

OPERATION OF PARALLELED DC-DC CONVERTERS TAKING INTO ACCOUNT CABLE RESISTANCES FOR LOAD SHARING APPLICATIONS

Abhimanyu Kumar Yadav¹, Vishal Mehra³, Abhijit Ray¹, Makarand Lokhande²

¹School of Solar Energy, PDPU, Gujarat, India.

²Electrical Engineering Dept, SVNIT, Surat, India

³College of Agriculture Engg. & technology, Godhra, India

ABSTRACT

In this paper two DC-DC converters connected in parallel with the purpose of load sharing by applying droop method is considered. This method requires no communication interconnection and compensates for converter parameter variations and imbalances in line impedance. The DC-DC converter input source can be any DC source such as photovoltaic module and wind turbine or fuel cell and it is a closed loop system. In this work proportional-integral (PI) controller, will have their performance evaluated to control the paralleled converters connected to DC micro-grid. The PI controller is tuned by particle swarm optimization (PSO) method. The designing of stable DC-DC converter with primary droop current-sharing control, the stability of the interconnected parallel DC-DC converter system was studied. When the cable resistance of the paralleled DC converters differs, the interconnected system might be unstable and due to this the uneven load sharing occurs. To resolve this issue to some extent without the use of communication lines, a novel technique is applied to parallel DC boost converter in order to optimize the large uneven current sharing. The parallel converter must provide an even load sharing and secondly redundancy. Simulation results are presented in the paper using Mat lab/Simulink to confirm the concept.

KEYWORDS: DC-DC Converter, PWM Switching, PSO Algorithm, Renewable Energy.

I. INTRODUCTION

Distributed generation systems are gaining popularity due to drastic increase in energy demand and it is indispensably required for sustainable development. DC micro-grids are the most appropriate solution for the integration of the renewable and distributed energy resources as well as distributed energy storage systems. This concept has been developed to handle the rapid penetration of renewable energy systems especially the photovoltaic sources and wind turbines. These can prove to be the effective power source in future, if on the consumer side, the techniques to generate, control, store the surplus part of the energy is done and to be able to manage them.

DC micro-grid power system comprises of several standard DC-DC converters configured in various topologies through interconnected cables to obtain the desired output voltage, current, and power [1–3]. The paralleled power source extends many merits such as a easy scalability, convenience to fix maintenance and high reliability over wide load region, [4]. In real time applications, the paralleled DC-DC converters may be located at large distance from each other and therefore, unequal lengths of cable connecting them to the load they share is required. This unequal cable length results in different cable impedances and this is one of the reasons to the uneven current sharing among the converter

output current. Therefore, the equal current sharing control among each of DC/DC converters is the key performance index and it is one of the hindrances before the DC micro-grid power system.

In order to obtain equal current-sharing control in the parallel DC-DC converters system, the current-sharing control should be designed. The most popular current sharing control scheme is the active current-sharing control scheme, especially; the master-slave and average current sharing controls [5,6,7]. These literature provides the key theoretical study in the master slave and average current sharing controls. These techniques require the fast communication channels or bus protocol and their network structures are very complex. However, the control system analysis of the droop current-sharing control seems to have little study. In the server power system infrastructure, the parallel DC converters system plays the key role to provide low voltage and high output current capability through the feeble designed interconnected system [8].

In [9] a droop controlled superconductive dc system catering to a small zone is analyzed. In [10] the implementation and experimental evaluation of a new current-sharing technique for paralleled power converters is presented which uses the information naturally encoded in the switching ripple to achieve current sharing and requires no inter-cell connections for communicating this information. Sliding Mode Control (SMC) is another nonlinear control method suitable for switched mode DC converters. It is considered to be a robust control strategy against parametric uncertainties [11], but the major drawback of SMC is the chattering phenomena [12,13]. In [14] a robust democratic current sharing technique for good current sharing by adjusting the voltage references of the DC modules based on the differences between the average current is analyzed. Here, a low pass filter and a comparator is used along with sensing resistor in order to share the load current among the converters. The simplest technique for paralleling of DC converters is a droop method, which uses no wire interconnection among control circuits of the parallel converters. The droop method is easy to implement, and it offers simple module extension. However, the current sharing accuracy is achieved at the penalty of poor output voltage regulation. In general, the better the current sharing, the worse voltage regulation is for the converters, so conventional power supplies do not share current well because of good regulation of output voltage. Therefore, design of high performance control for the parallel DC converters power system is a challenge for the system being nonlinear and time variant nature.

In this paper, modelling of DC Boost converter is discussed in section II and its transfer function is evaluated. In section III, the design of PI controller tuned by PSO algorithm is described and the choice of an appropriate set of K_p and K_i value for the PI controller is determined. The section IV describes about

two identical closed loop converters in parallel topology and connected to a resistive load. Here the analysis of paralleled DC converter system taking cable resistances into account is analysed using with and without signal conditioning block. The resultant average currents of both converters are processed into w-factor block then compared. The output of the comparator is compared with reference voltage. This operation is applied for different cable resistance and load. The simulation for different cable resistances and load variations are presented and the resultant output load voltage and load sharing current of individual converter is analyzed.

II. DC BOOST CONVERTER DESIGN

The DC boost converter consists of a DC input voltage source V_s , inductors, filter capacitor, controlled switch S , diode D and load resistance R_L . The schematic of closed loop DC boost converter is shown in figure1. The output voltage of boost converter is always greater than the input DC voltage. If the switch operates with a Duty ratio D , then in case of boost converter voltage gain is as,

$$M_V = \frac{V_o}{V_s} = \frac{1}{1-D},$$

Where, V_o is output voltage and D is Duty cycle of the pulse width modulation (PWM) signal used to control the Mosfet ON and OFF states. The parameters of DC Boost converter is tabulated in Table 1.

Table1.Simulation parameter in boost converter

| Parameters | Values |
|---|---|
| Input voltage | 24 V |
| Output voltage | 48V |
| Switching frequency | 100KHz |
| Inductance | 18mH |
| Capacitance | 980µF |
| R _L , r ₁ ,r ₂ | 26Ω,0.05-0.09Ω |
| PID gain | K _p =114.32, K _i =11.56 |

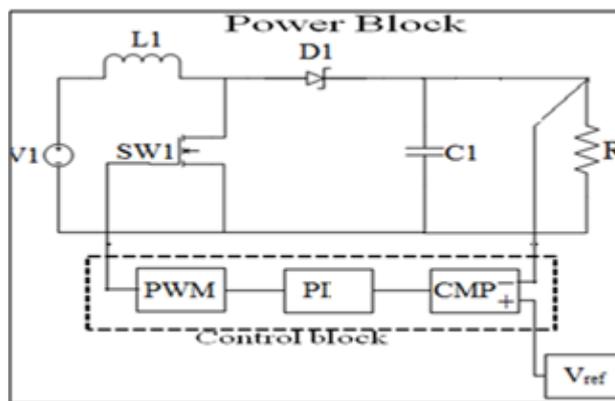


Figure 1.Closed loop DC boost converter

The closed loop converters tries to control the output voltage overshoot voltage using PID controller and pulse width modulator operating at a fixed frequency of 100 KHz as shown in Fig1. The open loop, the transfer function of boost converter is given below in equation 1.

$$\begin{aligned}
 T.F = \frac{V_o}{V_{in}} &= \frac{\left(\frac{1}{LCR_L}\right)}{S^2 + \frac{S}{LCR_L} + \frac{1}{LC}} \\
 &= \frac{2.18 \cdot 10^3}{S^2 + 2.18 \cdot 10^3 S + 56.7 \cdot 10^3} \quad (1)
 \end{aligned}$$

III. DESIGN OF PI CONTROLLER TUNED BY PSO ALGORITHM

The performance of a closed loop converter is highly influenced by controller parameters. The controller ensures stable operation of the converter. In practice, The PID controller is the most common used for the control of DC-DC converters due to their acceptance in all control system [14,15]. Two different algorithms were used for tuning the gain parameters of the PID controller and their results are compared [16].

The PID controller provides control signals which are relative to the error between the reference signal and the actual output, to the integral of the error and to the derivative of the error. The general equation of control signal for a PID controller is as follows:

$$u(t) = K_p [e(t) + \frac{1}{T_i} \int_0^t e(\tau) d\tau + T_d \frac{d}{dt} e(t)] \quad (2)$$

The gain of PI controller used is determined by particle swarm optimization (PSO) algorithm [16]. PSO is a multi-agent parallel search technique where say n flying entities fly through the multidimensional search space as the algorithm progresses through discrete time steps i.e. t=0, 1,2, ..., while keeping the population size m constant. In the standard PSO algorithm, each particle's current position $X_i(t) = [X_{i,1}(t), X_{i,2}(t), \dots, X_{i,n}(t)]$ and its current velocity $V_i(t) = [V_{i,1}(t), V_{i,2}(t), \dots, V_{i,n}(t)]$, where $i=1, 2, \dots, m$ is considered and accordingly its personal best position $P_i(t)$ and global best position $G(t)$ is found with respect to the origin of search space. Here one position is declared better than another if the former gives

a lower value of the objective function than the latter. This function is called the fitness function. Each particle's initial position vector component $X_{i,j}(0)$ is picked randomly from a predetermined search

range $[X_{Lj}, X_{Uj}]$ and its velocity components is initialized by choosing at random from interval $[-V_{jmax}, V_{jmax}]$. The initial settings for $P_i(t)$ and $G(t)$ is given in equations (3),(4) and (5) respectively.

$$P_i(t) = X_i(0), \quad (3)$$

$$G(0) = X_k(0) \quad (4)$$

$$\text{such that } f(X_k(0)) \leq f(X_i(0)) \forall i \quad (5)$$

where, $\forall i$ represent for all values of i .

The iterative optimization process for the initialized particle begins and the position and velocities of all the particles are updated by the following recursive equations (6), (7). Given equations are for j th dimension of the position and velocity of the i th particle.

$$V_{id}(t+1) = \omega V_{id}(t) + C_1 \Phi_1(P_{id}(t) - X_{id}(t)) + C_2 \Phi_2(P_{gd}(t) - X_{id}(t)) \quad (6)$$

$$X_{id}(t+1) = X_{id}(t) + V_{id}(t) \quad (7)$$

Where ω : Time-decreasing inertial weight factor designed by Shi and Eberhart [17]. $C_1=2.4$, $C_2=1.6$. Two constant multipliers called self-confidence and swarm confidence respectively, Φ_1, Φ_2 . Two uniformly distributed random number. The iteration is fixed for certain number of time steps or until the fitness of the best particle at a certain time step is better than a predefined value is obtained. The fittest vector of the final population upon termination of the algorithm is taken as the possible solution of the problem. PSO is more efficient in maintaining the diversity of the swarm, since all the particles use the information related to the most successful particle in order to improve themselves, whereas in Genetic algorithm, the worse solutions are discarded and only the new ones are saved [18]. The PSO parameter used in this application is given in table 2.

Table2. PSO parameter and value

| PSO Parameter | Value |
|--------------------------------|---------|
| Population size | 20 |
| Vmin | -3 |
| Vmax | 3 |
| C ₁ ,C ₂ | 2.4,1.6 |
| No. of Iterations | 40 |

IV. PROPOSED MODEL FOR LOAD SHARING USING PSO TUNED PI CONTROLLER

The concept of load sharing among the paralleled DC converters using the renewable energy sources such as Photovoltaic, wind and fuel cell etc., can contribute to sustainable development. In figure2, it is shown that the two DC converters are paralleled and cable resistances connecting them to the load are r_1 and r_2 . The voltage sources (V_1, V_2) can be any renewable source such as photovoltaic, wind or fuel cell etc. The converters are connected by cables of unequal resistances, which implies that they are located at uneven distance from the load and due to this condition there is unbalance in the current sharing.

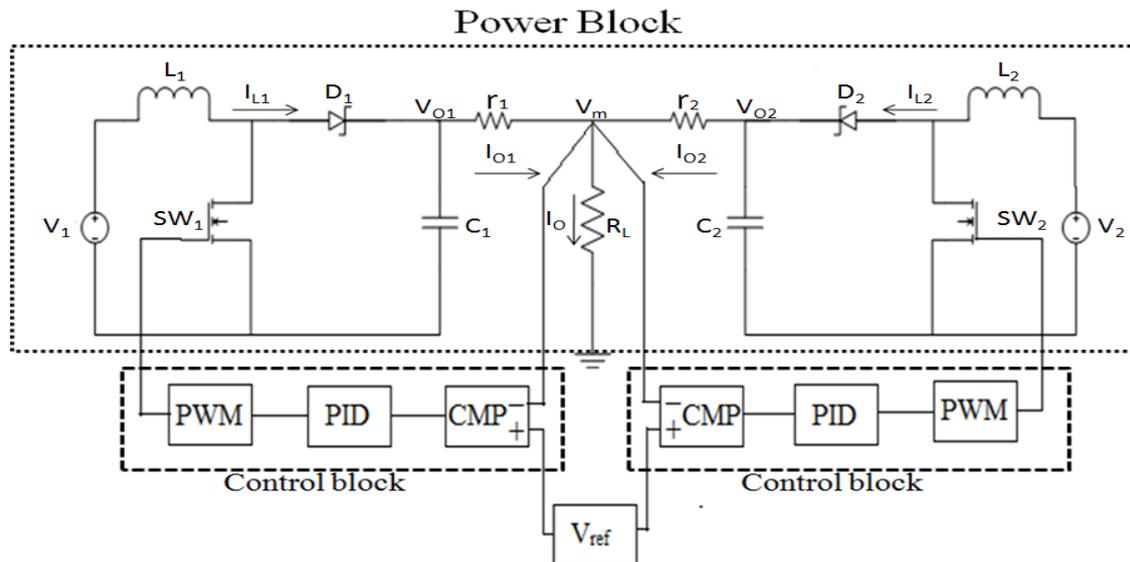


Figure 2. Paralleled closed loop Boost converters without signal conditioning block

Case1. Parallel DC converter using PSO tuned PI controller without droop method

The identical closed loop converters are connected in parallel at equal distance to the load without current sharing mechanism is considered. The voltage V_{o1} and V_{o2} are the regulated voltage of left and right DC converter respectively. The cable resistance of both converters is initially kept constant and later the cable resistance of left converter is varied in sequence (50-70-90 mΩ) and right converter cable resistance is decreased to 30 mΩ at 80msec. The converter load current I_{o1} is of left converter and I_{o2} is of right converter. The load resistance value is kept constant at 8Ω during the simulation. In figure3, it is noted that as the cable resistances varies due to position of DC converters at varying location; there is unequal current contribution to the load R_L .

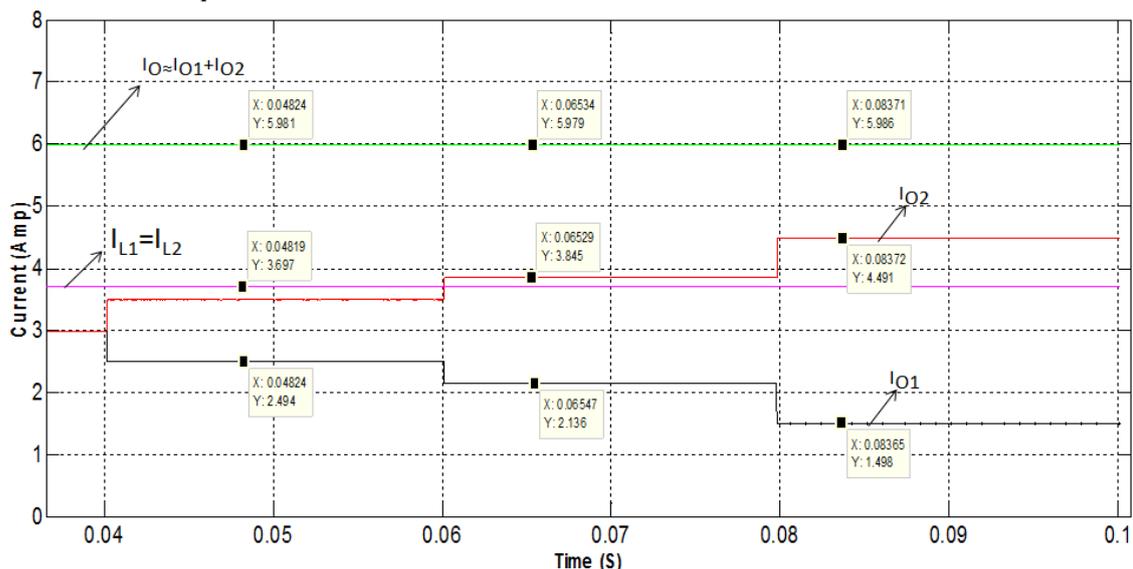


Figure 3. Current parameters of the paralleled connected DC Boost converters without droop method.

There is also variation in load voltage as shown in figure4 but individual output voltage is regulated constant by the PSO tuned PI controller. The current variation by large difference due to location of converters at large distances can result in more stress on one converter and may result in converter failure.

At the 80msec, when the right converter cable resistance was changed from 50 to 30 mΩ, and left converter cable resistance remaining on 90 mΩ, we observe that there is increase in load voltage by 0.06 volt. However, the load voltage variation is less as compared to load current of both converter.

Therefore, Droop control method along with PSO tuned PI controller applied here is used to minimize this large difference in current of both converters, as discussed in case2.

In figure6 and figure7, it is observed that, this large variation in output load current and voltage is optimized.

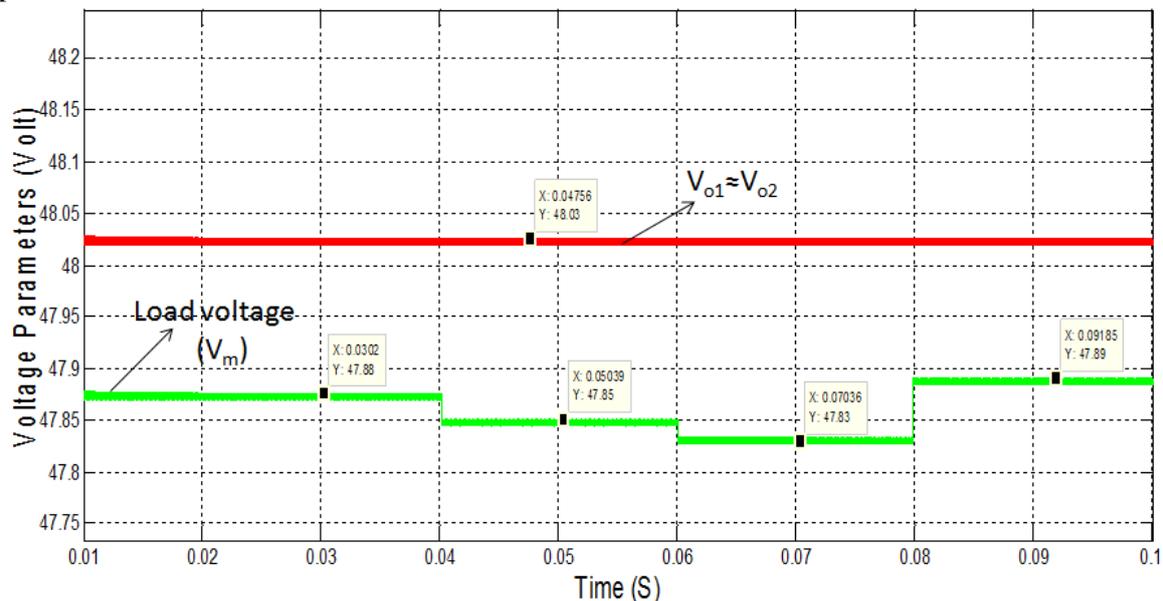


Figure 4. Voltage parameters of the paralleled connected DC Boost converters without droop method.

Case2. Parallel DC converter using PSO tuned PI controller with droop method

The identical closed loop boost converters are connected in parallel at varying distance to the load with current sharing mechanism is shown in figure5. DC micro-grid comprises of several such DC converters, configured in parallel topology. There is variation in voltage magnitudes of two nodes with change in the power flow across their interconnecting cables, which implies the voltage of each node depends on the load distribution across the system [20]. According to droop control concept, the source currents depend on the node voltages of the converters which results in source currents to depend on the load distribution due to the interconnecting cable resistance. In this paper, realization of voltage regulation by the PSO tuned PI controller of individual boost converter is precise and the required load voltage regulation and the desired current sharing is satisfied. As shown in figure5, the individual converter's output current is processed by the W-factor block and compared with a comparator. The current equivalent voltage of it is compared with reference voltage and the resultant voltage used to switch on the PWM switch of the left DC converter. This operating voltage which controls the PWM of left converter is compensated by the signal conditioning block in order to achieve the desired current sharing.

To achieve a desired range of load current distribution ratio, an appropriate cable resistance must be determined as given in [19].

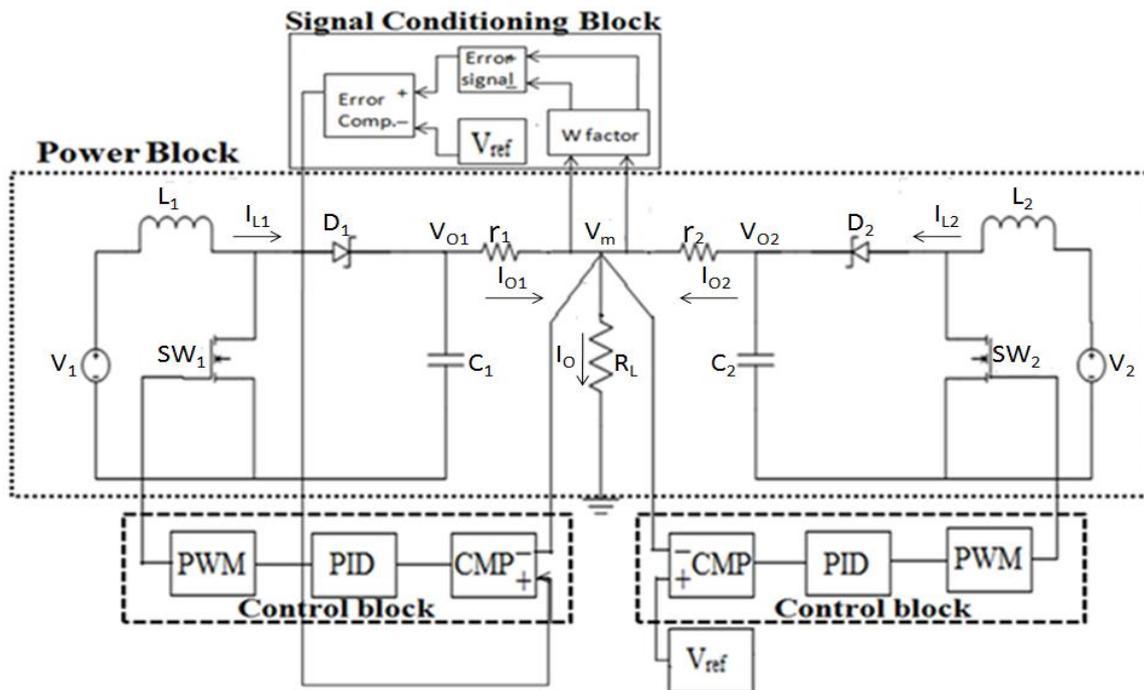


Figure 5. Paralleled closed loop Boost converters with signal conditioning block

In figure6, the result of the load current sharing is presented by changing the Load value. Deviation in source currents from their ideal value verifies good steady state performance of the proposed scheme. For a particular range of load value, it is observed that the droop technique along with PSO tuned PI controller result in better performance. Increasing the droop gains results in less deviation of source currents at the cost of increased voltage variation[20]. In figure7, load voltage and individual DC converters terminal voltage is shown.

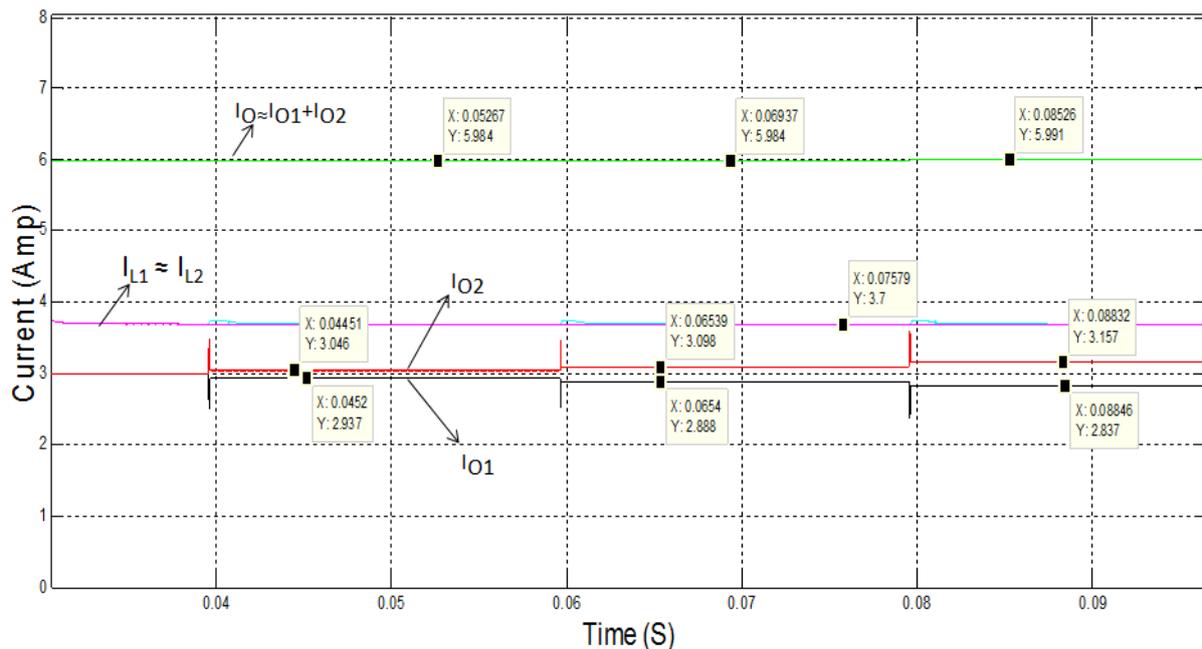


Figure 6. Current parameters of the paralleled connected DC Boost converters with droop method.

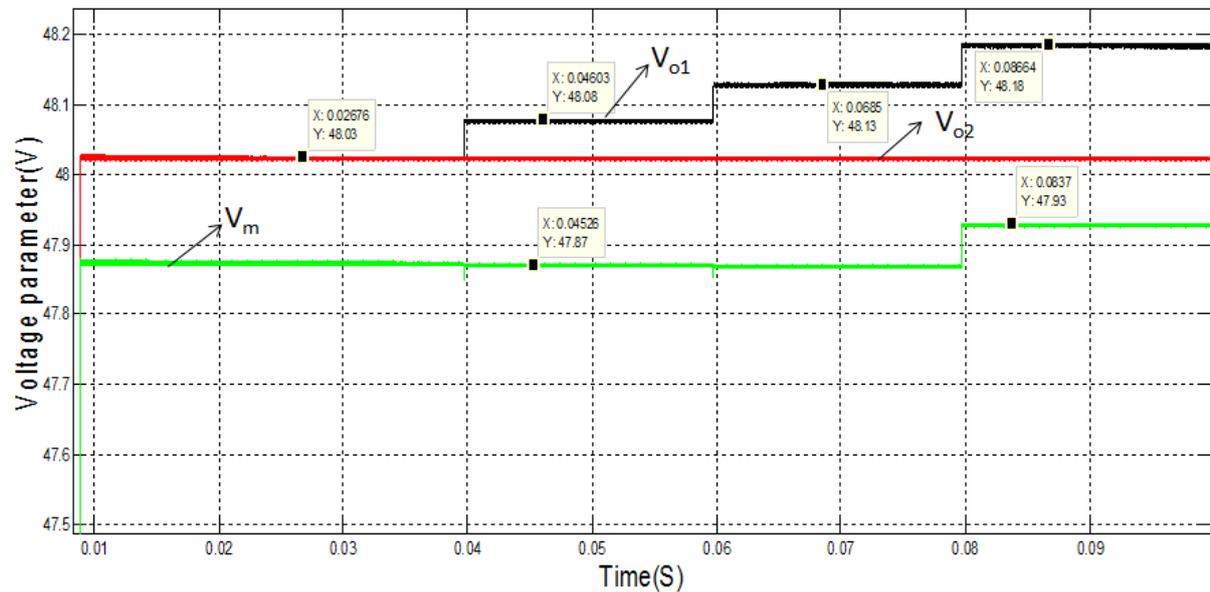


Figure 7. Voltage parameters of the paralleled connected DC Boost converters with droop method.

The left DC output voltage converter deviates from ideal value of 48.03 to 48.18V when the cable resistances difference is 50mΩ and load resistance varies from 8 to 14Ω. This deviation in voltage is just 0.31% and load voltage deviation is just 0.125%. In figure8, the DC converters parameters is kept same and the cable resistance of left and right converter is 50 and 90 mΩ respectively. The current I_{o2} , I_{o1} are load current of right and left DC converters and I_{L2} , I_{L1} are inductor currents of respective DC converter. The load resistance is varied from 2Ω to 14Ω.

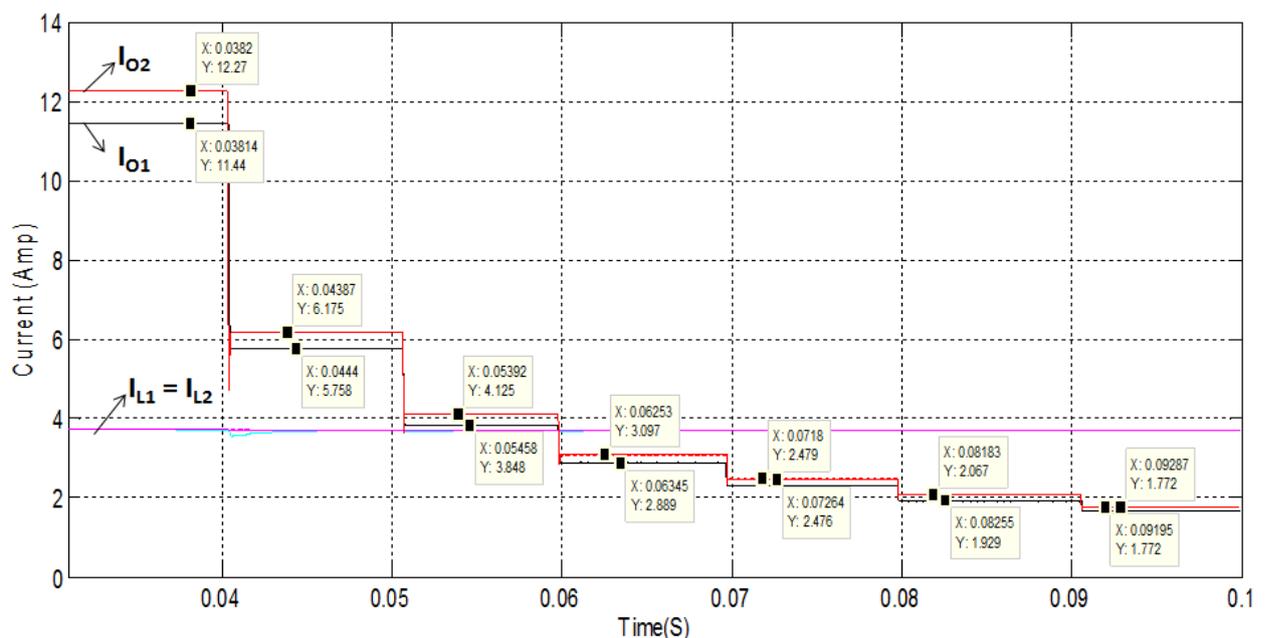


Figure 8. Current parameters of the paralleled connected DC Boost converters with load variation.

In figure 8, it is also observed that as the load value changed from 2 to 14Ω, while other parameters is kept constant, the load current difference is decreased to minimum, which implies near to equal load current sharing without additional communication line. In [21]-[24] the hybrid power system combined with a rechargeable secondary battery is discussed. The fast dynamic response and high reliability is achieved by using several novel control designs for FC–battery hybrid power system which enables both active current sharing and power source management control in such hybrid systems.

V. CONCLUSION

In this proposed method, the boost converter is designed to step-up the fluctuating voltages of renewable sources such as solar and wind to a higher constant DC voltage. It uses voltage feedback to keep the output voltage constant. This fixed output voltage across the shared load is regulated near to a fixed reference voltage value through the PI controller tuned by the PSO algorithm. In this paper, it is shown that cable resistance has significant impact on the performance of parallel connected converters. Therefore, this parameter has to be taken in account for effective converter design. The droop control method achieves good current sharing on compromising with the voltage regulation without requirement of any communication channel. The operating control voltage, which controls the PWM of each converter, is compensated by the corresponding controllers. The voltage V_m at load is maintained near to 48V. It has been shown that current-sharing can be improved with a proper choice of converter cables. Output currents of each power modules are well balanced at step change of load and vice versa. Droop in the steady state is minimized by the proposed control method. It shows the proposed controller can reduce the voltage variation by droop control technique and increase the current balance among the power modules. This technique can provide protection to the switching MOSFETs of the DC converters from overheating and power stress.

VI. FUTURE WORK

As the power generation using solar power had increased dramatically because it is pollution free as compare to power generation using fossil fuel. Therefore, in standalone systems, these kind of paralleled DC converters will play a vital role if the proper control strategy (PSO tuned PI controller) taking cable resistances into account for power generation along with maximum power point tracking for the solar and wind will be applied. The medium to low voltage DC applications for residential use will be more reliable and efficient in future. These medium to low voltage network can later be reconstructed which may results in formation Medium range DC power micro-grids.

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AUTHORS

Abhimanyu Kumar Yadav has completed his B.E in Electronics and communication in 2007 and he is pursuing his PhD in Integration of renewable of renewable for DC microgrids. His area of interest is in renewable energy, power electronics and process control.



Abhijit Ray's research is focused on thermoelectric and photovoltaic (solar) energy conversion materials and devices. The current research interest extends to study electrical and thermal properties of new thermoelectric materials showing large figure of merit at high temperatures. Current materials of interest include polycrystalline and amorphous Si, CdTe and CIS. His research Interest is in Materials for Clean Energy (Thermoelectric, Solar) and Sensors and his Specialization is in Experimental Condensed Matter Physics.



Vishal Mehra has completed his masters in Instrumentation and process Control from NSIT, University of Delhi. Currently he is assistant professor in College Of Agricultural Engineering And Technology, Godhra, Gujarat and he is having teaching experience of two years.



Makarand Lokhande has worked on an operation and control of inverter interconnected microgrids during his Ph.D program at IIT Bombay. His master's degree is in power system from Electrical Engineering Department, Government College of Engineering Pune. His research Interests are in Power electronics, power systems, electrical machines, distributed generators, microgrids, renewable energy sources, energy management.

