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Cyber Physical Implementation of Improved Distributed Secondary Control of DC Microgrid

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***Abstract*—This paper presents a cyber physical system implementation of an improved distributed secondary control (IDSC) scheme of islanded dc microgrid (DCMG). The IDSC scheme mitigates the hidden issues of primary control with included droop technique for the distributed generation unit (DGU) in a DCMG by providing the adjustable voltage compensation, improves voltage regulation and enhances the current sharing of all DGUs. The voltage compensation of IDSC is the resultant of two voltage components, i.e., average distributed integral voltage controller and average current controller. The dynamic consensus algorithm is used to obtain the global average values in the for distributed secondary controlusing relatively low bandwidth communication. The impact of communication time delay on the stability in IDSC based DCMG with two DGUs is presented. The performance of IDSC scheme is validated on a microgrid scenario, which includes parallel connection of four DGUs and common load. The real-time cyber physical system of DCMG is implemented on OPAL-RT test platform that combines the device layer on FPGA, control and cyber layers on CPU of OP5700 by using eFPGASim and RT-LAB.**

Keywords—Distributed generation, cyber physical system, distributed cooperative secondary control algorithm, consensus algorithm, DC microgrid

I. Introduction

Microgrids are becoming popular in power distribution systems [1]. Since various types of sources (i.e. solar PV, battery storage) are dc and dc powered loads, e.g., appliance, are becoming available, DC microgrid are gaining in popularity. The Distributed Generation unit (DGU)s and energy storage are used to maintain the stable operation in an islanded microgrid. The primary issues of DCMG, [2][3] are current sharing and voltage regulation due to fact that the DG units are connected in parallel to the common DC bus or network. Centralized, Decentralized, Distributed and Hierarchical control methods have been proposed to achieve reliable operation of DC microgrid (DCMG).

Centralized algorithms require fast communication while purely local controllers exhibit poor performance. require sophisticated Algorithms, [5]-[9] such as fixed and adaptive droop techniques, average voltage controller and average current controller to provide the voltage compensation, and slope adjustment of droop curve have been proposed. The distributed integral average concept, [7] is used in UPS systems based ac microgrid to improve the average power sharing, and quick recovery of voltage and frequency. The virtual drop based simple algorithm is proposed in [10], and observer based algorithm is proposed in [11] to address the issues of voltage restoration and current sharing. This paper uses the concept of distributed integral gain average concept, [7] to replace the conventional proportional+integral (PI) controller in the secondary control layer.

The dynamic consensus algorithm based improved distributed secondary control (IDSC) of the cyber physical system DCMG (CPS-DCMG) is used to ensure the current sharing and voltage regulation, and improve the control performance. The IDSC is consists of two control loops, average distributed integral voltage compensation and average current controller, and the output of IDSC is fed to the primary control layer with droop technique of the DGU. The remainder of the paper is organized as follows: Cyber physical system description of IDSC based DCMG, and its control structure are explained in Section II. The small signal modelling approach of improved distributed secondary controller and the stability analysis with communication time delay between DGUs are presented in Section III, whereas in Section IV the real time simulation validations of IDSC based DCMG are provided. Conclusions are given in Section V.

II. Cyber Physical System Of Idsc Based Dc Microgrid

In this section, the cyber physical system of DCMG and IDSC structure are discussed. Fig. 1 illustrates the cyber physical system of islanded dc microgrid that contains physical layer (device layer and control layer) and cyber layer. The DC/DC converter based *DGU* (device layer) is interfaced to the DC bus of networked microgrid and serves as an interface to the loads. The local control system, control layer, includes primary control with droop technique and distributed secondary control.

The primary control is a current control loop based outer voltage loop to regulate the output voltage of DGUi, and droop control algorithm to ensure the equal power/current sharing of *DGU1*, *DGU2*, …, *DGUn*. The secondary control provides the voltage compensation, δV to the primary control to restore the dc bus voltage, and it is consists of two compensations, δVv_s and δVio. δV_v_s, is the output of proportional control local i^{th} *DGU* voltage and average distributed integral voltage of neighboring DGUs. The δV_io is the voltage compensation and it is the output of average output current controller compensation. Thus, δV to ensure the equal current sharing in all DG's and dc bus voltage restoration. The i^{th} DGU equations of the δVv_s and δVio are as follows:

$$\delta Vv_s = K_{P_{Vs}}\left(V_{dc_{ref}} - V_{on}\right) + \frac{1}{n}(ICVs1 + ICVs2 + \cdots + ICVsi + \cdots \ldots + ICVsn) \quad (1)$$

$$ICVsn = \frac{K_{IVs}}{s}\left(V_{dc_{ref}} - V_{on}\right) \quad (2)$$

$$\delta Vio = K_{P_{is}}\left(i_{on} - \frac{1}{n}\left(i_{o1} + \cdots .. + i_{o(n-1)}\right)\right) + \frac{K_{Iis}}{s}\left(i_{on} - \frac{1}{n}\left(i_{o1} + \cdots .. + i_{o(n-1)}\right)\right) \quad (3)$$

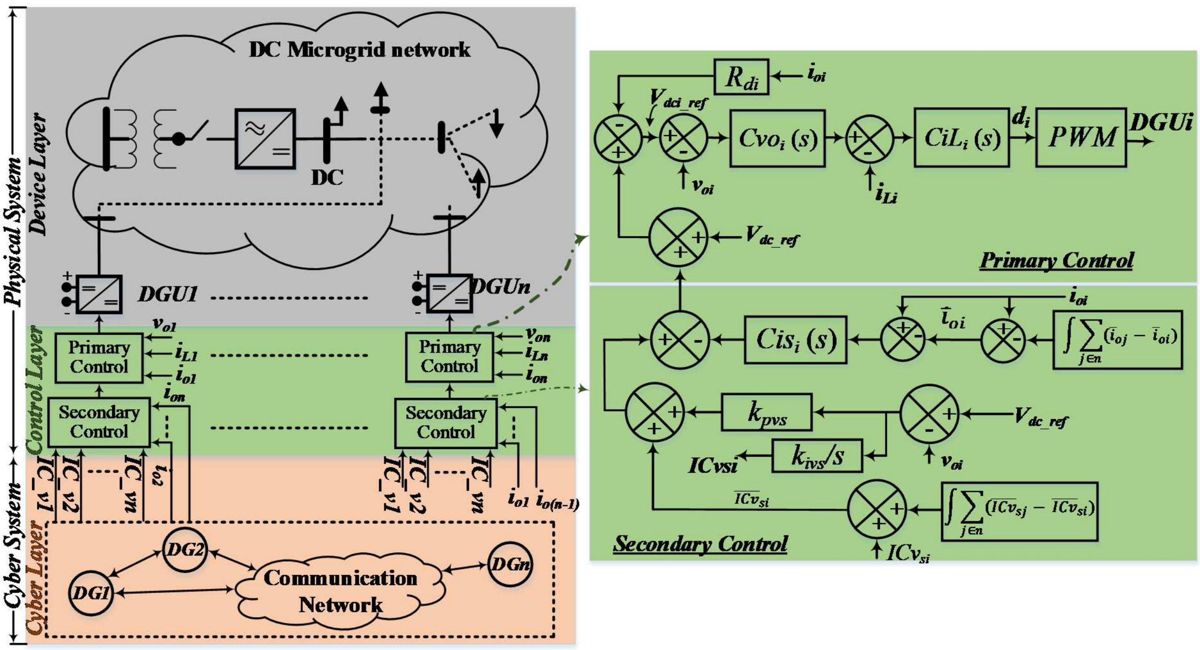

Fig. 1. Cyber Physical System of improved distributed secondary control of DC microgrid

where, k_{pvs} and k_{ivs} are the proportional and integral gain constants of the secondary voltage controller, k_{pis} and k_{iis} are the proportional and integral gain constants of the secondary average current controller. $ICvsi$ is the output of integral gain of *DGUi*.

Dynamic average consensus algorithm (DACA), [12] is used for the DGU states update to estimate the average voltage/current across the DCMG with the neighboring information of DGUs, and the corresponding equation in continuous time domain is as follows:

$$\bar{x}_i(t) = x_i(t) + \int_o^t \sum_{j\in n} a_{ij}[\bar{x}_j(\tau) - \bar{x}_i(\tau)]d\tau \tag{4}$$

$\bar{x}_i(t)$is the average value of *DGUi*, $\bar{x}_j(t)$is the average value of *DGUj,* i.e., neighboring unit information. $x_i(t)$ is the local measurement of *DGUi*. a_{ij} is the communication link status, $a_{ij}>1$, if there is communication link between i^{th} and j^{th} DGUs otherwise $a_{ij}=0$. From (4), any change in the local measurement, $x_i(t)$ directly effects the state update, $\bar{x}_i(t)$ of *DGUi*. The variation in $\bar{x}_i(t)$ information passes through the communication network and alter the state values of neighboring DG units. The discrete time domain representation of (4) at k^{th} sample time is given by,

$$\bar{x}_i(k+1) = \bar{x}_i(k) + x_i(k+1) - x_i(k) + \varepsilon \sum_{j\in n} a_{ij}[\bar{x}_j(k) - \bar{x}_i(k)] \tag{5}$$

'ε' is the constant edge weight and decides the algorithm convergence rate.

III. Stability Analysis of Distributed Cooperative DCMG Control

In DCMG, 'n' number of DGUs (DGU1, DGU2, …,DGUi,..., DGUn) are considered for the stability analysis of the impact of communication time delay/latency on the distributed cooperative secondary control algorithm. The system of 'n' DGUs are interconnected with different cable lengths and to the common load, R_L. The admittacne matrix (Y) of this system is given by,

$$\begin{cases} \mathrm{I_o} = \mathrm{YV_o} \\ Y = Z^{-1} \end{cases} \tag{6}$$

I_o is the vector of output current of all DGUs, [i_{o1}, i_{o2}, …. i_{on}]' and V_o is the vector of output voltage of all DGUs, [v_{o1}, v_{o2}, …. v_{on}]'. The impedance matrix, Z is as follows:

$$Z = \begin{bmatrix} R_{c1}+R_L & \cdots & R_L \\ \vdots & \ddots & \vdots \\ R_L & \cdots & R_{cn}+R_L \end{bmatrix} \tag{7}$$

The output current of *DGUi* is given by,

$$i_{oi} = Y_{ii}v_{oi} + \sum_{\substack{j\in n \\ i\neq j}} Y_{ij}v_{oj} \tag{8}$$

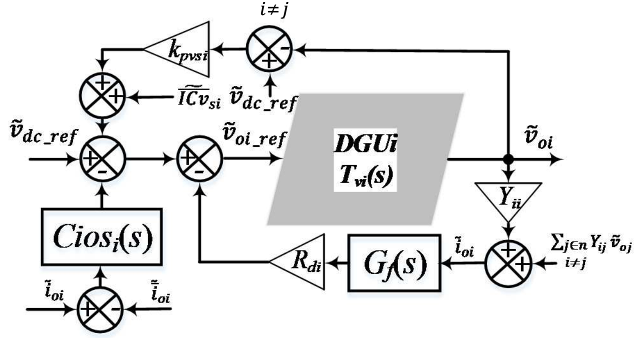

Fig. 2. Small signal model of IDSC control block diagram of *DGUi*

The small signal modelling approach is applied to get the time invariant system and the block diagram is shown in Fig. 2. The corresponding output voltage equation of i^{th} DGU is as follows:

$$\tilde{v}_{oi} = T_{vi}(\tilde{v}_{dc\_ref} + \widetilde{\delta v}_{vsi} - \widetilde{\delta v}_{ioi} - R_{di}G_f\tilde{\imath}_{oi}) \tag{9}$$

T_{vi} is the closed loop transfer function of i^{th} *DGU* output voltage, R_{di} is the droop constant and the G_f is the 1st order filter. The small signal modelling equations of voltage compensation components are given by,

$$\begin{cases} \widetilde{\delta v}_{vsi} = k_{pvs}(\tilde{v}_{dc\_ref} - \tilde{v}_{oi}) + \widetilde{ICv}_{si} \\ \widetilde{\delta v}_{ioi} = C_{ioi}(\tilde{\imath}_{oi} - \tilde{\bar{\imath}}_{oi}) \end{cases} \tag{10}$$

$$\begin{cases} \widetilde{\widetilde{ICv}}_{si} = \frac{1}{n}\left(\widetilde{ICv}_{si} + \sum_{\substack{j\in n \\ i\neq j}} \widetilde{ICv}_{sj}(t-\tau_d)\right) \\ \widetilde{ICv}_{si} = k_{ivs}\left(\tilde{v}_{dc\_ref} - \tilde{v}_{oi}\right) \\ \tilde{\tilde{\iota}}_{oi} = \frac{1}{n}\left(\tilde{\iota}_{oi} + \sum_{\substack{j\in n \\ i\neq j}} \tilde{\iota}_{oj}(t-\tau_d)\right) \end{cases} \quad (11)$$

The transfer function of communication time delay, $f(t\text{-}\tau_d)$ is represented by using pade approximation, [13] , and is as follows:

$$\begin{cases} L\{f(t-\tau_d)\} = e^{-s\tau_d}F(s) \\ e^{-s\tau_d} = \frac{(1-0.5\tau_d s)}{(1+0.5\tau_d s)} \end{cases} \quad (12)$$

The closed loop transfer function, $\tilde{v}_{oi}/\tilde{v}_{dc\_ref}$ is obtained from (9) to (12), and dominant poles of this transfer function with different values of communication time delay, τ_d (i.e., varied from 0.01ms to 100ms) on s-plane plot is shown in Fig. 3. It can be observed that all real poles and complex poles on the left half of s-plane, and moving towards the right half of the s-plane as the values of τ_d increases. Thus, IDSC scheme shows the stable operation with large value of τ_d.

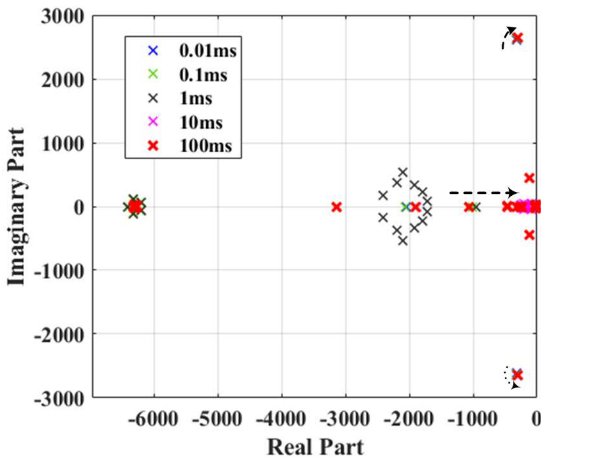

Fig. 3. Dominant poles of closed loop transfer function of IDSC based *DGUi* with variation in the value of communication time delay.

IV. Real Time Simulation Validations of CPS-IDSC-DCMG

To validate the performance of consensus algorithm based IDSC-DCMG, the real time implementation of low voltage DC microgrid is simulated in OPAL-RT 5700 with four boost converter-interfaced DC sources operating in parallel and a common load.

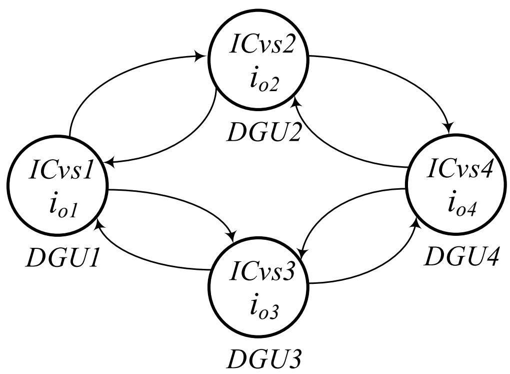

Fig. 4. Communication network topology for the DCMG

The execution of device layer, i.e. 4 DGUs on FPGA, and control layer, i.e. primary and dynamic consensus based secondary distributed layer on CPU, Cyber layer with communication network topology as shown in Fig. 4 on of the CPU and FPGA utilize RT-LAB and eHS solver, which are proided by OPAL-RT. The communication delay time, τ_d (=1ms) is considered to pass the information between two neighboring DGUs. The real time cyber physical system of DCMG testbed is showing in Fig. 4. The DCMG specifications are given in Table I.

TABLE I. Parameters Of The DGU In DCMG

No.	Parameter	Specifications
1.	DGU	Boost DC/DC Converter
2.	Source voltage of DGU	10V
3.	DC bus voltage	24V
4.	Switching frequency, f_s	10 kHz
5.	Inductance, L_i	0.4mH
6.	R_L (for 4 DGUs)	0.72Ω @ P = 0.8kW
7.	C_{in}	500 µF
8.	C_{out}	1000 µF
9.	Cable resistances, R_{c1}, R_{c2}, R_{c3}, R_{c4}	83mΩ, 62.9mΩ, 73.3mΩ, 67mΩ
10.	R_{di}	0.1412
11.	Current sharing constant, m_1,m_2,m_3,m_4	1
12.	Communication time delay, τ_d	1ms

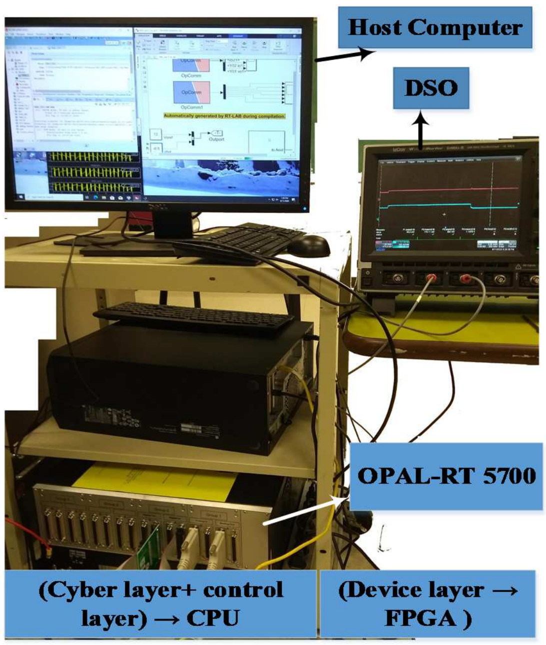

Fig. 5. Real time simulation test bed by using OP-5700

The boundary limits on the dc bus voltage are v_{dcmax} = 26.4V and $v_{dc\ min}$ = 21.6V. Real time simulations of dynamic consensus based IDSC-DCMG are tested under the load disturbances at the instants of time t_1 and t_2. At t=0s, the IDSC structure is activated and DCMG is running at the maximum load current of common load, R_L (i_o = 33.33A). The

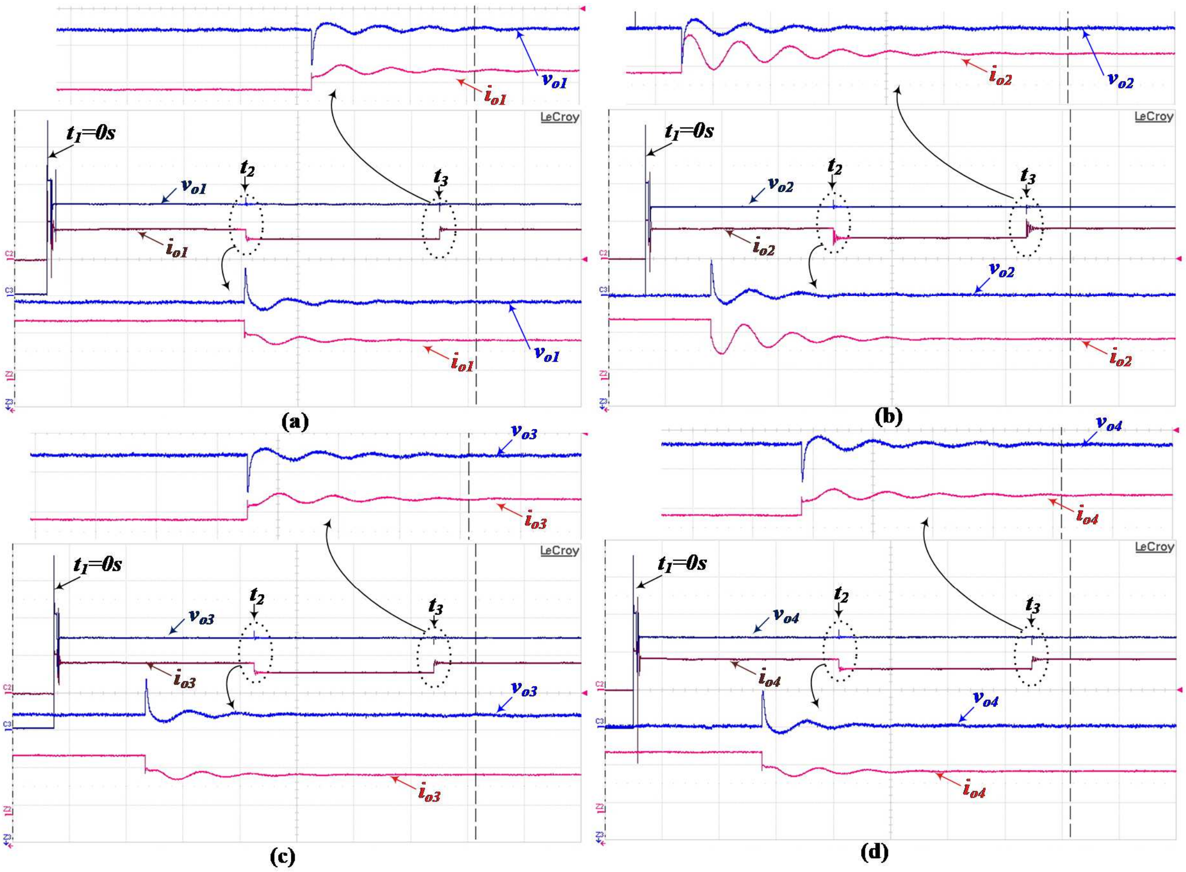

Fig. 6. Dynamic response waveforms of consensus algorithm based IDSC of DCMG with four DG units: (a) *DGU1* voltage, v_{o1} (10V/div) and current, i_{o1} (10A/div, 5s/div); (b) *DGU2* voltage, v_{o2} (10V/div) and current, i_{o2} (10A/div); (c) *DGU3* voltage, v_{o3} (10V/div) and current, i_{o3} (10A/div); (d) *DGU4* voltage, v_{o4} (10V/div) and current, i_{o4} (10A/div). The corresponding zoomed waveforms (200ms/div) are shown at the instant of load changes for all 4 DG units.

corresponding all DGUs output voltage and currents are shown in fig. 6 (a)-(d). It can be observed that all DGUs output currents are equal and dc bus voltage value is regulated at the reference value (=24V) as shown in Fig. 7.

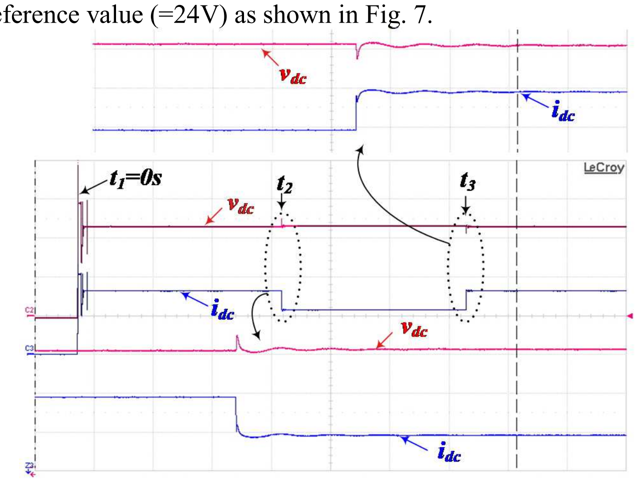

Fig. 7. Dynamic response waveforms across the common load point in a DCMG.

Now, the performance of DACA based IDSC is validated further through load disturbances. At t=t_1s, the load is changed from 33.33A to the 23.33A. i.e. 30% suddenly decreased and the real time simulation waveforms of all DGUs are shown in Fig. 6 (a) to (d). The zoomed version waveforms are also shown in the same figure. The dc bus voltage waveform is shown in Fig. 7. Similarly, t=t_2s, the load is changed from 23.33A to the 33.33A. i.e. 30% suddenly increased, and the corresponding waveforms are shown in Fig. 6 (a) to (d) and Fig. 7. It can be observed from the dynamic load performance that the DACA based IDSC_DCMG is operating in equal current sharing, dc bus voltage restoration within the boundary limits of v_{dc} and the low bandwidth communication.

V. Conclusions

In this paper, dynamic consensus algorithm based distributed secondary control scheme is presented for the cyber physical system of DC microgrid. This control algorithm is overcome the hidden issues of primary control layer with droop technique, i.e., current sharing error, voltage regulation and low bandwidth communication. The distributed control algorithm and cyber physical system are discussed. The IDSC scheme is employed in each DG unit, and four DG units with interconnected different cable lengths, and validated the system under dynamic load conditions. The real time simulation results shows that the IDSC scheme improves the current/power sharing, voltage regulation and the requirement of shared information of i^{th} DGU with neighboring DGUs.

Acknowledgment

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