DESIGN AND DEVELOPMENT OF A LV TEST FACILITY FOR DC ACTIVE DISTRIBUTION SYSTEM

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ABSTRACT
In this paper we report on design, assembly, commissioning and testing of a LV DC test facility, developed in the framework of national R&D project, designed to be operated both connected and isolated from the AC CESI RICERCA Distributed Generation micro-grid. Simulation results of developed front-end control strategy are reported and discussed: a voltage DC bus dynamic error lower than 2% is obtained even for severe and sudden load changes.

INTRODUCTION
The needs to integrate a large amount of distributed energy resources (DERs) and to provide high power quality level to the end users increase the interest for DC power distribution systems [1, 2]. Potential advantages of low voltage (LV) DC distribution networks compared to LV AC conventional grids include: enhanced overall energy efficiency of power distribution systems, higher transmission capability, filtering of voltage disturbances and hence improved voltage quality experienced by customers. Moreover, improved reliability and cost efficiency of the distribution network with potential economical savings for both public distribution systems and special applications are foreseen.

Considering the promising results obtained by previous investigations, on January 2006, a new project was started to develop a DC test facility to study the behaviour of a distribution DC network and its components both in steady state and in presence of different type of disturbances or faults.

The LV DC test facility is a micro-grid interconnected to an existing AC test facility with a high penetration of Distributed Generation (DG). The commissioning of the DC micro-grid in its present form was concluded on January 2009. However, a new project started already to allow the future evolution of the LV DC micro-grid to experimentally investigate the potential benefit and possible drawbacks in distribution networks.

In this paper we report on design, assembly, commissioning and testing of a LV DC micro-grid, developed in the framework of national R&D project, designed to be operated both connected and isolated from the AC CESI RICERCA (CR) DG test facility. The CR DG test facility consists of renewable energy sources, co-generation plants, energy storage systems and controllable loads that can be connected at different points of an automated LV grid working in radial, ring and meshed configurations [3]. Design of the LV DC micro-grid and of its main components as well as of the adopted control strategies for the front-end converter is reported for both its present structure and in view of its already planned future extension.

THE LVDC MICRO-GRID
The present LV DC micro-grid has a voltage level of 400V and it is composed of a front-end AC/DC converter, a photovoltaic field emulator, several energy storage systems, two controllable loads, and will be provided with a supervision and control-management system enabling the efficient use of the available energy sources as shortly described in the following.

Test Facility Architecture: present and future

Fig. 1 shows the conceptual scheme of the DC distribution micro-grid in its present (A) and future (B) structure. In fact, even if the whole hardware has been designed for the future structure of the DC grid, as a first step a 2-conductor configuration has been designed, assembled and commissioned. In the first half of 2009 the 2-conductor LV DC test facility will be extensively employed to experimentally validate the simulation results on the effects of some typical transients (e.g., AC voltage dips, generation and load sudden fluctuations, control strategy) on the voltage DC bus stability. In the 3-conductor DC micro-grid configuration, an additional 100 kW converter will be added to the present front-end converter (constituting its forth leg) to compensate for unbalanced generation and load conditions.

Fig. 1. Schematic of electric circuit of DC test facility: (A) 2-conductor and (B) future 3-conductor configuration.
Main Component Characteristics

Front-End Converter
The 100 kW front-end AC/DC bi-directional converter is the key component of the DC grid; it allows the power flow from the AC to the DC grid to sustain the loads in case of insufficient or no generation, and also the opposite flow in case of generation surplus. Most importantly, it oversees and controls the stability of the voltage DC bus at all times.

Energy Storage Systems: Battery and Supercapacitor
Several energy storage systems are installed in the DC test facility and they have an important role to improve the power quality and in the efficient energy management. In particular, there are two ZEBRA™ batteries, each one with a peak power of 32 kW, a capacity of 64 Ah and an open circuit voltage of 279 V. These batteries are coupled to DC grid by 35 kW DC/DC bi-directional converters to allow batteries charging and discharging process. ZEBRA™ battery belongs to the family of high temperature batteries; in fact its internal operating temperature is in the range 260-360 °C. This high temperature is necessary to keep the electrodes (i.e. sodium and nickel chloride) in the liquid state. Moreover, ZEBRA™ batteries have a very high specific energy, (about four times that of lead acid battery: 100-120 Wh/kg vs 22-25 Wh/kg), no gaseous emissions, and a remarkable energy efficiency (better than 90%, according to the discharge rate).

However, to compensate very fast fluctuations in the DC voltage due to faults, dips propagation from AC grid or sudden load and/or generation changes in the DC grid, no. 2 supercapacitor banks each constituted of no. 24 modules (30 kW for 4 s) with a maximum voltage of 384 V are connected to the DC grid by 35 kW DC/DC bi-directional converters.

Photovoltaic-Field Emulator
One of the potential benefits of DC grids is the easier and more efficient integration of renewable sources. However, owing to the limited power from PV fields available at our site for both space constrains and meteorological conditions, we opted for a 35 kW PV-field emulator. In this way, we have controllable power available at anytime, so the experimental activity is not bounded to weather conditions and daytime.

Programmable Loads
Two programmable purely resistive load-banks are installed in the DC micro-grid, these units can provide a total load of 60 kW with step sizes of 1 kW.

Supervision&Control and Data Acquisition Systems
The supervision and data acquisition system allows to record the experimental data resulting from the field tests, to monitor power quality and electrical transients, and to communicate information to the central control system in order to optimize economic and power quality aspects.

Management and Control Strategy
The control of the LV distribution system is very important for achieving the proper operation of the interconnected devices and the desired continuity of supply to the various loads fed by the dc network.

The proposed control logic allows: fast intervention and automatic exclusion of the energy sources, efficient management of the devices connected to the DC bus through adequate reference voltages, improvement of the dynamic interconnection between devices and DC network, achieving an improved system power quality. By a central control strategy different optimized DC voltage reference values are assigned to the various power electronic converters of the DC micro-grid. These dynamic voltage thresholds (adjustable according to sources availability and grid needs) set the dispatching priority among the front-end converter and the generation and storage units. The highest threshold associated to a specific converter corresponds to the maximum priority level. An example of the voltage thresholds configuration is illustrated in Fig. 2.

Control of the AC/DC Front-end Converter
Fig. 3 shows the scheme of the AC/DC front-end converter. The mains supply is connected to the converter by a 400/200 V wye-delta transformer. In Fig. 3 are shown the internal resistances $R_f$ of the converter inductors $L_f$, the three legs of the IGBT converter, and the DC link smoothing capacitors $C_d$ with middle point grounded for safety and protection reasons [4].

The sizing of the DC link capacitors takes into account the DC voltage ripple minimization, the hold-up time, and the expected power fluctuations on the DC side. The front-end converter participates to the regulation of the DC network voltage [4] and also detects islanding condition occurrence by comparing the AC grid voltages and frequency with their admissible ranges. The AC/DC front-end converter works as a DC current source, modulated by the voltage DC error signal $(V_{D1} + V_{D2}) - V_{Dref}$ using a proportional-integral (PI) regulator for obtaining null steady state error of the DC voltage.

![Fig. 2. Voltage thresholds assigned to the different power system components of the DC test facility.](image)
Fig. 4. Reference currents control scheme.

Simulation Results: Case Study
The characteristic data of the DC micro-grid are reported in Table I. The simulations were conducted using the software package Matlab-Simulink that allows a detailed modelling of power converters and the proposed control strategies. In order to check the DC system robustness, heavy step variations of the DC power load has been simulated, as reported in Fig. 5a. The DC power change has been imposed by switching the resistive load $R_2$.

TABLE I: MICRO-GRID DATA

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated power</td>
<td>100 kW</td>
</tr>
<tr>
<td>AC line-to-line voltage</td>
<td>400 V</td>
</tr>
<tr>
<td>Rated frequency</td>
<td>50 Hz</td>
</tr>
<tr>
<td>$L_s$</td>
<td>0.1 mH</td>
</tr>
<tr>
<td>$R_s$</td>
<td>2 mΩ</td>
</tr>
<tr>
<td>$C_F$</td>
<td>0.5 mF</td>
</tr>
<tr>
<td>AC transformer ratio</td>
<td>2/1</td>
</tr>
<tr>
<td>$V_D$ DC voltage</td>
<td>400 V</td>
</tr>
<tr>
<td>$L_F$</td>
<td>0.05 mH</td>
</tr>
<tr>
<td>$R_F$</td>
<td>0.1 mΩ</td>
</tr>
<tr>
<td>$C_D$</td>
<td>40.8 mF</td>
</tr>
<tr>
<td>$R_1$ Load 1</td>
<td>20 Ω</td>
</tr>
<tr>
<td>$R_2$ Load 2</td>
<td>3.2 Ω</td>
</tr>
<tr>
<td>$I_{ML}$ Total DC generation</td>
<td>50 A</td>
</tr>
</tbody>
</table>

In our simulation at the time instant $t = 0.13$ s the total DC power exchanged with the AC grid vary from 58 kW imported to 12 kW exported; at time instant $t = 0.28$ s the opposite power inversion occurs. The key control variable $G$, involved in (1) is depicted in Fig. 5b. Fig. 6 illustrates that the DC-bus voltage, subsequent to a power flow inversion, is fast stabilized at its reference value of 400 V. As it can be seen, by the proposed control a dynamic error lower than 2% is obtained.
The AC currents $i_{Fabc}$ flowing through the converter inductors are illustrated in Fig. 7. The over imposed ripple at the switching frequency is evident. Before the transition occurrence the active components of the currents are in phase with the AC voltage, and the converter is functioning as rectifier. Subsequent the transition, the active currents and voltages are 180° phase shifted and the power is flowing from the DC network towards the mains supply. In order to compensate the capacitive reactive power over $C_F$, a reactive components are also present in $i_{Fabc}$ currents.

It is worth to underline that, by means of a suitable control strategy, the DC solution would increase the quality level for the end users and the whole distribution network.

In this paper we reported on the design and assembly of a LV DC test facility, developed in the framework of national R&D project, designed to be operated both connected and isolated from the AC test facility with Distributed Generation. Special attention has been also devoted to the DC grid management-control strategy and its optimization. The DC test facility in its 2-conductor configuration has been already commissioned and tested and in the first half of 2009 will be extensively employed to experimentally validate the simulation results on the effects of some typical transients (e.g., voltage dips on the AC side, generation and load sudden fluctuations, management and control strategy) on the voltage DC bus stability. Afterward, the DC test facility will be converted in the 3-conductor configuration. A wider range of experimental activity will be possible by this latest configuration and an additional 100 kW converter will be added to the present front-end converter to compensate for unbalanced generation and load conditions.

Acknowledgments
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REFERENCES

CONCLUSIONS
The increasingly widespread use of DC current, both in generators and in electrical equipments, leads to consider the possibility of integrating the various devices by means of a local DC distribution system. This solution would make possible a simplification of the present distribution system. In fact, in the DC distribution system the total number of converters is lower compared with the AC solution and their structure is less complex, even if it is necessary to have the AC/DC front-end converter interfaced with the grid.