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Coordination control of multiple micro sources in islanded microgrid based on differential games theory

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ABSTRACT

To deal with the deviations of frequency of microgrid system composed of multiple micro sources caused by load disturbance, the load frequency control of islanded microgrid system is studied based on linear quadratic differential games theory in this paper. Considering the operating characteristics of each micro source, different objective function weighting matrix is selected, and the control strategy of non-cooperative feedback Nash equilibrium of each micro source in microgrid system is researched. The simulation results show that the control strategy can accomplish system control targets, make full use of the various of characteristics of each micro source and balance the benefit of them. At the same time, the control strategy has good robustness to external disturbance and parameter variation of the internal unit.

0. Introduction

The emergence and development of microgrids have contributed to widespread connections among distributed generation (DG) units. The key technological challenge of islanded operation of the microgrid is to retain power balance, voltage stability, and frequency stability through the coordination and regulation of various micro-DG units [1–3]. Researchers around the world have conducted many studies on control strategies for microgrids [4–6]. From the perspective of the operation control structure, the primary control strategies for microgrid systems are master/slave control, peer-to-peer (P2P) control, and hierarchical control. Master/slave refers to the mode in which the microgrid operates based on one master controller coupled with a number of slave controllers. In this mode, communication between the master controller and slave controllers is essential, and the slave controllers are subject to control by the master controller [7–9]. Moreover, because of the introduction of the static droop characteristics of the power sources in conventional synchronous generators, P2P control strategies for DGs with inverter have attracted significant attention. Currently, the most frequently adopted P2P strategy is droop control [10–12]. In hierarchical control strategies, DG units and loads at the field level are managed using multi-level coordination and regulation [13–16].

Microgrid operation control generally requires cooperation, coordination, and negotiation among multiple participants. However, based on the currently existing operation control strategies, controllers functioning at different levels could exhibit mutual independence (and even conflict) between control targets. If coordination is disregarded in the control strategy design, the control actions could interfere with each other, producing control effects that deviate from the initial objectives. Nevertheless, even if some control strategies are equipped with global coordination functionality, it remains difficult for them to provide mathematically clear coordination and control schemes that can satisfy all involved participants, which is undesirable. Specifically, with the continuous growth of DG amount in microgrids, this self-oriented combination of DG systems is likely to cause problems such as system power oscillation and energy efficiency reduction.

Game theory has been widely adopted for evaluating how multiple parties make decisions that are beneficial to themselves (or their entire group) according to their own capabilities and available information when there exist connections and conflicts of interests. Game theory has widespread applications in power systems to solve the coordination of participants[17–20]. Differential game derived from game theory and optimal control theory can be used to solve for the dynamic system control strategy evolving multiple participants [21]. The linear quadratic differential game, a significant subgroup of the differential game, is developed based on the linear model of a dynamic system, in which the game is described using quadratic payoff functions for every participant [22]. The differential game is introduced in power system researches recently. In [23] a novel framework based on the principles of differential games is proposed to analyze the smart grid security. A two-

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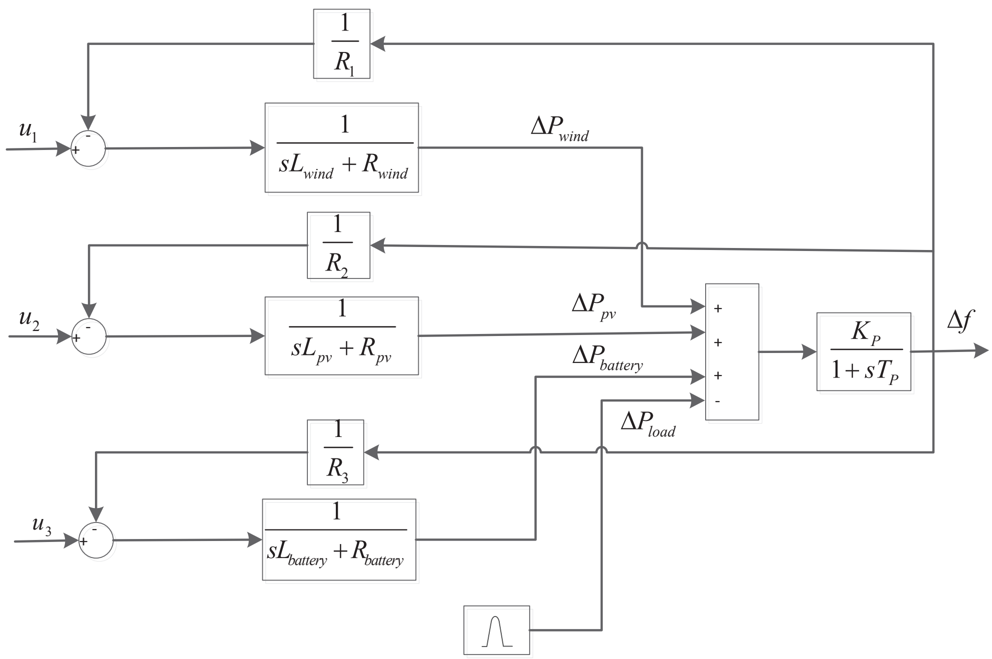

Fig. 1. Linear model of microgrid system with multiple micro-DGs.

level differential game framework is proposed in [24] to study the demand response program and a large population demand response management can be achieved [25]. The differential game is also applied in power systems for studying the distrubance suppression of excitation systems and frequency control [26].

In this paper, a differential game model for a microgrid integrating with multiple DGs is constructed by using the linear quadratic differential game. The coordinated frequency control strategy of the microgrid system in islanded operation mode is investigated. The feedback control strategy for each micro-DG units is determined by treating themselves as game participants. Simulation and computation results indicate that superior control efficiency and robustness in terms of frequency fluctuation suppression can be obtained by applying the proposed approach.

1. Linear quadratic differential game and Nash equilibrium

A linear dynamic system with N participants can be expressed as

$$\dot{x}(t) = Ax(t) + \sum_{i=1}^{N} B_i u_i(t) \tag{1}$$

where $x(t)$ is the system state variable vector, $u_i(t)$ is the control strategy adopted by the ith participant, A is the system state matrix, and B is the system control matrix.

The payoff function for the ith participant is

$$\min J_i = \int_{t_0}^{\infty} [x(t)^T Q_i x(t) + u_i(t)^T R_{ii} u_i(t) + u_j(t)^T R_{ij} u_j(t)]dt,\ j \neq i \tag{2}$$

where t_0 is the start time of the game, Q_i is the weight coefficient matrix corresponding to the system state variables, and R_{ii},R_{ij} are the weight coefficient matrices corresponding to the system control variables. Here, Q_i is a symmetric matrix, and R_{ii},R_{ij} are positive definite matrices. Q_i defines the weights on the system state variables while R_{ii},R_{ij} defines the weights on the control input in the cost function. The larger these values are, the more penalization on these corresponding signals. Basically, choosing a large value for Q_i means trying to stabilize the system with the least possible changes in the system state variables and vice versa. The choosing of R_{ii},R_{ij} is similarly.

We assume that all of the game participants are able to observe the system states, that linear time-invariant feedback control strategies are adopted by all participants, and that the participants have no reasons to cooperate with each other, because of conflicts of interests. Therefore, the control strategy for each participant can be written as $u_i = F_i x(t)$, $F_i \in R^{m_i \times n}$, where $R^{m_i \times n}$ is the strategy space of the i^{th} participant, m_i is the dimension of the control vector, and n is the dimension of the system state variable vector. Each participant can control $x(t)$ by adjusting its own control strategy $u_i(t)$ for the purpose of minimizing the payoff function value. The payoff function for each participant does not depend on only its own strategy; it is also strongly influenced by strategies of the other participants. Moreover, minimization of one payoff function usually requires coordination with the other participants, from which the game is generated.

For the linear quadratic differential game between Eqs. (1) and (2), the Nash equilibrium $\overline{F} = (\overline{F}_1,...,\overline{F}_n) \in F$ can be defined using Eq. (3).

$$\sup J_i(\overline{F}_1,...,\overline{F}_i,...,\overline{F}_N,x_0) \leqslant \sup J_i(\overline{F}_1,...,F_i,...,\overline{F}_N,x_0) \tag{3}$$

Based on the theory of linear quadratic differential game [27], the Nash equilibrium can be determined by using the method demonstrated below Assuming that there exists a $n \times n$ real symmetric matrix P_i satisfying the following condition:

$$\left(A-\sum_{j\neq i}^{N} S_jP_j\right)^T P_i + P_i\Big(A-\sum_{j\neq i}^{N} S_jP_j\Big)-P_iS_iP_i + Q_i + \sum_{j\neq i}^{N} P_jS_{ij}P_j = 0 \tag{4}$$

$$A-\sum_{i=1}^{N} S_iP_i \text{ is stable} \tag{5}$$

where $S_i = B_iR_{ii}^{-1}B_i^T$,$S_{ij} = B_iR_{ii}^{-1}R_{ji}R_{ii}^{-1}B_i^T$, $i \neq j$, then the Nash equilibrium $\overline{F} = (\overline{F}_1,...,\overline{F}_n) \in F$ can be defined as

$$\overline{F}_i = -R_{ii}^{-1}B_i^TP_i,\ i = 1,...,N \tag{6}$$

2. Model of microgrid integrated with multiple micro-DGs

Treating each micro-DG in a microgrid as a game participant, when the microgrid suffers a disturbance (such as a load fluctuation), participants can choose optimal strategies based on their own payoff functions.

A typical mathematical model of a microgrid integrated with micro-