J. Electrical Systems 20- 10s (2024):2208-2219

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Adaptive Distributed Control for Microgrids Facing Topological Changes and Generation Variability

Journal of Electrical Systems

Abstract: - In microgrid operation and control, particularly in islanded mode, numerous critical issues must be addressed to achieve satisfactory performance. Controlling a microgrid to support the plug-and-play functionality of distributed generating (DG) units under varying communication topologies and generation intermittency is particularly challenging. To tackle these issues in a DC microgrid, this paper presents the design of an adaptive dynamic consensus algorithm-based distributed secondary controller. This distributed controller adapts to the generation intermittency of renewable-based DGs without any energy storage support while also enabling the seamless integration of DG units into the existing structure. Proportional loading and global voltage regulation are accomplished by supplementing the primary droop controller with correction terms generated by the consensus controller. The proposed scheme is fully distributed, relying solely on the consensus controller embedded within the DG unit's controller. Simulation results demonstrate the effectiveness of the proposed distributed consensus-based cooperative control scheme in achieving proportional load sharing with variable generation from renewable-based DGs under changing communication topologies.

Keywords: Reneable Generation, Microgrid Control, Plug and Play, Consensus, Distributed Control

I. Introduction

The Microgrids are the alternatives of the main grid at the locations where it is not feasible to get electricity from the main grid. Technical advancements, cleaner and alternate sources of energy, reduction in carbon footprints, integration of renewables and requirement to meet the future energy demands are the main forces for advancement and deployment of renewable fuel source based distributed generation [1]. The capability of operation in isolation from the main grid makes microgrid more reliable substitute for main grid. Microgrid not only supports the local loads in usual and emergency condition but also gives added features like power quality, power reliability and security, improved fault immunity, ancillary services to match up with the growing power demand when connected to main grid [2].

The power capacity of microgrid may range from few kilowatts to gigawatts scale at low or medium voltage to handle load requirements [3]. Smart is the new future of the conventional grid, connecting small generating stations. These small units are controlled and operated independently and in coordination are the microgrids. Microgrids have two modes of operation: (i) Grid connected mode and (ii) Islanded mode. For connection and disconnection from the main grid, either static transfer switch (STC) or power converters are used. STC and power converters play key role in grid synchronization and power flow control [4-5]. For satisfactory operation of microgrid, efficient control schemes are adopted at different levels, specifically in islanded mode of operation. The control hierarchy of microgrid has three levels of control; top two levels are responsible for rendering the reference to achieve requisite characteristics at the load bus, whereas the third level is the implementing stage [6-8]. Top level is called tertiary level and it comes in existence when microgrid operates in grid connected mode. Tertiary level sets up the references for distributed energy resources (DERs) to adjust the power flow control in an optimized way. In islanded mode, secondary level control serves the purpose of generating the references for each DG. Here, DGs operate in voltage and power control mode simultaneously. The primary level adjusts the output of DGs as per the references supplied by tertiary/secondary level accordingly. For detailed study of microgrid control hierarchy, readers may refer [8-12]. It is important to note that, in islanded mode the microgrid has to maintain bus voltage as well as proportional sharing of the load between DGs. To accomplish this task, the state information of each and every DG is collected at a common point called microgrid central controller (MGCC) and is processed to generate decision variables, i.e., the references for the primary controller [13, 14]. The top levels are essential in microgrid

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control hierarchy to accurately track the references as primary level control can't track the references accurately due to dominant resistive nature of the power lines at low/medium voltage. The centralized control schemes are the conventional ways for proportional power sharing and tracking the reference voltage in microgrids. MGCC needs huge and complex communication network with large bandwidth as operation of whole microgrid relies on it. The reliability of microgrid reduces due to presence of single point of failure. Further, it is not always convenient to process all information to a single point. It increases problem dimensions together with data load and privacy issues. Nowadays, distributed control techniques are evolving as the solution in microgrid control schemes where control strategy is implemented in distributed fashion. These techniques are also fully resilient as compared with those centralized techniques [14–17]. In distributed control schemes, the main idea is to defragment the huge and complex information to several units. Each unit is capable to react independently to any change. In such schemes, a sparse communication network with low bandwidth is enough for smooth operation of microgrid as a whole. The cooperative control techniques such as master-slave control, gossip algorithm and consensus-based control are very popular nowadays and are able to regulate the output of multiple distributed generators. In master-slave control, multiple units follow a single unit known as master unit to achieve the desired objective. This is synonymous to MGCC as if master unit fails the whole system may collapse [18]. Consensus based control scheme effectively shares and utilizes the information between the agents to facilitate distributed control by following a virtual leader responsible to drag the output of followers in the same direction as of its own.

The control scheme based on consensus algorithm has two-level of control [15]. In which microgrid cartelized control (MGCC) mechanism is replaced by secondary controller by sharing information between the neighbors only. The interaction among the DG units plays the key role in coordinated control. Any change in the communication network affects the performance of the consensus controller so, design of appropriate protocol and control algorithm for consensus-based controller to reach the desired goal is quite important. The topology between DGs may vary dynamically due to the addition or removal of DGs links. This is similar to the case of moving objects communicating with the nearest neighbor, due to their motion the existing links may fail or new links may be created [19]. When there is change in the communication topology, by the analysis of the graph Laplacian the convergence of consensus protocol is investigated. In renewable based distributed generation (DG), the communication link variations are very frequent as power generation depends upon time and weather. To address the flexibility of plug and play of DGs in microgrid, there is not much literature available [12, 16, 20]. Further, intermittent generating nature of renewable based generation is not significantly incorporated by any author. So, due to intermittent generation characteristic, there is always variation in communication topology of DGs. Hence, it is very challenging to monitor and control over large number of DGs under varying communication topology due to its stochastic nature.

When renewable based DG unit is operating, in which power output is weather dependent then due to change in weather the output power also changes. So, such units generate partial power at that instant and can't be considered as connected or disconnected until they are not generating any power at all. This kind of unit can be considered as a variable capacity DG unit. Improper handling of such DGs units may give rise to circulating currents and again the plug and play not only facilitate power sharing but also offers high economical operation of microgrid along with future expansions possibilities. In literature no major studies has done to focus on intermittency in renewable based generation, the main objective of this paper is to extract power from a renewable DG even when the generated power is low without any support of energy storage devices till the demand is met through consensus based distributed controller in continuous communication mode. This work also incorporates the plug and play of DGs. Furthermore, the main objectives of this paper can be summarized as follows:

1. To design a secondary level distributed cooperative control scheme for DC microgrid, based on consensus algorithm by sharing the states of the neighboring DGs only.
2. To achieve global voltage regulation corresponding to the desired voltage reference even when there is frequent addition and removal of DG units.
3. To achieve the proportional load sharing among the DGs connected to the common bus at any instant of time even when the output of certain renewable based DG is changing due change in environmental conditions.
4. To achieve proportional load sharing without any energy storage support until the load demand matches.
5. To design virtual adaptive droop controller capable to handle generation intermittency without affecting the performance of system.

The organization of rest of the paper is as follows. In section II, adjacency in communication graphs and graph Laplacian matrix design are explained. The proposed consensus protocol and implementation scheme are discussed in section III. Section IV contains the simulation results. The finally section V accommodates the conclusion and future possibilities.

II. ALGEBRAIC GRAPH PRELIMINARIES

The graphical representation of the communication system is simpler compared to networked structure. The redundancies and expansions in the existing system can be easily marked and visualized. The communication network can be designed independently and different from the electrical configuration for fast dynamic response and easy access to all DGs. The information (states of DGs) transfer is stipulated by the communication graph for information exchange between all the agents. The communication graph becomes weighted diagraph when edges are assigned with certain weight. Let $\mathbf{G} = (\mathbf{V}, \mathbf{E}, \mathbf{A})$ be a unity weighted undirected graph with nodes $\mathbf{V} = (\mathbf{Vi} \in \mathbf{N})$, here N is the number of nodes in the graph, set of edges, $\mathbf{E} \subseteq \mathbf{V} \times \mathbf{V}$ and $\mathbf{A} = [\boldsymbol{a_{ij}}]$ is the adjacency matrix. The entries of adjacency matrix are identified by the connection between the DGs. If $\boldsymbol{i^{th}}$ DG is connected to $\boldsymbol{j^{th}}$ DG then $\boldsymbol{a_{ij} = 1}$ otherwise 0, also $\boldsymbol{a_{ii} = 0}$. The elements [22] of the graph Laplacian matrix are given by

$$L = \begin{cases} -a_{ij} \; for \; \mathrm{i} \neq \mathrm{j} \\ \sum_{k=1}^{n} a_{ik} \; \text{for i} = \text{j} \end{cases} \quad (1)$$

When graph topology varies, the entries of the adjacency matrix change and hence, the graph Laplacian matrix also changes. A graph is said to be strongly connected if every node can be reached from any other node in the graph. The detailed study on graphs terminology accommodated in references [23] and [24].

A. Consensus in Microgrid for Time Dependent Technology

The most important feature of microgrid lies in the integration of distributed generating units (probably the renewable based) utilizing the locally available energy resources. The communication architecture forms the communication topology of the participating DGs in microgrid. Sometimes an energy storing device like electric vehicle may be willing to share stored power with the microgrid. Also, due to the intermittent nature of renewable energy, it is not well defined that certain source will behave like a constant power source as in case of solar PV generation. It may be possible that certain source is not generating any power at all. This may be because the environmental conditions that may not be in favor for continuous generation. So, it causes alteration in the communication topology and communication graphs [19]. This indirectly emphasizes that under switching communication topology microgrid should operate in a sense to not to adversely affect its operation while offering plug and play feature for participating DG units at the same time. The situation can also be a result of poor communication between the generating units which can result into disappearance/appearance of certain units from/in the communication network. Due to discontinuous communication among the DGs, the communication topology cannot be fixed.

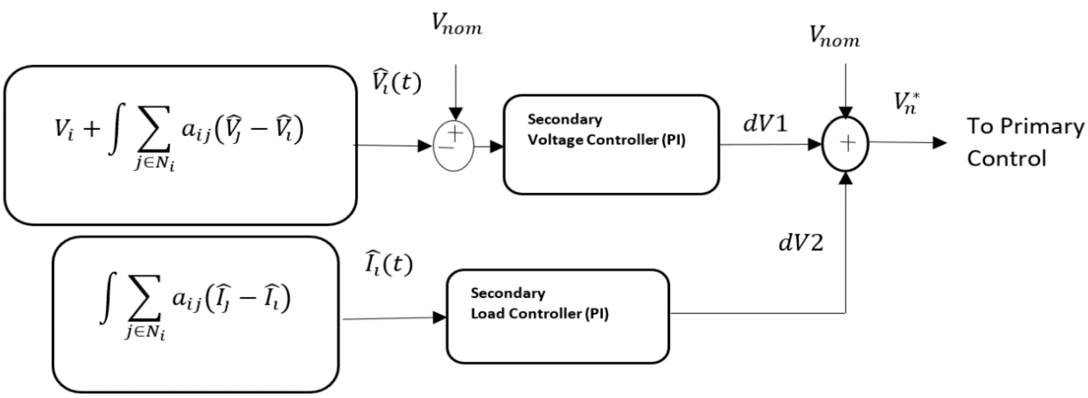

Fig. 1 Secondary Level Consensus Controller of $\boldsymbol{i^{th}}$ DG of Microgrid

So, basically, we are interested to achieve cooperation between the agents of multi agent system (MAS) communicating each other via an imperfect communication channel (weather intentional or unintentional).

Considering the effect of variable communication topology, the impact of switching topology on consensus is considered here.

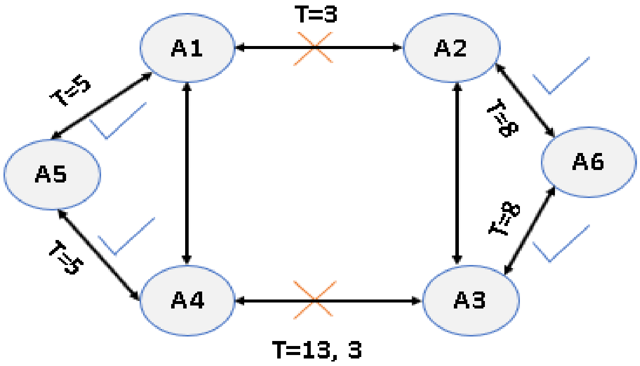

Fig. 2 Communication Graph with Variable Topology

Plug and play, i.e., addition or removal of DGs to existing structure does not require states' information of nearby units; rather, it only needs to know the global parameters, e.g., bus voltage in case of DC microgrid and voltage and frequency in case of AC microgrid [25]. Then, it is decided by microcontroller based local controller installed to each unit that how much power a DG can contribute and converter's output is adjusted by it accordingly.

The consensus protocol reflecting the uncertainty in topology is given by (2)

$$\dot{\hat{x}}_i(t) = \dot{x}_i(t) + \sum_{j=1}^{N_i(t)} a_{ij}(t)\left(\hat{x}_j(t) - \hat{x}_i(t)\right) \quad (2)$$

Where, $\hat{\boldsymbol{x}}_{\boldsymbol{i}}$is aggregated state (voltage or current in the present context) of $\boldsymbol{i^{th}}$ DG, $\boldsymbol{N_i(t)}$ is the neighbor of the $\boldsymbol{i^{th}}$ DG at time t. In terms of the graph Laplacian, the above protocol can be written in compact form as in [22].

$$\dot{\hat{x}}_i(t) = -L^t \hat{x}(t) \quad (3)$$

Where, $\boldsymbol{L^t}$ is graph Laplacian matrix at time 't' with corresponding adjacency matrix. Laplacian matrix "$\boldsymbol{L^t}$" plays the most important role in convergence of the protocol (3). The stability of the system defined by (2) or (3) can be described on the basis of the eigen values of the matrix $\boldsymbol{L^t}$. The Laplacian potential of graph G, may be defined as in [19].

$$\theta_G(\hat{x}) = \hat{x}^T L \hat{x} = 0.5 \times \sum_{j \epsilon N_i(t)} a_{ij}\left(\hat{x}_j(t) - \hat{x}_i(t)\right)^2 \quad (4)$$

From (4), it is clear that $\boldsymbol{\theta_G(\hat{x})}$ is always positive so, matrix $\boldsymbol{L^t}$ is always a positive semidefinite matrix. Which is certain for balanced or undirected graphs. The Laplacian matrix of balanced graph is always positive semidefinite. In balanced graph, in degree of any node is always equal to its out degree. Mathematically, it can be expressed as:

$$deg_{in} = \sum_{j=1}^{n} a_{ij} = deg_{out} = \sum_{j=1}^{n} a_{ji} \quad (5)$$

Where From above, the positive semidefinite matrix $\boldsymbol{L^t}$ has all its eigen values positive except one which is zero ($\boldsymbol{\lambda_1 = 0}$) and corresponding eigen vector is a matrix of single column with all one's i.e., $\boldsymbol{1 = (1,\ 1, 1 \ldots\ 1)^T}$. So, the selected protocol will solve the problem of average consensus when all the nodes of the graph agree, i.e., $\hat{\boldsymbol{x}}_{\boldsymbol{i}} = \hat{\boldsymbol{x}}_{\boldsymbol{j}}\ \forall\ \boldsymbol{i, j}$ [22]. For directed graphs, the nodes must form a spanning tree very frequently to reach the consensus [19]. The spanning tree is a directed tree connecting all nodes of a directed graph without traversing any node twice. In frequency domain, the stability of selected protocol is described on the basis of transfer function stability analysis in reference [26].

In the distributed control of microgrid using consensus protocol at secondary level the communication graph is taken as undirected one even after each switching period, so that the graph is always balanced. In network with switching topology, the set with finite collection consisting of different possible tree topologies is defined in advance for the units which are inoperable at certain time and removed from the graph [27]. In addition to that, new units can be added to the system with the knowledge of global variable i.e., DC bus voltage.

B. Control Methodology

This describes the control strategy is implemented for islanded microgrid in distributed fashion at secondary level. The consensus controller behaves like a virtual leader following architecture where the leader is temporary and one from the agents of MAS. The agent responding speedily to load change will be the temporary leader. It is not necessarily to be same every time. The communication topology is sensed by secondary controller which is responsible for taking action corresponding to any change.

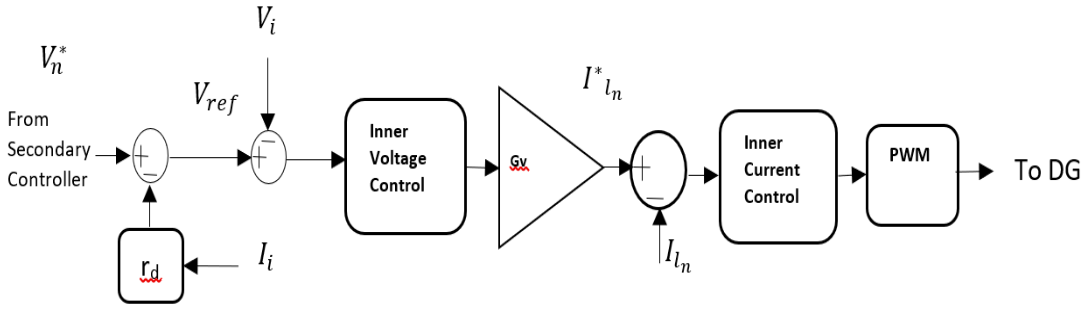

Fig. 3 Primary Controller of $\boldsymbol{i^{th}}$ DG of Microgrid

The communication network may be independent and different from the electrical configuration for fast dynamic response and easy access to all DGs. The primary level controller is virtual droop-based controller or simply a droop controller which can be an inbuilt feature of the converter control circuit. In Fig. 1, secondary control stage is shown in which the two correction terms dV1and dV2 are brough out from proportional load current sharing and reference voltage and DG's current output voltage at secondary level controller.

$$dV_1 = (V_{nom} - (V_i + \int \sum_{j\in N_i} a_{ij}(\hat{V}_j - \hat{V}_i))) \times (K_{psv} + K_{isv}/s) \quad (6)$$

$$\boldsymbol{dV_2 = (\int \sum_{j\in N_i} a_{ij}(\hat{I}_j - \hat{I}_i)) \times (K_{psi} + K_{isi}/s)} \quad (7)$$

The output voltage ($\boldsymbol{V^*}$) of the secondary consensus controller for individual DG is obtained as follows.

$$\boldsymbol{V^* = V_{nom} + dV_1 + dV_2} \quad (8)$$

Where, $\boldsymbol{V_{nom}}$, $\boldsymbol{K_{psv}}$, $\boldsymbol{K_{isv}}$, $\boldsymbol{K_{psi}}$ and $\boldsymbol{K_{isi}}$ are desired DC bus voltage, proportional and integral gain constants of secondary voltage and current PI controllers respectively. Finally, the reference voltage for inner primary voltage controller with $\boldsymbol{K_{ppv}}$ proportional gain and $\boldsymbol{K_{ipv}}$ integral gain is given by

$$\boldsymbol{V_{ref} = V_n^* - I_i \times r_d} \quad (9)$$

Where, In view of the generation intermittency, consensus at variable capacity of DGs is used when generation capacity of the renewable based source is not fixed. For proportional load sharing, a new per unit system different from conventional approach [21, 26]. The base unit for individual DG is taken as its rated capacity itself. This is same as the percentage loading of individual DG. The neighbor's communicated data, i.e., voltage output and per unit loading ($\boldsymbol{I_{pu}}$) with variable capacity is processed by individual DG controller for reference update in the droop controller and by dint of the action is initiated for proportional load sharing. The convergence of the selected protocol and stability analysis of equation (2) is illustrated by simulating the communication graph of Fig. 2 in MatLab. The communication topology of the graph is varied at different instants of time as indicated in Fig. 2.

Starting with some initial state values of all six agents and dynamically varying the state values together with communication topology, the consensus is achieved asymptotically. Initially agents A_1, A_2, A_3 and A_4 are connected to each other. The states of agents A_2 and A_3 are varied at time $\mathbf{t = 4}$s as shown in Fig. 4(a), 4(b), 4(c) and 4(d). To analyze the effect of link failure, the link between agents A_1 and A_2 is disconnected at time $\mathbf{t = 3}$s, but as the graph is still connected Fig. 4(a), the consensus is still achieved asymptotically without affecting the convergence rate even when there is change in the states of agents A_2 and A_3.

Table 1. T Primary and Secondary level PI Controllers Gains.

Controller Gains	Proportional	Integral
Primary (PI)	$K_{ppv} = 1.56$	$K_{ipv} = 60.79$
	$K_{ppi} = 3.16$	$K_{ipi} = 54.316$
Secondary (PI)	$K_{psv} = 0.01$	$K_{isv} = 0.6$
	$K_{psi} = 0.05$	$K_{isi} = 1.4$

To see whether an additional unit is capable to synchronize with the existing system, two new agents A_5 and A_6 are connected in communication channel of A_1-A_4 and A_2-A_3, at time $\mathbf{t} = \mathbf{5}$s and $\mathbf{t} = \mathbf{8}$s respectively. Before connection, the agents A_5 and A_6 are brought in synch with agents to which they are going to be connected. All agents of the graph reach consensus simultaneously as A_5 and A_6 were already in synch with their neighbors as see from Fig. 4(b). At time $\mathbf{t} = \mathbf{13}$s the graph is separated in two parts by removing link between A_4 and A_3. But as all agents has already achieved consensus hence, link failure has no effect on consensus (see Fig. 4(c)).

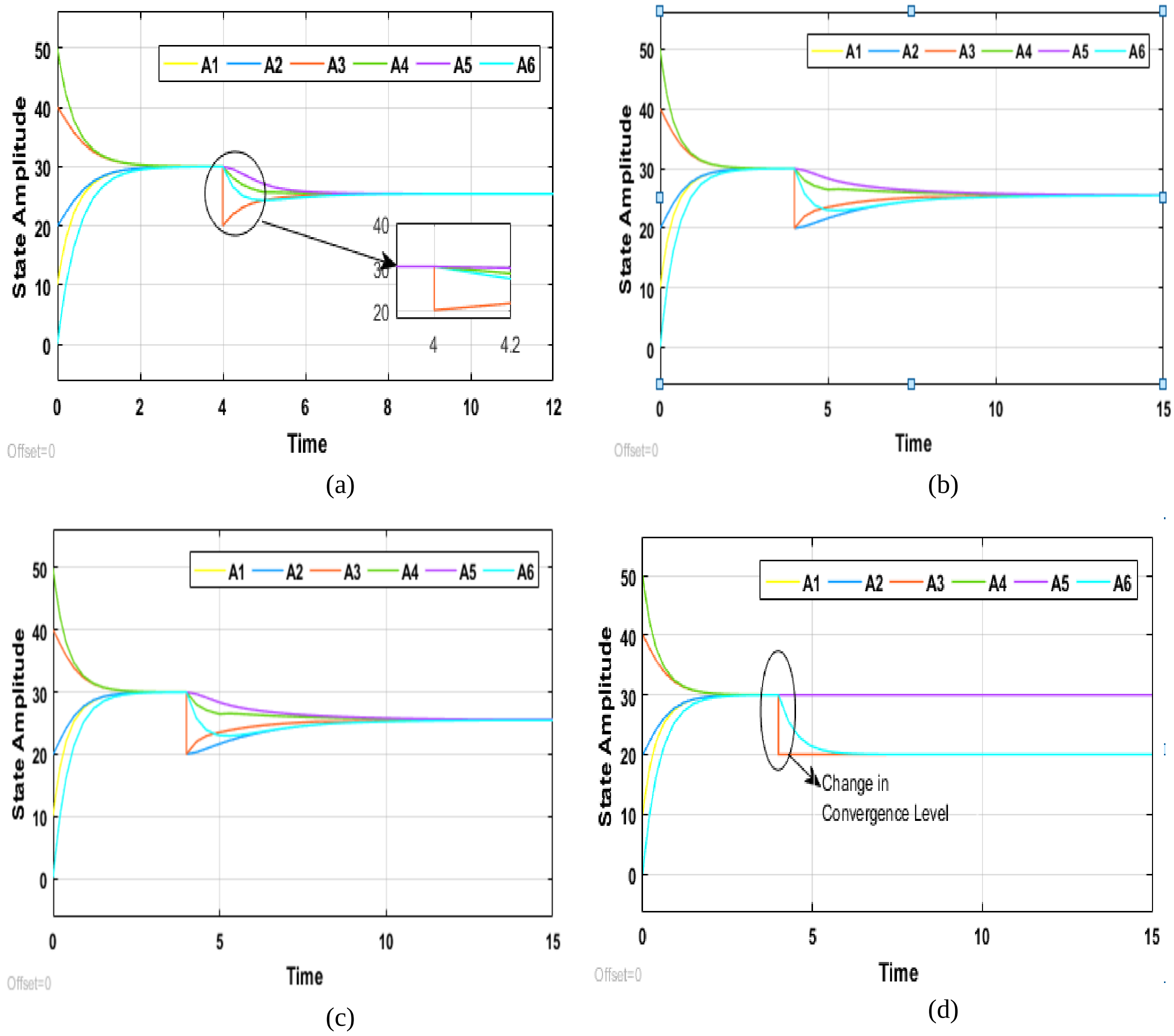

Fig. 4. Convergence of DynamiFig. 4 Convergence of Dynamic Consensus Algorithm. (a) Addition of Agents A_5 and A_6 at $t = 5$s and $t = 8$s Respectively, (b) Link failure Between A_1 and A_2 at $t = 3$s, (c) Link Failure Between A_3 and A_4 at $t = 13$s and (d) Link Between A_1 - A_2 and A_3 - A_4 Failed Simultaneously at $t = 3$s.

To see the effect of graph partition, the link between A_1-A_2 and A_3-A_4 are disconnect simultaneously at $\mathbf{t} = \mathbf{3}$s. It can be seen from Fig. 4(d) that now two groups (A_1, A_4 and A_5) and (A_2, A_3 and A_6) reach to consensus with different values and have no effect on one another. So, to achieve consensus between all agents of a graph, the following points can be summarized;

1. The graph Laplacian matrix should be balanced. For undirected graph, the graph Laplacian matrix is always balanced.
2. In variable topology with undirected links, the communication graph should always be strongly connected or connected frequently enough to reach consensus.
3. When consensus has already achieved, there is no effect of link failure until any event has not happened.

When communication graph is divided into parts, any change in the state of agents before convergence will lead the failure of consensus process i.e., consensus between all agents will never be achieved although different groups will reach to consensus individually which may be same or not for all units. To include the generation intermittency an adaptive virtual resistance droop controller is designed along with adaptive consensus controller to achieve the consensus between all DGs including one with variable generation. When power generation changes, the power converter connected to respective DG will boost up the output voltage to the bus voltage but no compensation to the current change can be provided without using energy storage units like batteries etc. to share proportional load. The primary controller includes inner voltage, inner current and droop controller (Fig. 3) and accordingly, DC bus voltage is regulated. Firstly, the parameters of DG's adaptive virtual droop controller are calculated so that DG can actively participate within its capability without adversely affecting the performance of the system. The virtual impedance or droop slope for fixed capacity power source is calculated as follows [21]:

$$\boldsymbol{r_d} = \Delta \boldsymbol{V_{max}}/\boldsymbol{I_{max}} \quad (10)$$

Where, $\Delta \boldsymbol{V_{max}}$ is allowed maximum voltage deviation and $\boldsymbol{I_{max}}$ is the maximum output current of respective DG. Selection of virtual resistance plays key role in primary controller performance. To achieve the desired droop response at variable power generation, the parameters of the adaptive droop are calculated as below:

$$\boldsymbol{r_{d_{max}}} = \Delta \boldsymbol{V_{max}}/\boldsymbol{I_{max}} \quad (11)$$

Where, $\boldsymbol{r_{d_{max}}}$ is the droop resistance of DG operating at maximum rated capacity. If output of the DG changes, then droop resistance is given by:

$$\boldsymbol{r'_d} = \boldsymbol{r_{d_{max}}}/\boldsymbol{I_{sc}} \quad (12)$$

Where, $\boldsymbol{I_{sc}}$ is the numeric value of the short circuit current (i.e., maximum output current at the time of output variation) at varied capacity of DG. At secondary level to achieve proportional load sharing at varied capacity, the current consensus block should be capable to track consensus even when there is change in power output of any DG. To reach the current consensus, the per unit value at current consensus part must be capable to sense the variation in power generation. Let again $\boldsymbol{I_{sc}}$ be the short circuit current measured at certain DG when its output is changed and $\boldsymbol{I_{ln}}$ is the current supplied by it to the microgrid bus load. Then, per unit value of the current fed to the current consensus controller to achieve proportional load sharing is given by:

$$\boldsymbol{I_{pu}} = \boldsymbol{I_{ln}}/\boldsymbol{I_{sc}} \quad (13)$$

Where, $\boldsymbol{I_{sc}}$ is a variable quantity as it is the current delivered by DG with variable capacity like solar PV and so as the $\boldsymbol{I_{ln}}$. The proportion gain "$\boldsymbol{G_v}$" after primary voltage controller is calculated as:

$$\boldsymbol{G_v} = \boldsymbol{I_{sc}}/\boldsymbol{I_{max}} \quad (14)$$

This $\boldsymbol{G_v}$ block generates reference ($\boldsymbol{I^*}_{\boldsymbol{l_n}}$) which is after comparison with the line current supplied by respective DG, is fed to its inner current controller which is a PI controller with proportional and integral gains $\boldsymbol{K_{ppi}}$ and $\boldsymbol{K_{ipi}}$ respectively. The main feature of the proposed control scheme is that it doesn't need any energy storing units and DG can participate in load sharing to its maximum available capacity.

III. RESULTS AND DISCUSSION

The proposed distributed control algorithm is implemented and tested through MatLab simulation. DC bus voltage V_{nom} is taken as 380V. Four DG sources of capacity $\mathrm{DG1} = \mathrm{DG2} = 7.6\mathrm{kW}$ and $\mathrm{DG3} = \mathrm{DG4} = 3.8\mathrm{kW}$ with respective local loads $\mathrm{L1} = 2.5\mathrm{kW}$, $\mathrm{L2} = 2\mathrm{kW}$, $\mathrm{L3} = 3\mathrm{kW}$ and $\mathrm{L4} = 3\mathrm{kW}$ are connected to DC bus through RLC filter as shown in Fig. 5. The parameters of RLC filter are 0.1Ω, 3×10^{-3}H and 2×10^{-3} F respectively. Load connected to DC bus is 4.8kW and a switching load of 1kW is connected after 2 seconds and removed after 4 seconds. The transmission line parameters are depicted in Fig. 5. The whole strategy is divided into four cases. First three cases address the problem of changing communication topology among the DGs and case four shows efficacy of designed control to tackle the problem of generation intermittency.

A. Case-1

Keeping all other configuration parameters same as described above, the communication topology among the DGs is varied to see the effect of switching of DGs on the performance of consensus based secondary controller. In Case-1, a new link between the DG1 and DG2 is formed at time $\mathrm{t} = 5\,\mathrm{s}$ and remains connected, the communication topology change is shown in Fig. 6. As both DGs were already the part of the topology, there is no effect of new link formation between these two DGs. There are no visible traces for this event as seen in Fig. 8, although this may increase the speed to achieve the voltage consensus at secondary level control and hence the controller will rapidly reach to nominal DC bus voltage. The DGs voltages vary at $\mathrm{t} = 2\mathrm{s}$, due to 1kW switching load as seen in Fig. 7.

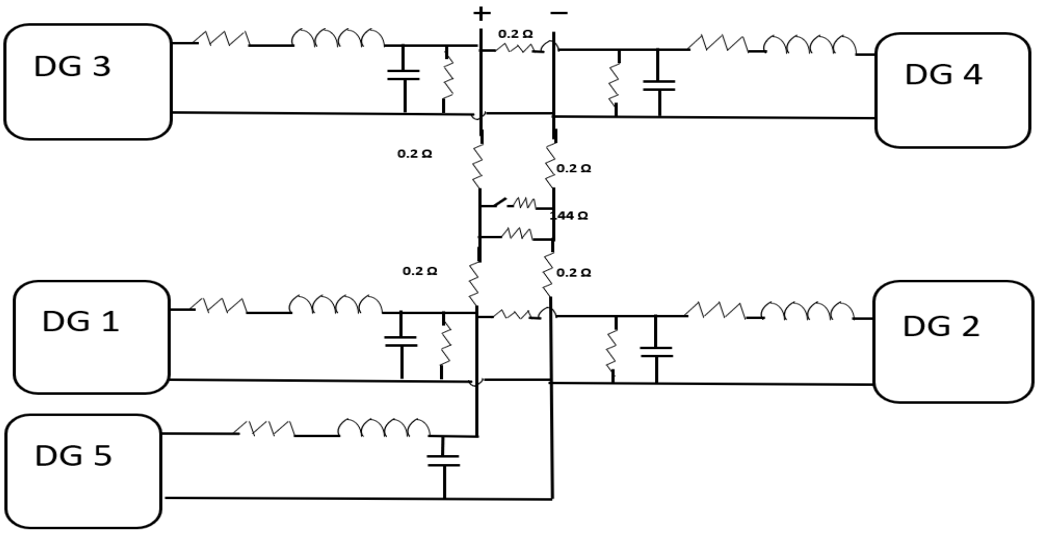

Fig. 5 Electrical Connection of all DGs

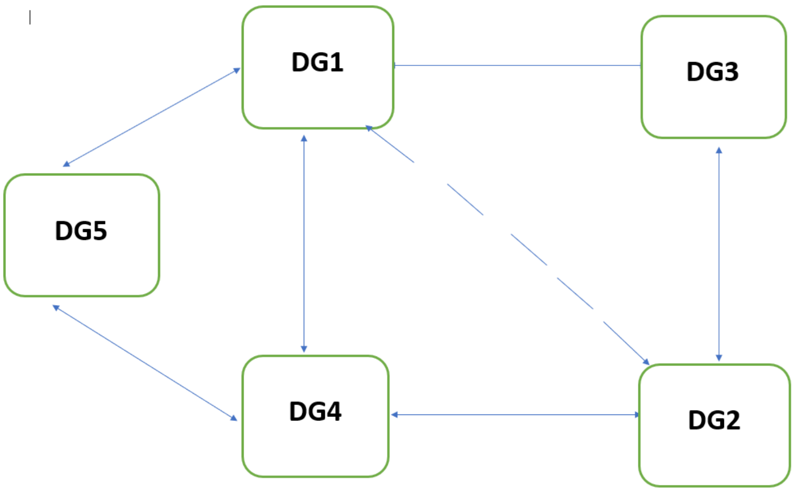

Fig. 6 Communication Topology of Microgrid DGs style

B. Case-2

To see whether a newly added unit is capable to synchronize with the existing structure without threatening the stability of microgrid a 5th DG is added at time t = 3s, as shown in black color with bold waveform in Fig. 7. This unit is added to communication channel of DG1 and DG4 as shown in Fig. 4, and receives states information of DG1 & DG4 only. As other DGs of the microgrid may not have information of any additional unit, the change in the output of DG1 and DG4 immediately reflected at secondary consensus controller which force the other DGs to adjust their output accordingly. This new unit has same capacity as that of DG3 but without any local load. DG3 and DG4 loaded equally as are having same rated capacity and local load. The voltage of this unit is brought equal to DC microgrid bus voltage by its converter before synchronization. The load shared by 5th unit is proportional to its rated capacity when this unit is connected to point of common coupling. In Fig. 10, the pink waveform shows that 5th DG is sharing power proportionally and load on all other units is reduced by same amount. Fig. 7 shows the DC bus voltage; due to variation in the load connected to it, a small change in voltage can be seen but these variations are within the allowable voltage deviation as per IEEE std. 1564-2014.

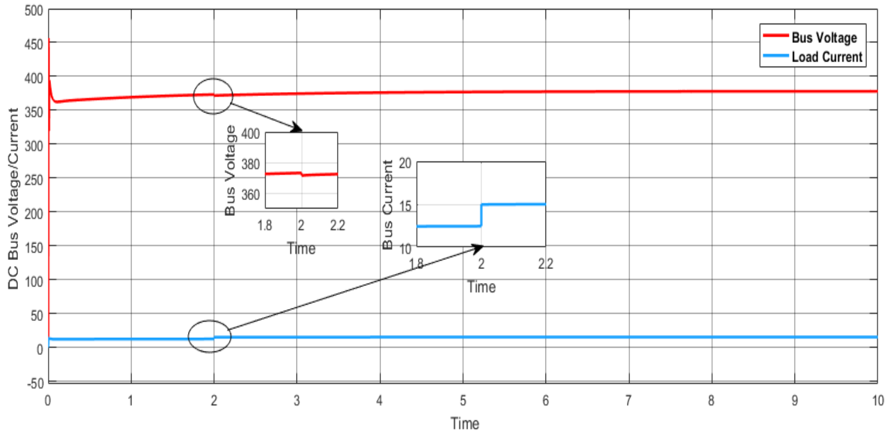

Fig. 7 DC Bus Voltage and Current

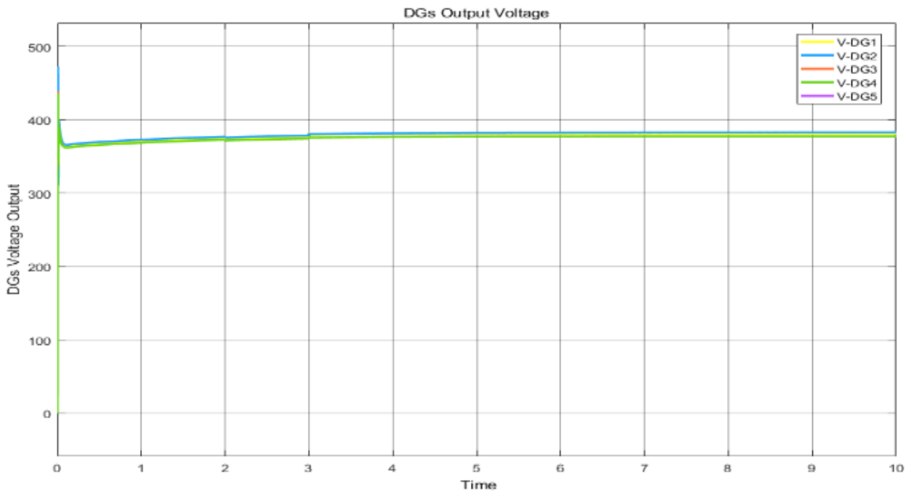

Fig. 8 DGs Voltages without Plug in of 5th DG

C. *Case-3*

In this case, the link between DG1 and DG4 is no longer continued. Removal of this link at $t = 7$s doesn't make any change in the system voltage.

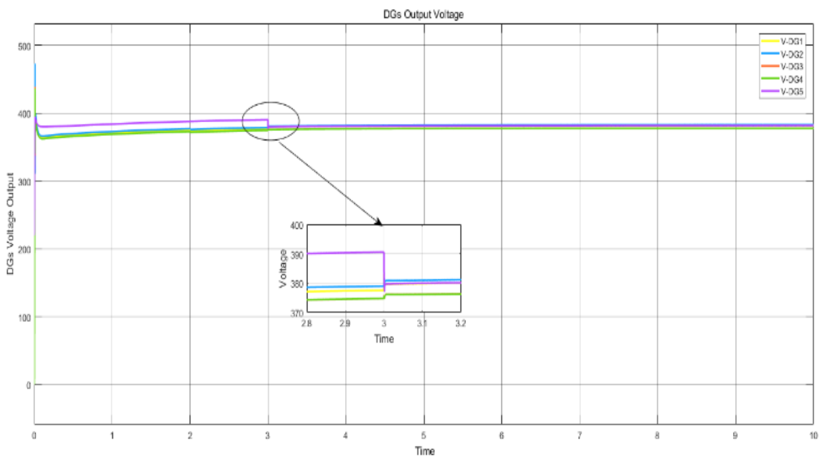

Fig. 9 DGs Voltages with Additional Unit

D. *Case-4*

The Above cases show the effect of switching topology, case 4 shows the effectiveness of the consensus based distributed secondary control when output power of certain DG changes with time. In this case, intermittency of the renewable sources is manifested by a source with variable capacity. The capacity of DGs, DG1 = DER2 = 7.6kW, DG4 = 1.9kW and DG3 is considered as a variable capacity source. The capacity of DG3 is varied at $0 \leq t \leq 3$, $3 \leq t \leq 6$ and $6 \leq t \leq 10$ to 3.8kw, 1.9kW and 0.76kW respectively.

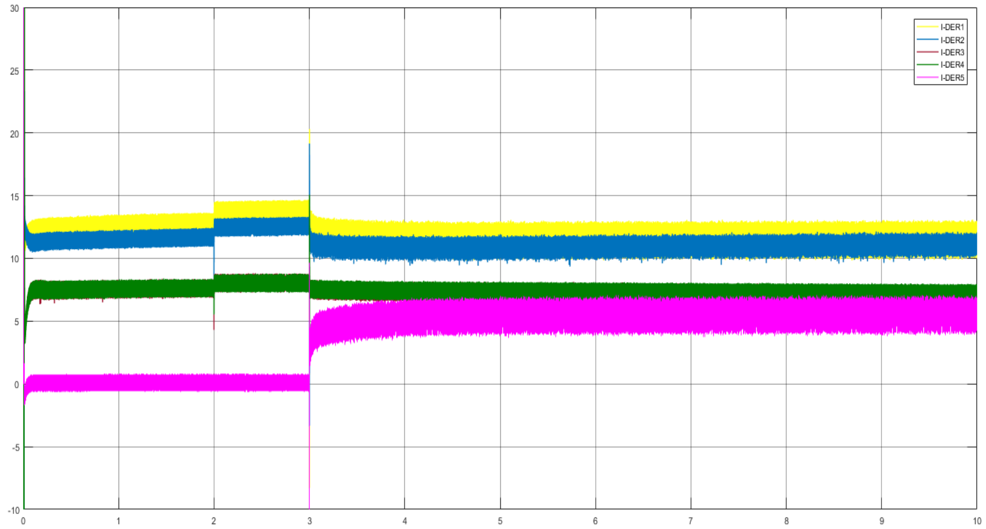

Fig. 10 DGs Load Sharing After Adding a new Unit to Microgrid

Fig. 11 shows the load sharing among the DGs. DG3 shares load corresponding to its variable capacity. Initially DG3 shares almost double load compared to DG4 for $0 \leq t \leq 3$. When capacity of DG3 changed to 1.9kW, it shares load equal to DG4 as both having same rating for period $3 \leq t \leq 6$ and finally almost half loading compared to DG4. During complete operation, the per unit loading of each source is still equal. This shows the efficacy of the consensus based distributed secondary control of microgrid. The microgrid voltage is still maintained to rated value with permissible tolerance.

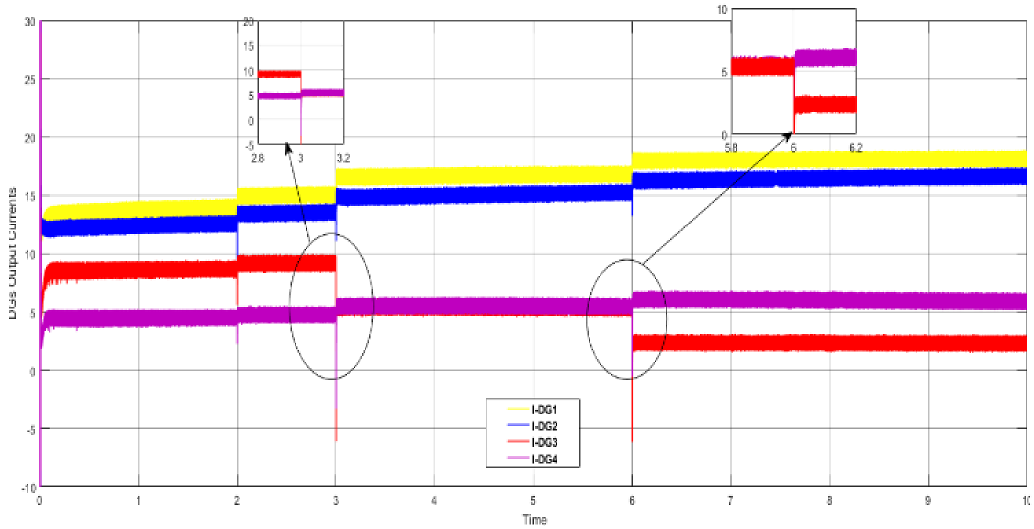

Fig. 11 Effect of Variable Generation on Load Sharing

Fig. 12 shows that the DG's output current has reached to consensus. In terms of load sharing, each DG has same per unit loading irrespective of the instantaneous power generation capability and switching of DG. The adaptive consensus protocol and virtual droop controller is capable to handle dynamic communication topology and generation intermittency simultaneously.

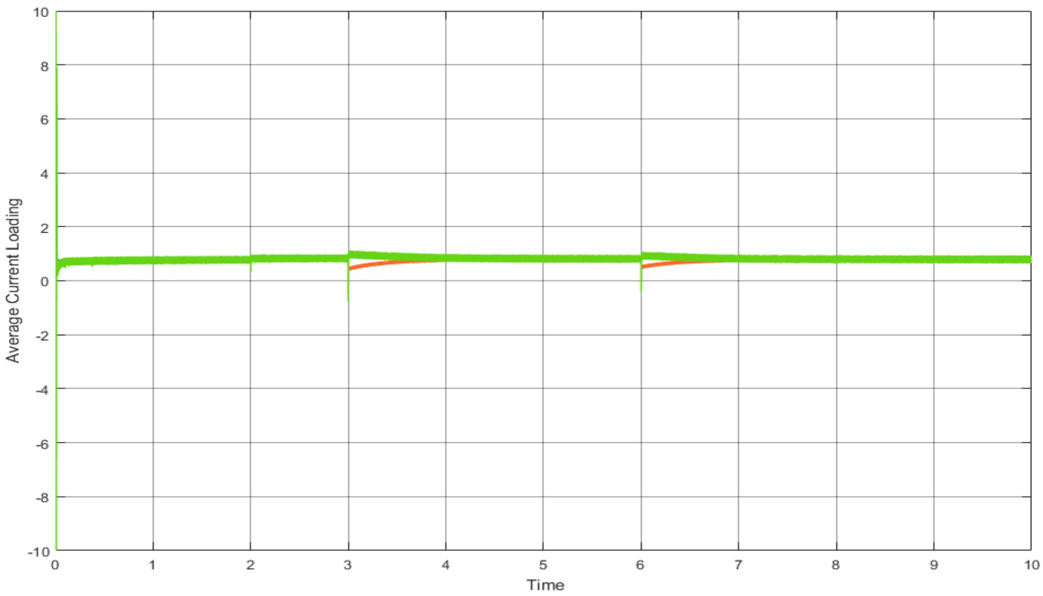

Fig. 12 DG's Current Consensus after each Disturbance

The results show that the consensus based distributed secondary control of microgrid is capable to handle the addition and removal of the DGs to the existing structure and fully resilient to link failure. The adaptive control at secondary and primary level, can easily achieve proportional loading even when the power output of certain DG is not fixed due to any reason.

IV. Conclusion

This paper proposes distributed control strategy of microgrid, based on the consensus algorithm that can efficiently accommodate the addition and removal of the DGs to the existing structure and capable to achieve proportional loading under generation intermittency. The intermittent and irregular generation from any renewable based DG can be modelled as a source of variable capacity to support the load. The adaptive droop controller and consensus controller can regulate DC bus voltage without using any energy storage support. From the futuristic viewpoint, the strategy can be extended to discontinuous data communication for reduced data transmission to not overburden the communication channel. Further, finite time consensus solutions can be adopted for rapid load distribution so as to have low settling time and fast transient response.

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