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Keywords

«Charging station», «Flywheel energy storage system», «Microgrid»

Abstract

Plug-in electrical vehicles will play a critical role in future smart grid and sudden connection of electrical vehicles chargers may cause huge power-peaks with high slew-rates on grid. In order to cope with this issue, this paper applies a distributed cooperative control for fast charging station with dedicated paralleled flywheel-based energy storage system. The distributed DC-bus signaling method is employed in the power coordination of grid and flywheel converters, and a distributed secondary controller generates DC voltage correction term to adjust the local voltage set-point through a dynamic consensus based voltage observer by communicating with its neighbors. The control system can realize the power balancing and DC voltage regulation with low reliance on communications. Finally, real-time hardware-in-the-loop results have been reported in order to verify the feasibility of proposed approach.

Introduction

Due to the increasing conventional fossil fuels' consumption and serious environmental pollution caused by carbon dioxide emissions, plug-in electric vehicles (PEV) may potentially replace the conventional automobiles in near future [1-2]. Therefore, it has been a critical issue and hot investigation how to provide comfortable and safe charging surroundings for PEV fleets in next generation smart grid. Up to now, Industry has defined 3 levels of charging patterns for EVs, among which Level 3 fast charging stations (FCS) are attractive to be a main charging style in future because its power rating could be up to 50 kW and save much charging time therefore meeting the comfort level of PEV drivers [3]. Taking into account all above, PEV will account for a large portion of energy consumption and have a considerable impact on grid. The sudden connection of PEV chargers may cause high slew-rates of power peaks at the point of common coupling (PCC), which may cause instabilities and contingencies.

All the power electronics components in a FCS are linked around a common DC bus [3] and the FCS system can be regarded a DC microgrid. In order to cope with the abovementioned issue, the control strategy previous developed for DC microgrid can be applied in a DC FCS. In [4-10], dedicated energy storage system (ESS) is considered to be connected to a common DC bus as an energy buffer. Up to now, most works on coordinate control of ESS are focusing on battery energy storage system (BESS) [4-8]. In [5],[6], adaptive control of paralleled connection BESS in DC microgrid is studied to realize the balancing of state of charge (SoC). In [7], an adaptive control is designed for a hybrid mix of different type of BESS, and the power is shared among the different batteries in line with their performance taking into account different battery characteristics. In [8], Kakigano applies fuzzy controller for coordination of BESS to balance the voltage in dc microgrids in a distributed manner.

However, there still exist some problems of BESS based system. The accuracy estimation of SoC of BESS is still an immature issue in either research or industry. Furthermore in a FCS considered in this paper, frequent charging/discharging cycles can seriously threaten the lifetime of batteries due to accelerating degradation which is the most common problem for BESS [9]. Compared to BESS, flywheel energy storage system (FESS) is a more mature, robust and faster technology, which has been extensively used for DC-link coupled power balancing in renewable energy generation applications [10],[11]. In [12], a droop control strategy is proposed for distributed power balancing of grid and FESS converter in a FCS. However, only one FESS is considered in the work and DC voltage deviation can be observed caused by the droop characteristic.

In this paper, based on a FCS infrastructure including multi paralleled FESS coupled in a common DC bus, a distributed DC-bus signaling (DBS) based cooperative control strategy is proposed to realize the power balancing of multi FESS. A dynamic consensus based voltage observer, previously used in microgrids [13], is employed to obtain the average value of DC voltage. The FESS can automatically adjust its operation according to variation of DC bus voltage. The strategy is able to maintain a stable DC bus and eliminate the adverse effect caused by disturbance when the PEV is suddenly connected to DC bus. Finally, a real-time simulation based on dSPACE 1006 is carried on to evaluate the feasibility of proposed strategy.

Description of FCS Structure

Fig.1 depicts the basic structure of FCS system upgraded with multi dedicated FESS, which comprises a set of DC/DC converters serving as PEV chargers and a number three-phase AC/DC converters connected with grid and paralleled flywheels, respectively. All the power electronics interfaces are connected to a common DC bus.

A buck DC/DC converter is applied as PEV charger following the control scheme provided by battery manufacturer which includes constant current and constant voltage charging stages. A low bandwidth controller is commonly derived since it is not critical to control with a rapid response for PEV charging process, therefore the moment of connection of PEV to the common DC bus is modeled as a step current disturbance to system.

The control objective is to balance this step power shock on grid with the coordination control of grid controller (GC) and flywheel controller (FC). The cooperative control strategy is implemented in a heretical structure, and the complete control block based on distributed bus signaling is deployed is presented in Fig. 2.

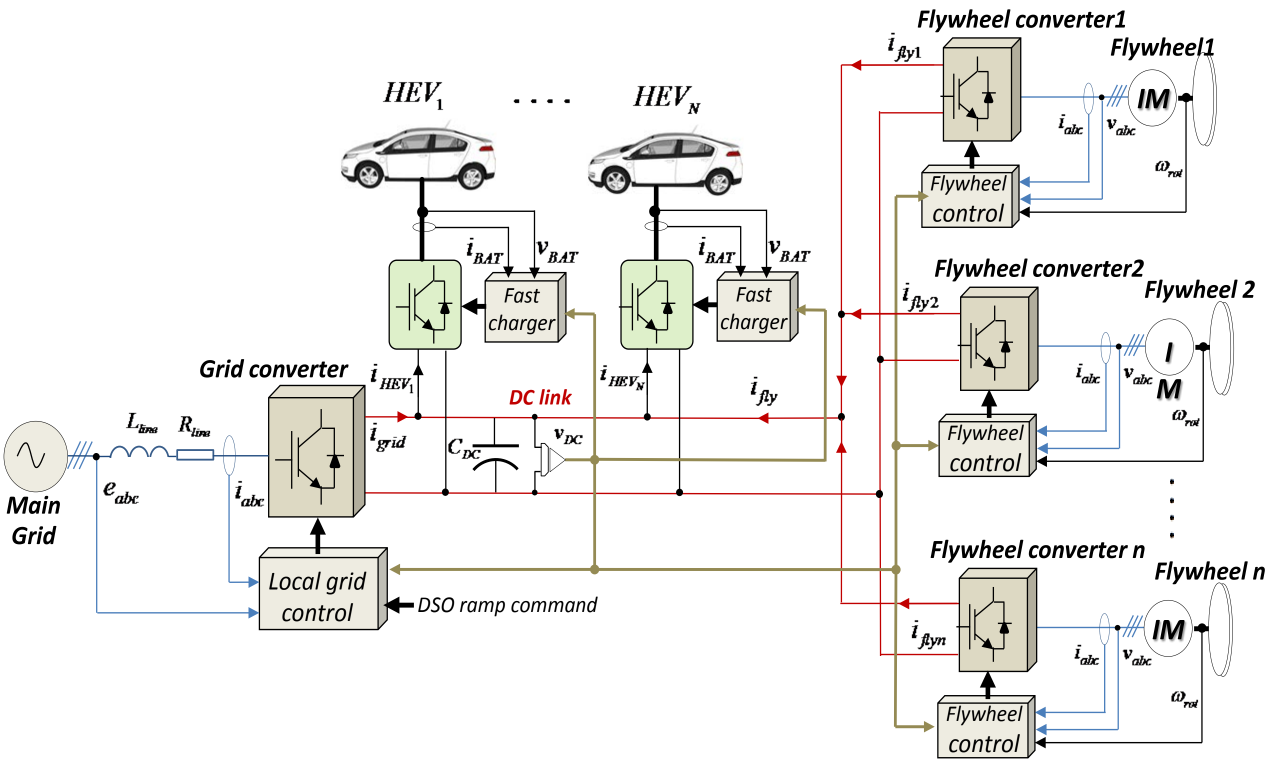

Fig. 1. Structure of the FCS system

Cooperative Control of System

(1) Primary controller

The primary control is employed in the GC and FC respectively for the purpose of power balancing between grid converters and flywheel converters by ramping the initial power peak. Distributed bus signaling strategy is implemented that GC and FC coordinate their operation according to the DC bus voltage deviations.

GC includes two control levels. The inner current loop is deployed in the synchronous reference frame (dq). The reference of the inner loop is provided by the DC voltage controller and reactive power controller. The Iq reference is set zero and the voltage controller was designed as a proportional gain followed by a rate limiter. The reference can be expressed as:

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

where K_1 is the proportional term and ψ is the function of rate limiter.

The indirect field oriented control [14] is applied on Flywheel controller, where flux and torque are decoupled and corresponding to *d* and *q* axis component respectively. The d-axis current reference is obtained using a flux controller and the rotor-flux position results from the rotor speed and slip speed. The q-axis current reference is generated by a droop controller, where the DC voltage vs speed droop control is implemented. The FESS can adjust its speed up and down according to the DC voltage variation. 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. Thus, the DC voltage droop law in steady state can be expressed as:

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

(2) Secondary controller

The distributed secondary controller is implemented on top of primary controller of GC and FC in order to help properly fine-tune the DC voltage reference and mitigate the voltage derivation caused by droop

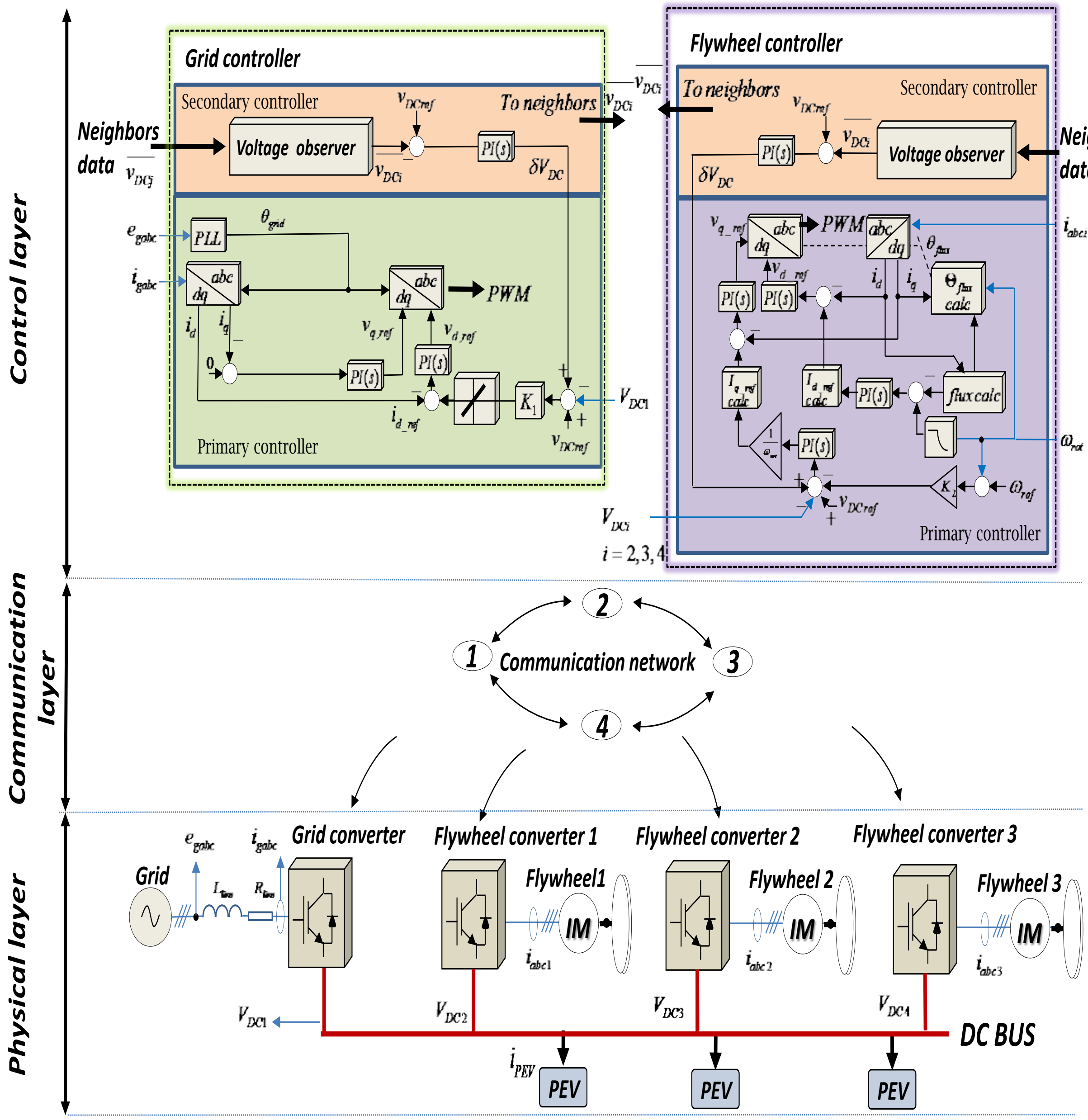

Fig. 2. Flywheel and grid converter control schemes

control in FC. The output of secondary controller is the DC voltage reference adjustment, which is obtained as follows:

$$\delta V_{DC}=\left(K_{p\delta}+\frac{K_{i\delta}}{s}\right)\left(V_{DCref}-\overline{V_{DCi}}\right) \tag{4}$$

where $\overline{V_{DCi}}$ is the estimated average value of DC voltage.

The estimated average DC voltage $\overline{V_{DCi}}$ is obtained from a voltage observer, as is shown in Fig.3, which uses a dynamic cooperative framework to process neighbors' information and estimate the average voltage across the FCS system. The discrete form of consensus algorithm can be presented as [15]:

$$x_i(k+1)=x_i(k)+\sum_{i\in N_i} a_{ij}\cdot(x_i(k)-x_j(k)) \tag{5}$$

where $i=1,2,\ldots,N$, N is the total number of nodes, $x_i(k)$ and $x_i(k+1)$ are information obtained by controller *i* at iteration *k* and *k*+1, and a_{ij} is the edge weight between nodes *i* and *j*, a_{ij} is 0 if node *i* and *j* are not neighboring node. N_i is the set of indexes of controllers that communicate with controller *i*.

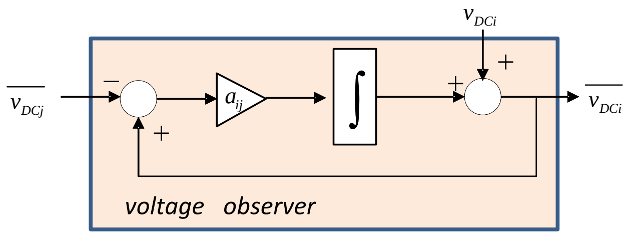

Fig. 3. Diagram of voltage observer based on dynamic consensus protocol

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

Table I. Real-times Simulation Electrcal Parameters

Electrical parameters	
C_{DC}	$2.2mF$
L_{line}	$3.8mH$
R_{line}	0.2Ω
$V_{grid}(p-p)$	$325V$
Flywheel parameters	
Stator inductor L_s	10.46 mH
Rotor inductor L_r	10.76 mH
Total leakage coefficient σ	0.0556
Inertia J	$10\ kgm^2$
Stator resistance R_s	1.945 Ω
Rotor resistance R_r	2.3736 Ω

Table II. Real-times Simulation Control Parameters

FC controller		GC controller		Secondary controller	
Droop coefficient	0.1	K_1	1.25	$K_{p\delta}$	0.01
T_{fly}	1e-4s	i_{rate}	10 A/s	$K_{i\delta}$	0.5
K_{pfly}	2.3	T_{grid}	1e-4s	$T_{\sec}$	1e-2s
K_{ifly}	20				

The PEV charger was programmed to extract constant current from the DC link which is consistent with the first and the most significant stage in the typical two-stage charging algorithms proposed by battery manufacturers. Simulation of the moment of connection of PEV to the charging station has been performed with and without secondary controller respectively. Simulation was performed for one full discharge/charge cycle of the flywheel ESS following the connection of PEV(s) at 40s. Waveforms of DC voltage for both cases are shown in the Fig. 4 in order to clearly demonstrate the differences in their performances.

The DC voltage dip caused by the PEV sudden connection lead to the saturation of the rate limiter in GC, and also cause a negative torque reference from droop controller in FC. Hence FESS supply the active power by reducing its rotational speed, DC bus recover to a value according to the speed vs DC voltage droop, meanwhile the grid current increase in a slope specified by the rate limiter. From 44 s the grid current is equal to the PEV current, and the grid current supply all the power to PEV, while starting to recharge the flywheels to the nominal speed. The speed of FESS is shown in Fig. 5 and the DC-side currents of grid converter, flywheel converter and PEV can be seen in Fig. 6. During the whole process, the DC bus recovers fast to common 650V after the initial dip due to the secondary controller and the paralleled FESS are able to share the power. The current sharing performance of the paralleled FESS is shown in Fig. 7. Small currents differences can be observed due to the inertia differences of flywheels.

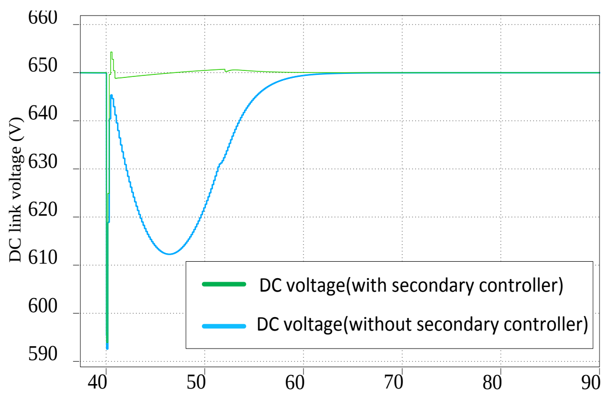

Fig. 4 DC link voltage

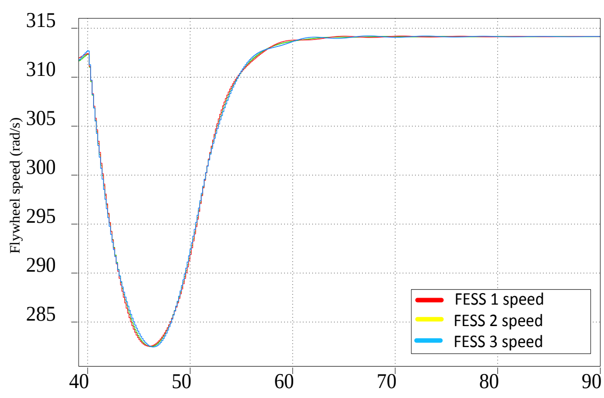

Fig. 5 paralleled FESS rotational speed

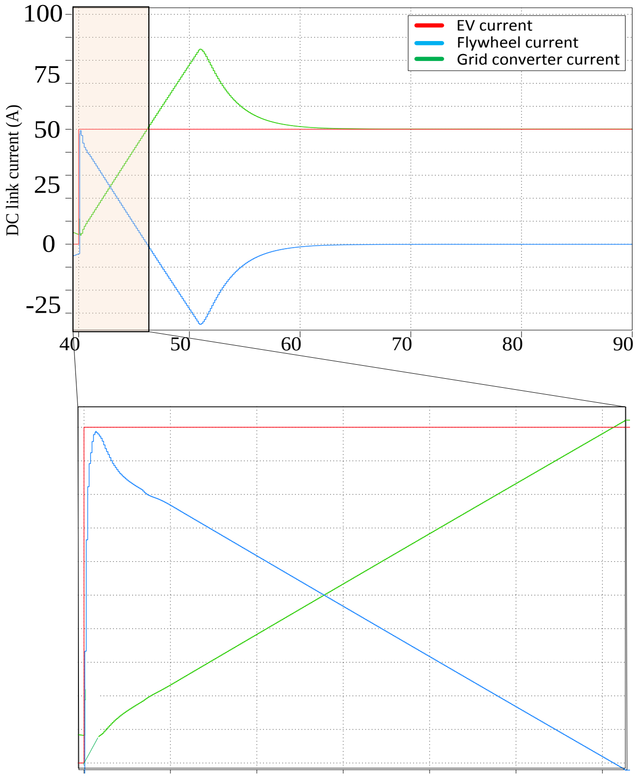

Fig. 6 DC link current of PEV, GC and FC

Fig.8 shows the grid converter AC-side current in proposed schemes. The grid-side current increases slowly in a ramp manner rather than a stiff step in order to eliminate the peak power impact on grid.

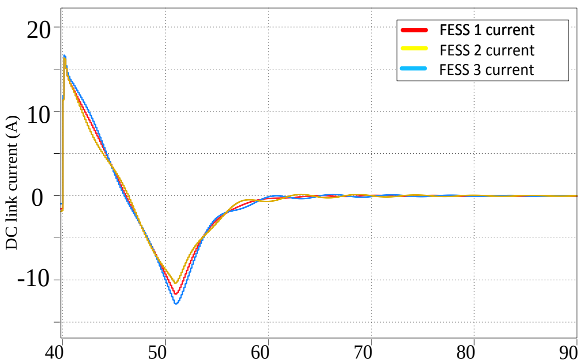

Fig. 7 paralleled FESS DC-side current

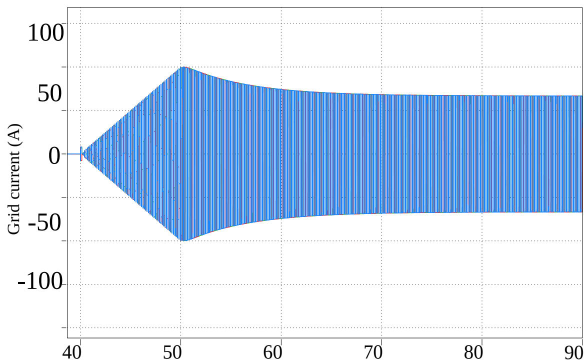

Fig. 8 Grid converter AC-side current

Conclusions

This paper proposes the use of dedicated paralleled FESS in FCS, including a cooperative control scheme applied for power coordination of each unit and DC bus voltage regulation. The proposed strategy can compensate the high slew-rated power peaks created by PEV connections. The control proposed carries out the distributed coordination of the grid converter and the multi-flywheel converters. Real-time hardware-in-the-loop results validate the feasibility of proposed scheme.

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