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Dynamic Consensus Algorithm based Distributed Unbalance Compensation in Islanded Microgrids

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Abstract—In islanded microgrids (MG), distributed generators (DG) can be employed as distributed compensators for improving the power quality (voltage unbalance and harmonics) in consumer side. Hierarchical control is usually applied with different control levels differentiated. In case of voltage unbalance compensation, droop control and virtual impedance can be applied in primary control to help the positive sequence active and reactive power sharing. Secondary control is used to assist voltage unbalance compensation. However, if transmission line differences are considered, the negative sequence current cannot be well shared among DGs. Accordingly, this paper analyzes the power flow in unbalanced islanded MG, proposes a dynamic consensus algorithm based distributed negative sequence current sharing method. Experimental results are shown to demonstrate the effectiveness of the method.

Index Terms--islanded microgrid, hierarchical control, voltage unbalance compensation.

I. INTRODUCTION

In a 3-phase islanded microgrid (MG) [1], several distributed generators (DG) are used to supply a common bus (CB). A power quality control center (PQCC) is established for taking care of power quality issues, such as voltage unbalance and harmonics. If unbalanced loads are connected on CB, voltage unbalance may appear which can affect the performance of sensitive equipment. The PQCC measures the 3-phase voltage on CB and calculates the voltage unbalance factor (VUF) [2], [3]. Based on the VUF limits on CB, the PQCC generates unbalance compensation references in $d-q$ reference (UCR_{dq}) and send them to DG units through low bandwidth communication links (LBCL) to employ DGs as distributed compensators [4]–[9]. The local control systems (LC) follow the UCR_{dq} and provide compensation support to the system. However, if the transmission lines are distinguished in parameters because of different distances, the negative sequence current cannot be well shared which causes unequal total load current sharing. In this case, the DG units which are located closer to CB have to supply more load current. In order to ensure accurate total

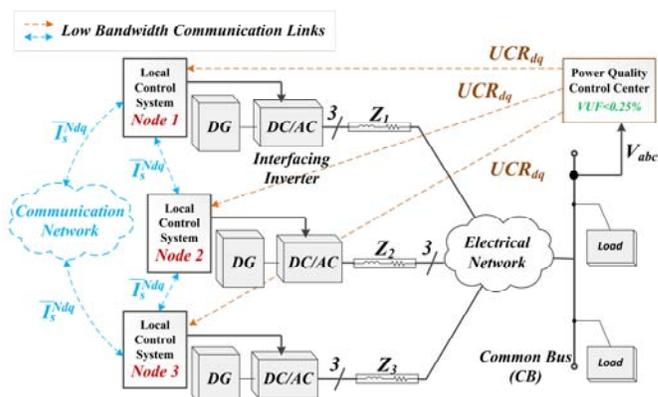


Figure 1. Single line representation of a 3-phase islanded microgrid.

load current sharing, this paper proposes a dynamic consensus algorithm (DCA) [10]–[12] based distributed negative sequence current sharing method. In Section II, the unbalanced system is analyzed and the proposed hierarchical control is introduced. Experimental results are shown in Section III to demonstrate the effectiveness of the method.

II. SYSTEM ANALYSIS AND HIERARCHICAL CONTROL

A. Unbalanced System Analysis

In order to clarify the compensation approach and negative sequence current sharing method, the unbalanced system is analyzed and the negative sequence equivalent circuit of a study case system is established. It can be demonstrated that in negative sequence equivalent circuit the unbalance load can be seen as a current source whose value is mainly determined by unbalanced load and positive sequence voltage, as shown in Fig. 2 (a) [13]. Based on this theory, the ideal compensation process is sketched in Fig. 2 (b). If unbalanced loads are connected, there appears negative sequence voltage on PCC (V_{CB}^N). Before compensation, the negative sequence voltage in both DG sides (V_s^N) are zero. By adjusting V_s^N , V_{CB}^N can be reduced to a lower level while the value of V_{s1}^N and V_{s2}^N are

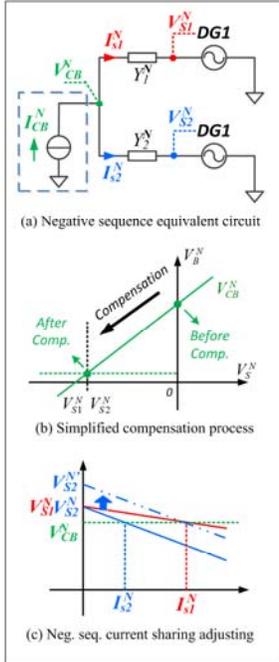


Figure 2. Unbalanced system analysis.

increased. However, if the admittances of the transmission lines have differences ($Y_1 \neq Y_2$), the negative sequence current cannot be well shared which causes unequal sharing of total load current as shown in Fig. 2 (c). This paper proposes a negative sequence current sharing method by properly adjusting the negative sequence voltage in DG sides (e.g. V_{S2}^N to V_{S2}^N in Fig. 2 (c)) without affecting the compensation.

B. Power in Unbalanced 3-Phase System

The power flow issue in unbalanced system has been clarified in [14], the 3-phase current can be taken as a superposition of instantaneous symmetrical sequence currents (positive- I^P , negative- I^N , zero- I^Z). Positive sequence power can be shared by using droop control and virtual impedance, zero sequence part does not exist in 3-phase 3-wire system, the negative sequence instantaneous power can be demonstrated as oscillating reactive power exchanged among three phases which causes power exchange between phases. The uneven sharing of negatives sequence current among DGs also incurs unequal sharing of total load current. Accordingly, this paper proposes a sharing control method with separate control loops over d - q components of negative sequence current.

C. DCA based Hierarchical Control Scheme

In order to implement the compensation control and negative sequence current sharing algorithm, a hierarchical control is proposed including two control layers and a communication layer, as shown in Fig. 3. In primary control, droop control and virtual impedance loop are used for positive sequence power sharing, they send voltage reference to inner voltage and current proportional resonant (PR) controllers.

The secondary control includes the power quality control from PQCC and the negative sequence current sharing loop in each LC [7], [8]. The PQCC measures the 3-phase voltage in

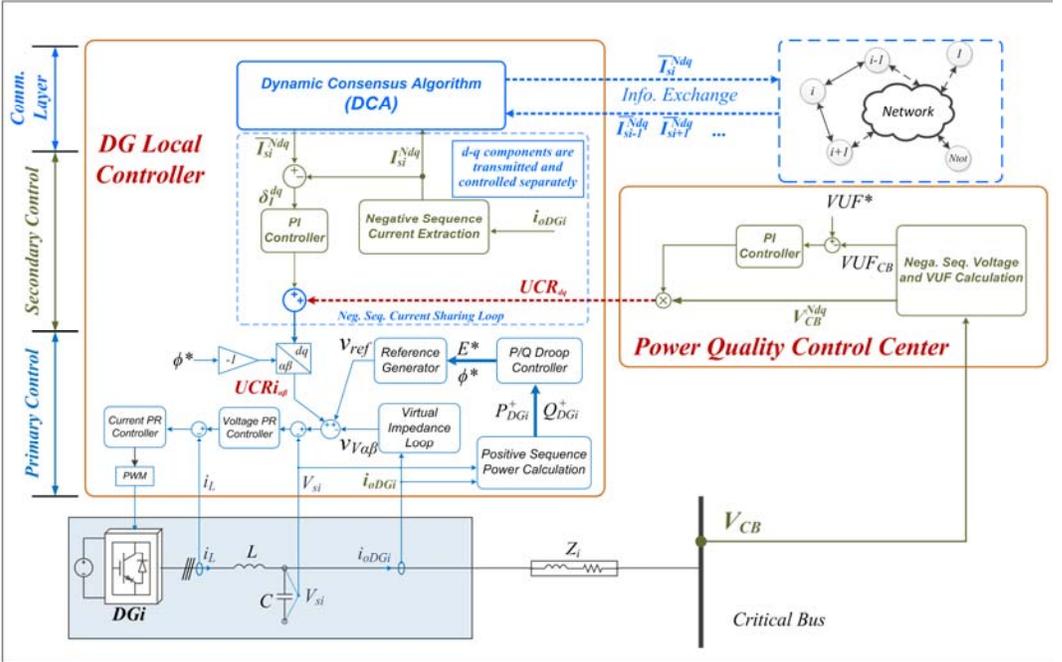


Figure 3. Hierarchical control scheme.

CB to obtain the VUF and negative sequence voltage in d - q reference. The PI control loop in PQCC tends to control the VUF on CB to a lower level (VUF^*). UCR_{dq} is generated and sent to each local controller through LBCL. The primary control loop follows the UCR_{dq} and adjusts the negative sequence voltage in DG side so as to lower down V_{CB}^N . In order to balance the negative sequence current, the negative sequence current sharing loop compares the d - q components of local negative sequence current (I_{si}^{Ndq}) with averaged value of d - q components of the negative sequence current from all the DG sides (\bar{I}_{si}^{Ndq}). I_{si}^{Ndq} can be measured locally, while \bar{I}_{si}^{Ndq} can be obtained by using DCA. The general purpose of DCA is to allow a set of agents to reach an agreement on a quantity of interest by exchanging information through communication network [11]. Based on this feature, each agent can obtain final averaging by transmitting its local information \bar{I}_{si}^{Ndq} to direct neighboring units.

III. CONSENSUS ALGORITHM

The general 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 case of MG systems, these algorithms can achieve the information sharing and coordination among distributed generators, consumers and storage systems. *Graph Laplacians* [15] describe the underlying communication structure in these kinds of systems and play a pivotal role in their convergence and dynamic analysis.

Considering the discrete nature of communication data transmission, the discrete form of consensus algorithm is considered. In addition, in order to ensure the convergence of consensus to accurate value in dynamically changing environment, a modified version of the algorithm, referred to

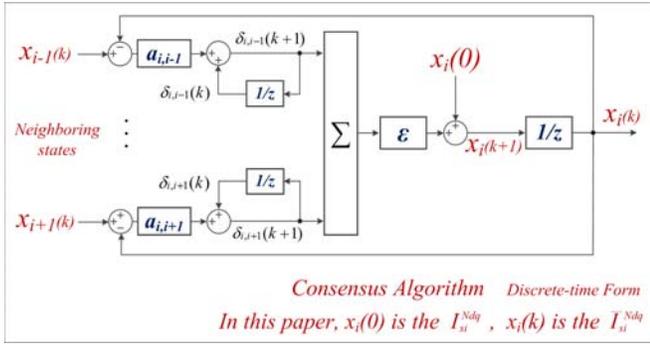


Figure 4. Dynamic Consensus Algorithm.

as dynamic consensus algorithm [10], is applied in this paper (see Fig. 4):

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

$$\delta_{ij}(k+1) = \delta_{ij}(k) + a_{ij} \cdot (x_j(k) - x_i(k)) \quad (2)$$

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 $\delta_{ij}(0) = 0$. Based on (1) and (2), it is explicit that the final consensus value will be reached regardless of any changes to $x_i(0)$.

In this study case, $\mathbf{x}(k)$ includes the discovered average value of negative sequence current in d - q references (\bar{I}_{si}^{Ndq}), and $\mathbf{x}(0)$ is the local measured negative sequence current (I_{si}^{Ndq}). Accordingly, DCA helps each local unit to discover the global average of negative sequence current.

As the constant weight ε defines the dynamics of the algorithm, it has to be properly chosen to ensure the fast and stable convergence of the algorithm. It is demonstrated in [12] that the fastest convergence can be obtained when the spectral radius (ρ) of matrix $W - (1/n_T) \cdot \mathbf{1} \cdot \mathbf{1}^T$ is minimized. The optimal ε that offers the fastest convergence speed can be calculated as:

$$\varepsilon = \frac{2}{\lambda_1(\mathbf{L}) + \lambda_{n-1}(\mathbf{L})} \quad (3)$$

where $\lambda_j(\cdot)$ denotes the j^{th} largest eigenvalue of a symmetric matrix. In the study case MG, a bidirectional communication network is established in which the three local control systems communicate with their neighboring systems.

Taking ring-shape communication topology as an example, the *Laplacian matrix* is defined as:

$$\mathbf{L} = \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} \quad (4)$$

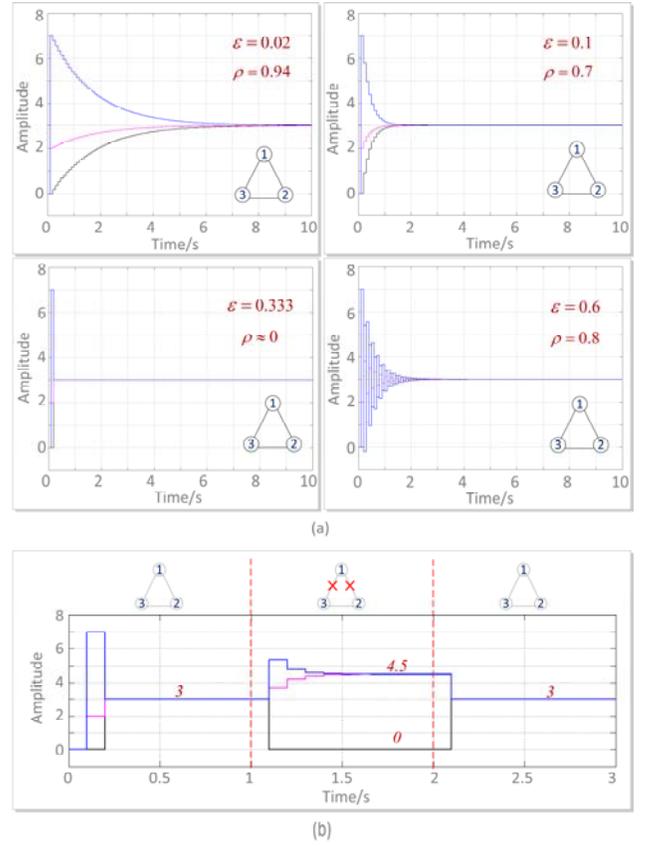


Figure 5. Consensus algorithm dynamics: (a) with different constant edge weight; (b) with online including/excluding units.

the eigenvalues of which are $[0 \ 3 \ 3]^T$. According to \mathbf{L} and its eigenvalues, the optimal $\varepsilon = 1/3$. A convergence speed comparison is shown in Fig. 5 (a), where the constant edge weight ε is changed from 0.02 to 0.6. It can be seen from the four figures in Fig. 5 (a) that when $\varepsilon = 1/3$ the distributed agents obtain fastest convergence speed.

Moreover, one of the most important objectives of applying DCA is to realize plug-and-play capability. The performance of DCA with online including/excluding units is shown in Fig. 5 (b). The three units start with initial value $[0 \ 2 \ 7]$ and first converge to average value. At 1s, one of the units stops communicating with the other two. The other two units are able to find a new averaging value between them while the excluded one restores to its initial value. At 2s, the communication links are recovered and the three units converge to the averaging value again.

IV. EXPERIMENTAL RESULTS

The proposed method is implemented in experimental setup to verify the effectiveness. The experimental results are shown in Fig. 6. The experimental setup is shown in Fig. 7. Three *Danfoss* inverters (2.2kW) are used to simulate DGs. dSPACE system is used to control those inverters. Resistive loads are connected to simulate unbalanced load conditions.

A loading and control activation process is conducted to obtain the experimental results, as shown in Fig. 6. Fig. 6 (a)

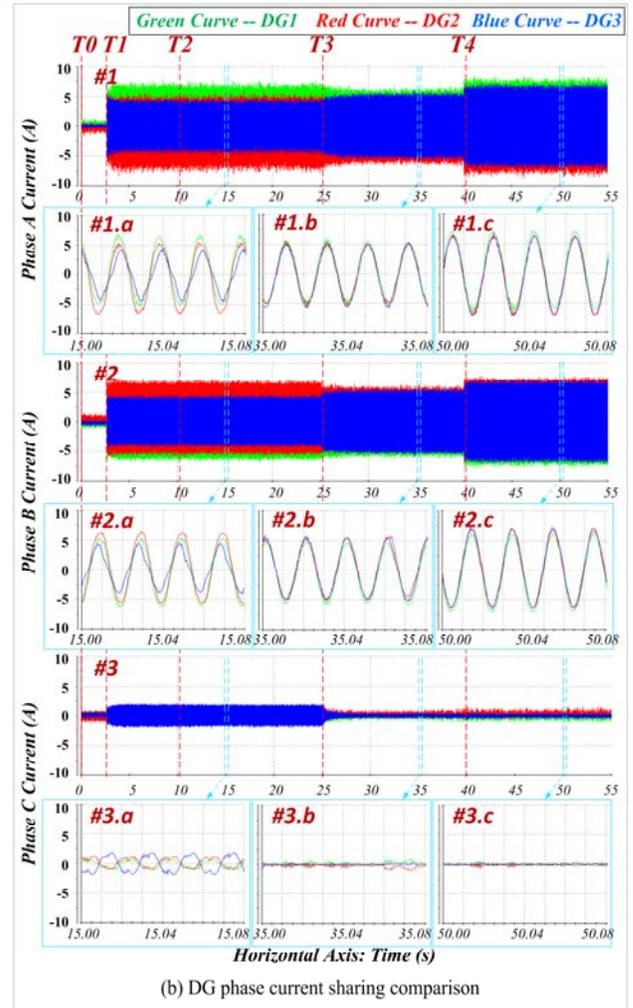
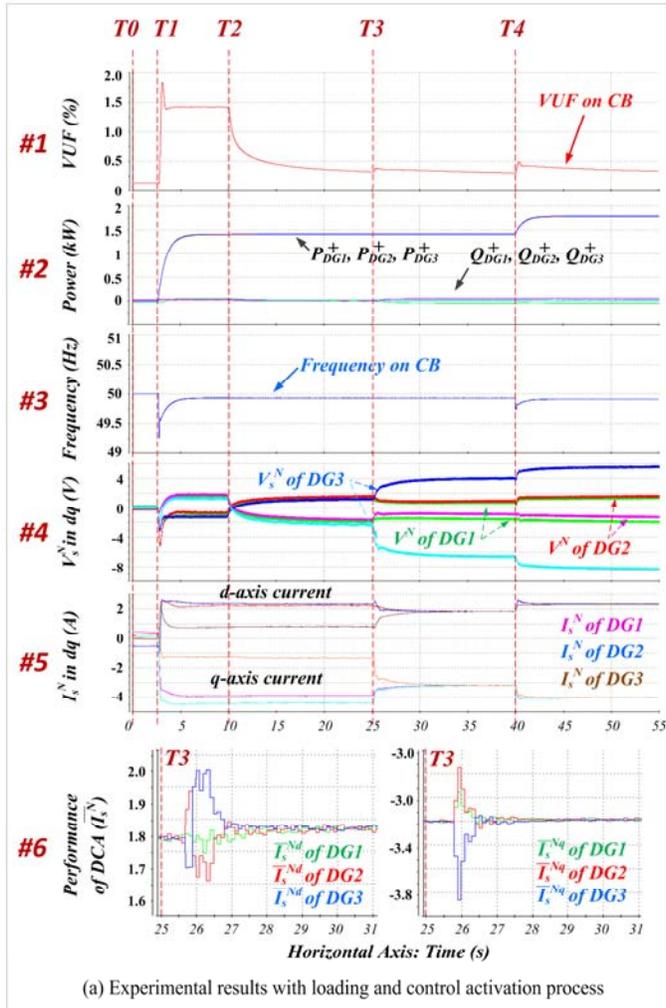


Figure 6. (a) Experimental results with loading and control activation process; (b) DG phase current comparison.

shows the performance of the system during the process. At T1, an unbalanced load is connected to the system which causes the increasing of VUF on CB (see #1 in Fig. 6 (a)). At T2, PQCC unbalance compensation is activated which helps the reduction of VUF on CB. And the negative sequence voltage and VUF value in DG sides are increased. This compensation process is introduced in Fig. 2. During this process, because of droop control and virtual impedance loop, the positive sequence active and reactive powers are well shared (see #2 in Fig. 6 (a)). However, because of unbalanced load, negative sequence current exists as shown in #5 in Fig. 6 (a). For the reason that negative sequence current and power are not feed through virtual impedance loop or droop loop, they are not well shared among DGs incurring unequal sharing of load current as shown in #1.a, #2.a, #3.a. The phase A/B/C currents of each DG are compared, and between T1-T3 the phase current of DG1, DG2 and DG3 has evident differences.

In order to enhance the load current sharing, negative sequence current sharing control is activated from T3. The negative sequence voltages in DG sides are adjusted (see #4 in Fig. 6 (a)) to change negative sequence current sharing (see #5 in Fig. 6 (a)). It can be seen that after activation, the negative

sequence current converge to the average value (#5 in Fig. 6 (a)), and the phase current differences are well reduced (#1.b, #2.b, #3.b). The dynamic of the DCA during activation is shown in #6 Fig. 6 (a). After activation, DCA helps each agent to converge to the same average value, and this value is used by each LC as negative sequence current sharing reference. As can be seen in #5 in Fig. 6 (a), after T3 the negative sequence

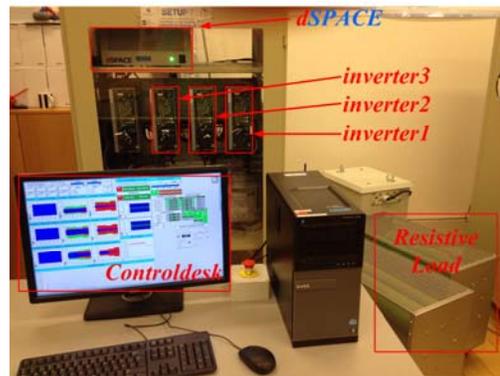


Figure 7. Experimental setup.

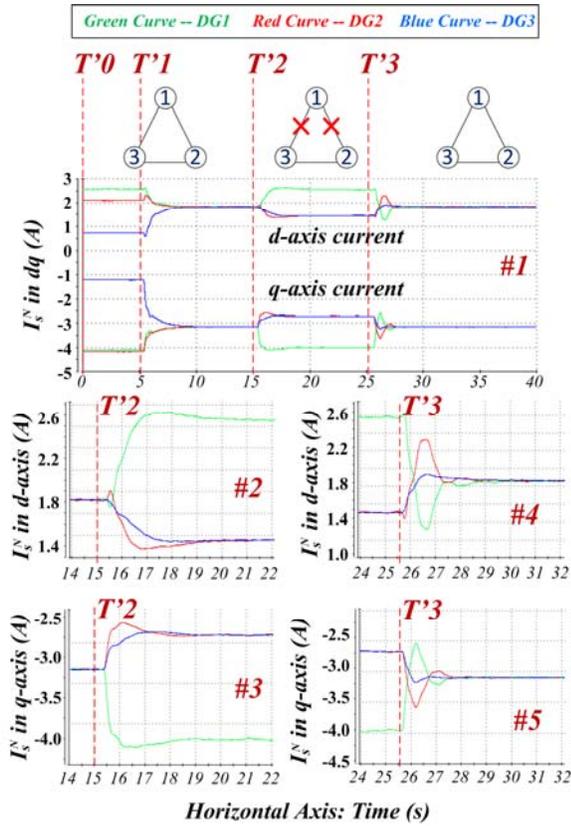


Figure 8. Validation of excluding/including unit.

currents of DGs converge to average value (d-axis and q-axis separately).

To test the performance of the overall control algorithm, another unbalanced load is connected to the system at T4. It can be seen from #5 in Fig. 6 (a) and #1.c, #2.c, #3.c in Fig. 6 (b) that, after loading the negative sequence currents and the phase currents of the DGs are still well shared.

The purpose of using DCA is to enhance the flexibility of the system which includes the capability of online excluding and including units. A process of excluding and including DG to share the negative sequence current is conducted as shown in Fig. 8. At $T'0$, the negative sequence current is not well shared. At $T'1$, the negative sequence current sharing is activated. At $T'2$, DG1 is excluded from the sharing control in case of communication fault or intentional operation. It can be seen from Fig. 8 (during $T'2$ to $T'3$) that the DG1 stops sharing the negative sequence current with the other two DGs while the other two DGs find the new averaging between them and continue sharing the negative sequence current. The dynamics during this process is shown in Fig. 8 #2 and #3 for d - and q -axis respectively. At $T'3$, DG1 is planned to re-join the current sharing. After this process, the total negative sequence current is accurately shared among the DGs again. The dynamics during this process is shown in Fig. 8 #4 and #5 for d - and q -axis respectively.

V. CONCLUSION

This paper proposes a dynamic consensus algorithm based distributed negative sequence sharing and unbalance compensation method. The unbalanced system is analyzed, the compensation and negative sequence current sharing proposal are introduced and discussed. Experimental results are shown to demonstrate that the proposed method is able to accurately regulate the current sharing among DGs. Also, the plug-and-play function is verified.

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