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Dynamic Consensus Algorithm based Distributed Voltage Harmonic Compensation in Islanded Microgrids

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Abstract

In islanded microgrids, the existence of nonlinear electric loads may cause voltage distortion and affect the performance of power quality sensitive equipment. Thanks to the prevalent utilization of interfacing power electronic devices and information/communication technologies, distributed generators can be employed as compensators to enhance the power quality on consumer side. However, conventional centralized control is facing obstacles because of the distributed fashion of generation and consumption. Accordingly, this paper proposes a consensus algorithm based distributed hierarchical control to realize voltage harmonic compensation and accurate current sharing in multi-bus islanded microgrids. Low order harmonic components are considered as examples in this paper. Harmonic current sharing is also realized among distributed generators by applying the proposed methods. Plug-and-play capability is demonstrated for flexible operation. The proposed method is based on proper analysis and modeling of the system.

Introduction

Microgrids (MG) [1] concept has been proposed aiming to adapt to the distributed generation, consumption and storage paradigm and liberate the operation of power distribution systems. It enables the possibility of islanding operation of each system fraction. However, a number of critical issues need to be addressed such as system stability, security, power control, as well as power quality.

The existence of nonlinear loads, such as power electronic devices, electric arc furnaces, fluorescent lighting, variable frequency motor drives, etc., may cause voltage and current distortion and finally affect the performance of sensitive equipment resulting in over heating or even malfunction [2]–[4]. In small scale islanded MG, system stability can be also influenced because of small system damping. Accordingly, it is necessary to limit the system harmonics within certain level [5].

In case of MG systems, thanks to the prevalent using of power electronic converters, information and communication technologies, the distributed generators can be used as compensators to ensure desirable power quality on consumer side [6]–[9]. However, a central controller is usually required which generates the common compensation reference for all the DG units [8], [9]. In addition, most existing studies fail to consider the current sharing issues under unbalanced or harmonic distorted conditions, which may cause over current fault to the compensating DGs which are located close to the compensating point. Accordingly, the objective of this paper is to realize distributed compensation

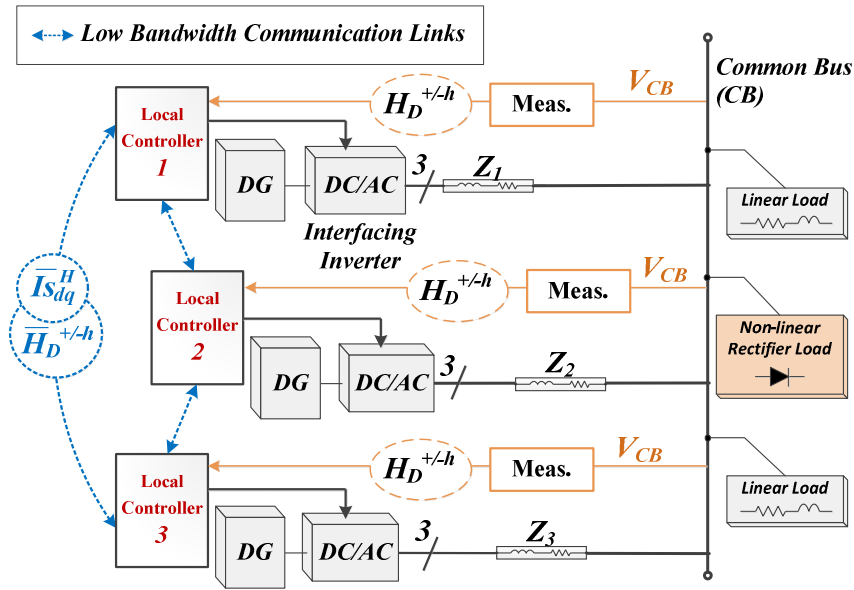


Fig. 1: Study case islanded three-phase AC MG.

control by applying proper information sharing and communication algorithms, and to avoid the using of a central controller and consequently enhance the system flexibility. Besides, the harmonic current sharing needs to be accurately controlled so that all the DG units can proportionally share the total load current according to their compensating capabilities.

A study case three-phase MG system is considered as shown in Fig. 1. Three DG units are installed to supply the loads on the Common Bus (CB). If nonlinear loads are connected to CB, voltage harmonics may appear affecting the performance of power quality sensitive equipment. In order to alleviate the voltage distortion, the DG units with interfacing inverters can act as distributed compensators. The harmonic distortion in dominate orders (e.g. H_D^{5-} , H_D^{7+} , H_D^{11-}) are first measured and calculated locally. Then the local controller (LC) can generate compensation reference to reduce the harmonic distortion on CB. Moreover, considering the measurement difference of DGs caused by different measuring points and equipment error, the average value is required. Also the accurate sharing of harmonic currents becomes important especially when large amount of nonlinear loads are connected. Accordingly, a communication algorithm is required to assist the discovering of global information like the average value of each order harmonic current (\bar{I}_{Sdq}^H), and the average value of voltage harmonic components in each order ($\bar{H}_D^{+/-h}$). Finally, in order to reduce the communication cost, communication links are only established between neighboring units. Based on the objectives described above, this paper dedicates to the system modeling, analysis and development of distributed control methods.

System modeling and analysis for harmonic compensation and current sharing

In order to achieve harmonic compensation and current sharing, this Section puts efforts to the modeling of harmonic distorted system. A 2-DG islanded system is considered in the analysis as shown in Fig. 2. The essence of this compensation approach is actually quite simple but effective. First of all, considering that the nonlinear loads can be seen as harmonic current sources under certain load conditions [10], an equivalent circuit can be established as shown in Fig. 2 (a). The harmonic current flow causes the distortion of common bus voltage. The aim of voltage harmonic compensation is actually to reduce the harmonic components on CB. The ideal compensation process is generally sketched in Fig. 2 (b). Consider that ohm's law is always obeyed:

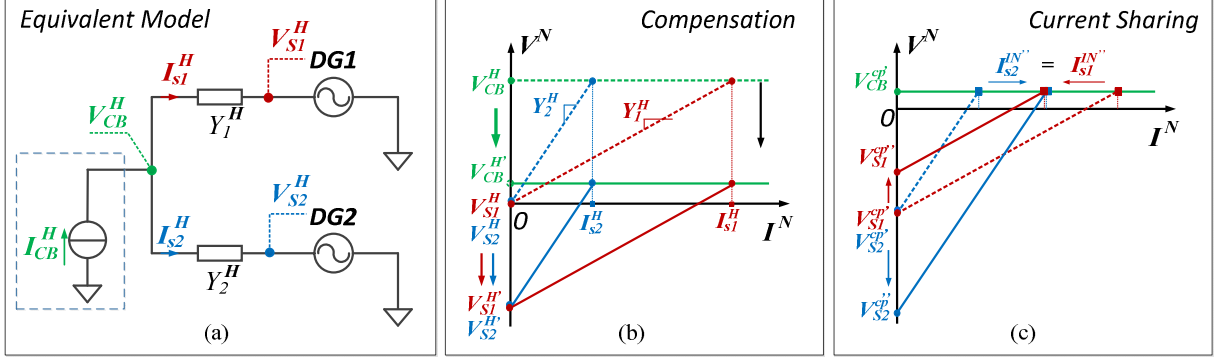


Fig. 2: (a) equivalent system model; (b) general compensation approach; (c) current sharing approach.

$$\begin{cases} \dot{V}_{CB}^H = \dot{V}_{S1}^H + \dot{I}_{S1}^H / Y_1^H \\ \dot{V}_{CB}^H = \dot{V}_{S2}^H + \dot{I}_{S2}^H / Y_2^H \\ \dot{I}_{CB}^H = \dot{I}_{S1}^H + \dot{I}_{S2}^H \end{cases} \quad (1)$$

where the superscript H stands for different harmonic components ($H = -5, +7, -11, +13, \dots$), \dot{V}_{S1}^H and \dot{V}_{S2}^H are the voltage phasors at DG sides, \dot{I}_{CB}^H , \dot{I}_{S1}^H and \dot{I}_{S2}^H are the current phasors, Y_1^H and Y_2^H are the admittances of distribution lines. As \dot{I}_{CB}^H can be seen as a current source if the load remains unchanged, \dot{V}_{CB}^H can be reduced to $\dot{V}_{CB}^{H'}$ by decreasing the harmonic voltage components in DG sides (from $\dot{V}_{S1}^H, \dot{V}_{S2}^H$ to $\dot{V}_{S1}^{H'}, \dot{V}_{S2}^{H'}$, respectively), as shown in Fig. 2 (b). In addition, if $\dot{V}_{S1}^{H'}$ and $\dot{V}_{S2}^{H'}$ are equally adjusted ($\dot{V}_{S1}^{H'} = \dot{V}_{S2}^{H'}$), the current flow \dot{I}_{S1}^H and \dot{I}_{S2}^H will remain unchanged. By applying this approach, the voltage distortion on CB can be mitigated. However, it can be also seen from Fig. 2 (b) that the current is not well shared if the distribution line admittances are different ($Y_1^H \neq Y_2^H$). With the same compensation references, the DG unit with larger admittance will provide more current which may cause overcurrent fault.

Accordingly, in order to balance the current while without affecting the compensation performance, the respective voltage components on DG sides can be readjusted. The simplified process is sketched in Fig. 2 (c). By properly adjusting DG compensation references (from $\dot{V}_{S1}^{H'}, \dot{V}_{S2}^{H'}$ to $\dot{V}_{S1}^{H''}, \dot{V}_{S2}^{H''}$), the current sharing proportion can be accurately controlled ($\dot{I}_{S1}^{H''} = \dot{I}_{S2}^{H''}$) while without affecting the voltage component on CB ($\dot{V}_{CB}^{H'}$).

Distributed Hierarchical Control Scheme

Based on the analysis above, a distributed hierarchical control scheme is proposed, as shown in Fig. 3, which includes primary and secondary control levels as well as a communication layer.

The primary control includes inner control loops for voltage and current control, droop control loops for active/reactive power sharing and virtual impedance loops. All the control loops in primary level are designed in $\alpha\beta$ frame. Detailed design of primary controllers can be found in [11].

The secondary control contains two dedicated loops for voltage harmonic compensation and harmonic current sharing. Three main harmonics, -5^{th} , $+7^{\text{th}}$ and -11^{th} , are considered in this study. The voltage harmonic compensation loop first measures and calculates the harmonic distortion level (i.e. H_D^5), which is actually the percentage of harmonic voltage amplitude compared with fundamental component as shown in Fig. 3. In order to eliminate the measurement error caused by different measuring points and devices, the local measured value is first transmitted to the neighboring units,

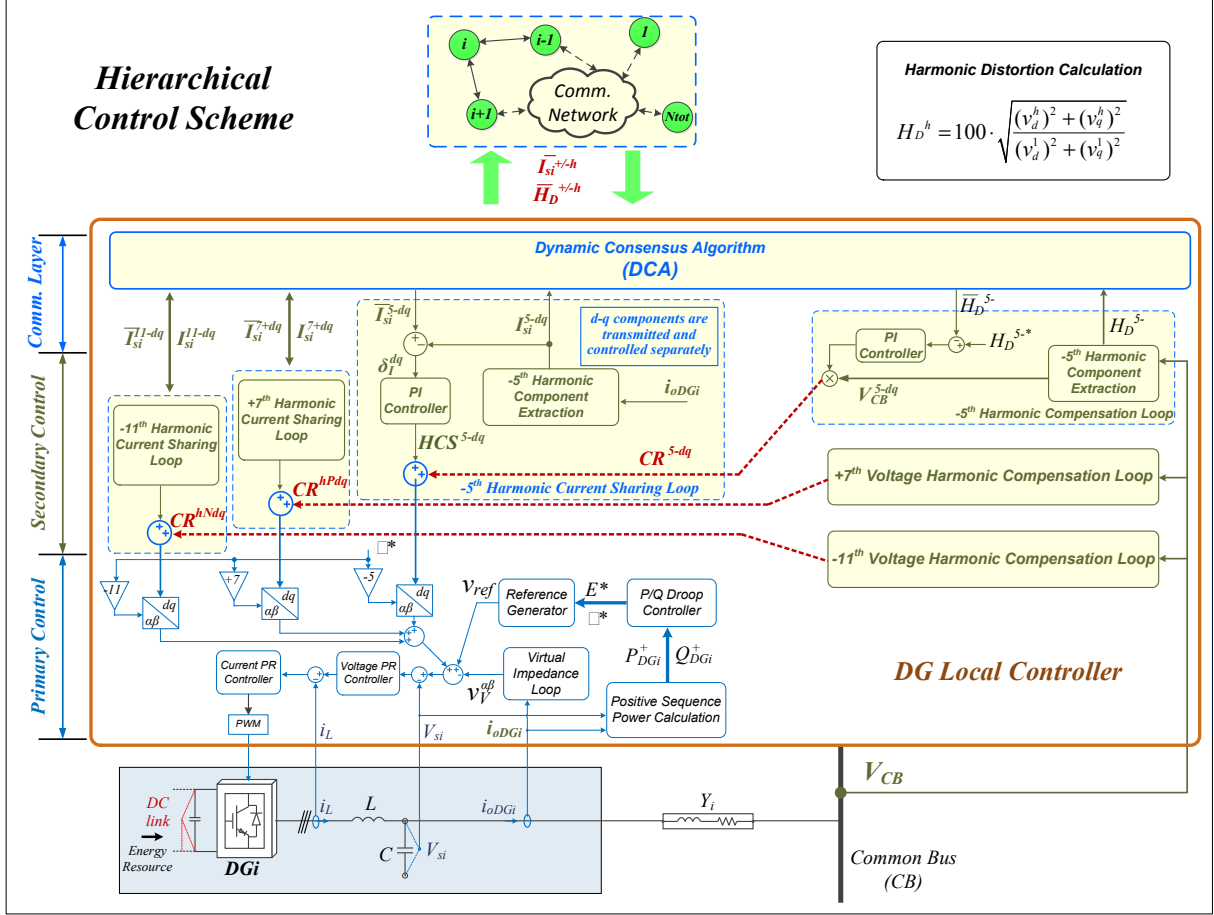


Fig. 3: Distributed hierarchical control scheme.

and by using of consensus algorithm, the global average value (i.e. \bar{H}_D^{-5}) can be obtained and used in the control loop comparing with desired value (H_D^{-5*}). Proportional and integral controller is used to generate the compensation reference and cancel the error.

With only droop control, the harmonic current cannot be accurately shared. Additional control loops are implemented in each LC as shown in Fig. 3. Taking -5th harmonic current sharing loop as an example, it compares the d - q components of local -5th harmonic current (I_{si}^{5-dq}) with averaged values of d - q components of the -5th harmonic current from all the DG sides (\bar{I}_{si}^{5-dq}):

$$HCS^{5-dq} = \left(\frac{k_{isc}^{dq}}{s} + k_{psc}^{dq} \right) \cdot (\bar{I}_{si}^{5-dq} - I_{si}^{5-dq}) \quad (2)$$

where k_{psc}^{dq} and k_{isc}^{dq} are the proportional and integral coefficients of the PI control loop for d - and q -axis currents respectively (d - and q -axis currents are controlled separately), I_{si}^{5-dq} is the locally measured -5th harmonic current in d - q reference, and \bar{I}_{si}^{5-dq} is the average -5th harmonic current discovered by using DCA realizing distributed information sharing and flexible operation.

Dynamic Consensus Algorithm

The DCA can help distributed units to reach an agreement on a quantity of interest through communication network. Considering the dispersed feature of generation, communication links are only needed between neighboring units, also the plug-and-play capability can be realized. The fundamental of DCA is shown in Fig. 4, which can be expressed using following equations [12]:

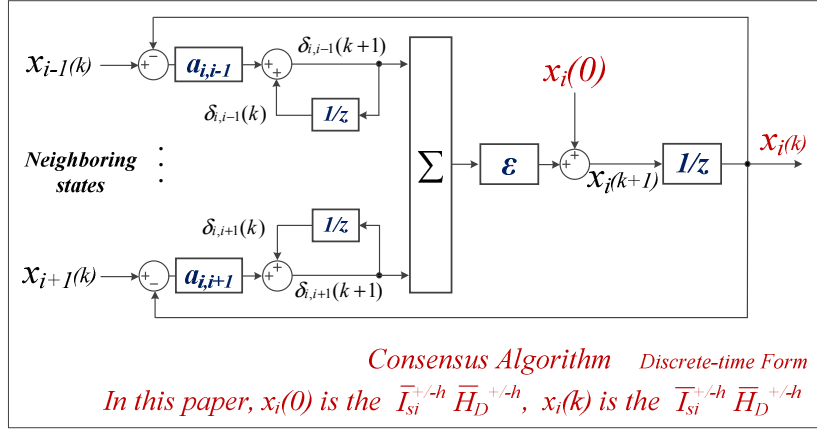


Fig. 4: Dynamic consensus algorithm.

$$x_i(k+1) = x_i(0) + \varepsilon \cdot \sum_{j \in N_i} \delta_{ij}(k+1) \quad (3)$$

$$\delta_{ij}(k+1) = \delta_{ij}(k) + a_{ij} \cdot (x_j(k) - x_i(k)) \quad (4)$$

where $x_i(k)$ is the information status of agent i at iteration k , and a_{ij} is the connection status between node i and node j . In that sense, if the nodes i and j are not neighboring, then $a_{ij} = 0$. N_i is the set of indices of the agents that are connected with agent i , ε is the constant edge weight used for tuning the dynamic of DCA, $\delta_{ij}(k)$ stores the cumulative difference between two agents, and $\delta_{ij}(0) = 0$, which realizes the accurate averaging during dynamic change conditions.

From a system point of view, the vector form of the iteration algorithm can be expressed as [13]:

$$\mathbf{x}(k+1) = \mathbf{W} \cdot \mathbf{x}(k) \quad (5)$$

with $\mathbf{x}(k) = [x_1(k), x_2(k), \dots, x_{n_T}(k)]^T$ and \mathbf{W} is the weight matrix of the communication network. If constant edge weight ε is considered, \mathbf{W} can be described as:

$$\mathbf{W} = \mathbf{I} - \varepsilon \cdot \mathbf{L} \quad (6)$$

$$\mathbf{L} = \begin{bmatrix} \sum_{j \in N_1} a_{1j} & \cdots & -a_{1n_T} \\ \vdots & \ddots & \vdots \\ -a_{1n_T} & \cdots & \sum_{j \in N_{n_T}} a_{n_T j} \end{bmatrix} \quad (7)$$

where \mathbf{L} is the *Laplacian matrix* of the communication network [14], [15], n_T is the total number of agents. The final consensus equilibrium \mathbf{x}_{eq} is:

$$\mathbf{x}_{eq} = \lim_{k \rightarrow \infty} \mathbf{x}(k) = \lim_{k \rightarrow \infty} \mathbf{W}^k \mathbf{x}(0) = \left(\frac{1}{n_T} \mathbf{1} \cdot \mathbf{1}^T \right) \mathbf{x}(0) \quad (8)$$

where $\mathbf{x}(0) = [x_1(0), x_2(0), \dots, x_{n_T}(0)]$ is the vector of the initial values held by each agent, $\mathbf{1}$ denotes the vector with the values of all the elements being 1. The detailed proof of the convergence can be found in [13].

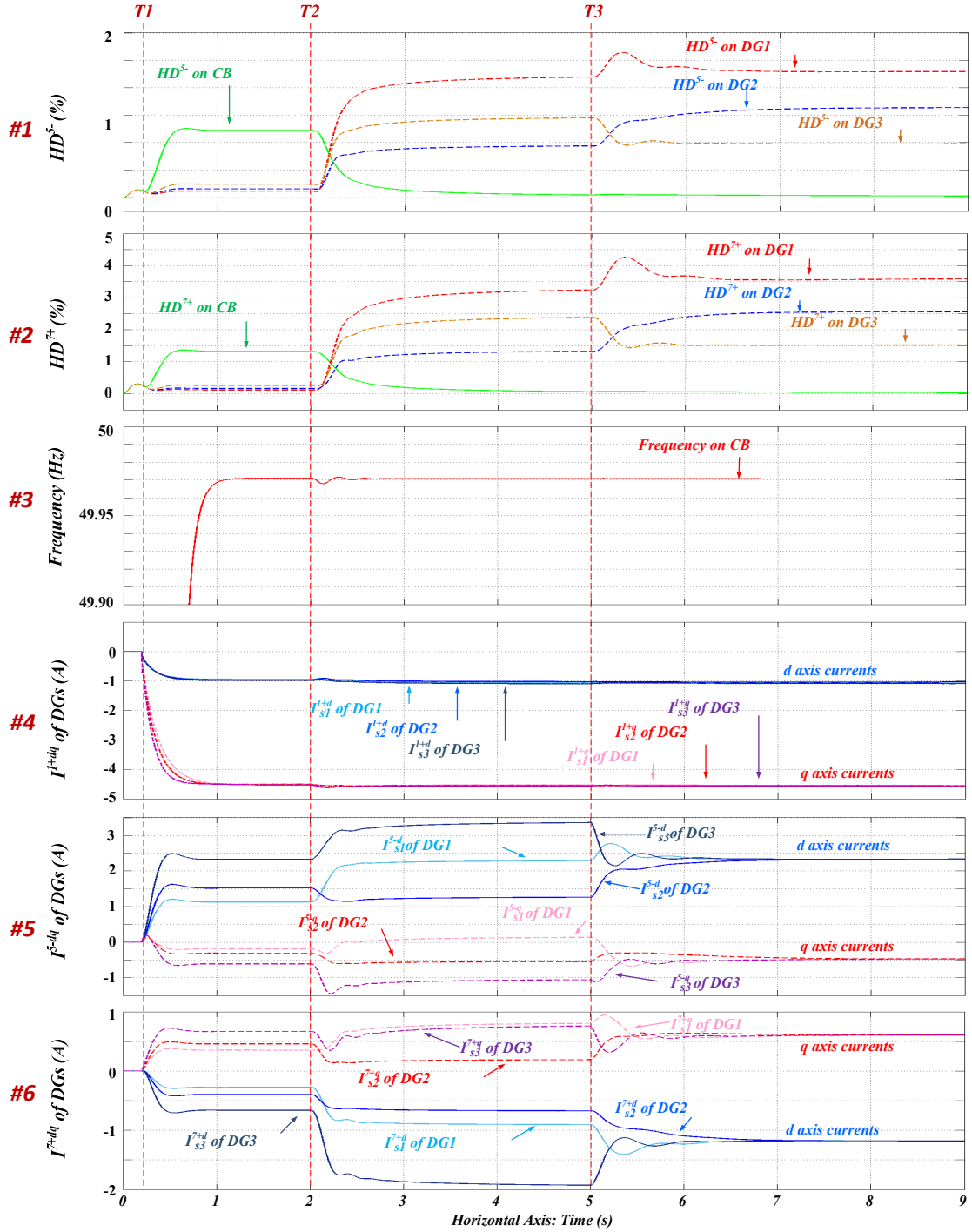


Fig. 5: Simulation results.

In this study case, $\mathbf{x}(k)$ includes the discovered average value of voltage harmonic distortion in each order ($\bar{H}_D^{+/-h}$) and harmonic current components in each order (\bar{I}_{si}^{Hdq}), and $\mathbf{x}(0)$ is the local measured values in each order (H_D^{5-} and I_{si}^{Hdq}).

Simulation Results

The study case system shown in Fig. 1 and the control system shown in Fig. 3 are established in Matlab/Simulink. Three DGs are used as compensators to reduce the voltage harmonics on CB. They

are considered the same compensating capability so that equal sharing of load current is expected (for DGs with different compensating capabilities, when normalized, will share the same per-unit value). The nonlinear load used in the simulation is based on 6-pulse diode rectifier. The sampling time of the DCA/communication part and the controller/MG part are set to 50ms and 1us respectively.

The 5th and 7th harmonics components ($H_D^{5^-}$ and $H_D^{7^+}$) are taken as examples and shown in Fig. 5 #1 and #2, respectively. The frequency is given in Fig. 5 #3. The fundamental current components, the -5th and +7th harmonic current components in dq reference frame are shown in Fig. 5 #4~#6 respectively.

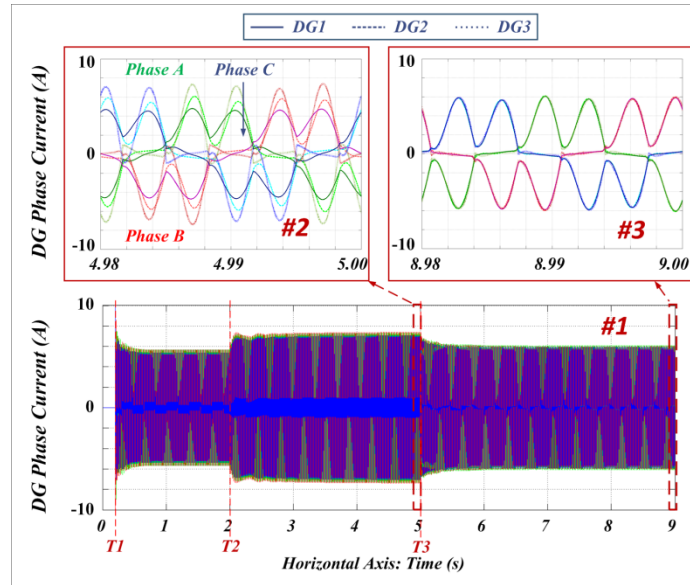


Fig. 6: DG Phase current comparison.

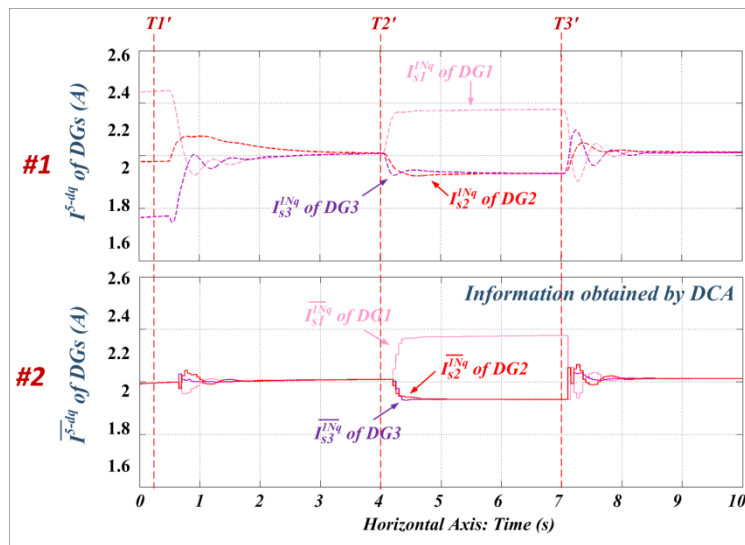


Fig. 7: Plug-and-play verification.

At T1, nonlinear load is connected in CB, which causes the increasing of $H_D^{5^-}$ and $H_D^{7^+}$. At T2, the voltage harmonic compensation control is activated to enhance the power quality in CB. It can be seen that after activation, the $H_D^{5^-}$ and $H_D^{7^+}$ on CB are both reduced to 0.2%, which is achieved by adjusting the harmonic voltage in DG sides (from T2 to T3 the $H_D^{5^-}$ and $H_D^{7^+}$ in DG sides are changed). The frequency is kept at 49.97 Hz. Although the power quality has been improved, the load current is not well shared as can be seen in Fig. 5 #5~#6 and Fig. 6 #1 and #2. In Fig. 5 #4, the positive

sequence fundamental current component is well shared due to the using of droop control. But the Fig. 5 #5 and #6 show that from T1 to T3 the -5^{th} and $+7^{\text{th}}$ harmonic current of the three DGs are different, which causes inaccurate sharing of load current as shown in Fig. 6 #2. It can be seen from Fig. 6 #2 that the peak value of DG3 current is around 7A while the DG1 is only 5A. At T3, the harmonic current sharing control loops are activated resulting in the convergence of the DG currents as shown in Fig. 5 #5 and #6. The Fig. 6 #3 shows that after activating the current sharing control, the DG currents are accurately shared among all the DG units.

Moreover, plug-and-play capability is demonstrated in Fig. 7. The -5^{th} harmonic current in q -axis is used here as an example. Fig. 7 #1 gives the current curves, and Fig. 7 #2 shows the dynamic of the DCA during this process. At T1', current sharing control and DCA is activated, the DG currents are converged to the same value. At T2', DG1 is excluded from the current sharing due to communication loss or intentional operation. DG2 and DG3 currents are able to converge to the new average value and DG1 is not participating. At T3', DG1 is included again into the sharing group. This process demonstrates that the proposed method realizes plug-and-play function.

Conclusion

This paper proposes a dynamic consensus algorithm based distributed compensation and total current sharing method. The system is first analyzed and modeled, based on which the compensation and current sharing approach is proposed. A complete hierarchical control scheme is introduced with primary, secondary and communication layer differentiated. Simulation results demonstrate that the proposed method is able to keep the desirable power quality in CB while ensuring accurate current sharing. The flexibility of the system is also enhanced with plug-and-play capability.

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