Consensus Algorithm based Two-Level Control Design for a DC Microgrid

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Abstract - **This paper presents two-level control of DC microgrid for proper voltage regulation and equal current sharing across the load. DC microgrid is emerging as an alternate solution for rural electrification but it needs a robust and stable control system for good quality power delivery and proper energy management. In this paper, four microgrids are joined together to form a cluster and jointly all four microgrids deliver equal current to a common load. Droop control is implemented as a local level control for the regularization of voltage and current sharing. In order to mitigate the deviations created by primary level, consensus algorithm is used for generating a universal voltage reference for all droop controllers. It has been found that in a two-level control structure there is lesser voltage deviation and proper current sharing among the units as compared to only droop control.**

Keywords – **DC Microgrid, Hierarchical Control, Droop Control, Consensus Algorithm**

I. INTRODUCTION

Electricity has become indispensable in modern life and almost all the items used in daily life are powered by electricity. According to the world bank's report, approximately 17% i.e. 1.2 billion people in the world are living without electricity or they have very little availability of electricity [1]. The main reason for such poor availability of electricity for such a large population is the fact that they remain far away from the central electricity grid system and the cost of laying the grid line up to such an islanded area is not economical [2]. Therefore, a small grid system with its own generation sources, storage systems, loads and control system seems to be an ideal solution for electrification of remotely located places. These small grid systems are popularly called microgrid which has been introduced as an idea more than a decade ago [3]. The major benefits of a microgrid system are high reliability, reduced distribution losses, minimal chances of blackout, remote electrification, and easy scalability. There are two types of microgrids based on their working electric signal type namely AC microgrid and DC microgrid. As evident from the name, DC microgrid has a common DC bus on which all the sources, energy storage systems (ESSs) and loads are connected through respective converters. DC microgrid has some inherent advantages over AC microgrid such as higher efficiency, direct interface to many types of renewable resources and ESSs, better compliance with consumer electronics, etc. DC microgrid can be connected to the utility grid for power shortages, but this needs a high-efficiency converter for AC-DC conversion which increases losses and system's cost also [4-6]. DC microgrid clusters appear as a better solution for handing power shortage problems in a microgrid. Multiples of microgrids are connected to each other and each microgrid can inject or absorb power from its neighboring microgrid in case of surplus or shortage of power respectively. A typical microgrid cluster with various sources and loads is shown in Fig. 1.

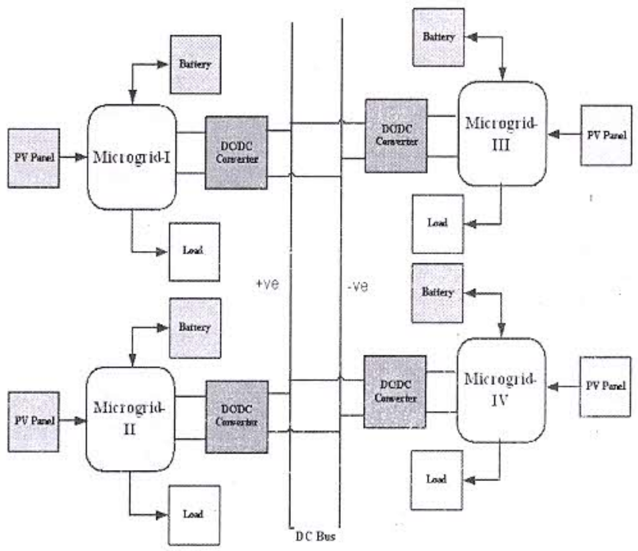

Fig. 1 Configuration of a Microgrid Cluster

In a DC microgrid cluster, the scheduling of power and energy management are two major challenges if multiple energy sources with different profiles and state of charges are connected in the system. Also, the important question is which microgrid should be chosen from the cluster to meet the demand for additional power. Therefore, in a DC microgrid cluster, the hierarchical control strategy is being preferred over other control strategies such as centralized control and decentralized control. Centralized control offers a great amount of control over power and energy management through a centralized controller that receives information from each unit. All benefits of a centralized controller come at the price of the requirement of a large communication network and prone to single point of failure, whereas decentralized control provides commands to converters on the basis of inputs from the converter or nearby converters. DC bus signaling, droop control, and power line signaling are three major decentralized control strategies that do not use a communication link to share commands. It does not require any large communication network and centralized controller but lacks the ability of proper supervised control of each converter. However, a hierarchical control strategy provides a supervised control through a low bandwidth communication network and it allows the local controller to have a strong voltage regulation and proportionate current sharing.

A hierarchical control strategy is a three-layered architecture with each layer having a particular task to accomplish. The three layers of hierarchical control strategy are primary, secondary, and tertiary layers [7-8]. The primary layer is also known as the local controller and is responsible for DC bus voltage regulation through local information of converter and adjoining converters. Most of the methods of decentralized control such as dc bus signaling, droop control, fuzzy logic control, etc. are implemented at the primary layer which utilizes local information and attempts to keep voltage stable. Droop control is the most widely adopted method because it is adaptive towards local variables, no communication requirement, significantly better voltage and current regulation along with easy implementation. However, only the use of only droop control is not fully effective for voltage regulation in a microgrid cluster environment [9-10]. A secondary controller with a response time slower than the primary is used to compensate voltage deviation caused by the primary level. The tertiary level controller is the top-level control used to maintain optimal operation between microgrids and solves optimization related problems by converging each agent to a common value thorough an adaptable solution [11]. In a microgrid cluster environment, a common reference voltage of operation for each microgrid is generated at the tertiary level and passed to the primary level of control through secondary control or directly. Genetic algorithm, particle swarm algorithm and consensus algorithm are commonly used at the tertiary level. The consensus algorithm provides faster convergence of agents with minimum data requirements as compared to its counterparts. In this paper, a two-level distributed control structure is designed for a microgrid cluster with droop control operating at the primary level and consensus algorithm at the tertiary level.

This paper is structured into different sections with discussions on droop control and consensus algorithm for power converters in section II. Section III presents the system and control design part followed by the simulation model and simulation results in section IV. The paper presents its conclusion in section V.

II. DROOP AND CONSENSUS ALGORITHM

The basic droop control pursues the linear vision to reduce the dc voltage in relation to the increase in output current. The conventional droop control method is expressed as: -

$$V_{dck} = V_{dc}^{*} - I_{dck} * R_{dk} \tag{1}$$

Here $V_{dck,}$ $V_{dc*,}$ $I_{dck,}$ R_{dk} specifies the converter's output voltage, the reference value of dc output voltage, the output current and the virtual resistance respectively with $k = 1,2,3...$[12]. But this relationship faces the deviation of voltage along with the asymmetric line drop. This prevents its execution from being a suitable system. The old-fashioned control design desires bottom level knowledge of system behavior. In a microgrid cluster environment, reference dc output voltage needs to be altered according to available power and energy in the grid for proper power and energy management. Therefore, in order to bring a common point of operation, the consensus algorithm is implemented by the multi-agent system (MAS) approach.

In recent times for power systems management and operations, the multi-agent system has been implemented. Here, each power source and load in the system are considered as autonomous agents. In this manner, a common communication interface is available for all the other agents which represent other components in the network. The prominent advantages of MAS approach over the traditional approaches for management and control of microgrid are unit autonomy, lesser data requirement, increased reliability and robustness of control system. The consensus is all about arriving to an agreement of an equal amount which depends on all agent's status and after applying mathematical tools, all agents try to converge at one point. Graph theory, matrix theory, and control theory are some of the tools that have been used to solve consensus protocols [13]. The network topology having multiple agents is represented through a directed graph as

$$G = (V, E) \tag{2}$$

Here V represents a set of nodes $V = (V_{1,}\ V_{2,}\ V_{3....}\ V_n)$ and E represents a set of edges for data exchange between nodes. Here nodes only exchange data with neighboring nodes. In graph theory, the Laplacian matrix emerges as the best approach for consensus protocols and attracted the attention of many researchers. The Laplacian matrix is defined as $L = D\text{-}A$, where D represents a diagonal matrix and A represents an adjacency matrix. The suitably arranged weight of the Laplacian matrix leads to a fast convergence and the eigen value of L defines global dynamics of the system [15]. The sum of all the elements in each row of L is zero. If the graph is strongly connected, then the eigen value of L is zero.

In any practical scenario, a discrete-time consensus algorithm is used due to discrete nature of digital controller and communication network. The basic discrete consensus algorithm with discrete-time integrator agents can be expressed as:

$$x_i(k+1) = x_i(k) + \varepsilon * \textstyle\sum_{j \in N_i} a_{ij} * (x_j(k) - x_i(k) \tag{4}$$

Where i is1, 2,..., nT number of agents, x_i is state of agent i, a_{ij} is connection status between node i and node j, is constant edge weight and N_i is set of indexes of the agents[13]. The constant weight is the primary parameter controlling the dynamics of the algorithm. A suitable chosen value of constant weight leads to fast and stable convergence of the algorithm.

III. CONTROL CONFIGURATION

The control block diagram of the overall system is presented in Fig. 2. The microgrid control structure involves first generating the reference voltage for the droop control which is obtained using the consensus algorithm which uses the output voltages (V_{DC1}, V_{DC2}, V_{DC3}, V_{DC4}) of the individual DC-DC Converters to generate DC-bus reference voltage (V_{DC}^*). The detailed explanation regarding the implementation of consensus droop for a microgrid cluster is explained as follows.

A. Consensus Algorithm for Generation of Reference DC-bus voltage

In a consensus algorithm, a set of distributed agents share information among each other through a communication network and reach an agreement on a quantity of interest. In the case of an MG system, distributed units share operative information and coordinate their operation by the means of the consensus algorithm. The communication structure in MG systems is well described by graph laplacians which helps significantly in dynamic analysis and convergence of the system.

Here, a bidirectional communication network is under consideration where each local controller (LC) system is communicating with their three neighboring systems. In case of our consideration, the Laplacian matrix for a 4 microgrid cluster communicating in ring-shape topology is given as:

$$L = \begin{bmatrix} 3 & -1 & -1 & -1 \\ -1 & 3 & -1 & -1 \\ -1 & -1 & 3 & -1 \\ -1 & -1 & -1 & 3 \end{bmatrix}$$

The eigen values of the Laplacian matrix L are given as

$$\lambda = [0\ 4\ 4\ 4]$$

According to L and its eigenvalues, the optimal   = 1/3.

The weight matrix for the above system is given as

$$W = I - \varepsilon L$$

Where W= Weight Matrix, ε is constant edge weight and L is the Laplacian matrix.

The flowchart for the consensus algorithm is shown in Fig. 3 and using the Weight matrix, the reference voltage for each sample period is evaluated as

$$V_{DC}^*(K+1) = W * V(K)$$

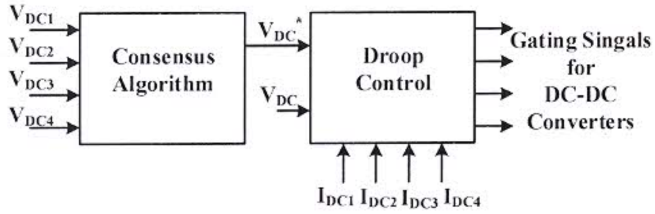

Fig.2. Overall High-Level Block Diagram for Microgrid Control

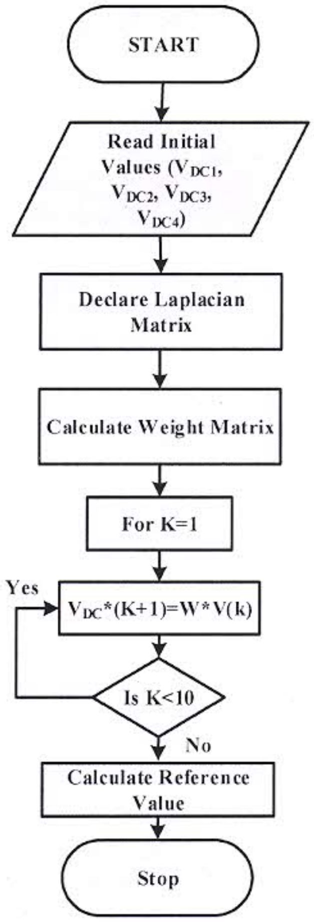

Fig.3. Flow Chart for the Consensus Algorithm

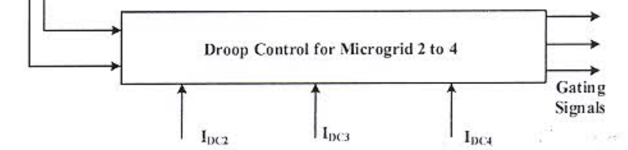

Fig.4. Droop Control Scheme for DC- Microgrid System

Once the reference voltage for the DC-bus is generated using the consensus algorithm, the local level control for the microgrid is implemented using a droop control-based technique as shown in Fig.4. In droop characteristics implementation, a parameter is proportional to the output current which modifies the output-voltage feedback loop characteristics in order to reduce the output voltage with an increase in the load current.

For each of the microgrid structures, the reference voltage (V_{DC}*) and output currents ($I_{DC1,2,3,4}$) are used to generate the individual reference voltage for the DC-Microgrid as

$$V_{DCi} = V_{DC}^{*} - K_d I_{DC1}$$

The droop factor is decided based on parameter K_d which is calculated based on the maximum droop permissible. Assuming a maximum drop of 5% of rated voltage, under full load condition of 10.5 A

$$\Delta Vm = 0.05 \times 48 = 2.4$$

$$I_{om} = 10.5A$$

$$K_d = \frac{\Delta V_m}{I_{om}} = 0.228$$

The individual droop references are compared with the sensed DC-link voltage (V_{DC}) and error is passed to a linear controller such as proportional-integral controller (PI) which generates appropriate duty ratio for individual DC-DC converters.

$$d(n) = d(n-1) + K_p \Delta ev_{dc} + K_i ev_{dc}(n)$$

The duty ratio signal is then fed to a PWM modulator which generates the necessary control signals for each of the four DC-DC converters forming a Microgrid cluster.

IV. SIMULATION MODEL AND RESULTS

The performance of the proposed consensus-droop control technique is tested on a Micro-grid cluster consisting of four DC-DC Converters connected to a common load. The system is simulated in the Matlab Simulink software system using the SimPower System Block set and the Simulink model of DC-microgrid cluster is shown in Fig. 5. The system parameters used in the simulation are presented in Table I.

TABLE I DESIGN PARAMETERS FOR SIMULATION

Components	Value
Input Voltage (Vin)	36 V
Output Voltage (Vout)	48 V
Load Current (I_L)	10.4 A
Switching Frequency (f)	100kHz
Duty Cycle (D)	26.4%
Inductor (L)	29.96uH
Capacitor (C)	114.414uF

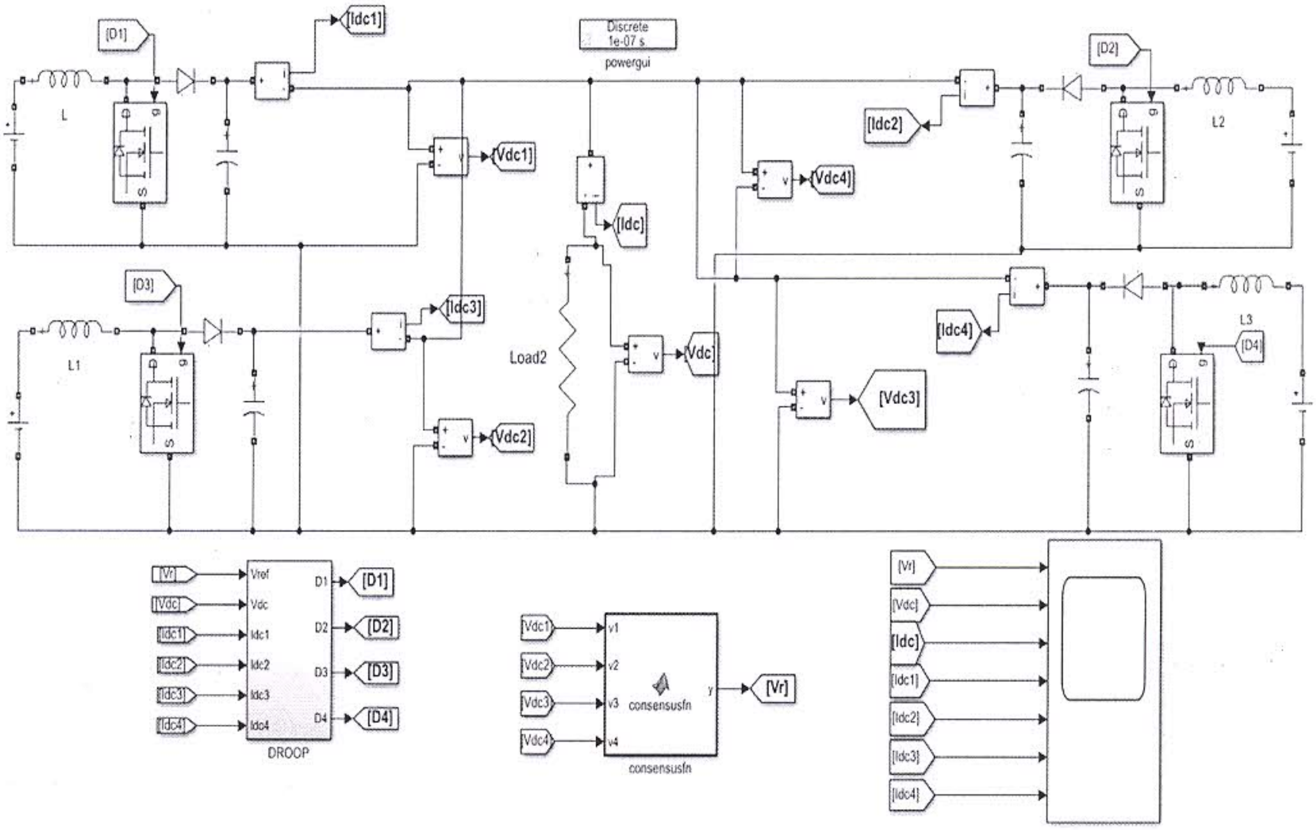

Fig.5. Matlab-Simulink Model for Performance Evaluation of DC- Microgrid Cluster

A. Performance of only Droop Control based DC Microgrid

The response of only droop control based DC microgrid is shown in Fig. 6. The fixed DC-bus voltage reference as in case of droop (V_{DC*}), actual DC-bus voltage(V_{DC}), DC bus current (I_{DC}), and DC current by each subsystem (I_{DC1}, I_{DC2}, I_{DC3}, I_{DC4}) in the cluster are shown in the Fig.6. The reference system bus voltage is at 48 V and all four converters are operating at slightly different input voltages.

The system is operating under steady-state conditions at the beginning with a DC-bus voltage around 48V with a steady-state error in DC-bus voltage. It can be seen that despite having different input voltages, each converter is sharing equal current to the common DC bus load. The system is subjected to a load change of twice the original value at t=0.5s. It can be observed that there is further deterioration in the voltage regulation of the DC-Bus due to step-change in load current. While the steady-state currents are shared equally between the individual microgrid currents, there is an overshoot or undershoot of around 30% with reference to the desired current in different microgrid currents during the transient period.

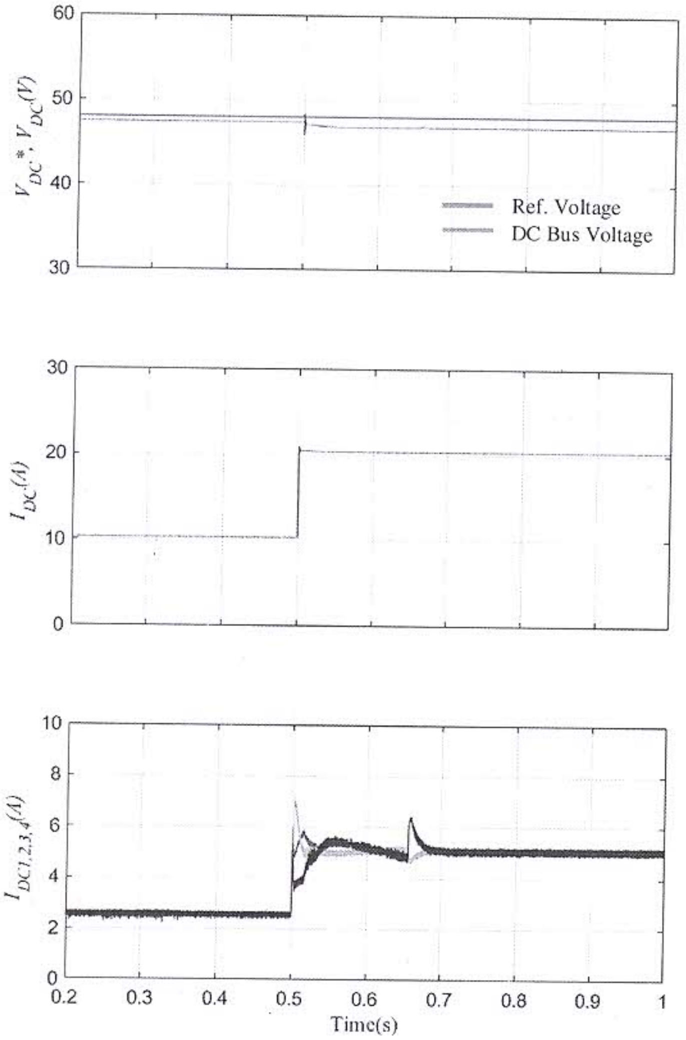

Fig.6. Dynamic Performance of DC-Microgrid Cluster based on droop control

B. Performance of Consensus-Droop Control Based DC Microgrid

The performance of the Consensus-Droop control-based DC-Microgrid system is presented in Fig.7. The signals captured are DC-bus voltage reference and actual sensed signal (V_{DC}^*, V_{DC}), the DC-bus current (I_{DC}), the DC currents supplied by each subsystem in the Microgrid cluster (I_{DC1}, I_{DC2}, I_{DC3}, I_{DC4}).

Initially, the system is operating in steady-state with DC-bus voltage at 48 V and power consumption is at around 480 W. It can be observed that the DC-bus power is equally shared by the DC-sources which are integrated through DC-DC converter at the DC-bus. At t=0.5s, a step-change in the DC-bus power is generated, and DC-bus power is now at 960W. It can be observed, that the system voltage is stable and regulated at its desired voltage level of 48V with tight regulation. Moreover, even under these dynamic conditions, the load power is equally distributed among the four DC-sources.

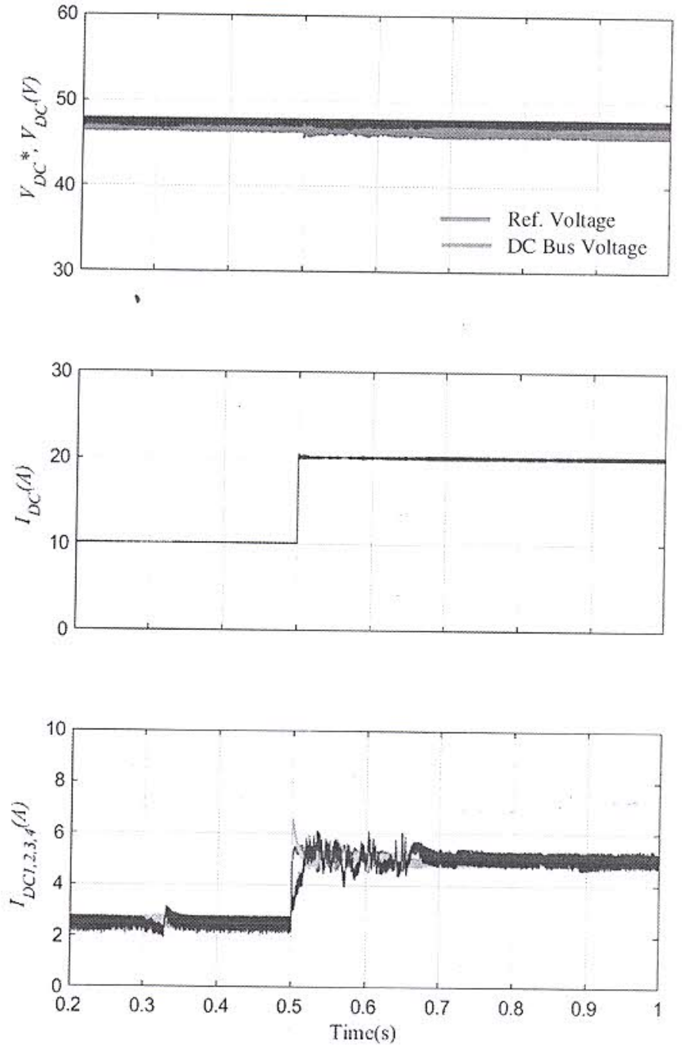

Fig.7. Dynamic Performance of the DC-Microgrid Cluster based on droop Consensus

CONCLUSION

The performance of a Consensus-Droop based control technique for control of a Microgrid cluster is presented in this work. The Consensus algorithm is used to generate the reference voltage of the DC-bus which is then fed to the droop controller which then generates gating signals for the individual subsystem of the Microgrid cluster. Matlab-Simulink software is used for performance evaluation of the system under dynamic loading conditions. In only droop-based control, there is an undesired overshoot or undershoot in current leading to unequal current sharing in dynamic conditions. It has been observed that the consensus-droop based control system is able to regulate the DC-link voltage with accurate current sharing among the different microgrid converters in dynamic and steady conditions.

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