Voltage and Reactive Power Control of Microgrids Based on Distributed Consensus Algorithm

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Abstract: In a low-voltage microgrid system, due to the influence of property of line impedance and other factors, the reactive power supplied by distributed generations could not be shared accurately based on conventional droop control. To improve the power sharing accuracy, a voltage and reactive power control approach of microgrids (MGs) based on distributed consensus algorithm (DCA) is proposed in this paper. Based on the communication technology and hierarchical control theory, an architecture of distributed hierarchical control is introduced which consists of local control level and distributed secondary control level. The local control level involves droop control, virtual impedance control and proportional-resonance (PR) voltage and current control to achieve reactive power sharing. In secondary control level, an observer is designed based on DCA to get global average value, which restores the voltage deviation and improves the accuracy of reactive power sharing. Besides, the method not only can reduce the high bandwidth requirements, but also improve the reliability and extended flexibility of MGs. Finally, the simulation experiment platform is built based on Matlab/Simulink software and dSPACE1103. Real-time simulation results are shown to demonstrate the effectiveness and robustness endowed by the proposed method. The results indicate that the DCA is very robust with respect to communication impairments, such as packet delays and random packet losses.

Key Words: Microgrids (MGs); Droop control; Distributed secondary control (DSC); Distributed consensus algorithm (DCA); Packet delays.

1 INTRODUCTION

In recent years, in order to solve the access problem of distributed generations (DGs), coordinate the contradiction between large power grid and DGs and improve the comprehensive utilization of energy. The concept of Microgrids (MGs) has been proposed and attracted significant attention [1]. MGs as a kind of special distributed generation system, which integrate a variety of renewable energy sources, energy storage, local load, monitoring protection device and the local power supply system of control units, which can autonomously operate in islanded mode or connect to the main grid [2].The distributed generators (DGs) in microgrid is mainly through power electronic equipment access to the power distribution system. Voltage Source Inverters (VSIs) are usually used for distributed generation interfaces in MGs. In the large scale microgrid, multiple inverters are usually required to be connected in parallel through the MGs. It is difficult to regulate voltage, frequency deviations and power sharing accuracy of the islanded MGs with multiple inverters. In order to avoid circulating currents among the converters, the droop-control method is often applied [3]. However, in MGs with multiple inverters paralleled, there are no inertias, and the feature of networks is mainly resistive. Mismatches in the physical parameters of inverters and in the line impedances that connect to inverters to the PCC degrade the power sharing accuracy. It will generate circulating current. The inherent tradeoff of this method between frequency and voltage amplitude regulation in front of power sharing accuracy cannot be avoided in islanded mode. As aforementioned, several methods have been proposed to improve the reactive power sharing by improving droop control mechanism. These approaches have changed the characteristics of traditional droop control, and most of the schemes are more complex and difficult to be applied in engineering practice [4]. To cope with these issues, a hierarchical control structure was firstly proposed in [5], which consists of three levels: primary control layer, secondary control layer and tertiary control layer, so that the microgrid can easily achieve standardization, which have been paid more and more attention in the industry. Some authors proposed secondary and tertiary controllers. The main problem to be solved in such works was the frequency control of system, however, voltage stability issue was not considered. In [6], the deviations of voltage and frequency are reduced by secondary control strategy was proposed, but the communication algorithm adopted cannot achieve accuracy of reactive power sharing. In [7], a decentralized coordinated control strategy has been proposed based on agent communication, but the scale of system is limited because of the numbers of required data exchanges.

In this paper, a voltage and reactive power control approach is proposed, including primary control layer and secondary control layer. In the secondary control layer, distributed secondary controller and primary controller are combined

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together and embedded in every DG, which as a node in the networked control system (NCS) and exchanges information between secondary controllers through the network.

This paper is organized as follows. In Section II, the structure of distributed hierarchical control and distributed consensus algorithm are described. Then, details of primary controller and distributed secondary controller for MGs are discussed in Section III. Section IV provides simulation experimental results of an islanded MG with two DGs. Conclusions are given in Section V.

2 DISTRIBUTED COORDINATED CONTROL APPROACH FOR ISLANDED MICROGRIDS

2.1 Distributed hierarchical control structure based on consensus algorithm

The conventional centralized control scheme may encounter severe challenges in applying a Networked Control System (NCS). Firstly, in order to achieve the optimal operating conditions, the MGCC will be required to have a high level of connectivity, which will impose a substantial computational burden and is more sensitive to failures and modeling errors than distributed control schemes. Another challenge is that the topology of MGs is unknown, because the variety of configurations of power grid and communication network topologies, "plug-and-play" technologies will make the topology time-varying. Thus, in order to control this kind of NCS, a robust algorithm should be able to operate correctly in the presence of limited and unreliable communication capabilities, and often in the absence of a central control mechanism.

In order to achieve fully distributed control, this paper applies a distributed consensus algorithm based distributed hierarchical control method to achieve reactive power sharing accurately and voltage restoration. The consensus algorithm based distributed hierarchical control scheme for an islanded MG is shown in Figure 1. In this architecture, primary and secondary controls are implemented in each DG unit. The secondary control is placed between the communication system and the primary control.

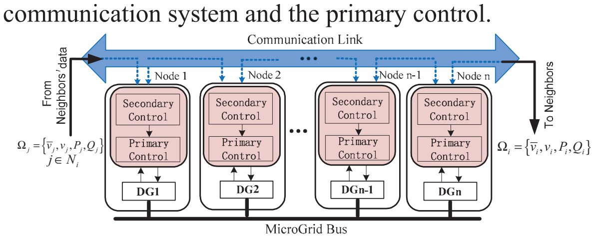


Fig.1 Proposed hierarchical control architecture for islanded MGs

2.2 Distributed consensus algorithm

Consensus problems and algorithms find their roots in the computer science area [8]. In recent years, they have been more and more applied in multi-agent systems, coordinated control, congested control, crowd control, complex dynamical network, etc. The purpose of consensus algorithm is to allow a set of distributed agents to reach an agreement on a quantity of interest by exchanging information through communication network. In the MGs system, these algorithms can be used to achieve the information sharing and coordinated control among distributed DG units. The basic distributed consensus algorithm with continuous-time integrator agents can be presented as,

$$\dot{x}_i(t) = -\sum_{j\in N_i} a_{ij}(x_i(t) - x_j(t)), \qquad i = 1,2,\cdots,n \tag{1}$$

where x_i is the state of agent node i .The state variable x_i can be expressed as the physical quantity of the actual syst em, such as voltage, current, frequency, etc. a_{ij} indicates th e connection status between node i and j ,if the nodes i an d j are not neighboring nodes, then $a_{ij} = 0$. N_i is the set of indexes of the agents that are connected with agent i . From a system point of view, the vector form of the iteration algorithm of the equation (1) can be expressed as follows:

$$\dot{X} = -L_n X \tag{2}$$

where L_n is the laplace matrix of network and related with the networked topology architecture. Considering the discrete nature of communication data transmission, the discrete-time form of the consensus algorithm (1) is used in this paper as follows,

$$\begin{aligned} x_i(k+1) &= \sum_{j=1}^{n} w_{ij}(k)x_i(k) = \\ x_i(k) &+ \sum_{j\neq i} w_{ij}(k)(x_j(k) - x_i(k)), \qquad i = 1,2,\cdots,n \end{aligned} \tag{3}$$

The vector form of equation (3) can be described as,

$$X(k+1) = W(k)X(k) \tag{4}$$

where $W(k)\in R^{n\times n}$ is the weight matrix of the communication network. The weight matrix is designed to a kind of random matrix and the elements of row or column of the matrix adds up to 1, the largest eigenvalue is single 1, the modulus of the rest of eigenvalues are less than 1.If the $W(k)$ is designed to double random symmetric matrix, then the final consensus equilibrium value will be achieved and presented as follows:

$$\bar{x}_i(k) = \frac{1}{n}\sum_{j=1}^{n} x_i(0), \qquad i = 1,2,\cdots,n \tag{5}$$

The detailed proof of the algorithm convergence can be found in. In this paper, the initial values are the locally measured DG terminal voltage and the inductor current.

The communication time delays of the actual networked control system is inevitable, the distributed consensus algorithm with time delays can be expressed as,

$$U_i(k+1) = \sum_{j=1, j\neq i}^{n} w_{ij}U_j(k-\tau) + w_{ii}U_i(k) \tag{6}$$

$$L_i^*(k) = \sum_{j=1, j\neq i}^{n} w_{ij}L_j(k-\tau) + w_{ii}L_i(k) \tag{7}$$

where τ is the communication delay, which is the integral multiple of sampling period T_s .When τ is less than T_s ,the communication delays have no effect on consensus convergence and when τ is more larger, the characteristic of consensus convergence is determined by the matrix $W(k)$.

In summary, distributed consensus algorithm can be adopted in the distributed secondary control, not only can reduce the effect of time delays on the system robustness, but also avoid the situation that centralized control relies on MGCC excessively .Thus, it improves the reliability and flexibility of MGs. The details of primary controller and distributed secondary controller are introduced elaborately in the next section.

3 DISTRIBUTED HIERARCHICAL COORDINATED CONTROL OF VOLTAGE AND REACTIVE POWER

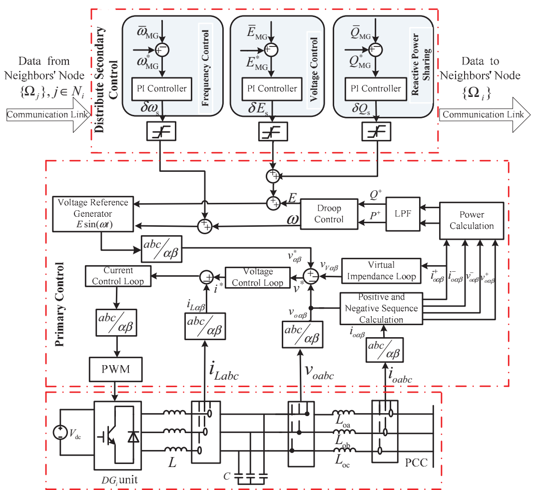


Fig.2 Scheme of distributed hierarchical control for a DG unit

Figure 2 depicts the details of distributed hierarchical coordinated control for a single DG unit in an islanded MG. It can be seen that the power stage of each DG consists of a distributed DC power, three-phase bridge inverter circuit and an LCL filter. Note that, the other DGs have the same power stage, but the line impedances are different. The local controller of each DG consist of voltage and current control loops, virtual impedance loop, and traditional droop control loop, which generate the gate signals for DGs interface inverters. Discrete distributed consensus algorithm is applied in the distributed secondary control level, which the global average values are obtained. Each converter transmits a set of data, $\Omega_j = \{\bar{v}_j, v_j, P_j, Q_j\}$ to its neighbors. The dataset transmitted by node i , Ω_j consists of four elements; its estimate of the average voltage across the microgrid $\bar{v}_j$, the measured local voltage v_j , and the measured per-unit active or reactive power P_j, Q_j .At the other end of the communication links, each converter j receives data from all its neighbors Ω_k , $k \in N_j$ with communication weights a_{jk} .These communication weights are design parameters and can be considered as data transfer gains.

3.1 Design of primary controller

The primary control includes current and voltage control loops, active and reactive power droop control loops and virtual impedance loop. All the control loops are designed in $\alpha\beta$ reference frame. Since the DGs and MG system are operating in islanded mode, P^+/f and Q^+/V based droop control are used for coordinating the operation of those DGs, which mimic the behavior of synchronous generators in conventional power system to achieve positive sequence active and reactive power sharing. Besides, in order to increase the response speed and help to improve the dynamic behavior of the power control, the differential term is applied to the droop control. Accordingly, the voltage and frequency are regulated by the droop control, as shown in Figure 2. The positive sequence output active and reactive power of the DGs is first calculated based on the instantaneous reactive power theory. Positive sequence active and reactive power (P^+ and Q^+) can be extracted by using low-pass filters. The calculated P^+ and Q^+ are then used by droop controller to generate voltage and frequency references.

3.2 Design of distributed secondary controller

In this section, we illustrate the use of the distributed consensus algorithm. In order to restore the deviation of voltage generated by the primary droop control, improve the accuracy of reactive power sharing, a distributed secondary controller is designed based on the distributed consensus algorithm.

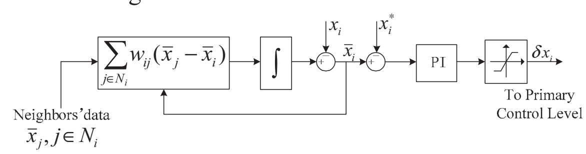


Fig.3 State observer and compensation value

In the secondary control, a state observer is constructed with the distributed consensus algorithm, which is used to obtain global average value. Figure 3 shows the coordinated distributed approach for the global averaging. The observer at node i receives its neighbors' estimates $\bar{x}_j$ ($j \in N_i$).Then, the observer updates its own estimate $\bar{x}_i$ by processing the neighbors' estimates and the local state measurement x_i .Using the four DGs as an example, the data sets Ω_j are achieved from neighborhood j ,according to the distributed consensus algorithm as shown in equations (3)~(5), if the $W(k)$ is double random matrix, for arbitrary $i \in [0, N]$, N is the sum of DG units, then data sets $\bar{\Omega}_i$ will converge to a global average value can be expressed as follows:

$$\lim_{k\to\infty} \bar{\Omega}_i(k) = \frac{1}{N}\sum_{i=1}^{N} \Omega_i(k) \tag{8}$$

Then calculate the difference between expected value and average value of the output voltage of every DG_i , meanwhile the difference will be transmitted to PI controller and amplitude limiting implement, ultimately achieve the compensation value δx_i .where x_i is the amplitude of DG_i output, $\bar{x}_j$ and $\bar{x}_i$ are the average value of the corresponding quantities obtained from node j and node i , respectively. x_i^* is the expected value of DG_i output.

In order to guarantee the convergence characteristic of system and have a good robustness with consideration of communication delays, the $W(k)$ matrix can be designed according to the Metropolis constructed method that proposed in the literature [9] and can be presented as follows:

$$w_{ij}=\begin{cases}\dfrac{1}{\max(n_i,n_j)+1}, & j\in N_i\\ 1-\sum\limits_{j\in N_i} w_{ij}, & i=j\\ 0, & others\end{cases} \tag{9}$$

where the $\max(n_i,n_j)$ represents this node and its neighboring nodes have a larger number of neighbors.

In Figure 2, secondary control in each DG collects all the measured value (frequency, voltage amplitude and reactive power) of other DG units by using the communication system and produces appropriate control signals that send to the primary control layer to remove the steady-state deviations. Therefore, the average values of angular frequency, voltage amplitude and the reactive power of DG units can be obtained as follows:

$$\bar{\omega}_{MG}=\frac{1}{N}\sum_{i=1}^{N}\omega_{DGi} \tag{10}$$

$$\bar{E}_{MG}=\frac{1}{N}\sum_{i=1}^{N}E_{DGi} \tag{11}$$

$$\bar{Q}_{MG}=\frac{1}{N}\sum_{i=1}^{N}Q_{DGi} \tag{12}$$

The average values are compared with the nominal angular frequency ω_{MG}^* , voltage E_{MG}^* and reactive power Q_{MG}^* of MGs and sent the compensation values to the primary controller of DG_i to correct the angular frequency, voltage and reactive power as follows:

$$\delta\omega_s = k_{pf}(\omega_{MG}^* - \bar{\omega}_{MG}) + k_{if}\int(\omega_{MG}^* - \bar{\omega}_{MG})dt \tag{13}$$

$$\delta E_s = k_{pE}(E_{MG}^* - \bar{E}_{MG}) + k_{iE}\int(E_{MG}^* - \bar{E}_{MG})dt \tag{14}$$

$$\delta Q_s = k_{pQ}(Q_{MG}^* - \bar{Q}_{MG}) + k_{iQ}\int(Q_{MG}^* - \bar{Q}_{MG})dt \tag{15}$$

where k_{pf} , k_{pE} and k_{pQ} are the proportional coefficients of PI controller, respectively. k_{if} , k_{iE} and k_{iQ} are the integral coefficients of PI controller, respectively. $\bar{\omega}_{MG}$ is the average angular frequency, $\bar{E}_{MG}$ is the average voltage and $\bar{Q}_{MG}$ is the average reactive power. $\delta\omega_s$, δE_s and δQ_s are the compensation values of frequency, voltage and reactive power, which sent to the primary control level to restore the deviations, respectively.

Therefore, the input ω_i and E_i of the three-phase voltage reference generating module are obtained, the calculating equation of ω_i and E_i can be expressed as

$$\begin{cases}\omega_i=\omega^*+\delta\omega_s\\ E_i=E^*+\delta E_s+\delta Q_s\end{cases} \tag{16}$$

4 SIMULATIONS ANALYSIS

In order to evaluate the effectiveness of the proposed DSC control strategy, a simulation experiment platform of an islanded microgrid was built based on Matlab/Simulink software, which includes two DGs, as shown in Figure 4. All DG units in the system have the same power rate of 3kW. The dSPACE1103 is a real-time platform used as an interface between the electrical part and the control part to produce a power hardware-in-the-loop simulation. The switching frequency was 10 kHz. The electrical setup and control system parameters are detailed in Table 1.

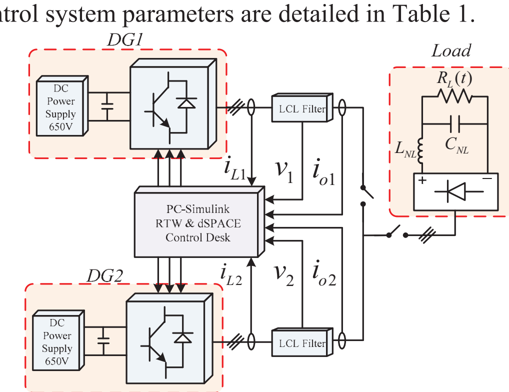


Fig.4 Simulation setup of an islanded MG with two DG units

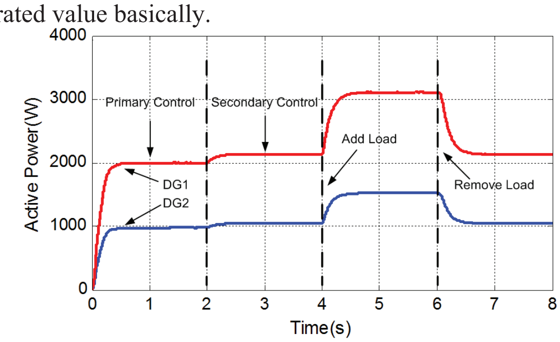
Table1. Electrical Setup and Control System Parameters

Parameter	Symbol	Value
Electrical Parameters		
Nominal Voltage	E	311V
Nominal Frequency	$\omega^*/2\pi$	50Hz
DC Voltage	V_{dc}	650V
Resistive Load	R_L	200/400Ω
Output Inductance	L_0	1.8mH
Filter Inductance	L	1.8mH
Filter Capacitance	C	25μF
dSPACE Sampling Frequency	f_s	10kHz
Droop Control		
Active Power Droop term	k_p	0.008Ws/rd
Reactive Power Droop term	k_q	0.16Var/V
Active Power Differential term	k_d	0.00002
Distributed Secondary Control		
Frequency Proportional term	k_{pf}	0.01
Frequency Integral term	k_{if}	4s^{-1}
Voltage Proportional term	k_{pE}	0.01
Voltage Integral term	k_{iE}	0.6s^{-1}
Reactive Power Proportional term	k_{pQ}	0.0001Var/V
Reactive Power Integral term	k_{iQ}	0.3Var/Vs

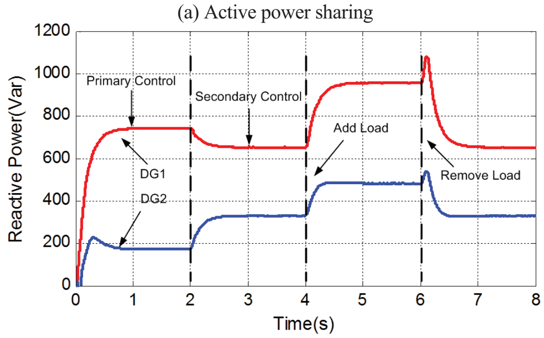
4.1 Dynamic performance evaluation of distributed secondary control system

For the sake of simplicity, when analyzes the system dynamic performance of distributed secondary control, the communication time delay was assumed to be negligible.

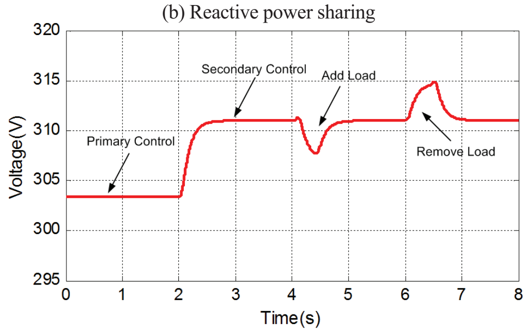
Firstly, the performance of voltage restoring control and power sharing control in microgrid are evaluated by the proposed distributed secondary control approach. Specifically, during the first 2s of operation, where the MG is under only the primary droop controller, so the output reactive power sharing of the DGs is completed. The experimental results are shown in Figure 5. From Figure 5(a) and (b), it can be observed that the active power can be shared accurately according to the proportion of 2:1, but the reactive power sharing deviation exists due to the line impedance so that the reactive power sharing is not accurate, and it can be seen from Figure 5(c), the DG output voltage deviation from the nominal value exists. Therefore, in order to remove the deviations, the proposed distributed secondary control (DSC) is implemented at t=2s, and as can be observed, reactive power sharing and DG output voltage deviations are gradually eliminated, so the reactive power can share accurately and the DG output voltage achieves rated value basically.



(a) Active power sharing



(b) Reactive power sharing



(c) Voltage control

Fig.5 Dynamic performance evaluation of MG based on DSC

In order to verify the dynamic performance of the proposed DSC, analyzing the effect of power sharing and voltage change in the presence of frequent load changes in the latter half of the experiment, where the load is increased by approximately active load of 1.5kW and reactive load of 0.4kVar for a short time at t=4s and then disconnected at t= 6s. As can be observed from Figure 5(a) and (b), due to the load change, there is a fluctuating deviation in the reactive power sharing. After implementing the DSC, it can be seen that the DSC can eliminate the deviation quickly that caused by rapid load variations, so the reactive power can be shared accurately according to the ratio of 2:1. From Figure 5(c), it can be seen that the DSC also has a good performance when rejecting DG output voltage disturbances caused by load variations.

4.2 System stability analysis with time delay

With development of networked control system theory and applications, the influence of time delay to networked control system should be considered. It is one of the most important factors of worsening system performance. The delaying information do not transmit to system on time will cause the system unstable. Specifically, the effects of three different delays on the performance of control system are studied. In order to simulate the low bandwidth communication characteristics of the secondary control layer and primary control layer, adding a delay module between the compensation signals of secondary control layer to the primary control layer, the delay module is directly connected to the PI controller of the secondary control. Taking voltage secondary control as an example, the control structure is shown in Figure 6.

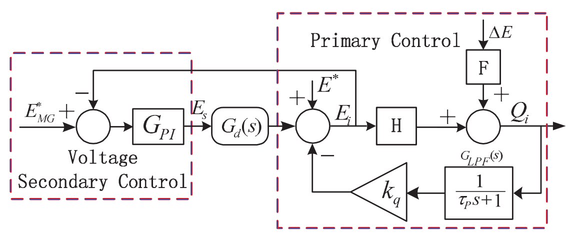
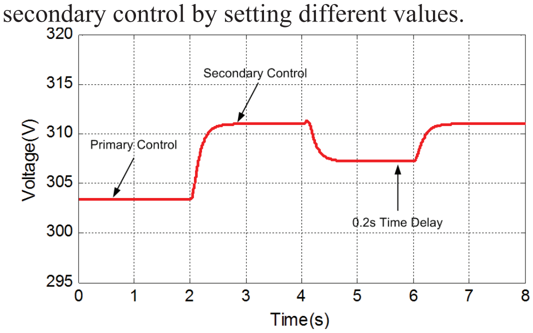


Fig.6 Structure of distributed secondary control with time delay

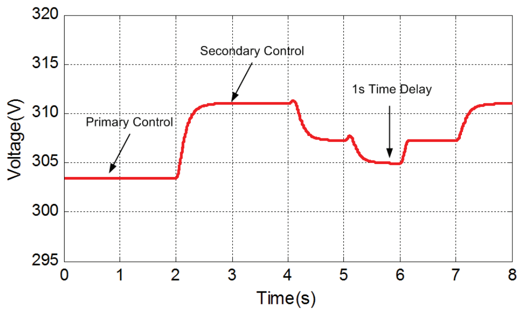
The transfer function of delay module can be presented as

$$G_d(s) = \frac{1}{T_d s + 1} \tag{17}$$

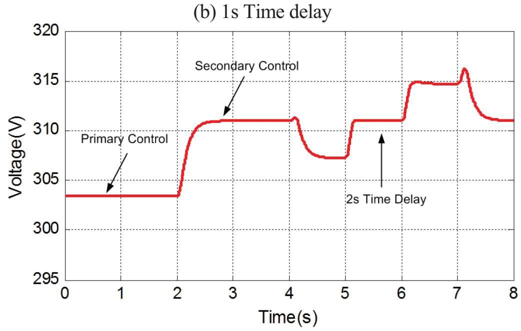
Where T_d is the network communication delay of every module. It can be simulated the communication time delay of secondary control by setting different values.



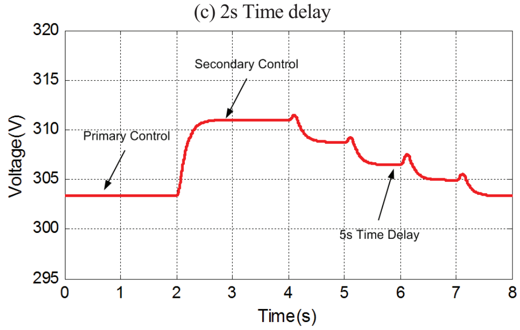
(a) 0.2s Time delay



(b) 1s Time delay



(c) 2s Time delay



(d) 5s Time delay

Fig.7 Dynamic performance evaluation of DSC with time delay

For the sake of simplicity, here only voltage is depicted. The variation of load is the same as the section 4.1. Figure 7 depicts how time delays affect the system DG output voltage, when DSC tries to remove voltage deviation caused by frequent load variations. The experimental results are shown in Figure 7, which includes three kinds of time delays. From Figure 7(a) and (b), it can be observed that the DSC can adjust voltage deviation caused by load variations when the time delay is less than 1s, which makes the DG output voltage to achieve rated value, and the overshoot is small. Therefore, the system has a good robustness. Besides, even if the time delay is set to 2s, the DSC slowly but successfully regulates DG output voltage deviation caused by load variations, and the system responses of DSC approach is acceptable, the experimental result is plotted in Figure 7(c). Nevertheless, we note that when the time delay is larger, for example, the time delay is set to 5s, as can be observed from Figure 7(d), the system loses the effect of DSC, which adjusts the voltage deviations, only primary control exists. Thus, there is an enormous deviation between the DG output voltages, thus the system is unstable. In addition, for the packet loss, it can be processed in accordance with the larger time delay.

5 CONCLUSIONS

In this paper, a distributed secondary control strategy has been proposed for the issues of voltage stability control and reactive power sharing of MGs. The distributed consensus algorithm is applied to design distributed secondary controller that eliminates the voltage and reactive power sharing deviations, which produced by the traditional droop control. The properties of proposed approach are evaluated by an islanded microgrid simulation experimental platform consist two DG units based on Matlab/Simulink and dSPACE1103. The simulation results verified that the proposed method can successfully restore the DG output voltage of system and properly equalize the reactive power, even if in the low X/R circumstances. In addition, the dynamic performance and robustness of control system are also investigated in the presence of time delays. Indeed, the results indicate that the system stability is not affected by the short time delay; however, the system will be unstable in the case of long time delay. Therefore, the results confirm the validity and feasibility of the proposed control approach.

REFERENCES

[1] Claudio A. Cañizares, Rodrigo Palma-Behnke. Trends in microgrid control, IEEE Transactions on Smart Grid, Vol.5, No.4, 1905-1918, 2014.

[2] J.M.Guerrero, M.Chandorkar, T. Lee, and P. C. Loh. “Advanced control architectures for intelligent microgrids-Part I: Decentralized and hierarchical control,” IEEE Trans. Ind. Electron, Vol.60, No.4, 1254-1262, 2013.

[3] Q. Shafiee, J. M. Guerrero, and J. C. Vasquez, “Distributed secondary control for islanded microgrids-A novel approach,” IEEE Trans. Power Electron, Vol.29, No.2, 1018-1031, 2014.

[4] Lee C T, Chu C C Cheng P T. A new droop control method for the autonomous operation of distributed energy resource interface converters, IEEE Transactions on Power Electronics, Vol.28, No.4, 1980-1993, 2013.

[5] J. M. Guerrero, Vasquez, J.e, Matas, and J. de Vicuna, Hierarchical control of droop-controlled AC and DC microgrids-A general approach toward standardization, IEEE Transactions on industrial Electronics, Vol.58, No.1, 158-172, 2011.

[6] Jinwei He, Yunwei Li, A enhanced microgrid load demand sharing strategy, IEEE Transactions on Power Electronics, Vol.27, No.9, 3984-3995, 2012.

[7] A. Bidram, A. Davoudi, F. L. Lewis, and Z. Qu, Secondary control of microgrids based on distributed cooperative control of multi-agent system, IET Gener. Transm. Distrib, Vol.7, No.8, 822-831, 2013.

[8] Long Hui, Fan Xiaoping, Liu Shaoqiang. Review of distributed consensus problem in multi-agent system, Computer Engineering and Applications, Vol.49, No.1, 36-42, 2013.

[9] Li Peijie, Lu Yong, Bai Xiaoqing, Wei Hua. Decentralized optimization for dynamic economic dispatch based on alternating direction method of multipliers, Proceedings of the CSEE, Vol.35, No.10, 2428-2435, 2015.