kg)	1460
Aerodynamic drag coefficient (-)	0.28
Frontal area (m^2)	1.9
Air density (kg/m^3)	1.29
Rolling resistance coefficient (-)	0.016
Wheel radius (m)	0.2794

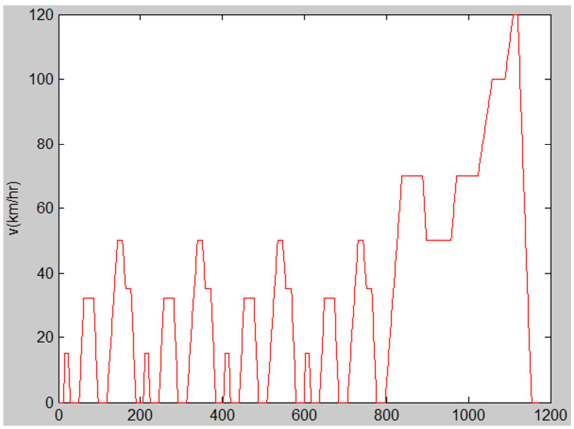

Figure 3. Time-series speed waveform of EPA NEDC Driving Cycle for a typical EV passenger car

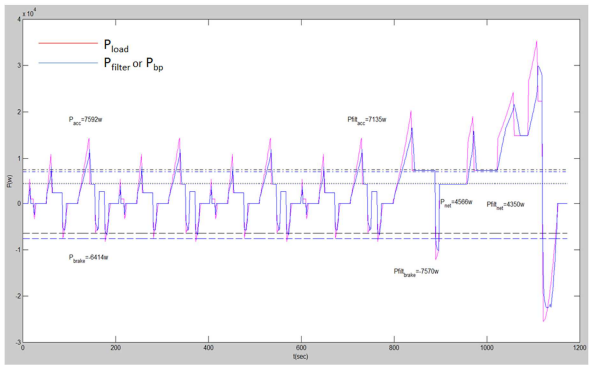

Figure. 4 Time-series power flow waveform for P_{load} and P_{filter} or P_{bp} of EPA NEDC Driving Cycle for a typical EV passenger car

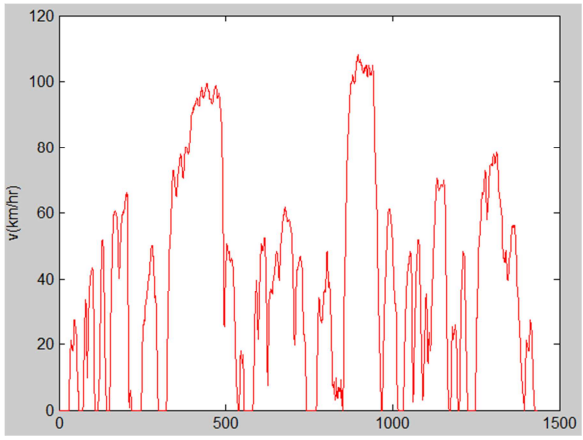

Figure 5. Time-series speed waveform of EPA LA92 Driving Cycle for a typical EV passenger car

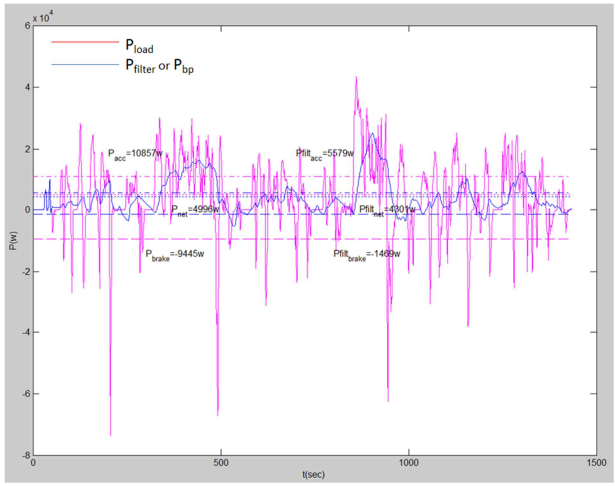

Figure 6. Time-series power flow waveform for P_{load} and P_{filter} or P_{bp} of EPA LA92 Driving Cycle for a typical EV passenger car

Note Peak-to-Average Power Ratio (dimensionless) is plotted in Table 2 for both scenarios for comparison. A further separation is provided between using battery pack alone (before) and adopting a sizable HESS system utilizing supercapacitor and power converter as power buffer (after) .

Table 2: Outcome of analysis over 2 extreme driving cycles

Driving Cycle	Peak-to-Average Power Ratio		% (Reduction)
	Before	After	
NEDC	4.61	3.95	-14.3%
LA92	3.87	2.3	-40.5%

As shown in Table 2, as well as from Fig. 3~6, it is demonstrated that significant power re-distribution occurs as a function of "aggressiveness" nature of the corresponding drive cycle. Namely there's only 14.3% instantaneous power peak gets re-channelled to the power buffer module in NEDC driving cycle as opposed to 40.5% in LA92 driving cycle.

The level of re-distribution seems linearly and effectively increase when the "aggressive" nature of the driving cycle ramps up. Therefore as a first order of estimation, this algorithm can be regarded as effective enough to address the original problem.

Further analysis is planned to use weighted averaging and probability density distribution techniques to better exploit and refine the algorithm as well as testing it in a real-world test-bed.

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References

[1] João P. Trovão, Paulo G. Pereirinha, Humberto M. Jorge, Carlos Henggeler Antunes, *A multi-level energy management system for multi-source electric vehicles – An integrated rule-based meta-heuristic approach*, Applied Energy, Volume 105, May 2013, Pages 304-318, ISSN 0306-2619

[2] Zhang Chenghui; Shi Qingsheng; Cui Naxin; Li Wuhua, *Particle Swarm Optimization for energy management fuzzy controller design in dual-source electric vehicle*, in Power Electronics Specialists Conference, 2007. PESC 2007. IEEE , vol., no., pp.1405-1410, 17-21 June 2007

[3] Ravey, A.; Roche, R.; Blunier, B.; Miraoui, A., *Combined optimal sizing and energy management of hybrid electric vehicles*, in Transportation Electrification Conference and Expo (ITEC), 2012 IEEE , vol., no., pp.1-6, 18-20 June 2012

[4] Schaltz, E.; Khaligh, A.; Rasmussen, P.O., *Influence of Battery/Ultracapacitor Energy-Storage Sizing on Battery Lifetime in a Fuel Cell Hybrid Electric Vehicle*, in Vehicular Technology, IEEE Transactions on , vol.58, no.8, pp.3882-3891, Oct. 2009

[5] Jaafar, A.; Akli, C.R.; Sareni, B.; Roboam, X.; Jeunesse, A., *Sizing and Energy Management of a Hybrid Locomotive Based on Flywheel and Accumulators*," in *Vehicular Technology, IEEE Transactions on* , vol.58, no.8, pp.3947-3958, Oct. 2009

[6] Junhong Zhang; Jih-Sheng Lai; Rae-young Kim; Wensong Yu, *"High-Power Density Design of a Soft-Switching High-Power Bidirectional dc–dc Converter," Power Electronics, IEEE Transactions on* , vol.22, no.4, pp.1145,1153, July 2007

[7] "Dynamometer Drive Schedules", [online]. Available: http://www3.epa.gov/nvfel/testing/dynamometer.htm (Accessed 20 Jan 2016).

Authors

Li Sun received his double M.E. degree in Automotive Engineering and Electronic Engineering from RMIT University, Australia in 2010, and 2012 respectively. Prior to that he has ten years design experience in Automotive industry for high power LED applications, switched mode power supplies, manufacturing machinery, variable speed drive, automatic transmission, and closed-loop control for servo actuators. He's currently pursuing a Ph.D. degree at the University of Technology, Sydney (UTS) for Hybrid Energy Storage System. His research interests are in modern Power Electronics and Energy Storage System (ESS) in fields such as Electric Vehicle (EV), Hybrid Electric Vehicle (HEV) and renewable energy. He is a registered member of the Institute of Engineer, Australia; Society of Automotive Engineers (SAE) and IEEE.

Nong Zhang received his B.E. degree in 1982 from Northeastern University, ME in 1984 from Shanghai Jiao Tong University, China, and Ph.D. in 1989 from the University of Tokyo, Japan. He worked at several universities in China, Japan, USA and Australia respectively before joining the Faculty of Engineering of the University of Technology, Sydney (UTS) in 1995. Since 2009, he has been Professor of Mechanical Engineering, at School of Electrical, Mechanical and Mechatronic Systems. For more than 20 years, Prof Zhang has been involved in research in areas of dynamics and control of automotive systems including powertrains with various types of transmissions, hybrid propulsion systems

, vehicle dynamics, passive and active suspensions; and mechanical vibration including experimental modal analysis, rotor dynamics, cold rolling mill chatter and machine condition monitoring.