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A distributed economic control and transition between economic and non-economic operation in islanded microgrids

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ABSTRACT

In islanded microgrids, traditional droop control tends to make the total operating costs higher as the power is distributed by capacity ratios of distributed energy resources (DERs). According to equal increment rate criteria, to minimize the whole expenses, an interesting marginal costs-based economic droop control is proposed in this paper, and the active power can be distributed by identical marginal costs among DERs under economic droop control. If some DERs have arrived at the maximum or minimum power, consensus-based "virtual" controller is applied to make marginal costs still be the same among the rest of DERs. Moreover, distributed secondary frequency controller (DSFC) is proposed to rapidly restore system frequency to the nominal value. As an ancillary service, the whole design can easily realize the transition between economic and non-economic operation only by altering the type of droop control. The above controllers only need to interact with neighbor DERs by sparse communication network, so that eliminating the necessity of a central controller. An islanded microgrid incorporating renewable generators, storage devices and conventional generators are presented to verify the effectiveness of the above controllers. Simulation results show that the proposed controllers can successfully make islanded microgrids realize economic operation and the above transition.

1. Introduction

Microgrids can be considered as a self-autonomous small-type power distribution system, which are integrated with several types of DERs [1]. The traditional droop control distributes power by the capacity ratio [2], it is easy to make the total operational costs higher as the generation costs and operating characteristics of different types of DERs are various. Therefore, in order to minimize the whole operating costs, it is necessary to take costs optimization into consideration such that achieving economic operation of the whole microgrids.

The optimization operation is generally based on a centralized approach in microgrids, and optimization methods, such as programming [3], or intelligent algorithms [4] etc. are used to solve the optimization model in the central management system. Then, the obtained instructions are transmitted to the local DERs such that achieving economic optimization in the whole network. In Ref. [3], a mixed integer programming method is used to solve the multi-objective optimization model. In Ref. [4], an economic dispatch problem for DC microgrids is solved by a heuristic method to realize economic power distribution. In Ref. [5], an optimal dispatch strategy considering storage devices is proposed to minimize the total operating costs aiming at grid-connected microgrids, and an improved dynamic programming technique is used to solve this model. A optimal economic dispatch problem including combined heat and power in microgrids is presented by Ref. [6], then to solve the mixed integer nonlinear problem, a modified particle swarm optimization algorithm is employed. However, with increasing kinds of DERs integrating into microgrids, the inherent shortcomings of centralized optimization are gradually known by researchers, such as, difficulty in large amount of data acquisition and processing, vulnerability to central point of failures and communication failures [7].

Aiming at the above mentioned shortages in centralized approaches, distributed economic operation of microgrids has soon attracted researchers' attention. For distributed economic dispatch, in Ref. [8], an distributed economic dispatch problem is proposed to minimize the total costs in microgrids incorporating generators and demands. Aiming at economic dispatch model including thermal generators and wind turbines, a projected gradient and finite-time average consensus algorithms is adopted in Ref. [9]. Ref. [10] has considered 2 parallel consensus algorithms, and economic power distribution is done with considering line loss. For distributed economic control, Ref. [11] introduces a fully distributed

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power optimization technique on the basis of equal increment rate criteria and consensus algorithm to minimize generation costs in autonomous microgrids where PQ control is used in DER models. However, voltage regulation and reactive power averaging are neglected, which must be considered in islanded microgrids. In comparison with PQ control, droop control is more prevalent and proper in autonomous microgrids, therefore, some scholars introduce autonomous economic droop control. Refs. [12–14] design a kind of economic nonlinear droop controller, which make DERs with higher price generate less power, and more power are output by cheaper DERs, thus the whole operational costs is cut down in some extent. Nevertheless, this controller is designed based on the DERs' operation costs, rather than marginal costs, therefore optimal economic operation can not be obtained in this way. Besides, secondary frequency and voltage regulation are also not included in these papers. Ref. [15] presents a kind of autonomous three-level control to achieve identical marginal costs among DERs, but dynamic response became slower because the low-pass filter is adopted to reduce the effect of non-linear droop control on the system stability. A kind of modified droop control based on marginal costs are proposed in Ref. [16], where marginal costs-voltage droop control is applied. But it is difficult to obtain equal marginal costs in primary control because of heterogeneous line impedance. Therefore, secondary control must be used, this make the system become complicated. Moreover, marginal costs for renewable energy sources and storage devices are not included in microgrids. Consensus algorithm is used to achieve equal incremental rate in traditional droop-controlled microgrids in Ref. [17], nevertheless the system stability is weakened as dominant node must be chosen to control the direction of the increasing or decreasing of marginal costs.

For grid-connected microgirds, PQ control is generally adopted because the voltage magnitudes and frequency of the microgrids is concise with the grid, and then the centralized controller is generally used to regulate the power of DERs. By contrast, system's frequency and voltage magnitudes may be lower than rating values as the droop control is a devious controller in islanded microgrids. So, centralized or distributed secondary control is necessary to restore frequency and voltage. Ref. [18] introduces a kind of centralized control scheme based on Model Predictive Control considering communication delays. However, the centralized approach needs to collect the information from all DERs, and then sends regulating commands after processing to each device. Although the control accuracy is high, single point of failure is easy to happen and reliability is low. Ref. [2] presents the new distributed controllers that require no knowledge of the network topology, impedances, or loads. Ref. [19] takes line impedances into consideration, and builds mathematical models to design a multi-agent-based distributed controller. Ref. [20] designs a consensus-based distributed controller on the basis of virtual synchronous generators. Ref. [21] adopts a finite-time distributed control approach in frequency and voltage restoration which enables the frequencies and voltage amplitudes at all the DERs to converge to the reference values in finite time. From the above references, we can know that distributed cooperative approach on the basis of multi-agent and consensus algorithms are well accepted due to the advantages against communication failures by sparse communication networks in recent years. An overview in the study of distributed multi-agent coordination is detailedly given in Ref. [22].

In view of the above mentioned shortages, this paper has made a contribution in the following aspects: (i) An interesting marginal costs-frequency droop control is proposed, equal marginal costs can be accurately achieved in primary control. (ii) Considering the power constraints of DERs, if some DERs have arrived at their upper or lower power limits, consensus-based "virtual" controller is applied to make equal marginal costs can still be achieved among the rest of DERs. (iii) To effectively restore the system frequency, DSFC is proposed to complete this goal in a distributed fashion. (iv) The system can easily achieve the transition between economic and non-economic stable operation in autonomous microgrids.

Apart from the above original contributions, virtual impedance is used in low-voltage network where line impedance is mainly determined by resistive to improve reactive power averaging [23,24], and the existing distributed secondary voltage controller (DSVC) [2] is used to reach a compromise between reactive power averaging and voltage regulation by choosing proper weight coefficients.

The paper is organized as follows. Section 2 introduces conventional droop control and the interesting marginal costs-frequency droop control. Moreover, marginal costs of different types of DERs are modeled based on their power characteristics. In addition, consensus-based "virtual" controller is also given at length here. DSFC and DSVC are both presented in Section 3, besides, overall control architecture have been clearly described in this part. The proposed controllers are tested in Section 4 under a range of conditions. Section 5 gives a conclusion for this paper.

2. Marginal costs-frequency droop control

To minimize the total expenses, this section analyzes the operating costs and corresponding marginal costs of different types of DERs, such as renewable generators, storage devices and conventional generators. The marginal costs-frequency droop control is proposed on the basis of traditional droop control.

2.1. Traditional droop control

In this paper, we use *P-f* and *Q-U* droop control in low-voltage network where line impedance is resistive. In this condition, virtual impedance loop is used to make the output impedance desirable at the line frequency (see the specific control architecture in Section 3) [25]. The traditional droop control is shown as

$$f_i = f^* - m_i P_i,\ m_i = \frac{f^* - f_{\min}}{P_{i,\max} - P_{i,\min}} \tag{1}$$

$$U_i = U^* - n_i Q_i,\ n_i = \frac{U_{\max} - U_{\min}}{Q_{i,\max} - Q_{i,\min}} \tag{2}$$

where $U_{\max}$, $U_{\min}$ is the upper and lower voltage limits. $f_{\min}$ is the allowable lowest frequency, and f^* is the nominal network frequency. $P_{i,\max}$, $P_{i,\min}$ is respectively the allowable maximal and minimal active power, similarly, $Q_{i,\max}$, $Q_{i,\min}$ is separately the allowable reactive power maximum and minimum. U^* is the rated network voltage, and P_i, Q_i is respectively the measured active and reactive power injection. f_i, U_i is the measured frequency and voltage magnitude of DER *i*. The gains m_i, n_i are the relevant droop coefficients.

2.2. Marginal costs-frequency droop control

If power limits of DERs are not considered, the minimum of total operating costs can be achieved when incremental costs for all DERs are equal. Therefore, the equal increment rate criteria can be used in distributed economic control of islanded microgrids [26].

Based on this criteria, in order to achieve economic operation of the whole microgrid, on the basis of traditional *P-f* droop control, and considering marginal cost ($L_i(P_i)$) of each DER, an interesting $L_i(P_i) - f$ droop control is proposed as follows

$$f_i = f^* - \lambda_i L_i(P_i),\ i = 1, 2, \ldots N_{\mathrm{DER}} \tag{3}$$

where N_{DER} is the number of DERs. $L_i(P_i)$ is the marginal cost or incremental cost of DER *i*, which would be discussed in detail in