On-site PQ Measurements in a Real DC Micro-grid

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Abstract—**The increasing use of distributed energy generation and storage has led to local direct current (DC) trial grids as an extension to traditional AC distribution networks. Like AC grids, DC grids must fulfil Power Quality (PQ) limits to guarantee a reliable operation for an acceptable quality of supply. However, knowledge about PQ in public DC systems is lacking, as is the related metrology and standardisation. On-site measurements have not yet been performed with sufficiently high accuracy and sampling rate to capture fast phenomena and broadband disturbances to determine the nature of the PQ phenomena occurring in such grids. In this sense, this paper shows a small part of the Living Lab of Smartcity Málaga, a real low-voltage DC grid property of Endesa, where the authors will carry out on-site metrology-grade measurement of the key parameters of the DC grid by mid-2022. This will provide dynamic voltage and current signals in the grid which help the scientific community to know the existent DCPQ phenomena in the grids. To this purpose, different operating modes of the micro-grid will be tested during the duration of the measurement campaign.**

Index Terms—**Power quality measurements, DC grids, smart grids, renewable energy, distributed generation.**

I. INTRODUCTION

For the last century, electricity has been generated, transported, distributed and used through alternating current networks. This has been the case since the so-called ”war of currents”, in which George Whestinghouse and Nikola Tesla supported alternating current (AC) and their opponent Thomas Edison defended direct current (DC). The easy of stepping up the voltage, favoring the transfer of power over long distances, and then stepping down to supply users, together with the invention of the induction motor, were the factors in favor of AC as the prominent form of electricity generation and use [1], [2]. From then on, the electrical power system was based on centralized generation, with AC transmission and distribution expanding worldwide. The generation units were mainly large hydroelectric and fossil fuel (coal and natural gas) plants offering stable and reliable energy at relatively low cost. They were usually far away from load centers, requiring long-distance transmission and multiple step changes of voltage to reduce losses before reaching load centers.

The development of power electronics (PE) and changes in load and generator characteristics have brought a major shift in the last decade. In this change, load specifications and characteristics, as well as power system control and safety requirements, have undergone an unprecedented evolution. On the other hand, renewable energy sources have also experienced a great development and penetration in the power system, reducing the contribution of conventional sources based on synchronous generation and affecting the stability, the security and the quality of power of the grid and, therefore, its reliability. To solve these problems, new concepts, such as ”smart grids” [3], ”microgrids” [4] and the more recent ”energy internet” [5], have been proposed for future electric power systems. All of them have in common the use of DC grids as part or all of the power grid.

DC grids have been proposed as solution to the current problems in the power systems, having some advantages over traditional AC grids. They are being developed at high voltage, HVDC, for the efficient transport of energy over long distances, at medium voltage to facilitate the integration of decentralised renewable generation plants into the electricity system and at low voltage, in micro-grids where the final equipment operates directly in direct current (DC) [6]. As advantages, one can count the absence of skin effect which means less losses, no need of synchronisation of grid connected systems, and the lack of reactive power control among others. However, there are some practical obstacles that need more attention from the research community, as it is the power quality (PQ) [7].

PQ indices are very well documented for AC grids in international standards and scientific literature. However, this is not the case for DC grids where only a short collection of papers can be found in the scientific literature. Several attempts to translate AC PQ indexes to DC have been done, including voltage fluctuations, voltage dips and interruptions, rapid voltage changes and ripple [8] [9]. However, standardisation and metrology requirements are still in their infancy or are being developed in projects such as the one where the research presented here is being carried out (EMPIR 20NRM03).

This paper is a contribution to the knowledge of power quality issues in DC grids by precisely characterising the existing phenomena in real conditions. A metrological-grade measurement system for DC power quality and the preparation of the measurements campaign in a real DC micro-grid are presented. The measurement campaign has not started at the moment of writing this paper but will be started by mid 2022.

The paper is organised as follows. Section II shows the test environment, providing all the details of the micro-grid. Section III covers the description of the measurement system

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and the details of the measurement campaign to be performed. Finally Section IV gives a summary of the contributions as conclusions.

II. TEST ENVIRONMENT

A. Description of the micro-grid

The integration of distributed energy resources, such as solar panels, small wind turbines and storage systems, is a key part of micro-grids. This means that electrical consumption can be balanced through an effective integration and operation of this kind of distributed renewable energy sources (DRES).

In this regard, a distributed and renewable micro-grid was chosen to be tested within the large smart grid of Málaga. Currently, this micro-grid, located in the Paseo Marítimo of Málaga (Spain), includes the following components:

- 1 small wind turbine (600 W)
- 9 small micro wind turbine (300 W)
- 1 solar power plant (9 kWp)
- 10 streetlamps with solar panels on top (950 Wp total)
- Pb battery storage units (30 kWh total)
- 1 super capacitor power bank (20 kW)
- 1 V2G charger (10 kW)

The small wind turbine, a 600 W-vertical-axis generator, is located on the seafront. Electrically speaking, it is connected to one Schneider Conext MPPT 80150 charger. It has a special aerodynamic design which limits the maximum rotating speed to 360 rpm even when the wind speed is higher than 30 m/s being safer and more reliable than traditional vertical axis wind turbines. There are also a total of 9 small wind turbines, model Urban Green Energy UGE-600, seamlessly integrated in the streetlamps. Each group of 3 wind turbines is connected to a Conext MPPT 60150 charger. Regarding photovoltaics, the micro-grid includes a total of 8 solar strings. Each group of 4 solar strings is connected to one Schneider Conext MPPT 60150 charger. This delivers a total power of 9 kWp on nominal conditions. Besides, 2 solar strings are connected together delivering 475 Wp each (they include 5 streetlamps each). Both strings supply power directly to one Schneider Conext MPPT 60150 charger. The battery bank is formed by 24 individual cells. The total capacity is 1000 Ah C10 with a nominal voltage level of 48 V. Because the installed batteries operate in DC and the distributed generators (DGs) generate in AC, the use of AC-DC converters is completely mandatory. Later, this DC energy is converted to AC by 2 power inverter systems. There is also one 10 kW Vehicle-to-Grid (V2G) Electric Vehicle (EV) charger that allows not also to charge the EV but also to discharge its battery to support the micro-grid. Besides, one super-capacitor bank of 20 kW and several Pb batteries (30 kWh) help to provide advanced capabilities to the operation of the system.

B. IED architecture

The Intelligent Electronic Device (IED) architecture of the micro-grid allows a distribution grid management based on three levels: The first level includes the basic elements connected to the micro-grid: wind turbines, photovoltaic panels, batteries, etc. Each of them is either controllable or only monitored by one SCADA placed at Paseo Marítimo.The second level includes the aggregation of the set of elements connected in the micro-grid, that is managed by the IED, also called i-node (see Figure 2). Regarding the third level of management, different set of grids/micro-grids are connected to a common platform, which provides the system operator with the necessary information to operate the grid in an efficient and secure way. This Distribution System Operator (DSO) Platform, so-called Energy Management System (EMS), is the element having the global information of the grid, thanks to the real time information received from the i-nodes and the model of the different micro-grids. The EMS sends high level commands to the i-Nodes, which must follow them during a given period of time. For instance, these orders may refer to different active or reactive power, voltage of frequency values at a certain node of the grid, etc. Thus, the platform generates high level set points to be accomplished by the group of grids or micro-grids connected to it.

The i-node of each micro-grid has its own management capability, reducing the complexity of the EMS commands, also reducing the requirements of communications systems, making possible a decentralized and bidirectional control. Thus, each IED i-node can apply a number of control policies to the elements connected to the micro-grid, without having to consult with the EMS. This improves response agility when facing non-predicted events, such as a sudden consumption increase: the EMS does not have to react, since the IED i-node solves the problem in an autonomous way. Thus, the resolution is faster than in the case when the EMS has to manage the situation.

Additionally, field element controllers may also act with a given independence degree, without the IED i-node having to intervene. As an example, a storage system could modify active and reactive power if it detects a voltage variation in the point to which it is connected. This detection and actuation is performed in a few milliseconds, solving the problem without IED the i-Node having to act, speeding the response and discharging the i-Node of this responsibility.

C. Management capabilities of the micro-grid

The i-node supervises and manages the micro-grid connected. In order to do this, it incorporates a model of the low voltage grid which allows making continuous power flow analysis. Thus, the final goal is that the micro grid associated to the i-node is as autonomous as possible, making decisions aimed to achieve the maximum operation safety and grid optimization. In this regard, the SCADA of the Paseo Marítimo has different operating modes that can be enabled or disabled upon request. This way, different scenarios can be designed to test the micro-grid, especially the existent power quality at the Point of Common Coupling (PCC). In this sense, Figure 3 illustrates the available working modes for the Málaga's micro-grid.

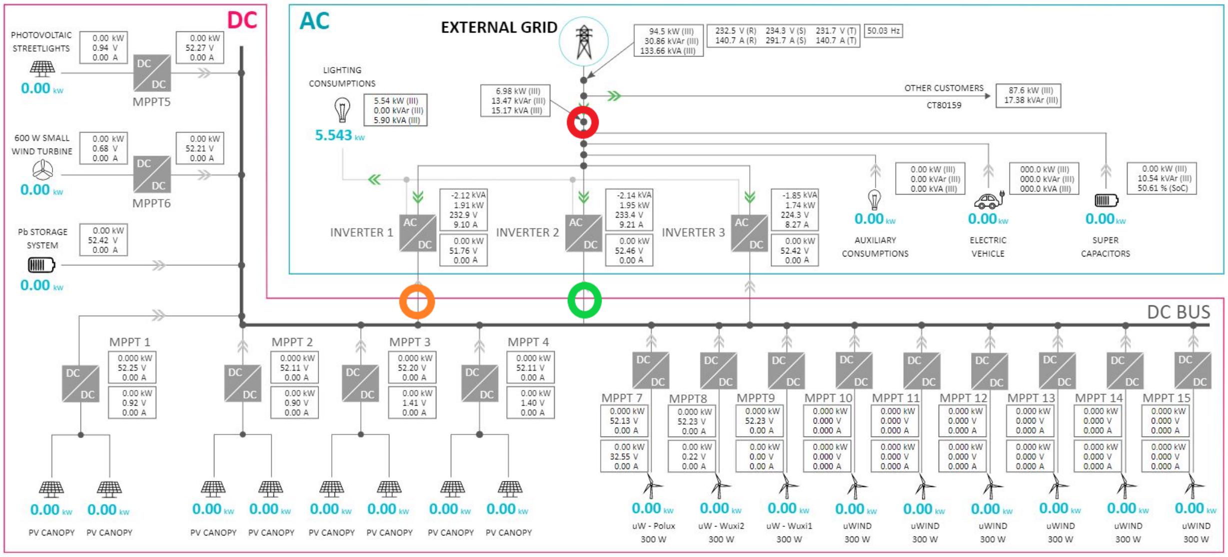


Fig. 1. Single-line diagram for the Málaga's micro-grid.

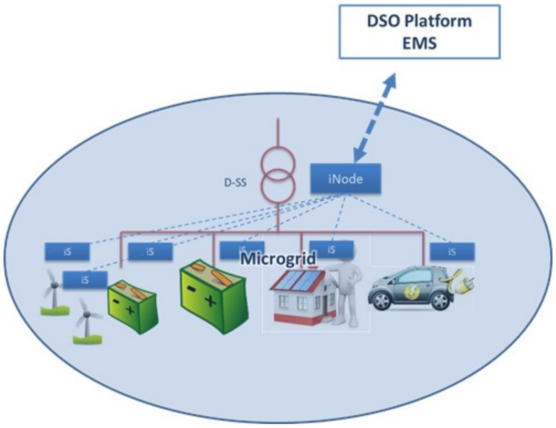
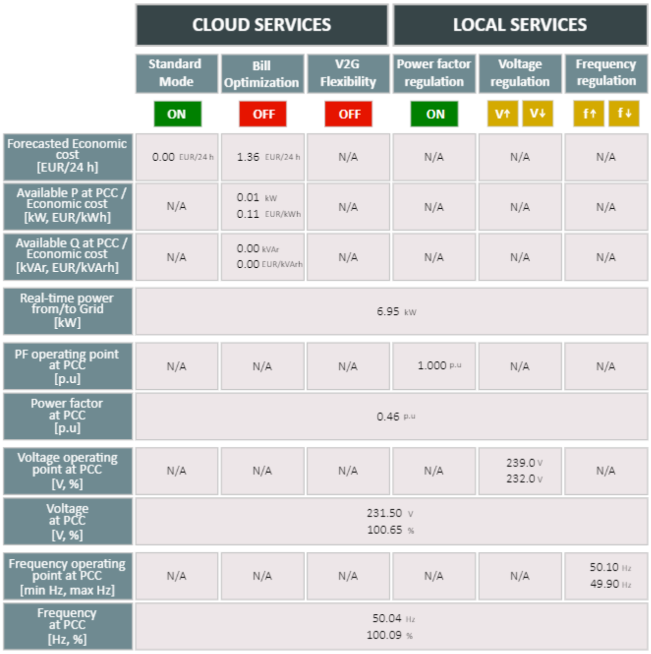


Fig. 2. Micro-grid associated to one EMS controlled by one i-node.



	CLOUD SERVICES			LOCAL SERVICES		
	Standard Mode	Bill Optimization	V2G Flexibility	Power factor regulation	Voltage regulation	Frequency regulation
	ON	OFF	OFF	ON	V↑ V↓	f↑ f↓
Forecasted Economic cost [EUR/24 h]	0.00 EUR/24 h	1.36 EUR/24 h	N/A	N/A	N/A	N/A
Available P at PCC / Economic cost [kW, EUR/kWh]	N/A	0.01 kW 0.11 EUR/kWh	N/A	N/A	N/A	N/A
Available Q at PCC / Economic cost [kVAr, EUR/kVArh]	N/A	0.00 kVAr 0.00 EUR/kVArh	N/A	N/A	N/A	N/A
Real-time power from/to Grid [kW]	6.95 kW					
PF operating point at PCC [p.u]	N/A	N/A	N/A	1.000 p.u	N/A	N/A
Power factor at PCC [p.u]	0.46 p.u					
Voltage operating point at PCC [V, %]	N/A	N/A	N/A	N/A	239.0 V 232.0 V	N/A
Voltage at PCC [V, %]	231.50 V 100.65 %					
Frequency operating point at PCC [min Hz, max Hz]	N/A	N/A	N/A	N/A	N/A	50.10 Hz 49.90 Hz
Frequency at PCC [Hz, %]	50.04 Hz 100.09 %					

Fig. 3. Different operating modes for the micro-grid.

III. THE DC POWER QUALITY SURVEY

A. On-site measurement equipment

As previously stated, the aim of this power quality survey is to carry out on-site measurements in the real DC grid after defining several use cases that will cover different working conditions. The waveforms obtained will be the base to compute different PQ parameters, most of them based on alternating current (AC) definitions and others yet to be defined for DC. In this regard, the equipment chosen for this purpose has to be flexible enough to measure DC content plus high frequency signals with a frequency bandwidth of at least 150 kHz (ripple content due to AC/DC power converters), both for current and voltage monitoring. Due to the nature of the micro-grid, where the maximum current will not exceed 200 A, 3 current transducers with a current range of 200 Arms were selected. Concretely, the model of the sensors is Signaltec CT200 AC/DC, with a bandwidth (-3 dB) from DC to 1.1 MHz. The uncertainty within the range of measurement is 0.001 %, a temperature coefficient of 0.2 ppm/K, an angular accuracy of 0.015º/kHz and a frequency influence of 0.01º/kHz. These current sensors are part of a multi channel current transducer system (Signaltec MCTS II), which is connected to the recorder via several plug-on burden resistors. Regarding voltage measurement, three HIOKI BNC differential probes P9000 were chosen. Their maximum range of measurement is 1000 V AC/DC and the DC amplitude accuracy is equal to ±0.5 % at full scale. Again, the three voltage probes will be connected to the recorder by using BNC cables. All the systems described before will be metrologically calibrated against international traceable standards, which ensure that the measurements obtained meet their calibration reports.

A computer-based platform was chosen as the system that will guide all the acquisition process. Concretely, a personal computer tower with one i5-11400 processor, 64 GB of RAM memory, 1 TB m.2 NVM Express Solid State Drive and one Eaton Ellipse PRO 650 uninterruptible power supply (UPS) will be the base of such recorder, allowing remote connections to supervise the measurement campaign. The Signaltec MCTS II plug-on burden resistors (current sensors) and the three HIOKI voltage probes will be connected to the tower, concretely to one PXIe National Instruments system. This PXI, equipped with 2 PXIe-6124 cards, provides high-performance (ADC resolution of 16 bits and a LSB_{rms} system noise of 0.95) and high-speed (up to 4 MS/s simultaneous sampling) data acquisition functionalities for a total of 8 input channels. These specifications exceed the requirements needed for the purpose of this work. For a higher performance, if needed, the system can be modified to use in parallel with the two PXIe-6124 cards one PCI 4462 DAQ module (4 channels with an ADC vertical resolution of 24 bits).

Although the solid-state drive (SSD) has a capacity of 1 TB, special attention must be paid to the fact of having suitable trigger mechanisms to detect DCPQ events. This will allow an automatic trigger for recording current and voltage waveforms when necessary, avoiding the unnecessary collection of continuous raw data and associated storage, transmission and data processing tasks. All data collected will be stored in a relational database which will ease consulting and fetching processes over the acquired data, even remotely.

B. The measurement campaign

Different working conditions of the micro-grid will be tested during the duration of the measurement campaign. Firstly, three different points of measurements will be chosen corresponding to the three available current and voltage probes described in subsection III-A. The first one will be the point where the micro-grid is connected to the electrical grid as their impact to the mains must be evaluated (red circle in Figure 1). The second and third points will correspond to the DC side of inverters number 1 and 2 (orange and green circles respectively). These points were chosen as these inverters are connected most of the time whereas the third one is only switched on when the first two are fully charged. This could happen just a few moments in the day (e.g. during a very sunny or windy day) so its contribution to the overall PQ is limited. After selecting the location of the measurement points, the duration of the campaign will be a key parameter to be fixed. In principle, the measurement campaign will last several weeks (or even months, depending on the information gathered during the survey), trying to cover as many different working conditions as possible, not only for the micro-grid but also for the distribution grid. It is clear that the impact of the first to the second will be different as the loading conditions of the distribution grid change constantly. Besides, different operating modes of the micro-grid, as well as their set-points (Figure 3), will be tested. This will be crucial to force the micro-grid to work outside its nominal point. For example, the activation of the voltage regulation mode by a temporary activation of the super capacitor banks will change the existent PQ at the PCC.

During the execution of the measurement campaign, the system will store current and voltage waveforms according to its implemented triggering rules. Besides, the waveform recorder will include preliminary real-time analysis tools for an on-line evaluation of some PQ parameters in both AC and DC and the detection of abnormal PQ events associated with DC grids applications. This will contribute to a revision of the current EN 50160 standard [10] by providing the data, methods, guidelines and recommendations necessary for the standardisation of voltage characteristics of public electricity supply, to the CENELEC CLC TC8X WG1. Additionally, this information will be very valuable for other technical committees, like the IEC TC85 WG20 (equipment for measuring and monitoring of steady state and dynamic quantities in power distribution systems) and the IEC SC77A WG9 (PQ measurement methods).

IV. CONCLUSION

Nowadays, with the increasing amount of systems devoted to a decentralized electrical generation, most of them working on the DC side, the accurate measurement of voltage and current waveforms imposed inside the micro-grids is of increasing importance for a suitable planning and exploitation of the electrical grid. This paper describes firstly the DC micro-grid selected for making a complete evaluation of the existent AC and DC content. Later, suitable recording equipment with proper trigger mechanisms to detect DCPQ events, as well as high-performance voltage and current transducers, were chosen. Undoubtedly, a great amount of data will be collected for the duration of the measurement campaign. It will include not only traditional ACPQ information, but also preliminary on-site DCPQ parameters for low-voltage DC grids. These parameters will be defined during the EMPIR project “Standardisation of measurements for DC electricity grids”. In this regard, the outcomes of this work will be crucial for regulation and standardisation of emerging DC grids.

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