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A cooperative control for the reserve management of isolated microgrids

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HIGHLIGHTS

- A cooperative control for reserve management of isolated microgrids is developed.
- The methodology is based on the sensitivity theory involving the Lyapunov theorem.
- It is aimed at maximizing the overall spinning reserve of an isolated microgrid.
- It is used in the real-time to alleviate the regulation burden of the master unit.
- Test results demonstrated the controller's ability to be self-adaptive.

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ABSTRACT

The purpose of this paper is to examine how a coordinated control strategy for managing the active power reserve in isolated microgrids is presented. This methodology can be applied in those microgrids where a specified generator assumes the role of the isochronous generator for the overall system. The derived algorithm evaluates control actions in the on-line environment by solving a constrained dynamic optimization problem aimed at maximizing the overall spinning reserve and, in particular, the reserve offered by the master unit equipped with the isochronous governor controller. The solution of this problem is obtained by adopting the direct Lyapunov theorem applied to the Sensitivity theory, ensuring the algorithm's stability.

Tests performed on the experimental microgrid, which has been built at the Polytechnic University of Bari, demonstrated the ability of the proposed methodology to share the regulation burden among all sources and storage systems, establishing adequate reserve margins of the master unit.

1. Introduction

Microgrids are becoming more and more interesting due to their ability to alleviate consequences of sudden grid outages, ensuring a reliable and uninterrupted energy supply by producing the required energy for the overall system and related ancillary services. However, due to the absence of the main grid support, the occurrence of power disturbances may move these systems to an insecure operating point of the stability region. This is much more likely to occur in microgrids having low or even null inertia. The need of real-time control strategies able to maintain the power balance at all times, has aroused the interest of many researchers in developing several control solutions [1–8], a minimum cost control strategy able to share the total load demand among all energy sources has been developed by tuning the Distributed Generators (DG) droop gradients, obtaining an optimal dispatch including non-programmable renewable energy sources. With the same aim, papers [9–13] suggest an optimization problem based on the mixed integer linear programming (MILP) method, whereas in [14] a multi-period gravitational search algorithm (MGSA) is developed. Nonetheless, it is worth noting that most commercially available inverters are not equipped with the droop control, therefore the adoption of droop control strategies will require the development of *ad-hoc* devices as is the case of the microgrids developed in [15–19]. At this stage in the development of microgrids, the vast majority of them are based on the master/slave controller [20–25]. In these microgrids the real-time power balancing is much more complex than droop-controlled ones. In fact, as outlined in [25], in these microgrids the generating unit acting as the master generator may not have sufficient generation capacity to cover all possible unbalances that could occur within the island. Therefore, a cooperative control strategy able to alleviate the regulation burden of the master generator is needed. To comply with this exigency, several control strategies have been developed in the last years. In [26–28] the centralized control strategies are able to share the total load demand among all microsources and storage devices which are suggested. By these approaches, control actions are evaluated by adopting an economic dispatch algorithm, considering all programmable as well as non-programmable sources, storage devices and loads with their uncertainties

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and disturbances. Power reserve margins are treated as constraints of the optimization problem by taking into account the day-ahead electricity market and reserve costs [29–31]. Focusing on the optimization of the spinning reserve of isolated microgrids, centralized controllers developed in [32–41] share the control burden among all microsources by adopting the Particle Swarm Optimization (PSO) algorithm based on the Monte Carlo method [32], the Mixed-Integer Linear Programming (MILP) [33], and the Conservative Power Theory [34–41].

Following the same aim, in this paper a real-time coordinated control strategy able to ensure an adequate security level in an isolated microgrid is proposed. Control actions are evaluated by solving a constrained dynamic optimization problem aimed at maximizing the overall spinning reserve and, in particular, the reserve offered by the master unit acting as the isochronous regulator. The solution of this optimization problem is evaluated by adopting the direct Lyapunov theorem applied to the Sensitivity theory, ensuring the algorithm's stability. The developed control strategy has been tested on the Experimental Microgrid built at the Polytechnic University of Bari.

2. Reserve classification for master-slave based microgrids

When operated in the isolated mode, master-slave controlled microgrids need a generator or a storage device which will control the voltage and the frequency, thus recovering any disturbance occurring on the system according to its capability curve. The required regulating power needs to be instantaneously provided by the master unit, otherwise the system would collapse. For microgrids having minimal or even null inertia, this phenomenon can be reached in tens of milliseconds. Hence, corrective control actions need to be promptly evaluated and applied in order to avoid the system blackout. This exigency cannot be supplied with slave devices with their slow reserves. Moreover, a practical communication system has latencies which are too large for primary control. In a sense, for master-slave controlled microgrids, the classification of the available reserve needs to be revised accordingly. The spinning reserve can be divided into the "primary reserve", which is then able to be developed in tens of milliseconds by the master unit, and the "secondary reserve", with an action ranging from seconds up to tens of seconds. Since the primary reserve is managed by the isochronous regulator of the master unit, a reasonably small frequency error will be produced until the generator has insufficient reserve availability. Therefore, the secondary controller will move power set-points of dispatchable generators and storage devices in order to restore the fixed amount of the primary reserve of the master controller.

The "stand-by" reserve will be constituted by all generating units and storage devices which can be available in tens of seconds up to a few minutes. Finally, the tertiary control level is aimed at performing the optimal dispatch of energy sources as proposed in [42]. One of the main necessities of the dispatch optimization performed at this control level, is to comply with inequality constraints related to adequate levels of reserve. For this reason, the solution of the optimization process will be power set-points of energy sources taking into account security margins for expected as well as unexpected contingencies.

3. Mathematical formulation of the cooperative control methodology

The aim of this section is to formulate a cooperative control methodology able to ensure adequate reserve margins in master-slave controlled microgrids. In this way, the derived optimization methodology will coordinate both primary and secondary reserves by controlling energy resources. For this purpose, let us consider a microgrid based on a master/slave controller consisting of $N = 1 + n_G + n_{RES} + n_S + n_L$ nodes, having one master unit, n_G dispatchable generators, n_{RES} non-dispatchable renewable sources, n_S storage devices and n_L loads. In order to formulate the overall optimization problem, the following basic elements of the procedure need to be defined.

3.1. The control variables

The variables that need to be adjusted in order to ensure a reliable and secure operation of the isolated microgrid are defined as follows:

$$\boldsymbol{u}(t) = [\boldsymbol{P}_G(t)\ \boldsymbol{P}_S(t)]^T \tag{1}$$

where

- $\boldsymbol{P}_G(t)$ is the n_G-dimensional vector of powers of all dispatchable generators involved in the reserve ancillary service.
- $\boldsymbol{P}_S(t)$ is the n_S-dimensional vector of powers at connection points of all storage devices involved in the reserve ancillary service.

Apex T denotes the transpose operator.

3.2. The objective function

The optimization problem will consist in a concurrent optimization aimed at maximizing the overall spinning reserve and it will be based on the following four error functions.

3.2.1. Primary reserve error function

During the isolated operation of the microgrid, the master generator will be called to increase or decrease its generated power output depending on unbalances occurring on the microgrid. In order to avoid possible violations of upper and lower power limits, its power output will be kept as close as possible to the specified set-point, restoring as much as possible the primary reserve of the master unit. With this aim, we define the primary reserve control error e_M^{pry} as the following scalar function:

$$e_M^{pry}(\boldsymbol{u}(t)) = P_M(t) - P_M^{set}(t) \tag{2}$$

where $P_M(t)$ is the active power produced by the selected master unit and $P_M^{set}(t)$ is its desired set-point.

Note that, in the master configuration, the isochronous regulator operates in the V-f control mode and thus it cannot comply with active power control signals coming from the secondary controller. As a consequence, the active power provided by the master unit can be regulated by managing the active powers provided by all other dispatchable sources distributed over the microgrid through the following relationship:

$$P_M(t) = \left[-\sum_{i=1}^{n_G} P_G^i(t) - \sum_{j=1}^{n_{RES}} P_{RES}^j(t) - \sum_{h=1}^{n_S} P_S^h(t) + \sum_{k=1}^{n_L} P_L^k(t) \right] \tag{3}$$

where

- $P_G^i(t)$ is the active power supplied by the generic *i-th* (for $i = 1,...,n_G$) dispatchable unit;
- $P_{RES}^j(t)$ is the active power injected by the generic *j-th* (for $j = 1,...,n_{RES}$) non-dispatchable RESs;
- $P_S^h(t)$ denotes the active power absorbed or injected by the generic *h-th* (for $h = 1,...,n_S$) storage system;
- $P_L^k(t)$ is the active power required by the generic *k-th* (for $k = 1,...,n_L$) load.

Substituting Eq. (3) into Eq. (2), the following primary reserve control error, e_M^{pry}, can be derived:

$$e_M^{pry}(\boldsymbol{u}(t)) = \left[-\sum_{i=1}^{n_G} P_G^i(t) - \sum_{j=1}^{n_{RES}} P_{RES}^j(t) - \sum_{h=1}^{n_S} P_S^h(t) + \sum_{k=1}^{n_L} P_L^k(t) \right] - P_M^{set}(t) \tag{4}$$

With this assumption, Eq. (4) is a scalar function of the vector $\boldsymbol{u}(t)$.

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