CONTROL ARCHITECTURE AND ALGORITHMS FOR ISOLATED MICROGRIDS

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ABSTRACT

The integration of distributed energy resources (DER) in old-conceived power systems is changing drastically the paradigm of the traditional power systems. This transformation is affecting the power systems over all geographical scales, both large interconnected grids and small islanded grids. It involves several operational aspects, like protection and control, as well as automation, to ensure safe operations, and enhance stability and efficiency. In this frame, the Enel Group is proposing interventions to innovate the operation of the small isolated Italian grids, aiming to increment the penetration of renewable energy sources (RES), reduce operational costs and environmental emissions. Among the interventions, an innovative control architecture and algorithm are proposed in this paper.

INTRODUCTION

Worldwide attention has recently been focused on the energy transition. This process involves all aspects related to the electricity sector such as production, distribution, and use of energy. Regarding the distribution of electricity, current electrical distribution networks require an evolution towards the concept of “smart grids” to meet the increasing penetration of RES that is crucial for the energy transition. The term "smart grids" refers to an electrical system deeply integrated with telecommunications networks that is able to improve efficiency and reduce reliance on traditional energy production, while ensuring network stability and security, even when weakly connected to or disconnected from a bulk system.

RES are generally interfaced with the main grid through power electronic converters, which are not provided of physical inertia, and, for this, they do not contribute to the transient stability. Consequently, the increasing spread of RES may be less impactful in the case of heavily interconnected electrical system, such as that of the national grid. However, it is crucial to consider the drawbacks related to the spreading of RES in the case of isolated distribution networks, like those on small islands. As the latter are usually characterized by low rotational inertia of small synchronous generators, they can face instability conditions because of the aleatory nature of RES production that makes the net load profiles more unpredictable. Thus, without the deployment of suitable control solutions, the percentage of the energy demand that RES can take up in the energy mix of such grids is very limited. Additionally, the lack of RES in small islanded distribution grids does not contribute to mitigate the energy production costs, that are generally higher because of logistical difficulties to make available traditional fuels. Due to the abovementioned aspects, this kind of networks represents the ideal context for testing innovative solutions and new ancillary services usually embedded in smart grids, microgrids (MGs) and energy communities.

In the wake of research and innovation related to microgrids control, E-distribuzione, the main Italian Distribution System Operator (DSO), and Gridspertise, a company that promotes the digital transformation of power grids worldwide, have collaborated since 2021 in the frame of the research project “Integrated Storage and Microgrid Innovation” (ISMI). The project aims to create a unified control architecture that is able to guarantee an efficient and stable management of microgrids. The proposed solution mainly consists of a central control unit which coordinates distributed power plants, both conventional and renewable, energy storage systems and breakers associated to dispatchable loads. The activities of the ISMI project are mainly being conducted in the Gridspertise LV Smart Grid laboratory, in Bari, where the solution presented in this paper has been implemented also in a Hardware-in-the-Loop (HIL) setup as described in [1], in order to evaluate the integration of the proposed control architecture in a real-time testing environment. As presented in [2], further research activities at the LabZERO laboratory of Politecnico di Bari contributed to the formulation of the control algorithm that manage the abovementioned control framework.

This paper presents the results obtained through simulations carried out on the electromechanical model of the Italian islanded distribution grid considered in the field of the ISMI project, in several operating conditions. Such network has been identified as a representative case to demonstrate the capabilities of the proposed control architecture. The simulation of the control architecture and the reference distribution power network has been carried out in a MATLAB/Simulink environment.

CONTROL ARCHITECTURE FOR ISOLATED MICROGRIDS

A microgrid (MG) is a group of interconnected loads and DERs, within clearly defined electrical boundaries, where all the controllable units are coordinated in such a way to ensure energy balance and stability with respect to the main grid [3]. MGs can operate in grid-connected or islanded mode, if connected or disconnected to the main grid respectively. Regardless of the operating mode, the control architecture is generally based on a hierarchical scheme that consists of three layers, namely primary, secondary and tertiary [3], [4].

The primary control is responsible for the operational reliability and the system stability, and it is operated on the fastest timescale, namely in the order of few milliseconds up to few seconds [5]-[7]. Generally, microgrids suffer of poor transient performance due to the high penetration of converter based DERs, which provide low inertia contribution. To cope with this issue, several authors investigated how control techniques like Synthetic Inertia (SI) and Fast Frequency Response (FFR) can be employed to provide frequency support in small-sized non-synchronous islands. As an example, in [8], the authors demonstrated how SI and FFR can be provided by LED streetlamps. Whereas, in [9] the authors investigated how to support the grid stability by employing SI on the local controller of a Battery Energy Storage System (BESS). The secondary control level, instead, deals with the power quality and the reliable operation of the microgrid [10]. If communication channels are adopted, it can be implemented through a centralized or a distributed architecture; otherwise, the control layer is considered decentralized. Finally, the tertiary layer is responsible for the optimal economic and technical management of the energy resources within the MG. In literature, different kinds of strategies for the optimal operation of energy resources in stand-alone MGs have been proposed. Usually, the resulting operational planning decisions rely on historical data and forecast methods. For instance, in [11] and [12], the authors investigated the application of a model predictive control technique that allows to elaborate and update in closed-loop feedback the dispatching orders towards controllable units, to guarantee the energy balance and the provision of reserve requirements.

Generally, the physical and functional grouping of the control system functionalities can be defined in several ways. That said, this work aims to propose a control architecture, where functionalities of the three control layers are integrated and operated according to the hierarchy depicted in Fig. 1, in a way that is suitable for various islanded MG configurations.

In the proposed control scheme, the primary control layer implements all the control functionalities operated by speed governors and excitation current regulators of diesel groups, and droop techniques to share DERs power contributions. The secondary layer of the architecture is decentralized and can be identified in local level devices that consists in plant controllers and breaker controllers.

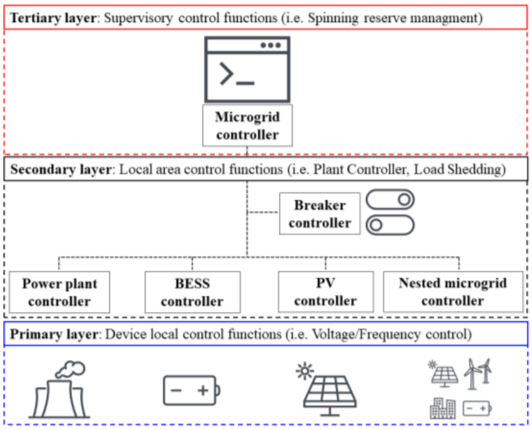

Fig. 1. Hierarchical scheme of the proposed control architecture.

It is assumed that the breaker controllers are able to provide measuring and protection functionalities, while the plant controllers, which are associated to each generation and storage plant, collect measures and states from single generating units or aggregation of different ones. This assumption is consistent with the specifications set by the Italian standard CEI 0-16 [13] which makes devices with monitoring capabilities to be mandatory for plants with relevant production. The norm also specifies the availability of several plant controlling functionalities, i.e. (a) active power limitation, (b) modulation of the imported/exported active power, (c) voltage regulation by supplying inductive/capacitive reactive power, (d) power factor setpoint, (e) reactive power regulation as function of the voltage, (f) power factor regulation as function of active power. In the control architecture, it is assumed that the implementation of some of the available functionalities (i.e., active power limitation) is made mandatory. Further functions, currently not considered in the abovementioned norm, like spinning reserve regulation, are assumed to be available at least for the islanded scenarios analyzed in this work. Breaker controllers are assumed in correspondence of secondary substation MV feeders, where specialized devices are already diffused in the Italian grids, and along LV lines, where remote monitoring and controlling capabilities are still an innovation proposal.

Finally, on the tertiary layer a central Microgrid Controller (MGC) gathers all the information received by the lower level and uses them to elaborate operative decisions. These decisions are then explicated by commanding operations and sending setpoints to the abovementioned plant and breaker controllers. In particular, the functionalities implemented in the MGC are: (a) collecting measures and status from the plant and breaker controllers, (b) processing, through a dedicated algorithm (described in the following section), the input status and measurements to determine the control actions, namely, (c) dispatching activation/deactivation commands and setpoints to the plant controllers, (d) commanding the operation commands of circuit breakers.

CONTROL ALGORITHM

The main purpose of the MGC algorithm is to verify the adequacy of the isolated system by assessing the operating reserve provided by the available resources. The MGC verifies that the available reserve is sufficient to withstand any major loss of generation from intermittent renewable sources or sudden load variations. Whenever system reserve is not enough, the MGC pre-emptively procures the needed extra reserve or evaluates preventive/corrective control actions. The algorithm is not only capable of commanding the preventive disconnection of loads to ensure operational reserve constraints, but also, in a non-preventive manner, evaluates the set of remote controllable disconnectors to be switched off and shed load during an under-frequency event. The algorithm is also able to deal with resources which reject the required control action or are non-responding. The MGC is also programmed to shed load or limit the power produced by intermittent generating units in the cases of excessive load or production. These additional functions are enabled even without the control of operating reserves and make it possible to inhibit unnecessary controls, solve problematic grid situations that could not be avoided in advance, and prevent the generation plant from reaching unfeasible operating points (negative net load or net load greater than the plant's maximum power output).

The algorithm, which is to be deployable in a commercial programmable logic controller (PLC), is programmed using finite state-based logics that can be implemented in a finite-state machine. In each operating state, the adequacy of the system is checked under specific conditions. If the conditions in the current operating state are not satisfied, a transition to a different operating state takes place. Each operating state transition results in a different grid condition and different actions by the MGC. The adequacy of the system is verified by assessing both the available upward and downward operating reserves, at the same time. These verifications are carried out simultaneously and affect different operating states of the MGC. Although the whole control logic of the MGC will be included in the simulated scenarios considered in the results section, for the sake of brevity, only a simplified description of the upward operating reserve assessment is given as example. Thus, having defined Rup_{MIN} as the minimum upward operating reserve to be guaranteed, Rup_{GP} as the upward operating reserve available by the conventional power plant, Rup_{BESS} as the upward operating reserve available by BESS and ΔRup as the missing upward operating reserve, the MGC will execute the following instructions:

State 1: Verify if $Rup_{GP} > Rup_{MIN}$. If this condition is false, move to State 2.

State 2: Enable BESS and verify if $Rup_{GP} + Rup_{BESS} > Rup_{MIN}$. If this condition is false, move to State 3. If BESS reserve is no longer needed, move to State 1.

State 3: Calculate $\Delta Rup = Rup_{MIN} - Rup_{GP} - Rup_{BESS}$ and request ΔRup to the power plant. If the generation plant rejects this request due to lack of availability, move to State 4. If ΔRup is no longer positive, move to State 2.

State 4: Define and enable the smallest number of controllable switches feeding dispatchable loads to trip for an underfrequency event. If this action is no longer required, move to State 3.

In order to avoid continuous transitions from state to state due for example to power fluctuations, hysteresis controls and delays are introduced. It is important to point out that in the considered example there is no control by the MGC over RES production because it directly impacts the downward reserve provision, whose description has not been reported in this paper for the sake of brevity.

RESULTS

In order to validate the proposed control framework, a reference simulation scenario has been identified, based on the network configuration of an Italian small island.

A detailed electromechanical model of the island's power system was built in *Simulink*, whereas the MGC algorithm was implemented using the *Stateflow* library. The island model was simulated adopting a 0.125 ms time-step, while the MGC algorithm updates the system state through a complete set of measurements every 3 minutes. The load profiles used during the tests were built from actual data collected by the distribution system operator, whereas an assumption related to the power generation from PV plants was made in order to simulate a scenario with a high RES penetration. The structure of the considered distribution power network is represented in Fig. 2.

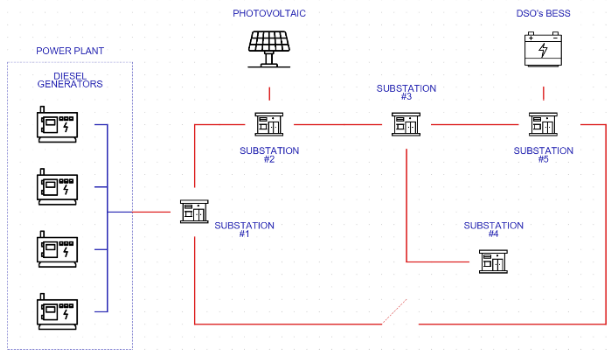

Fig. 2. Single-wire scheme of the simulated test microgrid.

It mainly consists of five secondary substations (from #1 to #5) where transformers interface the MV distribution network operated at 10 kV to LV sections operated at 400 V. The latter supply electricity at a rated frequency of 50 Hz to residential, commercial, and industrial customers that are not represented in Fig. 2 for the sake of clarity. The MV nodes are connected creating a loop that is open during normal operations. A switch disconnector allows the reclosure in the event of faults or possible maintenance operations. As shown in the schematic representation, the entire network is powered by a conventional diesel plant with four 480 kW generating units. Moreover, as the current presence of DERs on the examined power system is limited, and with the intend to increase their widespread, the validity of the proposed MGC control algorithm, integrated in the presented control framework, has been evaluated by enriching the simulated power grid with a 250 kW / 300 kWh BESS and a 500 kWp PV power plant. In the activities related to the ISMI project, the MGC algorithm was tested for several conditions and scenarios. In this paper, in order to be concise, only a single representative case study is shown. This test case was selected considering the actual main scope of the proposed control architecture which is to allow high penetration of RES producers in a small non-synchronous island. During the operation in a typical summer day, when the seasonal load and energy production of PV systems are high, the upward operating reserve available from the generation plant may not be sufficient to meet the required minimum upward operating reserve. The case investigated shows how upward operating reserve can be managed by MGC to withstand a sudden reduction of energy production.

It was assumed that at the 10:30 a.m. of the typical summer day under investigation, the total load consumption in the island was about 740 kW. The load was supplied by the PV production of about 337 kW, while the remaining 403 kW was supplied by the conventional diesel plant. The BESS was in standby with a null power exchange. In these conditions, the diesel plant could supply the load with a single 480 kW generating unit, and the Rup_{GP} was about 77 kW. This operating condition represents an emblematic case to demonstrate the effectiveness of the control action provided by the MGC. Indeed, in case of a clouding event causing the total loss of the PV power production, the secure operation of the power grid cannot be ensured. Even considering the Rup_{BESS} contribution (250 kW), the upward operating reserve was not enough to compensate a sudden and complete loss of PV generation. With respect to the described scenario, the effectiveness of the MGC actions was evaluated by comparing the results obtained by simulating three different cases:

Case 1: upward reserve not controlled by the MGC;
Case 2: the MGC requested additional upward reserve to the generation plant and the request was accepted;
Case 3: the MGC requested additional upward operating reserve to the generation plant with the request that was rejected, and a load shedding plan was evaluated.

In all cases, a drastic PV power reduction (from 100% to 0% in about 1 second) was assumed at 10:30 a.m., representing the upward operating reserve requirement Rup_{MIN} depicted with a dashed black line in Fig. 3. For the three cases, the same figure shows the overall upward operating reserve available according to the action of the MGC before the assumed contingency time.

In Case 1, without the MGC, the reserve was not sufficient at 10:30 a.m. In the other two cases, the MGC has already verified a lack of upward operating reserve at 10:12 a.m. and requested additional reserve to the generating plant. In Case 2, the generating plant turned on an additional diesel generator and fulfilled the request. In Case 3, instead, the request was refused and at the next iteration (10:15 a.m.) the MGC, which again verified the lack of upward operating reserve together with the refusal response from the generating plant, set-up a load shedding plan.

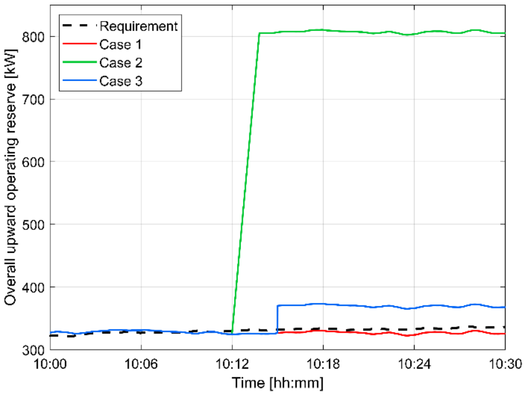

Fig. 3. Overall upward operating reserve for the three cases.

In subsequent iterations, up to the time of the supposed contingency (10:30 a.m.), the load consumption and non-programmable generation on the island did not vary to such an extent that the MGC changed its decisions. Fig. 4 shows the resulting frequency transients after the sudden clouding event, for each case.

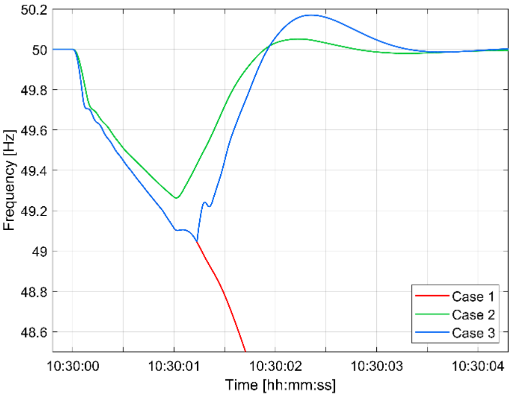

Fig. 4. Frequency dynamics for the three cases.

In Case 1, without the MGC, the frequency indefinitely dropped after the contingency because the upward operating reserve available on the island was not adequate to mitigate the rapid power variation. Differently, in Case 2, the MGC algorithm demanded to the power plant a ΔRup of about 10 kW. The plant accepted this request and turned on an additional diesel generating unit. It was assumed that starting a new diesel unit takes about 2 minutes and that the MGC controls are inhibited during this time interval. For the sake of representation, in Fig. 3, the overall upward operating reserve has been represented with a linear growth in that time interval. After this intervention, the Rup_{GP} became about 556 kW and the overall upward operating reserve, considering also the Rup_{BESS} of 250 kW, reached about 806 kW. The Rup_{GP} was more than sufficient to mitigate the PV power variation (-337 kW), and the frequency could be rapidly restored to its nominal value thanks to the primary and secondary frequency control of the power plant. In Case 3, the generation plant declined the request and the MGC had to enable the smallest number of controllable switch disconnectors to trip and shed load following an under-frequency event. In this case, the MGC enabled a single switch to interrupt a total load of about 41 kW, as shown in Fig. 3. In this test, it was assumed that the switch would trip instantly when the frequency drops below 49.1 Hz. This threshold represents the frequency deviation for which the BESS provides its maximum contribution during under-frequency events according to its droop control scheme. As shown in Fig. 4, Rup_{GP} and Rup_{BESS} were not sufficient to compensate for the total loss of generation at 10:30 a.m. and frequency continued to drop below 49.1 Hz. Thus, the load was shed few hundreds of milliseconds after the frequency reached this threshold, due to delays in frequency measurement and tripping. Consequently, the power plant obtained enough operating reserve to restore the frequency to its nominal value.

CONCLUSIONS

In this work a control architecture for non-synchronous distribution networks on small Italian islands has been proposed. The focus is on the MGC algorithm that oversee the proposed control framework, which has been designed to coordinate power resources (programmable and not), energy storages and breakers feeding dispatchable loads.

The effectiveness of the presented control algorithm has been evaluated by comparing results obtained through software-in-the-loop simulations, carried out on the electromechanical model of an Italian islanded distribution grid. The results demonstrated that the adoption of the abovementioned algorithm and control framework allow to prevent such grid to experience transient instability conditions due to unpredictable net-load fluctuations.

It is worth noting that, although out-of-the scope of the paper, the introduction of the proposed control algorithm and architecture demonstrated the increase of the hosting capacity, which enables higher RES penetration. Potentially, this benefit could be expected also for small portions of the continental MV (or LV) distribution grid operated and controlled with the proposed solution.

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REFERENCES

[1] G. Bianco et al., "Setup for HIL simulations of isolated microgrids at the Gridspertise LV Smart Grid Lab," 2022 AEIT International Annual Conference (AEIT), 2022, pp. 1-6, doi: 10.23919/AEIT56783.2022.9951819.

[2] S. Bruno et al., "Control and Power Hardware-in-the-Loop tests for low-inertia power systems," 2022 AEIT International Annual Conference (AEIT), 2022, pp. 1-6, doi: 10.23919/AEIT56783.2022.9951753.

[3] IEEE Standard for the Specification of Microgrid Controllers, IEEE Standard 2030.7-2017, 2017

[4] G. Razeghi et al., “Generic Microgrid Controller Specifications”, Advanced Power and Energy Program, University of California, Irvine, 1 Oct. 2016, DUNS Number: 04-670-5849.

[5] K.S. Rajesh et al., “A review on control of ac microgrid”, Renewable and Sustainable Energy Reviews, Volume 71, 2017, Pages 814-819, ISSN 1364-0321, https://doi.org/10.1016/j.rser.2016.12.106.

[6] F. Z. Peng et al., "Control and protection of power electronics interfaced distributed generation systems in a customer-driven microgrid," 2009 IEEE Power & Energy Society General Meeting, Calgary, AB, Canada, 2009, pp. 1-8, doi: 10.1109/PES.2009.5275191.

[7] S. Baudoin et al., "A review of voltage and frequency control strategies for islanded microgrid," 2012 16th International Conference on System Theory, Control and Computing (ICSTCC), Sinaia, Romania, 2012, pp. 1-5.

[8] S. Bruno et al., "Fast Frequency Support Through LED Street Lighting in Small Non-Synchronous Power Systems," in IEEE Transactions on Industry Applications, 2022, doi: 10.1109/TIA.2022.3223964.

[9] Bruno, S. et al., Power Hardware-in-the-Loop Test of a Low-Cost Synthetic Inertia Controller for Battery Energy Storage System. Energies 2022, *15*, 3016. https://doi.org/10.3390/en15093016

[10] A. Mohammed, et al., "AC Microgrid Control and Management Strategies: Evaluation and Review," in IEEE Power Electronics Magazine, vol. 6, no. 2, pp. 18-31, June 2019, doi: 10.1109/MPEL.2019.2910292.

[11] S. Bruno, et al., "Predictive Optimal Dispatch for Islanded Distribution Grids considering Operating Reserve Constraints," 2022 IEEE 21st Mediterranean Electrotechnical Conference (MELECON), 2022, pp. 518-523, doi: 10.1109/MELECON53508.2022.9842967.

[12] S. Bruno, et al., "Integration of Operating Reserve Constrains in the Predictive Optimal Dispatch of Energy and Storage Resources in Small Islands," 2022 IEEE International Conference on Environment and Electrical Engineering and 2022 IEEE Industrial and Commercial Power Systems Europe (EEEIC / I&CPS Europe), 2022, pp. 1-6, doi: 10.1109/EEEIC/ICPSEurope54979.2022.9854789.

[13] CEI Italian Standard, “CEI 0-16:2022-03 - Reference technical rules for the connection of active and passive consumers to the HV and MV electrical networks of distribution Company,” 2022.