IET Renewable Power Generation

Research Article

Distributed droop control of dc microgrid for improved voltage regulation and current sharing

ISSN 1752-1416
Received on 4th September 2019
Revised 23rd May 2020
Accepted on 25th June 2020
E-First on 14th September 2020
doi: 10.1049/iet-rpg.2019.0983
www.ietdl.org

Rohit Kumar[1,2] ✉, *Mukesh K. Pathak*[1]
[1]*Department of Electrical Engineering, Indian Institute of Technology, Roorkee, India*
[2]*Department of Electrical Engineering, National Institute of Technology, Uttarakhand, India*
✉ *E-mail: rohitkumarnit3010@gmail.com*

Abstract: DC microgrid is becoming popular because of its high efficiency, high reliability and connection of distributed generation with energy storage devices and dc loads. The main objective in the dc microgrid is to keep the dc bus voltage constant and equalise per unit current sharing among converters. The conventional droop control is used to equalise per unit current sharing similar to reactive power sharing in an ac microgrid. Nevertheless, the problem in conventional droop control is that equal current leads to a reduction of dc bus reference voltage and voltage regulation becoming unequal across each node due to unequal line resistance drop. The proposed controller works on adaptive droop and voltage shifting technique, which equalises the current sharing whether line resistances are similar or not and controls each output voltage to follow the respective bus reference voltage. The isolated dc–dc converters are used to simulate and validate the proposed control technique.

1 Introduction

The concept of a microgrid is introduced to integrate renewable energy sources such as photo-voltaic source, wind energy source etc. with energy storage system and ac utility line [1–24]. The main purpose is to minimise the dependency on fossil fuel and reduce the carbon emission to keep the ozone layer healthy. The microgrid is further divided into two types – grid connected and off the grid. When connected to the grid, it is called grid-connected mode otherwise it is islanded mode. With the introduction of new technologies such as the Internet of Things (IoT), the pace in integration of renewable energy sources with an ac grid is picking up fast. The problems of cyber attacks on such a grid are also receiving vide attention [25–28].

Initially, the ac microgrid came up to reduce the dependencies on the main grid line, extract the power from renewable energy and provide the electrical energy to the household. For control of the ac microgrid, the voltages and currents are transformed in stationary $\alpha\beta$ reference frame [29]. However, in the dc microgrid no such transformation is required. The problem arises when the dc nature of renewable energy is converted to ac and then back to dc to feed dc loads such as light-emitting diodes, computers, electronic ballasts and adjustable speed motor drives controlled by voltage source inverter etc. The number of conversion steps increases to supply the dc loads and efficiency of the system also reduces using two dc–ac and ac–dc converters.

The dc microgrid has originated to overcome the drawback of the ac microgrid, with additional advantages such as lack of frequency synchronisation, reactive power control, skin effect, power quality issues etc. The core issues in the dc microgrid are to minimise voltage regulation across connected loads with reference to bus voltage and equalise the per unit current sharing among converters (Fig. 1). Droop control is a popular technique in dc microgrid to equalise current sharing among converters like reactive power sharing in the ac microgrid. Conventional droop control works on adding virtual resistance in line to equalise current sharing. However, the problem arises when the reference bus voltage is reduced with an additional voltage drop and it also leads to poor voltage regulation. Selection of value of virtual resistance is a trade-off between current sharing and voltage regulation. The low value of virtual resistance leads to poor current sharing but better voltage regulation. However, the high value of virtual resistance leads to better current sharing and poor voltage regulation. Hence, a moderate value of virtual resistance is added to keep the current sharing equal and a voltage shifting term is added to the reference bus voltage to maintain the low-voltage regulation. Another problem encountered is the unequal line resistances which adversely impacts both current sharing and voltage regulation. To overcome these issues, adaptive virtual resistance concept is introduced. The current error term is subtracted from fixed virtual resistance and multiplied by output current. This adaptive resistance drop changes when output current deviates from the average output current of all converters. Hence, the current sharing accuracy is improved. Voltage regulation is still a major concern. This issue is addressed by adding a voltage shifting term which is obtained after subtracting adaptive virtual resistance drop from the bus reference voltage.

2 Literature review

Droop control method was first introduced for the current sharing of parallel voltage regulated module (VRM) application [2]. The secondary controller compares the actual sensed output current (i_0) of each VRMs with average sensed output current ($\bar{i_0}$). The comparator provides a voltage correction term only when i_0 is greater than $\bar{i_0}$, otherwise it is zero. Then, the product of fixed virtual resistance (R_d) and output current (i_0) is subtracted from reference voltage (V_o^*) and the result is added to the comparator output (δv_0) to obtain the reference voltage for the primary controller:

$$v_{\text{ref}}^* = V_o^* - R_d i_o + \delta v_0 \tag{1}$$

This method loses effectiveness for higher output current and is not able to achieve good voltage regulation across the load of each converter.

Centralised droop control technique was the first step for current sharing accuracy in the dc microgrid [3], which is shown in Fig. 2*a*. The centralised secondary controller compares the reference bus voltage with an average of the output voltage of all converters and after processing in the proportional–integral (PI) controller, the voltage shifting term obtained for the primary controller of each converter. Internal primary controller subtracts

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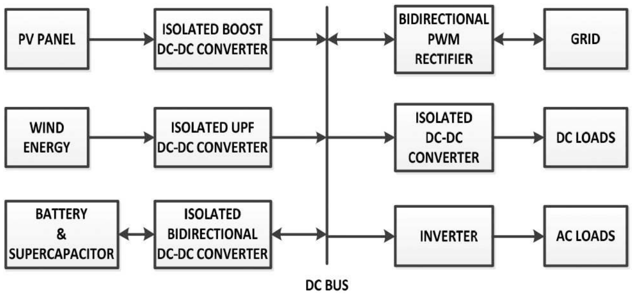

Fig. 1 *Paradigm of dc microgrid*

the product of fixed virtual resistance and output current from the reference bus voltage and adds it to the voltage shifting term obtained from a secondary centralised controller. The result is the reference voltage of inner primary control:

$$v^*_{\text{ref}j} = V^*_{\text{dc}} - R_{\text{D}} i_{oj} + \left(K_{\text{p}} + \frac{K_{\text{i}}}{s}\right)(V^*_{\text{dc}} - v_{oj}) \quad (2)$$

where $v^*_{\text{ref}j}$ is the reference voltage of primary controller of the jth converter, V^*_{dc} is the reference bus voltage, R_{D} is the fixed virtual resistance, i_{oj} is the output current of the jth converter, and v_{oj} is the actual load voltage of the jth converter.

This method is not much effective because of poor current sharing and voltage regulation and also suffers from the secondary controller. To overcome this problem, the distributed secondary controller is introduced. Distributed control technique provides a local secondary controller for each converter. The secondary controller gathers information of average of per unit output current of all converters (i^{avg}_{oj}) and multiplies it by respective rated output current (i^{rated}_j) and shift gain (K_j) to generate the voltage correction term (δv_{oj}) for the jth converter [4]. The product of droop resistance (R_{D}) and output current (i_{oj}) is subtracted from reference bus voltage (V^*_{dc}) and the result is added to the voltage correction term to provide set voltage ($v^*_{\text{ref}j}$) for the primary controller:

$$v^*_{\text{ref}j} = V^*_{\text{dc}} - R_{\text{D}} i_{oj} + \Delta v_{oj} \quad (3)$$

$$\Delta v_{oj} = K_j i^{\text{rated}}_j i^{\text{avg}}_{oj} \quad (3.1)$$

$$i^{\text{avg}}_{oj} = \frac{\sum_{m=1}^{n} i^{\text{pu}}_m}{n} \quad (3.2)$$

where n is the number of connected converters.

Digital average sharing control uses Δv_{oj} such that it compensates the droop resistance drop and keeps the set voltage of the inner controller equal to the reference bus voltage. To improve current sharing accuracy and voltage regulation, two voltage correction terms are added to the reference bus voltage [5], which is shown in Fig. 2*b*. The voltage correction term δv_1 obtained from the PI controller after processing of error between average output voltage (of all the converters) and bus reference voltage (V^*_{dc}). Similarly, the voltage correction term δv_2 is obtained from the PI controller after processing the error between the respective output current of converter and average output current of all the converters. The product of fixed virtual resistance (R_{D}) and output current (i_{oj}) is subtracted from the result obtained after the addition of voltage correction terms (δv_1 and δv_2) and bus reference voltage (V^*_{dc}). The result is the reference voltage ($v^*_{\text{ref}j}$) of inner primary control for the jth converter:

$$v^*_{\text{ref}j} = V^*_{\text{dc}} - R_{\text{D}} i_{oj} + \delta v_1 + \delta v_2 \quad (4)$$

$$\delta v_1 = \left(K^v_{\text{p}} + \frac{K^v_{\text{i}}}{s}\right)(V^*_{\text{dc}} - \overline{v_{\text{dc}}}) \quad (4.1)$$

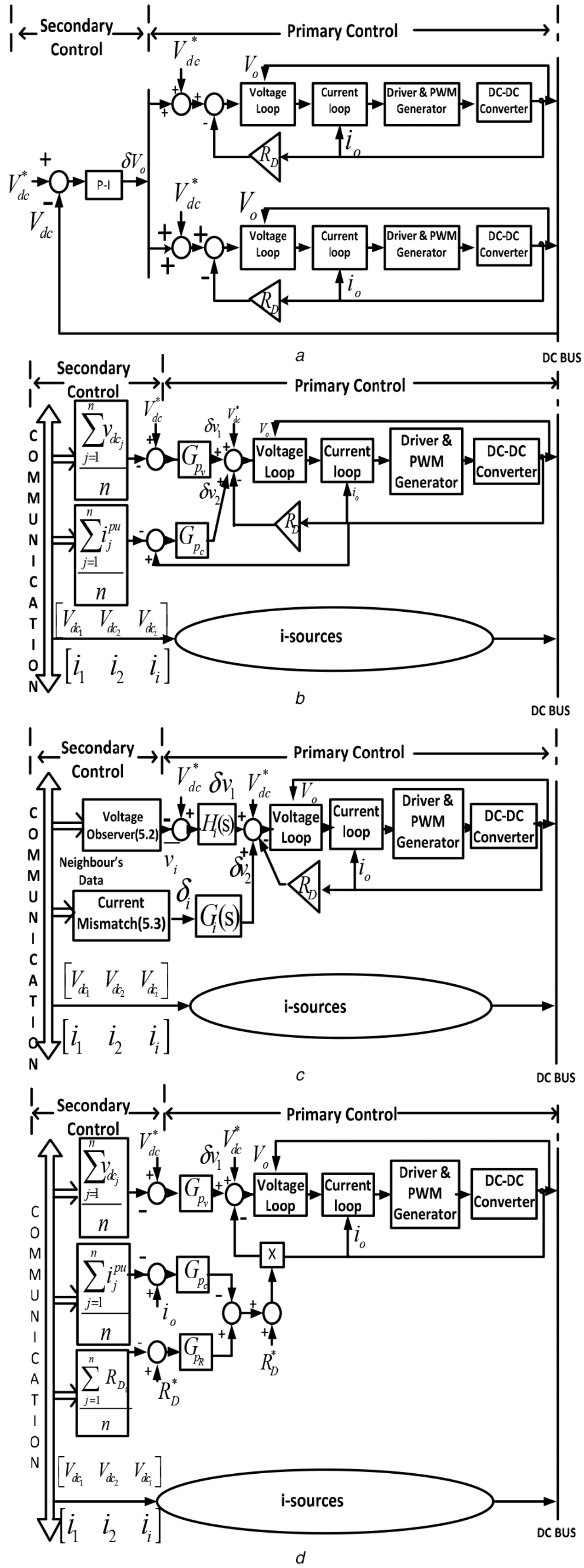

Fig. 2 *Existing secondary droop controller*
(a) Proposed in [3],
(b) Proposed in [5],
(c) Proposed in [6],
(d) Proposed in [7]

$$\delta v_2 = \left(K^i_{\text{p}} + \frac{K^i_{\text{i}}}{s}\right)(i_{\text{dc}} - \overline{i_{\text{dc}}}) \quad (4.2)$$

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where $\overline{v_{dc}}$ and $\overline{i_{dc}}$ are the average output voltage and current of the jth converter, K_p^v, K_i^v and K_p^v, K_i^i are the proportional and integral constants of voltage and current controller, respectively.

Instead of using the information of all converters, the secondary controller uses neighbours' information for generating voltage correction terms [6], which is shown in Fig. 2*c*. It consists of voltage and current regulators to generate two voltage correction terms (δv_1 and δv_2) to minimise the voltage regulation and provide equal current sharing, respectively. The voltage regulator estimates the average voltage for the jth converter by processing neighbours' estimate. Then, it compares with reference bus voltage and passes through a voltage controller to obtain the first voltage correction term (δv_1). The current regulator passes current mismatch (δ_j) through the current controller to obtain the second voltage correction (δv_2). The product of droop resistance (R_D) and output current (i_{oj}) is subtracted from reference bus voltage (V_{dc}^*) and the final result is added to both voltage correction terms to set reference voltage (v_{refj}^*) for inner primary control of the jth converter:

$$v_{refj}^* = V_{dc}^* - R_D i_{oj} + \delta v_1 + \delta v_2 \tag{5}$$

$$\delta v_1 = \left(K_p^v + \frac{K_i^v}{s}\right)(V_{dc}^* - \overline{v_j}) \tag{5.1}$$

Estimation of the jth converter's average output voltage by updating its previous value with neighbours' estimate ($\overline{v_i}$):

$$\overline{v_j} = v_j(t) + \int_0^t \sum_{j\epsilon N_i} a_{ij}(\overline{v_j} - \overline{v_i}) \tag{5.2}$$

The current mismatch output for the jth converter is

$$\delta_j = \sum_{j\epsilon N_i} a_{ij}(i_j^{pu} - i_i^{pu}) \tag{5.3}$$

where a_{ij} is the shift gain.

The same technique is used to make the virtual droop resistance adaptive, which varies with the current mismatch [6]. The output of current regulator [which is now denoted by $\delta r_j(t)$] is subtracted from fixed droop resistance (R_D) and multiplied by local output current (i_{oj}). The result is subtracted from the sum of the bus reference voltage (V_{dc}^*) and voltage correction term (δv_1) obtained from the voltage regulator to set reference voltage (v_{refj}^*) of inner primary control for the jth converter like previous method [6]:

$$v_{refj}^* = V_{dc}^* - r_{dj} i_{oj} + \delta v_1 + \delta v_2 \tag{6}$$

The value of adaptive droop resistance (r_{dj}) for the jth converter is

$$r_{dj} = R_D - \delta r_j(t) \tag{6.1}$$

To get rid of complex calculation for finding the average output voltage, the secondary controller is designed on the adaptive droop technique [7] as shown in Fig. 2*d*. This secondary droop technique generates three correction terms after comparing the average of output voltage, current and droops from corresponding output voltage, current and droop constant, respectively, and then processing it through the respective controller. The reference voltage of the primary controller for the jth converter is

$$v_{refj}^* = V_{dc}^* - r_{dj} i_{oj} + \delta v_1 \tag{7}$$

$$\delta v_1 = \left(K_p^v + \frac{K_i^v}{s}\right)(V_{dc}^* - \overline{v_0}) \tag{7.1}$$

The value of adaptive droop resistance (r_{dj}) for jth converter is

$$r_{dj} = R_D - \delta r_j(t) + \delta R_j \tag{7.2}$$

where $\delta r_j(t)$ and δR_j are the outputs of the current controller and droop controller after processing corresponding errors.

Adaptive droop resistance minimises the effect of unequal line resistance drop on current sharing. It varies when a current mismatch occurs. In the next section, the proposed variable droop resistance control has two degrees of freedom. Droop resistance varies with change in the output current of each converter from average current and change in the average output voltage from dc reference bus voltage. The output of the secondary voltage controller performs dual functions: shifting the characteristics of output voltage–current in voltage upward direction and changing its slope.

3 Analysis of current sharing and voltage regulation

As discussed in Section 2, the droop control technique is for enhancing the current sharing accuracy and reducing the voltage regulation across each load connected to the converter. Consider two dc voltage sources connected to the different loads in series with droop resistance. The loads have been connected in parallel as shown in Fig. 3.

The voltage–current characteristics of the equivalent circuit (shown in Fig. 4) show that when the droop resistance values are small, the voltage regulation across each load is less and the current error ($i_2 - i_1$) is more. However, when the droop resistance value is more, the voltage regulation across each load is more and the current error is less. Hence, it is found that a moderate value of droop resistance keeps both voltage regulation and output current error in the limit. Droop resistance is chosen such that there is a trade-off between voltage regulation and current sharing. However, conventional droop control technique is not able to enhance current sharing accuracy and reduce voltage regulation within an acceptable limit.

Adaptive droop control is employed here to enhance current sharing accuracy. This controller varies the value of droop resistance when there is an error between output current of each

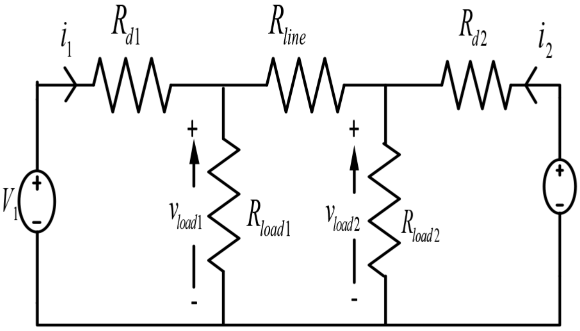

Fig. 3 *Simple dc microgrid equivalent circuit*

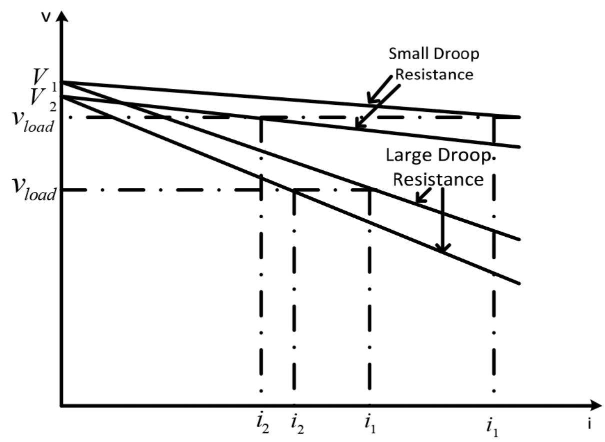

Fig. 4 *Voltage–current characteristics of equivalent circuit*

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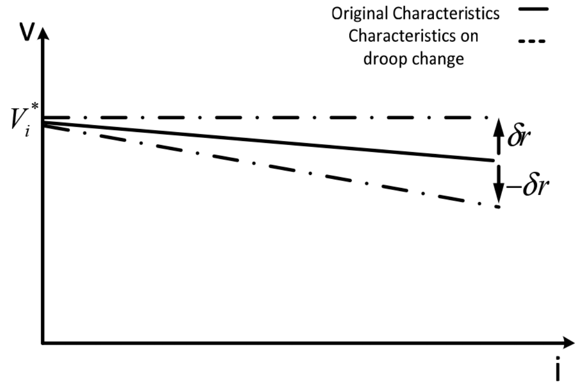

Fig. 5 *Voltage–current characteristics on change in droop resistance*

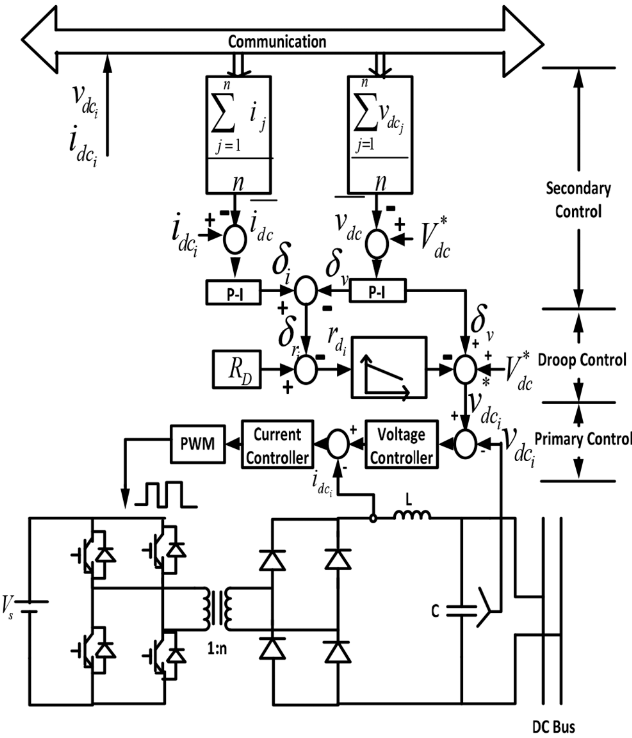

Fig. 6 *Proposed distributed secondary control*

converter or/and between average output voltage from reference bus voltage as discussed later in the proposed control circuit.

Consider only one end of the equivalent circuit as shown in Fig. 3. The droop resistance connected in series with supply is varying from its fixed value R_d. The voltage equation of the ith end is as follows:

$$V_i = v_{\text{load}_i} - r_{d_i} i_i \tag{8}$$

$$r_{d_i} = R_{d_i} - \delta r \tag{8.1}$$

where $i = 1$ and 2, R_{d_i} is the fixed droop resistance and δr is the change in droop resistance.

If the change in droop resistance (δr) is positive, slope increases and vice versa (as shown in Fig. 5). Now, the problem of current sharing and voltage regulation is automatically addressed due to change in droop (δr).

4 Proposed distributed secondary controller

As discussed in Section 3, the droop resistance plays an important role in improving the current sharing accuracy and voltage regulation across each load connected to the converter. However, the conventional droop control method that introduces a fixed droop resistance in series with supply is not so effective. The adaptive droop control is employed to vary the droop values according to the change in output current from the average output current or/and change in average output voltage from reference dc voltage (as shown in Fig. 6).

The reference voltage for primary control is

$$v^*_{\text{dc}_i} = V^*_{\text{dc}} - r_{d_i} i_{\text{dc}_i} + \left(K_{\text{p}}^v + \frac{K_{\text{i}}^v}{s}\right)(V^*_{\text{dc}} - \overline{v_{\text{dc}}}) \tag{9}$$

$$r_{d_i} = R_{\text{D}} - \delta r_i \tag{9.1}$$

$$\delta_{r_i} = \left(K_{\text{p}}^i + \frac{K_{\text{i}}^i}{s}\right)(i_{\text{dc}_i} - \overline{i_{\text{dc}}}) - \left(K_{\text{p}}^v + \frac{K_{\text{i}}^v}{s}\right)(V^*_{\text{dc}} - \overline{v_{\text{dc}}}) \tag{9.2}$$

where i denotes the parameter values of the ith converter, $v^*_{\text{dc}_i}$ is the reference primary voltage, V^*_{dc} is the reference dc bus voltage, r_{d_i} is the variable droop resistance, i_{dc_i} is the output current, $\overline{i_{\text{dc}}}$ is the average dc output current, $\overline{v_{\text{dc}}}$ is the average dc output voltage, K_{p}^i and K_{p}^v are the proportional constants of current and voltage secondary controller, respectively, and K_{i}^i and K_{i}^v are the integral constants of current and voltage secondary controller, respectively.

From (9), it is found that the reference voltage of primary control is obtained by subtracting the product of variable droop resistance and output current from reference dc bus voltage and finally added to a voltage shifting term that shifts the output voltage of the converter to the desired value. Variable droop resistance (r_{d_i}) is the difference of change in droop resistance (δr_i) from fixed droop resistance (R_{D}). Change in droop resistance (δr_i) is the difference of two terms those obtained from the output of secondary current and voltage controller.

From the above equations, it is noted that the output of the secondary voltage controller performs the following tasks:

(i) It works as a voltage shifting term that shifts the output voltage to the desired value.
(ii) It also adds to the variable droop resistance that will vary if average output voltage deviates from reference dc voltage (Fig. 7).

Similarly, the variable droop resistance (r_{d_i}) has two degrees of freedoms. It varies with the following:

(i) Change in output current from average output current.
(ii) Change in average output voltage from reference dc bus voltage.

The primary controller of the converter takes the new reference voltage ($v^*_{\text{dc}_i}$) obtained after processing through the secondary controller and droop controller. It consists of inner voltage and current controller to produce pulse width modulated (PWM) pulses to the converter. The converter used in this control is a full-bridge isolated dc–dc converter with phase-shifted PWM.

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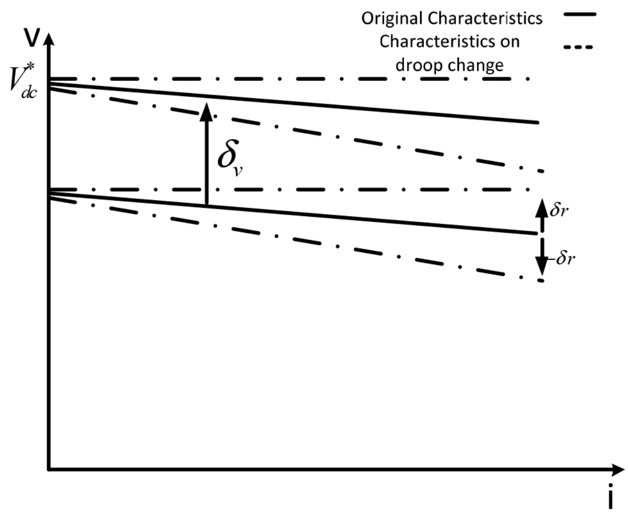

Fig. 7 *Voltage–current characteristics of proposed converter*

The proposed controller has the following advantages over existing controllers as described in Section 2:

(i) The voltage controller used in secondary control not only compensates the voltage drop due to droop resistance but it also varies the droop resistance.
(ii) The droop resistance varies with inequality in current sharing among converters and deviation of the average voltage of the system from dc bus reference voltage ($V_{\rm dc}^{*}$).
(iii) The controller can be used for both isolated and non-isolated dc–dc converters.
(iv) It does not involve complex calculation for finding average voltage and current mismatch of the system as in [6].
(v) If one of the converter stops working, the controller still works for remaining converters and hence improves the system reliability. This feature is demonstrated in the next section (Fig. 8).

5 Description of controllers used

There are mainly three controllers used in the proposed scheme:

(i) Secondary controller
(ii) Droop controller
(iii) Primary controller

5.1 Secondary controller

It consists of a voltage and a current controller, which matches the average dc output voltage to dc bus reference voltage and the average dc output current with the instantaneous current of the corresponding converter, respectively.

Output of voltage controller:

$$\delta_v = K_{\rm p}^{v}(V_{\rm dc}^{*} - \overline{v_{\rm dc}}) + K_{\rm i}^{v}\int(V_{\rm dc}^{*} - \overline{v_{\rm dc}}){\rm d}t \quad (10.1)$$

Output of current controller:

$$\delta_i = K_{\rm p}^{i}(i_{{\rm dc}_i} - \overline{i_{\rm dc}}) + K_{\rm i}^{i}\int\left(i_{{\rm dc}_i} - \overline{i_{\rm dc}}\right){\rm d}t \quad (10.2)$$

5.2 Droop controller

It takes the output of the secondary controller to compute a variable droop resistance to replace the fixed droop resistance. The variable droop resistance is adapted according to inequality in current sharing and voltage regulation across the load. The variable droop resistance is multiplied with respective converter current and subtracted from the sum of dc reference voltage and output of secondary voltage controller.

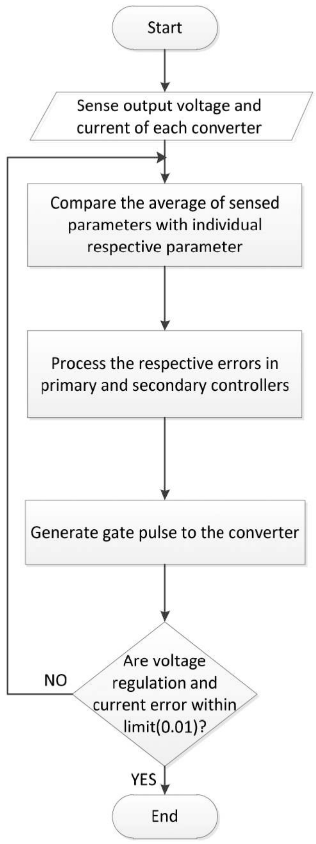

Fig. 8 *Flowchart to describe the working of controller*

5.2.1 Variable droop resistance:

$$r_{d_i} = R_{\rm D} - [K_{\rm p}^{i}(i_{{\rm dc}_i} - \overline{i_{\rm dc}}) + K_{\rm i}^{i}\int\left(i_{{\rm dc}_i} - \overline{i_{\rm dc}}\right){\rm d}t] + [K_{\rm p}^{v}(V_{\rm dc}^{*} - \overline{v_{\rm dc}}) + K_{\rm i}^{v}\int(V_{\rm dc}^{*} - \overline{v_{\rm dc}}){\rm d}t] \quad (10.3)$$

New reference voltage for the primary controller

$$v_{{\rm dc}_i}^{*} = V_{\rm dc}^{*} - r_{d_i} i_{{\rm dc}_i} + K_{\rm p}^{v}(V_{\rm dc}^{*} - \overline{v_{\rm dc}}) + K_{\rm i}^{v}\int(V_{\rm dc}^{*} - \overline{v_{\rm dc}}){\rm d}t \quad (10.4)$$

where i denotes the parameter values for the ith converter, $v_{{\rm dc}_i}^{*}$ is the reference primary voltage, $V_{\rm dc}^{*}$ is the reference dc bus voltage, r_{d_i} is the variable droop resistance, $i_{{\rm dc}_i}$ is the output current, $\overline{i_{\rm dc}}$ is the average dc output current, $\overline{v_{\rm dc}}$ is the average dc output voltage, $K_{\rm p}^{i}$ and $K_{\rm p}^{v}$ are the proportional constants of current and voltage

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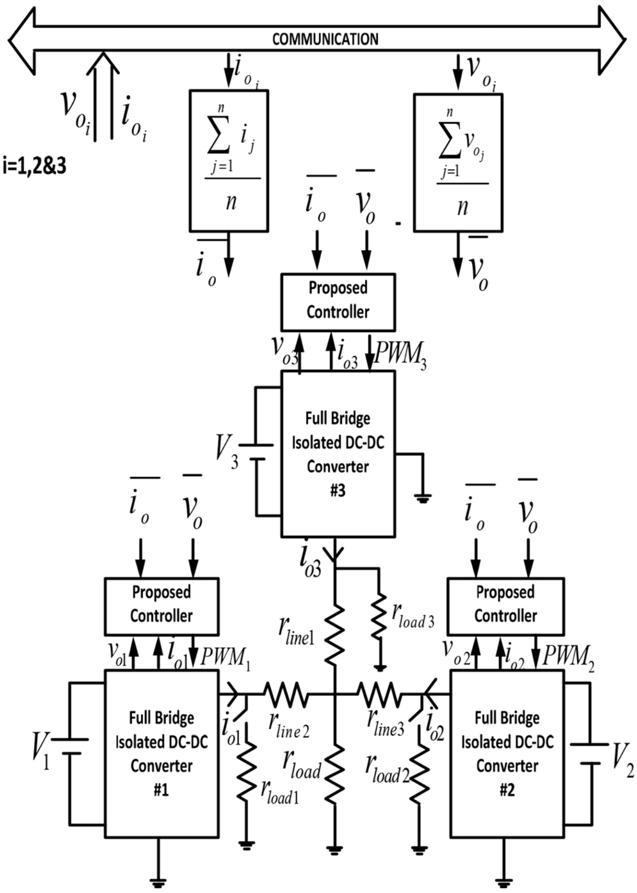

Fig. 9 *Prototype of proposed dc microgrid*

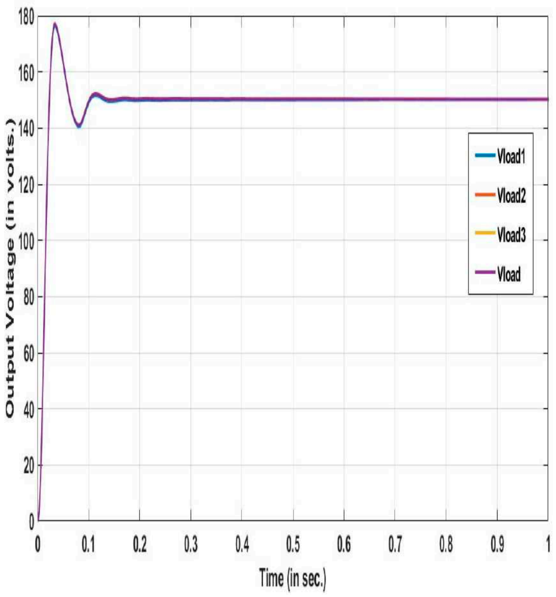

Fig. 10 *Output voltage across each load when only primary controller is active*

secondary controller, respectively, and K_i^i and K_i^v are the integral constants of current and voltage secondary controller, respectively.

5.3 Primary controller

It is a conventional controller used in a dc–dc converter for closed-loop control. It consists of a voltage and current controller which keeps the output load voltage at its new reference value as derived from the droop controller, while keeping the output current in the specified limit.

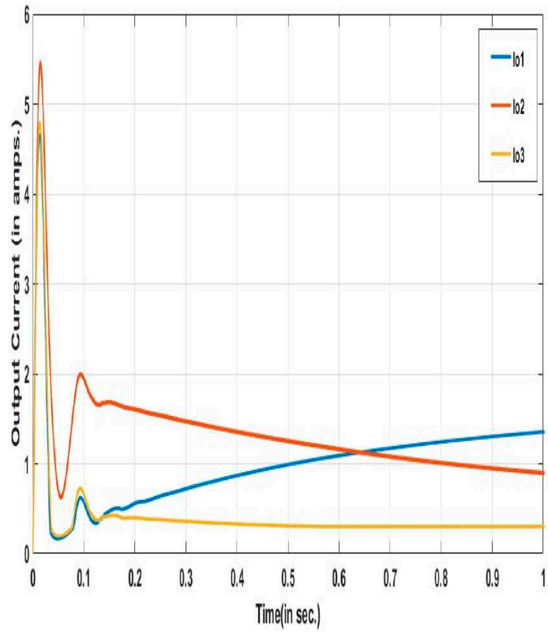

Fig. 11 *Output current of each converter when only primary controller is active*

6 Simulation and result

The proposed converter has been simulated in MATLAB/Simulink R2016a environment. There are three full-bridge isolated dc–dc converters connected to the dc bus, which has a common dc central load as well as local loads connected to the individual converter (as shown in Fig. 9). In this topology, the proposed controller, as described in Section 4, is used individually to run each converter connected to the bus. It takes the average values of output current and output voltage, processes in the controller to generate gate pulses to each isolated converter. The adaptive droop controller used in the proposed controller varies the value of droop resistance according to the errors of average output current from actual output current and average output voltage from reference bus voltage. The voltage drop due to the droop resistance is compensated by adding a voltage shifting term that is obtained by processing the error of average output voltage and reference bus voltage through proper PI controller. The secondary voltage controller performs dual works from shifting the output voltage to changing the slope of the output voltage–current characteristics. The droop resistance variation is analysed based on the degree of freedom, namely output of secondary current and voltage controllers. In this section, the importance of the proposed controller is also described i.e. when the secondary controller is not in working condition and the only primary controller is active. Then, current from each converter is different for different loads that lead to the circulating current among loads connected to the dc bus.

The study has been divided into the following cases:

Case I. When the only primary controller is active: In this case, the secondary controller and droop controller are removed and the only primary controller is active for a given reference bus voltage. It is observed that the output voltage across each load is the same but the output current at each load is different i.e. current sharing cannot be processed through the primary controller. Results of this case are shown in Figs. 10 and 11.

Case II. When the proposed controller is active: In this case, there are two possibilities when the droop resistance control is varied either due to current error or due to both current and voltage errors in the secondary controller.

Case IIA. Droop resistance is varied due to the current error only: Here, droop resistance is varied with a change in the output current of the converter from average output current. The secondary controller sets the reference bus voltage for the primary controller. Then, it is found that voltage across each load converges to reference bus voltage with reduced overshoot as compare to

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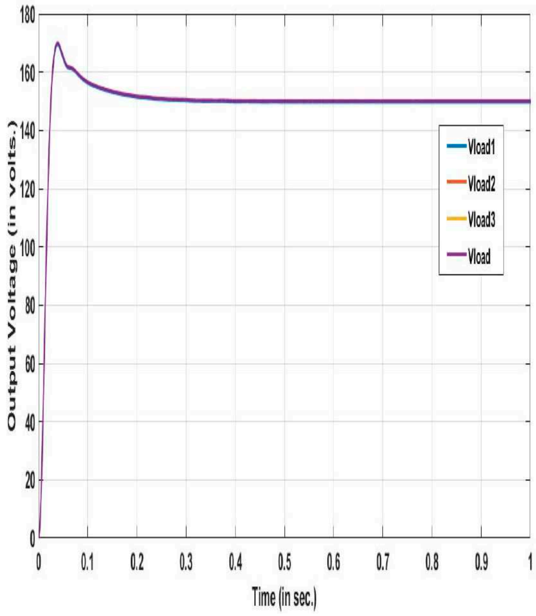

Fig. 12 *Output voltage across each load when proposed controller is active as per Case IIA*

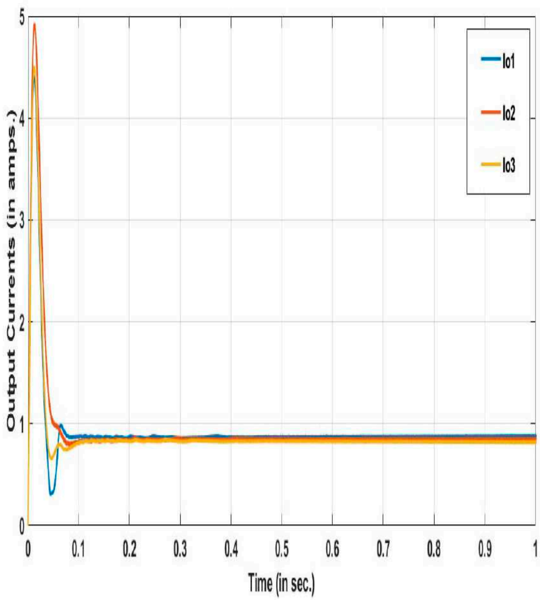

Fig. 13 *Output current of each converter when proposed controller is active as per Case IIA*

Case I and output current of each converter becomes equal i.e. current sharing accuracy is improved as shown in Figs. 12 and 13.

Case IIB. Droop resistance is varied due to both current and voltage errors in the secondary controller: In this case, droop resistance is varied with both changes in the output current of the converter from average output current and average output voltage from reference bus voltage. It is observed that voltage across each load converges to reference bus voltage with much lower overshoot as compared to last two cases and output current of each converter becomes equal with less overshoot as compare to the last method as shown in Figs. 14 and 15.

Case III. When one of the converter stops working: The first converter is stopped at $t = 0.3$ s, the current provided by that converter becomes zero but the local load connected to that converter is still supplied by the rest of the converters. The voltage regulation across each load and current sharing inequality for remaining converters is still almost zero as shown in Figs. 16 and 17, respectively.

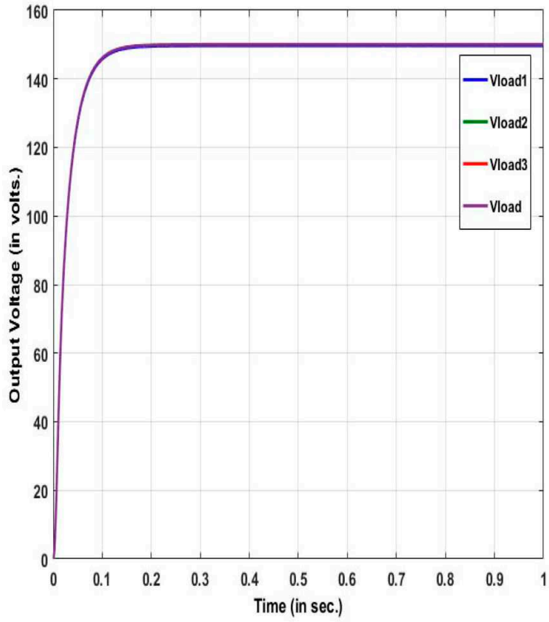

Fig. 14 *Output voltage across each load when proposed controller is active as per Case IIB*

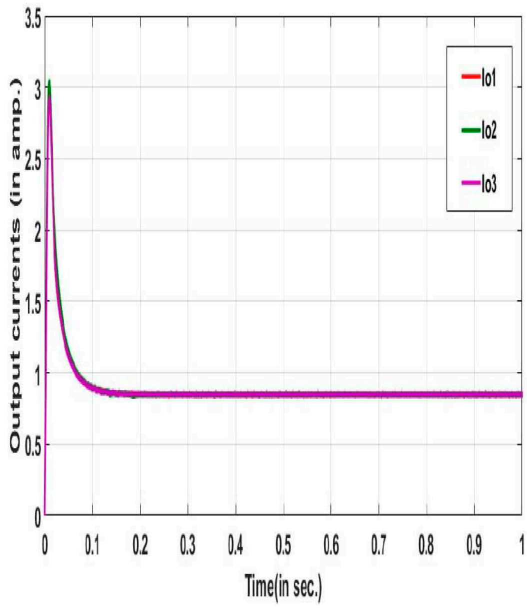

Fig. 15 *Output current of each converter when proposed controller is active as per Case IIB*

This shows the enhanced reliability of the system. The system is providing energy to the load but at a reduced voltage of 120 V and enhanced current than earlier cases.

7 Conclusion

The paper proposes an adaptive distributed secondary droop controller, which varies the slope of output voltage–current characteristics and shifts the output voltage across each load to a reference bus voltage. The available method in the literature consists of only one degree of freedom for variation of droop resistance, namely, the output of the secondary current controller. Moreover, controller behaviour is tested on non-isolated dc–dc converters. However, the controller proposed in this paper has two degrees of freedom for control of droop resistance, namely, output of both secondary voltage and current controller. Full-bridge isolated dc–dc converters are used to validate the controller behaviour. The simulation results show that when the only primary controller is active, converter currents are not equally leading to uneven current sharing. However, when the secondary controller

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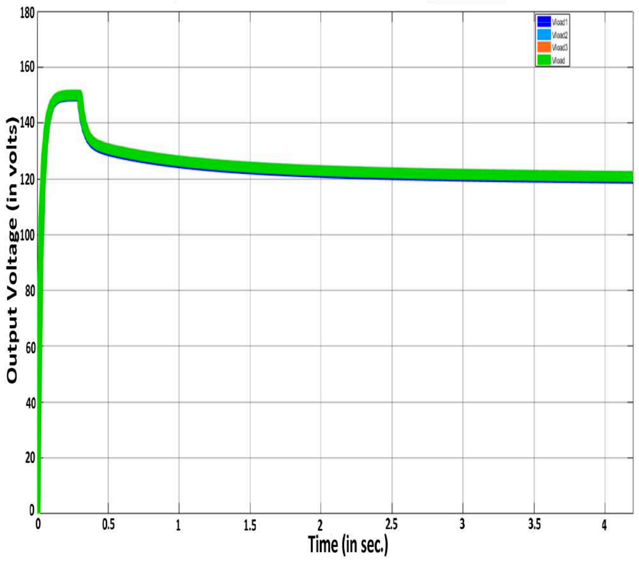

Fig. 16 *Output voltage across each load when converter #1 is stopped working at t = 0.3 s*

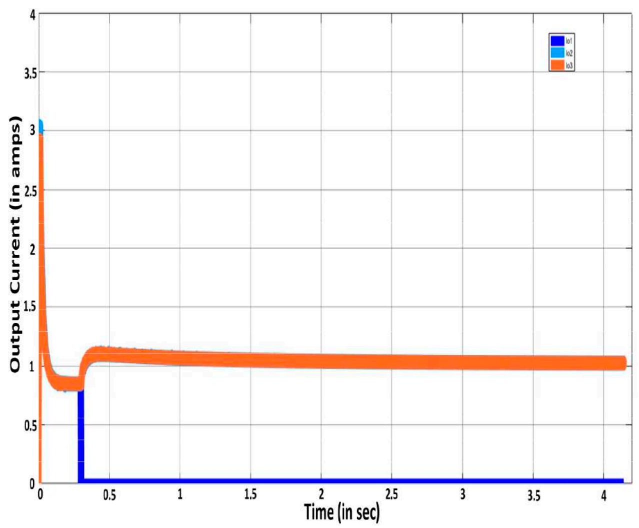

Fig. 17 *Output current of each converter when converter #1 is stopped working at t = 0.3 s*

with one degree of freedom is active, current sharing is achieved with overshoot. The voltage across each load also becomes equal to reference bus voltage with reduced overshoot. Finally, when the secondary controller with two degrees of freedom for droop resistance is active, current sharing is achieved with much lower overshoot and voltage regulation across each load is improved. Hence, it is concluded that the proposed controller is able to improve current sharing and reduce voltage regulation across the load. It can be used in both isolated and non-isolated dc–dc converters.

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