Electrical Power and Energy Systems 104 (2019) 734–743

Contents lists available at ScienceDirect

Electrical Power and Energy Systems

journal homepage: www.elsevier.com/locate/ijepes

Neighbor-prediction-based networked hierarchical control in islanded microgrids

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ARTICLE INFO

Keywords:
Power sharing
Consensus protocol
Network data-loss and delay
Neighbor-prediction control
H∞ robustness criteria

ABSTRACT

For the droop-controlled distributed generation units (DGs) in microgrids (MGs), the power sharing error associated with voltage difference of DGs can be attributed to the mismatched line impedance. To improve the power sharing accuracy in islanded MGs, a neighbor-prediction based hierarchical control strategy is proposed. In secondary control, a consensus protocol is used to regulate the DGs voltages interacted by communication network to the state of tracking synchronization. Thus, the error-free power sharing is obtained. Network data-loss and delay problems are considered. To stabilize the DGs' inner-loop control in which there is a delayed input, the H∞ robustness criteria of a dynamic model of DGs is derived. If the DG*i*'s voltage in network transmission loses, the prediction system of a neighbor will be activated to forecast the lost voltage for secondary consensus control by extreme learning machine (ELM). Thus, the voltages regulation will be back to normalization. Simulations in MATLAB confirm the effectiveness of proposed control in MGs.

1. Introduction

To solve the problems of current resource shortage and environment pollution, renewable energy resources, such as wind energy and solar energy, are widely used in actual power generation Ref. [1]. Affected by the weather and geographical location, the distributed characteristics of hybrid power generation can bring about the problem of 'how to integrate the different forms of power generation effectively to maintain a stable power supply for loads'. As shown in Fig. 1, microgrid (MG) is comprised of distributed generation units (DGs), energy storage devices and electrical loads. General DGs include wind turbine (WT) and photovoltaic panel (PV). DGs are connected to MG through inverters. By means of the communication network interaction, the local distributed controller of can control the interfaced inverter of each DG reasonably to achieve the DGs' coordination. MG is working as an autonomous small-scale power system, which will share the pressure of large power grid Ref. [2].

Generally, there are two operation modes, grid-connected mode and islanded mode, in MGs. In the first mode, the operation of the operation of DGs obeys the dispatching orders from large grid automatically. In the second mode, it is necessary to use an appropriate method to control the DGs' interfaced inverters Ref. [3]. Droop control, which is not dependent on the communication generally, is used as a common method to realize the DGs' plug-and-play in a decentralized way when MG operates in the islanded mode Refs. [4], [5]. In the mechanism of droop control, the DG's voltage is adjusted in accordance with its output powers. So, some problems of output power can be solved indirectly by optimizing DG's voltage.

In an MG with multiple DGs, the impedance of DGs' lines may be mismatched because of the different transmission distances or cable line lengths. It will result in the fact that DGs' voltages are unequal. And the power sharing error of DGs will appear Ref. [6]. So the power demand of loads can't be shared proportionally by DGs Ref. [7]. Some bad situations, such as the excess capacity operation or powers absorption, may exist. They are not allowed for the stable operation of MG.

To reduce the power sharing error, some measures have been proposed to improve the droop control. They are generally divided into the decentralized control and the coordinated control. A significant difference between them is their degree of dependence on communication. General decentralized controls in the existing studies are shown as follows. A virtual impedance method was used to balance line impedance in Ref. [8]. To compensate DG's voltage, a paralleling virtual capacitor and an adaptive control of powers were proposed in Ref. [9]. The study in Ref. [10] improved the voltage reference and droop coefficient by means of the compensation of line voltage drop. Combining with the virtual negative impedance, the virtual power source

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https://doi.org/10.1016/j.ijepes.2018.07.057
Received 12 April 2018; Received in revised form 2 July 2018; Accepted 24 July 2018
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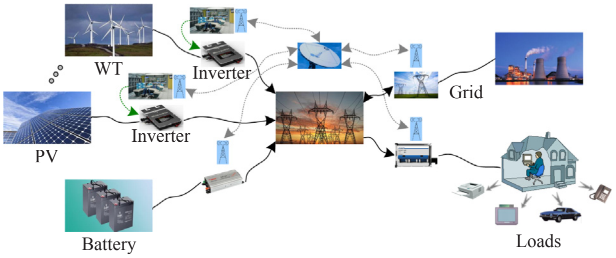

Fig. 1. A typical microgrid structure diagram.

was used to replace DG in the droop control in Ref. [11]. Authors in Ref. [12] used an inverse power factor droop control. In Ref. [13], a signal injection method based on the power error before and after injecting a small power information disturbance signal is used to minimize the power sharing error. Ref. [4] used a wavelet transform analysis, which regulates voltage by detecting loads change. Generally, an upper coordinated algorithm is added to the droop control in order to realize the coordinated control where DGs' interaction is supported by a stable communication. Some coordinated controls are shown as follows. In secondary control, the consensus algorithm was used to regulate voltages in Ref. [14] or restore voltages to their nominal value within a finite time in Ref. [15]. From Ref. [16], it was known that a PI compensator can be used to restore voltage to nominal value or remove the steady-state deviation. Ref. [17] proposed a sharing error reduction and voltage recovery method by changing the voltage bias. Besides, a pinning control algorithm to restore voltage in a consensus-based power secondary control was designed in Ref. [18].

With more MGs and DGs access, it is necessary to learn from the concept of cyber-physical system to control MG Ref. [19]. Physical-layer includes the MG's physical structure and DGs' control systems. Communication network is a medium to transmit the entire information of DGs. So MG's control system can be evolved into a typical networked control system (NCS) with an actual background. Due to the limited communication bandwidth of MGs, the channel congestion may result in the transmission delay or even data-loss. Their impacts on MG's control reliability, such as time-synchronization-loss of variables and destabilizing the dynamic performance, can't be ignored Ref. [20]. Each DG node is corresponding to a communication node. So the plug-and-play of any DG can change the topology of "one-to-one correspondence" interdependent communication network. The switching topology graph technology proposed in Ref. [21] can be useful.

Although the coordinated controls in Refs. [14–18] may be more accurate in power sharing control, the necessary discussion of communication delay and data-loss in DGs' interaction is universally missing. An intermittent or sparse communication technology for MG hierarchical control was used to maintain power sharing while reducing the network utilization to avoid large delay and data-loss in Refs. [22–24]. Considering the uncertain communication links, the power control was robust under the DGs interaction uncertainty in Ref [23]. An observer-based voltage regulation method in Ref. [24] was verified effective under the communication topology change, delay, and data-loss. Additional theoretical analysis seems to be necessary. The impact of network delay was analyzed and an allowable delay which MG can stay stable was derived in Refs. [25], [26]. The delay robustness was also studied in Refs. [27], [28] which used a delay-dependent H_∞ robust control to stabilize the delayed coordinated controller under the certain disturbance in MG. To eliminate the adverse effects of delay, the delay sliding mode control was used to ensure an optimal MG's stability in Refs. [20], [29]. Besides, Ref. [30] explained that the data-loss caused by channel congestion can be solved by compensation. But there are few relevant studies.

Different from above mentioned studies, a networked hierarchical control strategy subject to delay and data-loss is proposed to ensure the enhanced DGs' voltage regulation under a complex communication network environment. In the primary control, DGs' delay robustness is discussed in the inner-loop control, and the robustness criteria are derived. In the secondary control, the consensus algorithm is used to regulate voltages. Considering the possible data-loss, the event-triggered neighbor-prediction control scheme is proposed. The prediction system of a neighbor is used to forecast the lost data by extreme learning machine (ELM) Ref. [31] when the data-loss occurs. The normal voltages regulation of secondary control is ensured. The main characteristics of this work are as follows.

(i) In order to stabilize the inner-loop control with the input delay, the Lyapunov function stability criteria of H_∞ control corresponding to a certain DG's dynamic model is derived.
(ii) Secondary control includes data sensor, event generator, and consensus control. The corresponding functions are receiving data, handling data-loss, and regulating voltages.
(iii) An event-triggered neighbor-prediction control is proposed. Event-trigger means that when the voltage data of a DG loses (*Event*), the event-generator can sends a command to activate the prediction system of a neighbor (*Trigger*). The lost voltage will be forecasted by ELM and then transferred to secondary control.

The rest of this paper is organized as follows. Section 2 introduces the control systems in proposed control strategy. Section 3 mainly proves the delay robustness of inner-loop of primary control. Section 4 introduces the secondary control. Section 5 introduces the neighbor-prediction control. Section 6 shows the simulations under multi-case. Section 7 summarizes the paper and gives the conclusion.

2. Description of proposed control strategy

As shown in Fig. 2, the proposed control includes primary control, secondary control, and neighbor-prediction control. Each DG has its local primary control and prediction system. All DGs have the corresponding secondary control. The corresponding functions are described as follows.

2.1. Primary control

It is an autonomous closed-loop control system. The droop control in outer-loop can realize the basic adjustment of voltage in accordance with the powers. And the control method in inner-loop can hold the control robustness of DG in case of disturbance.

Power calculation: Actual dispatched powers of DG are calculated based on the actual output voltage and output current.

Droop control: Original command frequency and command voltage

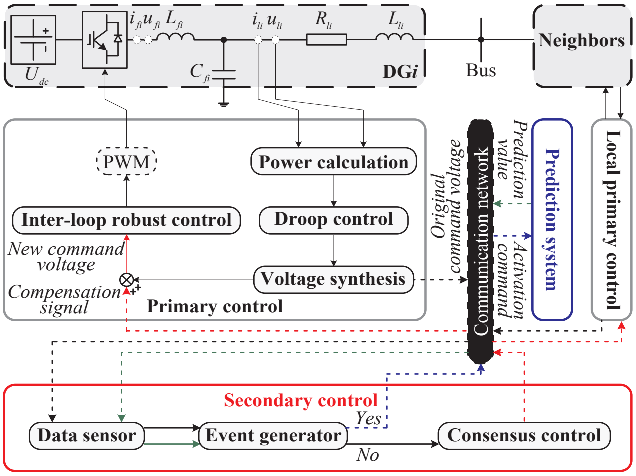

Fig. 2. Control flow diagram of proposed control strategy.