Two-Level Control for Fast Electrical Vehicle Charging Stations with Multi Flywheel Energy Storage System

SUN, BO; Dragicevic, Tomislav; Vasquez, Juan Carlos; Guerrero, Josep M.

Published in:
Proceedings of the 2015 IEEE First International Conference on DC Microgrids (ICDCM)

DOI (link to publication from Publisher):
10.1109/ICDCM.2015.7152059

Publication date:
2015

Document Version
Early version, also known as pre-print

Two-Level Control for Fast Electrical Vehicle Charging Stations with Multi Flywheel Energy Storage System

Bo Sun, Tomislav Dragicevic, Juan C. Vasquez, Josep M. Guerrero
Microgrids Research Programme www.microgrids.et.aau.dk
Department of energy technology, Aalborg University
Aalborg, Denmark,
Email-Address: {sbo, tdr, juq, joz}@et.aau.dk

***Abstract*— This paper applies a hierarchical control for a fast charging station (FCS) composed of paralleled PWM rectifier and dedicated paralleled multiple flywheel energy storage systems (FESSs), in order to mitigate peak power shock on grid caused by sudden connection of electrical vehicle (EV) chargers. Distributed DC-bus signaling (DBS) and method resistive virtual impedance are employed in the power coordination of grid and flywheel converters, and a centralized secondary controller generates DC voltage correction term to adjust the local voltage set point. The control system is able to realize the power balancing and improve DC voltage regulation with low reliance on digital communication technology. Algorithm has been developed in Matlab/Simulink and compiled to real-time simulation platform dSPACE 1006. Corresponding simulation results have been reported in order to verify the validity of proposed control strategy.**

Keywords—EV charging station; flywheel energy storage system; distributed bus signaling

I. INTRODUCTION

During last decades, it has been extensively recognized that the increasing conventional fossil fuels' consumption and carbon dioxide emissions are reasons to cause environmental deterioration and threaten human life. Particularly transportation sector is responsible for 25% world carbon dioxide emissions and the increasing numbers of conventional gasoline or gas-fueled automobile are considered to account for a great portion of total transportation pollutions [1].

Motivated by this situation, plug-in electrical vehicles (PEV) are attracting more attentions today and are potential to replace the conventional automobiles in near future [2]. It could be expected that a large amount of PEV will be on road and electrification is going to be the mainstream of transportation development. Therefore, providing an acceptable surroundings and necessary ancillary services of PEV fleets is a critical issue of next generation smart grid.

Up to now, industry has defined 3 level charging patterns for EV, which is classified according to different power rating [3]. Among three levels of charging, fast charging station (FCS) usually locates in public cite for commercial application like today's gas station. In the FCS, the battery pack of PEV is connected to a DC bus through a fast DC/DC charger, and the fast charging could be finished within several minutes with power rating up to 50 kW. So FCS is suitable for future transportation requirements and benefits the extensively penetration and development of EV. So the impact of a large number of PEV chargers connections to network should be also seriously concerned. However, following a large quantity of PEV and high power fast charging stations emerging, some technical problems have to be faced, for example, sudden connection of PEV chargers could cause a high power shock to the grid, and lead to rising of peak loading of distributed system that may cause the instability of the distributed network.

For the purpose of solving the possible adverse effect aforementioned, a dedicated battery energy storage system (BESS) is connected to a common DC bus to supply part of charging power in [4]. Regarding the state of charge (SoC) balance control of ESS, in [5],[6], the system with multi BESS system is analyzed based on the SOC adaptive droop control to realize the power and current sharing of each battery ESS. And in [7], a fuzzy control and adaptive droop method are deployed for power balancing the control of energy storage system. However, most previous control scheme is discussed based on BESS, moreover direct connection of battery pack may cause the unregulated DC voltage deviations and frequent charging cycling and high peak current caused by PEV charger connection would accelerate the degradation of battery [8]. Compared to BESS, flywheel energy storage system (FESS) could compensate the peak power with a faster response and support a larger numbers of charge/discharge cycles. In past, FESS has been extensively used for DC-link coupled power balancing in grid-connected applications [8],[9]. In [10], a distributed DC-bus signaling (DBS) strategy is applied for FCS control with a flywheel ESS to realize the distributed coordination of each unit in system. However, only one flywheel is considered, and the DC bus voltage presents

This paper was supported by ERANET EU Project "Flex-ChEV", www.flexchev.et.aau.dk

obvious deviation due to the DBS control, which may lead to system instability.

In this paper, multi paralleled flywheels driven by induction machine (IM) are installed within FCS and a two-level control strategy including primary and secondary controller is applied for the purpose of internal power coordination between units and obtaining a stable DC bus, and a centralized secondary controller is employed to generate DC voltage correction term for adjusting the local voltage set point. The proposed scheme can realize the internal power balancing against the adverse effect caused by PEV sudden connection and be expanded to seamlessly connect more FESS.

II. EV CHARGING STATION UPGRATED WITH FLYWHEEL ENERGY STRORAGE SYSTEM

The block diagram of characteristic EV fast charging station is depicted in Fig.1. The main components in the FCS system are as follows: a set of AC/DC converters as grid interface, a set of DC/AC converter as FESS interfaces, a set of DC/DC converter as fast chargers.

As is observed that, all the components in the system are connected around a 650V common DC bus. The system can be regarded as a DC microgrid with several converters connected to the DC bus. In this study, bidirectional three phase converters for grid and FESS interface can be operating in four quadrants which allow bidirectional active and reactive power flow; buck type DC/DC converter only absorb energy from DC bus and do not support a “vehicle to grid (V2G)” function which may accelerate the degrading of battery pack in PEV.

Grid converter generate the DC bus system, DC/DC converter for PEV charging can be regarded as load to the system, and FESS as an energy buffer will provide a fast active power support for the DC bus when there is any disturbance exerted to the system. Therefore it is critical to coordinate the power balancing of different converters in the system, especially when the PEV suddenly connected to the DC bus.

At that point, there are several aspects that need to be taken into consideration for control strategy designing as follows:

1) FESS can fast response to the disturbance and provide power compensation Grid should be protected from high power stress

2) FESS can recharge back to full state of charge (SoC) automatically after power compensation.

3) The DC bus variation should be limited in order to guarantee system stability.

4) The control should not have a heavy dependence on communication, especially between grid converters and flywheel converters.

III. OVERALL CONTROL ALGORITHM OF EV CHARGING STATION WITH FESS

In order to fulfill the requirements aforementioned, a two-level control algorithm is proposed for EV fast DC charging station, as is shown in Fig. 2.

PEV connection can be regarded as a load disturbance and the control of DC/DC converter for battery charging is commonly recommended by manufacture, including constant current stage followed by constant voltage stage. In this paper, the control mainly focuses on the power balancing between

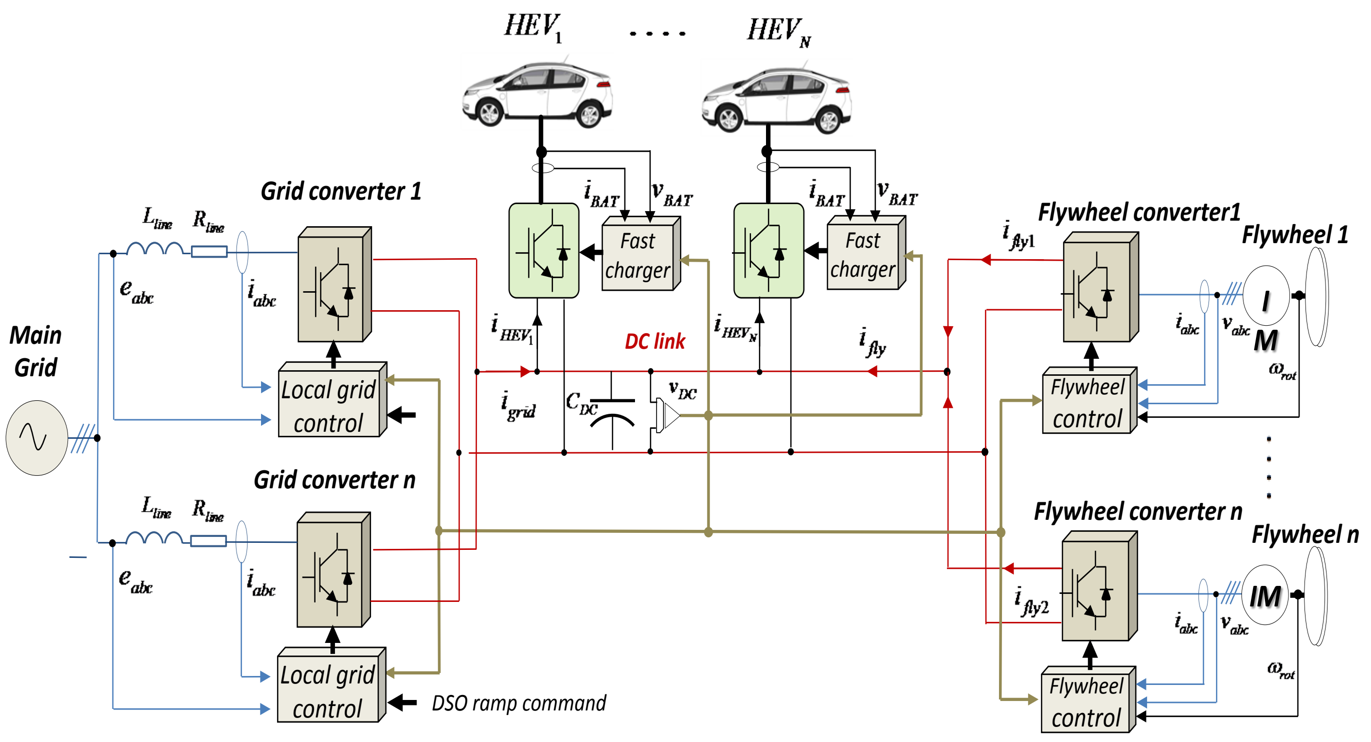

Fig.1 configuration of EV charging stations.

grid and flywheel converters.

A. Primary control

The primary control for the system is based on distributed bus signaling (DBS), which the grid and flywheel converters adjust their operation according to the DC bus variation. In this level, the system is able to work in a distributed manner without necessary communication.

1) Grid controller

Grid controller includes two control levels. The inner current loop is deployed in stationary ($\alpha-\beta$) frame. The reference of the inner loop is provided by the DC voltage controller and reactive power controller. The Iq reference is set zero as reactive power control is not the focus of this paper, and the voltage controller was designed as a proportional gain

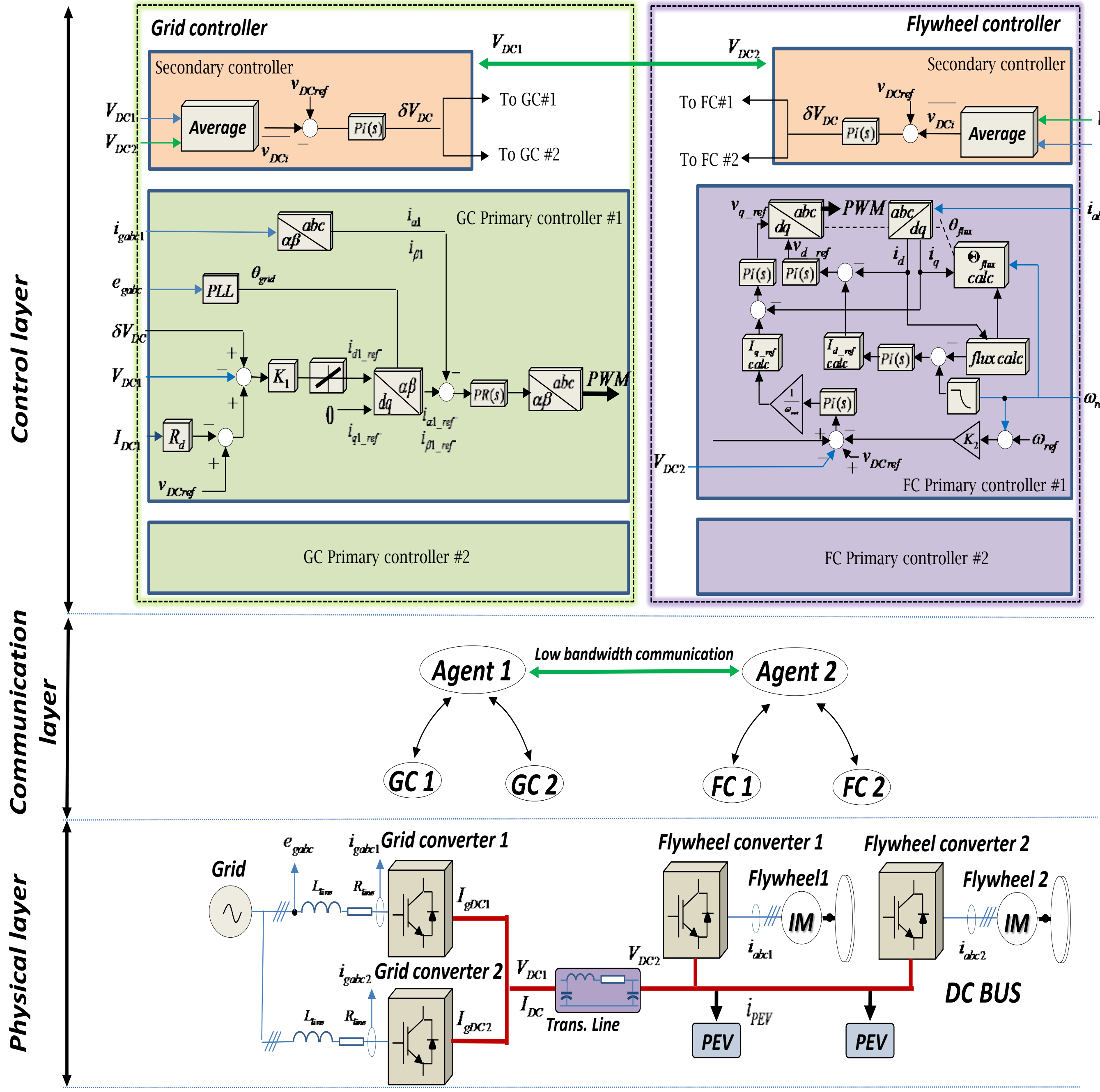

Fig2. Two level control structure for EV charging station

followed by a rate limiter. Rate limiter can prevent the grid current increase suddenly to a big value and protect the network, and the effect of rate limiter is detailed analyzed in [11]. Furthermore, in order to achieve a better sharing between different grid converters, virtual resistance, which is extensively used in DC microgrid, is employed in the voltage control loop.

The reference can be expressed as:

$$\begin{cases} i_{dref} = \psi(K_1 \left(V_{dc}^* - I_{dc} \cdot R_d - V_{dc}\right)) \\ i_{qref} = 0 \end{cases} \tag{1}$$

Where K_1 is the proportional term, R_d is virtual resistance and ψ is the function of rate limiter.

1) Flywheel controller

Flywheel controller use classical indirect field oriented control (IDFOC), where d-axis component corresponds to flux and q axis component corresponds to torque. The d-axis stator-current reference is obtained using a flux observer and the rotor-flux position results from the rotor speed and slip speed. The q-axis stator current reference is computed from the torque reference, which is generated by a droop controller, where the DC voltage vs speed droop control is implemented. The flywheel can automatically regulate the DC bus by speeding up and down around the nominal speed. The torque reference can be expressed as:

$$T_{ref} = \left(K_{pfly} + \frac{K_{ifly}}{s}\right)\left(\left(V_{dc}^* - V_{dc}\right) - K_2(\omega_m^* - \omega_m)\right) \tag{2}$$

Where K_2 is the droop coefficient, K_{pfly} and K_{ifly} are proportional and integral terms respectively.

And the DC voltage droop law can be expressed as:

$$V_{dc} = V_{dc}^* - K_2(\omega_m^* - \omega_m) \tag{3}$$

B. Secondary control

Due to the virtual resistance in grid controller and speed vs DC voltage droop in flywheel controller, the DC voltage has a voltage variation during operation. In order to eliminate this effect, secondary controller is used to adjust the DC voltage regulation. In practical applications, as grid converters are close in parallel connection and flywheels are positioned together in cabinets, it is reasonable to use two centralized controllers on top of grid and flywheel primary controllers respectively. Due to line impedances between grid and flywheel converters, a low bandwidth communication is deployed to calculate the average value of DC voltage. The adjustment term of secondary control can be expressed as:

$$\delta V_{DC} = \left(K_{ps} + \frac{K_{is}}{s}\right) \cdot \left(V_{DC}^* - \overline{V}_{DC}\right) \tag{4}$$

Based on the proposed control strategy, the response of the system coping with sudden connection of PEV can be divided into several stages:

1) The sudden connection of PEV causes a DC voltage dip first, which lead to the saturation of rate limiter in grid controller, and grid provide power in a ramping manner;

2) On the other hand, the flywheel discharging by reducing its speed and droop the DC voltage reference;

3) At the same time, due to the secondary controller, the DC voltage reference is adjusted online to eliminate the effect caused by droop and virtual resistance;

4) When the grid current ramps increasing and equalize with the load current, flywheel start to recharge back to nominal speed.

It should be noted that the system could operate even when the communication failed but with a DC voltage variation.

IV. Real-time simulation results

To investigate the operation of the proposed control scheme, a simulation model with the control structure shown in Fig. 2 was assembled in Matlab/Simulink and compiled into dSPACE 1006 in Microgrid lab Aalborg university [12].

The corresponding electrical and control parameters used for simulation may be found in Table I and II.

TABLE I. ELECTRICAL PARAMETERS

Electrical parameters	
DC bus capacitor C_{DC}	$2.2mF$
Line inductor L_{line}	$3.8mH$
Line resistor R_{line}	0.2Ω
DC bus voltage V_{dc}	$650V$
Grid voltage $V_{grid}\,(p-p)$	$325V$
Flywheel parameters	
Stator inductor L_s	$10.46\ mH$
Rotor inductor L_r	$10.76\ mH$
Total leakage coefficient σ	0.0556
Rotor resistance R_r	$2.3736\ \Omega$
Stator resistance R_s	$1.945\ \Omega$
Flywheel 1 Inertia	$10.2\ kgm^2$
Flywheel 2 Inertia	$9.8\ kgm^2$

TABLE II. ELECTRICAL PARAMETERS

Grid controller	
Voltage mode Proportional term	0.5
Virtual resistance	0.1
Time constant	1e-4s
Flywheel controller	
Droop parameter	0.05
Time constant	1e-4s
Secondary controller	
Proportional term	0.01
Integrator term	10
Time constant	0.01s

A simulation scenario of system response to PEV sudden connection can be seen from Fig.3 to Fig.6. Fig.3 presented the average DC voltage variation in two cases with and without secondary controller activated. PEV connection happens at 30s, and lead to a dip of DC bus voltage. According to the proposed DBS based control, the DC voltage recover back to nominal value 650V. In the situation without secondary controller, the DC voltage recovers according to the change of speed by droop law as is shown in Fig.4, and there is a small deviation due to virtual resistance; when secondary is activated as is shown as green line, the DC voltage is regulated more accurate and faster.

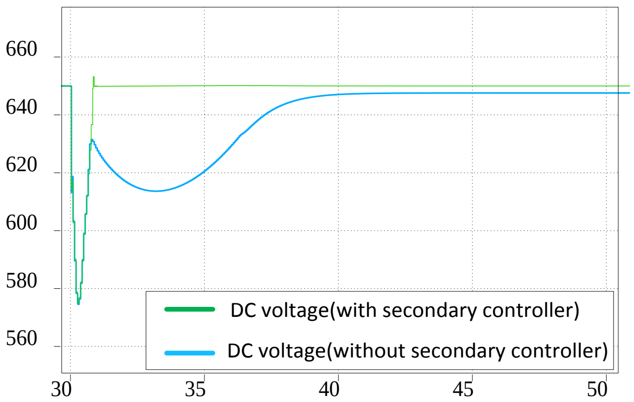

Fig.3 Average DC Bus voltage

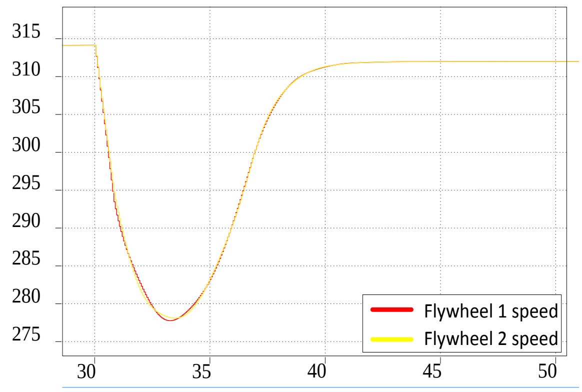

Fig.4 Rotational speed of flywheel

The DC current of PEV, grid and flywheel is presented in Fig.5 and grid current is shown is Fig.6. It can be observed that, due to the saturation of rate limiter, the grid current increasing in a ramping manner, and around 33s, the grid current equalize with the load current while the flywheel current is zero. After that point, the grid current exceeds the load current and the flywheel current is minus which means flywheel is charging. Until 40s, the flywheel is recharging to full SoC and grid only supplies power for PEV.

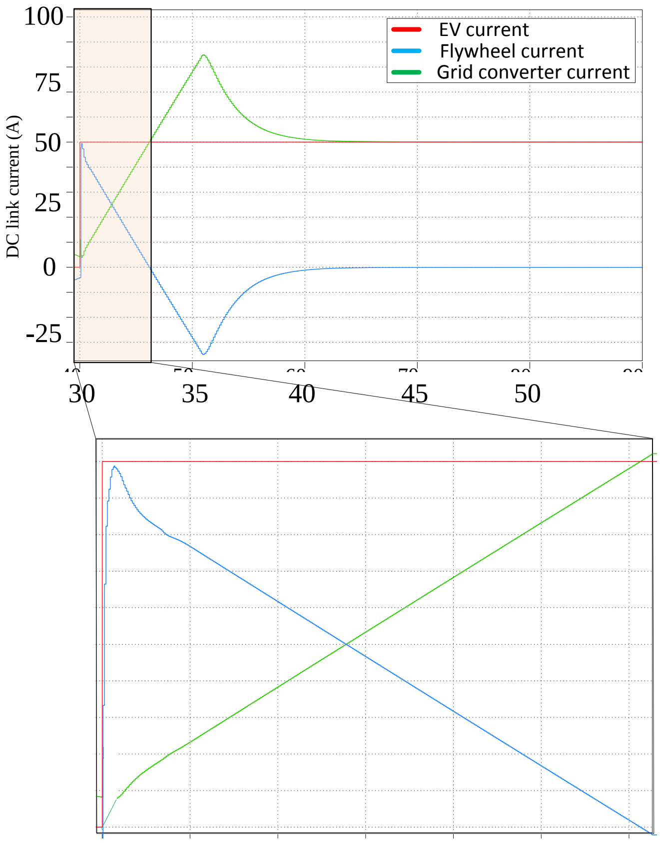

Fig.5 DC current of PEV, grid and flywheel converter

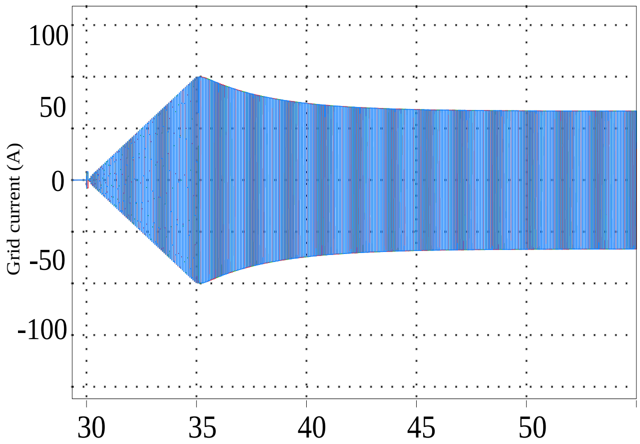

Fig.6 Grid current

V. Conclusion

This paper employs a dedicated paralleled flywheels ESS in a fast charging station, the proposed two-level control scheme is applied for power coordination of each units and DC bus voltage regulation. The proposed strategy could compensate the initial power peak by sudden PEV connection with distributed coordination of grid converter and multi flywheel converter. The real-time simulation results validate the feasibility of proposed scheme.

References

[1] A. Emadi, M. Ehsani, and J. Miller, Vehicular Electric Power Systems: Land, Sea, Air, and Space Vehicles. The Power engineering, Taylor & Francis, 2010.

[2] X. Chang, B. Chen, Q. Li, X. Cui, L. Tang, and C. Liu, "Estimating real-time traffic carbon dioxide emissions based on intelligent transportation system technologies," *Intelligent Transportation Syst., IEEE Trans. on*, vol. 14, no. 1, pp. 469–479, 2013.

[3] M. Yilmaz and P. Krein, "Review of battery charger topologies, charging power levels, and infrastructure for plug-in electric and hybrid vehicles," *Power Electron., IEEE Trans. on*, vol. 28, no. 5, pp. 2151–2169, 2013.

[4] D. Steen, L. Tuan, O. Carlson, and L. Bertling, "Assessment of electric vehicle charging scenarios based on demographical data," *Smart Grid, IEEE Trans. on*, vol. 3, no. 3, pp. 1457–1468, 2012.

[5] Xiaonan Lu; Kai Sun; Guerrero, J.M.; Vasquez, J.C.; Lipei Huang, "State-of-Charge Balance Using Adaptive Droop Control for Distributed Energy Storage Systems in DC Microgrid Applications," *Industrial Electronics, IEEE Transactions on* , vol.61, no.6, pp.2804,2815, June 2014

[6] Xiaonan Lu; Kai Sun; Guerrero, J.M.; Vasquez, J.C.; Lipei Huang; Teodorescu, R., "SoC-based droop method for distributed energy storage in DC microgrid applications," *Industrial Electronics (ISIE), 2012 IEEE International Symposium on* , vol., no., pp.1640,1645, 28-31 May 2012; doi: 10.1109/ISIE.2012.6237336

[7] H. Kakigano, Y. Miura, and T. Ise, "Distribution voltage control for dc microgrids using fuzzy control and gain-scheduling technique," *Power Electronics, IEEE Transactions on*, vol. 28, no. 5, pp. 2246–2258, 2013.

[8] H. Akagi and H. Sato, "Control and performance of a doubly-fed induction machine intended for a flywheel energy storage system," *Power Electron., IEEE Trans. on*, vol. 17, no. 1, pp. 109–116, 2002.

[9] S. Samineni, B. Johnson, H. Hess, and J. Law, "Modeling and analysis of a flywheel energy storage system for voltage sag correction," *Industry Appl., IEEE Trans. on*, vol. 42, no. 1, pp. 42–52, 2006.

[10] Tomislav Dragicevic, Stjepan Sucic, Juan C. Vasquez, Josep M. Guerrero, "Flywheel-Based Distributed Bus Signalling Strategy for the Public Fast Charging Station", *smart grid, IEEE tran. on*, vol.PP: no.99. 1-11, 2014.

[11] Shafiee, Qobad, Dragicevic, Tomislav, Juan C. Vasquez, Josep M. Guerrero, "Hierarchical Control for Multiple DC-Microgrids Clusters", *energy conversion, IEEE trans. on*, vol. 29, no. 4, pp. 922-933.

[12] Aalborg University, Dept Energy Technology, Microgrids research programme www.microgrids.et.aau.dk