

Voltage regulation and enhance load sharing in DC microgrid based on Particle Swarm Optimization in marine applications

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In this paper, the droop gain and voltage reference are optimized to help of Particle Swarm Optimization (PSO) technique such that the effect of the line impedances is minimized which is well accommodated for marine applications. An optimization problem is formulated with necessary constraints for various loads. The performance of the droop controller with the optimal droop parameters of dc distributed control scheme is verified through a simulation implemented in the MATLAB/Simulink environment.

[**Keywords:** Marine applications dc microgrid, load sharing, voltage regulation, droop control, PSO.]

Introduction

The concept of the microgrid was proposed several years ago in order to integrate sustainable energy sources and energy storage systems to electrify a remote area¹. In order to integrate various renewable energy sources, loads and modernized power converter such as photovoltaic modules, energy storage system, dc loads and efficient power converter have natural dc coupling. The dc microgrid is free from reactive power and harmonics. System efficiency and power quality are observed higher compared to ac systems²⁻³. Advantages of parallel-connected converters are expandability of output power, reliability, efficiency, and ease of maintenance⁴⁻⁵. It is also utilized in marine power application such as high quality power, reliable power supply, and high power conversion^{5, 6}.

The causes of dc bus voltage variations are sudden variations in the input power, parametric variations, load, and feedback error in current and voltage. Circulating current issues will arise if there is a mismatch in the converted output voltages⁷.

Primary control objective in parallel connected dc source is the output voltage within permissible limits, effective load sharing and high degree of power reliability⁸⁻¹². Hierarchical control structure divides overall control methodology in three levels. The primary control level is based on the droop-control method. It can include a virtual impedance control loop to emulate physical output impedance. Secondary control level regulates bus voltage regulation and the tertiary control level regulates power flow between dc microgrid and connected local grid. Primary and secondary control is attained by decentralized, centralized and distributed control¹¹⁻¹³. From the communication aspect, decentralized control schemes utilize power lines as dc bus signal is utilized for channel communication and does not exist in digital communication links. Therefore, the channel communications are normally used only for shutting corrupted components or changing operating modes of the system. However, it is not desirable for power sharing¹¹. Centralized control schemes are implemented based on a central controller and

communicates line with all other units through dedicated digital communication links. It provides the highest level of flexibility for achieving advance functionalities. There is the possibility of a single point of failure. In this way other units are over stressed which may lead to system instability¹². The distributed control scheme does not operate on based on central control units. This scheme only involves, among local controllers which can communicate through dedicated communication links and local controller can obtain local parameters knowledge by consensus principle. However, the system stability is degraded when communication delay increases in case of a communication dependent control scheme. Therefore, the distributed control schemes have been executed with the advantage over centralized and decentralized schemes such as reliability¹¹⁻¹², power quality¹⁴, stability¹², efficiency¹⁵ and expandability¹⁶.

In case of distributed control scheme, the aforementioned problem can be minimized through the compensation method without any additional communication, but there is a need for information about line parameters throughout the grid¹⁷. In¹⁸⁻¹⁹, line resistances estimation is implemented in place of the pre-calculated values, it requires the grid connected mode of operation for calculating line impedance before island mode operation. In this regard, the distributed controllers specify fixed parameters that yield optimized performance on an average basis as the system parameters vary within their specified limits.

In this paper, a robust droop-based distributed controller for dc microgrid is proposed. It is not an alternative to the distributed controller; rather it is demonstrated to have a complementary role, such that it can be implemented when there is a failure in the communication system. Trade-off between output current sharing and bus voltage regulation is minimized by optimized droop parameters which is based on PSO technique. It is verified for distributed control system where a communication system with low bandwidth is used to exchange information with a microgrid management center such that any modification in the parameters is imposed on-line in a response to major changes in the topology.

Materials and Methods

In Fig. 1, a dc microgrid has been consider help of two parallel connected dc distributed energy units (DEU), interfacing through source converter, droop resistance, cable resistance and common dc bus load sake for simplicity.

Reference voltages of output source converters can be expressed by

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

where as $V_{o,i}^*$, V_{ref} , $r_{d,i}$ and $i_{o,i}$ are the local output voltage reference, the global voltage reference, droop resistance and the output current of the i^{th} converter respectively.

The droop resistance of i^{th} converter may be optimized as⁶

$$r_{d,i} \gg \frac{\Delta V_{max}}{i_{o,i}^{max}} \tag{2}$$

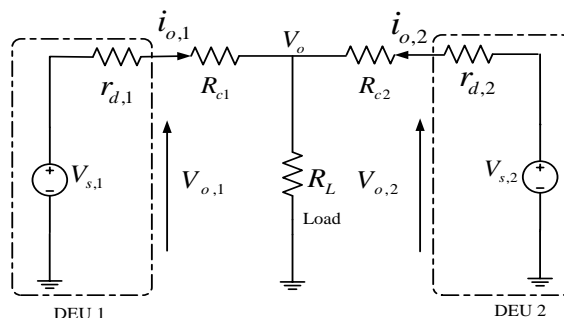


Fig. 1- Simplified model of a two-node dc microgrid.

where ΔV_{max} is the 5% of rated bus voltage and $i_{o,i}^{max}$ is maximum output current of i^{th} source converter.

In steady state, the output voltage and source converter output current of i^{th} source are expressed as

$$V_{o,i} = V_{s,i} - r_{d,i} i_{o,i} \tag{3}$$

$$V_{o,i} = V_o - R_{c,i} i_{o,i} \tag{4}$$

$$i_{o,i} = \frac{V_{s,i} - V_o}{(r_{d,i} + R_{c,i})} \tag{5}$$

where $V_{s,i}$ is input source voltage, $R_{c,i}$ is cable line resistance and V_o is the bus voltage.

The circulating current between the two converters can be expressed in Fig. 2 as:

$$\Delta i_{12} = \frac{(r_{d,2} + R_{c,2})(V_{o,1} - V_o) - (r_{d,1} + R_{c,1})(V_{o,2} - V_o)}{(r_{d,1} + R_{c,1})(r_{d,2} + R_{c,2})} \tag{6}$$

For proportional equal current sharing, Δi_{12} (6) can approximately equal to zero and this can be achieved by selecting droop resistances and a voltage reference according to the converter source module.

For two dc distributed energy sources, the voltage references offset analyzed due to the limits of physical execution. Significant unequal load distribution is a result of small sensed offset voltage^{7,13}. The droop characteristics for both energy sources are shown in

Fig 2. The proportional current sharing error can be finalized as

$$\Delta i_{12} = \frac{(r_{d,2} + R_{c,2})(V_o^* + \delta V_{o,1} - V_o) - (r_{d,1} + R_{c,1})(V_o^* + \delta V_{o,2} - V_o)}{(r_{d,1} + R_{c,1})(r_{d,2} + R_{c,2})} \quad (7)$$

where V_o^* is the rated bus voltage, $\delta V_{o,1}$ and $\delta V_{o,2}$ are reference offset voltage. If the droop resistances and the line resistances are equal $r_{d,1} = r_{d,2} = r_d$ and $R_{c,1} = R_{c,2} = R_c$, the bus voltage drop and current sharing error can be expressed as

$$\Delta V_o = \frac{1}{2} [(\delta V_{o,1} + \delta V_{o,2} - (r_d + R_c)i_o)] \quad (8)$$

$$\Delta i_{12} = \frac{(\delta V_{o,1} - \delta V_{o,2})}{(r_d + R_c)} \quad (9)$$

where i_o is the steady state of load current.

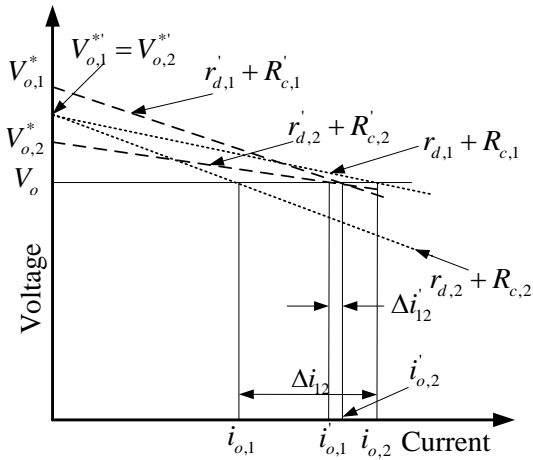


Fig. 2- Droop curve in DC microgrid with different droop resistance and source converter output voltages.

In Fig. 2, the droop resistances and output voltage references are adjusted so that minimized trade-off between proportional equal current sharing and bus voltage regulation within permissible limits. If $r_{d,1}' > (r_{d,1}$ or $r_{d,2})$, the current sharing error and bus voltage regulation may be given as:

$$\Delta i_{12}' = \frac{(\delta V_{o,1} - \delta V_{o,2})}{(r_{d,1}' + R_{c,1}')} < \Delta i_{12} \quad (10)$$

$$\Delta V_o' = \frac{1}{2} [(\delta V_{o,1} + \delta V_{o,2} - (r_{d,1}' + R_{c,1}')i_L)] > \Delta V_o \quad (11)$$

Due to various geographical locations, cable resistances of two cable lines are not practically equal¹³, it provides significant changes in current sharing and voltage regulation in Fig. 2. The proportional current sharing error and bus voltage regulation can be finalized as:

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

$$\Delta V_o = V_o - \frac{r_d + R_{c,1}}{2r_d + R_{c,1} + R_{c,2}} \quad (13)$$

The main objective in the proposed approach is to optimize the voltage references of source converters and droop resistances by minimizing the average of the current sharing error and voltage deviation across the dc microgrid. This objective is to overcome current sharing error and to maintain dc microgrid voltage in the permissible limit over different loading condition for different cable line impedances.

The optimization problem is formulated as searching the optimal droop resistance and voltage reference values for all sources to minimize current sharing error δ_c and voltage degradation error δ_v . For k^{th} loading condition these errors can be expressed by

$$\delta_{c,k} = \sqrt{\sum_{i=2}^N \left(\frac{(i_{o,1,k} i_{o,i}^{\max} - i_{o,i,k} i_{o,1}^{\max})^2}{(i_{o,i}^{\max})^2} \right)} \quad (16)$$

$$\delta_{v,k} = V_o - \sum_{i=1}^N \frac{V_{o,i,k}}{N} \quad (17)$$

where V_o is desire dc bus voltage, $V_{o,i,k}$ is the voltage across of i^{th} module converter and $i_{o,i,k}$ is the output current of i^{th} module, for k^{th} loading condition. The error $\delta_{c,k}$ depends upon droop resistance parameters and $\delta_{v,k}$ can minimize by selecting $V_{o,i,k}^*$ reference voltage of i^{th} module for k^{th} loading. The error in the dc microgrid system can be described as

$$e_k = w_c \delta_{c,k} + w_v \delta_{v,k} \quad (18)$$

where w_c and w_v are the weights for the $\delta_{c,k}$ and $\delta_{v,k}$.

Therefore, the total error function can be expressed as:

$$E_T = \sum_{k=1}^{N_o} (w_c \delta_{c,k} + w_v \delta_{v,k}) \quad (19)$$

and constraints are expressed by

$$\begin{cases} V_o - V_{o,i,k} \leq \Delta V_{\max} \\ i_{o,i}^{\min} \leq i_{o,i,k} \leq i_{o,i}^{\max} \\ r_d^{\min} \leq r_{d,i} \leq r_d^{\max} \\ V_o^{\min} \leq V_{o,i} \leq V_o^{\max} \end{cases} \quad (20)$$

The first two constraints are specified to satisfy desired operational requirements and the last two constraints in (20) are adjusted to help the optimization process to appraise only realistic droop parameters.

In case of any violation of these constraints, an auxiliary term $\delta_{d,k}$ is added to E_T as follows

$$E_T = \sum_{k=1}^{N_o} (w_c \delta_{c,k} + w_v \delta_{v,k} + \delta_{d,k}) \quad (21)$$

$$\delta_{d,k} = \delta_c(i_{o,i,k}) + \delta_v(\Delta V_{i,k}) \quad (22)$$

$$\delta_c(i_{o,i,k}) = \begin{cases} 0 & i_{o,i}^{\min} \leq i_{o,i,k} \leq i_{o,i}^{\max} \\ \beta & \text{else} \end{cases} \quad (23)$$

$$\delta_v(\Delta V_{i,k}) = \begin{cases} 0 & \Delta V_{i,k} \leq \Delta V_{\max} \\ \beta & \Delta V_{i,k} > \Delta V_{\max} \end{cases} \quad (24)$$

where $\Delta V_{i,k} = V_o - V_{o,i,k}$ and β is the constant, depends on the value of output current and output voltage of each source at any loading condition.

The PSO procedure was initially personalized the behavior of animal which is searching food and bird clumping. This PSO procedure provides facilities a population based searching for the optimum collection. This technique starting from randomly generated particles as demonstrated in Fig. 3²⁰. In that, each particle modifies its position and velocity based on its previous experience. The rest particles modified in such way so that these converged to global best result. In PSO algorithm, formula for position and velocity vector for each particle are expressed as²⁰⁻²⁴

$$v_q^{j+1} = w^j v_q^j + c_1 r_1 [x_{pbest,q} - x_q^{j+1}] + c_2 r_2 [x_{gbest} - x_q^{j+1}] \quad (25)$$

$$x_q^{j+1} = x_q^j + v_q^{j+1} \quad (26)$$

where $x_q^j = [x_{q1}, x_{q2}, \dots, x_{qN}]$ and

$v_q^j = [v_{q1}, v_{q2}, \dots, v_{qN}]$ are position, velocity of the q^{th} particle. The r_1 and r_2 are uniform random variables which lies in the range [0, 1]. The c_1 and c_2 are the acceleration constant that are used to define the effect of the local and global best positions on the movement of the N number of random particles. The w^j is the inertia weight for j^{th} iteration, which is defined as²¹

$$w^j = w_{\max} - (w_{\max} - w_{\min}) \frac{j}{j_{\max}} \quad (27)$$

where j_{\max} is the maximum number of iterations in computational run. The appropriate selection of w is required to achieve an equilibrium between local and global search²¹⁻²⁴. This is generally achieved decreasing the w linearly from the w_{\max} to w_{\min} . Similarly the global best position and local best position are traveled by any particle as:

$$x_{gbest} = [x_{gbest1}, x_{gbest2}, \dots, x_{gbestN}]^T \quad (28)$$

$$x_{pbest,q} = [x_{pbest,q1}, x_{pbest,q2}, \dots, x_{pbest,qN}]^T \quad (29)$$

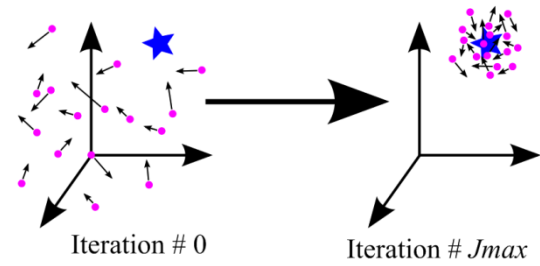
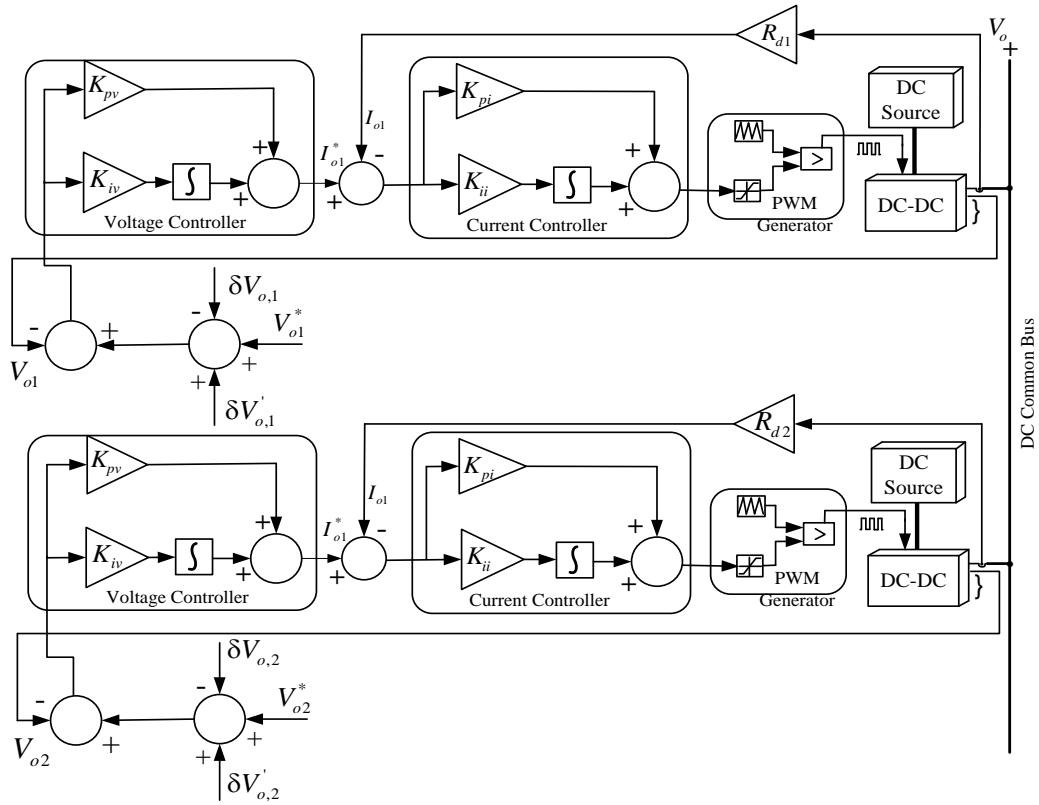


Fig. 3- Convergence of PSO random particles in i^{th} dimension

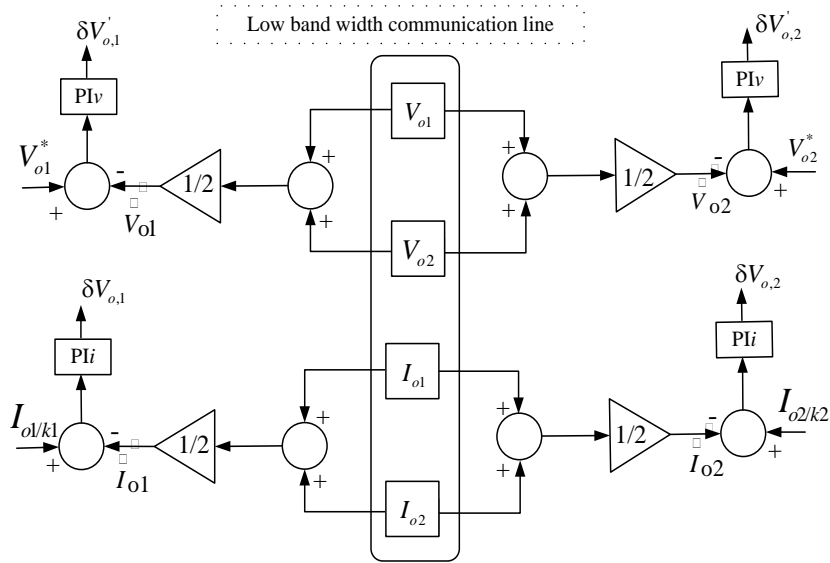
The PSO algorithm is used in (19-20) to seek for the optimal droop resistance and voltage reference for two source converters as given in Fig. 4. The optimal droop parameters are selected after over fiftieth iteration as shown in Fig. 6. These values are later used in the droop controllers implemented on each converter to realize improved current sharing, accuracy and reduced voltage degradation across the microgrid. In order to estimate the value of total error, a simulink dc microgrid is required as a second stage.

Table 1- PSO Parameters for dc microgrid

Optimization parameters	Symbol	Value	Unit
Desired system voltage	V_o	600	V
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, 10	Ω
Voltage references	V_o^{\min}, V_o^{\max}	570, 630	V
Inertia weights	w_{\min}, w_{\max}	0.3, 0.9	-
Acceleration constants	c_1, c_2	0.5, 0.3	-
Max. Iteration	k_{\max}	40	-
Number of particles	N_p	40	-



(a)



(b)

Fig. 4- Detailed configuration of distributed control scheme of dc microgrid.

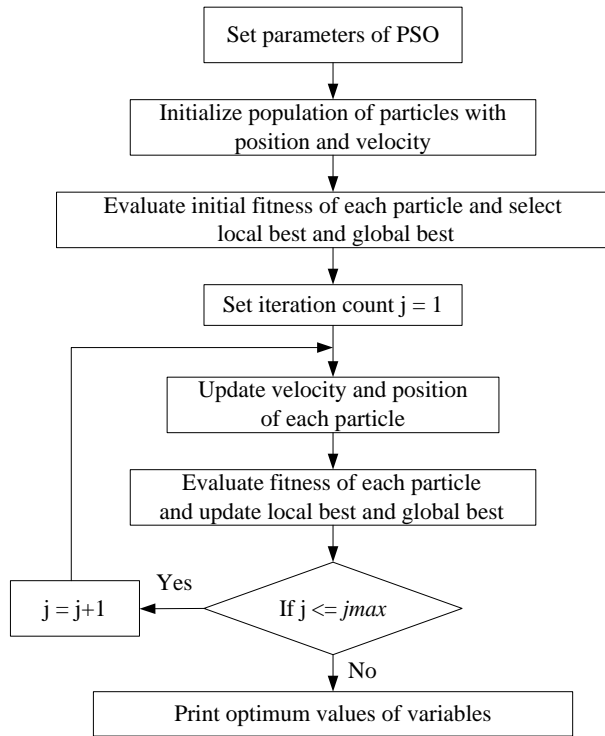


Fig. 5- Flowchart of PSO

Table 2- System parameters

DC microgrid Parameters	Symbol	Value	Unit
DC supply	V_{in}	200	V
Output capacitance	C	2.2e-3	F
Current rating for i^{th} converter	$i_{o,i}^{max}$	8	A
Converter inductance	L	10e-3	H
Switching frequency	f_{sw}	10	kHz
Duty cycle range	d	0.649-0.683	-
Nominal bus reference voltage	V_{ref}	600	V
Droop resistance	r_d	$0 < r_d < 10$	Ω
Optimal reference voltage	V_{ref}^{opt}	605.4, 594.6	V
Optimal droops resistance	r_d^{opt}	0.6, 0.9	Ω
Line impedances #1	$Z_{c,1}$	$2+50e-3i$	Ω
Line impedances #2	$Z_{c,2}$	$3+50e-3i$	Ω
Load resistance	R_{load}	60-120	Ω

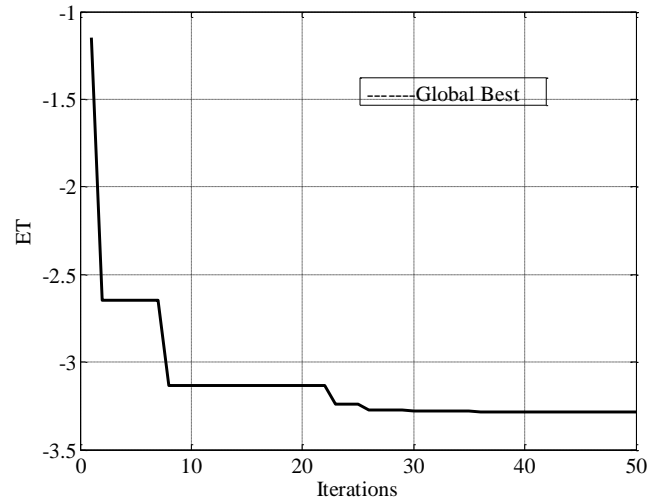


Fig. 6- The trajectory of global minimum total error values.

During the simulation stage, the output currents of the converters and the source converter voltages in the microgrid are calculated based on the recent particle i.e droop resistance and voltage reference $(r_{d,i}, V_{ref,i})$ for $i=1,2,\dots,N_o$ source converters. In the last stage, the calculated output current and node voltage values are used to determine the optimum minimum fitness value E_T and the optimal parameters for PSO tool are summarized in Table 1.

Results and Discussion

A simulation study for two parallel dc sources connected to common load has been implemented on MATLAB/Simulink. Basic circuit model and distributed control block diagram¹² of simulink test are shown in Figs. 1 and 5 respectively. The system parameters are summarized in Table 2. Cable line resistance of the two parallel source converter is considered as 3Ω and 2Ω respectively. Performance of distributed control dc microgrid with the optimal droop parameters is tested for low, medium and high loading condition. There are two tests conducted, one based on conventional droop control and second on optimized droop parameters by distributed control method. The conventional droop control test is activated up to 0.5 sec. and distributed control test based on optimize droop parameters is performed after 0.5 sec. The parallel source converters current are shown in Fig. 7 for common resistive load 80Ω , 100Ω and 120Ω . The current sharing error easily can be observed after 0.5 sec.

It is minimized significantly. Simultaneously, the dc bus voltage can be observed within permissible limits in Fig. 8. Current sharing errors and dc bus voltage regulations for both tests are summarized in Fig. 9 (a) and 9 (b) respectively. It can be observed that the trade-off between equal load sharing and dc bus voltage regulation is achieved up to 9 kW load.

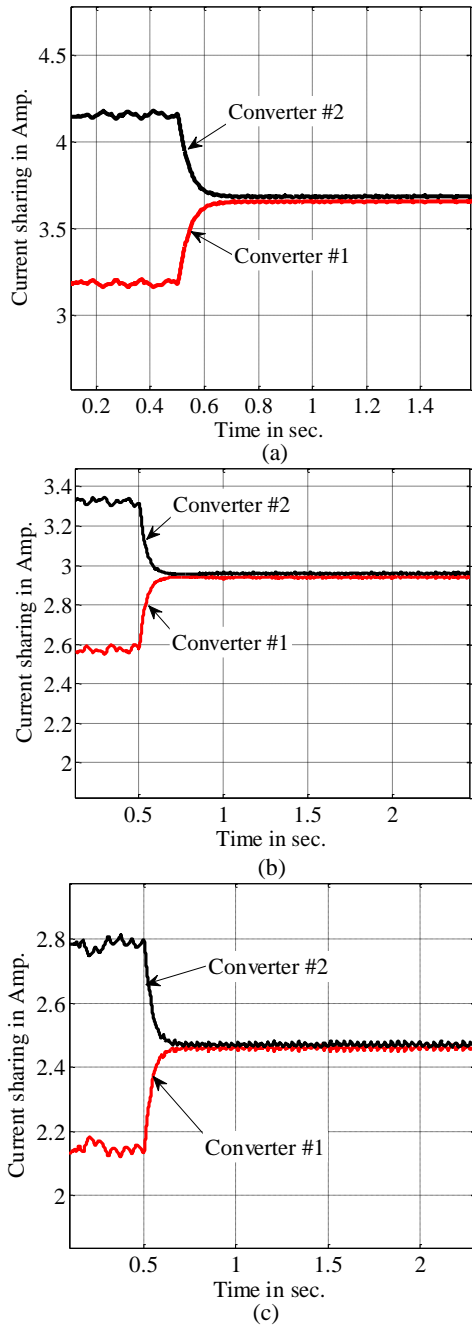


Fig. 7- The output load sharing for source converters to loads (a) 80 Ω (b) 100 Ω and (c) 120 Ω.

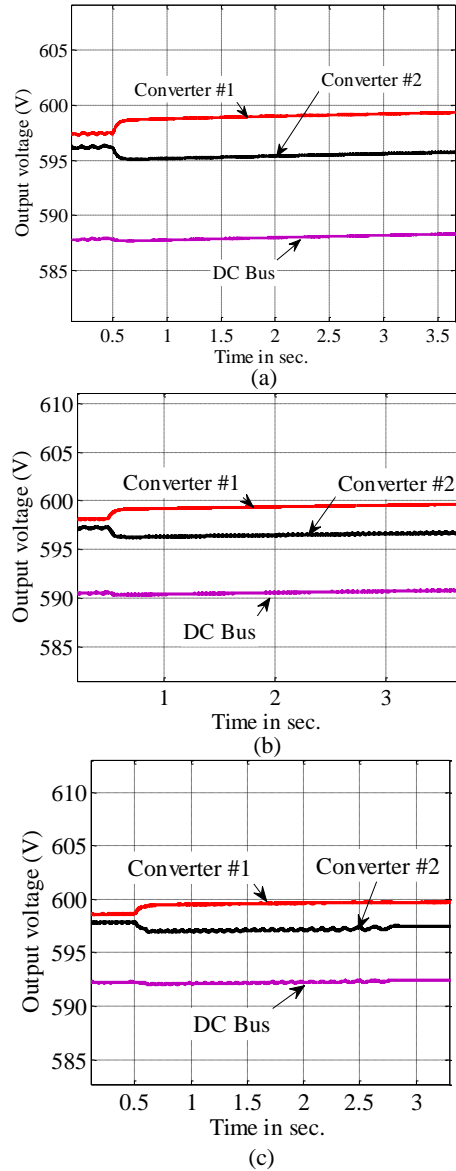
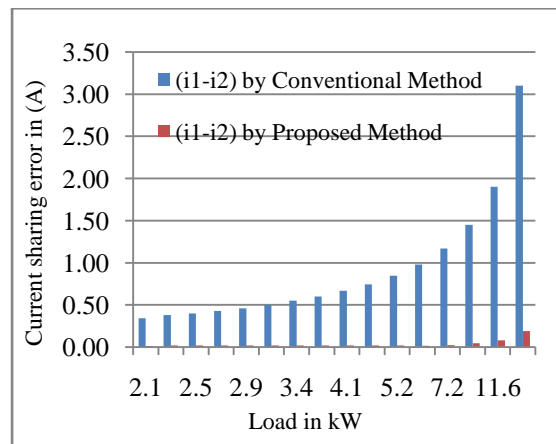


Fig. 8- A The source converter and dc bus voltage to loads (a) 80 Ω (b) 100 Ω and (c) 120 Ω.



(a)

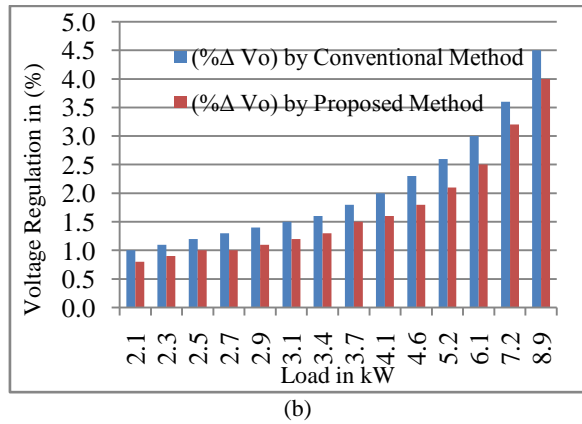


Fig. 9- (a) Current sharing error (b) voltage regulation for different loading conditions.

Conclusion

This paper presents a new methodology for droop parameter selection to reduce the inherent limitations of the distributed control method utilized in dc microgrids. It is observed that the conventional way of selecting droop parameters gives a large degree of trade-off between current sharing error and bus voltage degradation due to the effect of the line impedances. Minimizing current sharing error and the voltage regulation are compensated for different cable line impedances of the dc distributed system. It is demonstrated up to 9 kW load with the help of two equal rating parallel source converter. It can be used for marine applications with high power conversion, reliable power supply, and high quality power. Proposed method allows a significantly better performance over the conventional droop control. Simulation is performed in MATLAB/ Simulink environment.

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