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A novel adaptive control strategy of interconnected microgrids for delay-dependent stability enhancement

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ABSTRACT

To enhance the delay-dependent stability of interconnected microgrids, a novel adaptive control strategy is designed in this paper. Firstly, an adaptive robust control model is established to coordinate multi-MGs energy management. By regulating control parameters, Lyapunov stability without delay can be guaranteed. Secondly, stability evaluation methods considering uncertainty, such as mode perturbation and communication failure, are proposed to analyze delay-independent system. On this basis, to eliminate the adverse effects of delay caused by wide-area measurement, an active disturbance rejection stabilizer is designed here, which can be self-adjust adaptively via delayed time, and doesn't require multiple iterations in the parameters regulation. Through Schur complement theorem, the analytic expression of feedback gains is obtained from linear matrix inequalities. Finally, with an IEEE 118-node test feeder as an example, the numerical simulation verifies the feasibility of the proposed stabilizer under the cases of long delays.

1. Introduction

With the advance of renewable energy utilization technologies, a number of power electronic inverters have been connected to the power grid, where remarkable economic and social benefits are obtained. Microgrid (MG) is a cluster of loads, distributed generations (DGs) and energy storage systems (ESS), where DGs and ESS are accessed to MG through voltage source converters (VSC). VSC-based MG provides a feasible scheme for large-scale utilization of renewable energy sources. Furthermore, the development of the wide-area measurement system and communication technologies makes the smart distribution envision can be configured in multi-MGs.

In general, DER-based MGs are deployed as interconnected MGs in the regional power system. For rapid power adjustment of MGs, MGs may interact with each other by VSC-based interfaces. To achieve the precise load sharing in the interaction of DGs and MGs, droop control is utilized to simulate the highly inductive impedance between sources and small power angles. In this method, droop control with high gain is required to guarantee expected load sharing. On the other hand, but for the high gain, it has a negative effect on small-signal stability (SSS) which decrease the oscillation damping of generators in AC MGs, as investigated in [1–3]. To coordinate the contradiction [2], proposes an auxiliary loop to improve the SSS and frequency regulation of MGs, while ensuring satisfactory active load sharing among all VSCs with a predetermined allocation rate. For MGs with transmission delays and packet dropouts [4], propose a distributed energy resources control strategy to mitigate frequency fluctuations stemming from the volatility of renewable resources and fluctuating power demand.

The management of distributed energy resources (DER) via control strategies mitigates frequency fluctuations stemming from the volatility of renewable resources and fluctuating power demand.

The European Integrated Research Programme puts forward the concept of Web of Cell system on International Conference on Power Engineering [5]. In this framework, 'cell' is defined as interconnected flexible combinations of distributed generation within a certain power or geographical boundary [6,7] agree that the primary concern of the interconnected cluster is to design a control strategy to guarantee system stability.

Based on the above framework, the distributed control strategy with self-adaptive intelligence is the preferred method applied in the MG cluster control. On the premise of ensuring stability of clusters, droop gains are chosen rationally rather than conservatively, which optimizes the accuracy of power sharing. Under this method, within the feasible range, distribution system operator (DSO) does not need to dispatch internal adjustable DGs in MG directly, and has a good interface for MG autonomous energy management.

However, to perceive global state, wide-area measurement system (WAMS) introduces delay in interconnected MGs system inevitably

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Nomenclature

ω,U	angular frequency, voltage amplitude
P_G,Q_G	real and reactive power generation
P_L,Q_L	real and reactive power consumption
P_I,Q_I	real and reactive power injection
n_ω,n_U	droop gains of frequency and voltage
τ_δ,τ_U	time constants of δ and U
k_δ,k_U	angle and voltage compensation coefficients
d	time delayed
ACE_P,ACE_Q	area control error of real and reactive power
$\boldsymbol{x}$	system state vector
$\boldsymbol{u}$	control input vector
$\boldsymbol{y}$	controlled output vector
$\boldsymbol{A}$	system matrix
$\boldsymbol{A}_d$	delayed feedback matrix
$\boldsymbol{B}$	input matrix
$\boldsymbol{B}_1$	input control matrix
$\boldsymbol{B}_2$	input disturbance matrix
$\boldsymbol{C}$	output matrix
$\boldsymbol{D}$	feed-forward matrix
$\boldsymbol{V}$	Lyapunov functional
$\boldsymbol{H}$	Jacobian matrix
$\boldsymbol{F}_1$	feedback matrix of state
$\boldsymbol{F}_2$	feedback matrix of delayed state
$\boldsymbol{w}$	disturbance signal vector
$\boldsymbol{Z}_i$	symmetrical positive definite matrix
$\lambda_{\max}$	maximum eigenvalue of $\boldsymbol{F}$
γ	performance index
T_m	maximum delay
μ	maximum rate of delay change
$\boldsymbol{\pi}$	Markov state probability density matrix
$\boldsymbol{N}$,$\boldsymbol{M}$,$\boldsymbol{S}$	generalized free weighting matrix
$\boldsymbol{L}$	feedback gain matrix
$\boldsymbol{P}$,$\boldsymbol{Q}$,$\boldsymbol{R}$	symmetrical positive definite matrix
π_{ij}	transition probability from i to j

[8,9], where a new control problem arises. According to the economic game, changes of multi-MGs combination is common, for which stability of switched systems with delay need to be ensured. In particular, long delay may cause oscillatory instability, where auxiliary control must be designed to improve the access capacity of MGs.

So far, some research has been carried out on the above problems. For large-scale interconnected power system with WAMS [10], employs networked predictive control (NPC) to design a wide-area damping controller (WADC) for the generator exciter to enhance the damping of interarea oscillations. In addition, an adaptive time delay compensation method is applied power system stabilizer respectively [11]. For distributed energy system, economic dispatch of multi-MGs is discussed in [12–14], in which the dispatch of multi-MGs is studied in depth. However, practical engineering is still subject to the constraints of communication delay and uncertainty. For the delay and uncertainty of distributed communication in a MG [15–17], develops new distributed secondary cooperative control schemes to coordinate distributed generators (DGs) in islanded microgrids, the simulation in [15] verify the effectiveness under load variation, communication topology change, time delays and data drop-out. While [16] derives the maximum delay mathematical expression for internal communication in a MG. The discussed delay and uncertainty exist in distributed communication between neighboring DGs. And the communication uncertainty is caused by variable communication links and communication weights. However, when it comes to interconnected MGs, the region is larger, and the problem of delay-dependent stability is more serious [18,19]. To guarantee the delay-dependence stability of interconnected MGs, power flow calculation is necessary, which makes the control better be centralized rather than distributed. Hierarchical management schemes are designed in [20,21], where discussed delay exists in the communication between a single MG and a control center. On the other hand, to improve the control performance under delay [22,23], propose a distributed coordinated control, where the validity of a delay-dependent H^∞ robust control with memoryless feedback is demonstrated.

To enhance delay-dependent stability of interconnected MGs, an adaptive stability control strategy is proposed in this paper, where delay exists between a control center and MGs. DSO, as the center of all MGs, broadcasts stability criterion without delay to microgrid control centers (MGCC) and manages risk of switching delay system through interactive communication. For possible oscillation instability caused by the long delay, an H^∞ control with memory and memoryless feedback is proposed. The ultimate goal is to guarantee the stable operation of interconnected MGs.

Firstly, the equivalent model of interconnected MGs is established. Based on adaptive tracking control, interactive power between MGs can be precisely controlled. Secondly, the cause of the delay problem is analyzed. In this light, a sufficient theorem for ensuring delay-dependent system stability is proved. Thirdly, distributed robust droop management is applied to adaptively adjust the droop parameters for guaranteeing SSS. On the other hand, an H^∞ active disturbance rejection stabilizer is designed to eliminate the instability caused by delay. Ignoring the critical delay, the stabilizer proposed in this paper has a good effect on long delay access. Furthermore, the calculation of feedback gain does not require iterative computation.

This paper is organized as follows: In Section 2, an equivalent model of interconnected MGs is proposed. In Section 3, the effect of the delay introduced by wide-area state estimator on the stability control is discussed. In Section 4, based on the model and analysis before, we design an adaptive control strategy to ensure the small signal stability of the system and eliminate delay oscillation. Finally, in Section 5, an example of the IEEE 118-node test feeder demonstrates the effectiveness of this strategy.

2. Dynamic equivalent model of interconnected microgrids

Based on the modeling of droop control, the external characteristics of MG are modeled in this paper. Other literature, such as [23,24], analyses the model of a single DG in the form of VSG and VSC. While this paper model the cluster of DGs to describe the external characteristics of a MG. In addition, we properly simplify the high order dynamic characteristics, which makes it more conducive to practical application.

For a common VSC-based interface, the first-order droop controller is deployed in autonomous power sharing. The $P-f$,$Q-U$ droop characteristics of all DGs can be equivalent to the interface control functions:

$$\begin{aligned} \omega &= \omega_{ref} + n_\omega(P_G - P_L + P_I + \Delta P_{COI}) \\ U &= U_{ref} + n_U(Q_G - Q_L + Q_I + \Delta Q_{COI}) \end{aligned} \quad (1)$$

where P_G,Q_G are the real and reactive power generated in the MG, respectively. While P_L,Q_L correspond to the total power consumption. P_I and Q_I are the real and reactive power injection which can be calculated by the sum of the tie-line power. ΔP_{COI},ΔQ_{COI} are real and reactive acceleration power for the real-time center of inertia. n_ω is the MG frequency droop gain and n_U is that of voltage, which are the accumulation of internal droop characteristics:

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