Experimental Prototyping of a Microgrid with Mechanical Point of Common Coupling

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***Abstract*—The smartgrid is a key technology for the sustainable and smart utilization of the renewable energies. In this paper, a prototyping of a microgrid, assembled at the Sustainable Development and Energy Saving Laboratory (SDESLAB) of the University of Palermo, is presented and discussed. In detail, the microgrid presents only one mechanical point of common coupling (PCC) with the main grid and it is electrically separated from the main grid. In this way, the voltage variations of the main grid do not affect the microgrid electric quantities behavior. In order to validate the effectiveness of the voltage and frequency control, several experimental tests and analysis have been carried out. In detail, a no-negligible 11th spatial harmonic component and switching frequency harmonics components have been detected on the microgrid output voltage. Therefore, in order to cancel these harmonic components, a LCL filter has been designed and experimental validated in its effectiveness. The study conducted represents a first stage for the experimental realization of a hybrid microgrid electrically independent of the main grid.**

Keywords—Microgrid, Buck converter, LCL Filter, grid connection.

I. Introduction

Electricity generation, transmission and distribution systems play a fundamental role in the sustainable development of the countries and it is essential to invest resources and scientific efforts on the research of new and innovative solutions [1]-[5]. Since a relevant increase in the development and utilization of renewable energies has been detected in the last decade, it is necessary to address the issue of the control and management of energy flux according to the electricity demand. Furthermore, the renewable sources behavior and their widespread distribution in the territories require a transformation of electrical systems from centralized and linear to distributed and intelligent [6]. In this scenario, microgrids play an important role. In detail, this technology has a key role in the development of large-scale distributed power generation system and integration of the old electricity distribution system [7]. The distributed generation is crucial in order to satisfy a part of the global energy demand with significant pollution reduction, but its presence can cause technological criticalities in distribution networks that cannot be ignored. Therefore, in order to make efficient and reliable distribution systems, which integrates new technologies with traditional production centers, the topic of design, control and management of the microgrids is of considerable importance. The achievement of this goal requires countless studies covering different aspects, such as the more intelligent use of high-efficiency electric drives, power electronics needed for energy conversion and their control [8]-[15].

The advantages derived from the use of microgrid consist in high reliability, energy saving, additional energy storage systems with possible islanding operation for short periods [16]-[18]. The latter aspect can be of relevant importance for hospitals and service structures [19]-[21]. However, the microgrid presents critical aspects, such as the low self-regulation capacity, due to limited grid extension, and the complex management of the interface between micro and main grid.

In this paper, the experimental prototyping of a microgrid interconnecting with the national grid by means of a mechanical PCC is presented. In detail, this study represents the first indispensable research stage to address the crucial aspects of microgrids such as the optimal integration of several kind of load and energy source, the control of power electronics units or the electric drives for the optimization of the static and dynamic microgrid performances and the integration of the electric power management with the new and innovative communication technologies [22]. The designed microgrid is not electrically connected to the main grid and, therefore, it is possible to control the voltage and frequency in an independent manner. For control purposes, several experimental tests and analysis have been carried out. The paper is structured as follows: Section II describes the microgrid concepts and characteristics, Section III describes the microgrid assembled in SDESLAB of the University of Palermo and Section IV describes the prototyping and experimental results.

II. Microgrid Concept and Characteristics

In literature, there are several definitions of the microgrid concept. In detail, according to the American Department of Energy (DOE), a microgrid can be defined as an interconnected group of distributed and charged generators developed within a not defined electrical perimeter that acts as a single controllable entity against the external network [23]. In general, it is possible to define a microgrid as an electrical distribution system formed by controllable and non-controllable generation units (DG, Distributed Generation), energy storage systems (ESS), loads and a connection point (PCC, Point of Common Coupling) with the electricity distribution network [24]. Therefore, the microgrid represents an optimal solution to interconnect sources distributed in the territory, especially regarding the wind farm and solar farm that present random energy behavior. Thanks to their flexibility, it is possible to smartly and efficiently manage DG flux power. The compatibility is an important aspect for the integration purpose with the electrical distribution system and, consequently, for the distribution system transaction from centralized structure to smart and distributed structure. The various sources and loads must be connected through a communication system called the Power Management System (PMS). In a microgrid, the energy produced by the renewable energy sources such as wind, photovoltaic and geothermal can be used on-site and the surplus or the deficit of such energy can be exchanged with the network through the PCC. Therefore, microgrids tend to encourage local production rather than production deriving from the main network.

A key point for microgrids is the ability to work both on grid-connected working operation than off-grid working operation. A great part of the microgrids usually operate in grid-connected operating mode in order to maximize the advantages offered by the main grid and, for technical or economic reasons, they operate some times in off-grid or islanding operating mode. An appropriate storage system and a distributed generation capable of feeding the loads inside the microgrid are required for long periods in islanding operating mode. In detail, the storage capacity represents a key aspect of microgrids especially when the energy is locally generated. Moreover, the stored energy can be also a resource for the main grid. The development and diffusion of microgrids are becoming increasingly popular thanks to their control capacity, the flexible operating modes and the economic and environmental advantages deriving from the smart and efficient use of renewable energies. They will have an important impact on the electrification of rural areas in developing countries where it is possible a high penetration of renewable sources. Although the microgrid appears as a single perfectly controllable unit for the main power supply, it is composed by a set of energy sources and energy users interconnected through static converter systems (AC/DC and DC/AC) [24]. In a deeply interconnected system, the communication and control system plays a fundamental role [24]-[25].

The microgrid components can be classified in:

- Grid forming units;
- Grid supporting units;
- Grid parallel units.

The first components typology allow the frequency and power regulations inside the network and they represent by the diesel generators or controllable generators. Non-programmable loads and energy sources such as wind turbines and photovoltaic systems form the group of "grid supporting units". The grid parallel unit components are the control units employed for the control and management purpose.

III. SDESLAB MICROGRID

A. The scope

The microgrid assembled at the SDESLAB has been designed in order to have a grid electrically separated from the main grid. In this way, the control and regulation of the voltage and frequency are independent from the main grid parameter variations. The traditional grid-connected microgrid structure allows the bidirectional energy transfer. In this case of study, the microgrid presents only one common coupling point with the main grid that allows the energy exchange in a unidirectional way (from main grid to microgrid). At present, there is an AC ring where energy sources and loads can be connected. In future development, an additional DC ring will be realized in order to have different energy sources and loads typologies.

B. The structure

For the galvanic separation scope with the main grid, it is needed to employ an electric drive that transforms the electrical energy of the main grid in mechanical energy and subsequently in electrical energy for the AC ring of the microgrid. In detail, the electric drives is supplied by the main grid by the use of an rectifier stage and an inverter stage which makes the microgrid behaviour independent of the main grid voltage and frequency variations. The assembled structure of the microgrid is summarized in Fig. 1 and it is composed by:

- A DPS 30-A power converter (Automotion Inc.), which is directly connected to the electrical grid. The IGBT bridge of the inverter is made by POWEREX, Model PM30CSJ060. The main features of the inverter are summarized in TABLE I.

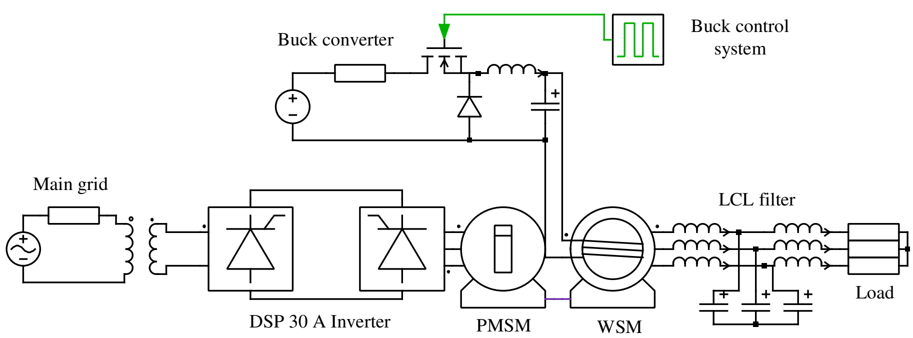


Fig. 1 SDESLAB microgrid structure scheme.

TABLE I. DSP 30-A MAIN FEATURES

Inverter	
Model	DSP 30
Input voltage	230 V
Rated frequency	50 Hz
Max output current (peak)	30 A
Rated power	6500 W
Rated DC voltage	310 V
PWM frequency	2-20 kHz

TABLE II. RATED VALUES OF PMSM

PMSM	
Model	MDFKSRS071-33
Voltage	325 V
Current	13,1 A
Torque	16,2 Nm
Power	5,9 kW
Frequency	175 Hz
Peak current	45 A
Peak torque	52 Nm
Pola pairs	3
Rated mechanical speed	3500 rpm
Weight	14,3 kg
Inertia	10 kg·cm^2

TABLE III. RATED VALUES OF WSM

Synchronous Motor	
Rated voltage	50 V
Stator rated current	8,6 A
Excitation rated current	23,5 A
Pola pairs	2

- A Permanent Magnet Synchronous Motor (PMSM) used as a mover for the synchronous generator. In order to keep constant the speed of PMSM, and consequently the microgrid frequency [26], a field-oriented control [27] is employed and implemented in a dSpace control board. The main data are reported in TABLE II.
- A three phase wound synchronous machine (WSM) is employed as a generator to feed the microgrid. In order to filter the presence of some harmonics component in the induced voltages, an AC LCL filter has been employed [28]. The main data are summarized in TABLE III.
- A buck converter has used in order to control and regulate the magnetizing current of the rotor that control the voltage level of the microgrid. In detail, this buck converter has been designed and built on the base of the microgrid requirements. Moreover, a 48 V and 25 A DC switching power supply was used as power supply.
- An Arduino Due was used to control the buck converter and to control the rotor excitation current. In order to monitor the signals acquired from the current probes, a graphic interface was created for the serial communication between Arduino and the PC. The Arduino Due Analog-Digital Converter module was used to acquire the microgrid voltages. The ACS712 current probe was used to acquire the rotor excitation current.
- A conditioning circuit has been built and employed for the microgrid voltages acquisition. This circuit allows to adapt the voltage microgrid acquisition signal to 0-3.3V range of the Arduino DUE logic.

In detail, an illustration of the electric drive assembled for feeding the microgrid is shown in Fig. 2, while the excitation current regulation circuit components are showed and Fig. 3.

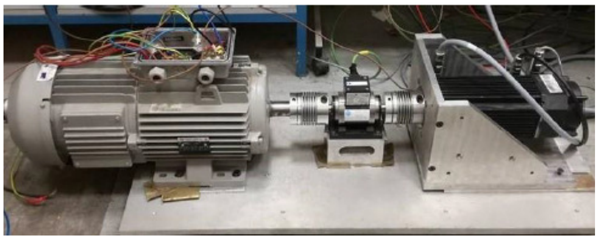
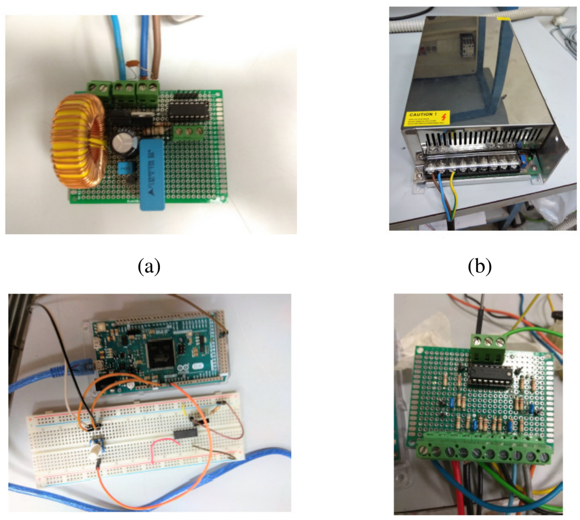


Fig. 2 Electric drive used for feeding the microgrid.



(a) (b) (c) (d)

Fig. 3 Excitation current regulation circuit components: buck converter(a), 48 V and 25 A DC switching power supply, Arduino Due board(c) and conditioning circuit(d).

IV. PROTOTYPING AND EXPERIMENTAL RESULTS

The prototyping of the microgrid has been carried out by means of experimental test. The control of the buck converter and, consequently, of the excitation current amplitude, is carried out by the use of Arduino DUE. The control consists of an internal current loop and an external control loop of the induced stator voltage. For this purpose, the PIs with an antiwind-up have been employed. The buck converter has been designed and manufactured entirely in the SDESLAB and the FQP32N MOSFET with attached IR2110 driver in low side configuration have been used. A first investigation has been carried out with an open chain control of the duty cycle that allowed to choose a satisfactory size of the electrolytic capacitor to level the output voltage from the buck converter. For the prototyping purpose, a no-load test has been carried out where the speed of the PMSM is controlled by the use of the FOC implemented in a dSpace prototyping board and its values regulated so as to adjust the induced voltage frequency equal to 50 Hz. In addition, the excitation current is controlled to obtain a value lower than the 10% of the rated excitation current. The induced voltage (yellow), the excitation current (cyan) and the buck converter output voltage (magenta) have been acquired by the use of the LeCroy Oscilloscope wavepro 7200A (Fig. 4).

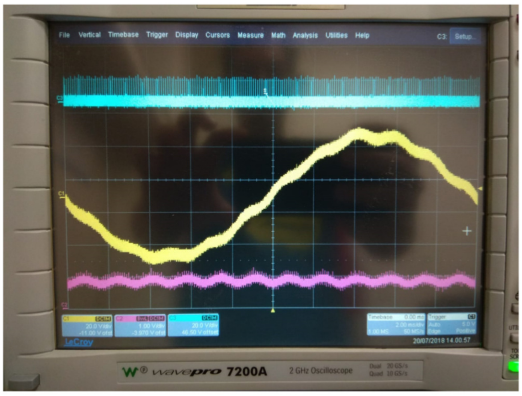


Fig. 4 Induced voltage, excitation current and buck converter output voltage acquisition.

From Fig. 4 it is possible to notice the presence of some harmonics components on the induced voltage. Therefore, harmonic analysis has been carried out and it is detected that the 11^{th} harmonic component (spatial harmonic) and the switching frequency component have amplitude, which is not negligible with respect to the fundamental at 50 Hz. In detail, the induced harmonic components are shown in Fig. 5 with the amplitude expressed in p.u. respect to the fundamental. Therefore, in order to reduce the amplitude of the induced voltage harmonic components, the use of a LCL filter is needed. The LCL filter has been designed and built according to the prescription reported in [29]. This procedure allows to reduce the amplitude of the switching harmonic component. In order to reduce also the spatial harmonic component that present different frequency, it is necessary to select bigger value of the inductances and the capacitor. Therefore, in order to evaluate the possible effectiveness of the LCL filter, a preliminary design study has been performed in the PLECS environment and the induced voltage signal, including the harmonic components identified, has been implemented. In detail, the simulation diagram is shown in Fig. 6.

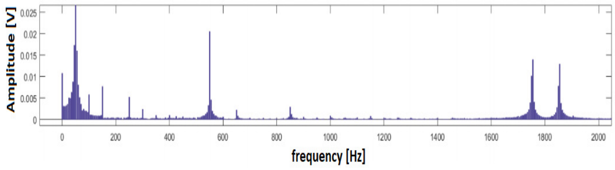


Fig. 5 Induced voltage harmonic components.

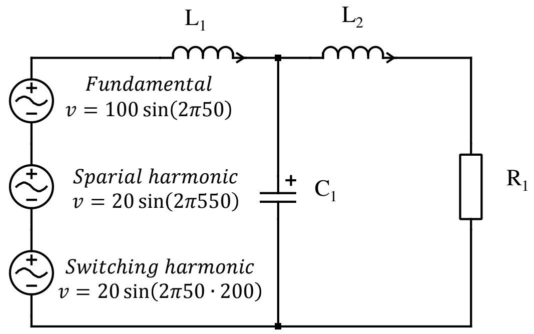


Fig. 6 PLECS simulation diagram for the design of the LCL filter.

As shown by the figure, the induced voltage signal of the microgrid has been simulated with the superposition of three signals:

- Fundamental voltage signal with amplitude equal to 100V and frequency equal to 50 Hz;
- Voltage signal at switching frequency of the buck converter equal to 10 kHz and amplitude equal to 10V;
- Spatial harmonic voltage signal with frequency equal to 550 Hz and amplitude equal to 20V.

After the simulation study, the parameter values of the LCL filter have been chosen equal to:

$$L_1=L_2=560\mu H \; ; \; C=2000\mu F \; ; \tag{1}$$

A photo of the LCL filter build is reported in Fig. 7.

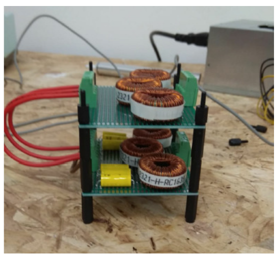


Fig. 7 LCL filter.

For the experimental validation of the filter effectiveness, a load test is carried out with a star connected ohmic-inductive load. Fig. 8 shows the comparison between the pre-filtering induced voltage waveform (magenta) and the post-filtering induced voltage waveform (green).

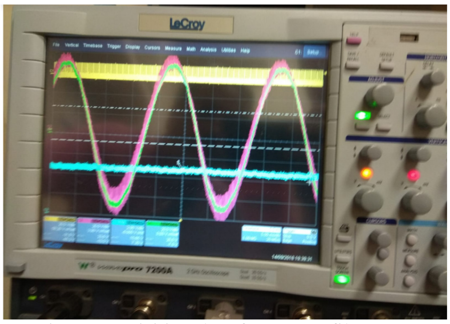


Fig. 8 Acquisition data from LCL filter test.

As shown from Fig. 8, it is possible to assert the effectiveness of the filtering action and, consequently, the amplitude reduction of the harmonics components.

A further investigation has been conducted on the excitation current control that depends from the acquisition of the microgrid induced voltage. As mentioned before, in order to acquire the voltage signals with Arduino, a conditioning circuit has been designed and built. This conditioning circuit must have the following features:

- Ensure the galvanic separation between the measurement circuit and the power circuit;
- Adapt the amplitude of the acquisition voltage signal to the 0-3.3 V range of the Arduino DUE acquisition module.

For this purpose, a 100 VA, 230V-12V transformer and two TL084A operational amplifiers have been chosen. In order to evaluate the effectiveness of the conditioning circuit, a simulation analysis was has been performed in PLECS environment. Fig. 9 shows the circuit diagram implemented in the simulation.

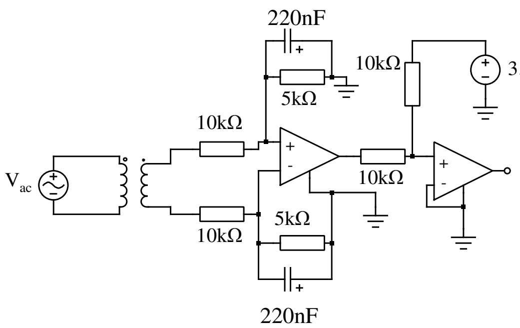


Fig. 9 Electrical wiring diagram of the conditioning circuit.

The simulation involves the signal conditioning into three different stages:

- A first attenuation stage where the induced voltage signal is reported to the conditioning circuit with the transformer. In detail, the rated induce voltage RMS value of the microgrid is equal to 50 V and the respective value at transformer output is 2.6V.
- A second stage where an operational amplifier further attenuates the signal in order to have a peak-to-peak value lower than 3.3V.
- A third stage where another operational amplifier regulates the variation range of the previous voltage signal respect to the 0-3.3V range of the Arduino acquisition module.

The circuit has been built and several tests have been carried out. In order to reduce the possible presence of the conducted and radiated disturbances due to the PWM modulation of the buck converter, an algorithm has been implemented on Arduino that allows to sample the voltage signal at the center of the modulation period. The acquisition of the microgrid induced voltage with Arduino is shown in. Fig. 10.

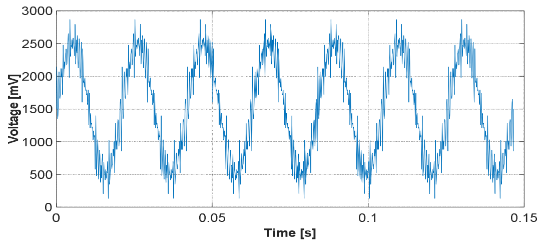


Fig. 10 Acquisition data from loaded microgrid by Arduino DUE.

In detail, it is possible to see the presence of noise in the acquired signals. Therefore, a digital moving average filter has been implemented in the Arduino control algorithm. Fig. 11 compares the signal before and after the moving average filtering action.

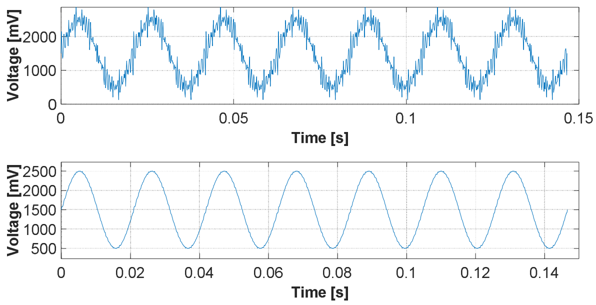


Fig. 11 Acquisition data before and after moving average digital filter

As shown in Fig. 11, the moving average filtering action is satisfactory and the signal can be used as a reference signal for the excitation current control. The load operations of the AC ring have been validated with further experimental tests.

V. Conclusions

This paper has presented a prototyping of an assembled microgrid, composed by an electric drive supplied from the national main grid and a WSM supplying an AC ring. The microgrid has no electrical connection with the national main grid and, therefore, the voltage and frequency control is totally independent from the main grid frequency and voltage variations. A LCL filter and conditioning circuit have been designed and built. The excitation current control was made with a low-cost Arduino controller and with a buck converter designed and self-built. The results obtained from experimental tests are satisfactory for the prototyping purpose. In future developments, the design and assembly of a DC ring will be addressed in order to obtain a hybrid microgrid. Furthermore, in order to obtain a flexible hybrid microgrid and perform other experimental investigations, additional RES like photovoltaic plants and micro wind turbines will be considered and connected to the microgrid.

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