Decentralized Control Method for Load Sharing and Circulating Current Minimization in Stand-alone DC Microgrid

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ABSTRACT: The increasing trends of the usage of renewable sources faces challenges in the reliable operation and control. The main issues related with parallel connected dc-dc converters in DC microgrid are load current sharing and circulating current. Droop control method is common technique used for load current sharing and the drawbacks of conventional droop method are poor current sharing and drop in dc grid voltage. This paper describes a figure of merit called Droop Index(DI) which is used to improve the performance of dc microgrid, which is a function of normalized current sharing difference and losses in the output side of the converters. By using an instantaneous virtual resistance R_{droop}, minimizes the circulating current and current sharing difference between the converters. The MATLAB/Simulink model of control strategy using droop index is developed and compare with conventional droop control method and validate its theoretical results.

KEYWORDS: Parallel Converters, Load Sharing, Circulating Current, Droop Index, Droop Method.

I.INTRODUCTION

Renewable energy sources play an important role in present electricity generation. The term renewable energy is derived from a broad spectrum of resources, i.e. it is based on self-renewing energy resources such as sunlight, biomass, wind, owing water etc. Because of these abundant self-renewing resources the concept of microgrid has been introduced. The microgrid concept has been developed because of sustainable energy generation and proper utilization of energy resources. The electrification of remote areas can be easily achieved through microgrid and now days the researches on microgrid increases. The benefits of renewable energy system are more attractive than they ever had before. Specially, energy from the sun is the best option for electricity generation as it is available everywhere and is free to harness. The merits of solar PV system are cleanness, relative lack of noise or movement, as well as their ease of installation and integration when compared to others. In 2000, about 288 MW are generated using photovoltaic system which includes 75 MW produced in United States. Electricity from the sun can be generated through the Solar Photovoltaic Modules (SPV). The SPV comes in various power output to meet the load [1]. However, the output power of a PV panel is largely determined by the solar irradiation and the temperature of the panel. At a certain weather condition, the output power of a PV panel depends on the terminal voltage of the system. To maximize the power output of the PV system, a high efficiency, low-cost DC/DC converter with a voltage and current feedback signal is employed to control the output voltage of the PV system at optimal values in various solar radiation conditions.The microgrid integrates energy sources, including renewable sources, storage systems, controllable and uncontrollable loads. Energy sources and storage equipment are connected directly or through power electronic converters. The microgrid can operate autonomously, but usually it operates in connection with the supplying grid. With the objective to electrify remote areas and energy islands, the microgrid concept is gaining more and more popularity. Nowadays, dc microgrids are becoming more attractive with the raise of dc power sources, storages, and the loads with natural dc coupling, e.g., photovoltaic modules, batteries, fuel cells, light-emitting diodes, and so on. With the comparison of the overall efficiency, it can be found that the efficiency of dc system is higher than the ac system. At the same time, dc does not require synchronization, and the problems caused by the reactive power and harmonics disappear. For these reasons, recently, there has been an increasing awareness on dc microgrids. The advantages of parallel connected converters are reliability, ease of maintenance, expandability of output power, efficiency etc.

II. RELATED WORK

The different load sharing methods have been discussed in the literature [2]-[7] where the most popular schemes are active current sharing and droop control methods. The hierarchical control, as in AC MGs, applies for DC MGs too and can be divided in three levels: Primary control: This control deals with the load sharing among the DGs. The DC-DC power converters of the DGs are responsible for this mechanism. Secondary control: This control is responsible for voltage fluctuations regulation. It is also responsible for the synchronization process to re-connect seamlessly the microgrid to the upper grid. Tertiary control: It sets the power flow between the DC MG and the upper grid. It is also known as energy management system and it communicates with the distribution system operator.The primary control is divided into two, Passive load sharing methods and Activeload sharing methods. The passive load sharing methods are mainly decentralized control methods which control decision making is carried out locally with the partial information in the scope of the individual components independently with minimum requirement of communication. Droop control method is come under this category. The active load sharing methods are mainly centralized control method which relies on a central controller which carries out the regulation functionalities through real-time feedback signals from the controlled terminals through communication. Failure in communication links can degrade the system reliability.The active load sharing methods are mainly divided into centralized control, master slave control, average load sharing and circular chain control. In this paper, describes the parallel operation of two boost converters with designed closed loop controller and to maintain the stability of the system by load sharing. If the output voltages of two converters connected in parallel are different circulating current is obtained and our aim is to minimize the circulating current and current sharing difference between the converters. The effective load sharing among converters is also achieved,i.e., load is equally shared or depending upon DGs ratings or costs.

III. ADAPTIVE DROOP CONTROL METHOD

In this method, the virtual resistance is calculated instantaneously using droop index calculation. First step is that a closed loop controlled boost converter is designed, i.e., the output voltage of the boost converter is maintained constant irrespective of load variations. For this a closed loop controller is designed with an inner current loop and outer voltage loop. State space average modelling technique is used for the closed loop PI controller design. After that, two converters are connected in parallel and the circulating current generated is minimized using the instantaneously calculated virtual resistance and the load is shared equally or depending upon converter ratings or cost.

A) STATE SPACE AVERAGE MODELING AND CLOSED LOOP CONTROL OF BOOST CONVERTER

A DC - DC boost converter consists of an inductor, diode, MOSFET used as a switch, output filter capacitor and resistive load. When the switch is closed and supply voltage is given, inductor current increases. When the switch is opened, both inductor and supply voltage gets discharged through the load. Hence a higher voltage at the output is obtained than the given input voltage. Assumptions made are the components are ideal and lossless and converter is in continuous conduction mode. Fig.1 shows the boost converter.
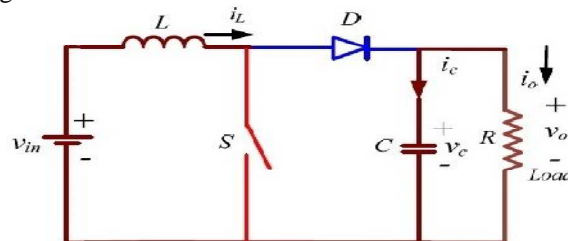

Fig. 1 Boost Converter

When the main switch is ON,

$$L\frac{di_L}{dt} = v_{in}$$

$$\tag{1}$$

$$C\frac{dv_o}{dt} = -\frac{v_o}{R}$$

When the switch is OFF,

$$L\frac{di_L}{dt} = v_{in} - v_o$$

$$C\frac{dv_o}{dt} = i_L - \frac{v_o}{R} \tag{2}$$

Averaging the state equations over a switching cycle and introduce perturbation in state variables and take Laplace transforms, the control equations are obtained as,

Control to output transfer function

$$\frac{\hat{v}_o(s)}{\hat{d}(s)} = \frac{(1-D)V_o - (LI_L)s}{(LC)s^2 + \frac{L}{R}s + (1-D)^2} \tag{3}$$

Control to input current transfer function

$$\frac{\hat{i}_L(s)}{\hat{d}(s)} = \frac{(CV_o)s + 2(1-D)I_L}{(LC)s^2 + \frac{L}{R}s + (1-D)^2} \tag{4}$$

Current to output transfer function

$$\frac{\hat{v}_o(s)}{\hat{i}_L(s)} = \frac{(1-D)V_o - (LI_L)s}{(CV_o)s + 2(1-D)I_L} \tag{5}$$

Two control loops an inner current control loop (fast loop) and outer voltage control loop (slow loop) are used to regulate the output voltage. Setting the outer voltage loop bandwidth (BW) lower than the inner current loop makes the design of controller easier. The average input current should be controlled to be dc, which requires that bandwidths of voltage and current loops are separated with a slow voltage loop and a fast current loop. Fig.2 shows closed loop controlled boost converter with two controllers.
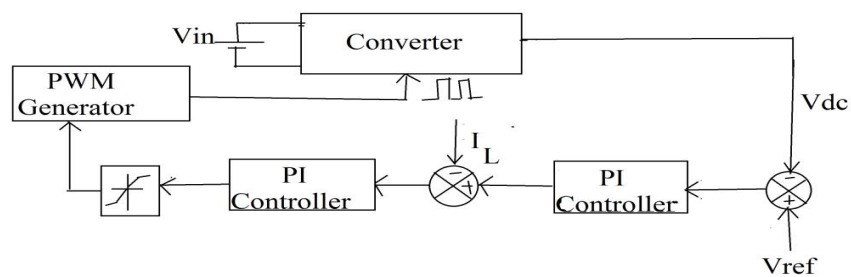

Fig.2 Closed Loop Controlled Boost Converter

B) CONTROL METHOD

When converters are connected in parallel and if there is change in output power or load, this will cause mismatch in converter output voltage which will cause circulating current flows between the converters. Fig.3. shows the steady state equivalent circuit for the dc output side of two parallel connected dc-dc converters. In this figure, V_{DC1}, V_{DC2}, I_1, I_2, and R_1, R_2 represent output voltages, output currents, and cable resistances of converter-1 (Conv-1) and converter-2 (Conv-2), respectively. The output side of the converter can be represented as a voltage source in series with the cable resistance. If $_{VDC1}$> V_{DC2}, I_{C12} is the circulating current component from Conv-1 to Conv-2 and I_1' the load component from Conv-1.
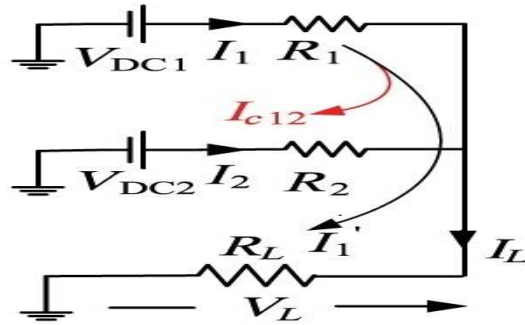
Fig.3 Steady-state equivalent side of dc output side[1].

By applying Kirchoff's voltage law,

$$V_{DC1} - I_1 R_1 - I_L R_L = 0 \quad (6)$$

$$V_{DC2} - I_2 R_2 - I_L R_L = 0 \quad (7)$$

The circulating current can be expressed as,

$$I_{c12} = -I_{c21} = \frac{V_{DC1} - V_{DC2}}{R_1 + R_2} \quad (8)$$

If $R_1 = R_2$, $I_{c12} = \frac{I_1 - I_2}{2}$

The virtual impedance method is used to implement R_{droop} and the control diagram of parallel converter is shown in Fig.4.This can be achieved by taking output currents feedback from Conv-1 and Conv-j, and multiplied with calculated R_{droop1} and R_{droopj}, respectively. In parallel-connected system, the circulating current becomes zero if the current sharing is proper. Simultaneously, insertion of the series resistor will cause the drop in the converter output voltage. Therefore, the proposed DI is taken as function of normalized current sharing difference and output power loss. The normalized power loss indirectly indicates the drop in the reference voltage. Calculation of minimum droop index is done by varying Rdroop and its maximum value will depend on the voltage regulation.

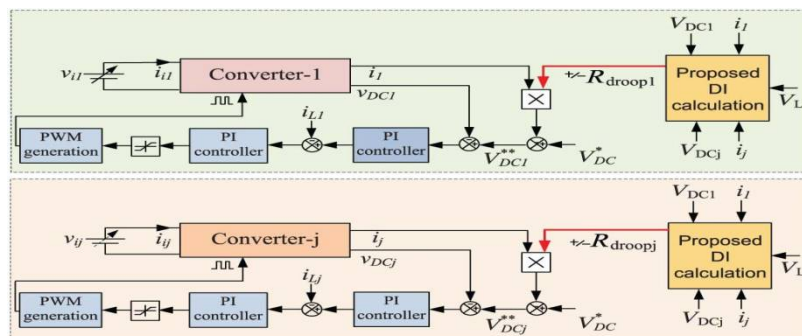$$DI = \min \frac{1}{2}[|I_1 - I_2| + P_{loss}] \qquad (9)$$

Fig.4 Control diagram of parallel converters with R_{droop} calculation[1].

IV.SIMULATION RESULTS

MATLAB/Simulink model of two parallel dc-dc boost converters with closed loop current and voltagecontrol are simulated. The output voltage should be maintained constantirrespective of load variations. The nominal parameters of boost converter are given in Table I.

TABLE I
NOMINAL PARAMETERS OF BOOST CONVERTER

Parameters	Value
Output Power	30W
Output Voltage	34V
Inductor	481μH
Filter Capacitor	65μF
Switching Frequency	10kHz

A) Without any droop control method

Simulink model of parallel connected boost converters without any droop control is shown in Fig.5. The variation in the converter voltage is analysed, i.e. three cases both the converter output voltages are same,Converter 2 voltage is increased, Converter 2 voltage is decreased are analysed. The cable resistance of both the converters are assumed same.
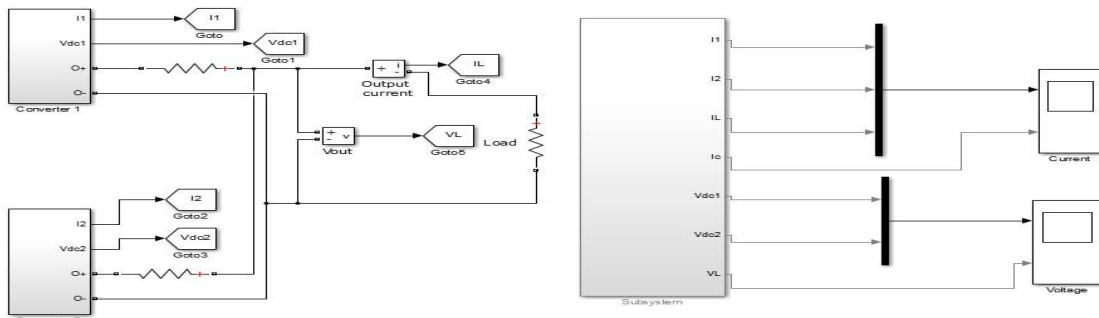

Fig.5 Simulink model of parallel connected converters without any droop control

Fig.6 shows the load, converter currents and circulating current of parallel connected boost converter without any droop control. For the time 0-0.1s the converter 1 and converter 2 current and load current are same and therefore circulating current is zero. For the time 0.1-0.3s converter 1 is more loaded compared to converter 2 and the circulating current obtained is shown in the figure. Then again converter 1 and converter 2 equally loaded and then from 0.5-0.7s converter 2 is more loaded compared to converter 1.
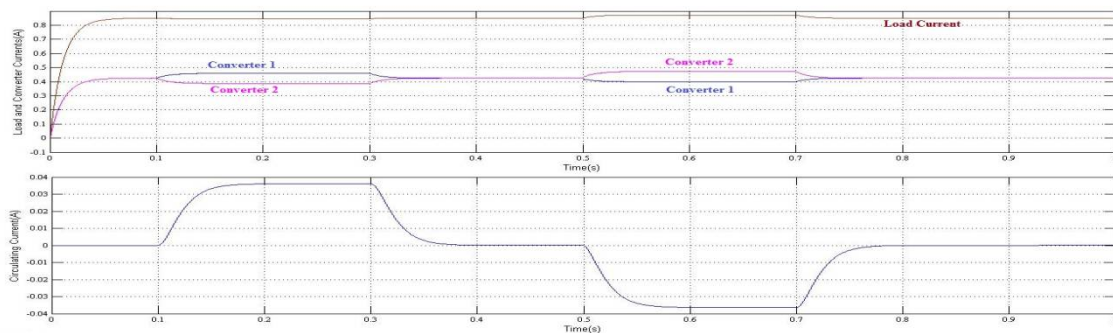

Fig.6 Load, converter currents and circulating current of parallel connected boost converter without any droop control

Fig.7 shows the load and converter voltages of parallel connected boost converter without any droop control. For the time 0-0.1s the converter 1 and converter 2 voltages are same. For the time 0.1-0.3s converter 1 voltage is greater than converter 2. Then again converter 1 and converter 2 output voltages are same for 0.3-0.5s and from 0.5-0.7s converter 2 output voltage is greater than converter 1.
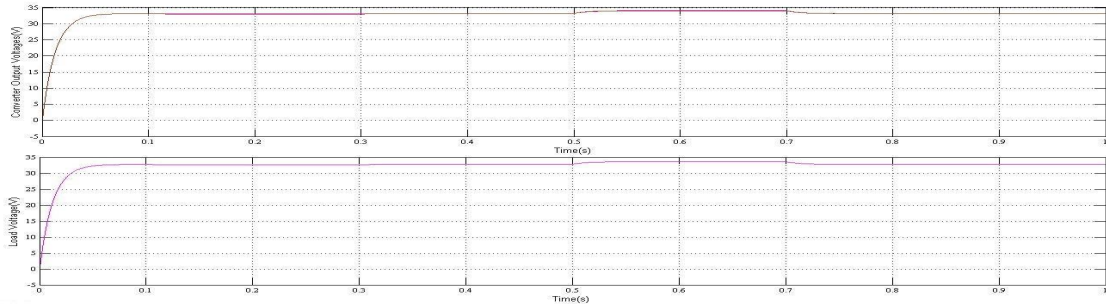

Fig.7 Load and converter voltages of parallel connected boost converter without any droop control

TABLE II
SIMULATION RESULTS WITHOUT ANY DROOP CONTROL

Time(s)	$V_{DC1}, V_{DC2}, V_L(V)$	$I_L, I_1, I_2(A)$	$I_{err}(\%)$	$|I_c|(A)$
0-0.1	33.2,33.2,32.8	0.85,0.425,0.425	0	0
0.1-0.3	33.2,33.1,32.7	0.85,0.462,0.39	7.2	0.036
0.3-0.5	33.2,33.2,32.8	0.85,0.425,0.425	0	0
0.5-0.7	34.1,34.2,33.5	0.872,0.4,0.472	7.2	0.036

B) Conventional droop method

In conventional droop method, a fixed resistance value is used to minimize the circulating current. The output current of each converter is multiplied with a fixed resistance value and the product obtained is compared with the reference voltage. The difference obtained is taken as new reference signal and the output voltage obtained is compared with the new reference signal. The conventional droop method Simulink model of each converter is shown in Fig.8.
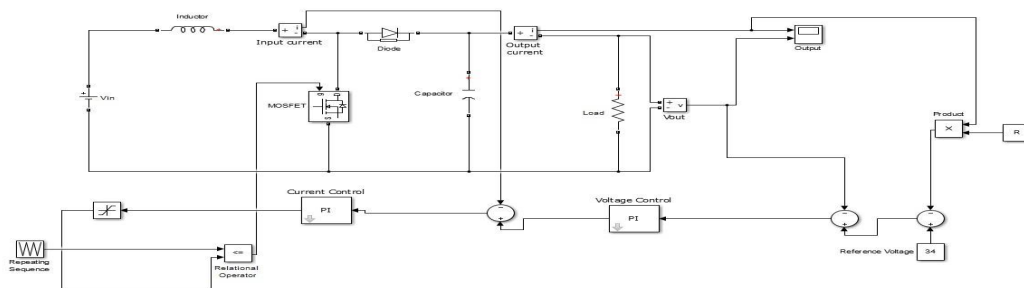

Fig.8 Simulink model of each converter with conventional droop control.

The load, converter currents and circulating current with conventional droop method are shown in Fig.9 and it shows that the circulating current is minimized into some extent. But in some cases, this method doesn't give better results.
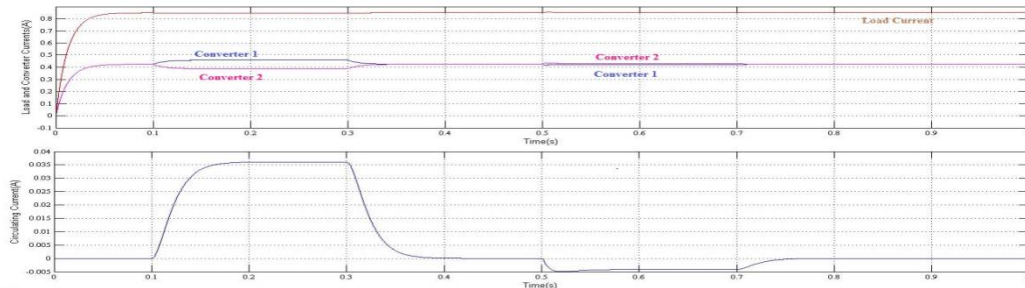
Fig.9 Load, converter currents and circulating current of parallel connected boost converter with conventional droop control

Load and converter voltages are shown in Fig.10 and it is clear that compared to without any droop control method the voltage difference between the time 0.5-0.7s is smaller and therefore the circulating current during this period is minimized. The simulation results for different cases are given in Table III.
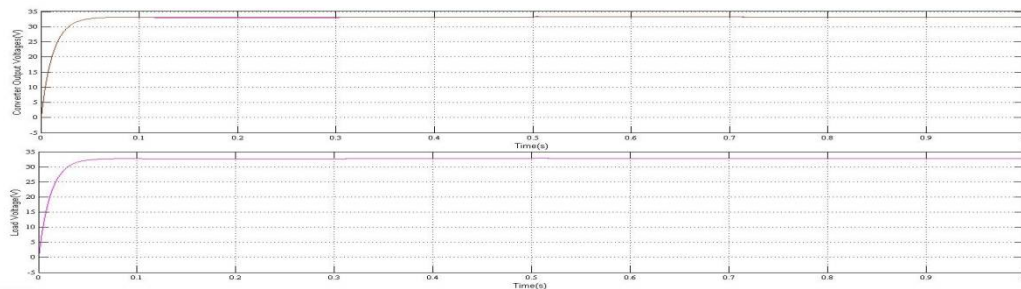

Fig.10 Load and converter voltages of parallel connected boost converter with conventional droop control

TABLE III
SIMULATION RESULTS WITH CONVENTIONAL DROOP CONTROL

Time(s)	V_{DC1}, V_{DC2}, V_L(V)	I_L, I_1, I_2(A)	I_{err}(%)	$|I_c|$(A)
0-0.1	33.2,33.2,32.8	0.85,0.425,0.425	0	0
0.1-0.3	33.2,33.1,32.7	0.85,0.459,0.386	7.2	0.036
0.3-0.5	33.2,33.2,32.8	0.85,0.425,0.425	0	0
0.5-0.7	33.1,33.2,32.75	0.85,0.421,0.43	0.9	0.0045

C) Adaptive Droop Control

In adaptive droop control method the virtual resistance value is calculated instantaneously by droop index calculation. The calculation of minimum DI is done by varying the droop resistance value and its maximum value will depend on the voltage regulation which means, the product of converter output current and R_{droop} should not increase the maximum allowable voltage deviation. If the rated voltage of dc grid is 34 ±5%V an each converter rated current is 0.44A, then the product of converter rated current and R_{droop} should be less than the maximum deviation in the dc bus voltage (1.7 V). MATLAB/Simulink model of adaptive droop control strategy for load sharing and circulating current minimization is as shown in the Fig.11.
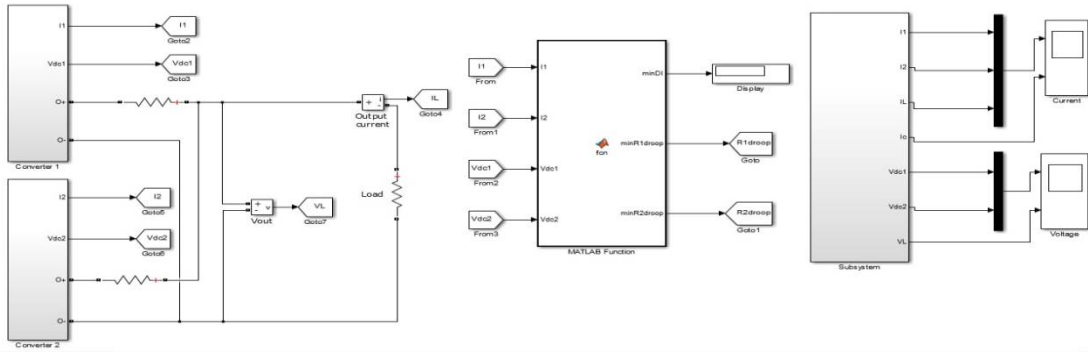
Fig.11 Simulink model of parallel connected converters with adaptive droop control

The load, converter currents and circulating current are shown in Fig.12 and from the figure it is clear that the converter 1 and converter 2 are equally shared and the circulating current is negligible in all cases.
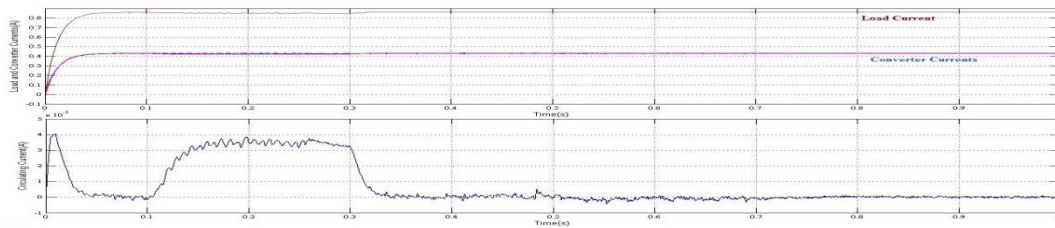

Fig.12 Load, converter currents and circulating current of parallel connected boost converter with adaptive droop control

Load and converter voltages are shown in Fig.13 and both the converter voltages are equal in all cases.Table IV shows the simulation results of different cases with adaptive droop control strategy.
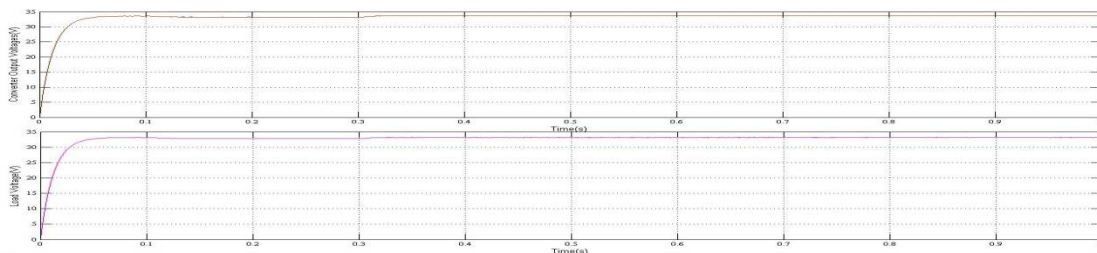

Fig.13 Load and converter voltages of parallel connected boost converter with adaptive droop control

TABLE IV
SIMULATION RESULTS WITH ADAPTIVEDROOP CONTROL

Time(s)	V_{DC1}, V_{DC2}, V_L(V)	I_L, I_1, I_2(A)	I_{err}(%)	$\lvert I_c \rvert$(A)
0-0.1	33.5,33.5,33.1	0.86,0.43,0.43	0	0
0.1-0.3	33.228,33.222,32.85	0.86,0.431,0.425	0.6	0.003
0.3-0.5	33.5,33.5,33.1	0.86,0.43,0.43	0	0
0.5-0.7	33.5,33.5,33.1	0.86,0.43,0.43	0	0

V.CONCLUSION

Adaptive droop control method calculates virtual resistance R_{droop} positive or negative values instantaneously based on the converter output voltage mismatch. This improve the current sharing difference and decreases circulating current between the converters, in transient as well as in steady state condition and it improves the voltage regulation. The effects of converter cable resistances are taken into account to verify the performance of themethod. The dc-dc converter is controlled by closed loop controls which have an outer voltage loop and inner current control loop. The simulation results show that the circulating current is minimized and load is effectively shared with this decentralized method. This method is effectively implemented for the converters with different cable resistances and alsofor DGs having different ratings.

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