Upgrade of a grid-connected storage solution with grid-forming function

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***Abstract*—In the EU-founded project OSMOSE, RTE and Ingeteam will install a demonstrator (Ringolab) to show the technical and economical viability of building a grid-forming function upon a traditional energy storage system. Although main theoretical results have already been validated on real hardware in a laboratory environment within the framework of the MIGRATE project, a grid-connected demonstrator represents a step further toward the standardization of grid-forming converters. In this paper we present its technical description and we show stable association of the grid-forming control with different DC side power sharing and energy management strategies while considering a hybrid energy storage system.**

I. INTRODUCTION

The 4 year EU-founded project OSMOSE started in 2018 and proposes an integrated approach to foster the affordable deployment of an optimal mix of flexibilities allowing network operators to ensure reliability under very high shares of renewable energy sources (RES). Within the framework of the work package 3 (WP3) different demonstrators will be deployed in order to investigate on the provision of different grid services using energy storage systems (ESS).

Nowadays batteries have found some room in specific markets to provide fast or enhanced frequency response to transmission system operators (TSO) [1], [2], [3]. Other projects exploit their potential for congestion management [4] and peak shaving [5]. Distribution system operators (DSO) have also used them to tackle different challenges associated to the massive integration of RES in a multi-services approach that includes voltage regulation [6], [7].

However, recent works on the MIGRATE project have proven that the type of control considered in those projects will encounter some limitations as the share of power electronic interfaced sources increases up to 100%. In this case, grid forming controls in some converters become a necessary condition to operate a system [8]. Despite their limited overcurrent capability, stable voltage source behaviour of parallel converters has been achieved with several control concepts, even during transients on the grid, such as phase-jump or three-phase fault.

Those results are today restricted to certain assumptions that we aim to raise in this project, such as the consideration of an ideal DC source and AC environment. The optimal sizing of a ESS that provides traditional grid services, such as frequency regulation, might change when considering grid forming related services, as coping with fast transients may constraint the power rather than the energy requirements.

Therefore, Ringolab demonstrator consists in a hybrid energy storage system (HESS) based on a mix of batteries and ultracapacitors. In this context, the grid-forming upgrade cost will be optimized by mutualizing the inverter rating between multi-services and/or potential multi-players that could provide specific services with dedicated devices.

This kind of HESS has been proposed in the literature for electric vehicles applications as they require both high power (acceleration and deceleration/regenerative braking phase) and high energy (range) [9]. In this paper, we consider the grid forming control published in [10] including the current limitation strategy based on a threshold virtual impedance (TVI), and we focus on suitable DC side control strategies.

The main original achievements of this work are then the stable association of AC grid-forming control with a couple of DC power and energy management strategies and the tunable share of energy reserve depending on required HESS grid-services. Full electromagnetic (EMT) studies and Control updates related to AC side harmonics and unbalances will be the object of a future work.

Section II describes the demonstrator final design and Section III discusses the DC side control strategies considered for the DC/DC converters to share power and energy among the HESS. Section IV presents simulation results based on RMS models. Conclusions are drawn in Section V.

II. DEMONSTRATOR DESCRIPTION AND MODELLING

Ingeteam will provide a 1 MVA rated power fully containerized solution based on a HESS consisting of:

- six lithium-ion battery racks (0.5 MVA 60 min),
- six ultracapacitor racks (1MW-10s),
- a 1 MVA Low Voltage (600V) inverter, and
- a 1 MVA 0.6/20 kV transformer.

A. Connection Grid

The HESS will be installed at Castelet substation in the south of France, which includes a 63 kV busbar with:

- a 63 kV line to Ax Les Thermes substation,
- a 63 kV line to Tarascon-Ussat substation,
- a 10 MVA 63/20 kV transformer dedicated to a power hydro generation unit,
- a 20 MVA 63/20 kV transformer dedicated to the power supply of an industrial consumer with underground cable. The 1 MVA demonstrator will be connected to the secondary side of this transformer by mid-2020.

As shown in Fig. 1, the industrial customer has high load variation and is expected to produce fast voltage angle and amplitude changes during the testing period.

Fig. 1. Load variation at the PCC

B. Technical specifications

The demonstrator will be based on off-the-shelf equipment, which complies with main international standards and grid codes, when applicable. Special attention will be payed to the following requirements that might apply to possible candidates for grid forming inverters, such as distributed generation, depending on the country and power level.

- Fault-ride through (FRT) capability for balance and unbalanced disturbances.
- Reactive current injection during faults.
- Anti-islanding.
- Energy neutrality.

The capability of the tested upgraded solution to fulfill these requirements, while functioning in grid forming mode, will be assessed during the demonstrator operation period. Indeed, Ingeteam industrial solution for low-level control and protection system seems compatible, at least, with one of the grid forming concepts proposed in MIGRATE and selected for this project. However, if the limitation strategy fails to keep the current/voltage within admissible ranges, during the very fast first uncontrolled transients for instance, semi-conductor blocking may be activated to prevent equipment damage, which might lead to untimely system disconnection.

In addition, requirements for fault current injection have been often specified through positive and negative sequence current/voltage characteristics and according to a given dynamics [11]. Although a grid forming control naturally injects high current while trying to keep the voltage during a fault, its contribution might not be tunable as a function of conventional droop curve parameters.

Moreover, the system might be required to disconnect under given criteria. For instance, in this project we will follow the H4 norm [12] of french grid code. However, ensuring that any islanding condition will induce electrical quantities to fall beyond the thresholds may be challenging.

Finally, the active power exchange between the network and a grid forming inverter depends on its set point and the mismatch between the frequency and its reference. This value is usually set to the nominal frequency, coupling grid-forming services and primary frequency control. Here, we aim to decouple these services with a *transient grid forming control mode* that uses the filtered measure of the system frequency as reference, making the inverter behave as a grid forming during transients but setting back the power to its set point even in case of frequency deviation.

The dynamics of this strategy will depend on the time constant of the first order low pass filter, which will be studied in subsequent stages of the project. Energy neutrality can then be achieved by acting on the active power set point as traditionally done for frequency services. In this project we will regulate the state of charge (SoC) of the battery to half of its capacity with a low time constant (30 min) in order to avoid negative effects on the overall frequency regulation and ensure that no energy (other than losses) is exchanged with the network in the observation window.

C. Grid forming services, KPI and expected performances

Main services associated to the grid-forming function include frequency and voltage smoothing [13]. In our HESS setting we can add battery output smoothing. The former will be evaluated in the real system by correlating the frequency and voltage amplitude variations to the costumer power change events and comparing their statistical behaviour before and after the connection of the HESS.

As an example: $metric_{2a} = \frac{RoCoF}{\Delta P}$ and $metric_{4a} = \frac{\Delta V}{\Delta P}$ will be calculated in the current situation so they can be compared to equivalent calculations following the commissioning of the demonstrator. For this purpose, a transient fault recorder (TFR) was installed at the point of common coupling (PCC) in February 2019. During a first measurement campaign, it has revealed several single-phase faults and certain level of harmonic distortion, in addition to significant load changes (see Fig.1).

During the project, together with the 4 points indicated in Section II-B, we will also assess the effectiveness of the DC side energy management and the converter current limitation strategies (even when the system survive the fault), as well as the energy not supplied due to converter capacity limits.

D. HESS models

Ingeteam first developed in Matlab a full EMT model of their converter including the grid-forming control proposed in MIGRATE [10]. Satisfying performances during three-phase faults and phase jumps were obtained [14]. However, root mean square (RMS) models offer a better trade of between accuracy and computation time when dealing with DC power and energy management strategies. In particular, as we have chosen to implement an active hybridization using DC/DC converters, the internal impedance of the battery and the ultracaps does not have any significant impact.

Hence, we have chosen an electrical-circuit model for the batteries which entails standard assumptions within the scope of the study, such as neglecting aging or temperature dependency. Indeed, this type of model is much simpler than electrochemical ones and therefore less computationally expensive, but they may be challenging to tune, especially with regard to the relation between the DC voltage and the battery SoC. In our case, as we consider commercial batteries, this data will be provided by the manufacturer. The electrical-circuit model is then composed of:

- a controlled voltage source,
- a charge/discharge-rate limiter,
- a voltage vs SoC lookup table, and
- a resistor representing the battery's resistance.

The battery SoC is one of the most important variables of the model. In general, it is defined as the ratio between its current capacity and the nominal one. The latter is given by the manufacturer and represents the maximum amount of energy that the battery can store. Although, there are many ways to estimate the SoC of a battery [15], a comprehensive discussion on this topic is beyond the scope of this work as for the demonstrator we will use the commercial SoC estimator implemented in the battery management system (BMS) and provided by the manufacture.

In this study, we consider the Ampere Hour (Ah) counting method, which is widely used in literature due to is its low computation burden. It integrates the battery charging/discharging current over time, i.e. the SoC is estimated based on the battery output current and the previously estimated SoC value ($SoC(t) = SoC(t-1) + \frac{I(t)}{Q_n}\Delta t$).

It is well known that the Ah counting method suffers from loss of accuracy as the time passes, due to: the unknown initial SoC, capacity fading, self-discharge rate, current sensor errors, etc. However, we can neglect those phenomena in the development of the DC/DC control strategy as we will rely on short-term simulations.

For ultracaps we consider that the voltage and SoC profile are almost the same and we limit the maximum current.

III. DC SIDE CONTROL STRATEGIES

The philosophy of the HESS control consists in delivering all fast acting services with the ultracapacitor, while the battery will progressively replace it and ensure the long-term services. For this purpose, the ultracap steady state output must be brought to zero at some point, and it SoC must be maintained close to half of its full charge.

A. Power sharing

Although more sophisticated strategies have been proposed in the literature [16], [17], here we consider two different control laws based on proportional-integral (PI) controllers as we focus on the stable operation of the grid forming function with finite available energy. The objective is to enable the parallel operation of both DC/DC converters and independently set the dynamic of each storage device.

a) PI-P controller: It consists in having a pure proportional controller on the ultracapacitor, and a PI controller on the battery brings the DC voltage to its setpoint ensuring that the contribution of the ultracap goes to zero in steady state (see Fig. 2).

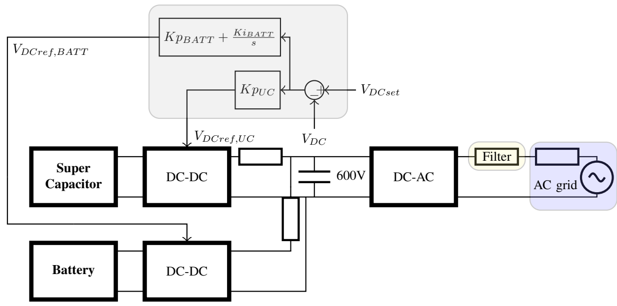

Fig. 2. PIP controller for DC side power sharing

The ratio between the proportional gain of the battery and the ultracapacitor regulates their relative dynamics following a change in the DC voltage.

b) Virtual RC circuit: The dynamic of each DC/DC converter is also set through 2 independent control loops, or VRC circuits [18], as shown in Fig. 3. The one related to the ultracapacitor must have a fast transient current response and a low stationary gain, while the battery system should react slowly to transients but exhibit a high stationary gain.

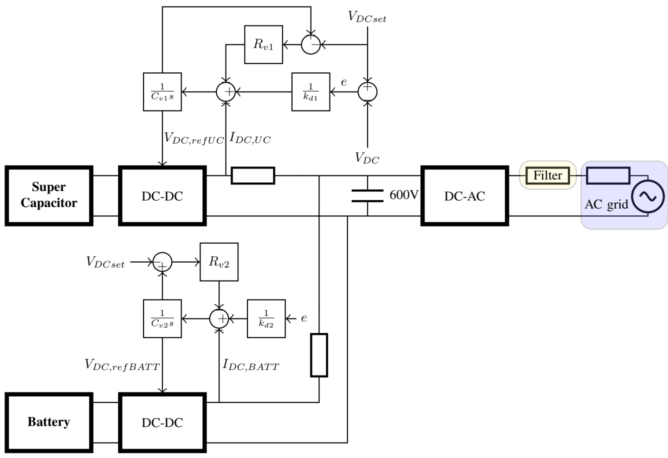

Fig. 3. Virtual RC circuit for DC side power sharing

The relation between the control parameters and DC side performances can be summarized as follows:

- In steady state: depending on the voltage difference ($V_{DCset} - V_{DC}$), a droop control is established. Droop curve parameters are ($\frac{K_{d1}}{K_{d2}}$).
- Transient current depends on the time constant of the equivalent virtual RC (VRC) circuit given by $\frac{C_{v1}K_{d1}}{C_{v2}K_{d2}}$

B. Energy management

a) Energy control in the UC: On the PIP control, an additional PI controller is used to regulate the ultracap SoC to 50 % of its maximal capacity by adapting its DC voltage reference as shown in Fig. 4. This allows the ultracap to act as a buffer to power variations. The gains of this PI are tuned to have a time response around 30 sec, ensuring that the ultracap will not be empty or full following a step event.

For safety reason, additional loops will be added to prevent both battery and ultracap from being empty or full. These loops will only become active when the SoCs are above 90% or below 10%. The controls will be tuned in such a way that these emergency actions are never activated.

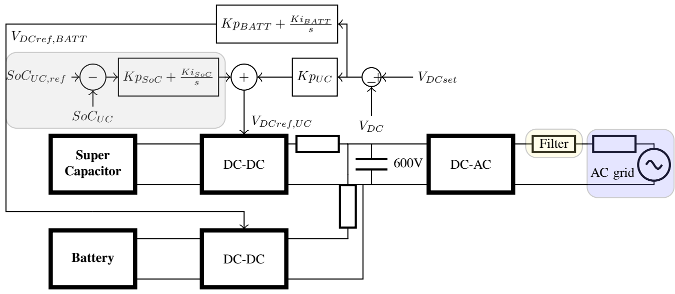

Fig. 4. PI controller for ultracap SoC regulation

b) Energy control in the battery: As aforementioned, a slow control regulates the energy in the battery. It is not represented here in the simulation as the time scale is a few order of magnitude slower than the controls of the ultracap.

IV. Simulation results on RMS model

To assess the control performance in this section we simulated two different events. A resistive and sudden load disconnection at the converter point of coupling represents a random fast transient daily occurring in the grid. Next, an active power reference step represents any long term service request (load shaving, secondary frequency, etc).

The test system consists in the HESS connected to an infinite bus (see Fig. 2), therefore the frequency will always go back to its nominal value after transients. Then, the load variation will be rejected by the inverter due to the grid forming frequency droop control. The interest is placed in how the grid-forming behavior is reported on the DC side, according to the chosen DC control strategy.

A. Power sharing during load variation

In case of a grid load variation, the grid forming inverter will absorb all the current variation to maintain the AC voltage. As a consequence, the DC current that feeds the DC bus must also be adapted and supplied either by the battery or the ultracap. Figure 5, shows the behaviour of the the VRC control following such an event. The DC current is shared almost equally between the storage devices, even though their dynamic differ. Then, both sources will react in a similar way at the very first instant after the load change, i.e. the grid forming function is evenly split.

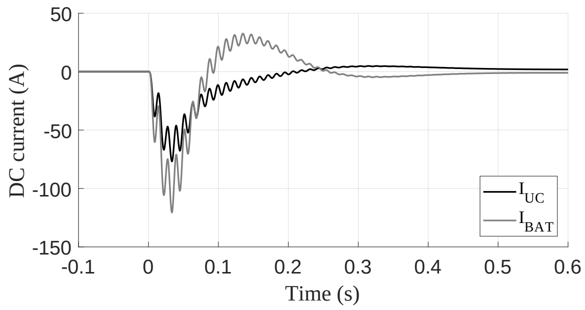

Fig. 5. DC current following load disconnection with VRC

The PIP control, on the other hand, ensures that the ultracap (black line in Fig. 6) takes the major part of the transient power limiting the battery output variation and ageing.

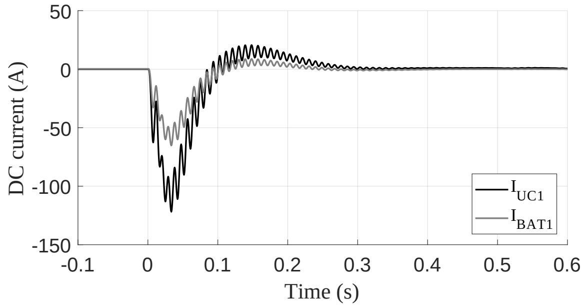

Fig. 6. DC current following load disconnection with PIP

This feature is highly desirable as one might consider that, with an appropriate control design, the fast response required by the grid-forming control can be provided by solely the ultracap of the DC bus. Hence, although the VRC control has interesting stability properties, because of its time scale decoupling and RC circuit analogy, it failed to fulfill the system requirements.

B. Energy sharing during power step

Following an active power reference step, as shown in Fig. 7, the ultracap injects high current during the first instant until it is replaced by the battery, independently of the control. Only the PIP control drives the ultracap current to zero in some seconds (PIP0 and PIP1, see Tab. I). The ultracap SoC control brings the current above zero once the battery has taken over the power step to restore the untracap charge level (PIP1). This energy is extracted from the battery.

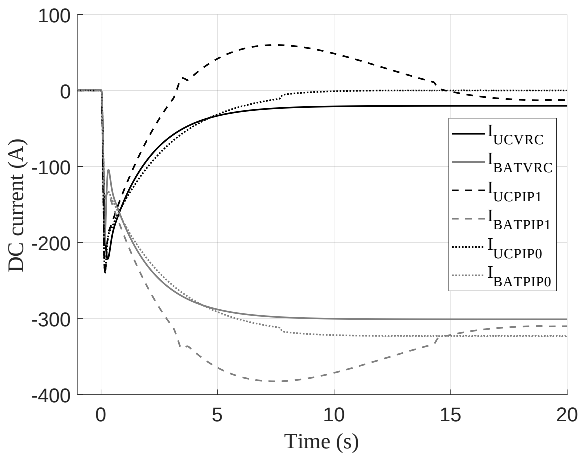

Fig. 7. DC current following power step

TABLE I
PIP CONTROL SETTINGS IN PU

Name	Kp_{BATT}	Ki_{BAT}	Kp_{UC}	Kp_{SoC}	Ki_{SoC}
PIP0	0.02	1	2	0	0
PIP1	0.02	1	2	0.02	0.002
PIP2	0.02	1	4	0.02	0.002

Figure 8 offers a closer look to the transient response considering a different tuning of the PIP control (PIP2 in Tab I) that highlights the impact of Kp_{UC} in the ultracap current injection.

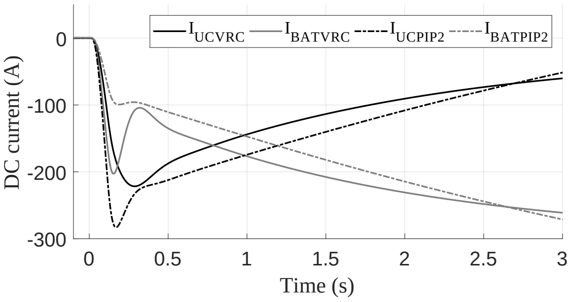

Fig. 8. DC current following power step

We observe that, compared to the VRC strategy, the PIP control ensures a higher participation of the ultracap during the first miliseconds (here almost three times the battery contribution), which harvests the battery output smoothing potential of the HESS behind a grid forming inverter.

Finally, Fig. 9 compares the SoC trajectories of both storage devices considering the three aforementioned control settings. A PI control on the ultracap SoC brings back its charge level to the desired value, here to half-loaded condition, ensuring that enough energy will always be available in the event of a future disturbance or setpoint change.

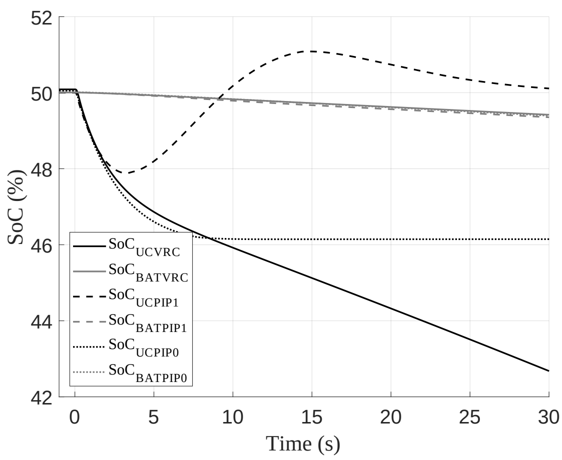

Fig. 9. SoC variation following power step

V. Conclusion

This paper presented the Ringolab demonstrator where off the shelf battery storage will be upgraded with DC/DC converter and ultracap to provide grid forming related services to the grid. Technical specifications were detailed. One of the objectives is to use the ultracap and the DC/DC converters to prevent the battery from dealing with fast transients brought by the grid forming operation of the inverter.

Controls for both power sharing between DC sources and energy management in the ultracap are illustrated with parameter sensitivity. Time domaine simulations were performed for load disconnection as well as power reference step to show the effectiveness of both controls with the selected parameters. The ultracap smooths the output power of the battery even during fast transient, which allows to use a BESS in grid forming mode with limited impact on the battery power output and therefore on its life expectancy.

As future steps, we expect to explore the stability limits of both strategies and assess their impact on the hardware design. We will also validate the results with EMT simulations with the real grid model, hardware-in-the-loop experience at the factory, and finally on-site testing.

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