Investigation of Communication Delay Impact on DC Microgrids with Adaptive Droop Control

Dimitris Baros
Department of Electrical and Computer Engineering
Democritus University of Thrace
Xanthi, Greece
dbaros@ee.duth.gr

Nick Rigogiannis
Department of Electrical and Computer Engineering
Democritus University of Thrace
Xanthi, Greece
nrigogia@ee.duth.gr

Nick Papanikolaou
Department of Electrical and Computer Engineering
Democritus University of Thrace
Xanthi, Greece
npapanik@ee.duth.gr

Michael Loupis
General Department
National and Kapodistrian University of Athens
Psachna, Greece
mloupis@uoa.gr

***Abstract*—This work aims to investigate the effects of communication delay in a DC microgrid, which operates under an adaptive droop control scheme. A case study of a residential DC microgrid is examined, which is essentially a household prosumer with power generation units, both on site and remotely, energy storage units and various loads. Conventional droop control schemes have been widely adopted in DC microgrids, although they cause voltage deviation, due to the different characteristics of generation units, whereas their performance is sensitive to line impedances. In order to compensate this deviation, while maintaining current sharing accuracy (adapting to line impedances), a distributed secondary controller is considered, which regards only the information of neighboring converters, by the aid of digital communication links. The impact of various communication methods, in terms of communication delay is examined and evaluated via MATLAB/Simulink simulations.**

Keywords—adaptive droop control, current sharing, DC microgrids, delay effects, renewable energy sources

I. INTRODUCTION

Recent research in the field of electric power systems as well as in power electronics, in both academic and industrial level, has focused on DC microgrids (MGs) which are constantly gaining interest. In general, DC distribution networks outweigh their AC counterparts, presenting increased reliability, higher efficiency and simpler control methods [1]–[5]. Furthermore, the majority of the emerging components of modern power systems, such as distributed generation units (DGs) (mainly from renewable energy sources - RES), electronically controlled loads and energy storage systems (ESSs) are inherently DC, which makes their interface with DC buses simpler, avoiding excessive power conversion stages [2]. In addition, issues such as synchronization or reactive power flow, or problems related to harmonics are not present in DC MGs [1], [2].

In parallel, given the intermittent operation and demand-response characteristics of electric loads, power sources (which may reflect various rated powers) must be dynamically controlled, in order to meet load power demands, preserving the DC bus voltage within an acceptable range. A load sharing approach is usually considered, where the total load demand is shared among the sources in proportion to their rated power. As the source voltages are the only parameters controlling power flow, they have to be tightly controlled to ensure the desirable voltage regulation [1], [2].

The standard DC MGs control method is based on a hierarchical approach, including primary, secondary and tertiary control levels [5]. The most popular technique for the primary controller is the droop control method, achieving proportional load sharing by means of cooperative operation among paralleled converters. This method is based on adding a virtual resistance (VR) on the source voltage regulator converter, which allows effective current/power sharing, whereas it provides active damping to the system, with plug-and-play capability [5], [6]. However, the performance of this method depends on line impedances. In general, higher VR values lead to higher current sharing accuracy, but also to poorer DC bus voltage regulation [7]. Hence, in order to achieve improved current sharing accuracy, VR values should be adapted, in respect to line impedances and critical load changes [5], [7]. Additionally, some DG units, such as photovoltaic (PV) systems or ESS, lack constant power supply capability, thus it is of paramount importance the VR values to adapt dynamically to load changes [7], [8]. A secondary control level is also necessary, so as to provide voltage restoration at DC buses. In this context, the adaptive droop control method has been proposed, as it offers improved reliability and flexibility, especially in case of multiple DGs [5]. The basic principle of the secondary control lies upon information exchange, between local droop controllers, to compensate the DC bus voltage deviation. The adaptive droop control scheme will be described in detail in Section III.

In order to achieve coordination among DGs in DC MGs, several communication approaches have been proposed, based either on a centralized controller, or a distributed control scheme [5], [9]. In centralized control all sensors information is transmitted from the local DG controllers to a central supervisory one, which processes the information and sends back operational set-points to the local controllers. Although it offers the best control capability, the reliability of these kinds of systems is relatively low, as its operation is mostly dependent on a single component. Moreover, with an increase in the number of DGs, extensive hardware is required [9]. On the other hand, in distributed communication control schemes no central controller is required, leading to increased reliability; local controllers communicate directly, so as to coordinate and achieve efficient MG control. Although distributed communication provides immunity to single-point failures, drawbacks such as high complexity, stability margins, time delays and measurement errors exist [9]. Various communication technologies, applicable to DC MGs control have been proposed such as low bandwidth communication (LBC) networks, which are advantageous compared to high bandwidth communication (HBC) for this kind of applications [10]. In general, for MG applications wide area network (WAN), neighboring area network (NAN) (e.g.

978-1-7281-9863-7/20/$31.00 ©2020 IEEE

LTE, Wi-Fi, WiMax) and home area network (HAN) (e.g. wired, ZigBee, Bluetooth, Wi-Fi) architectures have been proposed [11]. More detail regarding the communication delay of the above-mentioned protocols will be provided in Section II.

Nowadays, with the advances in communication technologies, such as the introduction of Internet of Things (IoT) and the transition to 5G cellular networks, future smart grids will consist of several smaller MGs that communicate and coordinate effectively with each other and with the utility grid [9]. Thus, communication technologies constitute a major component of modern residential MGs, imperative for efficient cooperation and energy transactions (e.g. between prosumer buildings or between buildings MGs and the electricity network), within the framework of smart grids and the emerging energy community concept.

In more detail, regarding the building sector, several studies have investigated the introduction of DC distribution in residential, commercial and industrial buildings, along with the potential electrical energy savings, in comparison with the conventional AC MG configuration [12]. According to [12], [13] the estimated energy savings in All-DC buildings ranges from 5% to 8% for residential and commercial buildings, without energy storage, whereas it may reach up to 14% by incorporating energy storage systems. Additionally, in cases of energy communities, the RES production may be shared among different buildings, by exploiting the advantages of virtual net metering scheme. This concept is also applicable to regions with large-scale buildings where there is no available space for RES installation and these DGs are installed in the near area [14]. It is well-known that energy savings in buildings is an issue of major importance; especially due to the short-term (by 2030) ambitious environmental goals that the European Union (EU) sets [15]. It is worth noting that in EU, buildings account for approximately 40% of the total primary energy consumption and 36% of greenhouse emissions. Thus, the need for highly efficient buildings is imperative [16].

In this context, this paper focuses on a case study of a residential DC MG, incorporating conventional and RES DGs (both on site and remotely), ESSs and various loads, which is fully autonomous, although grid-tied operation is available, in cases required. The aim of this work is to examine and evaluate the communication delay impact on the adaptively droop controlled DC MG operation, via MATLAB/Simulink simulations, considering various delay times.

II. DESCRIPTION OF THE SYSTEM UNDER STUDY

The residential DC MG under study comprises two power generation units on-site and an ESS, along with a remotely installed DG with an ESS. A block diagram of the studied system is depicted in Fig. 1.

In more detail, the building generation units consist of an integrated PV system and a micro cogeneration (combined heat and power - CHP) unit. Also, a battery ESS exists, so as to achieve autonomous building operation. As for the building loads, household appliances are considered, as well as an electric vehicle (EV) charger. All of the above loads are emulated via variable resistive and constant power loads. As regards the remotely installed DG unit, it comprises a PV system along with a battery bank. Finally, grid-tied operation is possible, in cases of high energy demand or excessive energy production. However, as the scope of this work is to evaluate the communication delay impact on the secondary controller, only standalone operation is considered.

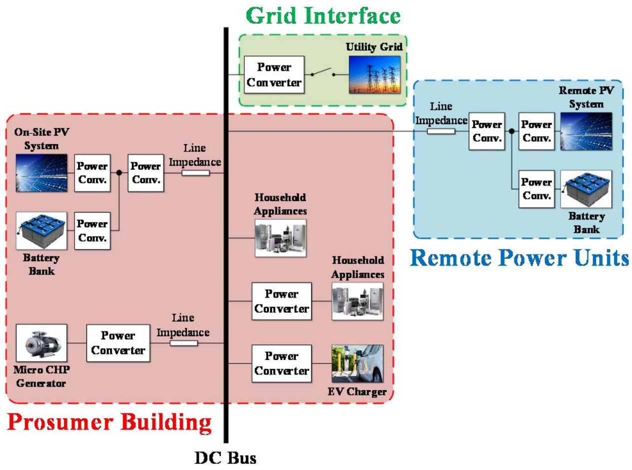


Fig. 1. Block diagram of the residential DC MG case study.

A detailed schematic diagram of the above described system is presented in Fig. 2. As for the PV systems, their interface is a boost DC-DC converter, implementing a simple perturb and observe (P&O) maximum power point tracking (MPPT) algorithm, whereas its output is fed to an interlinking DC/DC converter. In parallel, the ESS (battery bank) is connected to a bidirectional buck-boost converter, the output of which is connected to the same interlinking DC/DC converter. The control of the bidirectional converter is based on a higher-level charging/discharging controller, based on the operating mode (e.g. batteries charging or discharging according to the PV generated power and the DC bus loads power demands). In this context, the converter output voltage and the batteries SoC are taken into account, in order to provide a current set-point (source or sink) to the lower-level controller. The latter one is based on the peak current control method, which is popular for such applications, owing to the fast-dynamic response and inherent fault protection (current limit) [17], [18]. Finally, as for the CHP system, a micro turbine drives a synchronous generator which is connected to a front-end diode-rectifier, which feeds a separate interlinking DC/DC converter.

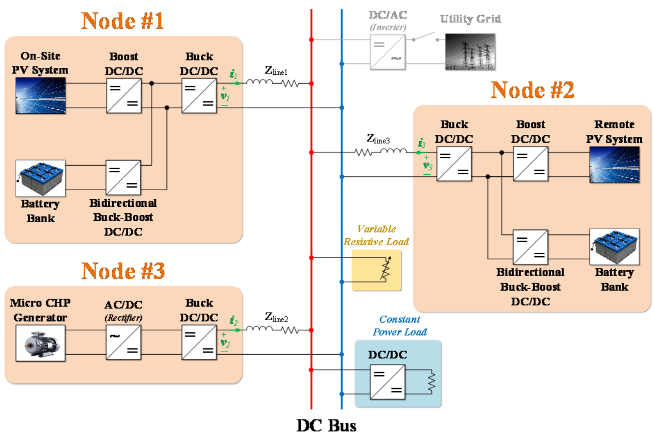


Fig. 2. Detailed schematic diagram of the studied DC MG system.

Each PV/battery system and the micro-CHP system, along with their interlinking power converters (active sources), constitute a respective node. Thus, the studied system has three nodes. It is noted that each interlinking converter is a step-down one, based on the common buck DC/DC topology. Although residential DC MGs suffer from lack of standardization, various voltage levels have been reported in scientific literature, mainly inspired by existing DC applications (transportation, telecommunications etc.) [19]. Hence, for the DC bus nominal operating voltage, the levels of 48 V and 380 V are considered in this work, which have been widely considered for residential DC MGs [19], [20].

In parallel, the aforementioned system nodes exchange information (in order to effectively cooperate and regulate their output voltage and current) via a digital communication network. Regarding communication, commonly wireless technologies are utilized for data exchange among the local controllers of a MG [9]. Table I presents a comparison of some common wireless communication protocols, in terms of delay and coverage range, based on several studies [11], [21], [22].

TABLE I. COMMON WIRELESS COMMUNICATION PROTOCOLS

Protocol	*Wi-Fi*	*ZigBee*	*LTE*	*HSPA*
Delay Time (ms)	up to 300	50 ~ 140	30 ~ 40	10 ~ 26
Range	Short	Short	Wide	Wide
Common Application	HAN/NAN	HAN	NAN/WAN	NAN/WAN

III. ADAPTIVE DROOP CONTROL SCHEME

In this paper, an adaptive droop control scheme for voltage restoration and proportional load sharing is considered. The detailed configuration of the proposed secondary controller is presented in Fig. 3, where local and neighbors information are processed, to adjust the local voltage set-point v_i^* [8]. A digital communication network is used for transferring the output voltages and currents of different converters [10].

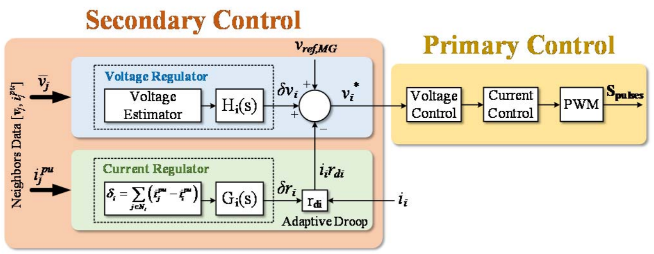


Fig. 3. Detailed configuration of the secondary controller based on cooperative adaptive droop control.

The voltage set-point for each converter includes two terms, produced by voltage and current regulators, as depicted in Fig. 3. Hence, the voltage reference for an individual converter can be expressed by:

$$v_i^* = v_{ref,MG} - r_{di} i_i + \delta v_i \tag{1}$$

where $v_{ref,MG}$ is the rated MG voltage, r_{di} is the droop gain, i_i is the operational current and δv_i is the voltage compensation term.

The voltage regulator includes a voltage estimator and a PI controller, in order to produce the voltage compensation term δv_i. The voltage estimator at each node estimates the average voltage across the MG, where $\bar{v}_i$ is the average voltage at node i. For this purpose, it employs a dynamic consensus protocol [8], which summarizes all the algebraic differences between neighbors estimated average voltages and its own [5]. The voltage estimator at node i receives its neighbors estimated values $\bar{v}_j$ $(j \in N_i)$, where N_i is the set of neighbors of node i. Then, the voltage estimator updates its own value $\bar{v}_i$ by processing the neighbors estimates and its local voltage measurement v_i, as follows:

$$\bar{v}_i(t) = v_i(t) + \int_0^t \sum_{j\in N_i} \left(\bar{v}_j(t) - \bar{v}_i(t)\right) dt \tag{2}$$

Then, the change in $\bar{v}_i$ propagates through the communication network and affects all other estimations. This estimation is then compared with the MG rated voltage value $v_{ref,MG}$, to produce the voltage correction term δv_i. In case that $\bar{v}_i$ deviates from $v_{ref,MG}$, the controller regulates δv_i, so as to eliminate the difference.

The current regulator at node i provides the input to the droop mechanism. In current-based droop mechanism, the droop gain r_{di} is considered as the internal virtual impedance and it characterizes the converter output impedance. Droop gains are designed and selected in order to achieve optimal cooperation and minimization of the output current sharing error. However, distribution lines compromise the current sharing accuracy of the droop controller. Hence, the droop gains are suggested to adapt to the MG loading conditions. For this purpose, a cooperative current regulator is embedded in the secondary control of each converter. Its main task is to compare the local per-unit current i_i^{pu} with the neighbors per-unit currents and calculate the current mismatch δ_i, by summarizing all the algebraic differences, as follows:

$$\delta_i = \sum_{j\in N_i} \left(i_j^{pu} - i_i^{pu}\right) \tag{3}$$

This mismatch is then fed to a PI controller $G_i(s)$, in order to produce the droop correction term δr_i, which leads to the new value of droop gain as follows,

$$r_{di} = r_{d0i} - \delta r_i \tag{4}$$

where r_{d0i} is the initial droop gain of each converter according to its nominal current, given by:

$$r_{d0i} = \frac{\varepsilon_v}{i_i^{rated}} \tag{5}$$

where ε_v is the maximum permitted voltage deviation at the DC bus and i_i^{rated} is the nominal current of each converter.

In case the per-unit currents of any two neighboring converters differ, the current regulators respond and adjust the droop correction terms δr_i, so as to achieve current sharing.

IV. SIMULATION RESULTS

In order to validate the proposed adaptive droop control scheme, a simulation test model of the studied DC MG depicted in Fig. 3 is developed in MATLAB/Simulink environment. It is assumed that the three interlinking buck DC/DC converters for the three power units (i.e. two PV/battery units and one micro CHP unit) have different current ratings. Thus, the rated current of the third converter (Node #3 – which corresponds to the micro CHP unit) is twice the rated current of the other two converters. Moreover, it is assumed that the impedance value of each distribution line is different, in respect to the node distance from the DC bus. A detailed summary of the main system parameters for the examined DC MG are presented in Table II.

Simulations are carried out and the impact of communication delay on the system dynamic performance (i.e. load step changes), as well as the secondary adaptive droop control are investigated. Although there are different possible voltage levels [19], this work focuses on a 48 V as well as a 380 V system configuration, in order to be in line with typical voltage levels of residential applications.

A. 48 V System

As regards the 48 V system configuration, the adaptive droop control scheme is implemented, based on a data network, so that various communication delays are tested to study their impact on system performance. Hence, the communication delay value is initially set to 30 ms, corresponding to a fast-wireless network and then to 300 ms, corresponding to a slower communication network. The output voltages and currents of interlinking converters, as well as the DC bus voltage and load current are depicted in Fig. 4, Fig. 5 and Fig. 6, where the load at DC bus changes between 0.6 Ω and 1.2 Ω. The controller performance in case of zero communication delay is presented in Fig. 4. The voltage regulation seems to be moderate, as depicted in Fig. 4a, due to the extremely high load current. Although the DC bus voltage drop is slightly above the maximum permitted voltage deviation (i.e. approximately 7% of $v_{ref,MG}$), the transient current sharing performance is excellent, as Fig. 4b denotes. The impact of different line impedances is eliminated and thus effective current sharing is achieved.

TABLE II. SUMMARY OF THE MAIN SYSTEM PARAMETERS

Symbol	Parameter	48 V System	380 V System
	Power Units		
i_1^{rated}	Rated Current of Unit #*i*	30 A	4 A
i_2^{rated}		30 A	4 A
i_3^{rated}		60 A	8 A
Z_{line1}	Line Impedance of Unit #*i*	0.1 Ω	0.5 Ω
Z_{line2}		0.3 Ω	1 Ω
Z_{line3}		0.1 Ω	0.5 Ω
r_{d01}	Initial Droop Gain of Unit #*i*	0.08 Ω	0.6 Ω
r_{d02}		0.08 Ω	0.6 Ω
r_{d03}		0.04 Ω	0.3 Ω
	Interlinking Buck Converters		
f_{sw}	Switching Frequency	50 kHz	50 kHz
C_{in}	Input Capacitance	470 μF	470 μF
C_{out}	Output Capacitance	1000 μF	1000 μF
L_f	Filter Inductance	800 μH	800 μH
	Primary Controller (for each node)		
$v_{ref,MG}$	Reference Voltage	48 V	380 V
k_{p1}	Proportional Voltage Term	1	1
k_{i1}	Integral Voltage Term	5	5
k_{p2}	Proportional Current Term	1.5	1.5
k_{i2}	Integral Current Term	0.9	0.9
	Secondary Controller (for each node)		
k_{p3}	Proportional Current Term	0.5	100
k_{i3}	Integral Current term	1	1
ε_v	Maximum Permitted Voltage Deviation (5% $v_{ref,MG}$)	2.4 V	19 V
t_{cd}	Communication Delay	30/300 ms	30/300 ms

When the communication delay is set to 30 ms, the adaptive droop controller performance seems to be affected, according to Fig. 5a, since the DC bus voltage deviation is approximately 15% of $v_{ref,MG}$, whereas its transient response seems to be slower. In addition, higher voltage overshoots as well as undershoots are observed during load steps. However, the load current sharing accuracy remains at an adequate level.

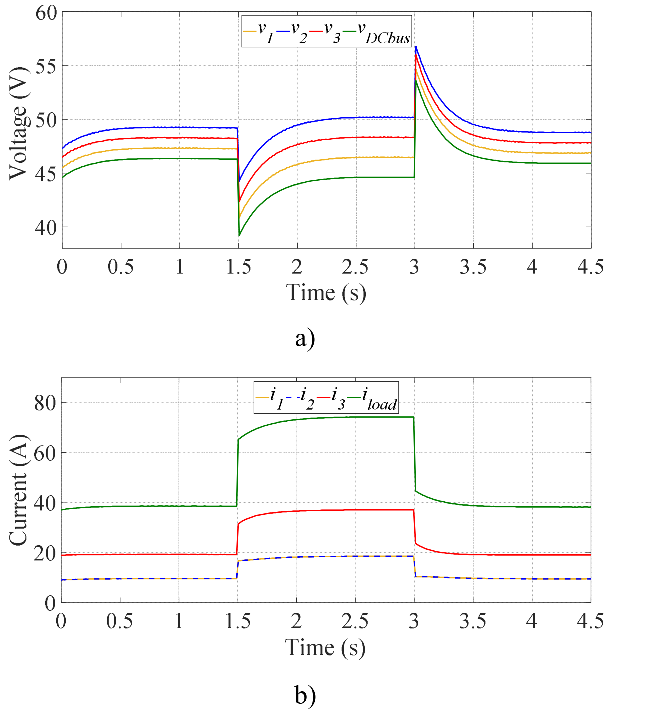


Fig. 4. Performance of the adaptive droop controller for the 48 V system in case of zero (0 ms) communication delay: a) power unit output voltages and DC bus voltage b) current supplied by each power unit and load current.

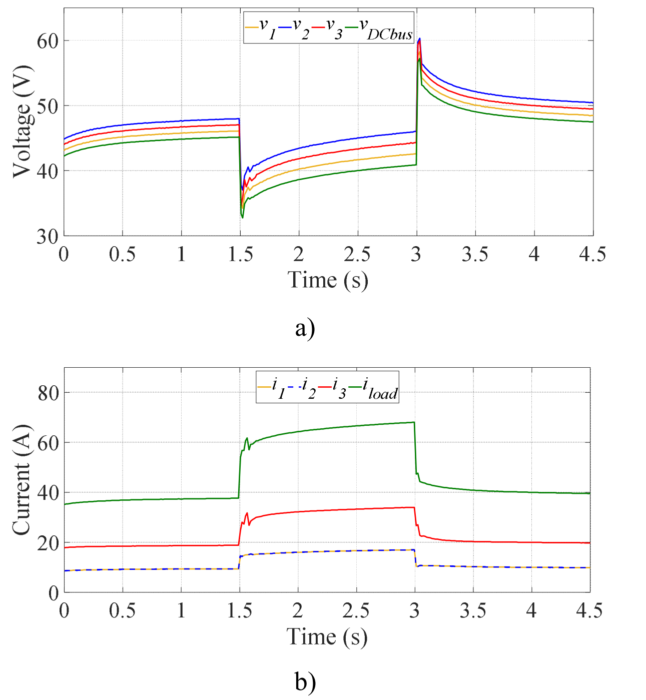
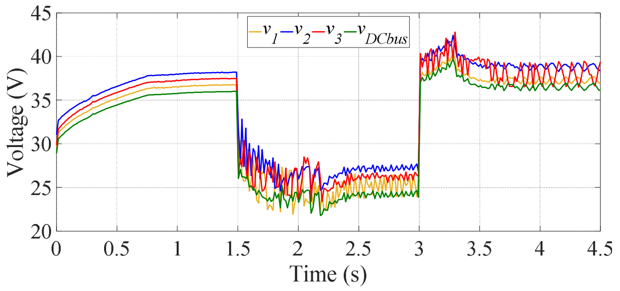
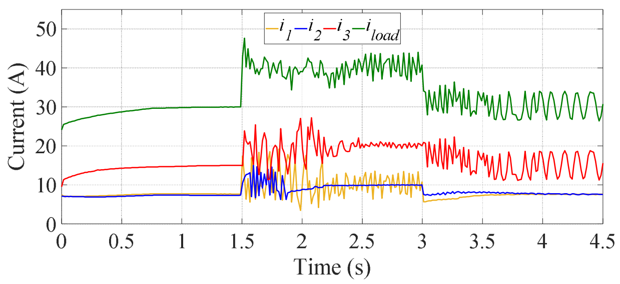


Fig. 5. Performance of the adaptive droop controller for the 48 V system in case of 30 ms communication delay: a) power unit output voltages and DC bus voltage b) current supplied by each power unit and load current.

Finally, when the communication delay is set to 300 ms, oscillations can be observed in both voltage and current waveforms, resulting in voltage regulation fail and relatively poor current sharing accuracy, as presented in Fig. 6. In more details, due to high communication delay, the voltage estimator fails to estimate the average voltage value of DC bus, resulting in calculation errors for voltage compensation terms. Moreover, the adaptive droop controller cannot accurately calculate the droop correction terms. Thus, for higher communication delay values, the adaptive droop controller performance is poor and system stability is jeopardized.



a)



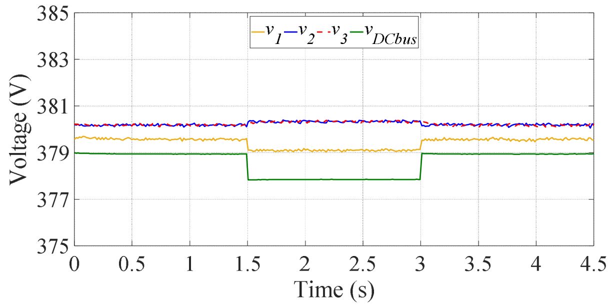
b)

Fig. 6. Performance of the adaptive droop controller for the 48 V system in case of 300 ms communication delay: a) power unit output voltages and DC bus voltage b) current supplied by each power unit and load current.

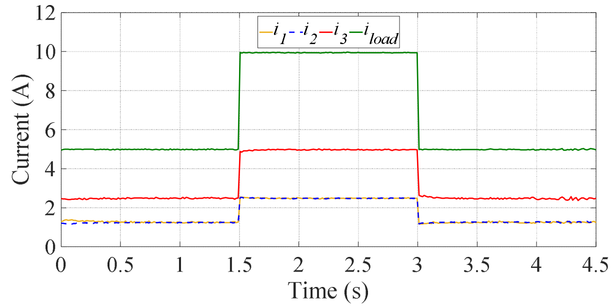
B. 380 V System

As regards the 380 V system configuration, its parameters are also depicted in Table II, whereas the same tests have been performed, as in 48 V configuration. The output voltages and currents of interlinking converters, as well as the DC bus voltage and load current are depicted in Fig. 7, Fig. 8 and Fig. 9, respectively. Load step changes occur at 1.5 s (increase from 5 A to 10 A) and 3 s (decrease from 10 A to 5 A). The controller performance in case of zero communication delay is presented in Fig. 7. The DC bus voltage drop is minor (i.e. approximately 1 V ~ 2 V), due to the voltage compensation term of the secondary controller. In parallel, the current sharing performance is excellent, as Fig. 7b denotes. The impact of different line impedances is eliminated and thus effective current sharing can be achieved.

When the communication delay is set to 30 ms, the adaptive droop controller performance is satisfactory, according to Fig. 8a, since the DC bus voltage deviation is similar to the zero-communication delay case. However, the communication delay impacts the current sharing, as it is depicted in Fig 8b, where current sharing balance among node#1 and node#2 is notably delayed, compared to the previous case.

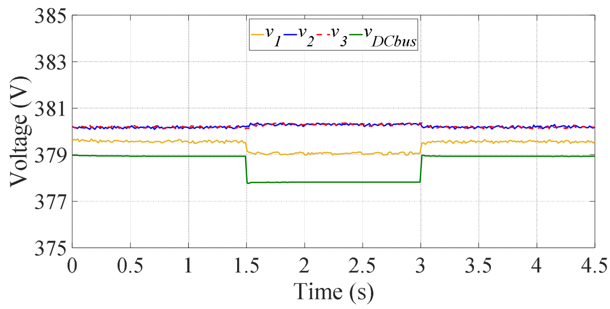


a)

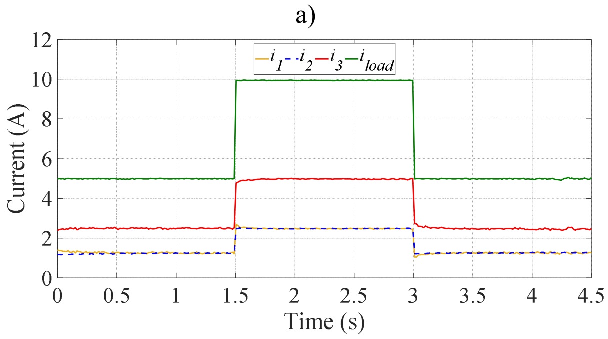


b)

Fig. 7. Performance of the adaptive droop controller for the 380 V system in case of zero (0 ms) communication delay: a) power unit output voltages and DC bus voltage b) current supplied by each power unit and load current.



a)



b)

Fig. 8. Performance of the adaptive droop controller for the 380 V system in case of 30 ms communication delay: a) power unit output voltages and DC bus voltage b) current supplied by each power unit and load current.

Finally, when the communication delay is set to 300 ms, oscillations can be observed in both voltage and current waveforms, resulting in poor current sharing accuracy and higher voltage undershoot, as presented in Fig. 9. In more detail, during load increase, the DC bus voltage falls below 373 V, which is notably greater, compared to zero and 30 ms delay cases. The main reason for these oscillations is the large communication delay; during this time, the adaptive droop controller cannot accurately calculate the droop correction terms, as well as exactly estimate the average voltage value, owing to delayed neighbors' voltage and current feedback signals. Hence, it is evident that for higher communication delay values, severe oscillations may occur and thus the stability of the control system is jeopardized.

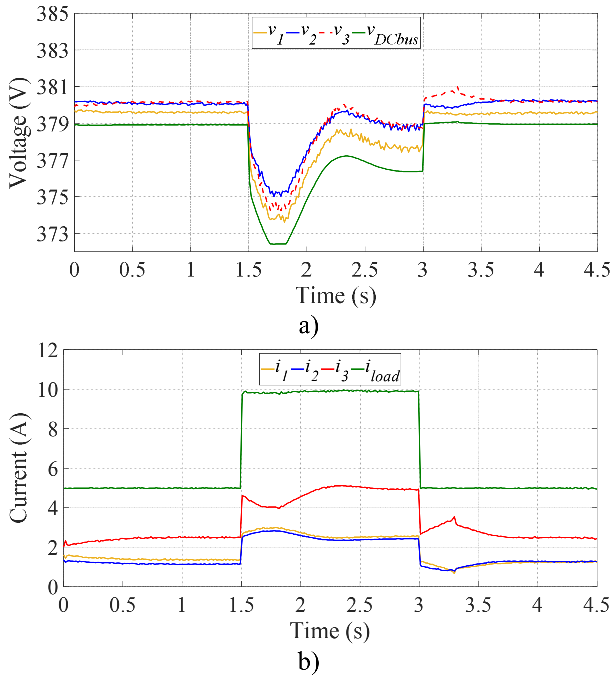


Fig. 9. Performance of the adaptive droop controller for the 380 V system in case of 300 ms communication delay: a) power unit output voltages and DC bus voltage b) current supplied by each power unit and load current.

V. Conclusions

This paper aims to contribute in highlighting the effects originating from communication delay in DC MGs performance, in terms of current sharing capability and DC voltage regulation. A residential DC MG (prosumer building and remote RES production) is considered, in islanded operation under an adaptive droop control scheme.

According to the presented results, it is concluded that for relatively small communication delays (e.g. 30 ms) the performance of the control system is almost unaffected. However, for higher communication delays the control system stability is not guaranteed, as oscillations and higher voltage deviations may occur. Hence, the impact of communication delay constitutes a challenging issue, which has to be considered in distributed control approaches with communication network.

Acknowledgment

The research work was supported by the Hellenic Foundation for Research and Innovation (HFRI) under the HFRI PhD Fellowship grant (Fellowship Number: 1455).

References

[1] T. Dragičević, X. Lu, J. C. Vasquez, J. M. Guerrero, “DC Microgrids— Part II: A Review of Power Architectures, Applications, and Standardization Issues,” IEEE Trans. Power Electron., vol. 31, no. 5, pp. 3528–3549, May 2016.

[2] T. Elsayed, A. A. Mohamed, O. A. Mohammeda, “DC microgrids and distribution systems: An overview,” Electric Power Systems Research, vol. 119, pp. 407–417, Feb. 2015.

[3] D. Baros, D. Voglitsis, N. Papanikolaou, A. Kyritsis, N. Rigogiannis, “Wireless Power Transfer for Distributed Energy Sources Exploitation in DC Microgrids,” IEEE Trans. Sust. Energy, vol. 10, no. 4, pp. 2039–2049, Oct. 2019.

[4] D. Kumar, F. Zare, A. Ghosh, “DC Microgrid Technology: System Architectures, AC Grid Interfaces, Grounding Schemes, Power Quality, Communication Networks, Applications, and Standardizations Aspects,” IEEE Access, vol. 5, pp. 1223012256, June 2017.

[5] T. Dragičević, X. Lu, J. C. Vasquez, J. M. Guerrero, “DC Microgrids—Part I: A Review of Control Strategies and Stabilization Techniques,” IEEE Trans. Power Electron., vol. 31, no. 7, pp. 4876–4891, July 2016.

[6] L. Meng et al., “Review on Control of DC Microgrids and Multiple Microgrid Clusters,” IEEE J. Emerg. Sel. Topics Power Electron., vol. 5, no. 3, pp. 928–948, Sep. 2017.

[7] F. Guo, Q. Xu, C. Wen, L. Wang, and P. Wang, “Distributed secondary control for power allocation and voltage restoration in islanded DC microgrids,” IEEE Trans. Sust. Energy, vol. 9, no. 4, pp. 1857–1869, Oct. 2018.

[8] V. Nasirian, A. Davoudi, F. L. Lewis, J. M. Guerrero, “Distributed Adaptive Droop Control for DC Distribution Systems,” IEEE Trans. Energy Conv., vol. 29, no. 4, pp. 944–956, Dec. 2014.

[9] M. Saleh, Y. Esa, A. A. Mohamed, “Communication-Based Control for DC Microgrids,” IEEE Trans. Smart Grid, vol. 10, no. 2, pp. 2180–2195, Mar. 2019.

[10] X. Lu, J. M. Guerrero, K. Sun, J. C. Vasquez, “An Improved Droop Control Method for DC Microgrids Based on Low Bandwidth Communication With DC Bus Voltage Restoration and Enhanced Current Sharing Accuracy,” IEEE Trans. Power Electron., vol. 29, no. 4, pp. 1800–1812, Apr. 2014

[11] M. Saleh, Y. Esa, A. Mohamed, “Impact of Communication Latency on the Bus Voltage of Centrally Controlled DC Microgrids During Islanding,” IEEE Trans. Sust. Energy, vol. 10, no. 4, pp. 1844–1856, Oct. 2019.

[12] V. Vossos, K. Garbesi, H. Shen, “Energy savings from direct-DC in U.S. residential buildings,” Energy and Buildings, vol. 68, pp. 223–231, Jan. 2014.

[13] D. L. Gerber et al., “A simulation based comparison of AC and DC power distribution networks in buildings,” 2017 IEEE Second International Conference on DC Microgrids (ICDCM), 27 - 29 June 2017, Nuremburg, Germany.

[14] Council of European Energy Regulators Report, Regulatory Aspects of Self-Consumption and Energy Communities, 2019.

[15] European Commision, GREEN PAPER: A 2030 Framework for Climate and Energy Policies, COM 169, 2013.

[16] D. D'Agostino, L. Mazzarella, “What is a Nearly zero energy building? Overview, implementation and comparison of definitions,” J. Building Engineering, vol. 21, pp. 200–212, Jan. 2019.

[17] N. Rigogiannis, D. Voglitsis, N. Papanikolaou, “Microcontroller Based Implementation of Peak Current Control Method in a Bidirectional Buck-Boost DC-DC Converter,” 20th International Symposium on Electrical Apparatus and Technologies (SIELA), 3 - 6 June 2018, Burgas, Bulgaria.

[18] N. Rigogiannis et al., “Experimental Investigation of a Digitally Current Controlled Synchronous Buck DC/DC Converter for Microgrids Applications,” 2019 Panhellenic Conference on Electronics and Telecommunications (PACET), 8 - 9 Nov. 2019, Volos, Greece.

[19] S. Moussa, M. J.-B. Ghorbal, I. Slama-Belkhodj, “Bus Level Choice for standalone residential DC nanogrid,” Sustainable Cities and Society, vol. 46, Apr. 2019.

[20] T. Dragičević, J. C. Vasquez, J. M. Guerrero, D. Skrlec, “Advanced LVDC Electrical Power Architectures and Micrograids: A step toward a new generation of power distribution networks,” IEEE Electrif. Mag., vol. 2, no. 1, pp. 54–65, Mar. 2014.

[21] H. Sherazi, R. Iqbal, S. Hassan, M. Chaudary, S. Gilani, “ZigBee's received signal strength and latency evaluation under varying environments,” J. Comput. Netw. Comm., vol. 2016, art. No. 5, 2016.

[22] M. Laner et. al, “A comparison between one-way delays in operating HSPA and LTE networks,” 2012 10th International Symposium on Modeling and Optimization in Mobile, Ad Hoc and Wireless Networks (WiOpt), 14 - 18 May 2012, Paderborn, Germany.