Power Quality Measurements Performed on a Large Wind Park at Low and Medium Voltage Level

Emilio Ghiani, Fabrizio Pilo, Gian Giuseppe Soma, and Gianni Celli

Abstract-- The integration of wind parks into the power system may cause power quality concerns. Thus, an important issue is the evaluation of how much the power quality would be affected by fluctuant power production and by the connection of the wind turbines to the power system.

This work investigates the impact of wind parks on the distribution network power quality. The field measurement results give important indications about the real effects of the integration of large interruptible renewable energy sources within the power system.

Keywords: Wind power, Power quality measurements.

I. INTRODUCTION

Wind power generation has experienced a very fast development worldwide mainly due to environmental reasons. In fact, many projects support government's commitment to the Kyoto Protocol, as well as the goal of the European Union to produce 22% of Europe's electricity from renewable energy sources by 2010. The majority of that new renewable power production is expected to come from the wind generation, which is actually the more convenient from the technical and economical point of view.

As the wind power penetration into the grid is increasing quickly, the influence of wind turbines on the power quality (PQ) is becoming an important issue. Usually, the generation of wind power occurs with the operation of multiple wind turbines (WTs) in arrangements denominated wind parks (or wind farms). The integration of these wind parks into the power system may cause power quality concerns and an important issue is the evaluation of how much the power quality will be affected by power production and by the connection of WTs to the grid. The connection of WTs to distribution networks is often hampered by power-quality considerations (i.e. by the concern of utilities for the possible deterioration of the network voltage quality) and the need to fulfill regulatory standards such [2]. Several investigations have been performed over the years, analyzing the steady-state and fast voltage variations, flicker emissions, switching transients and harmonics, which contributed significantly in better understanding the possible effects of the WT connection. In particular the studies [3], [4] dealt with the investigation of voltage fluctuations and presence of harmonics in large wind parks.

The purpose of this work is to analyze the power quality that occur in the electrical vicinity of a wind turbine at low voltage levels, and the interaction of the wind farm installation with the power system at the point of common coupling with the transmission grid at medium voltage level. Slow voltage variations and flicker as well as voltage sags, transients and harmonics are measured by means a modern digital measurement system. The field measurements results give important indication about the real effects of the integration of large wind power sources within the power system.

The structure of the paper is the following. In Section II, the wind power plant where the measurements have been performed is described. In Section III, the implementation of the methodology of measurement is presented. The most important measurements results are deeply discussed in Section IV.

II. WIND PARK DESCRIPTION

The measurements have been performed at the Littigheddu (Sedini) wind park located in Sardinia (Italy). The site has a good power availability with an average wind speed above 5 m/s (see Fig. 1) [1].

The wind park, that is one of the largest installations of wind turbines in Italy, started operating in 2005. It is constituted by 36 wind turbines in five strings with 1.5 MW doubly fed induction generator (DFIG) for a total power installed of 54 MW. Each machine is active yaw and pitch

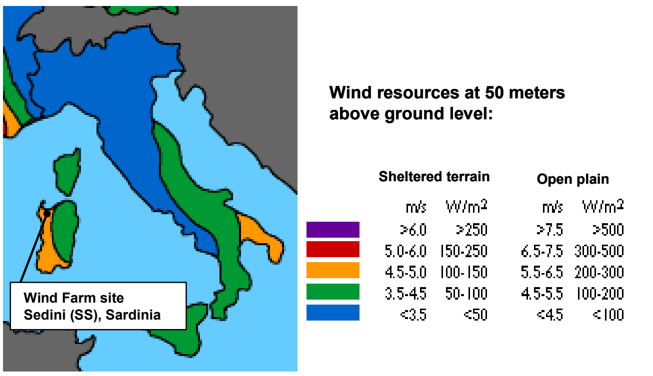

Figure 1. The Littigheddu (Sedini-Sardinia) wind farm location.

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regulated with power/torque control capability and has a rotor diameter of 70.5 metres.

In Fig. 2 the electrical system of each wind turbine is presented. A doubly-fed three-phase asynchronous generator has a wound rotor that is connected to the network through a pulse-width modulated IGBT frequency converter which controls the excitation system in order to decouple the mechanical and electrical rotor frequency and to match the network and rotor frequency. The wind turbine rotor is coupled to the generator through a gearbox which adapts the two different speeds of rotor and generator. The control system usually keeps the power factor to unity, but the wind park can also exchange reactive power with the rest of the network.

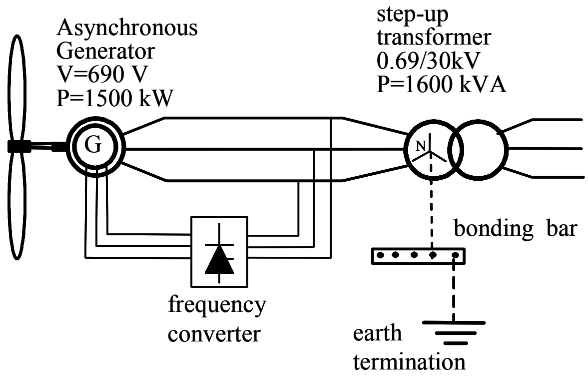

Figure 2. Electrical system of DFIG wind turbine

The stator windings of the generator are directly connected to a step–up transformer which transforms the voltage from the generator voltage of 690 V to the distribution level of 30.0 kV. Five cables, one for each string, with lengths ranging from 5.8 km to 7.6 km, transmit the energy to the MV/HV substation of interconnection with the 150kV Sardinian transmission network by means of a 30/150kV, 63MVA transformer.

III. POWER QUALITY MEASUREMENT SET-UP

Power quality is a generic term used to resume all the items connected to the disturbances existing in the supply voltage of an electrical power system or in the current absorbed by an electrical plant, when the ideal conditions of sinusoidal waveform, nominal frequency and amplitude, symmetrical voltages in a three-phase system and continuity of supply are not complied with.

When power quality measurements are performed on a system with wind production, due to the presence of electronic devices and frequency converters, the voltages and currents are usually nonsinusoidal quantities. In this application the measurement system has to be carefully chosen and, in particular, it has to be composed by transducers with high bandwidth, analog conditioning blocks, analog to digital converters and digital signal processing and, in case of long term measurements, a storage unit.

In the following, the measurement system installed in the MV and LV sections is deeply described.

A. LV measurement system

The following hardware components have been used:

- Power monitoring instrument Dranetz PX5, 8 channels, 4 voltage and 4 current, 256 samples/cycle, RMS Accuracy: ±0.1% of Reading, ±0.05% Full Scale, over 7KHz bandwidth, Measures flicker according to IEC 61000-4-15, Complies with IEEE 1159, IEC 61000-4-30 Class A and EN50160;
- Instrument voltage probes that can measure from 1 to 600 V.
- n. 3 current probes LEM FLEX RR3035, current ranges of 30/300/3000A, bandwidth: 10 Hz to 50 kHz, Accuracy: 1%.

The measurement system has been placed at the terminals of one of the wind turbine, between the generator's output and the LV side of the step-up transformer according to a 3 Phase, 3 Wire Wye connection. Three channels have been connected to voltage and current probes. The neutral has been connected to common and has been the reference for the three channels in order to measure the phase-to-neutral voltages. A simplified connection diagram is provided in Fig. 3 (for the sake of simplicity only one phase connection is depicted). The measurement system permits measuring the currents and voltages instantaneously. The following parameters have been configured for the measurement:, mean, maximum and minimum, RMS voltage and current values each minute; mean, minimum and maximum active and reactive power and power factor each minute; total harmonic distortion (THD) and individual harmonics calculated each minute; flicker measurements, calculated as per IEC 61000-4-15, with Pst (short term) interval equal to 10 minutes, Plt (long term) interval equal to 2 hours.

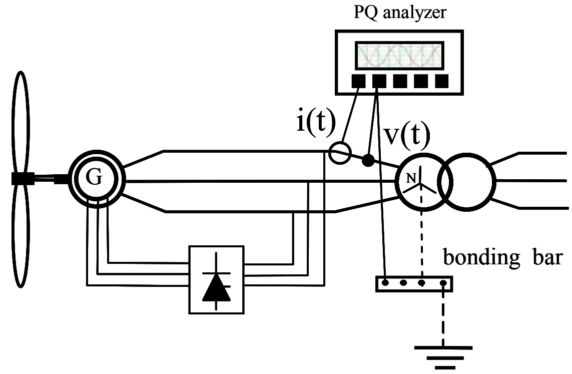

Figure 3. LV measurement set-up

B. MV measurement system

The following hardware components have been used:

- Power monitoring instrument Dranetz PX5;
- n. 1 PEARSON ELECTRONICS VD-305A capacitive voltage divider, nominal division ratio 2000:1, Maximum Pulse Voltage: 300 kV, bandwidth: 30 Hz to 4 MHz, Accuracy: ±5%.

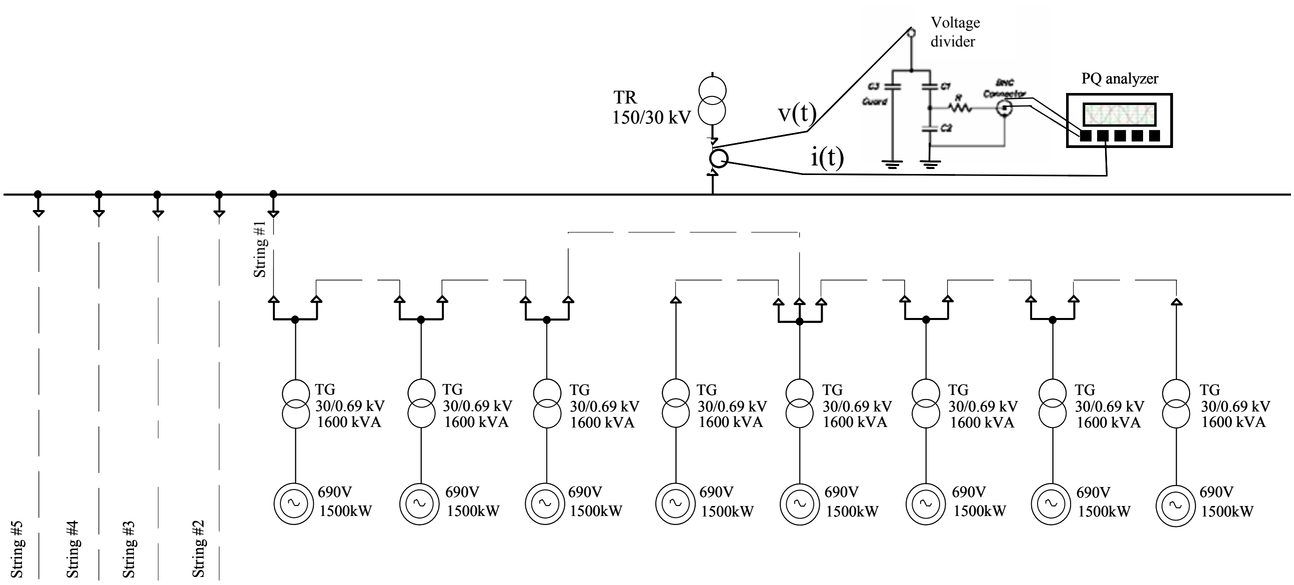

Figure 4. MV measurement set-up

- n. 1 current probes LEM FLEX, (see LV measurement section heading).

In order to analyze the collective behavior of the wind power plant the measurement system has been placed at the point of common coupling (PCC) with the transmission system according to a single phase connection. A simplified connection diagram is provided in Fig. 4.

IV. Measurement Results and Discussion

The data presented have been recorded since December 2005 and the measurement campaign is still taking place.

For the sake of brevity, only the most significant results are reported in the paper with a comparison between the parameters measured on the LV side of the single turbine and the same measure at the PCC of the wind farm.

A. Voltage waveforms analysis

The typical voltage waveform measured at the terminal of the generator is showed in Fig. 5. The Total Harmonic Distortion values, *THD* is equal to 2.77%. Individual harmonics have been measured giving lower values than the limits indicated in [2].

The harmonic emissions are quite high, because the measurements have been done between the generator and the low voltage side of the machine transformer. On the high voltage side of the transformer it can be expected a reduced harmonic distortion level due to the damping features of the transformer.

Distortion levels are usually high in DFIG turbines due to the frequency converter, depending on the commutation frequency. The distortion caused by the converter can be clearly observed in Fig. 5. Anyway, although harmonic distortion is an important issue in the case of variable-speed turbines, the high switching frequencies, the advanced control algorithms and the filtering techniques used in the wind farm

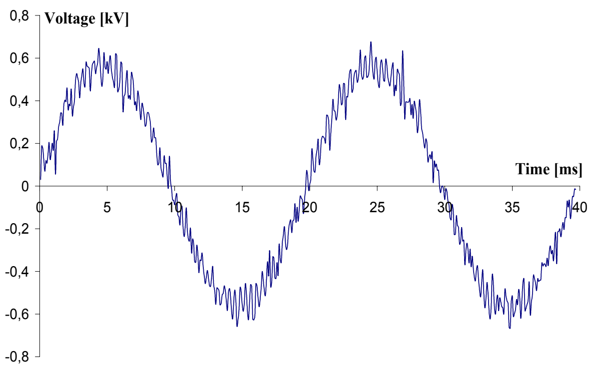

Figure 5. Phase-to-neutral voltage waveform at the terminal of the generator

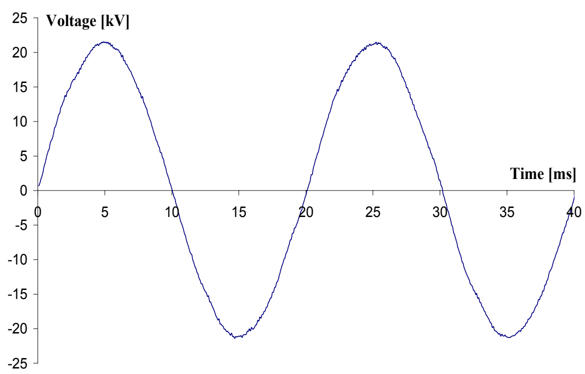

Figure 6. Phase-to-neutral voltage waveform at the PCC

allows reducing the distortion well down the maximum value tolerated by standards .

Fig. 6 presents the typical voltage waveform measured at the PCC of the wind farm between one phase and neutral. The Total Harmonic Distortion value, *THD* is equal to 0.93%.

This very low distortion level results from the combined smoothing effect due to the aggregation of the waveforms of the 36 generators.

Compared with maximum harmonic levels for the power system specified by EN 50160, even though this standard is not applicable to this context, these values of *THD* are largely within the limits.

This result permits stating that the wind park works without a particular negative impact on the transmission network and demonstrates that many power quality concerns about the integration of wind power within existing networks are not justified when DFIG turbines are installed.

B. Voltage Variations with Power Produced

It has been observed a voltage variation at the terminals of the generator depending on the power generated. Fig. 7 shows the trend of the active power and voltage RMS for a time period with high power production.

At full load the phase-to-neutral voltage RMS has been about 390.7V whereas at no load has been about 401V.

C. Long-term Voltage Variation Analysis

The measured RMS voltage values, under normal operating conditions, excluding situations arising from faults or voltage interruptions, during all the observation interval has been within the range of ± 5% of the nominal voltage.

D. Voltage sags and swells

The power quality analyzer has been set to register transients when thresholds have been exceeded. Voltages below 95% and above 105% of the RMS nominal value have been recorded.

Fig. 8 shows a voltage sag caused by the wind turbine disconnection from the electric system due to the excessive power production (overload condition).

During the eight month measurement period, 18 voltage sags have been registered at the terminal of the generator:

- 7 voltage sags between 10 and 20% depth and duration from one to five cycles;
- 5 voltage sags between 20 and 30% depth and duration from two to four cycles;
- 4 voltage sags between 40 and 50% depth and duration from two to four cycles;
- 2 voltage sags with a depth greater then 50% and duration from two to four cycles.

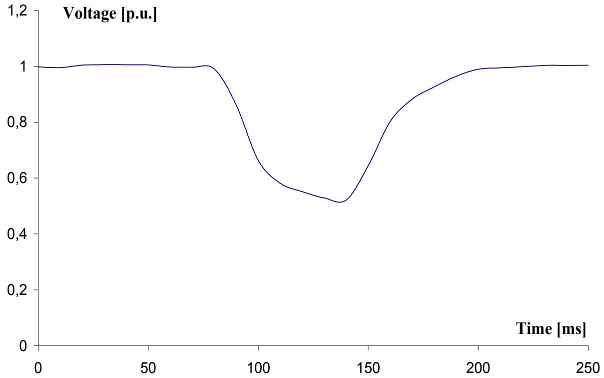

Figure 8. Voltage sag at the terminal of the generator

No voltage sags have been recorded at the PCC of the wind farm during the MV campaign of measurements, but it should be recognised that period of observation is too short to have a good statistics.

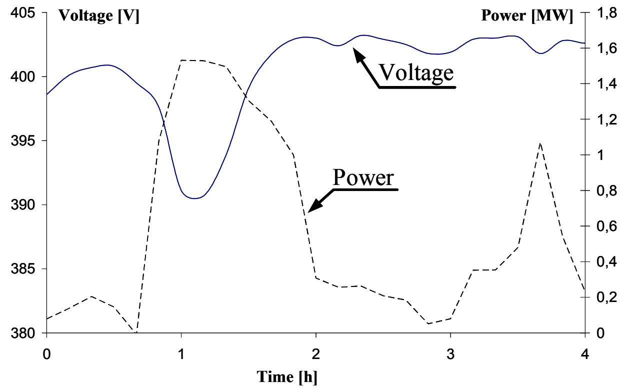

Figure 7. Voltage variation compared with power generated

E. Flicker

Flicker is a power quality disturbance normally associated with wind power production. The torque from a horizontal axis wind turbine has a periodic component at the frequency at

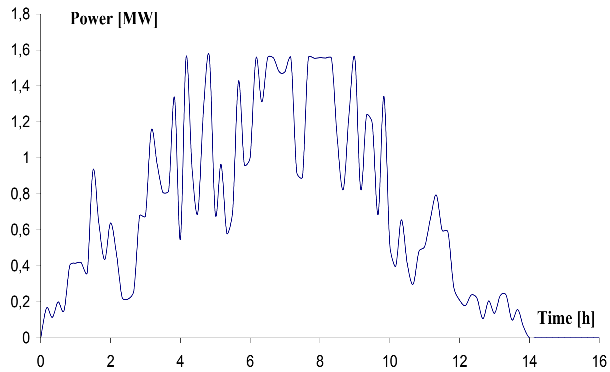

Figure 9. Power generated by the single turbine monitored

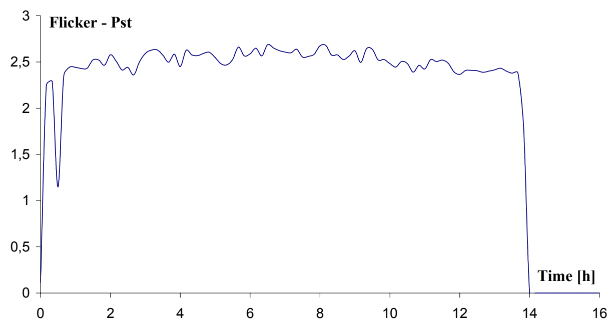

Figure 10. Flicker measured at the terminal of the generator

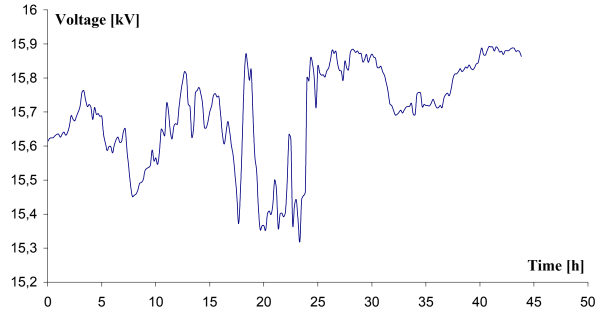

Figure 11. RMS voltage at the PCC

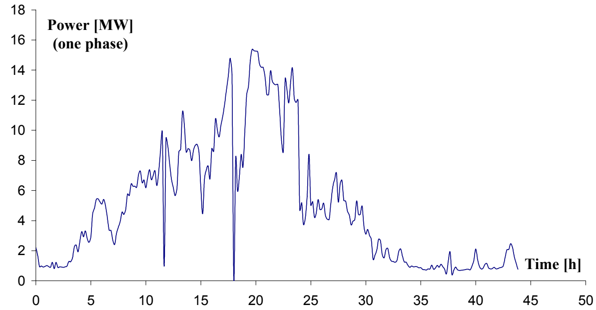

Figure 12. Power generated one phase at the PCC

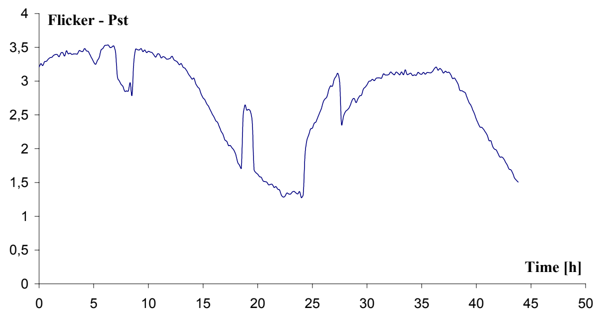

Figure 13. Flicker at the PCC

which the blades pass the tower (1-2 Hz) caused by a variation of the wind speed seen by the blade. Such variation depends on the combination of the tower shadow, wind shear and turbulence. The torque fluctuations are directly translated into output power fluctuations because there is only a partial buffer between mechanical input and electrical output. Depending on the strength of the network connection, the resulting power fluctuations can result in voltage fluctuations at a frequency that is still perceived by the human eye causing flicker. Flicker can become a limiting factor for integrating wind turbines even in relatively strong grids. Fixed speed wind turbine can cause high flicker whereas variable speed one can limit the flicker within reasonable values.

In the proposed measurement campaign the Flicker has been analysed at the LV connection of a single WT and at the PCC of the wind farm.

The measurements at the LV terminals of the wind turbine showed that the flicker level (Pst) is correlated with the active power produced by the generator. In particular the flicker level increases with the production and remain about constant even though the power changes as depicted in Figs. 9-10.

The flicker at the PCC depends on the power fluctuations caused by the 36 turbines of the wind farm is illustrated in Figs. 11-12-13. Measures have revealed that the flicker increases as the power produced decrease. As it can be observed in Fig. 11, part of this flicker effect could be imputable to the regulation action of the on-load tap changer (OLTC) installed in the substation transformer as well as caused by switching operations of start and stop of wind turbines [3].

This behaviour is typical for OLTC transformer with conventional automatic control systems. In fact, in the typical control of OLTC, the tap position is changed discretely in order to maintain the voltage within the permissible limits. Furthermore, the tap changing operation is dependent on the dead band and the time delay. The dead band and time delay element is adopted to reduce the effect of transient voltage variation and avoid unnecessary tap changing operation.

The results are in good agreement with other contributions related to measurements in similar conditions [4].

Reactive power diagrams are not depicted given that DFIG generators are operated with very high power factor (> 0.98).

V. CONCLUSIONS

In this paper, the power quality of a large wind park at the low voltage level and at the point of common coupling with the HV Sardinian transmission network is investigated. Flicker, harmonics, and voltage sags have been analyzed and correlated with wind characteristics of the site.

The investigation shows that the wind park works without a negative impact on the transmission network and demonstrates that many power quality concerns about the integration of wind power within existing networks are not justified when DFIG turbines are installed.

The correlation of the electric quantities measured and the wind characteristics will be analyzed in a future paper. This further analysis will be very useful for an experimental validation of wind turbine and wind farms models available in the literature.

VI. ACKNOWLEDGMENT

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VIII. Biographies

Emilio Ghiani was born in Oristano, Italy, 1973. He graduated in Electrical Engineering in 1999 at the University of Cagliari and in 2005 he received the Ph.D. degree in Computer Science and Electronic Engineering. Since 2003 he is Assistant Professor of Power Systems at the same University. Current research interests are in the field of MV distribution network planning optimization and power quality measurements. He is IEEE and AEI member.

Fabrizio Pilo was born in Sassari, Italy, in 1966. He graduated in Electrical Engineering at the University of Cagliari in 1992 and earned the Ph.D. from the University of Pisa in 1998. He became Associate Professor of Electrical Power Systems in 2001. His research activity is focused on electrical power systems, network planning and optimization, and neural networks. He is author of more than 90 papers published in international journals or presented in national and international conferences. He is IEEE and AEI member, CIGRE SC C6 invited observer and member of the CIRED TC.

Gian Giuseppe Soma was born in Sassari, Italy, in 1980. He graduated in Electrical Engineering at the University of Cagliari in 2005 and currently is a Ph.D. student. His research activity is focused on management of microgrid and power quality. He is AEI member.

Gianni Celli was born in Cagliari, Italy, in 1969. He received the electrical engineering degree from the University of Cagliari in 1994. He has been an Assistant Professor of Power System with the University of Cagliari since 1997. Current research interests are in the field of MV distribution network planning optimization, power quality, and neural networks. He is the author of several papers published on international journals or presented in various international conferences. He is IEEE and AEI member.