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OSMOSE: Grid-Forming performance assessment within multiservice storage system connected to the transmission grid

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SUMMARY

The European research project MIGRATE, and especially its Work Package 3 (WP3) demonstrated that grid-forming controls for some converters is a necessary condition to operate a system without synchronous machines with a sufficient level of reliability [1]. Despite the limited overcurrent capability of the converters, several control concepts showed their effectiveness to ensure the stable voltage source behaviour of parallel converters, even during transients on the grid, such as phase-jumps or three-phase faults. The main theoretical results have already been validated on real hardware in lab environment. However, until now, DC side dynamics, as well as unbalanced and disturbed AC grid conditions have often been overlooked. A step further toward standardisation of grid-forming converter should prove its technical feasibility taking into account those aspects. In the WP3 of the European research project OSMOSE, RTE builds upon the MIGRATE results to increase the maturity level of grid-forming converters. In concrete terms, RTE will install a demonstrator on its own network in August 2020: a one-Megawatt grid-forming inverter backed up with batteries (500kW for one hour) and ultra-capacitances (1MW for 10 seconds). Our previous work focused on the development of suitable DC side power sharing and energy management strategies and a negative sequence control using Matlab while considering an ideal network. In this work, we validate the latest version of the demonstrator control as will be implemented onsite with a more realistic grid model available in EMTP. Expected performance are observed: the ultra-capacitances smooth the battery power output and the overcurrent is limited. However, as the fault behaviour in grid codes was specified for grid following converter, additional work is required to make regulation and grid forming controls response compatible.

KEYWORDS

Grid-forming, hybrid energy storage, demonstrator.

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1. INTRODUCTION

Within the framework of the WP 3 of the EU-founded project OSMOSE, RTE and Ingeteam will install an industrial size demonstrator to show the technical feasibility and economic viability of providing grid-forming capabilities with a commercial hybrid energy storage solution. For this purpose, we aim to:

- Validate one possible implementation of a grid-forming control and a current limitation strategies in off-the-shelf converters. In this project we chose the filtered droop approach with Threshold Virtual Impedance (TVI) as they have been already tested in laboratory [2-3].
- Test the robustness of the developed controls, in a real environment, with constantly varying load, harmonics, unbalanced fault…
- Quantify the effectiveness of the grid-forming control regarding its impact on the local voltage wave form (amplitude, phase and frequency). For this purpose we have defined key performance indicator (KPI) and installed a transient fault recorder (TFR) on site.
- Assess the capability of the inverter to do multiservice such as primary frequency control or peak shaving while providing grid-forming associated ones [4].
- Ensure stable association of the grid-forming function with different strategies for energy management on the DC side between the ultra-capacitances (UltraCaps) and the battery, as well as the possibility to affect one specific AC service to a specific DC storage device [5]. The idea is to allocate grid-forming services, which are power intensive to the UltraCaps while the battery will provide the long term ones. We choose an active parallel hybrid connection as illustrated in Figure 1-left.

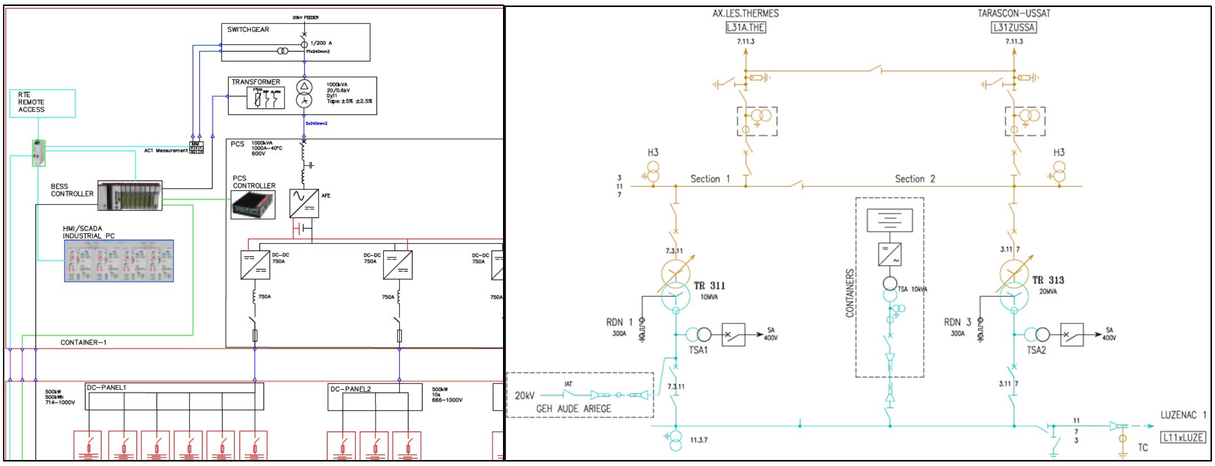

Figure 1. Left: Demonstrator configuration. Right: Single Line Diagram of substation (Castelet)

As the demonstrator exits the design stage, the paper will summarize the innovative solutions proposed to answer above mentioned objectives, especially regarding the following two main technical challenges:

- Manage the energy on the DC side, by advanced control of each DC/DC interfaces associated to the selected storage technologies (UltraCaps and Batteries).
- Adapt the grid-forming requirements of the AC/DC converter control with additional constraints from the hardware limitation of actual VSC and from unbalance and harmonics conditions of the targeted grid.

For this purpose, Section 2 describes the system, its model and the implemented control while its performance is assessed in Section 3 through time domain simulations on EMTP. Four scenarios are considered: load variations as well as a balanced and an unbalanced fault, based on on-site measurements when possible. Main contributions and future work are summarized in Section 4.

2. SYSTEM AND CONTROL DESCRIPTION AND MODELLING

The demonstrator (identified as "containers" in Figure 1-right) will be connected to the 20 kV bus bar of the Castelet substation located in the south of France, which corresponds to the secondary of a 20 MVA transformer dedicated to the power supply of an industrial consumer with underground cable. Section 2.1 describes the network modelling in EMTP, while section 2.2 and 2.3 details the controls developed in Matlab Simulink, which are used in EMTP as compiled files.

2.1. AC System and converter model in EMTP

The EMTP model represents the point of connection of the Osmose demonstrator at Castelet substation from 20kV load of RTE's client and up to 63kV lines connected to Castelet substation. The rest of RTE's network is represented by means of a Frequency Network Dependant Equivalent [7] giving a good representation of the short circuit level and of the frequency response of the network at Castelet substation.

2.2. Filtered-droop grid forming control

In our previous work we focused on the behaviour of the system under unbalanced conditions [4]. A sequence separation was added, and only the positive sequence (PS) component of the signals is fed into the grid-forming control selected from the literature [2]. As shown in Figure 2, the filtered-droop grid forming control is based on classical cascaded loops with a current control loop, a voltage control loop and an outer droop control for the active power and reactive power.

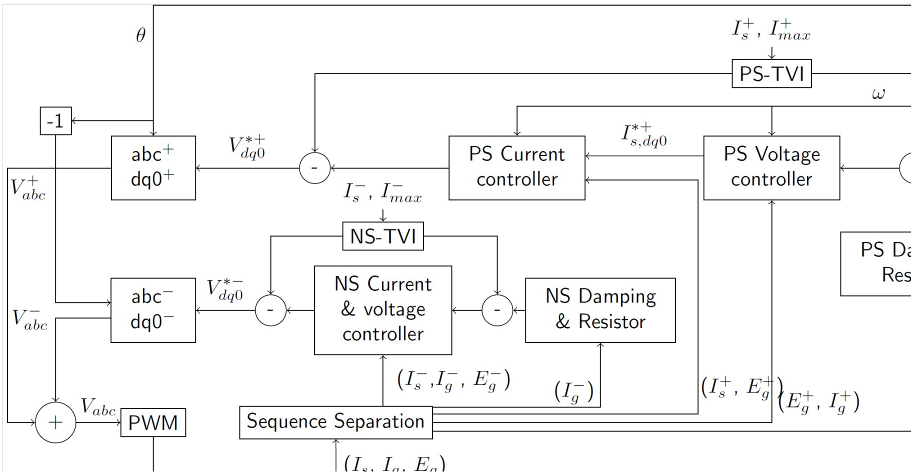

Figure 2. Implemented Grid Forming Control scheme

The main difference with respect to grid-following controls is that here the converter frequency is built from the error between the reference and measured active power and does not rely on the measurement of the grid frequency, i.e., there is no PLL in the implemented control but the controlled inverter can still be operated within a strong grid. Having such controls lead the inverter to behave as a voltage source during first instants after a transient, and therefore stabilizing the grid. In addition, current limitation is mainly based on a TVI rather than on a direct saturation to avoid control switch and reset, and to keep a voltage source behaviour during transients while protecting the converter against overcurrent. At the same time, a grid forming inverter naturally allows the islanded operation of a subsystem, and could also be considered as a potential black start source for future system. As for the present situation, black start is kept out of scope of the OSMOSE due to its limited size and the additional constraints it would raise.

Under unbalanced conditions, the principle is to generate a balanced voltage source, as a synchronous machine, while injecting a negative sequence (NS) currents, which is desirable for fault detection. However, phase over currents need to be avoided as inverters have limited overcurrent capabilities, and overpassing these limits can trip the device.

Here we propose to add a NS-TVI similarly to PS control loop to generate a NS voltage reference that would mitigate the risk of phase overcurrent. Zero sequence current are not studied here as the connection transformer coupling prevent them from crossing it. Different criteria can then be used to set the PS & NS maximal currents as well as the values of respective virtual impedance.

2.3. DC side control and model

The challenge of the DC side is to provide very fast DC current transient demanded by the AC side voltage source behaviour. The demonstrator has been designed to supply these fast transient solely with the Ultracaps. We could then show that grid-forming function can be implemented on an existing inverter provided the DC side is upgraded with a minimal amount of fast storage.

Accordingly, we considered two different DC side control strategies: a proportional-integral (PI) and a virtual RC circuit (VRC) and control in which the P controller drives the UltraCaps DC/DC converter and the integral action is carried by the battery DC/DC converter.

An outer loop for each device handles their state of charge (SoC). The UltraCaps SoC is regulated to 50% to allow fast response of the unit in both power flow directions. Then, the energy is supplied by the battery for longer lasting events. Both strategies, shown in Figures 3, offered desirable power sharing properties and stable association with the grid-forming control [5].

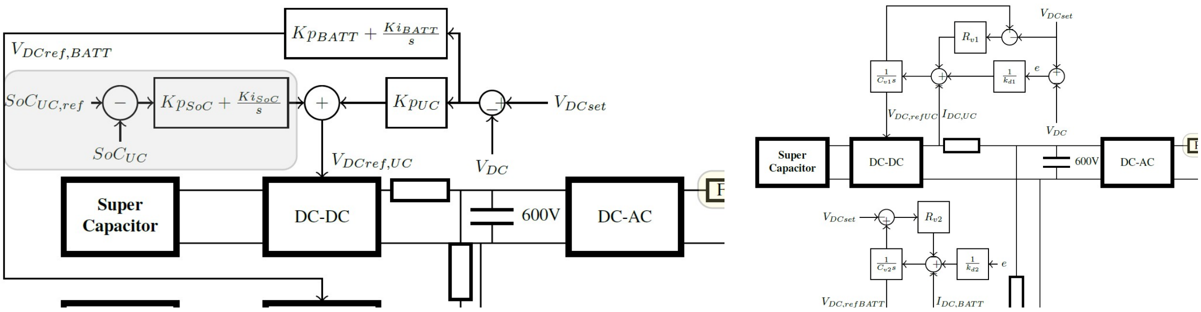

Figure 3. DC Control principle. A) left: PI-P. B) VRC

3. SIMULATION RESULTS

OSMOSE demonstrator model has been developed in EMTP software using special toolbox to directly import the control system from Matlab Simulink by the mean of a dll [8]. This technique ensures a unified modelling control approach with the benefit of accelerating the simulation time by a factor around 15 thanks to the nodal analysis used by EMTP to solve time domain simulation [9].

As illustrated in Figure 4, comparison between Matlab and EMTP simulations have been performed in order to validate EMTP model, showing a satisfactory match of the results for a sequence of multiple events including: change active power order, change of AC voltage order, single phase fault and three phases fault.

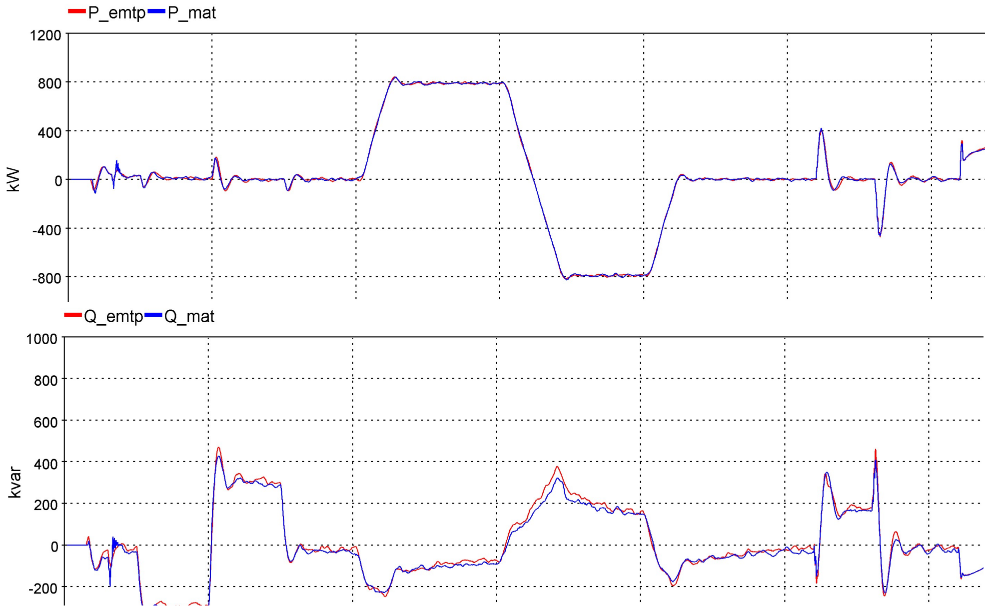

Figure 4. Comparison between Matlab and EMTP simulations (Inverter active and reactive power)

3.1. Load variation

A typical load variation from the grid has been recorded by the TFR showing a local load increase which has generated a 3.5% voltage dip. This measurement has been recorded in 2019, i.e. with no demonstrator connected. Figure 5 (left) shows measured voltage at the point of common coupling (PCC) (TFR) as well as the simulation results without the demonstrator connected (MAT1) to certify we managed to reproduce the event in EMT simulation. Then the same event is simulated when the demonstrator is connected and operating in grid-forming (MAT2). As expected, due to the relatively small size of the demonstrator (1 MVA) compared with strength of RTE grid (more than 100MVA) at this PCC, its impact on the voltage will only compensate for one percent of the voltage dip, which is hard to distinguish at this scale.

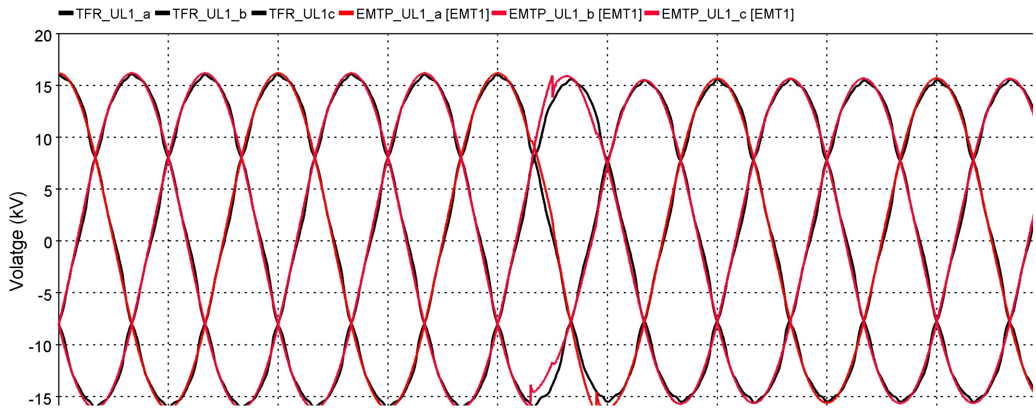

Figure 5. Measured (black) and simulated (red) voltage at PCC for load variation.

However, we can observe in Figure 6 and 7 that the grid-forming control still results in a very fast response, though the limited voltage dip does not bring the inverter current outside its rated operating conditions. It can be noted that the initial transient lead to short unbalanced situation (see the current in Figure 6 top-left), but more important that the voltage source behaviour of the grid forming converter offers an instantaneous response with a reactive power contribution of 250 kVar face to 3.5% voltage dip while the active power goes back to its reference, here zero (bottom-right).

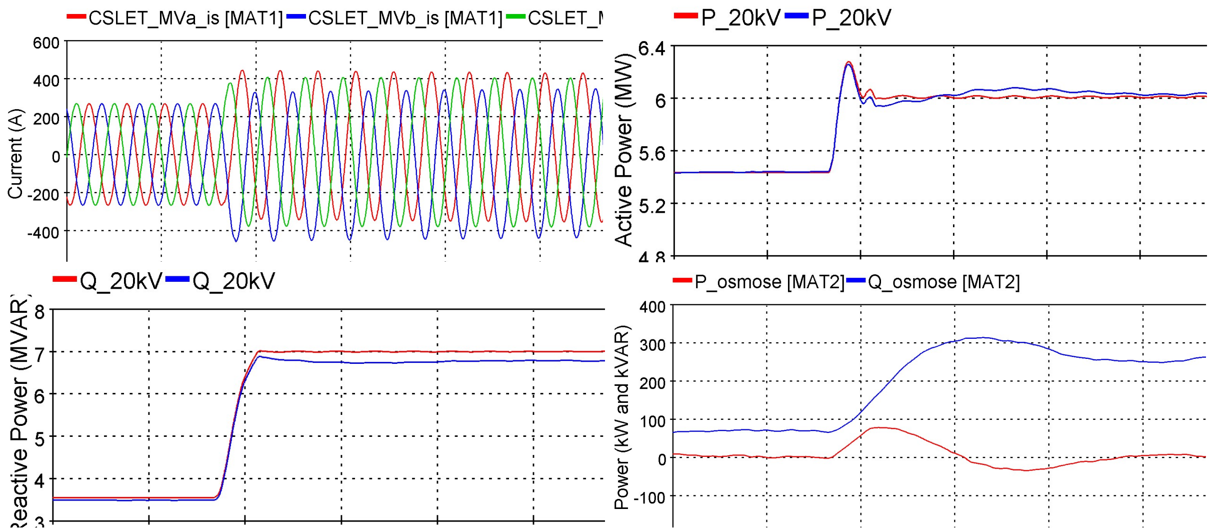

Figure 6. Feeder current, load step and inverter response

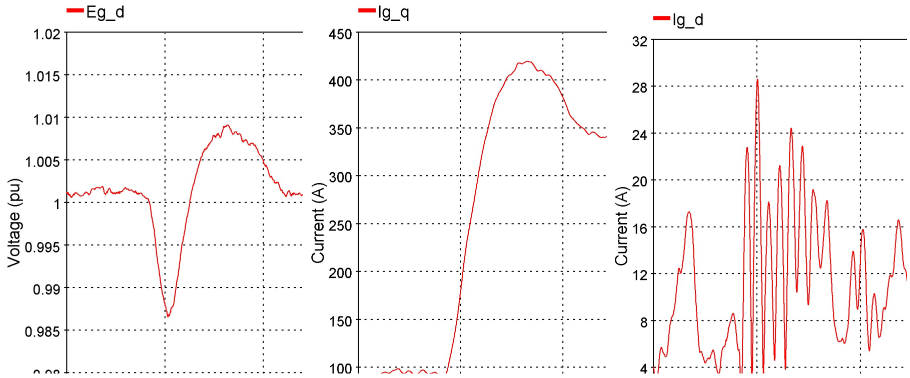

Figure 7. Grid forming response to load step (d-axis voltage & dq-axis current)

3.2. Single phase fault

Based on TFR measurement, showed in Figure 8-left, we could predict by EMT simulation the behaviour of the demonstrator under single-phase faults. However, due to the 0.6/20 kV transformer connection (ynD), simulations confirmed that the grid forming inverter will not be significantly stressed by this king of event. The harsh single phase fault being transferred into a phase to phase fault with low severity. Zero sequence impedance are still to be fine-tuned.

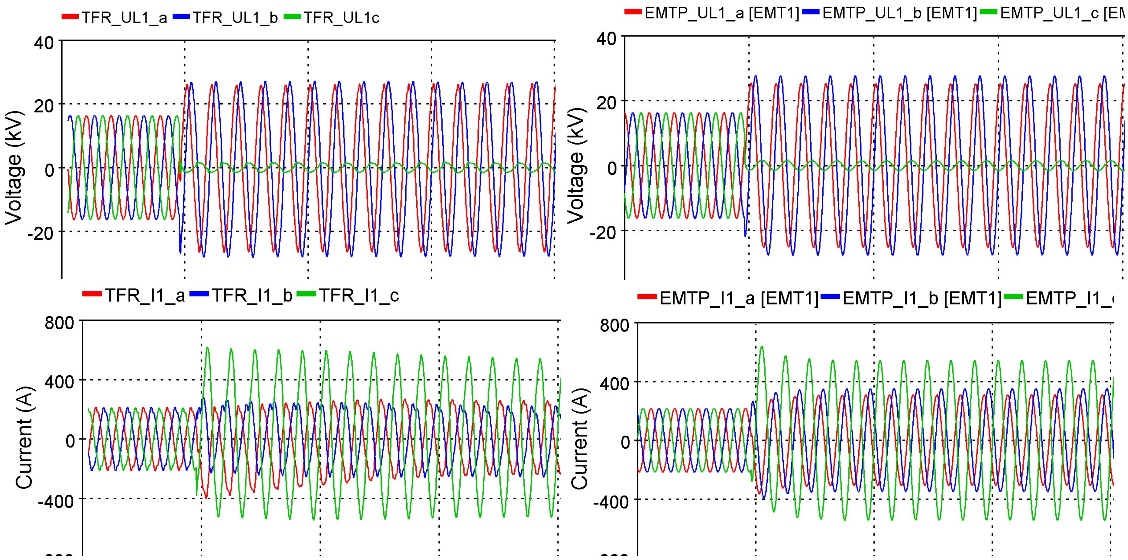

Figure 8. Measurements (left) and simulation results (right) for a single-phase fault in the feeder.

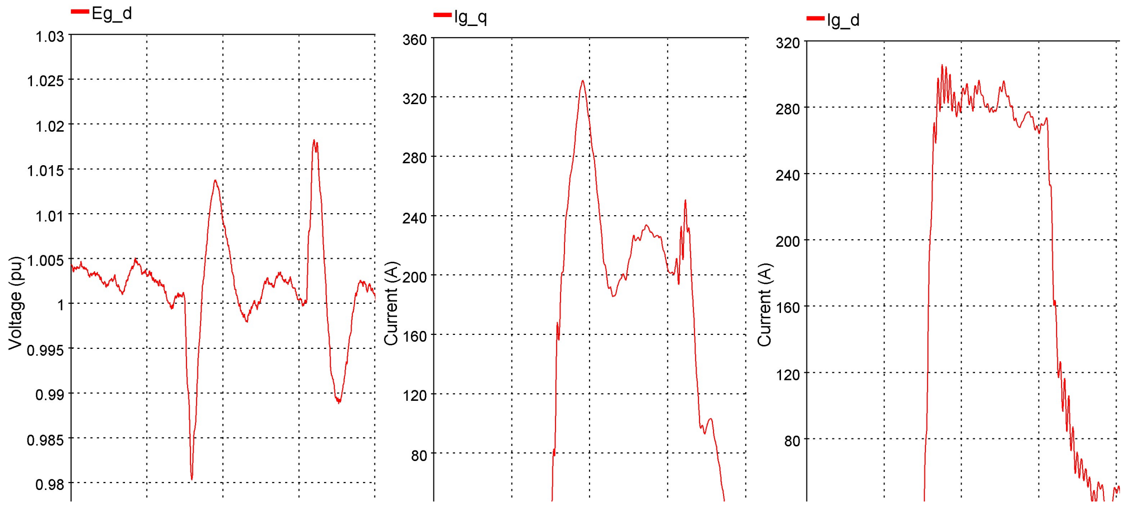

Figure 9. Inverter response for a single-phase fault in the feeder.

3.3. Three-phase fault

In order to assess the effectiveness of the current limitation strategy, a three-phase fault is simulated on the costumer site. Figure 10 shows again the voltage at PCC (top-left), the feeder current (top-right), the inverter voltage and current (middle) as well as the injected active and reactive power (bottom). It is observed that the TVI is effective in protecting the converter.

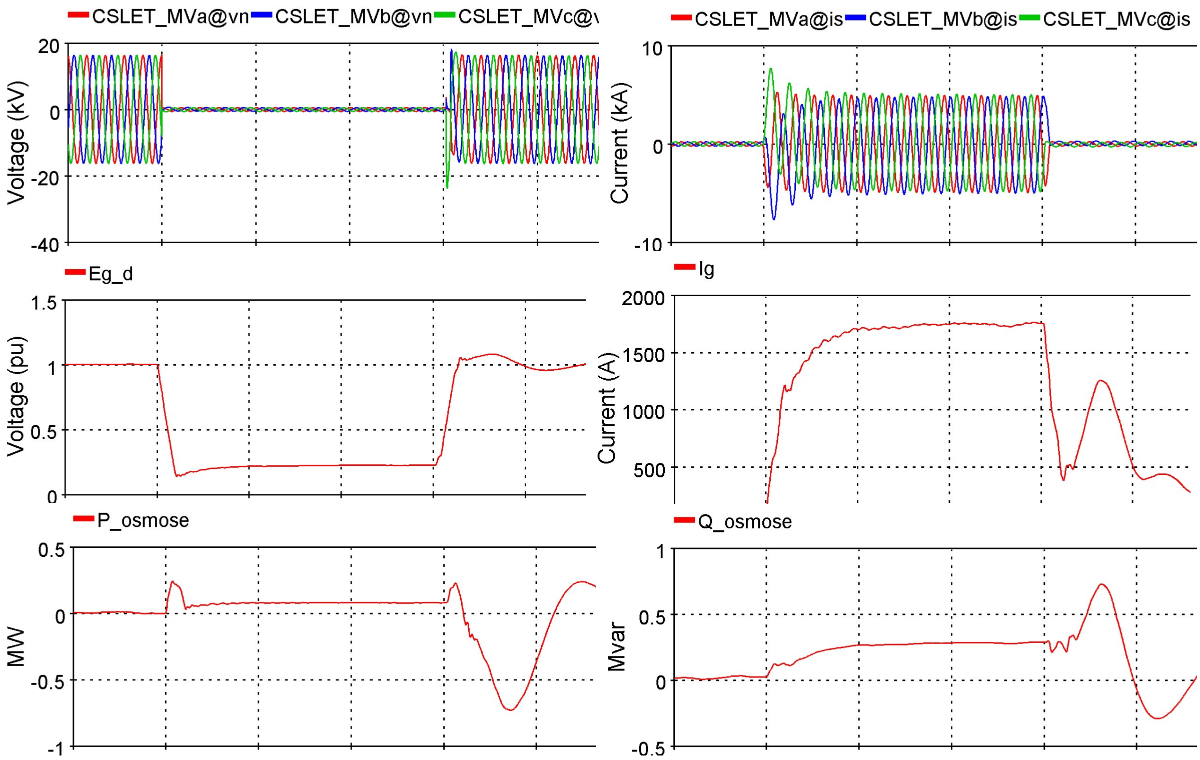

Figure 10. Inverter response to a three-phase fault in the feeder.

3.4. DC side response for power reference tracking

Grid forming performances have been validated considering more standard test such as active power or voltage references steps. Figure 11 shows how the transient active power is share on the DC side between the battery and the ultracaps. Control tuning was performed using an average model in Matlab. Then, final results were validation for the full EMT model. As expected, the ultracaps deals with the fast transient imposed by the grid forming control, and will be slowly replaced by the battery, and such control would avoid potential fast ageing of the battery

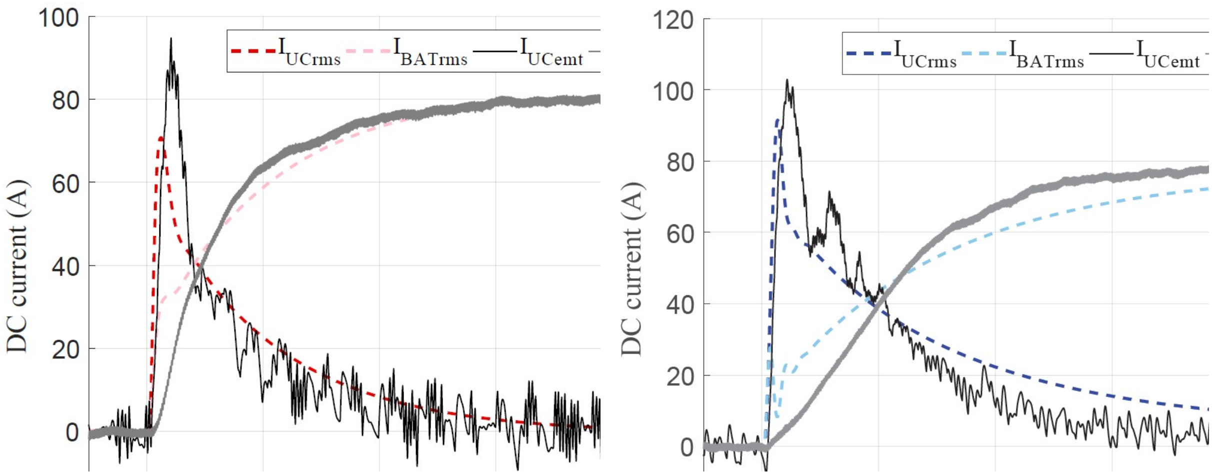

Figure 11. DC side response: battery and UltraCaps current. A) left: PI-P. B) VRC

3.5. Synchronization

In order to avoid hard transients and to ensure a smooth grid connection, the PCS (power conversion system) is synchronized with the grid before the closure of the main breaker. The fundamental phase-angle at the point of common coupling is tracked on-line in order to estimate direct and quadrature axes. To do so, a PLL (phase locked loop) is implemented. The output voltage of the converter is increased with a low derivative (low enough not to excite the grid connection filter resonance) and once the output voltage of the PCS and the grid are synchronized and with almost identical voltage amplitude, the main breaker is closed.

After the breaker closes, the PLL is deactivated and the active and reactive power set points evolve according to the droop characteristics. Thus, immediately after the synchronization, the PCS will start controlling frequency and voltage. For the particular case when the grid magnitudes are identical to the set points, the PCS won't inject any current to the grid (see Figure 12).

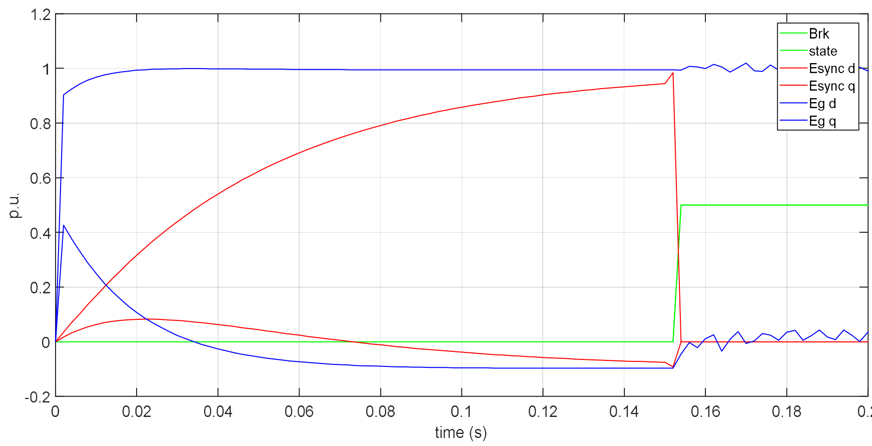

Figure 12. Synchronization process results obtained in Matlab-Simulink

4. CONCLUSIONS

This paper briefly described the demonstrator that will be installed on RTE's grid. It illustrated the performance of both grid forming control and specific current limitation for disturbed conditions. Even if the controls have proven to be robust and efficient within the MIGRATE project, the test carried out in this paper are issued from real events and conditions coming from the bus bar where the inverter will be installed. It can be seen that the current limitation in PS and NS is effective to limit the current even in case of unbalanced situation.

The paper also offer a prediction and discussion, based on simulation results, on the expected impact of the whole controlled storage system in the actual grid. Indeed, grid-forming control is meant to locally smooth the frequency variability at the point of connection. The simulations accuracy is guaranteed by an ongoing measurement campaign on the demo site. The real time series have been used to reproduce on field grid conditions in the chosen location which ensures that the proposed control strategies will survive the real conditions.

By reproducing the real grid conditions in EMT, we confirmed that, on the one hand, the demonstrator contribution in voltage support is only 1 % of voltage dip and can only be captured by highly accurate measurements. On the other hand, such frequent events are sufficient to observe the consequence on output currents.

In current grid code, it is usually required to inject reactive current when the voltage is low, the goal is to keep the voltage up, and it is also a way support as much as possible the voltage out of synchronous machines nearby so that they can feed the grid with maximum active power and thus limit the transient angle instability. For grid forming inverter, the requirement for reactive current injection is not necessary as the voltage source behaviour of the generation will spontaneously feed the grid with the current that give maximum voltage magnitude for a given grid impedance.

Hence, the grid-forming converter does not need active or reactive power priorization because it will naturally converge to a consensus with other voltage sources of the grid (other synchronous generators or grid-forming inverters) by sharing active and reactive power supply efforts. Indeed, in a more simplified case, two identical grid-forming inverters will try to feed a fault of a certain reactive-inductive ratio, equally distant from both sources, with equal share of active and reactive power ratio. Thus, the PQ priorization has no sense in a full inverter based system.

OSMOSE demonstrator will be an example of grid-forming control meant as a fundamental basis to build system with 100% of EP generation. It makes the inverter behave as a voltage source, but also it allows synchronized operation of multiple grid-forming control to build a meshed grid, and protects each devices from large transient expected from the grid, with no costly hardware oversize. The success of the demonstrator will be a next step into the industrial development of such solution.

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