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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.