Consensus-Based Distributed Control in Microgrid Under Switching Topology

Rinku Kumar, Pankaj Mukhija, and Manish Kumar Saini

Abstract Microgrids are an emerging source for emergency as well as remote load centers power supply. It provides power security with generation from the locally available resources. The most probably the resources used for power generation are renewable sources. Where at certain time of a day power production of renewable dependent source may reduce to zero. A centralized controller may handle such problems. However, distributed control under plug and play of DG units is very difficult task in renewable dependent microgrid. In this paper, a consensus-based distributed secondary controller adaptive to switching communication topology is designed for enhanced performance and reliable power supply. The load requirements along with the local load are met satisfactorily by the distributed control strategy devised in this paper. The simulation results show the efficacy of the proposed control strategy to achieve global voltage regulation and proportional load sharing when there is frequent change in the number of DGs operating in a microgrid.

Keywords Microgrid · Renewable integration · Switching topology · Consensus · Distributed control

1 Introduction

Microgrids are new and fast developing entity in power supply sector for delivering power to the locality where typically it is very difficult to supply power from the utility grid or for the critical loads. The microgrids are good supplement to the power grid for mitigating the power quality issues arising from switching of heavy loads and faults in the supply system, etc. For ancillary service supports, power generation industries have developed their own microgrids at different locations. Due to

R. Kumar · M. K. Saini (✉)
Deenbandhu Chhotu Ram University of Science and Technology, Sonipat, Haryana, India
e-mail: manishkumar.ee@dcrustm.org

P. Mukhija
National Institute of Technology, Delhi, India

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capability of microgrids to operate in grid connected as well as islanded mode, microgrids are the first choice for critical loads. Moreover, technical advancements, green energy production, depleting fossil fuels, environmental pollution, reliable power supply, etc., are the major factors for development and installation of renewable-based distributed power generation units [1]. Microgrid gives added features like improved reliability, better power quality, fault resiliency, ancillary services and support to meet the increasing power demands to utility grid in grid connected mode [2].

For satisfactory operation of microgrid, hierarchical control scheme is adopted. The hierarchical control structure has three different layers (primary, secondary and tertiary control) of implementation to track the references [2–4] required for the controller to achieve the desired output from the distributed generating units (DGs) connected to microgrid. Microgrid central control (MGCC), is the conventional scheme to control the microgrid [5–7] in which, all data for various DGs is collected to a common point to generate the control action for every DG's controller corresponding to the required set points [8, 9]. As the system size increases, the MGCC becomes sluggish due to increase in data dimensions. In addition to that, requirement of huge communication network, high bandwidth, system global knowledge, privacy concerns and presence of single point of failure, etc., are the major problems with centralized control of microgrid. To overcome these problems, the researchers have developed number of distributed control schemes [10–12]. The distributed control schemes are almost fully resilient to system faults and instability caused from overloads, system expansions, etc., [9, 13–15]. In distributed control, each DG is capable to take action without affecting the nearby units. The control hierarchy is implemented in distributed fashion. This paper aims to design a consensus-based distributed control scheme in which multiple agents agreed upon a certain quantity of interest to reach the desired objective. The stability analysis is of consensus scheme depends upon the communication tree among the agents, which describes the adjacency of all agents with respect to each other.

The designed controller is able to regulate the DC bus voltage and achieves proportional loading of the participating DGs in microgrid. The consensus-based cooperative control is a two-level control algorithm [13]. The top or secondary level replaces the MGCC by collecting information from the neighboring units only. The primary controller is augmented with two correction terms arising from voltage agreement and proportional load sharing between the generating units. To address flexibility of plug and play of DERs allowing space for some units to come in and go out in microgrid there is not much literature available [14, 16, 17]. Also, there is always variation in communication topology after addition and removal of DERs from microgrid which complicates the monitor and control of microgrid due to its random nature. When renewable-based DER such as PV unit is operating then either due to change in weather or change in solar irradiations the output power is not fixed. Such units cannot be considered as connected or disconnected at these instants of time until it is not generating any power. No major studies have been done to focus this point of renewable-based generation in proportional loading of DGs. The objective of this paper is to design a consensus-based distributed controller adaptive to plug and play of DERs and capable to handle the power demand of renewable-based DER microgrid. Rest of the paper is organized as follows: The communication graph adjacency and Laplacian matrix design are discussed in Sect. 2. Consensus protocol adopted and implementation scheme is given in Sect. 3. Section 4 contains the simulation and results of the proposed control strategy. Finally, the conclusion and future possibilities are discussed in Sect. 5.

2 Communication Graph Preliminaries

The communication graph indicates the flow of information (i.e., states of DERs) between the agents. Communication graph also known as weighted diagraph when certain weight is assigned to edges. Let $G = (V, E, A)$, is weighted diagraph with nodes $V = (V_i \in N)$, $N = (1, 2, 3, \ldots, n)$, the set of edges, $E \subseteq V \times V$, $A = [a_{ij}]$ is the adjacency matrix. Each entry of adjacency matrix indicates the connection between DERs, if ith DER is connected to jth DER then $[a_{ij} = 1]$ otherwise 0, also $[a_{ii}] = 0$. The elements of the graph Laplacian matrix $L = [l_{ij}]$, $l_{ij} = \sum_{k=1}^{n} a_{ik}$ for $i = j$ and $l_{ij} = -a_{ij}$ for $i \neq j$. For detailed study on graphs and related terminology readers can refer [18, 19].

3 Consensus in Microgrid Under Switching Topology

The renewable-based DGs such as wind, tidal or PV generator do not generate constant power for a full day. Also, some active consumers do not have enough power to feed the microgrid every time. Such incidents cause change in number of DGs sharing the load at common bus. Centralized/non centralized control microgrid control strategies evaluate reference values for individual DG, on the basis of total available power and load demand by collecting state information. This requires a communication link between the control center and DG controller. In distributed control schemes a spars communication network is enough to achieve the desired objective. The DGs connected via communication channel and capable to share information among them are known as neighbors of each other. The addition and removal of DGs indirectly emphasize that the microgrid should operate generously to facilitate the plug and play feature and allowing space for some units to come in and go out.

The poor communication among the DGs can also cause certain DGs to disappears/appears from/in the network. The distributed control scheme based on consensus theory is incorporated with switching communication topology is designed in this paper. When a new unit is to be connected to the existing structure, it only needs global parameters for synchronization. In AC microgrid frequency, phase and voltage are needed for synchronization while in case of DC microgrid the bus voltage is global parameter for synchronization [20]. Then depending on the available surplus power, the controller takes action and accordingly the converter's output is controlled.

The consensus protocol makes an agreement on certain quantity of interest among the interconnected agents by sharing the state information of neighboring units only. In mathematical form, the consensus protocol is given by Eq. (1), as follows:

$$\dot{\hat{x}}_i(t) = \dot{x}_i(t) + \sum_{j \in Ni} a_{ij}\left(\hat{x}_j(t) - \hat{x}_i(t)\right) \tag{1}$$

where $\hat{x}_i$ is aggregated state (voltage or current in case of microgrid control objectives) of ith DER. N_i—is the neighbors of the ith DER in fixed communication topology. If communication topology is varying, the neighbors of DGs becomes a variable quantity and (1) is modified as:

$$\dot{\hat{x}}_i(t) = \dot{x}_i(t) + \sum_{j \in Ni(t)} a_{ij}\left(\hat{x}_j(t) - \hat{x}_i(t)\right) \tag{2}$$

where $N_i(t)$—is the neighbors of the ith DER at time "t".

The convergence of above protocol relies on the formation of spanning tree between all agents and the graph must be balanced [21]. In balanced graphs, the sum of incoming and outgoing channels is equal. A communication tree is said to be spanning tree if each node is accessible from any node in the direction of information flow without encountering any node twice. A bidirectional graph is always balanced [10] as sum of incoming and outgoing channels is always equal so, the communication channels which can carry information in both directions are considered in this investigation. To investigate the switching topology operation, a set with finite collection of all possible spanning tree topology is designed in advance [21, 22]. Further, before adding a new unit to the microgrid, the output voltage of new DG is synchronized with DC bus voltage. The newly added unit after integration to microgrid will share the load proportional to its own power rating. The rated capacity of individual DG itself is taken as the base unit to determine the percentage loading of respective DG. The communicated states of DG's are processed by the controller of individual DG, for reference update for the droop controller to take action for proportional load sharing.

Droop controller takes action for the change in the load demand, low gain of droop controller causes the DG to aggressively change its output while high gain makes it sluggish. The droop gain of adaptive virtual droop controller is calculated as per the capability of the DG without adversely affecting its performance [16]. The droop gain is calculated as:

$$r_d = \Delta V_{\max}/I_{\max} \tag{3}$$

where $\Delta V_{\max}$ is maximum allowable change in voltage and $I_{\max}$ is maximum current rating. To incorporate intermittent generation, the droop gain of the adaptive droop controller is given by:

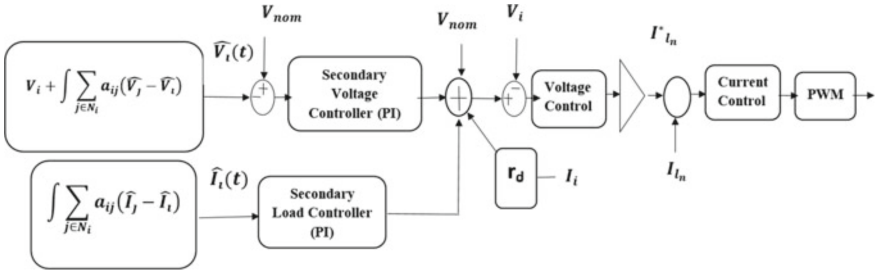

Fig. 1 Proposed consensus-based distributed control scheme of *i*th DG

$$r_{d\max} = \Delta V_{\max}/I_{\max} \tag{4}$$

where $r_{d\max}$ is the droop resistance used when DG is operating at its maximum rated capacity.

The reference current is fed to the inner current controller extracted from "*G*" block as shown in Fig. 1, and given to a PI controller to adjust the output. Figure 1 shows the complete distributed control strategy of distributed consensus-based secondary controller.

4 Results and Discussion

The test bed microgrid is simulated in MATLAB. The DC bus voltage is taken as 380 V. Four DG sources of capacity DG1 = DG2 = DG3 = DG4 = 7.6 kW with respective local loads L1 = L2 = L3 = L4 = 2.4 kW are connected to DC bus as shown in Fig. 2. Load connected to DC bus is 12 kW and a switching load of 2.4 kW,

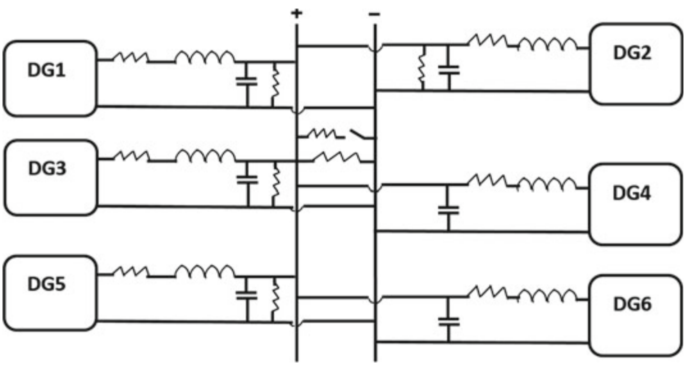

Fig. 2 Electrical connection of all DERs with microgrid bus

switching on at 3 s and removed at 6 s is also connected to microgrid. The whole strategy is divided into four cases.

4.1 Case 1: Formation of New Communication Link

The creation of link between the existing DG's in the microgrid control is investigated to analyze the performance of proposed distributed control scheme in this case. Keeping the configuration same explained above the communication topology is varied. In this case, at t = 4 s, a link between the DG3 and DG4 were established as indicated by blue dotted line in Fig. 3. This new link has no effect on the output of any DG as both units were already the part of the communication tree. Yet, this may cause high convergence rate to achieve consensus. The change visible at t = 3 s, is because connection of 2.4 kW switching load connected to the microgrid bus (Fig. 4). No visible traces can be seen for this change in communication graph, see Fig. 5 as system has already reached consensus.

4.2 Case 2: Addition/ Plug and Play of DG's

Two new DG units named as DG5 and DG6 are added to the microgrid as shown in Fig. 2. The communication topology for newly connected DGs is shown in Fig. 3. Before synchronization, the DG output voltage is brought up to the DC bus voltage. These DG units are connected to DC bus at t = 2 and t = 3, respectively, the output voltage of new plugged DGs is highlighted in black and sky blue colors in Fig. 6. The new units share load corresponding to their rated capacity and voltage drops slightly from no load to loaded condition. Figure 7 shows the current supplied by the each

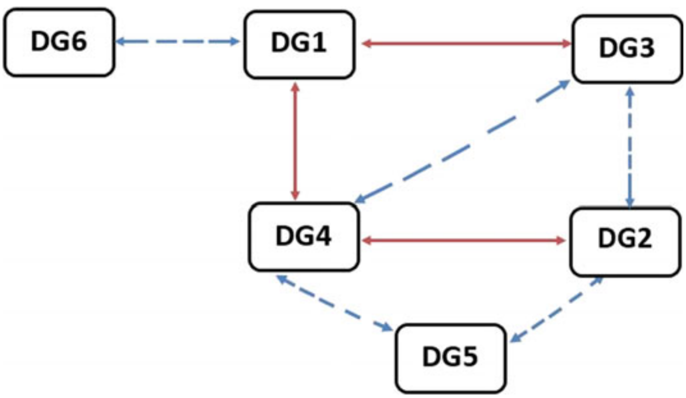

Fig. 3 Communication topology between the microgrid DGs

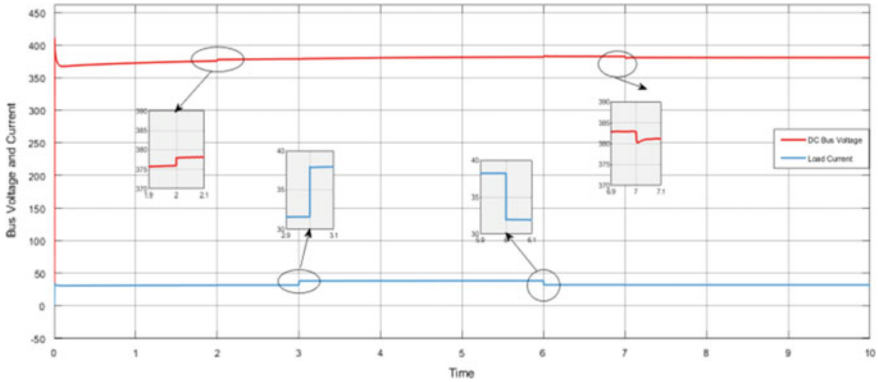

Fig. 4 DC bus voltage and current

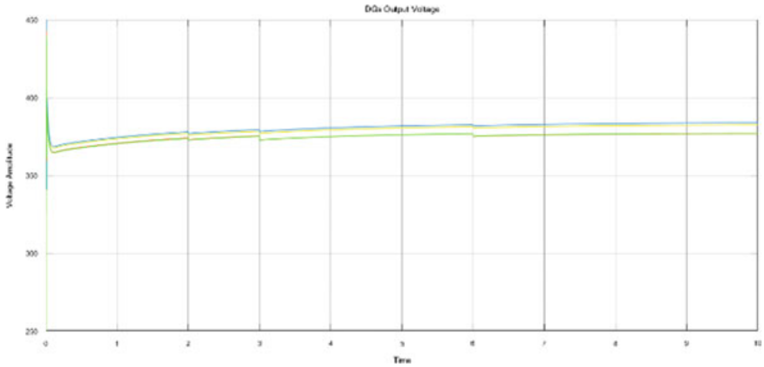

Fig. 5 DERs voltages without plug in of 5th and 6th DGs

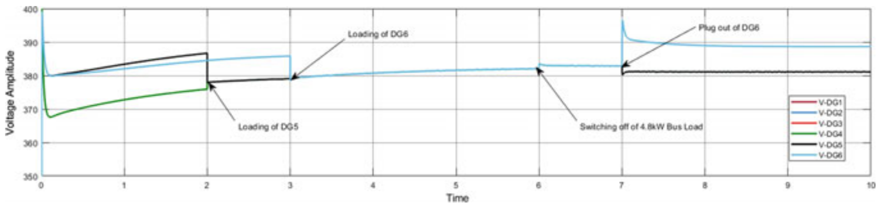

Fig. 6 DERs voltages with additional DG unit

DG to the microgrid common load. The amount of load shared by new DGs reduces the current loading of all other DG's correspondingly.

No local is connected to the new units, emulating units like fuel cell, electric vehicle or battery storage power supply. The rating of new unit is taken same as that of other DGs.

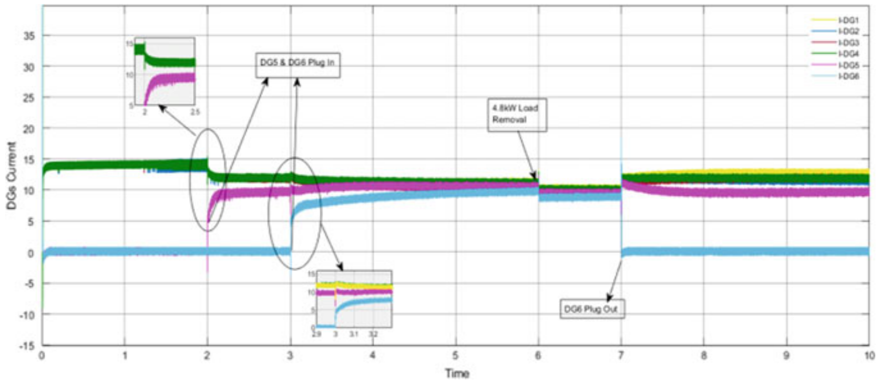

Fig. 7 DERs load sharing

4.3 Case 3: Communication Link Failure

To investigate the effect of communication link failure between the DG's a link connecting DG3 and DG2 is removed at t = 8 s. But, as all units already were in consensus so, it makes no changes in the output of the DG's. Removal of communication link such that it breaks the communication graph in two parts, in that case the two set of DGs corresponding to graph will reach to consensus in their respective set.

4.4 Case 4: Removal of a DG from the Microgrid

To investigate the performance of the designed controller for proportional load sharing after removal of certain DG the DG6 DG is isolated from the graph as well as form the microgrid at t = 7 s. The proportional of load sharing is shown in Fig. 7. The loading of all remained sources is increased to share the load shared by DG6 before isolation. Figures 8 and 9, respectively, show that the current and voltage consensus among all sources is reached after each variation which shows that the proposed

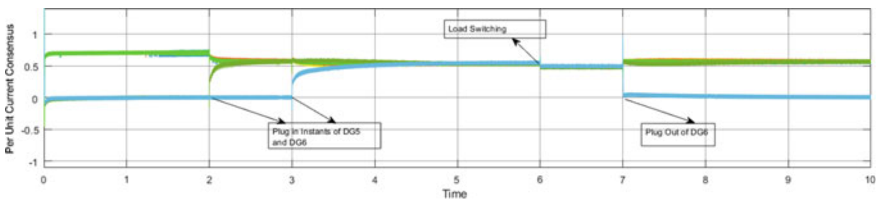

Fig. 8 DERs current consensus after each disturbance

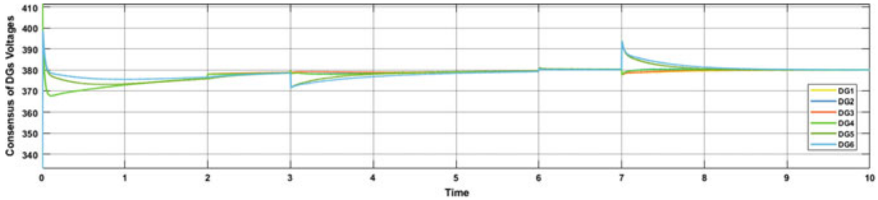

Fig. 9 DERs voltage consensus after each disturbance

controller is working effectively under variable communication topology and plug and play of DG's. The DC bus voltage is regulated within acceptable tolerance shown in Fig. 4.

5 Conclusion

The proposed consensus-based distributed secondary controller is effective to restore the microgrid voltage within acceptable deviations under switching topology of sources. The proportional load sharing between sources respective to their rating is successfully achieved even when certain DG unit either fails to communicate with neighbors or removed from the microgrid without affecting the performance of the other DGs of the microgrid. The proposed strategy can be extended for discontinuous data communication to reduce the communication cost. To have fast response characteristics, finite time consensus solutions can be adopted.

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