VOLTAGE CONTROL SYSTEM DEVELOPED INSIDE THE ITALIAN DEMONSTRATION OF GRID4EU: LABORATORY TESTS FIRST RESULTS

Lilia CONSIGLIO, Daniele STEIN
Enel Distribuzione S.p.A.– Italy
lilia.consiglio@enel.com
daniele.stein@enel.com

Diana MONETA, Giacomo VIGANO'
RSE – Italy
diana.moneta@rse-web.it
giacomo.vigano@rse-web.it

Ivan ROCHIRA, Carlo ARRIGONI
Siemens S.p.A. – Italy
ivan.rochira@siemens.com
carlo.arrigoni.ext@siemens.com

ABSTRACT

The Italian Demonstration of FP7 European project GRID4EU (www.grid4eu.eu), developed by Enel Distribuzione in partnership with Cisco, RSE, Selta and Siemens, is addressing the realization of an advanced control system to increase the Medium Voltage (MV) network hosting capacity of Distributed Generation (DG), thus maximising Renewable Energy Sources (RES) integration [1]. The core of the control system is a Voltage Regulation (VR) algorithm whose main features will be presented in the paper, along with VR off-line tests results. Furthermore, the paper will present the overall system integration tests that are being carried out, starting from the description of the laboratory set up and going through the first outcomes. The laboratory set up used for the overall system integration tests allows "Hardware in the loop" testing, thanks to real time digital simulation of the real power system.

INTRODUCTION TO THE VOLTAGE REGULATOR MAIN FEATURES

In 'active' distribution networks, where DG presence is significant and the power flows can reverse with respect to the design 'passive' condition, advanced monitoring and control methodologies are required. In 'active' networks, the traditional approaches relying largely on Primary Substation measurements and conventional control resources cannot always resolve possible impacts arising from power injection from DG, in particular over-voltages and high currents in some branches of the grid. The main change for enhancing the Distribution System Operator's (DSO) control possibilities is the DG participation to the system operation, together with the utilization of storage devices. Thus, relying on actual measurements, historic and forecasted load and generation profiles, a reliable estimation of the state of the system (*V, P, Q* at nodes and *I* in branches, substantially) can identify voltage and/or current violations in the present and in future periods. From this snapshot provided by the State Estimator block, the Voltage Regulator is able to identify an optimized condition for the MV network that guarantees achieving technical goals minimizing the overall dispatching cost. In summary [2], the algorithm calculates the minimum of a cost function taking into consideration and respecting the following constraints:

- Voltage at nodes within allowed range
- Current in branches within allowed range
- P, Q capabilities of controllable resources
- Energy capabilities of storage unit(s).

The cost function is composed by addends related to the requested displacement of controllable resources:

- OLTC transformers, which are directly operated by DSO;
- Reactive power injection/absorption from controllable third-party resources (sub-set of DGs);
- Active power from controllable third-party resources (sub-set of DGs, loads), not used in the demonstration;
- Energy in a storage unit, directly operated by the DSO. This device (1MVA/1MWh) is used for the voltage and the flow control and it can be connected to different feeders of the demo network.

For each resource the capability area {P,Q} and the cost for the displacement are defined. Power losses are not included either as regulation resource or as a single optimization goal, because the algorithm could otherwise limit them at the expense of the other parameters. They are minimized into the overall problem, but with the main goal of respecting the technical constraints.

VOLTAGE REGULATOR OFF-LINE TESTS

Before integrating the algorithm into the on-line telecontrol architecture, a comprehensive laboratory test phase was carried out to evaluate the algorithm's behaviour, to tune the technical and the cost parameters and to complete the definition of interfaces between the VR block and the "surrounding environment". Since the remuneration of the ancillary services is currently under discussion in the regulatory framework, here the 'costs' represent a ranking criterion among the available resources to get the desirable result. With reference to smaller portions or to the complete MV network under each of the two primary substations involved in the experimentation, tens of case studies were designed combining properly the following aspects:

- Load and generation profiles, representative of the day (Workday, Saturday, Sunday) and the season (Summer, Winter, Spring, Autumn);
- Position of the storage unit (on 2 different MV lines);
- 'Cost' for the regulation resources (i.e. merit order between them).

An example of off line testing is shown in Figure 1 below. A simplified scheme of a test network, comprising 2 MV feeder, ~130 MV and MV/LV nodes, 13 generator units (P_{tot}=15.5 MW, Q_{tot}=4.2 Mvar) of whom 5 PV plants are controllable.

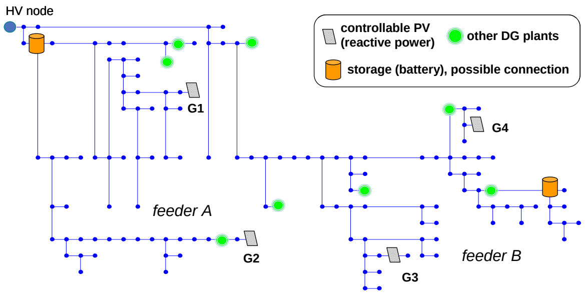

Figure 1 Simplified scheme of the test network for the example analysis.

The following graph summarizes the total load and total generation for a Summer Sunday on the MV network.

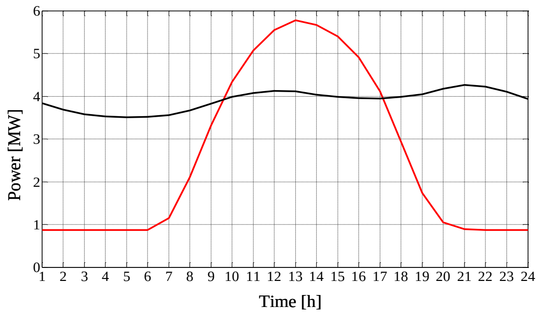

Figure 2 Total load (black) and generation (red) on the MV network in Figure 1 on a reference Summer Sunday.

Because of the reverse flow in the central hours of the day, and the unbalance between the two feeder ('A' is passive, 'B' is active), the algorithm requests the controllable PV plants in the 'active' feeder to absorb reactive power while in the other feeder the opposite occurs, to reduce the voltage gaps between the two lines. The OLTC keeps the MV bus-bar voltage on a proper high level to adjust the voltage in the whole network and to reduce the losses. The algorithm has identified a complete charge-discharge cycle for the battery (connected to feeder A), taking into account the 50% energy target to be reached at the end of the day (Figure 3).

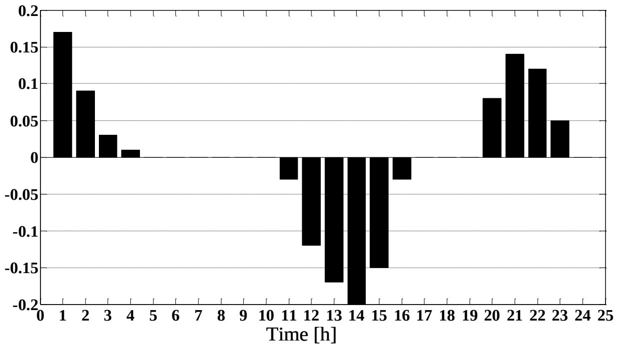

Figure 3 Calculated power profile (MW) for the storage unit.

SYNTHESIS OF RELEVANT RESULTS

The following general results can be drawn from the analysis of the case studies:

- The reactive power modulation by DG combined to the proper action of the OLTC succeed in limiting over- and under-voltages in nearly all the analyzed conditions;
- The duration of the time horizon affects the utilization of the battery (charge-discharge cycle); as expected, the best solution is to adopt a time horizon for the optimization comparable to the periodicity of load-generation profiles;
- Given the large reverse feeding during the Summer days the storage unit can help more effectively for the voltage control than for the energy shift;
- Apparently odd optimization results become clear taking into account the integral constraint on the storage and the effort in minimizing power losses.

ENEL'S LAB SET UP FOR OVERALL SYSTEM INTEGRATION

This section will present the lab set up for overall system integration testing in terms of data/commands exchanged, calculation algorithm execution and control system functionalities and performances.

<u>New Control Systems overall architecture with sub-systems</u>

Figure 4 shows the overall system architecture developed and extended for the Italian demonstration of GRID4EU project. The developments involved three main part of entire system (DSO Operation Control Center, HV/MV - Primary Substation and MV/LV - Secondary Substation). Each part consists of sub-systems which contribute to achieve project objectives. Some of these sub-systems are totally new, while other parts are extension of the current systems installed.
On DSO Operation Center (Figure 4) the following parts have been introduced/extended:

- Real time DB alignment system manager (**A.1**) on central SCADA system;
- Load and generation forecast server (**B**).

On Primary Substations the following parts have been introduced/extended:

- Network Calculation Algorithm System (HW platform to run SE and VR algorithms) - **NCAS** (**C**);
- Local SCADA System (**A.2**) and RTU (**TPT2020**);
- Integrated transformer protection (ITP – **DV7500**).

On Secondary Substations the following parts have been introduced/extended:

- Generator/Customer Energy Regulation Interface (**IRE**);
- Directional Fault Detector and Measurements acquisition device (**RGDM**).

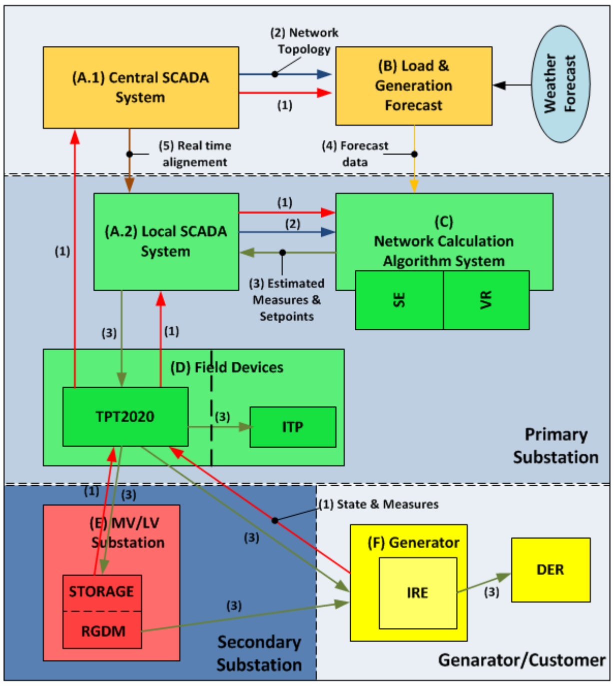

Figure 4 Overall system architecture

It is important to underline that the communication infrastructure enabling the information exchange between the different parts of the system is out of the scope of this paper, therefore it will not be treated and presented in detail.

Overall system infrastructure replication in Enel's Lab.

The architecture of Figure 4 has been replicated in Enel's laboratories in order to perform the overall system integration tests, before filed installation and tests. Figure 5 depicts all the components used for the laboratory set up, in particular:

- #1: Rack with Central SCADA and Load & Generation Forecast system - (A.1 + B);
- #2: Rack with primary substation control sub-systems (Local SCADA, Network Calculation Algorithm system and Remote Terminal Unit-TPT2020) - (A.2 + C + D);
- #3: Integrated Transformer Protection (DV7500) - (D);
- #4: Energy Regulation Interface (IRE) - (F);
- #5: Directional Fault Detector/Measurements acquisition device (RGDM) - (E);
- #6: RTDS® system (Real Time Digital Simulator).

Thanks to this set up it is possible to go through different kinds of integration tests, related to:

- Data and commands exchange between systems and devices;
- Single devices and overall system functionalities;
- Control strategies effectiveness thanks to real power system behavior and response simulation.

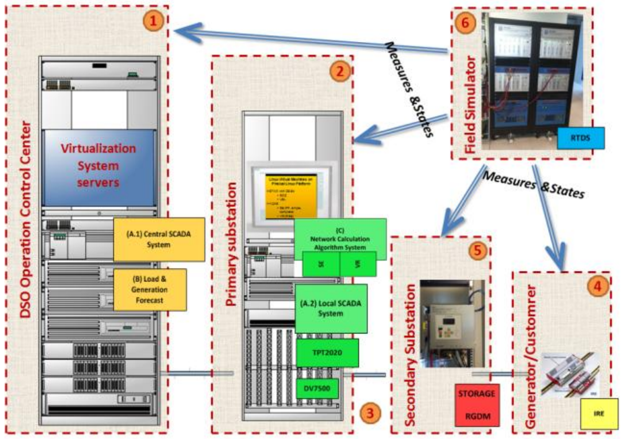

Figure 5 Laboratory set up scheme

Simulating the power system behavior is possible thanks to the use of Real Time Digital Simulator RTDS®, that is used to provide the real system response during closed-loop testing.

Main data flow Exchange to be tested

Due to their importance and criticality data flows exchanged among sub-systems are tested with particular attention. Referring to figure 4, main data flows are summarized as follows:

DSO Operative Center – Primary substation:

- (5) Real Time alignment between Central and Local SCADA systems – A.1→A.2;
- (4) Forecast data – B→C;

Primary Substation:

- (2) Network Topology – A.2→C;
- (3) Estimated measures and set points – C→A.2;

Primary Substation - Secondary Substation:

- (1)/(3) Generator/Customer State and Measures and Set Points – F←→D.

FIRST INTEGRATION TESTS CARRIED OUT

Integration tests have been divided into steps as follows:

- Phase I: Primary Substation (A.2 ↔ C)
- Phase II: Primary Substation ↔ DSO Operation Control Center (B)
- Phase III: Primary Substation ↔ DSO Operation Control Center (B+A.1)
- Phase IV: Primary Substation ↔ DSO Operation Control Center ↔ Secondary Substation & Generator/Customer
- Phase V: Primary Substation ↔ DSO Operation Control Center ↔ Secondary Substation & Generator/Customer ↔ RTDS®.

The first integration tests (**Phase I**) were performed on the Network Calculation Algorithm System (**NCAS**), addressing the integration of State Estimator (SE) and Voltage Regulator (VR), which are two different algorithms running on the same HW platform. The test network consists of two MV feeders connected to a primary substation MV bus-bar. All the integration tests were designed starting from the following functional division for the State Estimation algorithm:

- Power Flow
- Simple State Estimation
- Complete State Estimation.

The Power Flow is based only on the voltage measurements at the HV bus-bar of the Primary Substation and on the load and generation profiles. Whereas the Simple State Estimation is based on all relevant measures available for the Primary Substation (HV and MV busbar voltages, MV feeder currents, active and reactive power flows on the HV/MV transformers). Finally, the Complete State Estimation is able to compute even the available measures on the MV network (voltages, active and reactive power flows on branches).

The topological scenarios defined to test the **NCAS** functionalities were:

- "passive" network (only loads connected to the network, all the Distributed Generators disconnected) [Test Case ID 1]
- "active" network (all the Distributed Generators and loads connected to the network) [Test Case ID 2]
- reverse feeding scenario (feed all the network exploiting only one of the two power lines). [Test Case ID 3, Test Case ID 4]

The Voltage Regulator algorithm was triggered after each execution of the State Estimator. This approach allowed to test together the functionalities of the State Estimation algorithm, the Voltage Regulator performances and the whole data exchange inside the **NCAS** (i.e. to test the proper integration of all the different components). Each proposed test was duly described using "standard factory test forms" specifying objectives, pre-conditions/input data, test procedure, expected results and final outcome. The results of the State Estimation algorithm were evaluated focusing on voltages, currents and active/reactive power flows in Primary Substation and in Secondary Substations where Distributed Generation plants are connected. The overall outcome of the State Estimation algorithm is synthesized by a "*goodness index*" that is used to decide if it is possible/opportune to trigger the Voltage Regulator algorithm. At the moment, the "*goodness index*" threshold to trigger the VR is set equal to 10%. If the "*goodness index*" is $\leq$ 10%, the VR is launched, otherwise a new SE iteration is required. This threshold will be fine tuned going further with integration tests, in particular relying on "closed loop" test results. Referring to the Simple State Estimation functionality, table 1 shows the goodness indexes obtained during the first SE tests. Moreover, additional tests have been already designed to test the **NCAS** on the entire MV network involved in the field demonstration. A specific target of these tests is to evaluate the SE and VR algorithms performances depending on configuration parameters.

Test Case ID	Scenario	Primary Substation Measures						Goodness Index
		V HV [kV]	V MV [kV]	P HV/MV transformer [kW]	Q HV/MV transformer [kVAr]	I Feeder #1 [A]	I Feeder #2 [A]	
1	"passive" network	132,00	15,56	2279,59	414,37	53,11	32,93	**0,10%**
2	"active" network	132,00	15,56	-587,00	445,86	13,51	13,83	**0,83%**
3	reverse feeding #1	132,00	15,56	-441,79	342,68	20,55	0,00	**2,69%**
4	reverse feeding #2	132,00	15,56	-451,30	295,02	0,00	16,94	**8,41%**

Table 1 SE - Goodness indexes outcomes

Soon also the presence of the Energy Storage System will be considered by the **NCAS**. New specific tests will be designed and performed for the SE and the VR algorithms considering both single-period executions (15 minutes) and multi-period executions (based on load/generation forecast for the battery management).

CONCLUSIONS

Laboratory pre-integration (e.g. VR offline tests) and integration tests represent a key activity to be carried out before field deployment. Thanks to these tests it is possible to assess how the system components work in standalone mode and then put all of them together, to debug the entire system and to assess its functionalities and performances. Starting from the Voltage Regulator off-line tests, the paper has presented the steps to set up a laboratory for integration tests with power system simulation using RTDS®, and the first SE+VR integration tests results. In particular, these first tests have shown the correct flow of information within and between the blocks, according to the specified interfaces. Next action will be to go further, integrating step by step the Network Calculation Algorithm System with all the other systems and equipment, to finally achieve the entire system closed-loop testing with the simulated power system response.

REFERENCES

[1] D. Stein, L. Consiglio, J. Stromsather, "Enel's large scale demonstration project inside GRID4EU: the challenge of RES integration in the MV network", proceedings CIRED Conference, Stockholm 10-13 June 2013, Paper 1127

[2] D. Moneta, L. Consiglio et al., "Integrating larger RES share in Distribution Networks: Advanced Voltage Control and its Application on real MV Networks" proceedings CIRED Workshop, Lisbon 29-30 May 2012, Paper 0242.

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