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Research paper

Voltage Control and Load Sharing in a DC Islanded Microgrid Based on Disturbance Observer

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Abstract

Background and Objectives: Increasing DC loads along with DC nature of distributed energy resources (DERs) raises interest to DC microgrids. Conventional droop/non-droop power-sharing in microgrids suffers from load dependent voltage deviation, slow transient response, and requires the parameters of the loads, system and DERs connection status.
Methods: In this paper, a new nonlinear decentralized back-stepping control strategy for voltage control and load sharing of DC islanded microgrids is proposed. The proposed method is robust against the load variations and uncertainty in microgrid parameters and has excellent dynamic and steady-state performance under different operating conditions. The major purpose of the proposed controller is to improve the transient performance of MG with load variations and constant power loads (CPLs). The local controller regulates the terminal voltage of DC-DC converter regarding the local quantities without needs to additional data of other system components.
Results: For simplicity, the proposed method is simulated with PSIM software on a DC microgrid with two DGs. Different scenarios are studied to present the performance of the proposed method under different operating conditions.
Conclusion: The results indicate the capability of the proposed method for voltage control and load sharing in DC microgrids.

Introduction

Recently, DC microgrids have received much attention due to their high efficiency, use of renewable energy sources, and better compatibility with consumer electronics. Moreover, problems such as harmonics, unbalanced network, synchronization, reactive power compensation, power quality, and frequency control are not raised in DC systems [1]-[3]. Currently, the most common applications of the DC microgrids are the electric power supply of separate systems such as electric vehicles (EV), spacecraft, data centers, telecommunication systems (Telecom) and rural areas. DC microgrid structure depends on several factors such as source types, connectivity, load density, load behavior and operation environment [4]-[5].

Overall control of DC microgrid can be divided into three different categories of centralized, decentralized and distributed schemes [6]. Several control methods have been proposed for voltage regulation, power-sharing, maximum power point tracking (MPPT) and energy storage in DC microgrids [7]-[9]. One of the challenges of the DC microgrid is voltage stability because they cannot directly be connected to an infinite power source, such as AC main network; therefore, they operate in an island mode. Available controllers for islanded microgrid (ImGs) stability are mainly based on the droop control. The other challenge of the DC microgrid is power disturbances. Because of abrupt changes in the DC loads, DG units and storage systems

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output power variations caused to power disturbances. The DC bus voltage variation if not controlled properly, could failure the DC system protection. Therefore, an appropriate DC bus voltage control strategy shows a key role to certify good power quality and stable operation of the DC microgrid [10[[4]-[13][5]. Among the converters applied in DC microgrids, buck structure is one of the most important converters. This converter is used between the source and the load to create the desired voltage level [13]-[14].

Output voltage control of DC-DC power converters, which connected to a common microgrid can be degraded by the other converters connected to the same network. As well as, parameters variation of each converter and unknown transmission line between them can corrupt the terminal voltage control in variable load conditions. Considering these uncertainties is essential to develop a specific controller with high-performance behavior. With rapid advances in the fields of power electronics and modern control theory, advanced control methods have been proposed for buck converter systems such as sliding mode control (SMC), backstepping control, robust control, model predictive control (MPC) and so on [15]-[16]. Distributed control methods are designed based on the certain and accurate system model. It must be noted that uncertainties in loads, DGs connection status and parameters, line impedances and network topology may result in poor power-sharing and voltage instability.

The most quantity used as a disturbance signal is the load current while the non-linear loads affect the load current based control schemes adversely. Since the measurement of load uncertainties is normally difficult for sensors, disturbance observer (DOB) is the key method to estimate an optimal way [16]-[17]. Different effective approaches have been designed to estimate disturbances, through which disturbances can be controlled and uncertainties in the buck converter system can be determined [18]-[19]. In [19] and [20], extended state observer (ESO) method is used to estimate the disturbances of match and mismatch loads. Also, the use of nonlinear disturbance observer (NDOB) method has been also proposed to estimate the disturbances of the load [21]-[22]. This paper proposes a new nonlinear control strategy for the voltage control and load sharing of a DC Islanded microgrids that includes two arbitrary DGs.

One of the main challenges in DC MGs is that nonlinear behavior is created by CPLs. It is well known that CPLs have negative impedance effects, which may cause instability in a DC microgrid. The CPLs are nonlinear and exhibit a negative impedance V-I characteristic, which may cause instability of a DC MG. That means CPLs affect the power quality of the electric system and bring instability, which eventually might lead the system into failure [28]-[29].

In [30], the local controller created by passive elements is designed for voltage regulation and stability of DC MG with CPLs. The method is developed for a specific MG with full and exact knowledge of system parameters. In [31], the feedback linearization control strategy for buck converter when feeding a CPL is presented. This method improves the transient response in the presence of load disturbance. Transient and steady state performance of the closed-loop DC MG system with CPLs based on fuzzy modeling and controller is investigated in [32]. D-stable controller for nonlinear DC MG system is designed using LMI approach where the negative impedance characteristic of CPLs was compensated and the designed controller was suitable for the nonlinear nature of the DC MG system. Some works prescribed performance controller design for DC converter system with CPL in DC microgrid for stabilizing DC/DC boost converter [33].

Exact feedback linearization technique is employed then, a nonlinear disturbance observer is utilized to evaluate the dynamic change of load power and the composite nonlinear controller with prescribed performance is determined. Combining the NDO technique and prescribed performance control strategy, a novel complicated controller can be determined by the backstepping recursive design and its stability has been proven in a rigorous way. In this paper, a new nonlinear decentralized back-stepping control strategy for voltage control and load sharing of DC islanded microgrids is proposed. The proposed method is a plug and play technique which is robust against the load variations and uncertainty in microgrid parameters and has excellent dynamic and steady-state performance under different operating conditions. The contributions of the proposed method are as follows:

1) Global input-to-state stability of system consists of controller and observer is proved based on Lyapunov stability theorem (with some assumptions about the disturbance and its time derivatives).

2) Unmodeled dynamics in DC MGs such as uncertainties and unknown disturbances in the models are considered in the proposed control method.

3) Up to now, most of the control methods used the load current as a measurable disturbance signal. In the proposed method, the load current is assumed as a part of disturbance and is observed based on backstepping disturbance observer.

Several scenarios are simulated in the PSIM software to show the proposed control scheme performance under different conditions.

Modeling and Problem Setup

In this section, the dynamical model of the DC islanded MG is presented. The DC islanded MG is analyzed consisting of two DGUs. Fig. 1 shows the electrical diagram of the DC islanded MG by two DGUs with unmodeled loads.

By applying Kirchhoff's voltage and current laws to Fig. 1, the following set of equations can be written [10]:

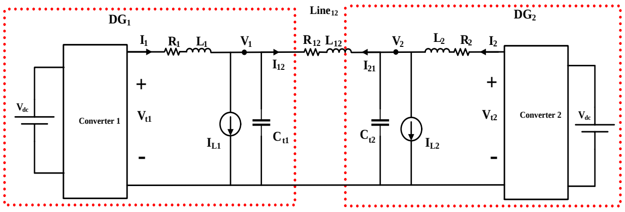


Fig. 1:Electrical diagram of a DC islanded MG with two DGUs.

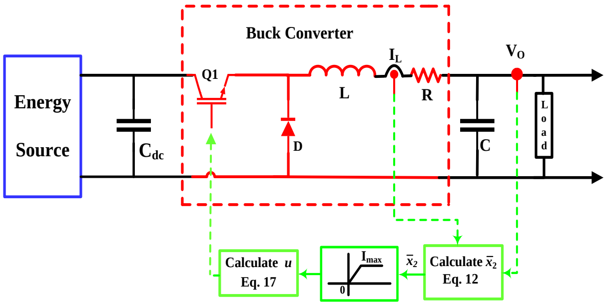


Fig. 2: Scheme of the controller for the DG unit.

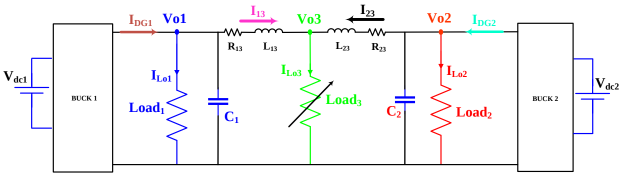


Fig. 3: Electrical scheme of the islanded microgrid in this study.

$$DGU_1 \begin{cases} C_{t1}\dot{V}_1 = I_{t1} - I_{12} - I_{L1} \\ L_{t1}\dot{I}_{t1} = V_{t1} - R_{t1}I_{t1} - V_1, \end{cases} \tag{1}$$

where, V_1 and I_{L1} are the input voltage and inductor current of buck converter, and C_{t1}, R_{t1} and L_{t1} are the filter capacitance and equivalent resistance and inductance of converter, V_{t1} and I_{t1} are voltage and current of converter, I_{12} is the transferred current between DGUs "1" and "2".

To represent a dynamical system affected directly by the state of the other DGU connected to it, inspired by [10], can be used a quasi-stationary line (QSL) approximation of the line dynamics. As in [22]-[24], we set $\frac{dI_{12}}{dt} = 0$ and $\frac{dI_{21}}{dt} = 0$ which results in:

$$I_{12} = -I_{21} = \frac{V_1}{R_{12}} - \frac{V_2}{R_{21}}, \tag{2}$$

where, V_2 is the output voltage of DGU_2, and R_{12}, L_{12} are resistance and inductance of line between DGU_1 and DGU_2. Initial states for the line currents fulfill $I_{12}(0) = -I_{21}(0)$. Furthermore, we set $L_{12} = L_{21}$ and $R_{12} = R_{21}$.

According to (1) and (2), QSL model can be generalized for a DC islanded MG with two DGs, shown in (3) [10]:

$$\begin{aligned} \dot{x}_1 &= \frac{-1}{R_{12n}C_{t1n}}x_1 + \frac{1}{C_{t1n}}x_2 + d_1 \\ \dot{x}_2 &= \frac{-R_{1n}}{L_{1n}}x_2 + \frac{-1}{L_{1n}}x_1 + \frac{1}{L_{1n}}u + d_2 \\ y_1 &= x_1, \end{aligned} \tag{3}$$

where, n indicates the nominal values of parameters, and $[x_1, x_2] = [V_1, I_{t1}]$, $[x_1, x_2] = [V_1, I_{t1}]$, $[x_1, x_2] = [V_1, I_{t1}]$ are the states, the control input, and the system output, respectively. In addition, d_1 and d_2 are system perturbations which are defined to represent the effects of the DG uncertainties and unknown load current and assumed to be time-varying and unknown. Means:

$$\begin{aligned} &d_1 = \frac{1}{C_{t1}}\left(\frac{1}{R_{12}}V_2 - I_{L1}\right) + \Delta_1 x_1 + \Delta_2 x_2, \quad d_2 = \Delta_3 x_1 + \Delta_4 x_2 \\ &\Delta_1 = \frac{1}{R_{12n}C_{t1n}} - \frac{1}{R_{12}C_{t1}}, \qquad \Delta_2 = -\frac{1}{C_{t1n}} + \frac{1}{C_{t1}}, \\ &\Delta_3 = \frac{1}{L_{t1n}} - \frac{1}{L_{t1}}, \qquad \Delta_4 = \frac{R_{t1n}}{L_{t1n}} - \frac{R_{t1}}{L_{t1}}. \end{aligned} \tag{4}$$

where, Δ_1, Δ_2, Δ_3 and Δ_4 are the differences between nominal and real values of parameters.

Assumption 2.1: It is supposed that the loads and line impedances are unknown to reflect the system uncertainties. As well as, all of the state feedbacks of each DGUs are available for its local controller.

Assumption 2.2: The state spaces are bounded. Furthermore, the arbitrarily lumped disturbances d_1 and d_2 are assumed to be unknown. As well as, these are bounded and their time derivatives are also bounded.

System Controller Design

Fig. 2 shows the schematic diagram of a DG in islanded mode operation. The DG is represented by an energy storage system, the buck converter, the C filter and voltage, and current control loops. The control loops use a nonlinear controller to regulate the converter's output voltage.

This section presents the proposed control method, which is based on a decentralized backstepping observer technique. The proposed method regulates the output voltage x_1 to the desired value x_1^* in the presence of disturbances d_1 and d_2. The x^* is the reference voltage of DC MGs and is a constant or stepwise reference signal. The detailed design procedure is given step by step in the following.

A. Disturbance observer design

Inspired by [25], a linear disturbance observer for the system (3) is designed as:

$$\begin{aligned} \dot{p}_1 &= f_1(x_1)+B_1x_1+\hat{d}_1 \\ \dot{p}_2 &= f_2(x_1,x_1)+B_2u_1+\hat{d}_1 \\ \hat{d}_1 &= \lambda_1(x_1-p_1) \\ \hat{d}_2 &= \lambda_2(x_2-p_2). \end{aligned} \tag{5}$$

that λ_1 and λ_2 are positive constant observer gains. According to (3) and (5), we have:

$$\begin{aligned} f_1(x_1) &= \frac{-1}{R_{12n}C_{t1n}}x_1, \qquad\qquad B_1=\frac{1}{C_{t1n}}, \\ f_2(x_1,x_2) &= -\frac{1}{L_{t1n}}x_1-\frac{R_{t1n}}{L_{t1n}}x_2, \quad B_2=\frac{1}{L_{t1n}}. \end{aligned} \tag{6}$$

The disturbance estimation is obtained from (5) in the following form:

$$\begin{aligned} \dot{\hat{d}}_1 &= \lambda_1(\dot{x}_1-\dot{p}_1)=\lambda_1(d_1-\hat{d}_1) \\ \dot{\hat{d}}_2 &= \dot{\lambda}_2(\dot{x}_2-\dot{p}_2)=\lambda_2(d_2-\hat{d}_2). \end{aligned} \tag{7}$$

Therefore, we define disturbance estimation errors as $e_1=d_1-\hat{d}_1$, $e_2=d_2-\hat{d}_2$. Taking the derivative of errors and combining them with (7), the observer error dynamics can be expressed as follows:

$$\begin{aligned} \dot{e}_i &= -\lambda_1 e_1+\dot{d}_1 \\ \dot{e}_2 &= -\lambda_2 e_2+\dot{d}_2. \end{aligned} \tag{8}$$

B. Composite controller design

A composite backstepping controller is designed by the following recursive procedure. First, the Lyapunov function can be selected as follows:

$$V_1=\frac{1}{2}z_1^2+\frac{1}{2}e_1^2, \tag{9}$$

that the Lyapunov function V_1 is positive definite, continuous and differentiable, and $z_1=x_1-x_1^*$. By differentiating both sides of (9), the following relationship can be obtained

$$\dot{V}_1=z_1\dot{z}_1+e_1\dot{e}_1=z_1(f_1(x_1)+B_1x_2+d_1(t))+e_1(\dot{d}_1-\lambda_1e_1). \tag{10}$$

Define

$$x_2=x_2-\bar{x}_2+\bar{x}_2=z_2+\bar{x}_2, \tag{11}$$

where, $z_2=x_2-\bar{x}_2$, and $\bar{x}_2$ is the virtual control in the backstepping method. Design the auxiliary function $\bar{x}_2$ as:

$$\bar{x}_2=\frac{-1}{B_2}[(k_1+\frac{1}{4\varepsilon_1})z_1+f_1+\hat{d}_1], \tag{12}$$

where, $k_1>0$ and $\varepsilon_1>0$.

Substituting (11) and (12) into (10), then using Young's inequality [26], leads in

$$z_1e_1\le\frac{1}{4\varepsilon_1}z_1^2+\varepsilon_1e_1^2. \tag{13}$$

According to (13), results in

$$\begin{aligned} \dot{V}_1 &\le -\lambda_1e_1^2+e_1\dot{d}_1+B_1z_1z_2+\varepsilon_1e_2^2-k_1z_1^2 \\ &= -(\lambda_1-\varepsilon_1)e_1^2-k_1z_1^2+B_1z_1z_2+e_1\dot{d}_1. \end{aligned} \tag{14}$$

Next, we choose the Lyapunov function as:

$$V=V_1+\frac{1}{2}z_2^2+\frac{1}{2}e_2^2. \tag{15}$$

that the Lyapunov function V_2 is positive definite, continuous and differentiable. The time derivative of (15) satisfies:

$$\begin{aligned} \dot{V} \le& -(\lambda_1-\varepsilon_1)e_1^2-k_1z_1^2+B_1z_1z_2+e_1\dot{d}_1+z_2[f_2+B_2u \\ &+d_2-\frac{\delta\bar{x}_2}{\delta z_1}(B_1x_2+f_1+d_1)-\frac{\delta\bar{x}_2}{\delta\hat{d}_1}\lambda_1e_1]-\lambda_2e_2^2+e_2\dot{d}_2. \end{aligned} \tag{16}$$

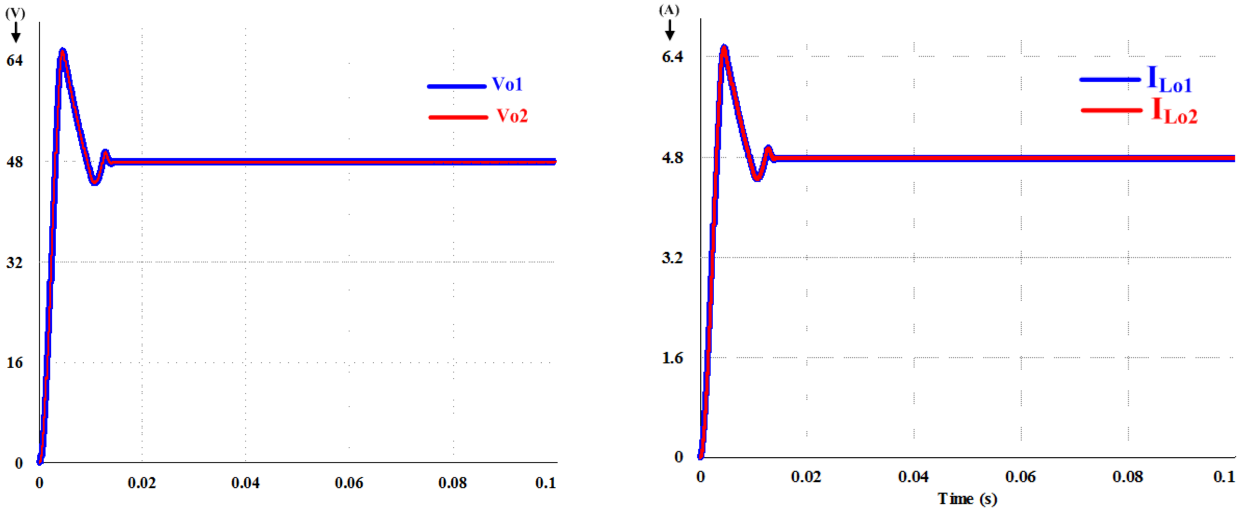
Finally, the following control is proposed to guarantee the voltage tracking error convergence:

$$u=\frac{1}{B_2}[\frac{\delta\bar{x}_2}{\delta z_1}(B_1x_2+f_1+\hat{d}_1)-f_2-\hat{d}_2-B_1z_1-(k_2+\frac{1}{4\varepsilon_2}+\hat{c}_2)z_2] \tag{17}$$

where $k_1,\ k_2,\ \varepsilon_1,\ \varepsilon_2>0$, $\hat{c}_2=\frac{1}{4\varepsilon_1}(\frac{\delta\bar{x}_2}{\delta z_1}+\frac{\delta\bar{x}_2}{\delta\hat{d}_1}\lambda_1)^2$ and pursuant to (12) $\frac{\delta\bar{x}_2}{\delta z_1}=\frac{-1}{B_2}(k_1+\frac{1}{4\varepsilon_1}-\frac{1}{R_{12n}C_{1n}})$, $\frac{\delta\bar{x}_2}{\delta\hat{d}_1}=\frac{-1}{B_1}$.

If the disturbances satisfy the condition of $\lim_{t\to+\infty}\|\dot{d}(t)\|=0$, and also $d(t)=0$ at the origin, where $d(t)=0$, the closed-loop system is globally asymptotical stable [27].

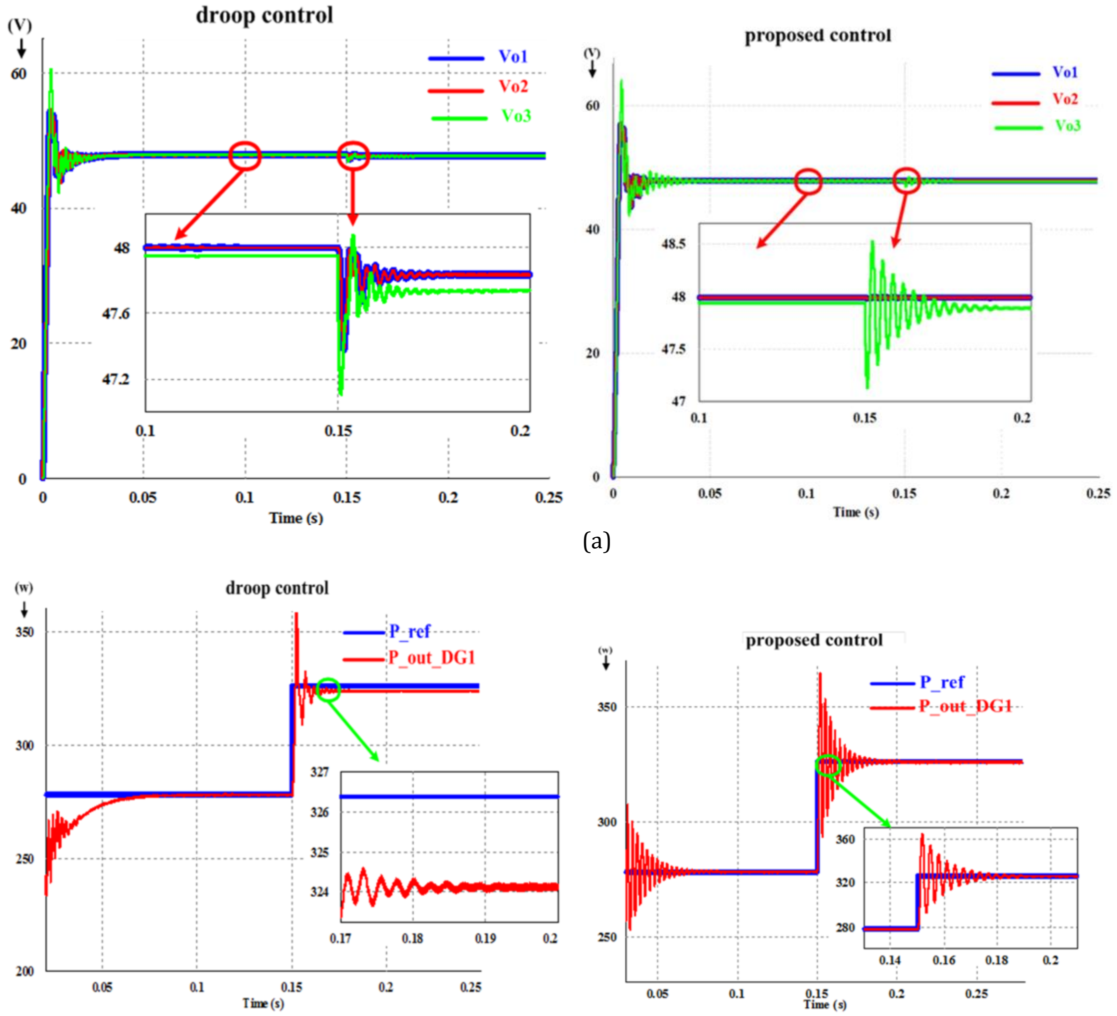
It should be noted that the desired output voltage can be achieved by tuning the parameter x_1^*.



(a)

(b)

Fig. 4: Scenario A: Steady-state performance. Simulation response of the DG_1 (blue), DG_2 (red). (a) Voltage response, (b) Current response.



(a)

(b)

Fig. 5: Scenario B: Load sharing. Simulation: (a) Output voltage, (b) Output power of DG_1.

Simulation Results

The case study system is shown in Fig. 3, where two DGUs supply three resistive loads with nominal currents of 4.8 A. the nominal voltage of the system is $48\ \mathrm{V}$ DC. In this decentralized control design for guaranteeing voltage stability, we consider DC islanded microgrid. The output voltage reference V^* has been selected at $48\ \mathrm{V}$. But output voltage reference is separate for each DGU, that local voltage controllers will be followed.

It is worth mentioning that to verify the proposed robustness of the method with respect to the parameters' uncertainties; the simulations are performed with 100% uncertainty in the parameters. The corresponding controller parameters, k_1, k_2, ε_1, ε_2, λ_1 and λ_2 are chosen as 200, 150, 0.9, 0.8, 3 and 2, respectively.

To verify the robustness performance of the system, a number of tests, including load changes and structure reconfiguration have been performed. The proposed control is simulated on PSIM software. Table 1 provides the DGUs, loads, and lines parameters of the understudy system in detail.

Table 1: System Parameters

Quantity	Value
R_1, R_2	0.5 Ω, 0.4 Ω
L_1, L_2	2 mH, 2.2 mH
C_1, C_2	2.2 mF, 2 mF
L_{13}, L_{23}	2 μH
R_{13}, R_{23}	0.1 Ω
V_{dc} (DC bus voltage)	48 V
R_{Load1}, R_{Load2}, R_{Load3}	10, 10, 24 Ω
f_{sw} (Switching frequency)	10 kHz
V_{dc1}, V_{dc2} (Voltage source)	60 V

A. *Scenario A- steady-state performance*

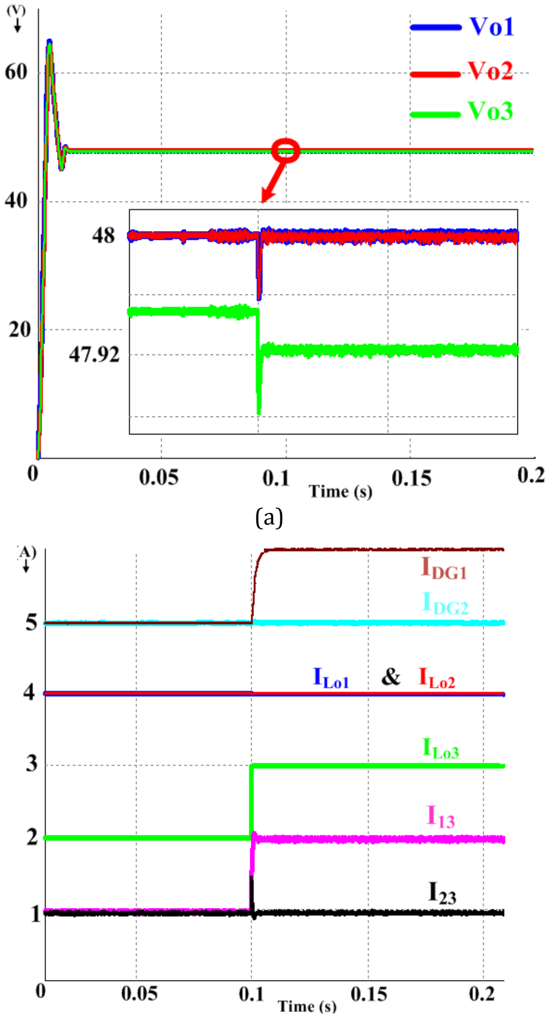
The load$_3$ is out of service as shown in Fig. 3. Voltage and current waveforms in a steady state are plotted in Fig. 4a and Fig. 4b. The resistance value of the loads is 10 Ω, which draws a 4.8 A current. As seen, the control scheme regulated the system voltage, supplying loads with their nominal currents.

B. *Scenario B- load sharing*

To compare the proposed method with conventional droop control for load sharing, case study system of Fig. 3 is considered. As seen, two DGs are supplying the local loads and the common load which is named as load$_3$.

To observe the dynamic response of both methods, the reference load current is stepped up from 2 to 4 A at $t = 150\ \mathrm{ms}$. It is worth to mention that both DGs participate identically in supplying the common load.

As seen, the proposed method achieves faster dynamic response, more accurate power-sharing and exhibits lower voltage in comparison to the droop-based method.



(a)

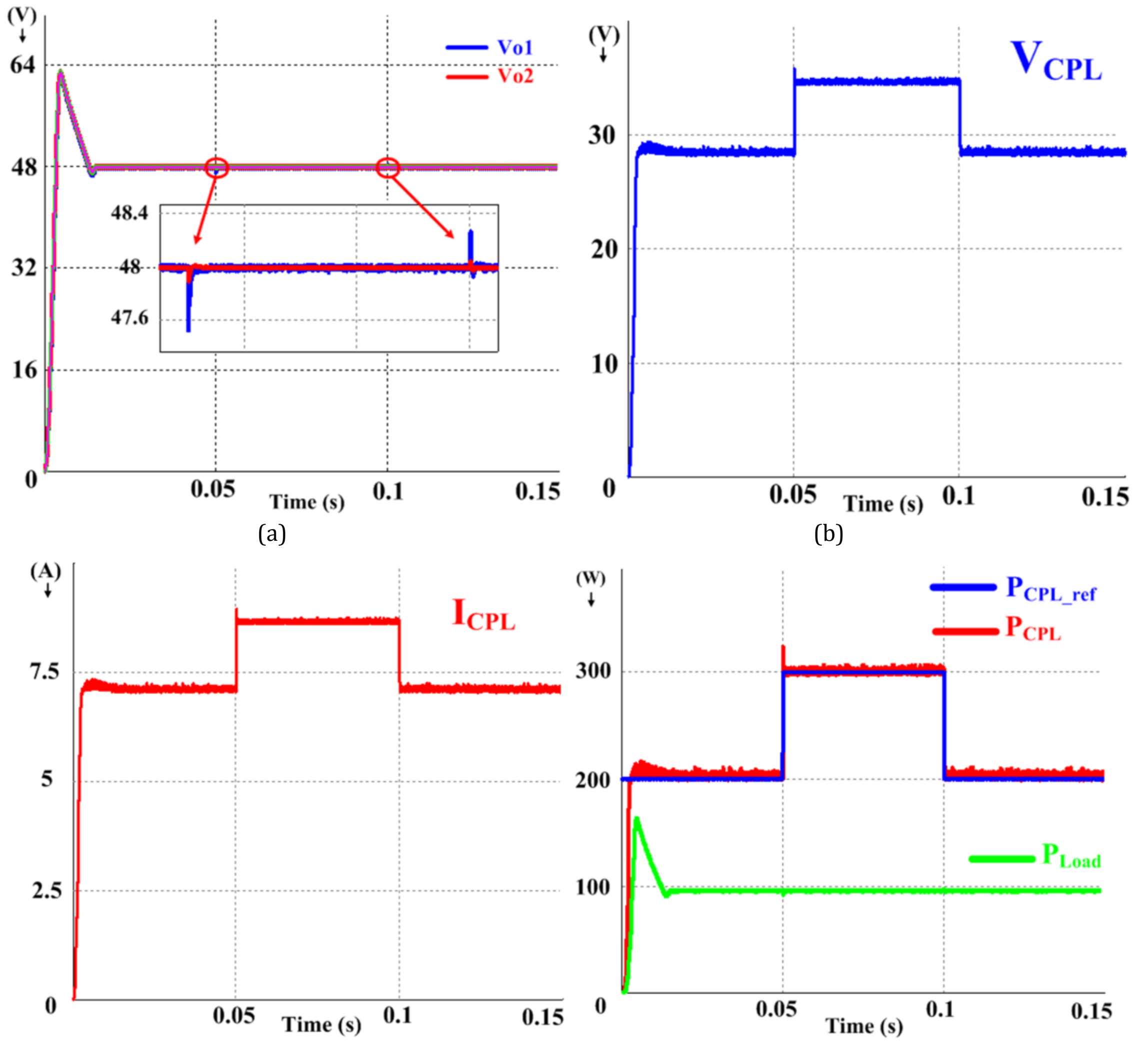
(b)

Fig. 6: Scenario B: Load sharing with DG2 power constraint. (a) Output voltages of DG_1 (blue), DG_2 (red), load3 (green), (b) Currents of DG_1 (dark red), DG_2 (turquoise), load1 (blue), load2 (red), load3 (green), line13 (purple), and line23 (black).

Fig. 5a represents the voltage variation during the increasing of load$_3$ where higher voltage variation for droop control is experienced. The output power DG_1 is shown in Fig. 5b, where the proposed method successfully follows the reference value, while the droop method tracks it with some errors.

The other case study system where load$_3$ is changed and the output current of DG$_2$ is limited. The resistance value of the load$_3$ is 24 Ω, which draws a 2 A current; rest of the local loads are 12 Ω, drawing 4 A.

It is assumed that the nominal current of DG$_2$ is 5 A.



(a) (b) (c) (d)

Fig. 7: Study C: CPLs. Simulation response of: (a) DC bus voltages, (b) Voltage of CPL, (c) Current of CPL, (d) Power of resistive load and CPL.

From to , that the load3 needs a 2 A current, the units 1 and 2 will supply it.

At the time , the value of load3 is changed from 24 Ω to 16 Ω and it draws a 3 A current. Fig. 6a shows that before , the load3 is supplied by units 1 and 2, and the voltages of all units remain at 48 V and the voltage of load3 is 47.95 V. But at the time , that the load3 is changed, unit 1 participate in load supply. The voltages of the units 1 and 2 remain 48 V, and the voltage of the load3 reaches to 47.92 V.

In Fig. 6b, the currents of the units are plotted. Before each of the units 1 and 2 generates a 5 A current, delivering 4 A to the local loads and 1 A to load3.

At the time, the load3 is increased from 2 A to 3 A, the DG1 generates 6 A, and delivers 2 A of it to load3, while DG2 generates the only 1A for load3.

Fig. 6 shows that the controller works well and maintains the voltage of the units at 48 V while supplying the loads under the constraints output current of DG units.

C. Scenario C- CPLs

This scenario represents the performance of the proposed controller for CPLs. The load is assumed as CPL which is modeled as a buck converter with a resistive load.

The reference power of load$_1$ is increased to 300 w at t=0.05 sec and it is set back at t=0.1 sec. Fig. 7 shows the bus voltages of the system under these transitions. Respectively, in Fig. 7a DC bus voltages, Fig. 7b voltage of CPL, Fig. 7c current of CPL, and Fig. 7d powers of resistive load and CPL are shown. As seen, the proposed controller maintains an accurate DC voltage in transient and steady-state regions without considerable fluctuation even in full CPL condition.

The output power DG_1 is plotted in Fig. 7. Once the reference power of CPL is changed, the output power of DG$_1$ successfully follows it.

Conclusion

In this paper, a decentralized control scheme for voltage stability in DC Islanded microgrids was presented.

The microgrid consists of two DGUs with local loads that can be parametrically uncertain. The purpose of the controller is to regulate the load voltage regardless of the load dynamics and other variations.

The new method presents decentralized robust backstepping voltage control and power-sharing based on disturbance observer. Different scenarios including external load variations and dynamic operation of CPLs was studied.

The proposed method mitigates the adverse effect of CPLs on voltage stability. Moreover, the voltage stability for the newly proposed method was analyzed and it was seen that the proposed method improves the voltage stability of DC microgrid.

Another advantage of this controller is robustness against load variations. Also, the proportional load current sharing can be exactly realized by using the proposed method.

Author Contributions

H. Amiri, collected the data and carried out the data analysis.

G. A. Markadeh and M. N. Dehkordi interpreted the results and wrote the manuscript.

Abbreviations

V_1	Input voltage
I_{L1}	Inductor current
C_{t1}	Filter capacitor
R_{t1}	Equivalent resistance
L_{t1}	Inductance of converter
V_{t1}	Voltage of converter
I_{t1}	Current of converter
I_{12}	Current between DGUs "1" and "2"
V_2	Output voltage of DGU_2 ,
R_{12}, L_{12}	Resistance and inductance of line between DGU_1 and DGU_2 .
d_1 , d_2	Disturbance
Δ_1, Δ_2, Δ_3, Δ_4	Differences between nominal and real values of parameters.
x_1,x_2	State variables of the system
x_1^*	Reference value
λ_1 , λ_2	Positive constant observer
V_{CPL}	Voltage of CPL
I_{CPL}	Current of CPL
P_{CPL}	Power of CPL
k_1, k_2, ε_1, ε_2	Positive constant

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