Index - Final Report

1. Final report

The final report must be prepared in English. Please fill in the following sections of the template.

1.1 Project details

Project title	**Flexible Electric Vehicle Charging Infrastructure (Flex –ChEV)**
Project identification	Flex-Chev 12258 project
Name of the programme which has funded the project	SmartGrids ERA-Net (3rd SmartGrids ERA-Net Joint Call), ForskEL
Name and address of the enterprises/institution responsible for the project	Narvik University College (new name: The Artic University of Norway) Address: Lodve Langes gt. 2 P.O. Box 385 8505 Narvik Norway
Project partners	Aalborg University (Denmark) Zagreb Universiy (Croatia)
CVR (central business register)	
Date for submission	29-4-2016

1.2 Executive summary

Hybrid Electrical Vehicles (HEV) chargers are expected to play a significant role in the total consumption of developed countries across the world. Today's commercially available HEV chargers are not flexible and present significant disturbance sources for the grid. Therefore, preservation of power systems secure operation will require new interventions to increase the flexibility of HEV chargers in a cost-effective way. The proposed project has obtained theoretical development and experimental verification of a new generation of fast HEV charging stations (CSs). Its principal functionality is to use dedicated Energy Storage Systems (ESS) within the station in order to compensate the adverse effects caused by charging, as seen from the grid. Flexible and fast CSs will be an essential part of the future intelligent power systems as projected by the Smart Grid concept. The prevailing concern in that sense is the combined impact of a large number of randomly connected Plug-in Vehicles (PEVs) in the distribution network. On the other hand, continually growing PEVs are likely to impose more specific and acute challenges in short term, it is also expected to expect that grid operators will impose strict demand-response requirements for the operation of CSs.

In this project, dedicated energy storage systems (ESSs) were proposed to be installed within the charging station as an energy buffer. Flywheel ESS (FESS) has been considered first since it is the most suitable technology for providing fast power compensation services. Also, it is a mature and economical technology which has high power density and no degrading problems caused by frequent charging and discharging. The CS upgraded with the dedicated FESS will compensate the adverse effect on the end-user function of PEV, as seen from the utility grid. Moreover, the proposed concept for flexible CSs can provide ancillary services, while not compromising the regular charging patterns recommended by the battery manufacturers. Consequently, the lifetime of battery is preserved and the PEV user's comfort level remains high. From Danish side, the project attracted an industrial company (WattsUp Power A/S) which deals with the design, manufacturing and operation of Flywheels. This company works together with Aalborg University for this project and other green power applications.

Accordingly, this project proposed a fast charging station structure which is combined with FESS. It supports a corresponding smart control strategy that could be termed *charging station to grid* (CS2G). It explores the possibility of using a dedicated ESS within the charging station to alleviate grid and market conditions but not compromise the PEV's battery charging algorithms or place the daily routine of the PEV owners in jeopardy. The overall control of FCS is divided into two layers structured into a hierarchical architecture with the layer being the closest to the physical equipment termed as primary layer and the one on top of it as secondary layer. Control design is hence carried out by following the common principle for management of both large interconnected and small distributed generation (DG) systems.

For the purpose of control optimization and parameter tuning of the primary layer, detailed modeling of grid ac/dc and FESS converters is built and analyzed. Based on modeling analysis, centralized and distributed control methods are both explored to realize the coordination control of each component in the system. Specially, this project proposes a "dc voltage vs speed" droop strategy for FESS control based on distributed bus signaling (DBS) concept. Then the concept is extended to apply for control of multi-parallel FESS structure. Additionally, an adaptive dc bus voltage control for grid converter is proposed to enhance the system stability and efficiency.

Aiming at alleviating the unexpected conditions in grid-side and providing ancillary services to distributed network, multi-functional controller in secondary control layer which enables four-quadrate operation ability is proposed to cope with different scenarios, such as PEV plug and play capability, active power compensation (load shifting), reactive power compensation, loss of grid power. Moreover, Centralized and distributed secondary control methods are explored and compared, especially a novel dynamic consensus control concept applied for coordination of paralleled grid interfaces and FESS. For this case scenario, stability issues have been investigated and analyzed based on new proposed control algorithms. First, small-signaling model of each component are built to study the dynamic stability of system operating at different stages in details. Due to the switching modes existing in the system, stability of switching system is studied based on common Lyapunov function method when the system switches its operation behavior between two modes. Next, due to the bidirectional operation feature and interaction behavior between multi power electronics converters, impedance model of the system is built to study the impedance based stability for the purpose of further optimizing the control and design of system. Finally, a downscaled FCS prototype with FESS has been built in the MicroGrid Research Laboratory at Aalborg University, and experiments and hardware-in-loop (HIL) simulation results are conducted to verify the effectiveness and feasibility with the proposed FCS concept, control schemes, modeling and stability analysis.

The project results have been disseminated in terms of scientific publications in top-tier international peer-reviewed journals (5) and conference papers (8) as can be seen in at the end of this report.

1.3 Project results

A. Objectives

The transportation sector is changing towards a greater electrification of vehicle fleets. According to the Electric Power Research Institute, it is estimated that by 2020 the Europe’s electric vehicle (EV) market is going to increase by 5 times, and up to 35% of the total vehicles in the U.S. will be plug-in EV (PEV). The industry has defined three levels of charging patterns for EVs:

- Level 1 comprises an on-board single phase ac charger of up to 2kW and usually takes place at residential households.
- Level 2 is typically used in private or public outlets with dedicated on-board single phase or three phase ac charger with power rating from 4kW to 19.2 kW.
- Level 3 has the highest power rating and uses a dedicated off-board dc charger of up to 240kW. This type of charger is often referred to as the fast charging station (FCS). The recommended charging profile is proprietary to the particular battery manufacturer, which commonly includes two stages: constant current and constant voltage stages. For instance, for a typical Level 3 charging profile of Nissan Leaf, the charging power is 50 kVA and duration time is around 30 minutes. Among the charging patterns, level 3 has the most significant impact on power system. FCSs will account for a considerable part of total energy consumption in future power systems and will have a great potential to provide flexible load control reserves managed by DSO.

Ancillary services by PEVs can be provided in different ways. For example:

- Vehicle to grid (V2G) based aggregation of PEVs is proposed to regulate the charging and discharging rate in order to contribute to the active power regulation of power system

- PEV chargers are controlled in unidirectional way to simply switch on or off and modify the aggregated charging pattern. A hysteresis control originally used for thermostatically controlled loads is employed for PEV charging to actively control the aggregated consumption of higher number of chargers. This is done by adapting individual PEV states of charge (SoC).

The signals from upper-level controller are used to determine the instantaneous charging rate. In order to keep the heath of battery, it is recommended that the charging profile defined by manufacturer is not interrupted.

However, the main limitation of all these strategies above is that the charging pattern recommended by battery manufacturers is compromised and thus the lifetime and reliability of PEV battery is reduced. In order to mitigate the adverse effects of discontinuous charging of PEV batteries, type 3 FCS can be enhanced with local energy buffers based on ESS

The overall milestones and deliverables of the project were completely fulfilled and there exist no deviation from the goals and sub-goals. A reduced scale pHEV CS laboratory scale prototype equipped with primary control and secondary control levels has been developed, by using a new control methodologies and by adding more added-values e.g. plug and play capabilities. Experimental tests also have been done in the platform. The project objectives are summarized as follows:

- Development of an averaged and detailed switching simulation models of fast HEV CS, dynamic and ageing models for several types of ESS technologies and implement primary control levels. Large-signal and small signal models have been developed. Energy storage systems as intermediate elements to deal with the energy flow from the grid to the EV chargers were also modelled.

- Development of a secondary control layer that incorporates necessary functionalities for grid support. The grid support has been based on reactive power injection when there are voltage fluctuations in the point of common coupling (PCC). The secondary control implemented here was unique since it does not need for any communications between elements. A concept called bus signaling (using the voltage level to indicate the state of charge of the ESS) was enough to fulfil the requirements inside the EVCS. However, we envision that for large scale implementation of EVCS, a coordination among them may be needed, so new concepts like Internet-of-Things (IoT) can be a further investigation topic.

- Select the most appropriate ESS technology for tracing the requirements of secondary layer. An extensive theoretical comparison between ESS has been made, so that most robust and reliable for this application were flywheel technologies. Further, in the middle of the project, WattsUp Power A/S approach Aalborg University to develop large scale flywheels, so that the outcomes of this project are being extended right now in another new project.

- Assemble a reduced scale experimental test bench and verify the simultaneous operation of primary and secondary layer during HEV recharge. The prototype was built and tested in Aalborg University, Microgrid Research Labs: http://www.et.aau.dk/department/laboratory-facilities/intelligent-microgrid-lab/. Notice that this is a lab-scale prototype (2-kW flywheel), while the real-life scale units are being produced in the new aforementioned project.

The aforementioned main objectives of the project were successfully accomplished. Flywheel technologies give a good answer to the key research questions of the project which were to find out the most appropriated ESS technology that can be integrated in EVCS's, aiming to reduce the peaks of current at the Point of Common Coupling (PCC) while supporting the grid at the same time.

Regarding project dissemination, scientific publications have been published in top-tier international peer-reviewed journals (5) and IEEE conference papers (8). Major part of the results was successful as expected, however, the huge number of new applications that can use flywheel technologies and interest from different companies was unexpected for us. New commercialization results are expected in the few years by integrating the control developed in this project for flywheel ESS.

In addition, after our preliminary research results, another research team of University of Electronic Science and Technology of China in Chengdu join our activities applying FESS to stabilize the grid in Wind Farms. Those results may be suitable in the Danish context in which an amount of wind energy generation could be store giving extra primary regulation spinning reserve.

In the software/communication aspect, control strategies for EVCS equipped with flywheel ESS have been developed, simulated and tested. The main role of the FESS in this case scenario was not to compromise the predefined charging profile of PEV battery during the provision of a hysteresis-type active power ancillary service to the overhead power system.

In that sense, when the active power is not being extracted from the grid, FESS provides the power required to sustain the continuous charging process of PEV battery. A key characteristic of the whole control system is that it is able to work without any digital communication between the grid-tied and FESS converters. Detailed system modeling and dynamics analysis of the controller are carried out for the different operating modes of the FCS system. A lab-scale prototype is built to validate the proposal. The presented experimental results proved the high accuracy of the theoretical analysis.

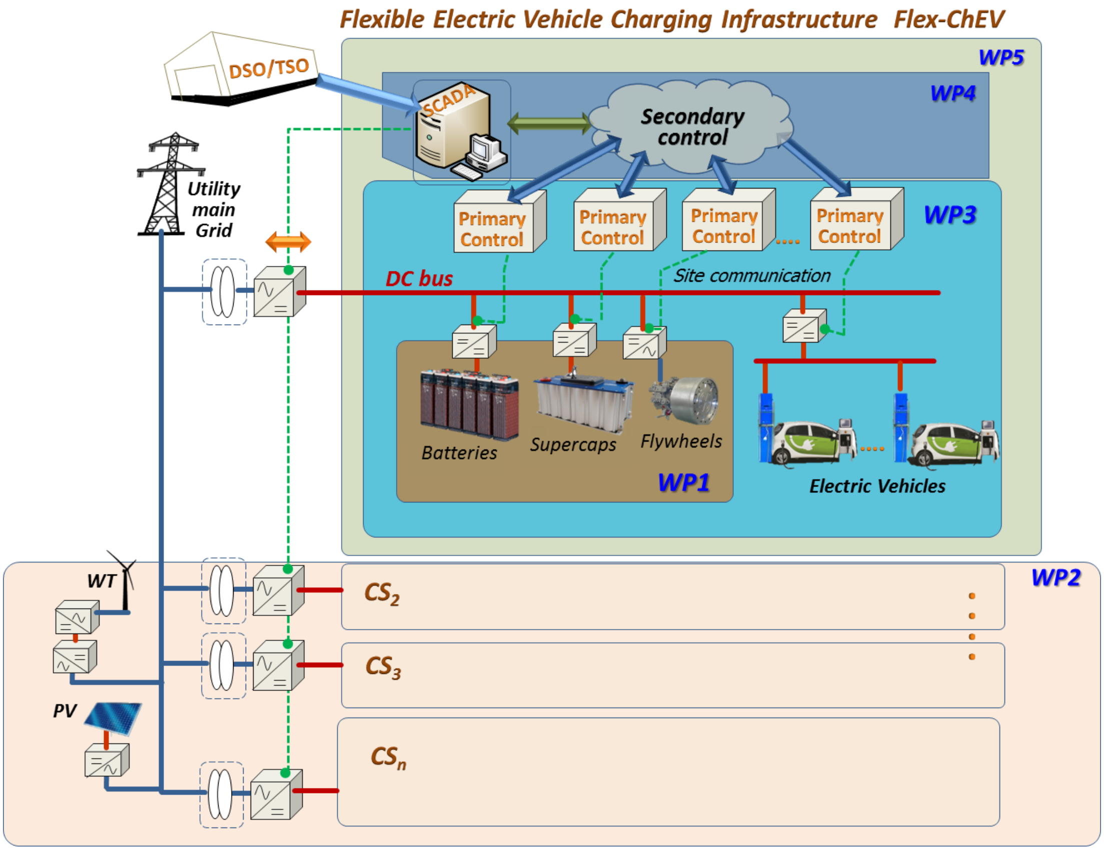


Fig. 1: Diagram of the electric vehicle charging station supplemented with energy storage systems under study.

Project Management and Participating Parties

Management Structure: the table below depicts the management structure of the project, which contained the following roles:

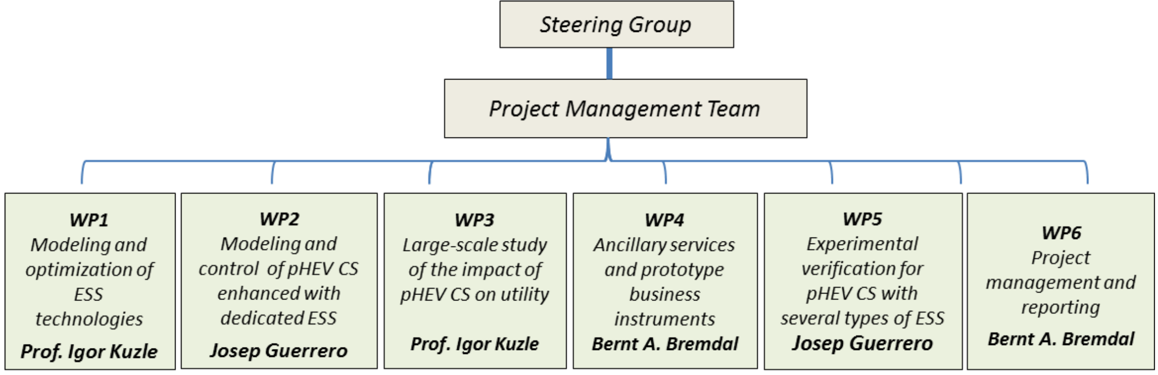


Fig. 2: Overview of the project organization of the Flex-ChEV project. The steering group oversees the project and supports the project management team.

Steering group consisted of one representative per project partner. The steering group acted on its own initiative and performed adjustments of the consortium structure, project plans and budget, but in accordance with the consortium preliminary agreement. The group will review progress in terms of deliverables and timetables.

• Prof. Josep Guerrero	Aalborg University (AAU), Denmark
• Prof. Igor Kuzle	University of Zagreb (UZ), Croatia
• Prof. Bernt A. Bremdal	Narvik University College (NUC), Norway

Project manager was in charge of the overall progression and management. Apart from that, project manager will coordinate all members of consortium from both administrative and financial aspect standpoints.

- Professor Bernt A. Bremdal will be Flex-ChEV project manager

Project management is the operative entity responsible for evaluation of scientific progress and realization of deliverables.

- Scientific coordinators: Prof. Josep Guerrero, AAU, Denmark
  Prof. Igor Kuzle, University of Zagreb (UZ), Croatia

Work package leaders are responsible for progress, reports and deliverables within the respective work packages.

WP1: Prof. Igor Kuzle,	UZ, (Croatia)
WP2: Prof. Josep Guerrero,	AAU, (Denmark)
WP3: Prof. Igor Kuzle,	UZ, (Croatia)
WP4: Prof. Brent Bremdal,	NUC, (Norway)
WP5: Prof. Josep Guerrero,	AAU, (Denmark)
WP6: Prof. Brent Bremdal,	NUC, (Norway)

B. Implementation

Fig. 3 depicts the aggregation concept of a number of FCSs. The aggregators (serving as intermediaries) generate the control references to each individual local FCS by processing the DSO commands. The basic structure of each FCS system upgraded with a dedicated FESS is also detailed in Fig. 3: a set of PEV chargers and a pair of three-phase ac/dc converters are connected around the common dc bus with grid and FESS, respectively.

A suitable control operation should fulfil DSO and PEV charging requirements at the same time, but also achieve a robust dc-link regulation, i.e. a stable and safe operation of the power electronics devices in all operating modes.

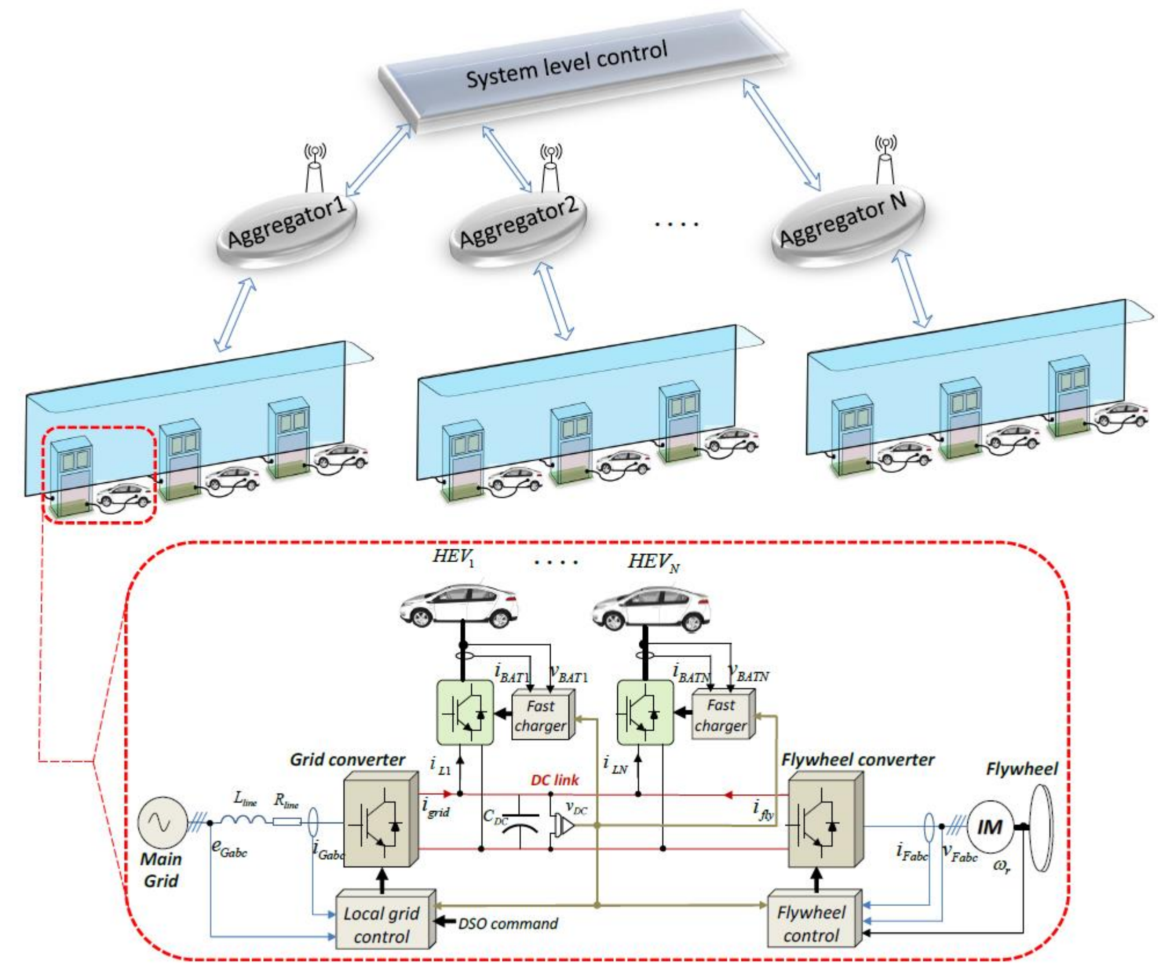


Fig. 3. Configuration of the FCS with dedicated FESS device and system level control structure.

Charging Station Structure

General structure of a FCS system upgraded with multi dedicated FESS is depicted in Fig. 4. As can be seen, the structure comprises a set of DC/DC converters serving as PEV chargers and a number of three-phase AC/DC converters connected with grid and paralleled flywheels, respectively. All the power electronics interfaces are connected to a common DC bus. The grid converter is in charge of generating a common dc link by connecting the PEV battery and flywheel through DC/DC and DC/AC converters, respectively. The dedicated FESS within the charging station is employed to alleviate grid and market conditions without compromising the PEV's battery charging algorithms or place the daily routine of the PHEV owners.

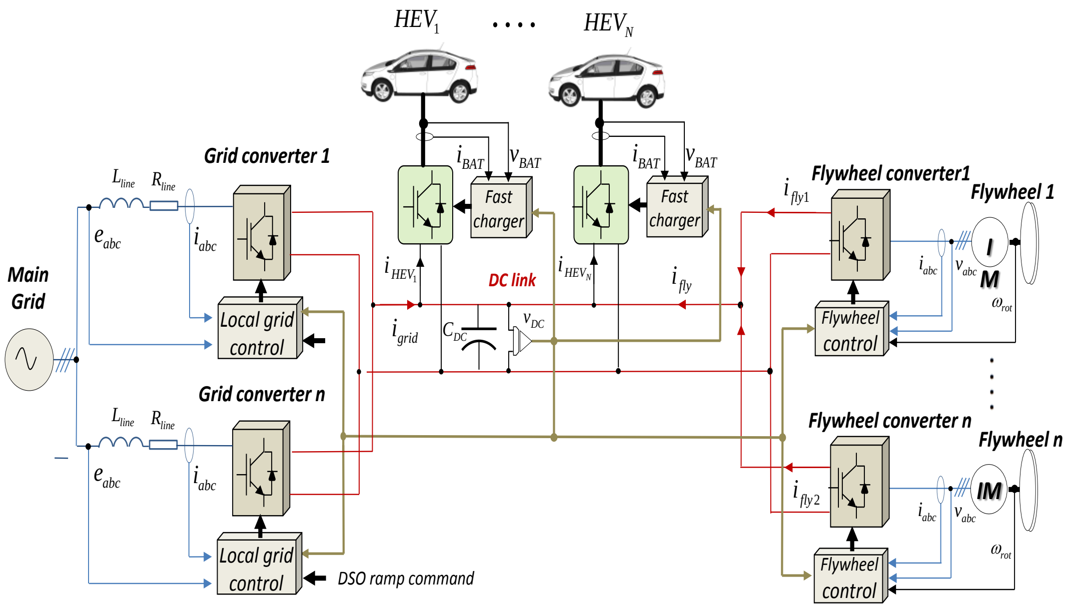


Fig. 4. Structure of the FCS system

The 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. As current and voltage only have relationship with the battery, this system does not need any feedback signals from FCS, thus the current introduced by the PEV charger may be regarded as a disturbance input that does not affect the system dynamic properties. The system dynamics around DC-link capacitor could be derived as follows:

$$C_{DC}\frac{dv_{DC}}{dt}=i_{grid}+i_{fly}-i_{PEV} \qquad (1)$$

where C_{DC} is the capacitance connected to the bus, i_{grid} and i_{fly} are the DC currents flowing from the grid and flywheels, respectively, while i_{PEV} is the current extracted by the fast DC charger(s). The PEV charger, grid converter (GC) and flywheel converter (FC) have their own specific dynamic features, so it is necessary to study the effect produced by each unit, in order to obtain the stability properties of the whole system. A brief review of GC and FC dynamics and their corresponding controllers will be presented in the following sections. More details about the proposed system architecture and control can be found in the listed publications below.

Primary Control

The primary control is employed in both grid converter (GC) and flywheel converter (FC) for the purpose of power balancing between grid converters and flywheel converters by ramping the initial power peak. Distributed bus signaling strategy is implemented to coordinate GC and FC operation according to the DC bus voltage deviations. Fig. 5 show the primary control schemes for a charging station equipped with a flywheel ESS.

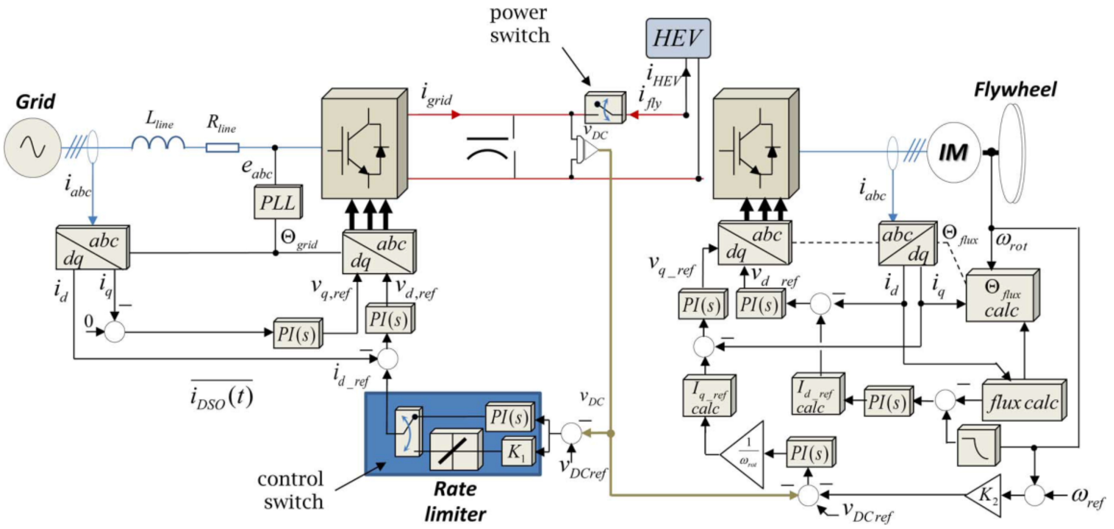


Fig. 5. Flywheel and grid converter control schemes for a CS equipped with a Flywheel ESS

Grid controller

A two-level PWM rectifier is used as an interface to be connected to the grid. The control scheme is deployed in d-q reference frame. The primary control of the grid controller includes two control loops namely inner control loops and DC voltage/reactive power controllers. The reference of the inner loop is provided by the DC voltage controller and reactive power controller. The Iq reference is defined by the reactive power controller. However, when there is no power command, the grid converter regulates the DC voltage and charges the flywheel. In such a situation, the Iq reference is set to zero. The voltage controller is designed as a proportional gain followed by a rate limiter (see Fig. 5). Therefore, the reference can be expressed as:

$$\begin{cases} i_{dref} = \psi(K_1(V_{dc}^* - V_{dc})) \\ i_{qref} = 0 \end{cases} \tag{2}$$

where K_1 is the proportional term and ψ is the function of rate limiter. As the stability analysis is derived based on DC-link and only active power exchange is considered in this application, following equation could be obtained:

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \frac{v_{DC}}{L_{line}} \begin{bmatrix} d_d \\ d_q \end{bmatrix} + \begin{bmatrix} -\frac{R_{line}}{L_{line}} & \omega \\ -\omega & -\frac{R_{line}}{L_{line}} \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} - \frac{1}{L_{line}} \begin{bmatrix} e_d \\ e_q \end{bmatrix} \tag{3}$$

where i_q and i_d, d_q and d_d are DC-like currents and duty ratios aligned with q and d rotating axes, respectively, while R_{line} and L_{line} are per phase resistance and inductance of the AC line.

It is assumed that the Id and Iq reference are followed instantaneously, and considering the grid voltage is synchronized with d-axis and reference for q axis is set to zero, the DC link current from grid could be expressed as:

$$i_{grid} = 1.5\frac{v_d i_d}{v_{DC}} \tag{4}$$

(4) may be linearized around the operating DC voltage, obtaining:

$$\hat{i}_{grid} = 1.5\frac{(e_d + 2I_d R_{line} + I_d L_{line} s)}{V_{DC}}\hat{i}_d \tag{5}$$

where Id is the equilibrium value of i_d.

Flywheel controller

The Flywheel controller adopts the indirect field oriented control (IDFOC), which is considered to have a fast and accurate response. The synchronous reference frame is also used for modeling and control of the machine, 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 controller 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:

$$T_{ref} = \left(K_{pfly} + \frac{K_{ifly}}{s}\right)\left(\left(V_{dc}^* - V_{dc}\right) - K_2(\omega_m^* - \omega_m)\right) \tag{6}$$

where K_2 is the droop coefficient, K_{pfly} and K_{ifly} are proportional and integral terms respectively. The DC voltage droop law can be expressed as:

$$V_{dc} = V_{dc}^* - K_2(\omega_m^* - \omega_m) \tag{7}$$

Based on the classical vector control approach, the d-q model in flux coordinates can be represented as follows:

$$\begin{bmatrix} \dot{i}_d \\ \dot{i}_q \end{bmatrix} = \frac{v_{DC}}{\sigma L_s}\begin{bmatrix} d_d \\ d_q \end{bmatrix} + \begin{bmatrix} -\frac{R_s}{\sigma L_s} & \omega_{mR} \\ -\omega_{mR} & -\frac{R_s}{\sigma L_s} \end{bmatrix}\begin{bmatrix} i_d \\ i_q \end{bmatrix} - \frac{1}{\sigma L_s}\begin{bmatrix} 0 \\ \omega_{mR}\psi_r \frac{L_0}{L_r} \end{bmatrix} \tag{8}$$

where L_s, L_r, R_s, R_r are stator and rotor inductances and resistances, respectively and L_0 is the mutual inductance; i_d and i_q are d and q-axis currents in field coordinates, ω_{mR} is flux rotational speed, i_{mR} is the magnetizing current, while ψ_r is the rotor flux; σ is the total leakage coefficient.

The flywheel current flowing towards the common DC bus may be expressed as:

$$i_{grid} = 1.5 \frac{v_d i_d + v_q i_q}{v_{DC}} \qquad (9)$$

The resulting expression around V_{DC} can be linearized as:

$$\hat{i}_{fly} = 1.5 \frac{2(R_s + \left(\frac{L_0}{L_r}\right)^2 R_r) I_q + \frac{\omega_{rot0} L_0^2 I_d}{L_r} + \sigma L_s I_q s}{V_{DC}} \hat{i}_q \qquad (10)$$

The swing equation of the flywheel governs the changes in the rotational speed of the rotor:

$$J \frac{d\omega_{rot}}{dt} = 1.5 p (1-\sigma) L_s i_{mR} i_q \qquad (11)$$

where J is the flywheel inertia and p is the number of pole pairs. More details on the small signal modelling and stability analysis of the grid converter and Flywheel ESS can be found in the below mentioned publications.

Secondary Control

Due to the virtual resistance in grid controller and speed vs DC voltage droop in flywheel controller, the DC bus voltage has a voltage variation during operation. In order to eliminate this effect, a secondary control loop is employed. The secondary controller provides a voltage correction term, to be added to the DC voltage reference mitigating the voltage derivation caused by droop control in FC.

In majority of applications, e.g., microgrids, the secondary control level is typically implemented in a centralized fashion. Such architectures require peer-to-peer communication between the central controller and the power electronics interfaces, which increases system complexity and compromises its scalability and reliability. Furthermore, the central controller exposes a single point-of-failure, i.e., any failure in the controller renders the entire system inoperable. To address these limitations, distributed control schemes have recently gained attraction. For instance, they have been proposed for both DC and AC microgrids. Distributed control offers scalability, simple communication network, and improved reliability while being resilient to faults or unknown system parameters. In this control paradigm, each agent (i.e., an inverter) exchanges information with other agents according to a sparse communication network, i.e., every agent makes its decision based on the behavior of its neighbors.

In this project, both centralized and distributed approach are examined. The implementation of the centralized secondary controller is depicted in Fig. 6. As it can be seen, the measured DC bus voltage is sent to the secondary controller through a communication link and after comparing with DC voltage reference, it passes through a PI controller to generate the voltage correction term.

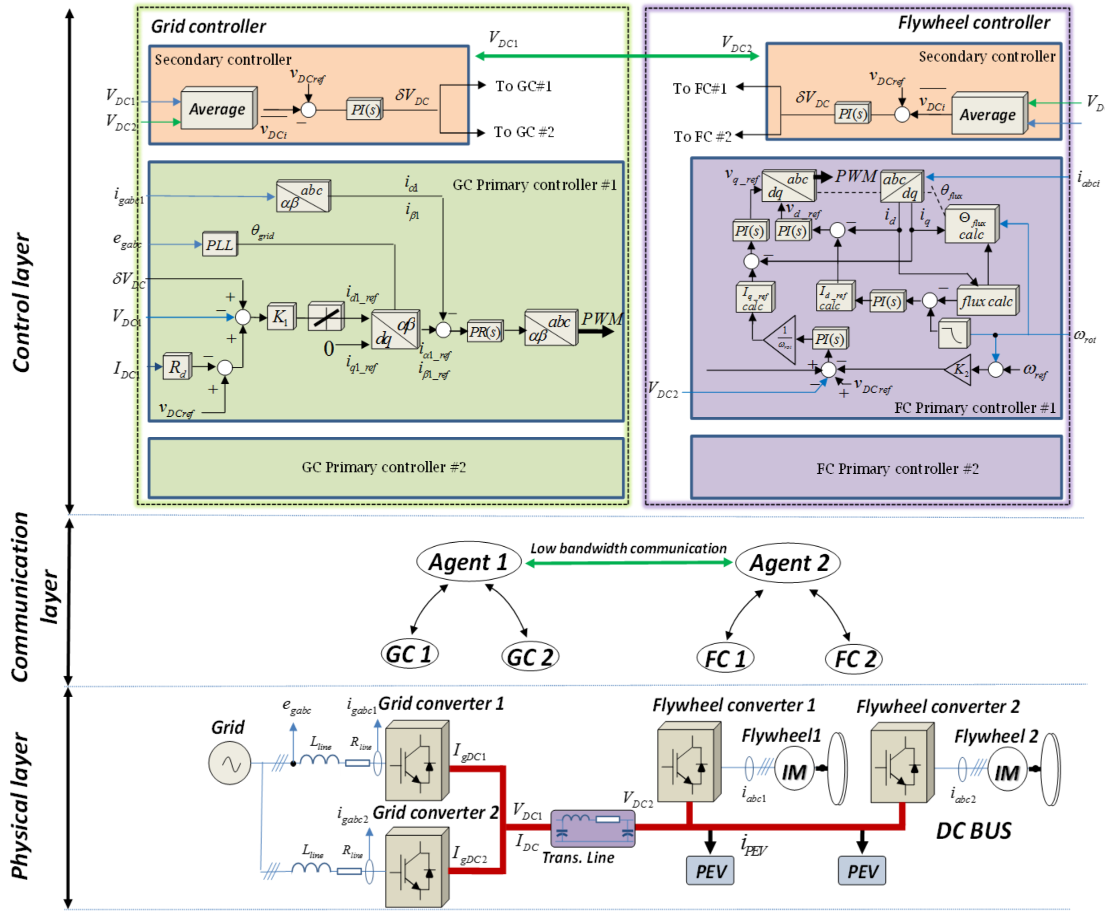


Fig. 6. Centralized secondary control scheme implemented on a FCS.

The voltage secondary loop can be expressed as follows:

$$\delta V_{DC} = K_{p\delta}\left(V_{DC}^{*} - V_{DC_i}\right) + K_{i\delta}\int\left(V_{DC}^{*} - V_{DC_i}\right)dt \qquad (12)$$

where $K_{p\delta}$ and $K_{i\delta}$ are the PI controller parameters of the secondary control, V_{DC}^{*} is the DC bus reference, and V_{DC_i} is the measured DC bus voltage. The control signal (δV_{DC}) is sent to the primary control level of each converter in order to remove the steady state errors produced by the droop control.

To avoid using a centralized controller, a distributed control approach is used. In this approach, each converter is augmented with a local secondary controller. The local controller uses the estimation made by a voltage observer to adjust the DC voltage set point and provide global DC bus voltage regulation accordingly (see Fig. 6). The voltage secondary controller provides a voltage correction term, dV_{DC}, to regulate the DC bus of converter *i*. Each controller has an estimator, highlighted in Fig. 4, that estimates the average of the DC voltages across the converters' outputs, $\bar{V}_{DC_i}$. The difference between this estimation and the reference DC voltage, V_{DCref}, is then fed to a PI controller, $H_i(s)$, to obtain the voltage correction term, dV_{DC}. Cooperation among all the converters guarantees having the averaged DC voltage regulated at the rated value. The estimator module at node i (see Fig. 4) provides the estimation of average DC voltage, and exchanges this estimation with its neighbors. The estimation is based on the so-called dynamic consensus protocol

$$\bar{V}_{DC_i}(t) = V_{DC_i}(t) + \int_0^t \sum_{j \in N_i} a_{ij}\left(\bar{V}_{DC_j}(t) - \bar{V}_{DC_i}(t)\right)\mathrm{d}t, \tag{13}$$

where V_{DC_i} is DC voltage at node i, and $\bar{V}_{DC_j}$ is the estimate of the average voltage provided by the estimator at node j. N_i denotes the set of all neighbors of the node i (i.e., inverter i), and a_{ij} is communication weight where $a_{ij} > 0$ means node i receives data from node j, and $a_{ij} = 0$ otherwise. In the updating protocol, the local voltage, V_{DC_i}, is directly fed into the estimation process which implies that any voltage variation at any node, e.g., node i, immediately affect the estimation at that node, $\bar{V}_{DC_i}$. Given a connected communication graph, the variation in $\bar{e}_i$ will be broadcasted across the network and affect all other estimations. A sparse communication network provides algorithmic scalability. Each converter communicates only with its neighbors on a communication graph. As long as the graph remains connected, the controller objectives are achieved.

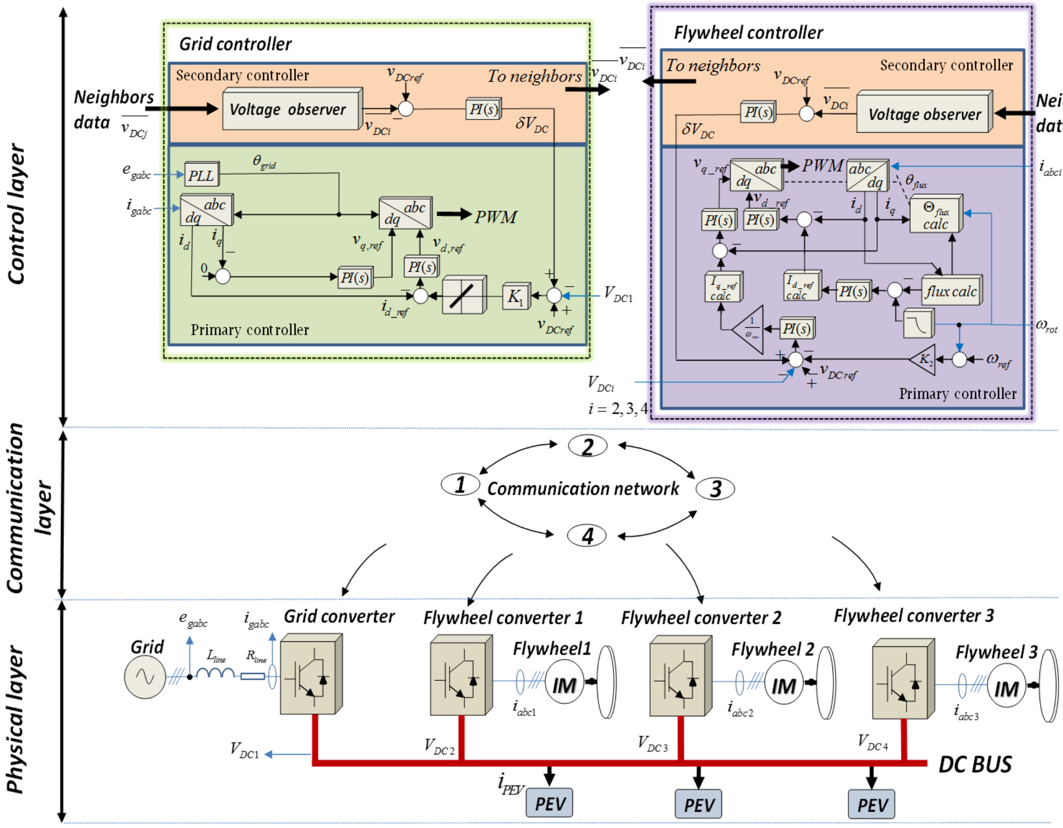


Fig. 5. Distributed secondary control scheme implemented on a FCS ancillary services

In line with the previous works of this project, some ancillary services have been studied. These services are provided by the dedicated ESS for the off-board FCS, and the regular charging patterns recommended by the battery manufacturers will not be compromised while the lifetime of battery is preserved.

Vehicle-to-grid (V2G) describes a system in which plug-in electric vehicles communicate with the power grid to sell demand response services by either delivering electricity into the grid or by throttling their charging rate. In the other words, sending active power from a vehicle to grid is called V2G. This concept has been discussed in the literature for several years. The implementation method, effects and economic benefits of this operation have been a focus in recent decade. The batteries of EV can be regarded as bulk energy storage when connected to the grid in charging mode, however this operation has to interfere the recommended charging pattern by battery manufacturer, which may accelerate the degrading of battery, thus, reducing its lifetime.

Supplying ancillary services using off-board chargers are more advantageous compared with using on-board chargers since off-board charging stations are not mobile, are rated at much higher power levels, and can be allocated by a utility grid via an annual agreement. Off-board charging stations located in shopping malls, restaurants, or other public locations that are stationary and rated at higher power levels can provide ancillary services to the grid without the need of engaging the EV battery with the grid, thereby preserving their lifetime.

Reactive Power Support

Recent studies on V2G concept shows that EV battery is not affected due to reactive power operation. The design, control and assessment of onboard chargers has been discussed in providing reactive power support for the utility grid, however, the reactive power support by onboard charger is limited by the mobility and power rating.

Reactive power compensation service in a fast charging station can be done by a control strategy for off-board chargers. In this approach, due to the apparent power limitation of grid converter, the active power supplied to EV has to be reduced as a trade-off when reactive power support is requested by grid. As a result, the regular charging process of EV is affected, which may lead to a decreased battery life-time. As another approach, it is proposing to employ an independent energy storage system (ESS) to the common DC bus. This way, the ESS could create a power buffer to share some active power with the EV. Although battery is most commonly used ESS, the degradation is a serious problem of BESS for long periods in aggressive environments (high current peaks, frequent cycling). Compared to BESS, flywheel is a mature and cheap technology with high power density which supports for large number of charge/discharge cycles.

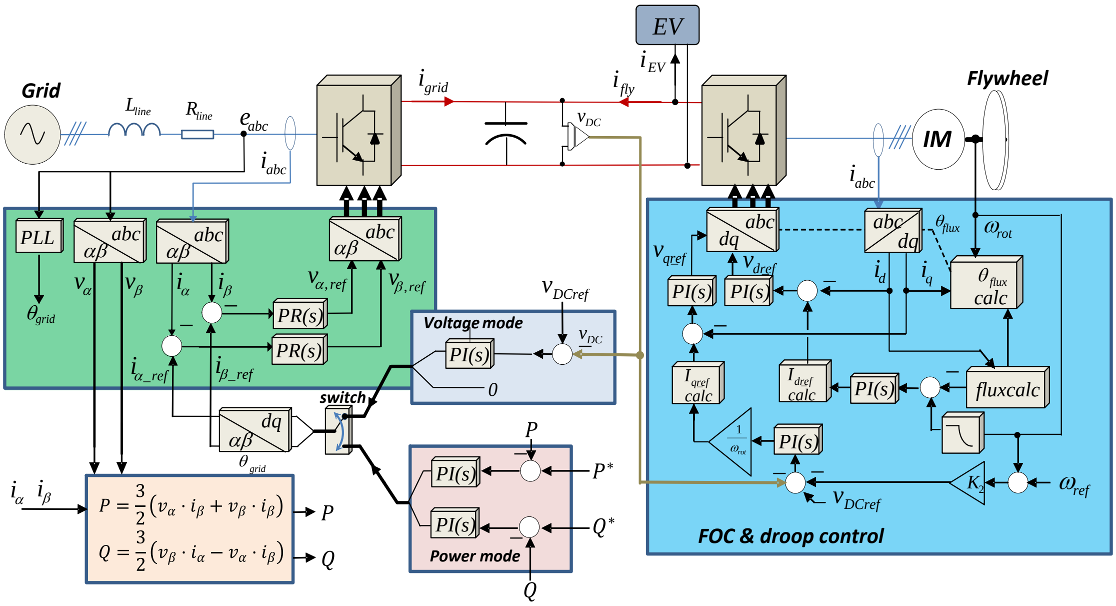


Fig. 6. Full scheme of a FCS control system providing reactive power support

The dedicated flywheel ESS considered to upgrade the off-board charging station is used for sharing part of active power when reactive power support is supplied to the grid utility. A supervisory control scheme is proposed for coordination of each part of the system. In particular, a distributed bus signaling (DBS) strategy has been applied so that the communication between grid and flywheel converters is not needed. Based on the proposed scheme (see Fig. 6), the charging station could supply the reactive power to the utility grid without compromising the charging algorithm and battery life time.

As Fig. 6 shows, the proposed controller operates in two modes:

1) ***Voltage mode:*** when there is no power command, the grid converter regulates the DC voltage and charges the flywheel. More detail of this mode was presented in the previous sections.

$$\begin{cases} i_d^* = K_p\left(V_{dc}^* - V_{dc}\right) + \dfrac{K_i}{s}\left(V_{dc}^* - V_{dc}\right) \\ i_q^* = 0 \end{cases} \tag{14}$$

2) ***Power mode:*** If there is a power request from the EV user or DSO, the controller will follow the active and reactive power commands, and the flywheel regulates the DC voltage.

$$\begin{cases} i_d^* = K_p\left(P^* - P\right) + \dfrac{K_i}{s}\left(P^* - P\right) \\ i_q^* = K_p\left(Q^* - Q\right) + \dfrac{K_i}{s}\left(Q^* - Q\right) \end{cases} \tag{15}$$

In power mode, the control should follow the apparent power operation limit shown in Fig. 7. The active power reference is depending on the PEV battery pack size, the

State of Charge (SoC), and the user choice for the charging type while the reactive power reference is directly received from the DSO.

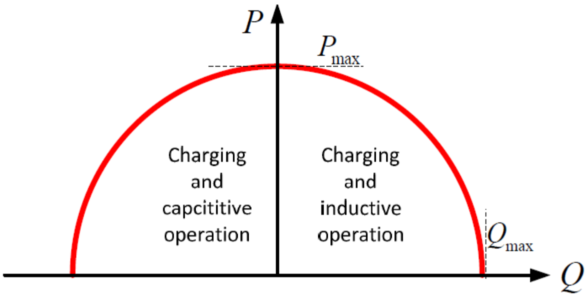


Fig. 7. Apparent power operation limit

Based on the proposed control approach described above, the FCS coordinates its operation according to different EV users' requests and the grid power commands. When there is a reactive power command from DSO, the extracted active power from the grid to charge the EV battery is reduced. Accordingly, the dc bus voltage deviates from the acceptable range. At the time, the flywheel provides the required active power for the EV by reducing its rotation speed. When the power mode operation terminated, the grid converter starts to regulate the DC bus and to charge the flywheel back to nominal speed.

Flexible Load Control

Recently, extensive studies on system level control of ancillary service provided by demand side management has been shifted into focuses. As considerable energy consumers, PEVs are also anticipated to provide such services from load side, especially in weak grids formed by intermittent renewable energy sources, such as wind turbines and photovoltaic arrays. V2G based aggregation of PEVs has been proposed to regulate the charging and discharging rate in order to contribute to the regulation of power system. Also, PEV charging stations can be controlled in unidirectional way to simply switch on or off and modify the aggregated charging pattern according to the command from aggregator. A hysteresis control originally used for thermostatically controlled load is employed for PEV charging to modify the respective state of charge (SoC). The signals from upper-level controller can shift the SoC band up and down. All the controls strategies above are generated from the system-level viewpoint, and they all share the same serious disadvantage that the charging process of battery pack in PEV has to be compromised when supplying ancillary services to grid. Thereby, the lifetime of PEV battery gets affected to some extent.

In the project, a hysteresis conception has been employed to be implemented on the power electronics level in a local charging station with multi flywheels ESS, as shown in Fig. 8. Using the flywheel ESS, the control does not modify the SOC band of battery pack, but controls the energy band extracted from the grid. As a result, the CS upgraded with FESS are able to provide the regulation services, while not compromising the regular charging patterns recommended by the battery manufacturers. Consequently, the lifetime of battery is preserved and the PEV user's comfort level remains high.

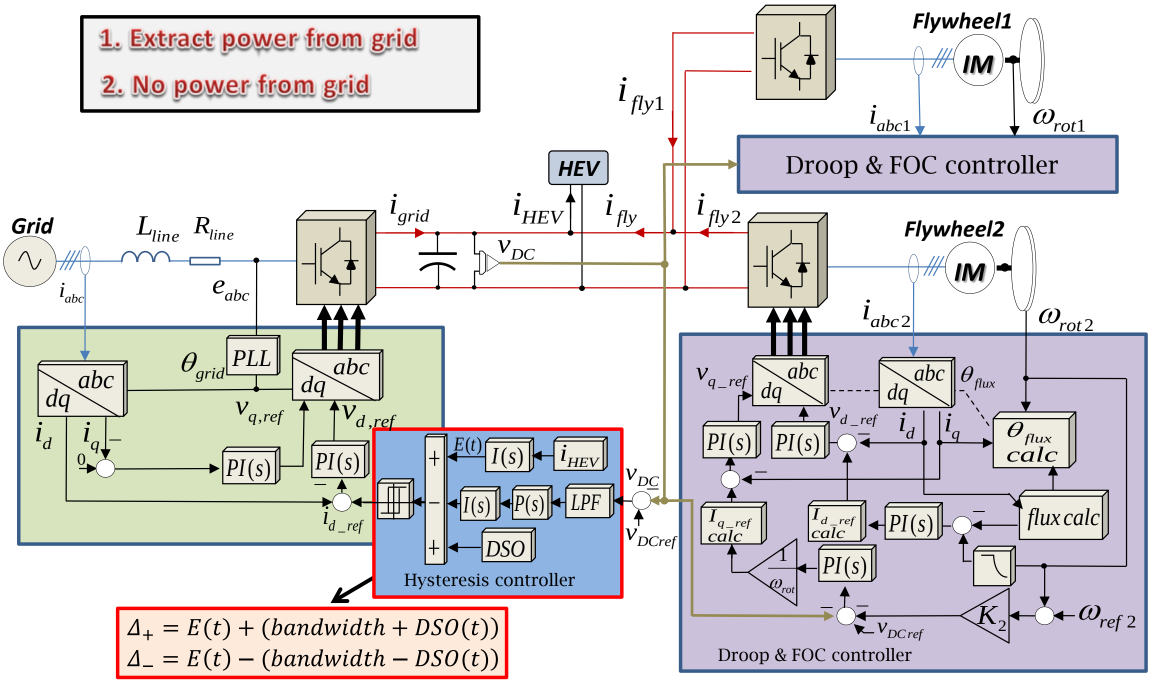


Fig. 8. Overall control diagram that incorporates hysteresis controller

The hysteresis controller is implemented on the grid-side converter, where the algorithm for one PEV charging station can be formulated as follows:

$$\Delta_+ = E(t) + (bandwidth + DSO(t)) \tag{16}$$

$$\Delta_- = E(t) - (bandwidth - DSO(t)) \tag{17}$$

with bandwidth being the allowable dead-band around the mean scheduled energy, DSO(t) is the real-time control signal from distributed system operator, E(t) is the total energy requested by the particular charger.

As a result, instead of intermittent charging and discharging in conventional scheme, the system operates in two conditions: extract energy from the grid and no energy output is supplied from the grid. In condition 1, the grid supplies the power to the PEV and in condition 2 the multi FESS compensates the power to the PEV according to the DBS control law. Meanwhile, the command signal from DSO is also respected to shift the consumed energy band up and down to request regulation service from the CS. Throughout the whole process, the charging pattern of PEV will not be interrupted.

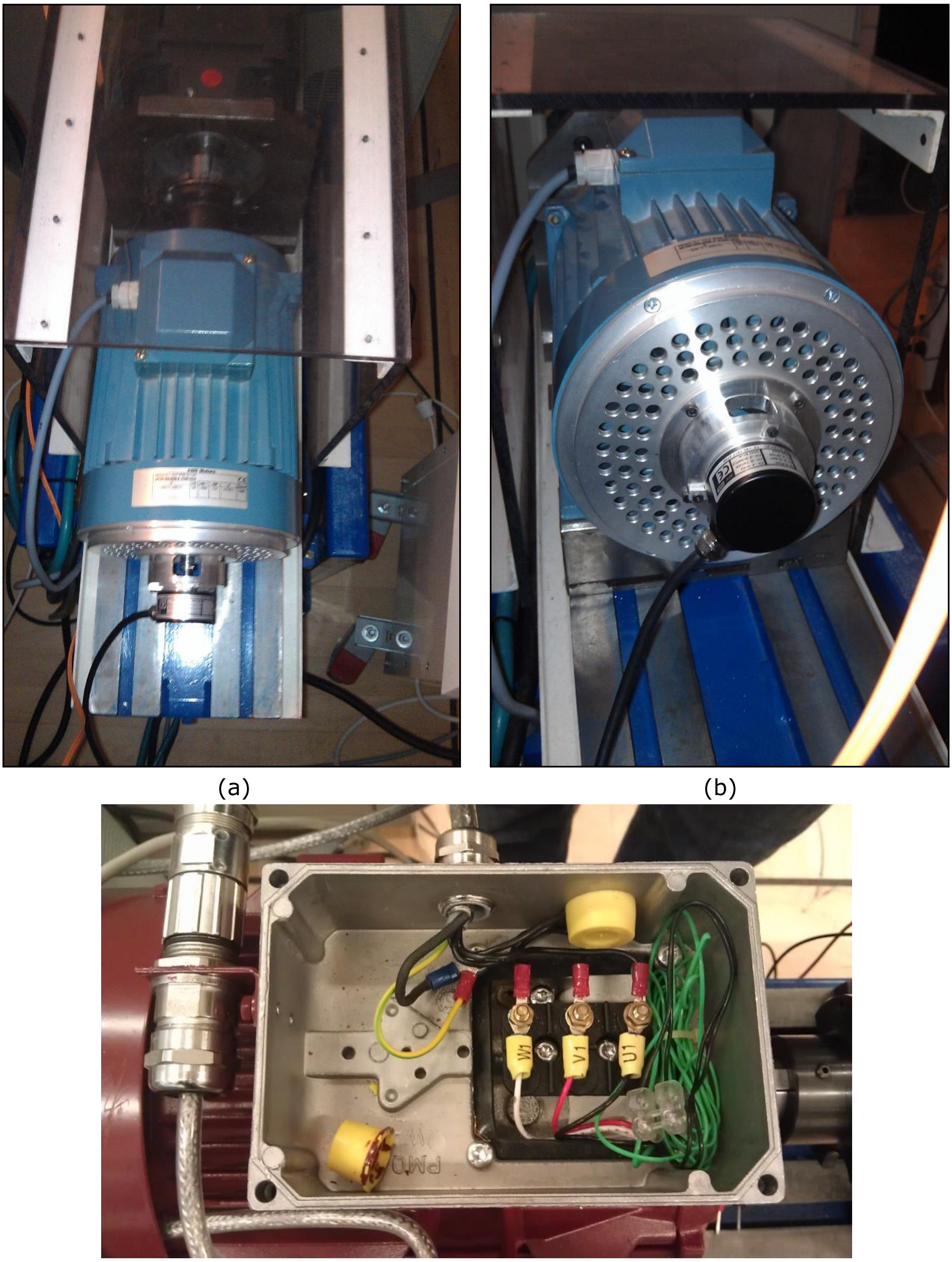
Hysteresis control more gives a higher respect to the user's comfort level willingness. When the charger is turned on, the SoC actually increases at a faster rate than the nominal profile, until it encounters the upper deadband. At that point the charger switches off. When the actual SoC intersects the lower deadband, the charger turns on again. The process is repeated until the PEV is fully charged. In that sense, total charging time remains virtually the same as if there was no intervention. Based on this scheme, the system-level controller can then make adjustments to the charging profile. The adjustment command signals will be typically given by distributed system operator (DSO) which can deploy its decision making strategy based on combination of different strategies, such as predicting variation of renewable source production and load consumption and so on.

C. Implementation

The project results have been implemented in the microgrid research laboratory of Aalborg University (AAU), see Fig. 9. The Microgrid Research Laboratory (MGL) is a powerful platform of research and teaching for microgrid technologies allowing to test and implement control and energy management strategies for Microgrids configurations and technologies. The laboratory is based on dc-ac power electronics converters controlled by dSPACE systems. The flexibility of this platform allows multiple configurations like grid-connected and islanded Microgrids, DC-AC and hybrid Microgrids, or multiple Microgrids clusters.

Fig. 9. Microgrid Research Lab at Aalborg University.

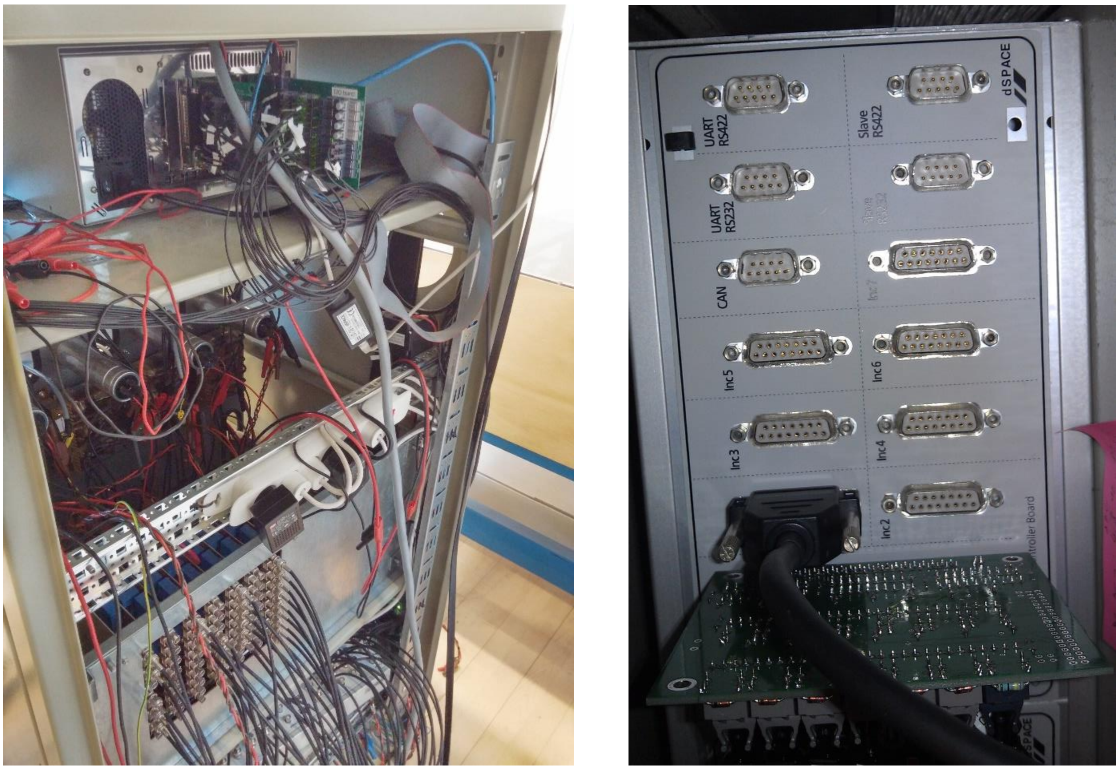
In this project, one setup has been developed in order to perform the experimental results, according to the stablished objectives. As depicted in Fig. 10, a flywheel system has been assembled, including the electrical part connected to a three-phase three-leg inverter commanded by PWM signals sent by means of fiber optics and connected to a DSP board from dSPACE1003 real-time platform.



(a) (b)

(c)

Fig. 10. Flywheel energy storage system.
(a) Flywheel; (b) Encoder; (c) Three phase electrical connection.



(a) (b)

Fig. 11. Cabinet details: (a) Filters and DAQ boards (b) connections of the digital I/O and to the encoder board.

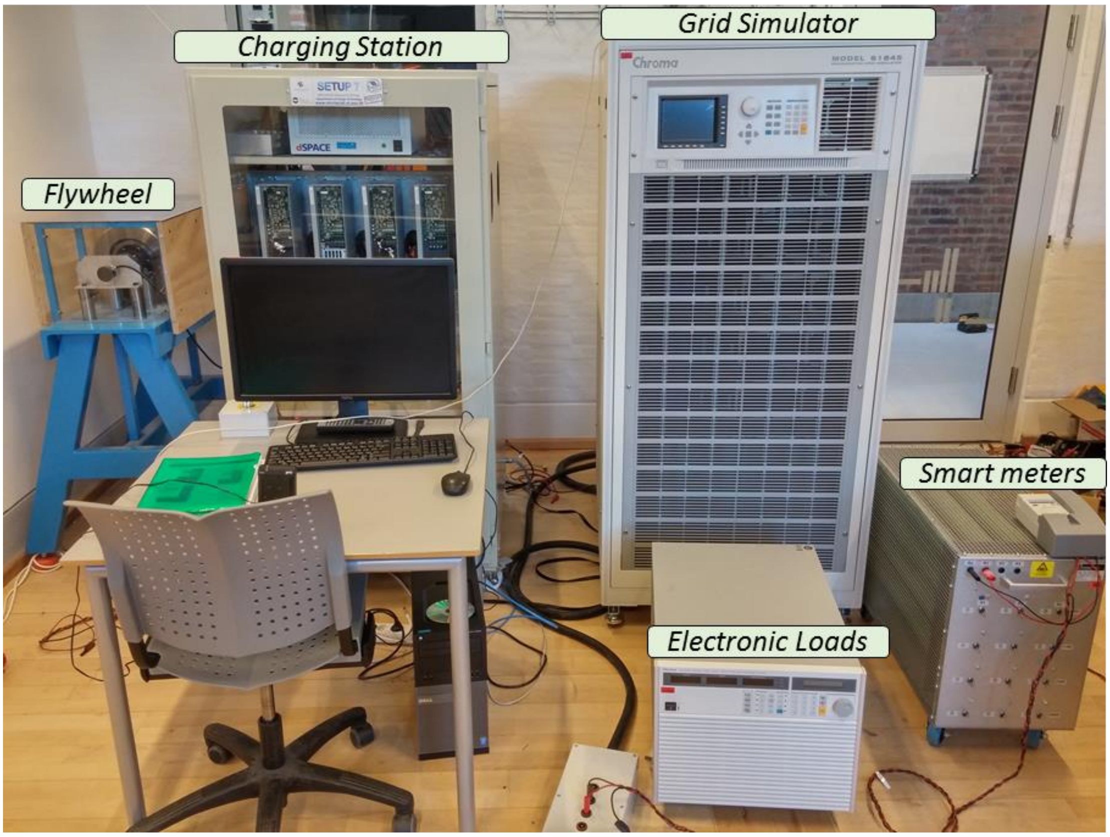


Fig. 12. Electrical vehicle charging station laboratory setup.

It will explore the possibility of using a dedicated energy storage system (ESS) within the charging station to alleviate grid and market conditions but not to compromise the PHEV's battery charging algorithms or place the daily routine of the PHEV owners in jeopardy.

The board DS3001 has been used for incremental encoder interface purposes. The DS3001 is designed for position control applications with sensors providing digital phase information. The board comprises five parallel input channels, each providing everything needed to connect an incremental encoder and process its output signals: a regulated encoder power supply with sense lines, differential or single-ended inputs for the encoder's two phase lines, and an index input.

The experimental setup was built with the parameters described in Table I. Fig. 13 shows the experimental setup consisting of two Danfoss 2.2kW inverters, a FESS driven by a 2.2kW induction machine, voltage and current LEM sensors, input L filter, and dSPACE1006 to implement the proposed control algorithm. The switching frequency of the inverters was set to 10 kHz. The system was connected to the grid through a 10 kVA isolation transformer, and a resistive load was used to emulate PEV loads. In order to demonstrate the performance of the system in reduced time, the experiments were performed in seconds timescale.

TABLE I. REAL-TIME SIMULATION PARAMETERS

Electrical parameters		
DC link capacitance	C_{DC}	2.2mF
Line inductor	L_{line}	3.8mH
Line resistance	R_{line}	0.2Ω
Grid phase voltage	$V_{grid}(p-p)$	325V
Induction machine parameters		
Stator inductance	L_s	12 uH
Rotor inductance	L_r	12 uH
Leakage factor	σ	0.5556
Flywheel inertia	J	0.8 kgm^2
Stator resistance	R_s	1.945 Ω
Rotor resistance	R_r	2.3736 Ω
GC controller		
Proportional gain	K_1	1.25
Time constant of current loop	T_{grid}	1e-4s
FC controller		
Speed reference	ω_{ref}	157 rad/s
Droop gain	K_2	0.1
Outer proportional term	K_{pfly}	0.85
Outer integral term	K_{ifly}	2.8
Time constant of current loop	T_{fly}	1e-4s

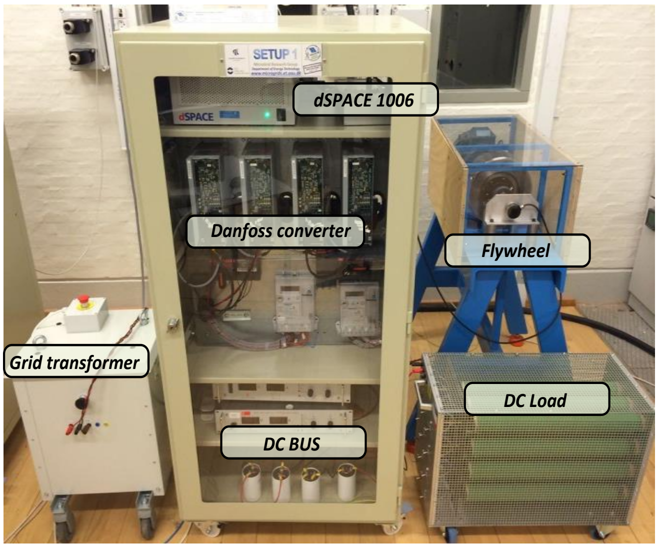
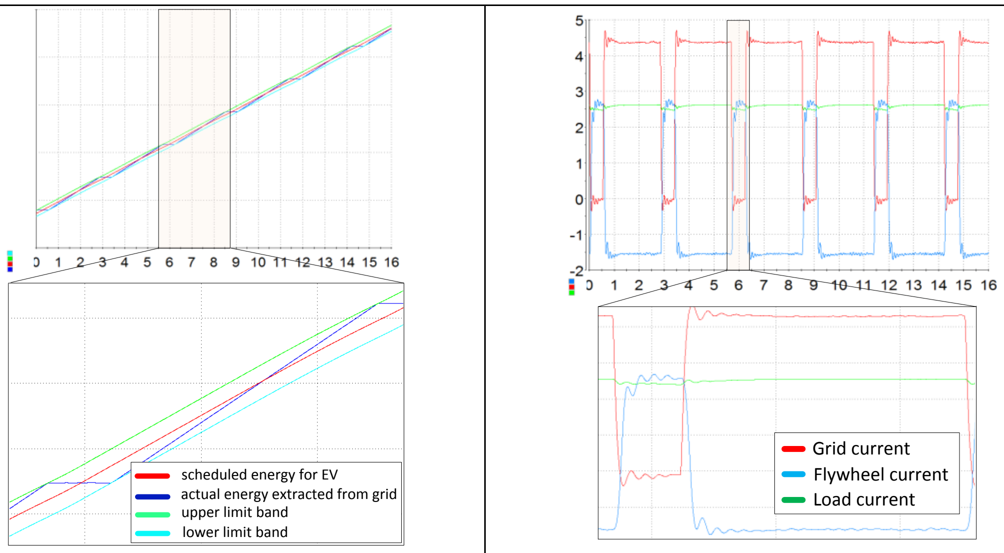


Fig. 13. Photograph of the experimental setup

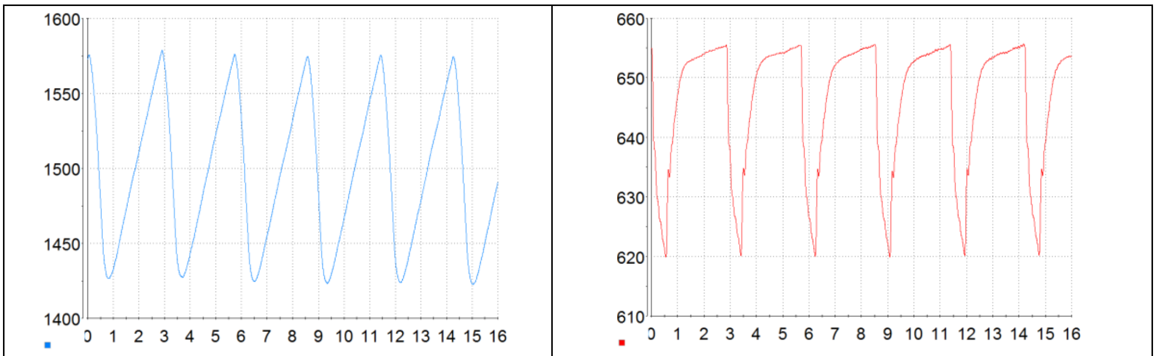
Due to the hysteresis controller signals, the grid converter output power to DC bus alternately, when the actual accumulated energy intersects the upper limit, the GC stops supply the active power to DC bus, and recovers when the lower limit is interested causing deviations of DC bus voltage. Maximum deviations from the common value of around 20V can be observed which is acceptable. According to the DC voltage varies, the flywheel controller adjusts the speed based on the droop law. When the DC voltage is decreasing, the flywheel reduces speed and compensate the active power for the load, accordingly when the DC voltage is recovering, the flywheel recharges it back to nominal speed. The DC voltage and the flywheel speed operate around each nominal value.

Finally, the grid and flywheel alternatively supply the active power to load in order to guarantee the PEV charging not affected.



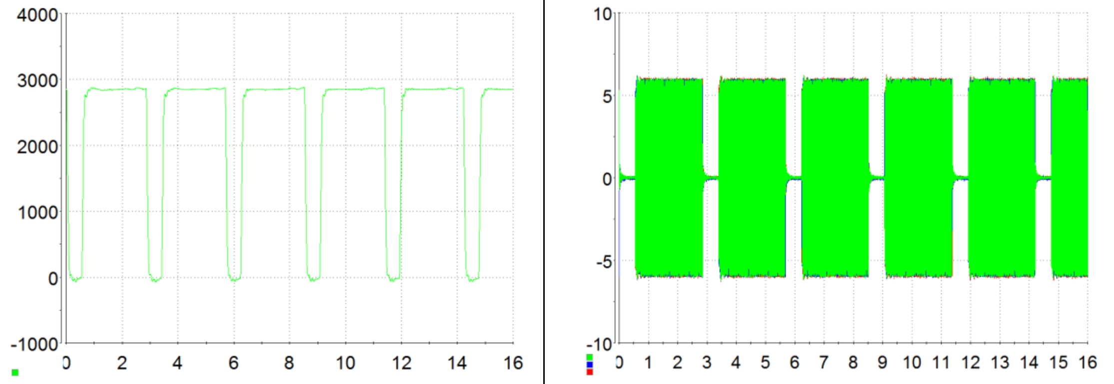
a) Hysteresis control signals

b) DC link current of PEV, GC and FC



c) Speed of flywheels

d) DC link voltage

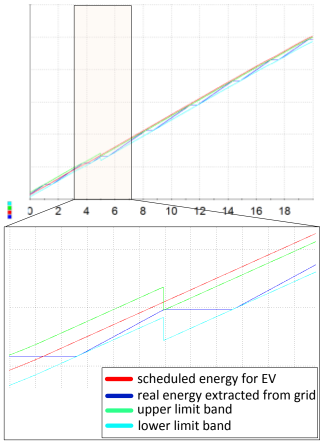


e) GC active power

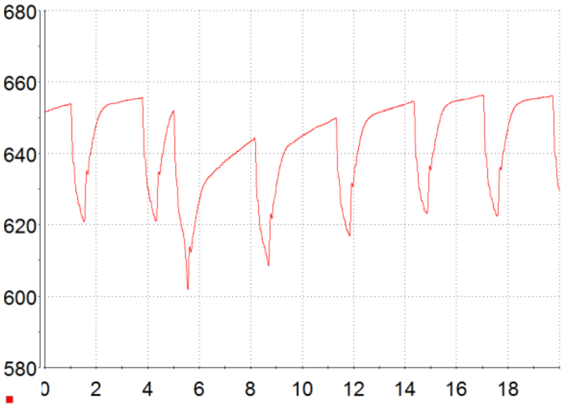
f) Grid ac-side current

Fig. 14. Results derived from the research done

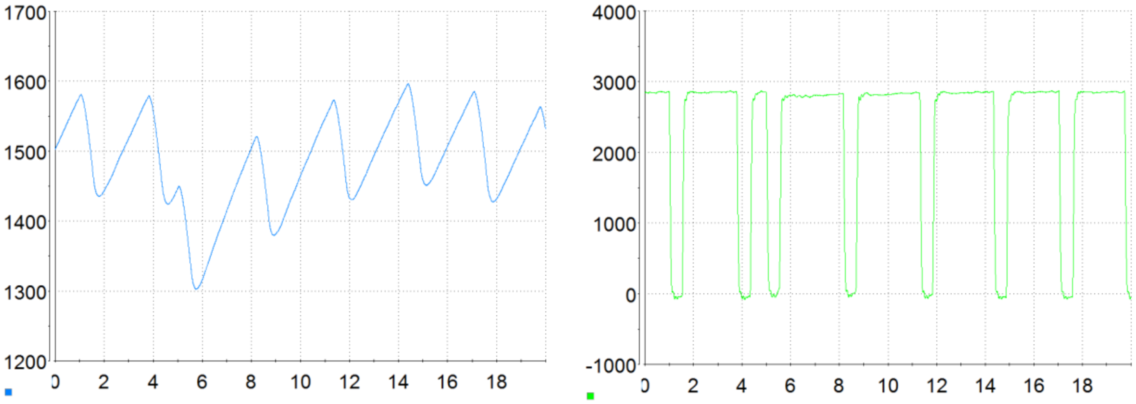
The figures below depict the response when the system receives a regulation signals from the aggregators. At the time of 5 sec, signal from DSO changes from 0 to -1.5 and hence the boundary region is shifted downwards. This causes the intersection point with upper limit comes earlier which lead to the CS stop extracting power from grid. Within the CS, this causes low frequency oscillation of flywheel speed, but due to slow outer PI voltage regulator, it again stabilizes around nominal speed. For utility, it means that the load consumption reduces for some periods. This way, large amount of CS is aggregated and shift their energy consumption up and down to provide the ancillary services eliminating the adverse effects caused by active power fluctuation.



a) Hysteresis Control Signals

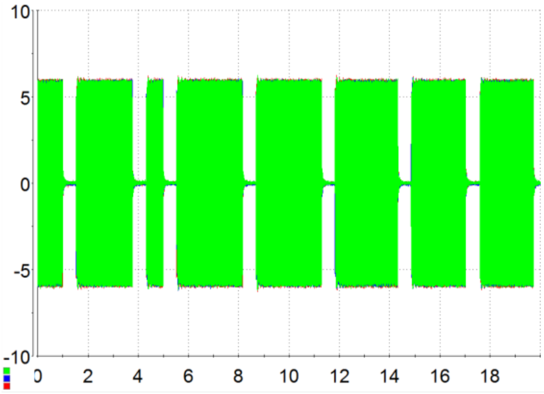


b) DC Link Voltage



c) *Speed of Flywheels*

d) *GC Active Power*



e) *Grid ac-side current and GC active power*

Fig. 15. Ancillary services results provided by the CS

1.4 Utilization of project results

The results of the project reflect that flywheels could be used to reduce the peak of current demanded by the EVCS, giving the possibility of spinning reserve and other ancillary services to the grid, such as voltage support. The company WattsUp Power A/S is interested in the manufacturing of flywheels to be for the ongoing and many future applications, such us maritime microgrids, islanded systems, weak grids, intermittent renewable energies (solar/wind), and so forth. In this sense, a new business plan based on the same technology and control architectures developed is being developed now in a project funded by Innovationsfunden and the Maritime Fund, entitled Efficiensea: see www.efficiensea.et.aau.dk

From Flex-ChEV directly no patent is proposed, but some of the control strategies and IPRs adapted to different flywheel applications will be patent on the second aforementioned project. We expect that this company will be pioneer in Denmark to develop such a promised and competitive technology at both national and international levels.

A Ph.D. student (Mr. Bo Sun) has been co-supervised by the project manager and a post-doc was hired directly by the project. As a result, a number of articles have been published as they can be seen in the end of this section.
PhD abstract: http://www.et.aau.dk/phd/ongoing-phd-projects/control-strategies-for-hybridized-energy-storage-systems-in-microgrid-applications/

Furthermore, the outcomes of this research are presented every year in a PhD course named DC Microgrids at the Department of Energy Technology of Aalborg University. More information can be found in: http://www.et.aau.dk/digitalAssets/216/216563_dcmg-2017.pdf

Publications:

The project has been disseminated in a total of 5 top-tier peer reviewed international journals (ISI indexed) and 8 IEEE conferences. They are organized as follows in yearly basis:

- Year 2014

[C1] Flexible Local Load Controller for Fast Electric Vehicle Charging Station Supplemented with Flywheel Energy Storage System. / Dragicevic, Tomislav; SUN, BO; Schaltz, Erik; Guerrero, Josep M. Proceedings of the IEEE International Electric Vehicle Conference 2014 (IEVC). IEEE Press, 2014. p. 1-6.

[C2] Modeling and control of flexible HEV charging station upgraded with flywheel energy storage. / Dragicevic, T., Shafiee, Q., Wu, D., Meng, L., Vasquez, J. C., & Guerrero, J. M. Multi-Conference on Systems, Signals Devices (SSD), 2014 11th International (pp. 1–7). doi:10.1109/SSD.2014.6808864.

[J1] Flywheel-Based Distributed Bus Signalling Strategy for the Public Fast Charging Station. / Dragicevic, T., Sucic, S., Vasquez, J. C., & Guerrero, J. M. Smart Grid, IEEE Transactions on. doi:10.1109/TSG.2014.2325963

[J2] Modeling and Nonlinear Control of Fuel Cell / Supercapacitor Hybrid Energy Storage System for Electric Vehicles. / El Fadil, Hassan; Giri, Fouad; Guerrero, Josep M.; Tahri , Abdelouahad . In: I E E E Transactions on Vehicular Technology, Vol. 63, No. 7, 09.2014, p. 3011-3018.

- 2015

[C3] Distributed Bus Signaling Control for a DC Charging Station with Multi Paralleled Flywheel Energy Storage System. / Sun, Bo; Dragicevic, Tomislav; Vasquez, Juan Carlos; Guerrero, Josep M.; Savaghebi, Mehdi. Proceedings of the 2015 6th IEEE Power Electronics, Drives Systems & Technologies Conference (PEDSTC). IEEE Press, 2015. p. 65 - 70.

[C4] Distributed Cooperative Control of Multi Flywheel Energy Storage System for Electrical Vehicle Fast Charging Stations. / Sun, Bo; Dragicevic, Tomislav; Quintero, Juan Carlos Vasquez; Guerrero, Josep M. Proceedings of the 2015 17th European Conference on Power Electronics and Applications (EPE'15 ECCE-Europe). IEEE Press, 2015. p. 1-8

[C5] Provision of Flexible Load Control by Multi-Flywheel-Energy-Storage System in Electrical Vehicle Charging Stations. / Sun, Bo; Dragicevic, Tomislav; Andrade, Fabio ; Vasquez, Juan Carlos; Guerrero, Josep M. Proceedings of the 2015 IEEE Power & Energy Society General Meeting. IEEE Press, 2015. p. 1-5.

[C6] Reactive Power Support of Electrical Vehicle Charging Station Upgraded with Fly-wheel Energy Storage System. / SUN, BO; Dragicevic, Tomislav; Savaghebi, Mehdi; Vasquez, Juan Carlos; Guerrero, Josep M. PowerTech, 2015 IEEE Eindhoven. IEEE Press, 2015. p. 1-6.

[C7] 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. Proceedings of the 2015 IEEE First International Conference on DC Microgrids (ICDCM). IEEE Press, 2015. p. 305 - 310 .

[C8] Managing high penetration of renewable energy in MV grid by electric vehicle storage. / Kordheili, Reza Ahmadi; Bak-Jensen, Birgitte; Pillai, Jayakrishnan Radhakrishna; Savaghebi, Mehdi; Guerrero, Josep M. Proceedings of the 2015 International Symposium on Smart Electric Distribution Systems and Technologies (EDST). IEEE Press, 2015. p. 127 - 132.

- 2016

[J3] Sun, Bo; Dragicevic, Tomislav; Freijedo Fernandez, Francisco Daniel; Quintero, Juan Carlos Vasquez; Guerrero, Josep M. A Control Algorithm for Electric Vehicle Fast Charging Stations Equipped with Flywheel Energy Storage Systems. In: I E E E Transactions on Power Electronics, Vol. PP, No. 99, 2016.

[J4] Coordinated Control for Flywheel Energy Storage Matrix Systems for Wind Farm Based on Charging/Discharging Ratio Consensus Algorithms. / Cao, Qian; Song, Y. D.; Guerrero, Josep M.; Tian, Shulin., In: IEEE Transactions on Smart Grid, Vol. PP, No. 99, 2016.

[J5] Assessing the Potential of Plug-in Electric Vehicles in Active Distribution Networks. / Kordheili, Reza Ahmadi; Pourmousavi, Seyyed Ali; Savaghebi, Mehdi; Guerrero, Josep M.; Hashem Nehrir, Mohammad. In: Energies, Vol. 9, No. 1, 34, 01.2016.

Communication and dissemination activities:

The project has been continuously updated in the following two websites:

General project website: http://flexchev.com/

Danish part project website (Aalborg University): http://flexchev.et.aau.dk/

Keynote speech: Prof. Josep Guerrero gave a keynote speech IEEE ENERGYCON 2014 (Dubrovnik, Croatia), under the title: "*Microgrid Technologies for Future Electric Vehicle Charging Stations*"

The content of the keynote speech can be found in this link: http://www.slideshare.net/jucovas/josep-guerrero-as-keynote-speaker-at-energycon2014?ref=http://www.et.aau.dk/research-programmes/microgrids/activities/flexible-electric-vehicle-charging-infrastructure-flex-chev/

Workshops and project events:

17/06/2014	Kick-off meeting
14/09/2014	Web page launch
06/11/2014	Aalborg workshop
18/06/2015	Dubrovnik workshop invitation
23/02/2015	Zagreb coordination meeting
24/02/2015	ERA-net day presentation
18/06/2015	Zagreb partners meeting
02/10/2015	Dubrovnik workshop (Croatia)
06/11/2015	Aalborg 2nd worshop (Denmark)
21/01/2016	Narvik workshop (Norway)

1.5 Project conclusion and perspective

A. Main conclusions of the project

The results of the project are pointed out as follows:

- Flywheels are a clean technology very promising for applications to store huge amount of power to be delivered in few time. As a clear contrast advantage is that they do not generate chemical residual components, can be for some time overloaded, and have a huge range operation of voltages and currents.
- Flywheels can be connected in a DC microgrid, such as an EVCS, in order to reduce the PCC short-circuit current, e.g. the nominal installed electrical power.
- Flywheels also can provide primary regulation and ancillary services, not only solving the EVCS main problems, but also helping and supporting the grid. This technology can help to cope with the 2020 energy objectives in Europe and in Denmark to achieve 100% of renewables in the near future.

B. Future perspectives

Connected with another project now starting in the H2020 (Vicinity), according to the E-mobility Business cluster there is a high focus on the industry growth and a business/market potential disciplines in Denmark which include V2G technology, new charging infrastructure, Information and Communication Technology (ICT), etc. Research and innovation on equipment and IoT solutions for EVs will make them smarter, more automated and efficient. In fact, there will be a future project *Virtual Neighbourhood of Intelligent (Transport) Parking Space* which will be deployed and demonstrated in Tyske, Halden in Norway. Towards this direction, the required infrastructure will be discussed in collaboration with other partners (i.e., TINYM and HAFENSTROM A/S), for the use case demonstration (see Fig 16 -18).

Fig. 16: "Teaterkvarteret, Tromsø, Norway" – future smart parking test pilot site

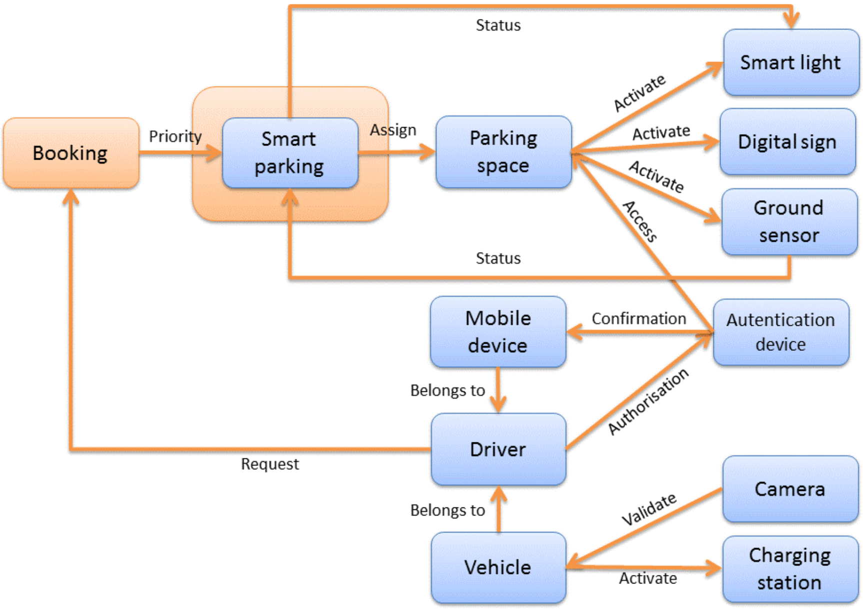


Fig. 17: Overall smart parking process flow diagram from the drivers perspective

Fig 18. Garage Parking Site "Teaterkvarteret, Tromsø, Norway"

Cooperative Vehicle-Infrastructure Systems: designed and developed innovative technologies that allow cars to communicate and network directly with the roadside infrastructure. The aim of this perspective is to bring major benefits for drivers as well as road authorities and managers, by allowing vehicles to communicate – and cooperate – directly with each other and with roadside infrastructure. The achievements derived from this future project will be applied in test sites in several countries across Europe, to increase road safety and efficiency and reduce the environmental impact of road transport.

1.6 Annual export of electricity (only ForskVE)

1.7 Updating Financial Appendix and submitting the final report

The Financial Appendix is updated and submitted with the financial numbers for the entire project.