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***Abstract*—In microgrids, the distributed generators (DG) can be used as distributed compensators so as to compensate the voltage unbalances in the critical bus. However, the power quality disturbance in generator sides and local buses may be affected and exceeds the limit. It can be more convenient to implement tertiary control so as to adjust the compensation efforts among DGs and ensure the acceptable power quality in local buses. Moreover, as centralized control methods have certain disadvantages, such as low flexibility, expandability and heavy computation burden, this paper proposes an agent-based distributed hierarchical control method. Communication links are required between neighboring units. Consensus algorithm and optimization algorithm are implemented in tertiary control for global information discovery and local optimal decision-making respectively. The tertiary control gives lower level controller a tertiary compensation gain to adjust the local DG compensation effort so as to ensure the acceptable power quality in the local bus while keeping the best power quality in critical bus. Simulation results are shown to demonstrate the effectiveness of the method.**

***Keywords*—microgrids; voltage unbalance compensation; distributed hierarchical control; consensus algorithm; optimization**

I. INTRODUCTION

In three-phase AC microgrids [1], [2], voltage unbalances may appear due to unsymmetrical transmission lines or unbalanced loads, which deteriorate the performance of power quality sensitive equipment. Traditional series active filters or shunt active filters [3]–[5] can be implemented so as to compensate the unbalances at the critical bus. In case of microgrids, distributed generators (DGs) can be considered as possible solution for unbalance compensation while avoiding the implementation of extra compensation equipment [6], [7]. Furthermore, the compensation efforts among DGs can be shared so as to relieve the burden of single compensating equipment [8]–[12].

A cooperative unbalance compensation method was proposed in [9] in order to make all the DGs equally share

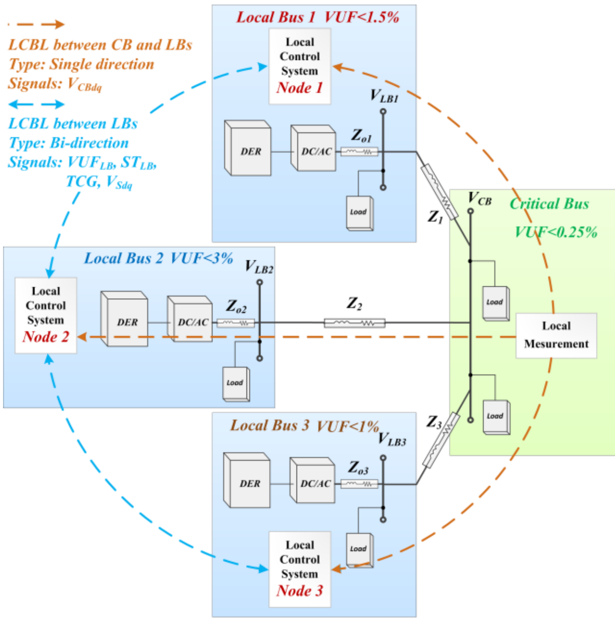

Fig. 1. Single line diagram of a study case three-phase AC microgrid.

compensating current. The even compensation is enabled by implementing an additional droop loop for negative sequence power sharing. In [10], the inverter-interfaced DGs are used for compensating the unbalances in point of common coupling (PCC). Each DG injects zero and negative sequence current triplets with identical magnitude but in the opposite phase with the unbalances measured in PCC. Based on this strategy, it is demonstrated in a case study that the unbalance factor in PCC can be kept within acceptable margin during daily operation. Similarly, a hierarchical control is proposed in [11] and [12] so as to use DGs to compensate unbalance voltage in the PCC in an islanded microgrid. The hierarchy consists of two levels: primary (local) and secondary (central). A compensating reference is generated by centralized secondary control and sent to local primary controller. Then every primary controller follows the compensating reference and controls the DG to evenly share the compensation efforts.

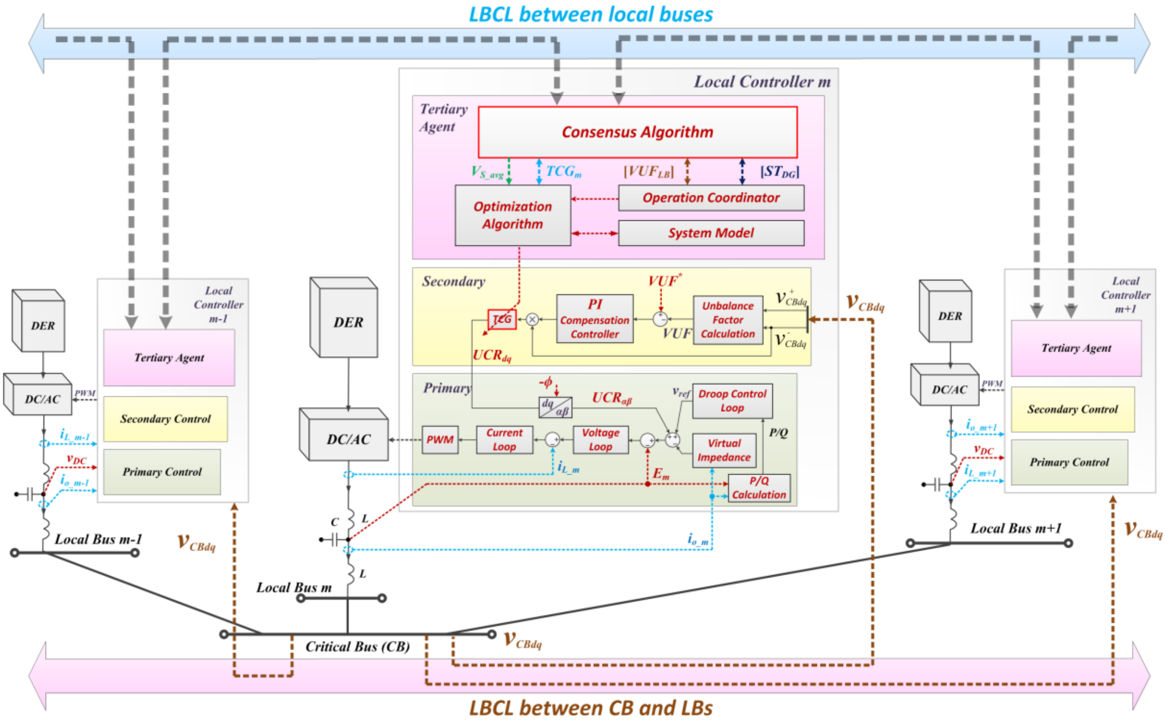

Fig. 2. Distributed hierarchical control scheme.

However, the above mentioned methods consider only the power quality in PCC while neglecting the unbalance limits in DG sides and other local buses. The power quality requirements are usually distinguished according to different areas and different types of consumers. A more convenient solution in that sense is to keep the best power quality at critical bus (CB) or PCC while taking care of the power quality limitation in other buses at the same time. This feature has been demonstrated in the projects in Consortium for Electric Reliability Technology Solutions (CERTS) [13] and Sendai, Japan [14]. A power quality control center is established for controlling the power quality in different areas.

Instead of building extra compensation facilities, this paper implements a tertiary control method for optimal power quality control in a multi-bus AC microgrid. The tertiary level consists of consensus algorithm and optimization algorithm which are used for global information discovery and local decision-making, formulating an agent-based tertiary control. Distributed secondary unbalance compensation is also applied, the compensation effort of which can be adjusted by tertiary compensation gain (TCG) given by local tertiary agent. Droop control and inner proportional-resonant (PR) current and voltage control loops are used in primary control. By combination of these three control levels, a distributed hierarchical regulation of optimal power quality within the microgrid system is realized.

This paper is organized as follows. A study case microgrid and its distributed hierarchical control system are introduced in Section II. In order to perform optimal power quality regulation, Section III analyzes the unbalance system based on which the system model is established. Section IV presents the dynamic consensus algorithm and local optimization method. Section V gives the simulation results done in Simulink to demonstrate the effectiveness of the method.

II. Case Study Microgrid and Distributed Hierarchical Control Architecture

A. Case Study Microgrid

The case study microgrid is shown in Fig. 1. Three DGs are connected to local buses to supply power to the islanded system. A critical bus (CB) exists in the system and it has the highest power quality requirements. Voltage unbalances may appear due to the connection of unbalanced loads in the CB or other buses. The DGs can be used as distributed compensators for compensating the voltage unbalances in CB. However, the compensation may influence the power quality in local bus, and each local buses (LB1~LB3) may also have distinctive voltage unbalance limit. As voltage unbalance factor (*VUF*) [15] is usually used to measure the voltage unbalance level, we assign the *VUF* limits in CB, LB1, LB2 and LB3 to 0.25%, 1.5%, 3% and 1% respectively. However, if the compensation efforts are always equally shared, the *VUF* in LBs may be out of acceptable limit. Accordingly, instead of always making all the DGs equally sharing the compensation efforts, additional regulation level which adjusts the compensation effort among DGs is implemented here so as to ensure the *VUF* values in all local buses are within acceptable limits.

B. Distributed Hierarchical Control

First of all, in order to achieve distributed decision making functions, communications are necessarily needed for coordinating the operation of the DGs. Two types of low bandwidth communication links (LBCL) [16] are established in this paper as shown in Fig. 1 and Fig. 2. Directed LBCLs are used between critical bus and local control systems. Unbalance voltage in CB (V_{CBdq}) are measured and sent to local control systems in *dq* reference. Undirected LBCLs are required between neighboring DGs for information sharing.

In tertiary control level, a dynamic consensus algorithm (DCA) is applied for global information discovery, as shown in Fig. 2.The following information are required so as to perform distributed control:

- *VUF* in each local bus (VUF_{LB});
- The status of each local DG (ST_{DG});
- The average value of all the TCGs (TCG_{avg});
- The average value of all the negative sequence voltage in DG sides (V_{Savg}^{N});

The VUF_{LB} and ST_{DG} are used for determining the *VUF* in other local buses and the status of other DG units so as to coordinate the operation of DGs. The TCG_{avg} and V_{Savg}^{N} are used by the optimization algorithm. A *TCG* is generated by the optimization algorithm and sent to secondary controller for adjusting the compensation effort.

The secondary controller receives the CB voltage in *dq* reference (V_{CBdq}), based on which the *VUF* is calculated and compared with reference value. The difference is sent to a proportional-integral controller, the output of which is multiplied by the CB negative sequence voltage so as to generate the compensation reference (UCR_{dq}). It is noteworthy that the UCR_{dq} has the inversed direction with negative sequence voltage in CB. Before sent to primary level, it is multiplied by *TCG*.

In primary level, UCR_{dq} is transferred to *αβ* reference ($UCR_{\alpha\beta}$). Along with the output of droop control and virtual impedance loop, the compensating reference is given to inner voltage and current PR controller.

Based on this distributed hierarchical control scheme, the voltage unbalances in CB can be compensated while the *VUF* values in LBs are also under control.

III. Unbalance System Analysis

In order to control the *VUF* in LBs to desirable value, the unbalance system model needs to be established. We assume the presence of unbalanced loads in each bus, as shown in Fig. 3 (a). The sequence voltage and current in *120* system can be calculated based on classical method [17]:

$$\begin{cases} Y_s = A^{-1} \cdot Y_p \cdot A \\ V_s = A^{-1} \cdot V_p \\ I_s = Y_s \cdot V_s \end{cases} \tag{1}$$

where Y_p and V_p are respectively the admittance matrix and phase voltage in 3-phase system, Y_s, V_s and I_s are respectively the sequence admittance matrix, sequence voltage and sequence current, and *A* is the transformation matrix between 3-phase system and symmetrical component system. The approximated positive and negative sequence voltage can be obtained by solving (1):

$$\begin{cases} \dot{I}^{P} \approx \dot{V}^{P} \cdot Y + \dot{V}^{P} \cdot Y_u \\ \dot{I}^{N} \approx -a^2 \cdot \dot{V}^{P} \cdot Y_u \end{cases} \tag{2}$$

from which a conclusion can be drawn that the negative sequence current is determined by positive sequence voltage and the unbalance load. In addition, as the positive sequence voltage in each bus has small variation due to allowed operation limitations, the unbalance load can be seen as a current source, as shown in Fig. 3 (b). Based on this model, the negative sequence quantities between buses obey the equation:

$$\dot{V}_{LBm}^{N} = (\dot{V}_{Sm}^{N} \cdot Y_{om}^{N} + \dot{V}_{CB}^{N} \cdot Y_{m}^{N} + \dot{I}_{LBm}^{N}) \big/ (Y_m^N + Y_{om}^N) \tag{3}$$

where the superscript *N* denotes negative sequence quantities, $\dot{V}_{CB}^{N}$ is the voltage at CB, $\dot{V}_{Sm}^{N}$ is the voltage in the m^{th} DG side, $\dot{V}_{LBm}^{N}$ and $\dot{I}_{LBm}^{N}$ are the voltage and current in the m^{th} LB. Y_{om} and Y_m are the admittances between DG and LB, and between LB and CB. As $\dot{V}_{CB}^{N}$ is measured and fixed by compensation control, $\dot{I}_{LBm}^{N}$ can also be obtained in LB, $\dot{V}_{LBm}^{N}$ can be controlled by adjusting DG side negative sequence voltage $\dot{V}_{Sm}^{N}$ locally.

However, the local change of $\dot{V}_{Sm}^{N}$ may cause compensating error in CB. In order to coordinate the operation of all DGs as well as searching for desirable $\dot{V}_{Sm}^{N}$, the consensus algorithm and optimization method are implemented and introduced in the next section.

IV. Consensus Algorithm based Local Optimization

In order to perform optimization function, global information is required. Dynamic consensus algorithm (DCA) is applied in this paper for global information discovery. The general purpose of consensus algorithms is to allow a set of agents to arrive to an agreement on a quantity of interest by exchanging information through communication network, while these agents are only required to communicate with neighboring agents. In the following part, the optimization problem is formulated and analyzed. The application of DCA is also presented.

A. Optimization Problem Formulation

As discussed before, the control objective is to control the *VUF* in each LB to a desired level while keep the best power quality at CB. The objective function for each local controller can be formulated as:

$$F_{obj} = \min\left\{ \left| VUF_{ref} - VUF_{LBm} \right| \right\} \tag{4}$$

which means the objective is to minimize the difference between *VUF* in the m^{th} LB to the reference value VUF_{ref}. In this paper the VUF_{ref} is defined as:

$$VUF_{ref} = \begin{cases} k_{LBm} \cdot VUF_{avg}, \ if \ \ k_{LBm} \cdot VUF_{avg} \le VUF_{lmt\_m} \\ VUF_{lmt\_m}, \quad \ if \ \ k_{LBm} \cdot VUF_{avg} > VUF_{lmt\_m} \end{cases} \tag{5}$$

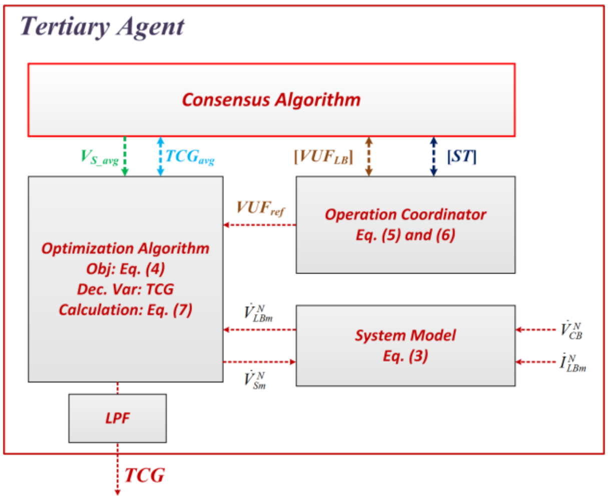

Fig. 4. Detailed tertiary agent structure.

which means that the *VUF* in the m^{th} LB is controlled to a value with proportional k_{LBm} to the average of *VUF* values in all LBs if the reference value is less than or equal to the local *VUF* limit (VUF_{lmt_m}). Otherwise, the reference value is set to *VUF* limit if $k_{LBm} \cdot VUF_{avg}$ is larger than VUF_{lmt_m}. k_{LBm} can be set by the operator which defines the relative importance of the LB compared with other LBs.

The average value of all the *VUF* in LBs is calculated as:

$$VUF_{avg} = \frac{\sum ST_m \cdot VUF_{LBm}}{\sum ST_m} \tag{6}$$

where ST_m denotes the availability of the local DGs in mth LB (ST_m=1 means there is DG capable of providing more compensation effort in LB_m while ST_m=0 means the local compensation effort is on the limit or unavailable). When the local DG is out of service or the *VUF* in LB is on the upper limit, *ST* will be set to 0. And if the system detects that all the ST values become 0, either the power quality of less importance busses has to be sacrificed or new DGs has to be started for sharing the compensation efforts.

In this optimization problem, TCG is used as decision variable which has a range of 0.2~2. The change of *TCG* is actually to adjust the compensation proportion among DGs. However, if the total amount of *TCG* is changed, the *VUF* in CB will not be able to be kept at the reference value. Accordingly, the sum of total *TCG* values should be equal to the total number of compensating DGs, in other words, the average value of *TCG*s (TCG_{avg}) should be equal to 1. The the decision variable is multiplied by TCG_{avg} in each local optimization algorithm so as to ensure the fixed total amount of compensating efforts. In addition, the average value of negative sequence voltage in DG sides (V_{Savg}^N) are also needed so as to calculate the optimal DG side negative sequence voltage:

$$V_{Sm}^N = TCG \cdot TCG_{avg} \cdot V_{Savg}^N \tag{7}$$

The detailed tertiary agent layer is shown in Fig. 4. Genetic algorithm is used for performing optimization function.

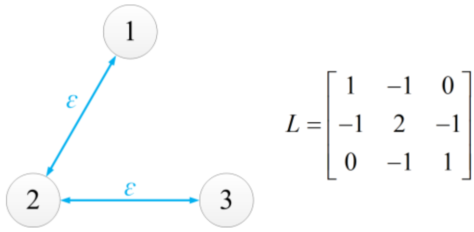

Fig. 5. Communication topology between agents and its *Laplacian* matrix

B. Dynamic Consensus Algorithm

Based on the analysis above, the information required by each local controller include $\boldsymbol{VUF}_{LB}$=[VUF_{LB1}, …, VUF_{LBN}], $\boldsymbol{ST}$=[ST_1, …, ST_N], TCG_{avg} and V_{Savg}^N. Accordingly, each agent needs to send these information to the neighboring agents. DCA is implemented in each agent so as to help all the agents reach consensus. The discrete form of consensus algorithm can be presented as [18]:

$$x_m(k+1) = x_m(k) + \sum_{n \in N_m} a_{mn} \cdot (x_n(k) - x_m(k)) \tag{8}$$

where m=1,2,…,N_{oC}, N_{oC} is the total number of agent nodes. $x_m(k)$ and $x_m(k+1)$ are the information obtained by agent m at iteration k and $k+1$ respectively. a_{mn} is the *edge weight* between node m and node n, a_{mn}=0 if the nodes m and n are not neighboring nodes. N_m is the set of indexes of the agents that are connected with agent m. From a system point of view, the vector form of the iteration algorithm can be expressed as [18]:

$$X(k+1) = W \cdot X(k) \tag{9}$$

where W is the *weight* matrix, $X(0) = [z_1, z_2, ..., z_m, ..., z_{N_{oC}}]$ is the vector of the initial values hold by each agent. In addition, a modified version of this algorithm [19] is used in this paper so as to help the accurate convergence under dynamic initial state change. With this modification, the algorithm (7) can be rewritten as:

$$x_m(k+1) = z_m + \sum_{n \in N_m} a_{mn} \cdot \delta_{mn}(k+1) \tag{10}$$

$$\delta_{mn}(k+1) = \delta_{mn}(k) + x_n(k) - x_m(k) \tag{11}$$

where $\delta_{mn}(k)$ stores the cumulative difference between two agents, and $\delta_{mn}(0) = 0$. According to (9) and (10), the final consensus value depends on z_m, and regardless of any changes to z_m, the algorithm can converge to appropriate average.

In this paper, constant edge weights are used, with the *weight* matrix defined as:

$$W = I - \varepsilon \cdot L \tag{12}$$

where ε is the constant edge weight and L is the *Laplacian* of the communication topology. Furthermore, it is demonstrated in [20] that the fastest and stable convergence can be obtained when ε is chosen based on:

$$\varepsilon = \frac{2}{\lambda_1(L) + \lambda_{n-1}(L)} \tag{13}$$

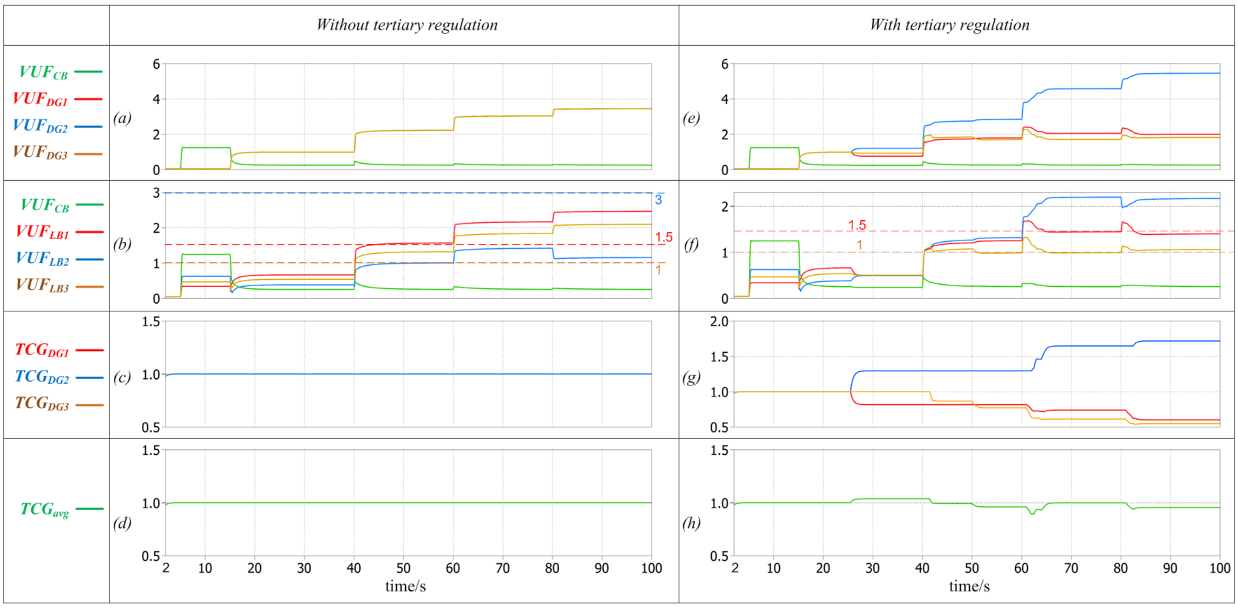

Fig. 6. Distributed hierarchical control scheme.

where $\lambda_j(\cdot)$ denotes the j^{th} largest eigenvalue of a symmetric matrix. Based on the topology of Fig. 5, the eigenvalues of L are $[0\ 1\ 3]^T$ which gives the optimal ε =1/2.

V. Simulation Results

In order to testify the proposed distributed hierarchical control method, the study case microgrid model and the control system are established in Simulink. The simulation results are shown in this section. The detailed control parameters of secondary level and primary level can be found in [11]. The microgrid configuration and the tertiary level parameters are shown in TABLE I. The optimization cycle is set to 1s which means the optimization algorithm is executed every 1 second. The consensus algorithm cycle is set to 0.1s, which means a 100ms communication speed is considered.

TABLE I. Microgrid Configuration and Tertiary Parameters

Output filter para.	L (mH)	1.8
	C (μF)	25
Transmission line para.	Y_{om} (S)	*0 + j1.7693*
	Y_1 (S)	0.1269 - j0.6379
	Y_2 (S)	0.3032 - j1.7148
	Y_3 (S)	0.2155 - j1.0153
VUF limit in LBs	VUF_{lmt_1}/ VUF_{lmt_2}/ VUF_{lmt_3} (%)	1.5/3/1
CB VUF reference	VUF^* (%)	0.25
Tertiary para.	k_{LB1}/ k_{LB2}/ k_{LB3}	1/1/1
	optimization cycle (s)	1
	constant weight ε	1/3
	consensus algorithm cycle (s)	0.1

A. Simulation Results Comparison

The simulation results are shown in Fig. 6. Fig. 6 (a)~(d) are the results without tertiary control, the *TCG*s are fixed to 1. Fig. 6 (e)~(h) show the system performance with distributed tertiary control. The *TCG*s are changed by local optimization algorithm. At 5s, unbalanced loads are connected in CB which causes the increasing of *VUF* values in all buses. At 15s, secondary compensation is activated. The *VUF* in CB is decreased to 0.25% while the *VUF* values in DG sides are increased. At 25s, the tertiary control is activated in (e)~(h), as the values of $k_{LB1}/k_{LB2}/k_{LB3}$ are all set to 1, the *VUF* in the three LBs should be controlled to same level since no constraints are violated. As can be seen in Fig. 6 (f) that, after 25s, the *TCG* values are changed which help the *VUF* in LBs converge to same value. At 40s, more unbalanced loads are connected in CB, and the *VUF* in all the buses are increased. The *VUF* in CB is fast recovered by secondary control while the *VUF* in other LBs may be out of pre-set limits. As shown in Fig. 6 (b), after 40s, the *VUF* in LB3 exceeds the limit value of 1%, while in Fig. 6 (f), with tertiary control the *VUF* in LB3 is controlled to 1%. At 60s, another loading process is executed in CB which causes the increasing of *VUF* in all buses. Without tertiary control, the *VUF* values in LB1 and LB3 are both out of the acceptable range after 60s, as shown in Fig. 6 (b). While the Fig. 6 (f) shows that the tertiary control is able to control the *VUF* in LB1 and LB3 to boundary value (VUF_{lmt_1}=1.5%, VUF_{lmt_3}=1%). At 80s, some unbalanced loads are connected in LB2, *VUF* value in LB2 is decreased while the ones in other buses are increased as shown in Fig. 6 (b). In Fig. 6(f), after the loading at 80s, the tertiary control is also able to keep the *VUF* values in LB1 and LB3 within acceptable range. Fig. 6 (g) shows the local change of *TCG*s in the three local controllers. Fig. 6 (h) indicates that the average value of all the *TCG*s can be coordinated around 1 which means the total amount of compensation efforts is constant, and the *VUF* in CB is always kept at 0.25% during the whole loading process.

B. Dynamic Information Consensus

The transition process at 40s is used here to show the performance of DCA, as shown in Fig. 7. Fig. 7 (a) shows the consensus of *VUF* values in each local agent. By using DCA, all the agents can obtain the *VUF* values in the other two LBs. Fig. 7 (b) shows the information of available DG statues (*ST*). As can be seen in Fig. 6 (f) that after 40s, the *VUF* value in LB3 reaches the limit, accordingly DG3 is not able to provide more compensation effort. The status of DG3 is set to 0. All the other agents obtain this information and adapt themselves to the condition change. Fig. 7 (c) and (d) shows the averaged value of the negative sequence voltage in all DG sides and the averaged value of all the *TCG*s which are used by optimization algorithm. These results demonstrate that DCA is able to provide accurate information for lower level controllers.

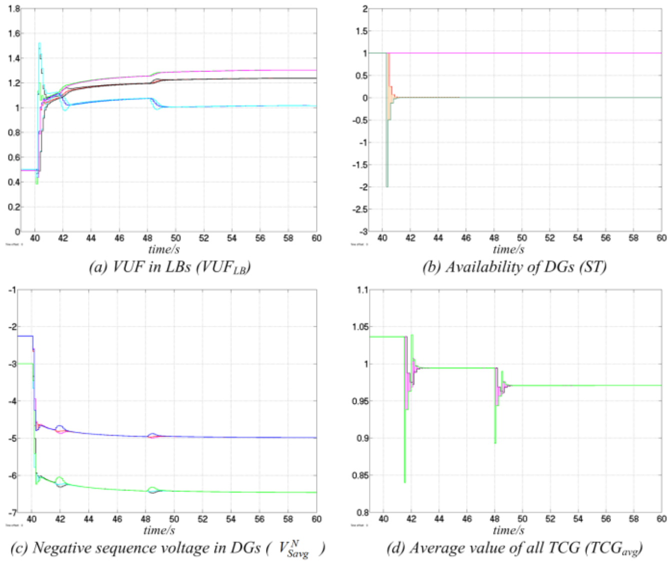

Fig. 7. Simulation results of dynamic consensus algorithm.

VI. Conclusion

This paper proposes a distributed hierarchical control method for the power quality control in a multi-bus AC microgrid. Three control levels are implemented in each local controller. The tertiary control consists of consensus algorithm and optimization algorithm. The consensus algorithm enables the global information discovery and the performing of local optimization method. Tertiary level provides secondary level with TCG which is used for adjust the compensation effort of the local DGs. The compensation reference is given to primary control which follows the reference so as to compensate the voltage unbalance in the AC microgrid.

The simulation results demonstrate that the proposed distributed hierarchical control is able to keep the required unbalance level in CB while also taking care of the power quality in LBs. This method can be applied to AC microgrid system with more DGs and buses without increasing the computational complexity, for the reason that each local agent solves an optimization problem with only one decision variable.

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