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Original Citation:
Prince - Electrical Energy Systems Lab A pilot project for smart microgrids / Cagnano, A.; De Tuglie, E.; Cicognani, L.. - In: ELECTRIC POWER SYSTEMS RESEARCH. - ISSN 0378-7796. - 148:(2017), pp. 10-17. [10.1016/j.epsr.2017.03.011]

Availability:
This version is available at http://hdl.handle.net/11589/117254 since: 2022-06-08

Published version
DOI:10.1016/j.epsr.2017.03.011

Prince — Electrical Energy Systems Lab
A pilot project for smart microgrids

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ABSTRACT

The aim of this paper is to define an organized approach for improving the economic, reliable and secure operation of microgrids operating either in the On-grid or in the Off-grid. According to this methodological approach, a microgrid can be operated into five Operating Modes and five Transitions. Proper management of each of them has been examined and implemented on the existing microgrid developed at the Prince — Electrical Energy System Lab of the Polytechnic of Bari. This microgrid can be considered a hard test bed for dynamic stability studies since it is an inertialess system.

1. Introduction

Microgrids play a key role in the integration of Distributed Generators (DGs) and, in particular, of Renewable Energy Sources (RESs). Nonetheless, their practical implementation into actual distribution networks is still hindered by several technical issues mainly related to their operation, protection and control [1]. As consequence, many experimental microgrids have been built for research purposes focusing on these topics [2–26]. Most of these microgrids, [2–8], can operate only in the grid connected mode and they provide useful test beds for optimal management problems and optimal dispatching strategies. Other microgrids [9–16] can operate only in the islanding mode and they have been mainly used to develop new protection schemes or to investigate on voltage and frequency stability issues.

Several microgrids are able to be operated in On-grid and Off-grid mode, with or without power interruption. The CERTS microgrid is used as a test bed for developing suitable control strategies in order to stabilize the microgrid during state transitions. Moreover, this system adopts a self-adaptive protection scheme able to protect the microgrid in all possible operating states [17–19]. The microgrid installed in the National Technical University of Athens (NTUA), focuses on developing black start procedures [20,21]. Other projects, such as NICE GRID, PREMIO and IREC [22–29] must be mentioned for their contributions in developing new protection schemes and control strategies for the islanding detection. In particular, in Refs. [27–29] new tools are suggested for the optimal management of an isolated microgrid. The optimal control actions are evaluated by solving an optimization problem aimed at minimizing the total operating costs of the microgrid by adopting a mixed-integer nonlinear algorithm.

The experimental AC microgrid installed at the Polytechnic of Bari must be included in the list of uninterruptible microgrids. The main purpose of this project is to verify the possibility of realizing a microgrid integrating components already installed in a distribution grid. For this reason, microgrid's components are chosen among those commercially available and thus, without any droop control. Moreover, in order to realize a realistic microgrid, each dispatchable source is chosen so that its capability cannot comply any possible unbalances which may occur on the system. These design choices require new control procedures for managing the microgrid in an economic, reliable and secure way.

The topic of the system security has been widely investigated in the last years for large scale systems following the pioneer work [30]. On the contrary, very few papers focus on microgrids security [31,32]. Moreover, these works regard microgrids operating in On-grid or in Off-grid, disregarding the transitions between these two states. In this paper an organized approach able to guarantee an economic, reliable and secure operation of a microgrid in all its operating and transition states is proposed. The approach has been

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implemented and tested on the experimental microgrid built at the Polytechnic of Bari.

2. Operational states of a microgrid

Fig. 1 reports a schematic representation of the main functions for the supervision and the control of a microgrid in all operating states and transitions. It provides a good conceptual picture of the overall control requirements of a microgrid.

For most of the time the microgrid lies in a Secure or Normal State, which can be either in parallel with the utility grid or in the islanded mode. In these states the main concerns regard the economic management of the system. Anyway, technical constraints are continuously monitored in order to judge if the system moved in an Insecure State. If an Insecure State is detected, the EMS (Energy Management System) must focus on the system security disregarding economic issues. The microgrid can directly move from one Normal State to another. The transition from the On-Grid to the Off-Grid mode can follow a system perturbation or it can be planned. The opposite transition (from Off-Grid to the On-Grid) can be intentionally activated by the system operator through a Synchronization procedure. The Emergency State can be reached coming from the Normal State as well as from the Alert State if particular contingencies occur. In this state the EMS must promptly recover the system security, otherwise a general blackout could occur. The Blackout can be recovered by actuating the On-Grid or Off-Grid Black Start procedures.

In what follows, details on the functions needing to be implemented in all states and transitions will be given.

2.1. *Grid connected state*

In the grid connected state, control actions are centrally evaluated by solving an economic optimization problem aimed at minimizing the trade-off between the internal production and the power exchanged with the utility grid. To achieve this objective, the optimization problem is formulated according to classical economic dispatch algorithms. However, in order to comply with an Off-Grid transition, reserve constraints must be considered in the optimization problem. Reserve providers must be selected based on their operating costs, their availability, and their production plan. Moreover, for those microgrids that can be operated in the islanded mode by a master/slave control scheme, the SCADA (Supervisory Control And Data Acquisition) must select a generator able to take the master function. The master will be chosen as the generator having the largest available reserve among all available generators. For this purpose, the SCADA iteratively monitors the power of generators and, if the tie line breaker is opened, the selected generator will take the master function.

The power factor regulation at the connection point represents another task of the controller. The reactive power can be provided by inverters interfacing generating units, even if their adoption led to greater conduction and switching losses. In this case, an optimal reactive power flow able to share the control burden among all possible reactive power sources need to be implemented [33,34].

2.2. *Island State*

The Island State can be reached if an unpredicted event or an intentional trip of the tie-line occurs. The system, in the Island State lies in a normal or a secure state. Like the case of the grid connected state, economic objectives and operational issues are the main tasks. Consequently, the same routines will run, excepting those related to the reserve and the reactive power management.

For those microgrids adopting a master/slave controller, the isochronous controller will take the overall regulation effort due to any unbalance occurring on the system. Thus, the regulation capacity of the master generator must be greater than the expected maximum power unbalance. If this condition is not satisfied, a cooperative control strategy is needed. In this case, a routine able to share the control burden among all sources in accordance with their reserve margins and their ramp-up and ramp-down rate limits is implemented. With this function the power produced by the master generator will be kept, as close as possible, to around 50% of its rated power. Among others, also batteries can be selected to be the master. In this case, in order to maximize the duration of the master function of the batteries, another task aimed at keeping the State Of Charge (SOC) close to 50% need to be considered.

The reactive power management function will tend to minimize costs associated to the reactive power provision. In fact, it must be considered that, as in the case of the On-Grid mode, the reactive power provision is not costless [35]. Since in the Island State the master (the voltage forming) is responsible of supporting the system voltage, the control burden will rely only on it. In order to relieve the master unit from the total control burden, a routine will engage all other reactive sources, thus reaching the optimality condition for the reactive power provision.

2.3. *Alert State*

Starting from Normal Operating states, particular dispatching policies can move the system operating point in the Alert State. In this state, although the microgrid still operates with all variables within their allowable limits, its safe margins are dangerously reduced. This means that, if a particular disturbance occurs, the microgrid would enter in the Emergency State, in which some operating limits are violated (N-1 security criterion). This situation could cause the trip of some devices due to the intervention of their protections. For this reason, when the system is in its alert state, the preventive control needs to be activated. It consists in finding a new suboptimal equilibrium point where all limits are guaranteed even if the hypothetic contingency occurs [36,37].

2.4. *Emergency State*

Unpredicted events may move the system from Normal or Alert States to the Emergency State, where some limits are violated. At this stage, the corrective control needs to be quickly activated. If the event is not the trip of the tie-line, the corrective control will take the advantage of the distribution network support. In this case, particular attention is paid to the tie-line flow that must be less than the Total Transmission Capacity (TTC) [38,39]. Even if inverter-based components are very quickly, they cannot be controlled in the real time since their time responses are not compatible with the fast dynamic behaviour of the system. At this stage of knowledge, the only way to operate a corrective control seems to be the generation/load/storage shedding [40]. Anyway, in microgrids with minimal or null inertia the blackout phenomenon is characterized by very fast dynamics. For this reason, the lack of time to take appropriate corrective measures against catastrophic events on the system makes corrective control actions less effective as in the case of big power systems.

2.5. *Blackout*

With the system in the emergency state, if corrective control actions are not able to bring back the microgrid in its normal state, a general blackout can take place. The blackout starts by a single event that gradually leads to cascading outages and ends with the system collapse.

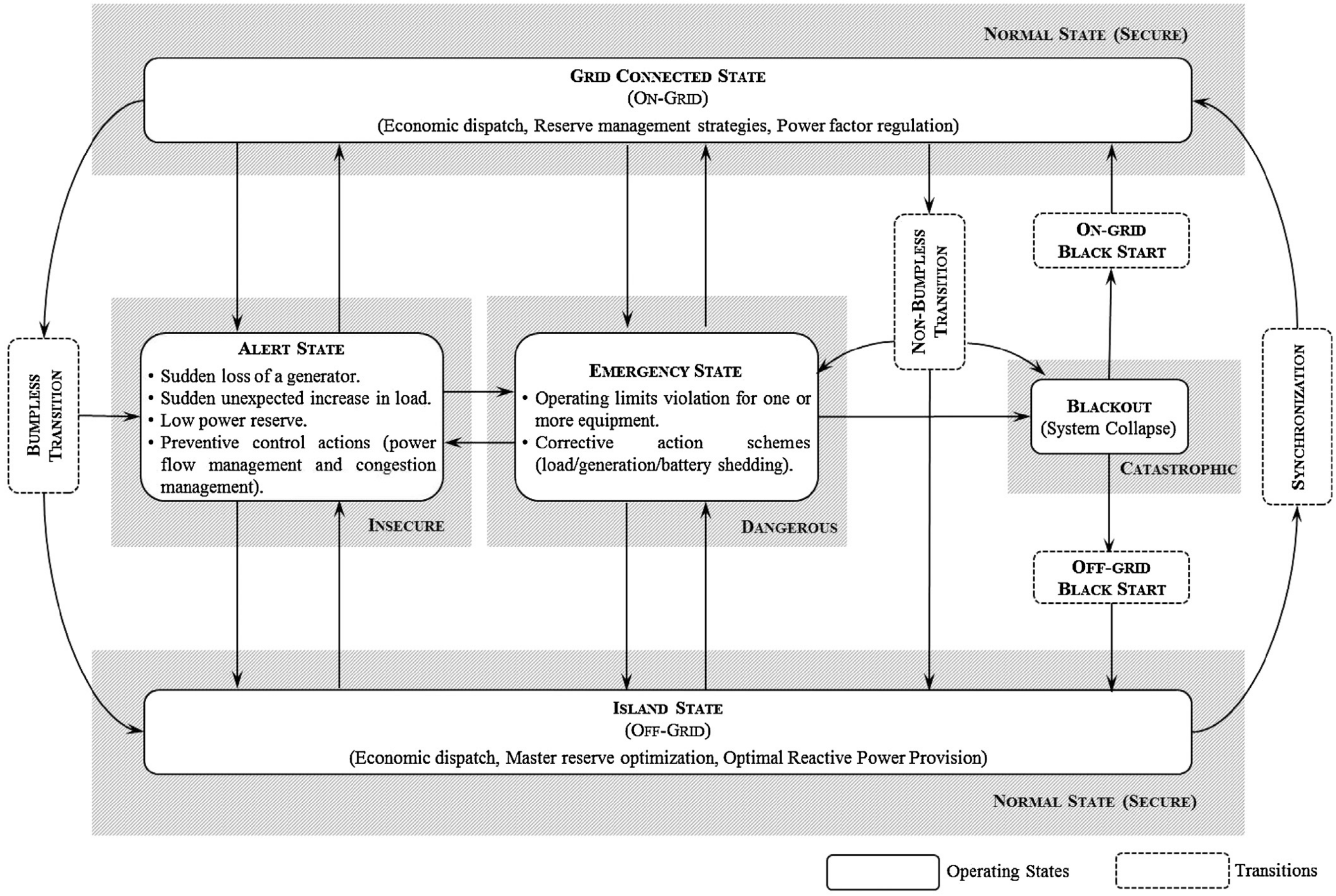

Fig. 1. The EMS control strategies related with the microgrid operating states.

2.6. *Non-Bumpless Transitions*

The Island State can be reached coming from the Grid Connected State through the accidentally or intentionally Non-Bumpless Transition. The causes that lead to an emergency island may be endogenous or exogenous. In the first case an internal fault can cause the opening of the tie-line breaker. The subsequent islanding condition is easily and promptly detected by the SCADA system since it continuously monitors the status of all breakers and, in particular, of the tie-line breaker. If exogenous, the islanding is caused by the loss of power due to a fault in the distribution grid. The islanding condition is produced by the anti-islanding relay which is triggered by an over- and under-voltage, and over- and under-frequency (OV/UV and OF/UF) functions. In this case, the island is obtained when such relay detects an anomalous operating system condition by opening the tie-line breaker. This event could move the system in an insecure operating point of the stability region, especially for those microgrids having low inertia or even null. As consequence, the control system must recover such unsafe condition in a very short time.

The intentional island is more simple to be managed because it is activated by a voluntary opening of the tie-line breaker, thus the control system has enough time to react to this perturbation.

In the emergency island as well as in the intentional island, the absence of the distribution network support can give rise to a rapid voltage or frequency collapse, which moves the system operating point in the Emergency State.

2.7. *Bumpless Transition*

The Bumpless Transition is obtained by smoothly moving the system from the On-Grid to the Off-Grid state. This is done by a control loop able to get the tie-line power flow equal to zero. If such condition is achieved, the opening of the tie-line breaker will not produce significant perturbations. As consequence, the risk of blackouts is minimized. With this function, the controller shares the actual tie-line power flow among all microgrid sources. Control actions are evaluated on the base of capabilities and the operating point of all devices.

2.8. *Synchronization Transition*

With the system operated in the normal Island State, if technical or economic circumstances suggest to reconnect the microgrid to the distribution network, the operator can start the reconnection procedure. For this purpose, the voltage reference signal (the distribution network voltage) must be sent to the Synchronization controller. For those microgrids adopting the master/slave controller, this signal must be sent directly to the master generator that will adapt the overall system frequency and voltage magnitude to the reference signal.

2.9. *Black start*

After the blackout occurrence, the operator can choose to run a black-start procedure. In particular, he can choose to restore the system in the On-Grid state [41,42] or in the Off-Grid state [43,44].

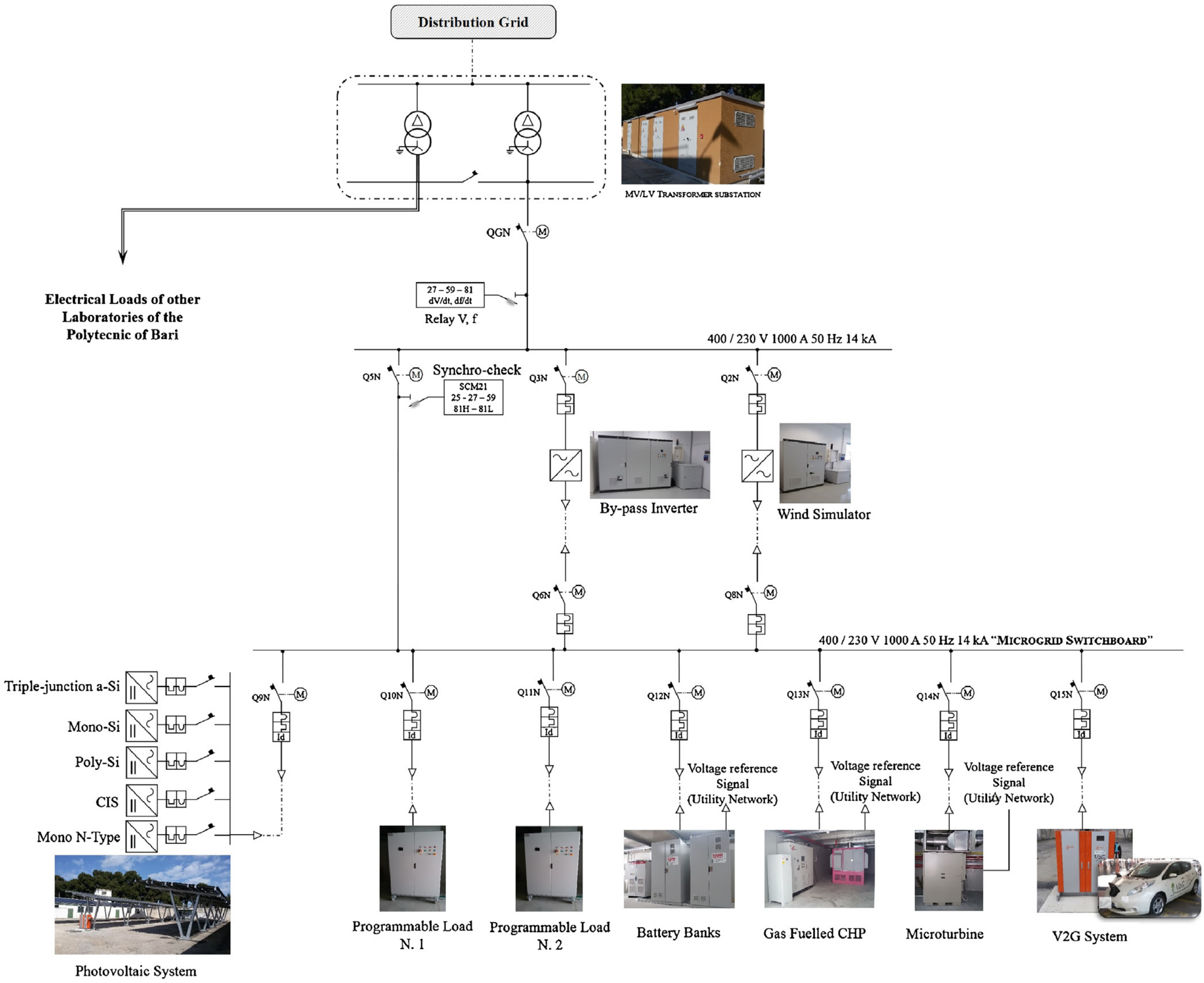

Fig. 2. The one-line diagram of the Prince Lab experimental microgrid.

3. The Prince lab microgrid

The aim of this section is to give a brief description of the experimental microgrid built at the Polytechnic of Bari.

3.1. *The microgrid architecture*

In Fig. 2 the one-line diagram of the AC microgrid is shown.

The microgrid is connected to the utility grid through a dedicated MV/LV transformer with a rated power of 1250 kVA and the main switch (QGN). This device is equipped with a protection relay (ANSI 27S1, 27S2, 59S1, 59S2, 59Vo, 81), enabling it to isolate the microgrid following grid outages. The microgrid can also be intentionally isolated through another switch, named "by-pass switch" (Q5N). After islanding, a Synchrocheck Relay (ANSI 25, 27, 59, 81) enables the microgrid to be reconnected to the main grid if adequate conditions occur. A second possible way to connect the microgrid to the main grid is offered by the four quadrant AC/AC inverter, named "by-pass inverter", having a rated power of 200 kVA. This converter can be operated as a current source by fixing its active and reactive powers. In this case, this device can be operated as an alternative load or generator. Moreover, the by-pass converter can be used to implement the Bumpless Transition the On-Grid to the Off-Grid operation mode. In fact, it allows to manage its active and reactive power production so that the power flowing on the by-pass switch is minimized or nullified.

3.2. *The main components of the experimental microgrid*

With the exception of the vehicle-to-grid (V2G) charging station, all devices (generators, storages and loads) have been chosen among those commercially available thus, new control functions able to manage the microgrid in an economic, reliable and secure way have been developed or they are in a developing stage. Each component is interfaced to the microgrid through an inverter, giving rise to an inertialess system.

The main components of the microgrid are:

- a 120 kWe natural gas fuelled CHP system;
- a 30 kWe natural gas fuelled micro-turbine;
- a photovoltaic plant with a rated power of about 50 kWp;
- a wind simulator having a rated power of about 60 kWp.
- two Sodium–Nickel battery banks having a total storage capacity of 210 kWh and a maximum charge/discharge power of 60 kW;
- a vehicle-to-grid (V2G) system;
- 2 × 120 kW inverter-based programmable loads.

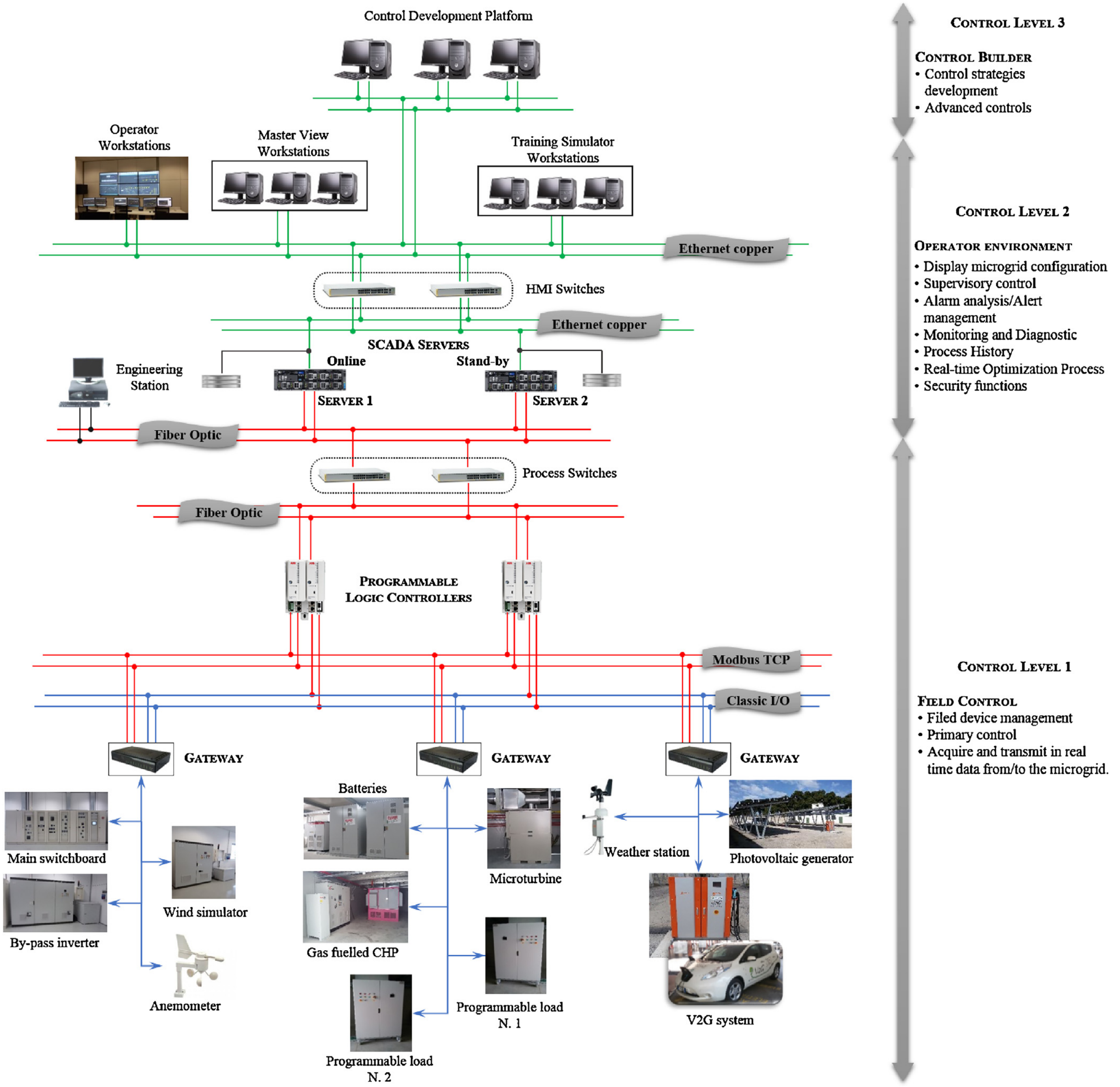

Fig. 3. The structure diagram of the hardware of the SCADA system.

A complete description of the microgrid's components can be found in Ref. [45].

3.3. The SCADA system

With the aim to develop a powerful tool for researchers, the SCADA system has been structured to be a completely open and flexible platform. With this tool new power management and control strategy schemes can be easily implemented and tested. Fig. 3 shows the SCADA system infrastructure.

The first control level is accomplished by local controllers or actuators installed on each field device. These controllers are able to manage the associated device by actuating control signals coming from the upper level. Measurements on the microgrid are sent to the control centre by digital meters installed on each unit. Field devices are connected to three gateways via I/O network. Each gateway locally conveys information from/to field devices and transmits them to the Control Level 2 via an Ethernet communication network. Even if the communication protocol IEC 61850 can be considered attractive for its speed, the vast majority of currently produced devices adopts traditional protocols such as Modbus, Profibus, etc. For this reason, in order to avoid an expensive adaptation of the devices to the IEC 61850, the Modbus/TCP IP protocol has been adopted. However, all variables needing fast processing, such as those related to the system security, are transmitted from/to the field through physical I/O points.

Functions concerning the optimal operation of the microgrid are implemented in the second level of the SCADA. This control level is composed by two twin servers in hot backup configuration. The servers communicate via fiber optic with two twin PLCs (Pro-

Table 1
Initial active powers of all microgrid components.

CHP [kW]	Microturbine [kW]	BESS [kW]	PV [kW]	Load 1 [kW]	Load 2 [kW]	UPS [kW]	Tie-line flow [kW]
27.2	1.7	4	19.3	−24.0	−30	−9.4	11.2

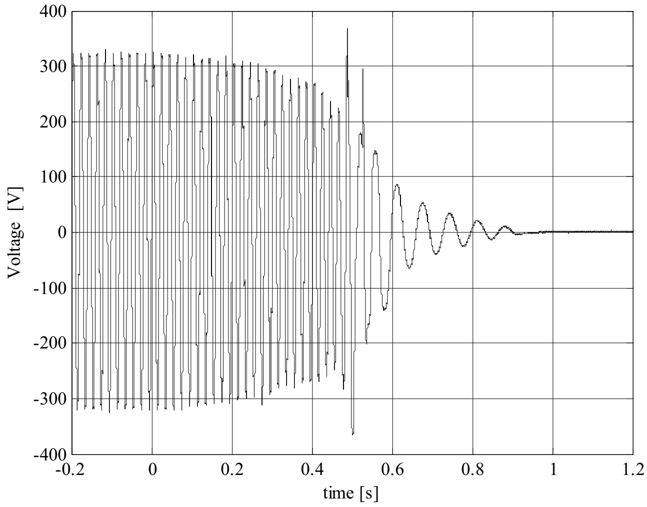

Fig. 4. Oscilloscope waveform of the microgrid's voltage during the blackout.

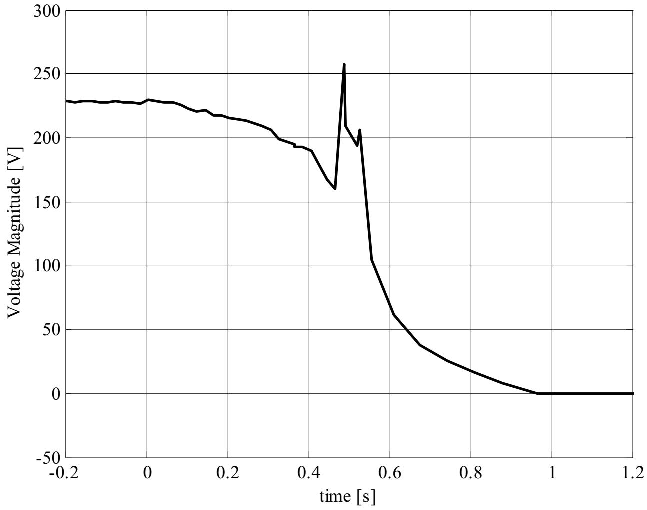

Fig. 5. Magnitude of the microgrid's voltage during the blackout.

grammable Logic Controllers) that directly interact with the main microgrid switchboard and all controllers of inverters interfacing the microgrid components.

The third control level is designed to make the system completely open. In this level, any control strategy developed in the Matlab/Simulink® environment can be easily implemented by researchers.

4. Experimental results

In order to show the performances of the proposed EMS, two experimental tests have been performed: the transitions from On-Grid to the Off-Grid mode and the vice-versa. For this microgrid, these tests seem to be particularly critical for its survival due to the total absence of inertia. In fact, in order to understand how much the microgrid is sensitive to blackouts, a preliminary blackout test

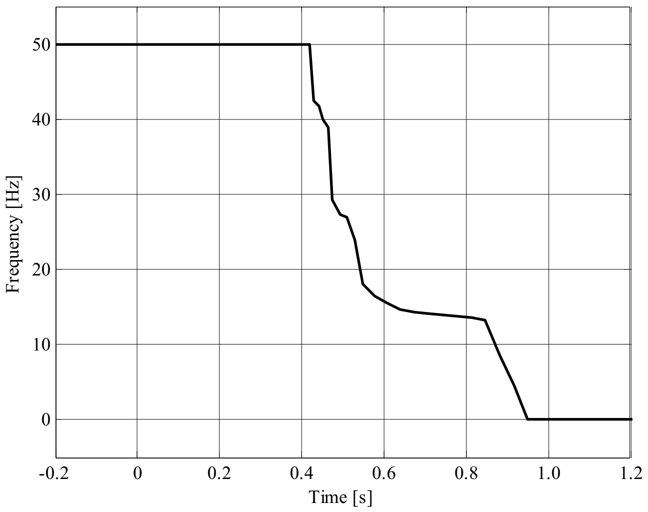

Fig. 6. Microgrid's frequency behaviour during the blackout.

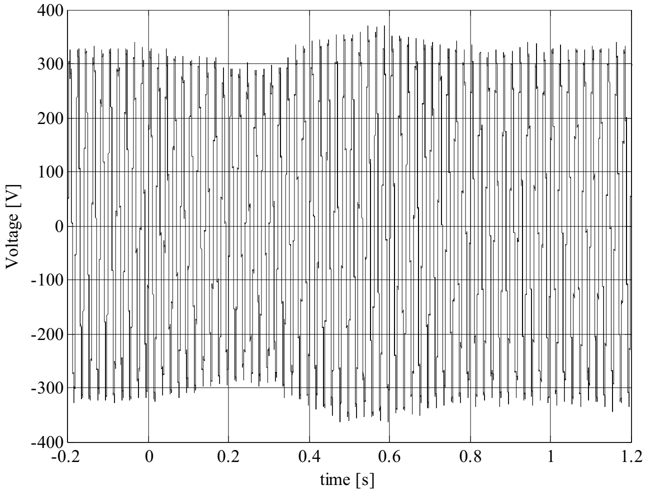

Fig. 7. Oscilloscope waveform of the microgrid's voltage during the transition from On-Grid to the Off-Grid.

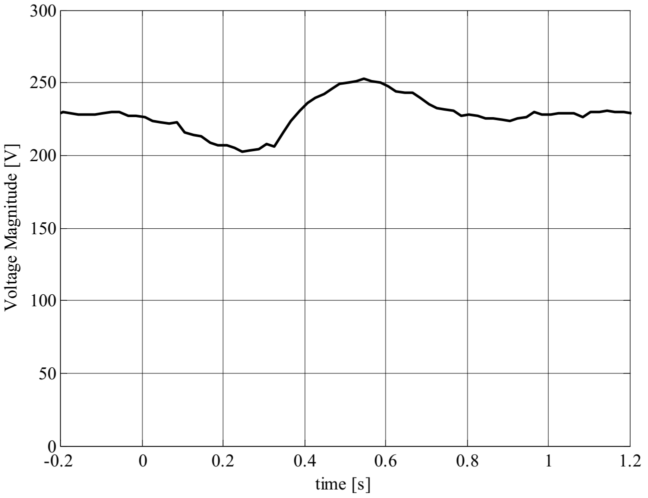

Fig. 8. Microgrid's voltage magnitude behaviour during the transition from On-Grid to Off-Grid.

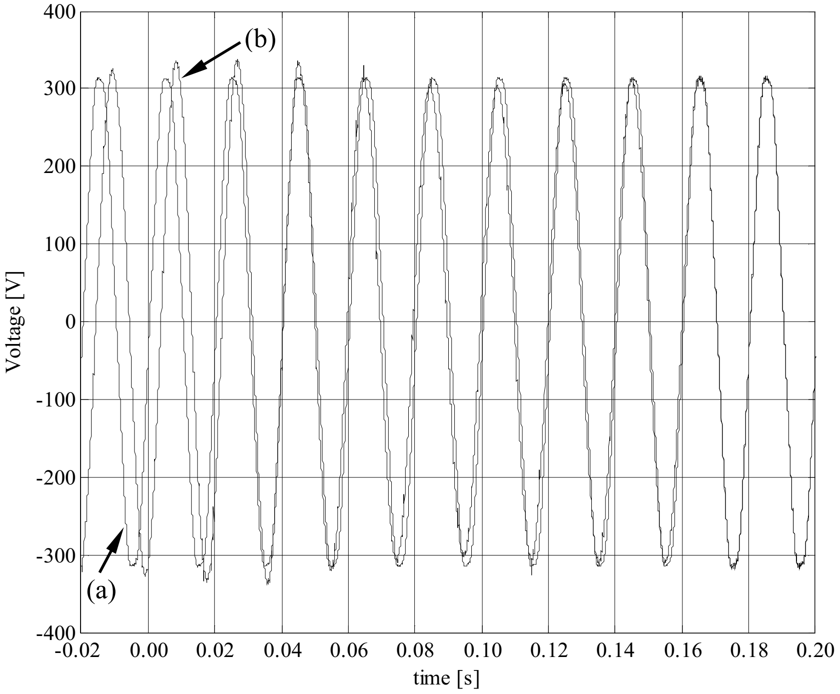

Fig. 9. Oscilloscope waveforms during the synchronization process: (a) main grid voltage; (b) microgrid voltage.

has been conducted. This condition has been realized starting from the operating point reported in Table 1.

By disabling the master function for all generators and by opening the tie-line breaker at t = 0 s, a blackout occurred on the system. In Fig. 4 the microgrid's voltage waveform is shown.

From this waveform, the voltage magnitude and the frequency are evaluated and shown in Figs. 5 and 6. From Fig. 5 it can be noted that, following the perturbation, the loss of the distribution grid support caused a voltage droop, reaching at t = 0.47 s the value V = 159.7 V, corresponding to 70% of the nominal voltage V_N. At this voltage value, the microgrid experienced a cascading events with all components shutting down progressively. The frequency, stable at 50 Hz until that time, exhibited a rapid droop as shown in Fig. 6.

As can be noted, the absence of inertia in the system makes the perturbation particularly hard. In fact, it took about 1 s to declare the system operating point in the Blackout state. Anyway, after t = 0.47 s the system has passed "the point of no return" and the blackout seems to be inevitable.

Under the same operating condition, we tested the islanding transition of the microgrid by adopting the CHP as the master. Figs. 7 and 8 show the oscilloscope waveform of the microgrid's voltage and its magnitude. We do not show the frequency behaviour of the microgrid since it remained constant during all the transition.

As can be noted, the sudden loss of the main grid, gave rise to a voltage drop equal to −13.4%. After a transient overvoltage (+8.2%), the nominal voltage was promptly recovered by the master generator in about 800 ms.

A resynchronization test was performed on the system. Denoting with t = 0 s the starting time of the reconnection procedure, in Fig. 9 we show the voltages at both sides of the tie-line breaker. At about t = 0.17 s the tie-line breaker closed moving back the microgrid in the On-Grid state.

5. Conclusions

Lessons learned in building the experimental microgrid in the Prince — Electrical Energy Systems Lab at the Polytechnic of Bari, have been made possible the definition of an organized approach for the optimal management of microgrids. This approach could represent a guideline for researchers and practitioners in designing, developing and implementing of reliable microgrids. The analysis performed on the experimental microgrid revealed that the Operating Modes of a microgrid can be: On-Grid, Off-Grid, Alert, Emergency, and Blackout. Obtained results suggest that a flexible microgrid will be basically characterized by the following five Transitions: On-Grid Black Start, Off-Grid Black Start, Bumpless Islanding, Non-Bumpless Islanding and Synchronization. For each of the given states and transitions, main technical issues are described for the optimal management of a microgrid.

Particularly critical seem to be the transitions from On-Grid to Off-Grid mode and vice-versa due to the absence of inertia for those microgrids having a high penetration of devices interfaced with inverters. In this situation, has been presented the Bumpless Transition as a useful tool for mitigating effects deriving from the islanding process.

Experimental tests performed on the inertialess microgrid demonstrated that the developed islanding and re-synchronization procedures are able to move the system among the two normal operating states avoiding any interruption in power supply service.

Disclaimer

The Polytechnic of Bari developed all the control strategies. The contribution of ABB is limited to the implementation of the routines running in the SCADA system of the Prince — Electrical Energy Systems Lab microgrid.

Acknowledgments

The Project "Innovative Processes for Energy Conversion –"PrInCE" has been founded in the framework of the European Regional Development Fund (ERDF) under grant PONa3_00372-2013.

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