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ENHANCEMENT OF VOLTAGE REGULATION AND LOAD SHARING IN DC MICROGRID USING PSO AND FUZZY LOGIC

B. MOHAN[1], C.D. VARAPRASAD[2], T. NARASIMHA PRASAD[3]

[1]Assistant professor, Assistant Professor, EEE Department, PVP Siddhartha Institute of Technology, Vijayawada, Andhra Pradesh, India

[2]Lecturer, School of Electrical and Computer Engineering, Haramaya institute of Technology, Haramaya University, Ethiopia

[3]Assistant professor, Assistant Professor, EEE Department, PVP Siddhartha Institute of Technology, Vijayawada, Andhra Pradesh, India

E-mail: [1]mohan.victory1@gmail.com, [2]narasimhaiete@gmail.com

ABSTRACT

In DC Microgrid stand-alone applications, the main problem is to maintain DC bus voltage regulation and load sharing among distributed generating sources are affected by unequal line impedances. The control strategy is designed in such a way that the sources are assumed to feed current to DC bus via virtual resistance called droop resistance and line impedances. Load sharing between distributed generations (DG) sources is improved done by optimizing droop resistance values, voltage reference values using PSO (Particle Swarm Optimization). A fuzzy logic based distributed control strategy is implemented considering the optimized droop resistance values obtained from PSO, for droop control in order to achieve voltage regulation and load sharing effectively among DG units. The performance of fuzzy based droop controller with optimal droop parameter of DC distributed control scheme is shown better compared with existing PI controller-based approach and results are verified through simulation in MATLAB/SIMULINK.

Keywords: *DC Microgrid, PSO, Fuzzy Logic, Droop Control, Secondary Control, Load Sharing*

1. INTRODUCTION

The concept of the Microgrid was proposed several years ago in order to assimilate sustainable energy sources and energy storage systems to electrify a remote area. To integrate various renewable energy sources, and loads in DC Microgrid, DC-DC converters design and its control are gaining paramount importance. The DC Microgrid is free from reactive power and harmonics. System control is easy and its efficiency is observed to be higher compared to AC systems. As renewable sources like photovoltaic (PV) and wind generators are weather reliant, sudden variations in the input power due to its parametric variations, causes the changes in output voltages of DC-DC converters to which these are fed. Load variations also affects the DC voltage output of individual converters. This mismatch in the converted output voltages causes circulating currents to flow among parallel connected converters in DC Microgrid [1]. But the advantages of parallel connected converters include improving load sharing, reliability, efficiency and ease of maintenance [2]. Thus, the Primary control objective in parallel connected DC source is to maintain output voltage within permissible limits, avoiding circulating currents, effective load sharing with high degree of load reliability [3][4]. The total control methodology is divided into three tiers by a hierarchical control structure [5]. The droop-control approach is used at the primary control level. A virtual impedance control loop is included to simulate physical output impedance [6]. When the DC Microgrid is grid connected, the secondary control level governs bus voltage regulation, and the tertiary control level regulates power flow between the DC Microgrid and the associated local grid. Decentralized, centralized, and distributed control are used to achieve primary and secondary control. The implementation of centralized control systems is based on a central controller that connects with all

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other units via specialized digital communication lines. There's a chance that a single point of failure will occur [7]. Other units are overworked as a result, which could lead to system instability. The distributed control strategy does not rely on central control units to function. This approach only involves local controllers that can connect via dedicated communication channels and use the consensus principle to get local parameter information. In the case of a communication dependent control strategy, however, system stability suffers as communication delay increases. As a result, distributed control schemes have advantages over centralized and decentralized control schemes in terms of reliability, power quality, stability, efficiency, and expandability.

Information about line parameters is necessary throughout the grid in the case of a distributed control mechanism. Line resistance estimation is used instead of pre-calculated values, and it necessitates using the grid linked mode of operation to determine line impedance before using the island mode. In this case, the distributed controllers set fixed parameters that, when the system parameters fluctuate within their specified ranges, produce optimal performance on an average basis. From the communication aspect, in distributed control schemes, secondary control is distributed and utilize power lines carriers which is referred as low bandwidth communication network for channeling the DC bus voltage signals among DGs, thus dedicated communication lines are not required. As a result, channel communications are often utilized primarily to shut off DGs when the system is malfunctioning or changing operating modes. The solar system comprises of a photovoltaic generator linked to a DC/DC boost converter controlled by a PSO fuzzy MPPT control to extract the most possible power at the PV terminals at any given time [8]. In conventional control, the steady state error is present, with fuzzy controller input and output gains are tuned using the PSO optimization approach to achieve superior outcomes with 0% steady state error [9]– [11]. As a result, adjusted droop parameters based on PSO and Fuzzy approaches minimize the trade-off between output current sharing and bus voltage regulation [12] [13].

In this paper, For DC Microgrids, a robust droop-based distributed controller is presented. It is not designed to be a replacement for the distributed controller; rather, it is intended to play a supporting function in the event of a communication system failure. Droop parameters obtained in PSO is substituted as reference for Fuzzy and change in droop resistance obtained from fuzzy is added to this reference to obtain overall droop resistance for both DC-DC converters. Only few works are discussed about updating the droop parameters, the research gap in updating the droop coefficients based on voltage error is presented in the present work. Thus, the control action is completely based on droop coefficient.

2. MATERIALS AND METHODS

This section describes the droop characteristics for different droop coefficient combinations for both DGs and also the application of particle swarm optimization to identify droop coefficients and modelling aspects of droop control strategy.

2.1 Optimization of Droop parameters of DC Microgrid using PSO:

DC Microgrid with two DC distributed generators (DGs) connected in parallel and interfacing with a shared DC bus via droop resistance; cable resistance is considered as shown in Figure 1. Output source converter reference voltages can be written as,

$$V_{o,i}^{*} = V_{ref} - r_{d,i} i_{o,i} \quad (1)$$

Where, $V_{o,i}^{*}, r_{d,i}$ and $i_{o,i}$ are the local output voltage reference, droop resistance, and output current, of the i^{th} converter respectively, and V_{ref},is the voltage reference of common DC bus.

The droop resistance of i^{th} converter can be written as,

$$r_{d,i} = \frac{\Delta V_{max}}{i_{o,i}^{max}} \quad (2)$$

$$V_{o,i} = V_o - R_{c,i} i_{o,i} \quad (3)$$

$$i_{o,i} = \frac{V_{s,i} - V_o}{(r_{d,i} + R_{c,i})} \quad (4)$$

Where, $V_{s,i}$ is source voltage, $R_{c,i}$, $r_{d,i}$ are cable resistance and droop resistance of generator i respectively and V_o is the bus voltage. The current that circulates between the two converters. i.e., Δi_{12} can be expressed in figure2Figure 1 as:

$$\Delta i_{12} = \frac{(r_{d,2}+R_{c,2})(V_{o,1}-V_o)-(r_{d,1}+R_{c,1})(V_{o,2}-V_o)}{(r_{d,1}+R_{c,1})(r_{d,2}+R_{c,2})} \quad (5)$$

The current error for proportional current sharing among the converter terminals, Δi_{12} is to be almost equal to zero and this is realized by choosing droop resistance , $r_{d,i}$ and a voltage reference $V_{o,i}$ according to the i^{th} DG rating. But offset voltages $\delta V_{o,i}$ of the i^{th} generator results in unequal load

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distribution among the DGs. By considering offset voltages, droop resistance of i^{th} DG is changed from , $r_{d,i}$ to $r'_{d,i}$ which are droop resistance of i^{th} DG without and with considering offset voltages respectively. The current sharing error in Eqn. (5) can be rewritten as,

$$\Delta i'_{12} = \frac{(r'_{d,2}+R'_{C,2})(V_o^*+\delta V_{o,1}-V_o)-(r'_{d,1}+R'_{C,1})(V_o^*+\delta V_{o,2}-V_o)}{(r'_{d,1}+R'_{C,1})(r'_{d,2}+R'_{C,2})} \quad (6)$$

Where, $\delta V_{o,1}$ and $\delta V_{o,2}$ are the reference offset voltages and V_o^* is the rated DC bus Voltage reference, If the modified droop resistance, cable resistance of both the DGs are considered to be equal, i.e., $r'_{d,1} = r'_{d,2} = r_d$ and $R'_{C,1} = R'_{C,2} = R_c$, and substituting in eqn. (6), the voltage drop at the DC bus and current sharing error can be reduced to,

$$\Delta V_o = \frac{1}{2}[(\delta V_{o,1} + \delta V_{o,2} - (r_d + R_c)i_o] \quad (7)$$

$$\Delta i'_{12} = \frac{(\delta V_{o,1}-\delta V_{o,2})}{(r_d+R_c)} \quad (8)$$

Where, i_0 is the load current under steady state and $i_{0,i}$ and $i'_{0,i}$ are the current shared by i^{th} DG, without and with considering offset voltages respectively.

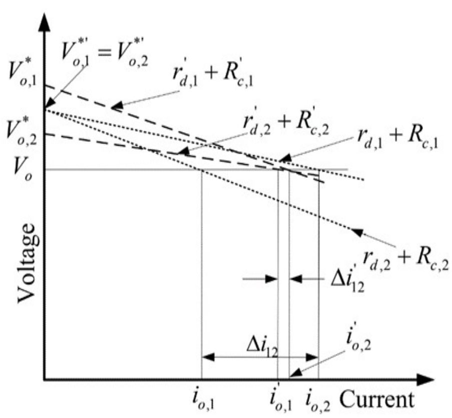

Figure 1: Droop characteristics of DC sources with dissimilar droop resistances and converter output voltages.

To minimize the trade-off between current sharing and maintaining bus voltage regulation within allowed limits, the droop resistance and output voltage references are adjusted. If $r'_{di} > (r_{d,1}$ or $r_{d,2})$, and if considering equal resistances, i.e.,$r'_{d1} = r'_{d2} = r'_d$, The current sharing error and bus DC voltage regulation can be expressed as follows:

$$\Delta i'_{12} = \frac{(\delta V_{o,1}-\delta V_{o,2})}{(r'_d+R_c)} < \Delta i_{12} \quad (9)$$

$$\Delta V'_o = \frac{1}{2}[(\delta V_{o,1} + \delta V_{o,2} - (r'_d + R_c)i_L)] > \Delta V_o \quad (10)$$

Because the cable resistances of two cable lines are not nearly equivalent due to different geographical locations, considerable variations in current sharing and voltage regulation occur, as shown in Figure 1. The proportional current sharing error as well as the bus voltage deviation can be calculated as follows:

$$\Delta i_{12} = \frac{V^*_{o,1}}{(r_{d,1}+R_{c,1})} - \frac{V^*_{o,2}}{(r_{d,2}+R_{c,2})} - V_o\frac{\{(R_{c,2}-R_{c,1})+(r_{d,2}-r_{d,1})\}}{(r_{d,1}+R_{c,1})(r_{d,2}+R_{c,2})} \quad (11)$$

$$\Delta V_o = V_o - \frac{r_d+R_{c,1}}{2r_d+R_{c,1}+R_{c,2}} \quad (12)$$

In the proposed method main objective is to improve the voltage references of distributed generator source converters, as well as their droop resistances, in order to reduce the average current sharing error and voltage variation of sources connected across the DC Microgrid. This is to keep DC Microgrid voltage within acceptable limits under various loading conditions and cable line impedances. For all sources, the optimization problem is posed to find the ideal droop resistance and voltage reference values for all sources to optimize the voltage degradation error δ_v and current sharing error δ_c . Errors can be expressed for k^{th} loading condition are,

$$\delta_{c,k} = \sqrt{\sum_{i=2}^{N}[\frac{(i_{o,1,k}i^{max}_{o,1} - i_{o,i,k}i^{max}_{o,1})^2}{(i^{max}_{o,i})^2}} \quad (13)$$

$$\delta_{v,k} = V_o - \sum_{i=1}^{N}\frac{V_{o,i,k}}{N} \quad (14)$$

For k^{th} loading condition, V_o is desire DC bus voltage, $V_{o,i,k}$ is the voltage across of i^{th} DG and $i_{o,i,k}$ is the output current of i^{th} DG, The error $\delta_{c,k}$ depends is determined by the droop settings and $\delta_{v,k}$ is reduced by using $V^*_{0,i,k}$ reference voltage of i^{th} module for k^{th} loading. Thus, the error defined for PSO in the DC Microgrid system is

$$e_k = w_c\delta_{c,k} + w_v\delta_{v,k} \quad (15)$$

Where w_v and w_c are the weights for the $\delta_{v,k}$ and $\delta_{c,k}$ .Therefore, the total error function can be expressed as:

$$E_T = \sum_{k=1}^{N_o}(w_c\delta_{c,k} + w_v\delta_{v,k}) \quad (16)$$

Constraints can be defined as:

$$\begin{aligned} &V_o - V_{o,i,k} \leq \Delta V_{max} \\ &i^{min}_{o,i} \leq i_{o,i,q} \leq i^{max}_{o,i} \\ &V_o - V_{o,i,k} \leq \Delta V_{max} \\ &V^{min}_o \leq V_{o,i} \leq V^{max}_o \end{aligned} \quad (17)$$

The first two constraints are set to meet desirable operating requirements, while the last two are modified to aid the optimization process in evaluating only realistic drop values. In the event

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that these limitations are violated, an auxiliary term $\delta_{d,k}$ is appended to E_T as follows:

$$E_T = \sum_{k=1}^{N_o}(w_c\delta_{c,k} + w_v\delta_{v,k} + \delta_{d,k}) \quad (18)$$

$$\delta_{v,k} = \delta_c(i_{o,i,k}) + \delta_v(\Delta V_{i,k}) \quad (19)$$

$$\delta_i(i_{o,i,k}) = 0: i_{o,i}^{min} \le i_{o,i,k} \le i_{o,i}^{max} \quad (20)$$

$$\beta: else$$

$$\delta_v(\Delta V_{i,k}) = 0: \Delta V_{i,k} \le \Delta V_{max} \quad (21)$$

$$\beta: \Delta V_{i,k} > \Delta V_{max}$$

Where $(\Delta V_{i,k}) = V_0 - V_{0,i,k}$ and the constant β depends upon the value of output voltage and output current of each source at a kth load condition.

2.2 Modelling of droop control using PSO generated references:

When considering unequal cable line resistance, the key problem of DC Microgrid is maintaining bus voltage management within acceptable limits and effective equal current sharing in per unit. Equal current sharing allows maximum power from source converters to be used up to the specified bus voltage regulation. A DC distributed system consists of a series of parallel connected DGs, source converter interfacing, droop resistance, cable line resistance, and a common load. In Figure 2, two DGs are taken into consideration to simplify traditional droop control analysis. The i^{th} source converters nominal reference voltage can be expressed as,

$$V^*_{o,i} = V_{o,i} + r_{d,i}i_{o,i} \quad (22)$$

Where $V^*_{o,i}$, $V_{o,i}$, $r_{d,i}$, $i_{o,i}$ are voltage reference, output voltage nominal values, droop resistance, the output current of i^{th} source converter respectively. The droop resistance is evaluated as,

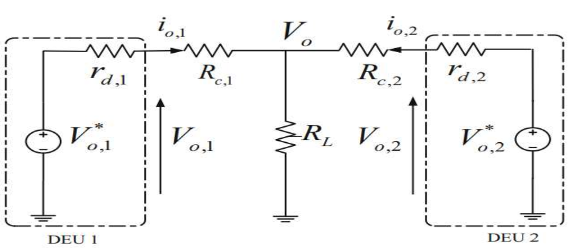

Figure 2: A Simplified simulation circuit.

$$r_{d,i} \le \frac{\Delta V_{max}}{i_{o,i}^{rated}} \quad (23)$$

Where ΔV_{max} is the 5% of DC bus rated voltage and $i_{o,i}^{rated}$ is rated source current of i^{th} converter. In steady state, the i^{th} source converter output voltage of is defined as:

$$V_{o,i} = V_o + R_{c,i}i_{o,i} \quad (24)$$

From (22) and (24), the current output of i^{th} converter is expressed as:

$$i_{o,i} = \frac{V_{o,i}{}^* - V_o}{(r_{d,i} + R_{c,i})} \quad (25)$$

The current sharing error in the presence of two DGs is expressed as:

$$\Delta i_{1,2} = \frac{(r_{d,2}+R_{c,2})(V_{o,1}{}^* - V_o) - (r_{d,1}+R_{c,1})(V_{o,2}{}^* - V_o)}{(r_{d,1}+R_{c,1})(r_{d,2}+R_{c,2})} \quad (26)$$

i_1, i_2 can be close to zero for equal current sharing, and this can be done by using droop resistances and a nominal voltage reference.

Due to the limitations of physical execution, the voltage references offset was investigated. The cable line resistance between the source converter and the DC bus cannot be expected to be zero in practice. Voltage reference offset is used to compensate for voltage drop caused by unequal cable line resistance.

The i^{th} source converter voltage reference offset of and bus voltage regulation are given as:

$$\delta V_{o,i} = V_{o,i}{}^* - V_o{}^* \quad (27)$$

$$\Delta V_o = V_o{}^* - V_o \quad (28)$$

The source converter output current error in (25) and bus voltage regulation are expressed as:

$$\Delta i_{12} = [(r_{d,2} + R_{c,2})(V_o{}^* + \delta V_{0,1} - V_o) - (r_{d,1} + R_{c,1})(V_o{}^* + \delta V_{0,2} - V_o)] / [(r_{d,1} + R_{c,1})(r_{d,2} + R_{c,2})] \quad (29)$$

$$\Delta V_o = \frac{1}{2}[(r_{d,1} + R_{c,1})i_{o,1} + (r_{d,2} + R_{c,2})i_{o,2} - \delta V_{o,1} - \delta V_{o,2}] \quad (30)$$

For similar droop resistance, the error in current sharing and DC bus voltage regulation are redefined as:

$$\Delta i_{12}{}' = \frac{(\delta V_{0,1} - \delta V_{0,2})}{(r_d + R_c)} < \Delta i_{12} \quad (31)$$

$$\Delta V_o = \frac{1}{2}\left((r_d + R_c)(i_{o,1} + i_{o,2}) - \delta V_{o,1} - \delta V_{o,2}\right) > \Delta V_o \quad (32)$$

Where, $(r_d = r_{d,1}{}' = r_{d,2}{}') > (r_{d,1}), (r_{d,2})$ and $(R_c = R_{c,1} = R_{c,2})$

Figure 4 shows the current sharing error and voltage regulation for various droop resistance values. When the droop resistance is bigger than the prior value, the current sharing error is reduced compared to previous current sharing. The bus voltage regulation is increased in this situation compared to the prior bus voltage regulation. When cable line resistance and droop resistance are adjusted, there is a trade-off between current sharing error and bus voltage regulation. As shown in Figure

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5, the droop resistances are tuned to reduce equal current sharing while keeping bus voltage regulation within allowed limits, which are given as:

$$\Delta i''_{12} = \left[\left(r''_{d,2} + R_{c,2}\right)\left(V_o^* + \delta V_{0,1} - V_o\right) - \left(r''_{d,1} + R_{c,1}\right)\left(V_o^* + \delta V_{0,2} - V_o\right)\right] / \left[\left(r''_{d,1} + R_{c,1}\right)\left(r''_{d,2} + R_{c,2}\right)\right] \quad (33)$$

$$\Delta V_o = \frac{1}{2}\left[\left(r''_{d,1} + R_{c,1}\right)i''_{o,1} + \left(r''_{d,2} + R_{c,2}\right)i''_{o,2} - \delta V_{o,1} - \delta V_{o,2}\right] \quad (34)$$

Where $r''_{d,1}$ and $r''_{d,2}$ are modified droop resistances. As a result, if the droop resistance and the offset voltage reference can be adjusted, the trade-off between current sharing error of the source converters and bus voltage regulation can be minimized within permitted ranges.

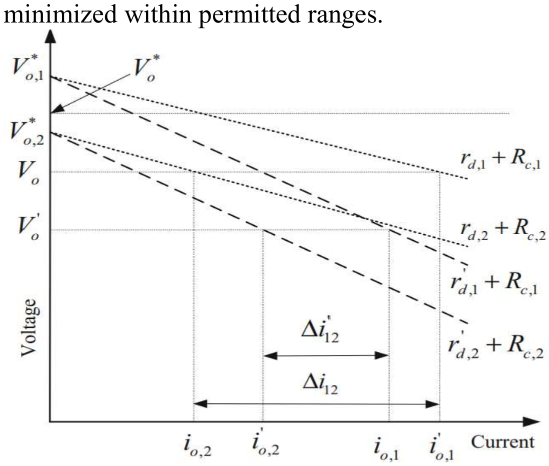


Figure 3: Droop curve in DC Microgrid for an equal droop resistance.

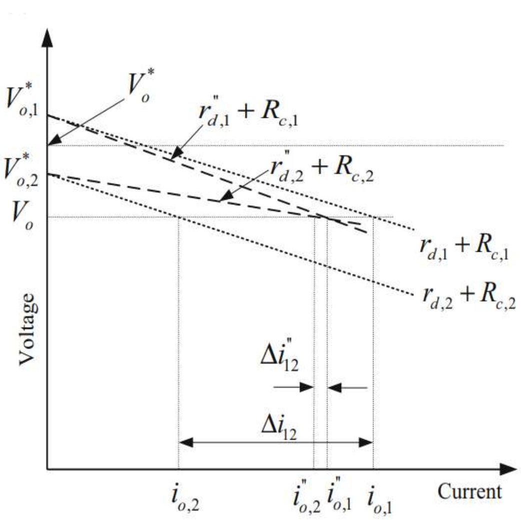


Figure 4: Droop curve in DC Microgrid for different droop resistances.

3. PROPOSED CONTROL STRATEGY

The major goal of the FIS for regulating droop resistances is to maintain DC bus voltage regulation within allowed limits by ensuring load current balance in per unit (p.u) among distributed energy sources. Through a communication link with the proposed control, all of the source converters communicate average current sharing in p.u [14]. The average current of the communication line is an important parameter for PI current control, and the PI controller generates the duty cycle

Droop resistance affects source converter reference current, and cable resistance affects bus voltage regulation. The voltage regulation on the bus should not exceed 5% of the reference bus voltage. As a result, the FIS should be built to follow the relationship between droop fluctuation and bus voltage regulation. Because the rated bus voltage is 600 V, the bus voltage range is 30 V within permitted limits. When voltage regulation (Vo) is near the minimal value, i.e., 25 V, the fuzzy rule is used, and droop resistance should be large because more droop resistance is required for minimizing circular current in parallel source converter operation. Maintaining the lowest droop resistance while Vo is at its greatest, i.e., +25 V.

The trapezoidal membership functions are used for controlling droop resistance when bus voltage regulation exceeds allowed limits, whereas the triangular membership functions are chosen for a linear zone of droop characteristic. The triangle membership functions are derived for linear zone bus voltage regulation between 25 and 25 V. For Medium negative (MN), small negative (SN), Null (NU), small positive (SP), and Medium positive (MP), these functions are examined (MP). Big negative (BN) for bus voltage regulation less than 25 V and Big positive (BP) for voltage regulation greater than 25 V are the trapezoidal membership functions. The membership function range is chosen in such a way that the relationship between incremental droop resistance and bus voltage regulation is linear. The droop resistance of the i^{th} source converter is thus managed as,

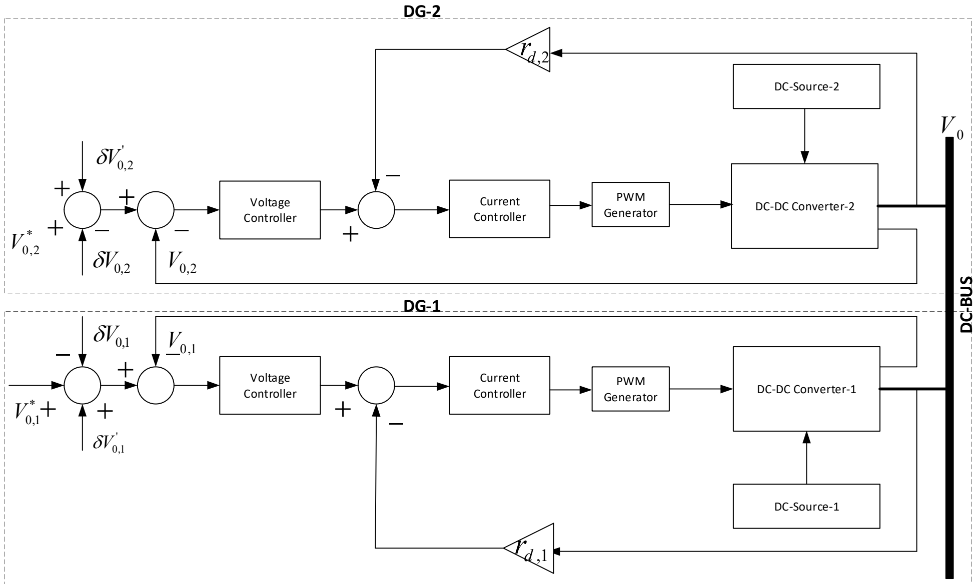
$$r_{d,i} = r_{d,o} + \Delta r_{d,i} \quad (35)$$

Where, $r_{d,o}$ and $\Delta r_{d,i}$ is static and dynamic droop resistance.

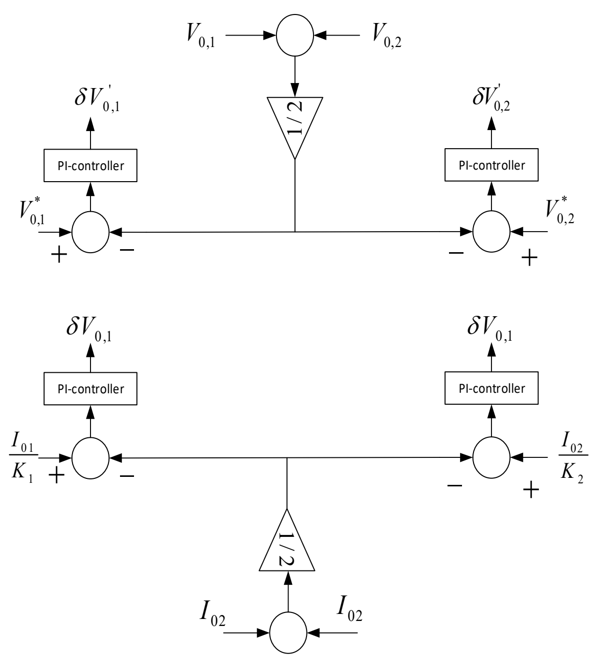
3.1 Existing conventional controller-based droop control strategy with optimized references obtained using PSO:

Figure 6 shows the PSO algorithms used in Eqns. (16) and (17) to find the best droop resistance and voltage reference for two source converters.

PSO is used to find the ideal droop settings when the training error E_T reaches a minimum value after more than 50 iterations, as shown in Figure 7. These droop resistance values are employed in the droop controllers for each converter at this level to achieve increased current sharing, accuracy, and reduced voltage degradation across the micro grid. As a second stage, a comparable DC micro grid is required to estimate the entire error value. The output currents of the converters and the source converter voltages in the DC Microgrid are estimated during the simulation stage using the most recent particle, i.e., droop resistance and voltage reference (r_{di}, V_{ref}) for $i = 1, 2$ source converters. The estimated output current and node voltage values are utilized in the last stage to determine the ideal minimum fitness value E_T and the PSO tool optimal parameters, which are presented in Table 5.1.



(a)



(b)

Figure 5: Detailed configuration of distributed control scheme of dc micro grid(a) and its distributed secondary control scheme(b).

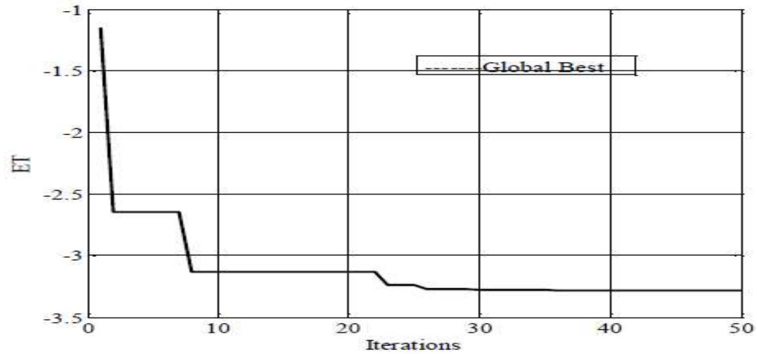


Figure 6: The trajectory of global minimum total error currents.

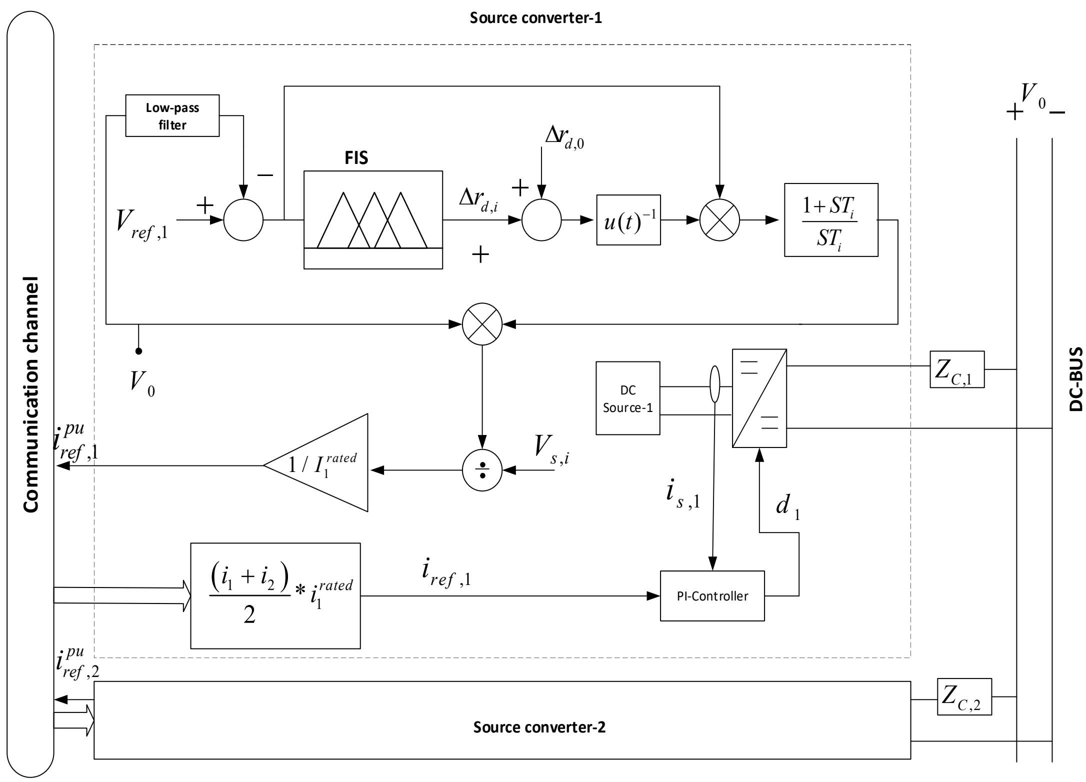


Figure 7: The proposed control block diagram of DC Microgrid.

3.2 Modified Fuzzy logic controller-based droop Control droop strategy with optimized references generated using PSO:

Figure 8, shows that the suggested fuzzy control strategy outperforms traditional PI control in terms of improving transient response and lowering mean squared error [15]. Without selecting an offset reference voltage, each droop controller tries to balance an impedance behavior by altering the converter output voltage in response to changes in the source converter current. From the suggested distributed control block diagram, the current and power reference of the i^{th} source converter is expressed as:

$$I_{ref,i} = G_i(s) * \left(V_{ref,i} - \left(\frac{w_{Lpf,i}}{s+w_{Lpf,i}}\right) * V_{o,i}\right) * \frac{V_{o,i}}{V_{s,i}} \quad (36)$$

$$P_{ref,i} = I_{ref,i} V_{o,i} \quad (37)$$

$$G_i(s) = \frac{1}{r_{d,i}}\left(1 + \frac{1}{sT_i}\right) \quad (38)$$

$$T_i = \frac{4}{w_{Lpf,i}} \quad (39)$$

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Where T_i the integral is time constant, and $w_{Lpf,i}$ is the low-pass filter cut-off frequency.
It is for cutting off high harmonic frequencies and quick oscillations of the DC micro grid bus voltage of the i^{th} source converter. Substituting Eqn. (37) for (38) and assuming a low-pass filter gain of zero dB, the source rated power is given as:

$$P_{rated,i} = D_i(1 - D_i)\frac{V_{ref,i}^2}{r_{d,i}} \quad (40)$$

Where,

$$D_i = \left(1 - \frac{V_{o,i}}{V_{ref,i}}\right) \quad (41)$$

The control surface of fuzzy inference system is shown in Figure 8.The corresponding member ship functions for inputs, voltage and change in voltage and output, change in droop resistance as are shown in **Error! Reference source not found.**.

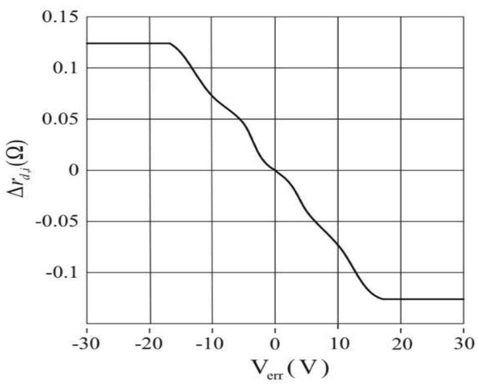

Figure 8: Control surface of the FIS.

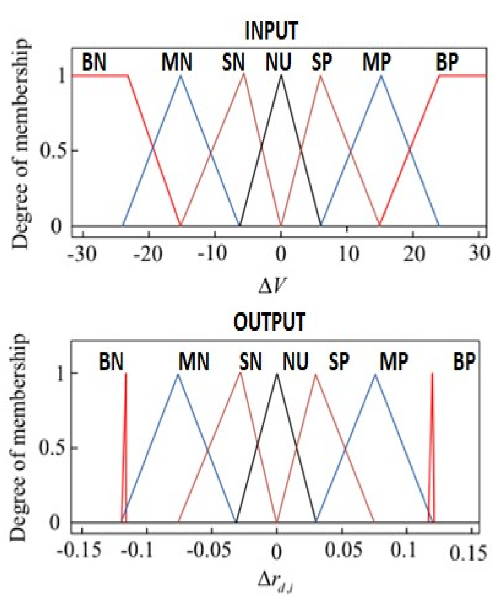

Figure 9: Membership functions: change in bus voltage as input and corresponding change in droop resistance as output $\Delta r_{d,i}$.

Table 1 : Fuzzy rules for $\Delta R_{d,i}$.

	Input-1 ΔV, input-2 d/dt ΔV, Output $\Delta r_{d,j}$						
	BN	**MN**	**SN**	**ZO**	**SP**	**MP**	**BP**
BN	BP	BP	BP	MP	MP	SP	NU
MN	BP	MP	MP	MP	SP	NU	SM
SN	BP	MP	SP	SP	NU	SN	MN
NU	MP	MP	SP	NU	SN	MN	MN
SP	MP	SP	NU	SN	SN	MN	BN
MP	SP	NU	SN	MN	MN	MN	BN
BP	NU	SN	MN	MN	BN	BN	BN

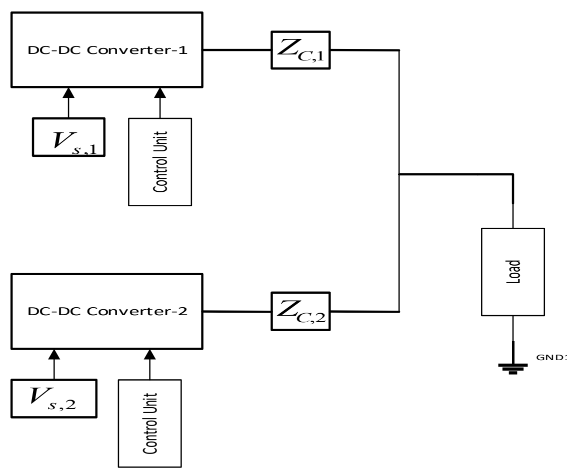

Figure 10: The block diagram of simulation circuit.

4. SIMULATION RESULTS

The block diagram of simulated system is shown in Figure 10.The simulation is carried out for two cases explained as below:

Case1:

In the first case, droop control parameters are optimized with PSO and substituted in the existing control strategy and, the best solution obtained as shown in Figure 12,

BestSol =
Position: [596.3713 630 2 2 5.7856 8]
Cost: -0.02775

PSO output with additional coefficients Kappa, phi, Chi **as** shown in Figure 13,

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BestSol =
Position: [616.8481 629.8044 2 1.9803 8 8]
Cost: -0.00056

Table 2: Simulated system and controller parameters.

Item	Symbol	Value	Unit
DC Supply ($\forall_i$=1, 2)	$V_{s,i}$	200	V
Inductance of DC-DC converter.	L	10e-3	H
Capacitance of DC-DC converter.	C	20e-3	F
Line parameters	$Z_{c,1}$ $Z_{c,2}$	2+5e-3i 3+5e-3i	Ω Ω
Load		1.2-5.7	kW
Controller parameters: Reference voltage ($\forall_i$=1, 2)	$V_{ref,i}$	600	V
Current rating for i^{th} converter	I_i^{rated}	8	A
Droop resistance ($\forall_i$=1, 2)	$r_{d,o}$	1.4	Ω
Number of source converters	N	2	
Low-pass filter cutting frequency	w_{Lpf}	100π	Rad/sec
Time constant	T_i	4/100π	s

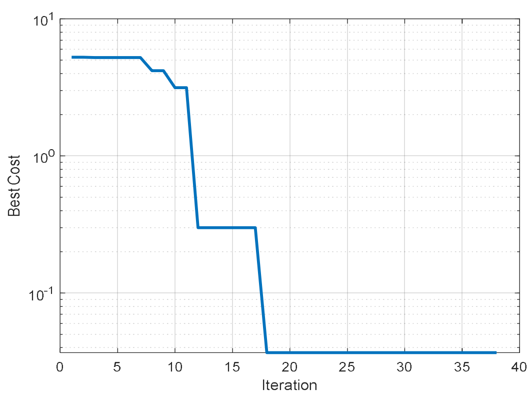

Figure 11: Output for PSO without additional coefficients.

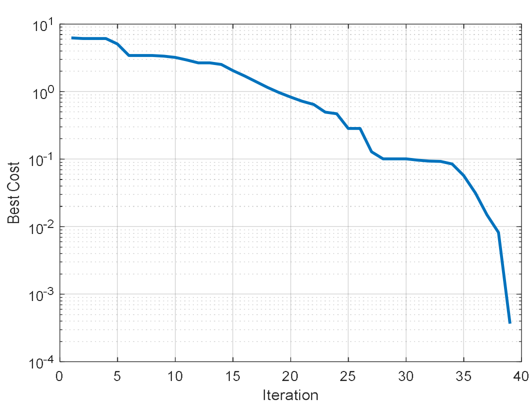

Figure 12: Output for PSO with additional coefficients.

Best cost values without and with considering the additional coefficients are shown in Figure 11 and Figure 12 respectively. By including these parameters, the cost function is comparatively converged better. DC link Voltage and total load current waveforms with PSO are shown in Figure 13.It is clear that DC link voltage and current are reached its reference value, i.e., 600V within 0.01 sec. Thus, the transient response is remarkably good.

Current Sharing among DGs without optimization and without droop resistance (rd1=rd2=0) is shown in Figure 14.
Current Sharing among DGs with particle swarm optimization and droop resistance (rd1=1.7686; rd2=0.8542) is shown in the Figure 15.
In this case the current sharing among DGs is almost identical and its value is I1=I2=4.8A. Voltage current waveforms with load changes from 2850 watts to 5700 watts with PSO (rd1=1.7686; rd2=0.8542) is shown in the Figure 16.At 0.4 sec the controller response time to change in load current is 0.05 sec.

Case2:

In the second case, Parameters are optimized using PSO and are considered as reference parameters for implementing the modified fuzzy based control strategy in which existing PI controllers are replaced with fuzzy controllers.

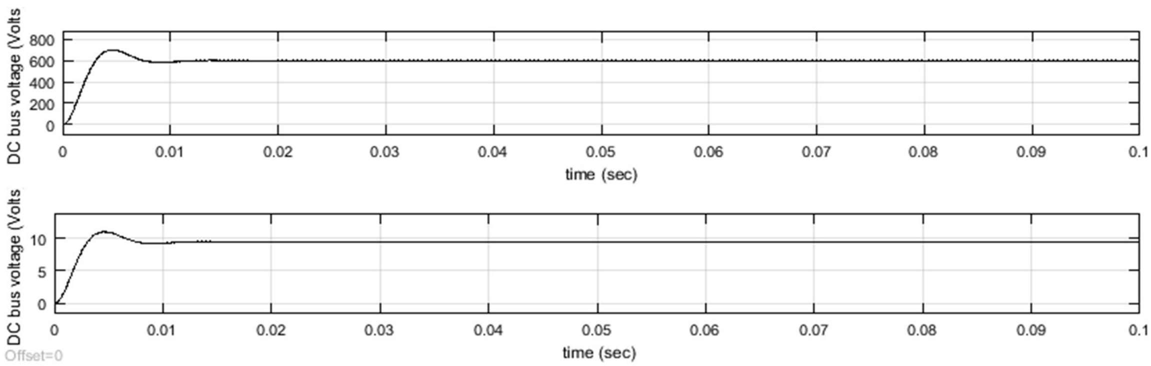

Figure 13: Voltage waveforms with PSO.

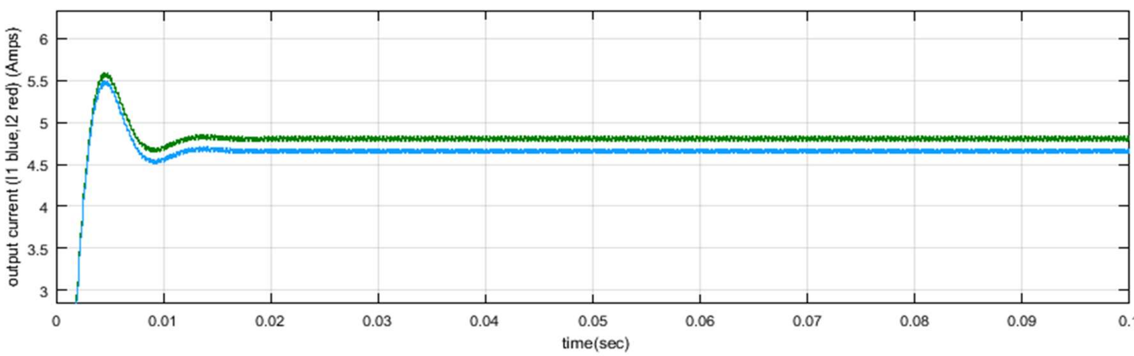

Figure 14: Current sharing without PSO.

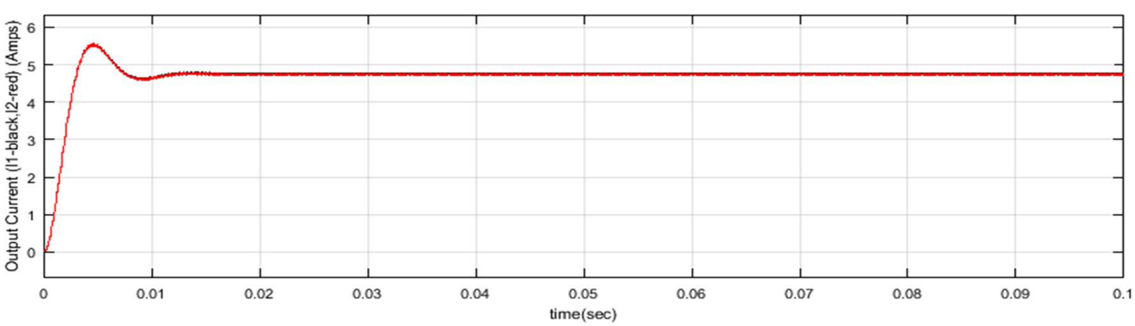

Figure 15: Current sharing with PSO.

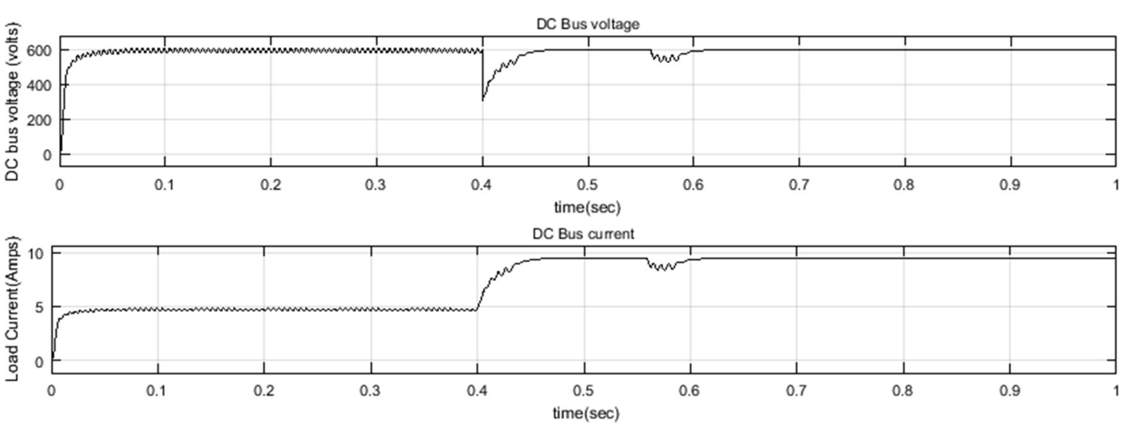

Figure 16: Voltage current waveforms with load changes.

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In Figure 17, it is evident that the response time of DC link voltage with fuzzy controller to reach its reference value is 0.002 sec which is exceptionally fast compared to conventional droop control. Similarly, the current response time is also simultaneously improved as shown in Figure 18 with Fuzzy and PSO.

Voltage and total load current waveforms of DGs with load changes from 2850 watts to 5700 watts with Fuzzy and PSO with different droop characteristics (rd1=1.7686; rd2=0.8542) is shown in Figure 19, and its corresponding current sharing between two DGs is shown in Figure 20.

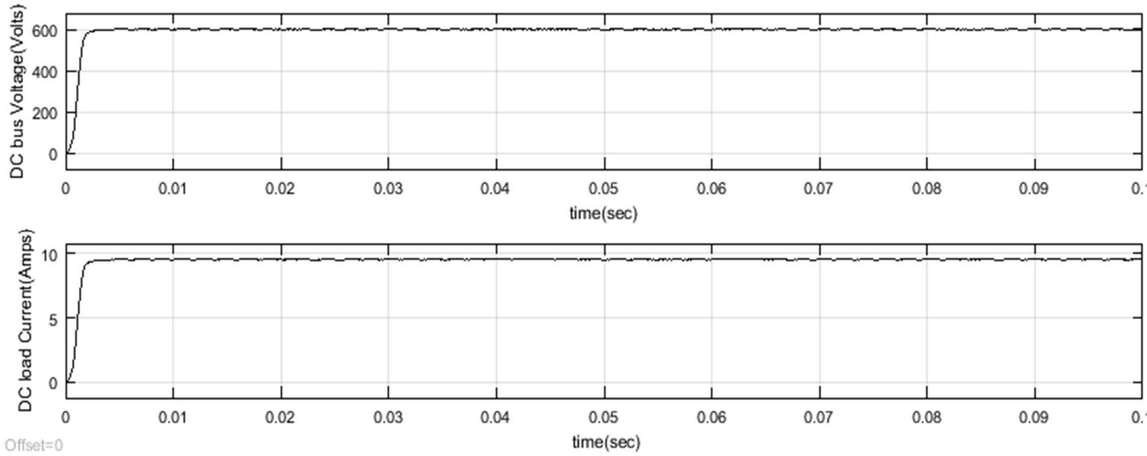

Figure 17: Voltage current waveforms with Fuzzy PSO.

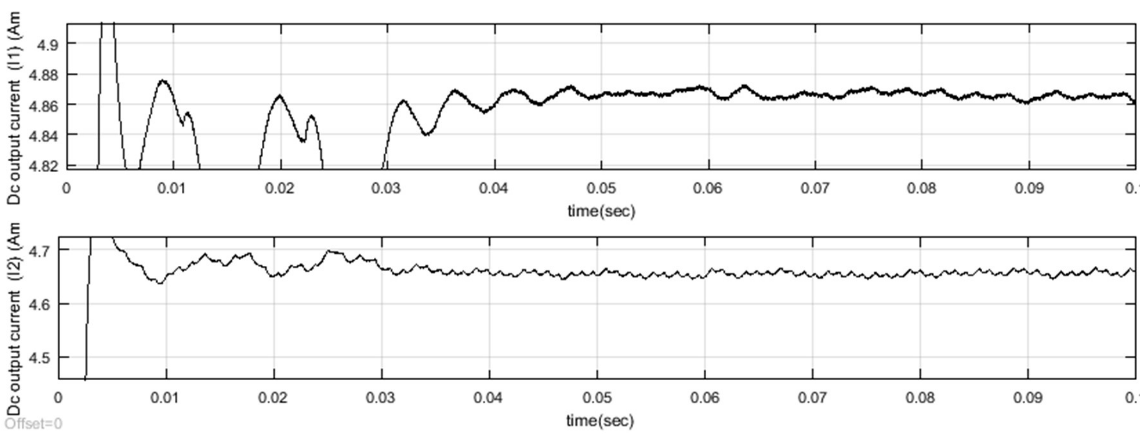

Figure 18: Current sharing with Fuzzy and PSO.

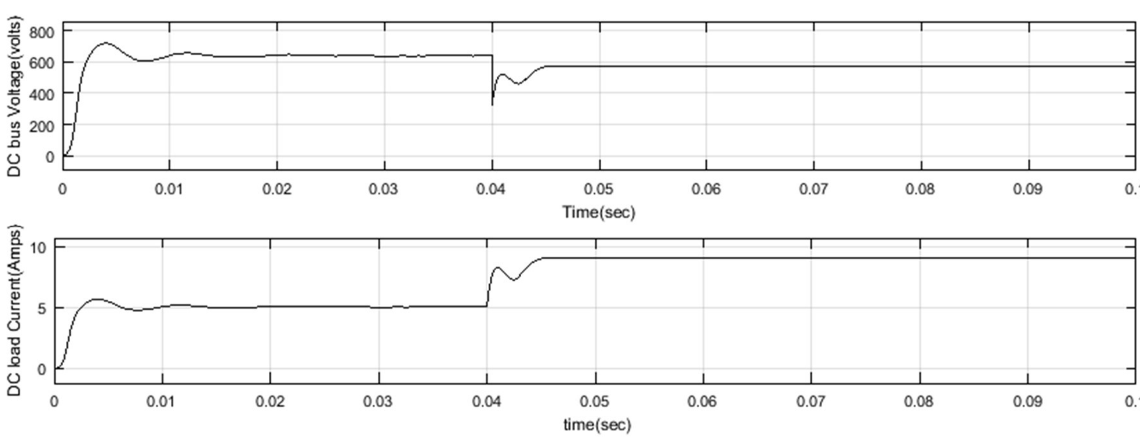

Figure 19: Voltage current waveforms with load changes.

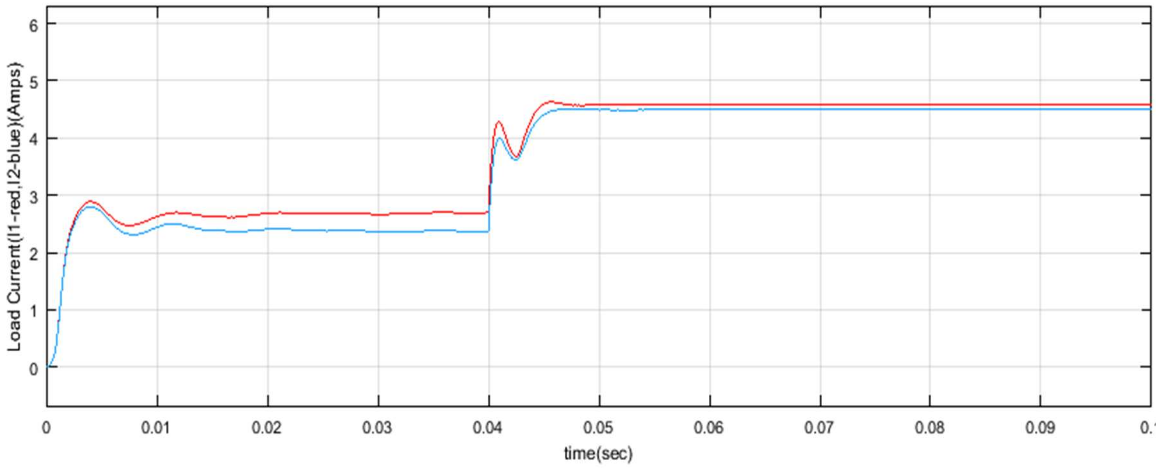

Figure 20: Current sharing between two DGs using Fuzzy and PSO.

Table 3: PSO Parameters for DC Microgrid

Optimization parameters	Value
Desired system voltage, V_0	600V
Constant weight for δ_c , W_c	0.8
Constant weight for δ_v, W_v	0.1
Droop resistances, r_d^{min}, r_d^{max}	0.1 Ω,10 Ω
Voltage references, V_0^{min}, V_0^{max}	570 V,630 V
Inertial Weights, W_{min}, W_{max}	0.3,0.9
Acceleration Constants, C_1,C_2	0.5,0.3
Maximum iterations, K_{max}	40
Number of particles, N_p	40

Table 4: System Parameters.

DC Microgrid parameters	Value
DC supply, V_{in}	200V
Output capacitance, C	2.2e-3
Current rating for i^{th} converter, $i_{0,i}^{max}$	8A
Converter inductance, L	10e-3H
Switching frequency, f_{sw}	10KHz
Duty cycle, d	0.649-0.683
Nominal bus reference voltage, V_{ref}	600V
Droop resistance, r_d	$0 < r_d < 10$

Optimal reference voltages, V_{ref}^{opt}	605.4V to 695.6V
Optimal droop resistances, r_d^{opt}	0.6 Ω,0.9 Ω
Cable impedance, Z_{c1} #1	2+50e-3i Ω
Cable impedance, Z_{c2}#2	5+50e-3i Ω
Load resistance, R_{load}	60-120 Ω

Table 5: System parameters for PSO and Fuzzy

System Parameter		Value
DC-DC converter		
Input Voltage, V_{in}		200V
Output Voltage, V_{out}		600V
Inductance, L		7.4e-3
Capacitance, C		1.75e-5
Switching frequency, F_{sw}		15KHz
DC cable resistance		
R_{c1}		2
R_{c2}		0.79e-2
L_{c1}		4
L_{c2}		0.79e-2
Control and Optimization parameters		
PSO	K_{pv}, K_{iv}	100, 909.09
	K_{pv},K_{ic}	100, 9090.09

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5. CONCLUSION

Voltage regulation with Fuzzy PSO is improved, but Current Sharing is better in PSO alone than Fuzzy PSO technique. In Fuzzy PSO technique, Droop parameters obtained in PSO is substituted as reference for Fuzzy and change in droop resistance obtained from fuzzy is added to this reference to obtain overall droop resistance for both DC-DC converters. In Fuzzy we get the voltage contains small number of ripples but the main advantage here is in operates in less time when compared to the PSO. Where in PSO we get ripple free output but it takes some amount of time to settle. Here we are changing the half load to full load in a span of time to observe working of the PI controllers in changing of load.

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