

Optimal Droop Offset Adjustments for Accurate Energy Trading in Rural DC Mini-Grid Clusters

Joan-Marc Rodriguez-Bernuz, Adrià Junyent-Ferré, Xin Xiang

Department of Electrical and Electronic Engineering

Imperial College London

London SW7 2AZ, UK

jmr115@ic.ac.uk

Abstract—Off-grid micro-grids and solar home systems have become an enabler for the electrification of rural areas in developing countries. Their future integration into full-scale grids poses multiple technical challenges. This paper presents a concept of local DC mini-grid formed by the interconnection of nearby micro-grids. This is envisioned as a step towards the bottom-up development of a larger grid. The paper places special emphasis on the analysis of the controller structure, which is based on a variation of the common droop controller. Generally, decentralised droop schemes present inherent limitations to achieve, simultaneously, DC voltage regulation and accurate energy tracking. The decentralised controller proposed here improves conventional approaches by optimally adjusting the droop controller setpoints based on an Optimal Power Flow (OPF) algorithm that takes into account the characteristics of individual converters and the energy trading commands. This approach can benefit from the communication layer required by the energy trading system. The control design of the mini-grid is customised for its deployment on a variation of the dual active bridge (DAB) power electronic converter. Despite the use of a centralised OPF, the system stability is guaranteed by the decentralised low-level controller. The performance of the control approach and its sensitivity to unknown system parameters is measured and validated through detailed simulation studies.

Index Terms—mini-grids, droop control, optimal power flow

I. INTRODUCTION

As of today, an estimated total of 1.1 billion people lack access to electricity [1]. This issue is particularly concerning in remote locations of sub-Saharan Africa, where it has been suggested that 700 million people will still not have access to electricity by 2040 [1]. The drop in costs of photovoltaics over the years has made off-grid solar home systems become very popular [1]. Individual solar home systems usually suffer from poor reliability and under-utilisation due to the lack of redundancy and the intermittency of the load. Grouping multiple neighbouring consumers by connecting them to a common micro-grid could mitigate these problems and enable a reliable and cost-effective supply for critical loads (e.g. cooling units in medical centres). On the long term, these micro-grids could be integrated into a larger countrywide grid. It has been suggested that this countrywide grid could be built from the bottom-up,

starting by interconnecting neighbouring micro-grids creating local mini-grids. This second level aggregation could bring benefits in terms of better utilisation of the generation and energy storage units and enhanced resilience. The energy exchanged amongst micro-grids could be performed following energy trading strategies [2].

The interconnection of micro-grids to form a mini-grid involves multiple technical challenges. For instance, it may not be possible to connect two existing micro-grids together by installing a new line between them. This is because micro-grids that were designed to operate in isolation may be designed to follow incompatible standards (e.g. 110V and 230V or AC and DC) or they may regulate their voltage using incompatible methods that impede their direct connection. One way to overcome this incompatibility is to use a power electronic converter as the interface between each micro-grid and the mini-grid. The mini-grid could be designed to use DC in order to enable the use of power converters with high power density and better overall efficiency [3]. The terminals of the mini-grid could be controlled in a decentralised fashion by means of droop controllers. Two main droop controller configurations are commonly found in the literature: voltage-current (V-I) and voltage-power (V-P) [4]. The basic droop configurations do not guarantee a perfect predefined tracking of the power orders and the even distribution of the load amongst the connected terminals. This is due to the voltage drop across line impedances and, to a certain extent, to the quality of the sensors of the terminals. The problem is aggravated by the adoption of fixed droop gains regardless of the power flow condition. To overcome this problem, recent work [5] has presented a decentralised adaptive droop such that a seamless transition between different operating modes is achieved improving the power-sharing accuracy of the system although the reference tracking is not explicitly addressed. Other approaches (e.g. [6]) use multiple hierarchical control layers where different cascaded controllers tuned at different bandwidths target different objectives; however, the control complexity of the micro-grid is increased.

This paper presents a suitable solution using a single control loop to connect multiple micro-grids together using power electronic DC/DC converters with galvanic isolation to form a DC mini-grid. The paper gives an overview of the characteristics of the system under consideration and provides special

This work is supported by the EPSRC under the project EP/R030235/1 “RENGA: Resilient Electricity Networks for a productive Grid Architecture”

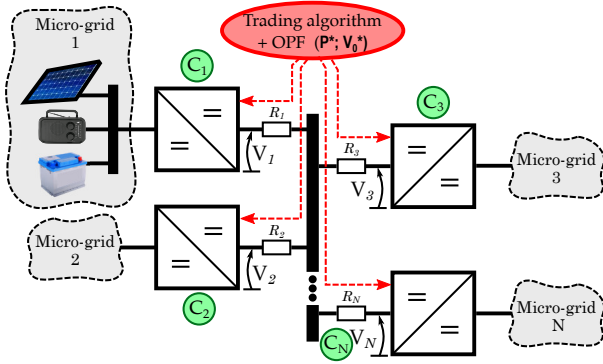


Fig. 1. Illustration of three-node mini-grid interconnection.

emphasis on the analysis and discussion of the chosen control structure. The mini-grid under consideration sets particular operation requirements. Namely, the terminals of the network must accurately track their power order and share the duty to regulate the DC voltage. Ideally, the controller must perform successfully with little prior knowledge of the line impedances to simplify deployment. A number of papers found in the literature analysed algorithms to improve the power tracking capabilities of micro-grid droop-governed converters [7]. However, the approach presented in [7] still required a main grid-interfaced converter to regulate the DC link and guarantee the system stability while the other converters performed power tracking. The idea was that droop regulation would be adopted only when the main converter was unavailable and power tracking degraded. Other approaches in the literature introduce low-bandwidth communications to improve droop characteristics of the system and enhance the power-sharing accuracy amongst the converters [8]. The improvement of droop controllers using communications links can also be found in the HVDC grids literature. In [9], the communication link of the HVDC system is used to optimise the droop coefficients and enhance system efficiency. The improvement is achieved by solving an Optimal Power Flow (OPF) that tunes the configuration of each terminal. A similar approach adapted to the characteristics of a low voltage system is investigated in this paper.

II. MINI-GRID ARCHITECTURE

The mini-grid concept investigated here aggregates nearby self-sustained micro-grids enabling energy exchanges amongst them. The setpoint of each converter connected to the mini-grid is updated periodically following energy trading algorithm. The system is suitable for the deployment of different energy trading algorithms considering different optimisation goals (e.g. [2]) or energy market structures. The regulation of the voltage of the mini-grid requires the power balance across the mini-grid to be maintained at all times. This is achieved by letting all converters to make adjustments to their setpoints based on a distributed control law that relies on local information. An illustration of the mini-grid is shown in Fig. 1. Note that each of the nodes ($C_1, C_2, C_3, \dots, C_N$)

correspond to self-sustained micro-grids with local energy resources (i.e. generation, storage and loads). These micro-grids have their own internal control that enables them to operate autonomously even if the mini-grid is unavailable. The idea that the system may handle outages of the mini-grid is a distinctive feature of the concept presented in this paper.

Recent works found in the literature have compared the benefits of using AC versus DC in the electrification of developing rural areas [10]. Interestingly, low voltage direct current (LVDC) is found to simplify the connection loads, generation and energy storage units, which are often interfaced using power electronic converters (e.g. PV, Li-ion batteries, LED lights, phone chargers, etc). As of today, the downside of DC is the uncertainty in terms of standard voltages in use. The choice of optimum voltage levels for those systems is still a matter of debate and it depends on a number of factors including the cost of the power conversion, transmission distance, protection, safety requirements, etc. Some common LVDC levels in use are 48 V, 120 V, 230 V, 380 V [10].

The peak power demand of a small-scale rural micro-grid varies depending on a number of circumstances; prior studies have noted that a great number of users have peak demand in the range between tens and hundreds of watts [11]. Sizing of a converter to interface a micro-grid to the mini-grid implies a trade-off between future-proofing and affordability. For example, a power rating of multiple tens of kilowatts may be costly and hard to justify for a small community but a converter of only tens of watts may be impractical due to the cost of laying the lines of the mini-grid. Here, a reference value of ≤ 1 kW is chosen. It is assumed that micro-grid systems are located nearby such that connection distances are relatively short (e.g. 500 m in straight line). Taking this into account, the nominal **mini-grid voltage** (V_{link}) is set as **200 V** and the **micro-grid is assumed to run at 48 V** [11]. The cross-section of the cable is considered as 10 mm² with an equivalent resistance of 1.95 Ω /km. The overall resistance of each line is considered as: $R_1 = 1.014 \Omega$, $R_2 = 0.55 \Omega$ and $R_3 = 0.78 \Omega$.

III. INTERFACE CONVERTER

The dual active bridge (DAB) converter is a popular topology for bidirectional DC/DC conversion with galvanic isolation in medium-power applications [12]. A voltage step-ratio between input and output is achieved through the turns ratio of its internal transformer. However, the design of DABs for a large voltage step-ratio poses a challenge on the efficiency and power density due to the additional losses introduced by circulating currents and the reduction of the soft-switching area. Here a modified DAB converter with a voltage-doubling configuration on the high side is adopted to meet the requirements of the micro-grid application.

Generally, the DAB presents much higher voltage stress on the switching devices located on the high-voltage (HV) bridge, which limits the use of LV power devices with better performance. In addition, the DAB usually accounts for a DC-blocking capacitor near the transformer to eliminate offsets

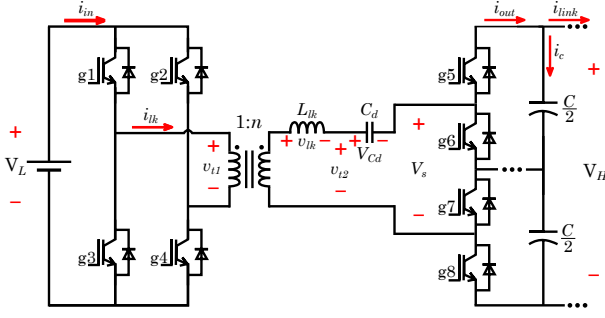


Fig. 2. Customised DAB schematic.

TABLE I
CUSTOMISED DAB AND CONTROL PARAMETERS

Parameter	Value	Parameter	Value
Power	1 kW	n	1:2.5
V_L	48 V	L_{lk}	11 μ H
V_H	160-240 V	C_d	10 μ F
C	440 μ F	f_{sw}	100 kHz
ζ	$\sqrt{2}$	ω_0	2100 rad.
K_P	0.0043	K_I	3.2168
α, β	0.5	K	0.094

arising from the unsymmetrical parameters or transients; although this capacitor might not provide any other benefits. To overcome these limitations, the two half-bridges of the HV side are combined in series to form a three-level structure, which not only reduces the voltage stress of secondary switches but provides good flexibility for various configurations of interconnected DC bus and alleviates the voltage stress on the transformer as the DC-blocking capacitor takes half responsibility of the conversion step-up (see Section III-A). The illustration of the resulting converter is provided in Fig. 2 together with its operating waveforms in Fig. 3.

A. Converter Analysis and Modelling

The average model of the proposed topology can be derived following an analogous derivation to that of the conventional DAB [13]. Neglecting the dead-times of the bridges and the series resistance of the transformer, the resulting cycle of the transformer current i_{lk} is shown in Fig. 3. The equations that describe each of the stages are shown below.

$$t_0 - t_1 : L_{lk} \frac{d}{dt} i_{lk}(t) = nV_L + V_{Cd} \quad (1)$$

$$t_1 - t_2 : L_{lk} \frac{d}{dt} i_{lk}(t) = nV_L + V_{Cd} - V_H \quad (2)$$

$$t_2 - t_3 : L_{lk} \frac{d}{dt} i_{lk}(t) = -nV_L + V_{Cd} - V_H \quad (3)$$

$$t_3 - t_4 : L_{lk} \frac{d}{dt} i_{lk}(t) = -nV_L + V_{Cd}. \quad (4)$$

The relationship between the DC capacitor voltage V_{Cd} and HV link V_H is derived from the steady-state voltage-second balance of the leakage inductor over one switching cycle:

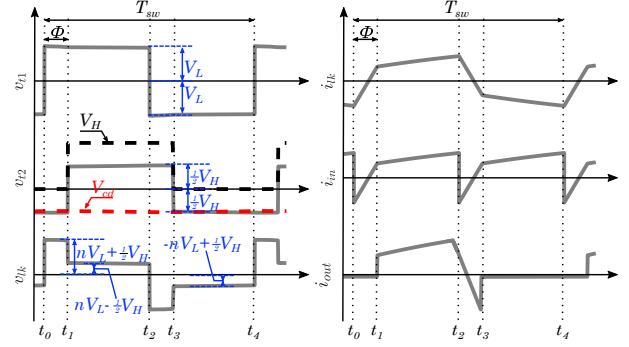


Fig. 3. Custom DAB system trajectories.

$$(nV_L + V_{Cd})\phi + (nV_L + V_{Cd} - V_H)(T_{sw}/2 - \phi) + (-nV_L \dots + V_{Cd} - V_H)\phi + (-nV_L + V_{Cd})(T_{sw}/2 - \phi) = 0. \quad (5)$$

This shows how the DC capacitor C_d in the secondary side contributes to the step-up conversion between V_L and V_H ($2V_{Cd} = V_H$). The equivalent converter model can be obtained by averaging the transformer currents over one switching cycle (1)-(4). The converter input current can be expressed:

$$i_{in} = \frac{1}{T_{sw}} \left(\int_{t_0}^{t_1} (1) dt + \int_{t_1}^{t_2} (2) dt + \int_{t_2}^{t_3} (3) dt + \int_{t_3}^{t_4} (4) dt \right) \quad (6)$$

where T_{sw} is the switching period. Note that the output current can be obtained following identical procedure. The resulting average system currents are as follows:

$$i_{in} = \frac{dT_{sw}(V_{Cd} - V_H)(d - 1)}{2L_{lk}} \quad (7)$$

$$i_{out} = -\frac{dT_{sw}V_L(d - 1)}{4nL_{lk}} \quad (8)$$

where d is the phase-shift ratio ($\phi = d \frac{T_{sw}}{2}$).

IV. LOW-LEVEL CONTROLLER

The lowest level of control of the interface converter presented in Section III resembles the conventional DAB. The modulation of the primary and secondary power bridges generates a high-frequency square voltage on the transformer terminals (see Fig. 3). These voltages can be phase-shifted by an angle ϕ , which enables to control the power exchanged between the two bridges. The phase-shift command is determined by a proportional-integral (PI) regulator and a droop controller (see Fig. 4). The role of the droop controller is to let the converter settle close to the setpoint given by the energy trading algorithm while providing some room for adjustment in order to stabilise the DC system. The droop controller generates

a voltage reference that is tracked by the closed-loop output voltage control. It is possible to design the control to make the mini-grid inherently stable upon connection and disconnection of converter terminals by designing the controller gains using the passivity-based guidelines described in [14]. The relevant dynamics for the control design are give by (9). In order to choose the closed-loop gains, a linear approximation of the plant is derived in (10). The controller gains are obtained considering the i_{link} current as a disturbance:

$$\frac{d}{dt}V_H = \frac{1}{C} \left(\underbrace{-\frac{dT_{sw}V_L(d-1)}{4nL_{lk}}}_{i_{out}} - i_{link} \right) \quad (9)$$

$$\frac{d}{dt}\delta V_H = \frac{1}{C} \left(\underbrace{\left(-\frac{T_{sw}\tilde{d}\tilde{V}_L}{2nL_{lk}} + \frac{T_{sw}\tilde{V}_L}{4nL_{lk}} \right)}_{G_p} \delta d \right) \quad (10)$$

where over-script $\sim$ denotes quiescent values. The linearisation is performed at nominal operating point.

The closed-loop transfer function has the form of a second-order system (11) and PI gains (12) can be adjusted as below:

$$\frac{\delta V_H}{\delta d} = \frac{\frac{G_p}{s} \left(\frac{K_P s + K_I}{s} \right)}{1 + \underbrace{\frac{G_p}{s} \left(\frac{K_P s + K_I}{s} \right)}_{G_c}} = \frac{G_p K_P s + G_p K_I}{s^2 + G_p K_P s + G_p K_I} \quad (11)$$

$$K_P = \frac{2\zeta\omega_0}{G_p}, \quad K_I = \frac{\omega_0^2}{G_p} \quad (12)$$

where ζ is the damping coefficient and ω_0 is the natural oscillatory frequency of the second-order system.

The controller dynamics in Fig. 5 are presented for the average and switching converter models given that the tuning parameters are based on the average equivalent model derived in (7)-(8). First, the system response to a reference step-change from 200 V to 240 V is shown when the converter is operating at full load (1 kW). Next, the system disturbance rejection capability is also shown (i_{link} changes from 0 to 5 A). It is seen that the average model matches the switching model with a good level of accuracy and the controller response is adequate.

V. OPTIMISED DROOP REFERENCE CONTROLLER

The mini-grid system requires a precise energy exchange mechanism which is difficult achieve using conventional droop controllers given the dichotomy between DC bus regulation

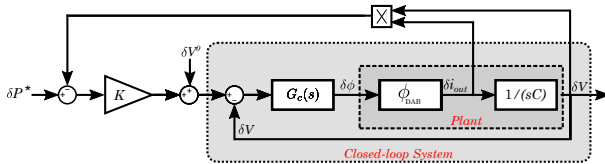


Fig. 4. Schematic of the control loop.

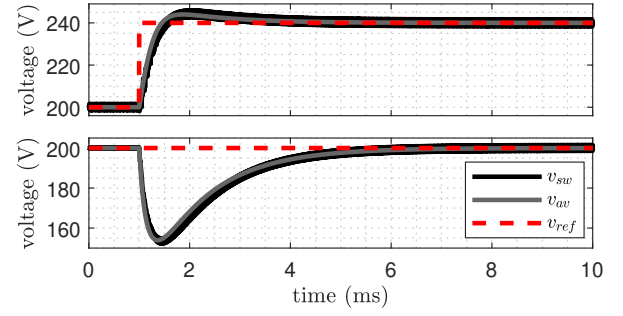


Fig. 5. Performance of the closed-loop controller.

and power tracking [15]. Generally, droop-controlled converters acting as constant power sources require of 1) an additional power control loop and 2) a grid-interfaced converter (or a slack converter) to ensure adequate DC voltage regulation. Given the twofold objective considered in this particular mini-grid, an OPF algorithm similar to the one presented in [9] is adopted. By adjusting the droop offset points of each individual converter, the tracking accuracy is increased while system DC value is kept close to nominal. The calculation of the optimal droop setpoints can be done in a higher level of control, where trading commands are decided [2]. Interestingly, the droop dynamics can be included in the definition of the OPF, and the setpoint updates can be sent together to each individual converter when power references are updated by the trading algorithm.

A. Voltage-Power Droop Definition

The description of the droop controller is provided to N buses, representing N interface converters (see Fig. 1). The power injected by each converter can be written as:

$$P_i = V_i \left(\sum_{j=1}^N Y_{ij} V_j \right) \quad (13)$$

where i represents the i^{th} bus of the system, P is the power exchanged by converter i , V is the terminal bus voltage and Y_{ij} is the admittance between converters i and j .

The droop controller is designed as a V-P mapping. Therefore, the converter voltage at bus i is defined as:

$$V_i = V_i^0 + K_i(P_i^* - P_i) \quad (14)$$

where K_i is the droop gain of the converter connected at bus i , P_i^* is the power reference to be tracked and V_i^0 is the droop offset point. K_i gives the sensitivity of the power output of the converter.

B. Optimal Power Flow Calculation

The droop setpoints of each converter can be determined by solving an optimisation problem that takes into account the droop and the system parameters. Then, power injected by each converter can be written by combining (13) and (14) as:

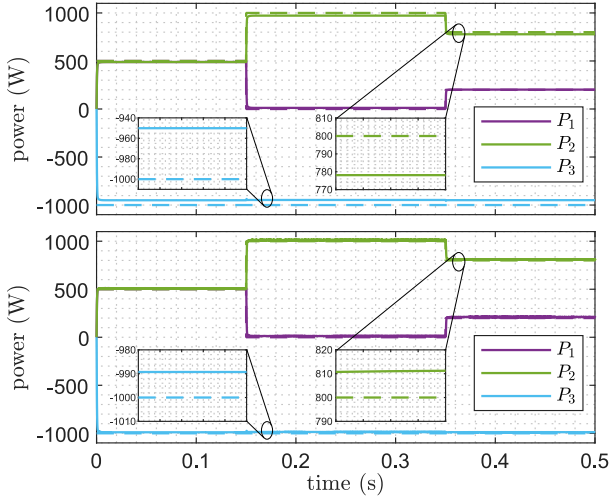


Fig. 6. Power tracking performance under ideal operating conditions. Upper figure: conventional droop. Lower figure: OPF droop.

$$P_i^* = V_i^2 Y_{i,i} + V_i \sum_{j=1, j \neq i}^N Y_{i,j} V_j - \frac{V_i^0}{K_i} + \frac{V_i}{K_i}. \quad (15)$$

The optimal operating configuration of each individual converter can be determined by solving an optimisation problem considering the individual bus dynamics in (15), given a vector of power references $\mathbf{P} := [P_1^* \ P_2^* \ \dots \ P_N^*]$. Then, system bus voltages $\mathbf{V} := [V_1 \ V_2 \ \dots \ V_N]$, power $\mathbf{P} := [P_1 \ P_2 \ \dots \ P_N]$ and offsets $\mathbf{V}^0 := [V_1^0 \ V_2^0 \ \dots \ V_N^0]$ are the optimisation variables. The optimal operating point is defined as trade-off between DC voltage regulation and power reference tracking:

$$\min. \quad \underbrace{\alpha \sum_{i=1}^N (P_i - P_i^*)^2}_{\text{term 1}} + \underbrace{\beta \sum_{i=1}^N (V_i - V_{link})^2}_{\text{term 2}} \quad (16)$$

where α and β are weights to trade-off power tracking and nominal bus voltage error (**term 1** and **term 2** respectively). Likewise, (16) is subject to the system modelling constraints and the optimisation can be defined to provide operating setpoints that do not exceed specific operating boundaries:

$$\begin{aligned} \text{subject to} \quad & (15), \quad i = 1, \dots, N \\ & V_i^{min} \leq V_i, \quad i = 1, \dots, N \\ & V_i^{max} \geq V_i, \quad i = 1, \dots, N \end{aligned} \quad (17)$$

where V_i^{min} and V_i^{max} are the minimum and maximum voltages of each bus in the micro-grid. Then, the optimisation problem determines the optimal setpoint references $\mathbf{V}^0$.

VI. SIMULATION PLATFORM & VALIDATION

The system performance is validated in *Matlab Simulink* in a simulation model which considers a three-bus system following the structure shown Fig. 1. The system parameters are provided in Section II, and the converter and control parameters are shown in Table I.

TABLE II
MAXIMUM DEVIATION RESPECT REFERENCE VALUES.

	Fixed $\mathbf{V}^0$		Optimal $\mathbf{V}^0$	
	$ \Delta V $	$ \Delta P $	$ \Delta V $	$ \Delta P $
C_1	0.5%	2.2%	1%	1.8%
C_2	1.3%	2.8%	1.6%	1.2%
C_3	2.45%	5.3%	1.9%	1.4%

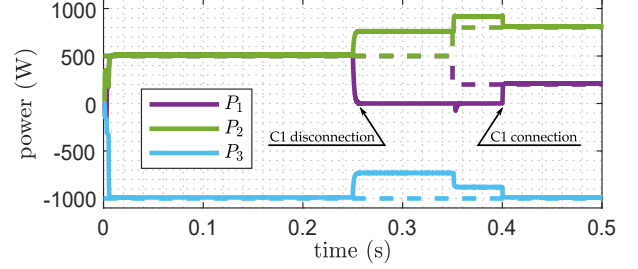


Fig. 7. Power tracking performance under non-ideal operating conditions

A. Normal Operating Conditions

The system capability to track power references under normal operating conditions is compared between a conventional droop approach (i.e. $\mathbf{V}^0 = V_{link}$) and the OPF presented in Section V. The performance of each scenario is shown in Fig. 6. First, C_1 and C_2 receive a command to inject 500 W into the DC link while C_3 absorbs 1 kW. Note that the references would be determined by an upper energy trading algorithm, e.g [2]. Next, at time 0.2 s the reference changes, and C_1 has to inject 1 kW and C_2 does not exchange energy. It should be noticed that the time scale at which the reference changes does not correspond to a real scenario but is provided for illustration purposes only. Afterwards, the reference values change at time 0.35 s and C_1 and C_2 inject 800 W and 200 W respectively. The results show that the proposed approach has smaller power tracking error than the conventional droop. A summary of the largest deviations is provided in Table II.

B. Robustness Validation

This section discusses the robustness of the system to unknown line impedances, loss of in-feed caused by the disconnection of converters and delays in updating the setpoint of individual converters. Unlike the results shown earlier in Fig. 6 where systems delays were not considered and impedances in the OPF matched those in the simulation, the results shown in Fig. 7 consider a non-ideal scenario. Then, the estimated impedance provided to the OPF has the following error: R_1 50%, R_2 30% and R_3 20%. Likewise, the following communication delays between the OPF and the converters is established: $C_1 \sim 5$ ms, $C_2 \sim 3$ ms and $C_3 \sim 4$ ms. Despite the data inaccuracy, it is found that the three converters settle at a power exchange that is close to the reference value. Also, the delays only cause a minor transient mismatch and the system is kept stable at all times. The loss of converter C_1 is also simulated at time 0.25 s. The loss is not notified to the energy trading algorithm, which causes the power references to be

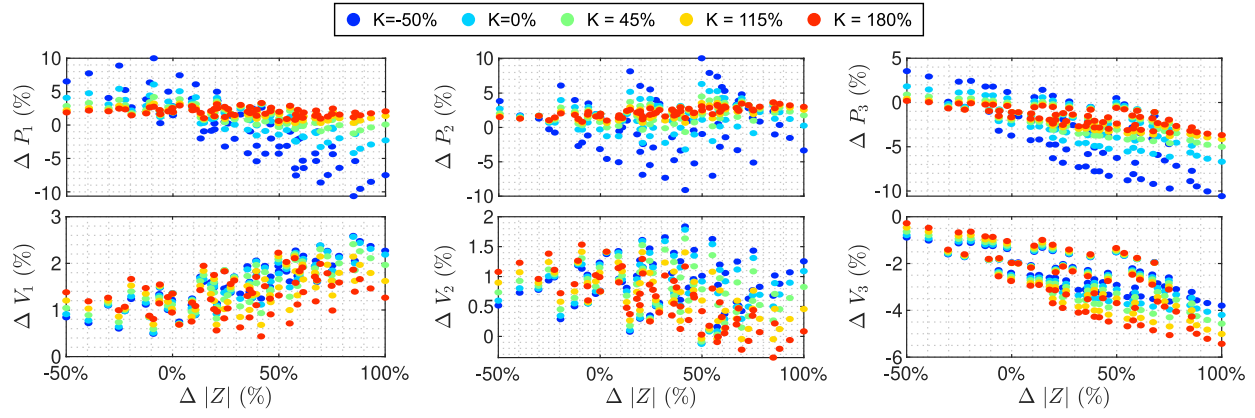


Fig. 8. Power and voltage deviation at each bus for different droops and grid impedance variations.

inconsistent. The power imbalance makes the droop controllers to change the power references of the converters that remain in operation to ensure stability. The trading algorithm provides an updated reference at time 0.35 s that is still inconsistent with the disconnection of $C1$, but once again the system remains stable thanks to the droop controllers of $C2$ and $C3$. The recovery of $C1$ is simulated at time 0.4 s and then the system stabilises at a point that is consistent with the references.

The performance of the system when line impedances are not known accurately is shown in Fig. 8, which shows the deviation of bus voltage and power injections for different line parameters and droop coefficients. The OPF parameters are kept as in Section II but individual line impedances in the simulation model are modified to vary between -50% and 100% of their nominal values. The 2-norm of a vector with all line impedances variations is used to quantify the deviation respect to the nominal values, $|\Delta Z|$. Likewise, different droop gains defined as variations to the base value listed in Table I are considered to illustrate how the droop setting can change the effect of the impedance variation. The results show that larger droop gains make the system more robust to impedance data inaccuracies, in all cases the error of power and voltage of the nodes is kept well below 10% deviation despite having a large deviation on the estimated line impedances.

VII. CONCLUSIONS

This paper has presented a concept of DC mini-grid that is used to enable a series of self-sufficient micro-grids to trade energy amongst them. The concept uses a variation of the DAB converter to connect the micro-grids to the mini-grid. A low-level controller with a single loop is combined with an OPF algorithm that uses the communications system required for the energy trading negotiation. This enables accurate DC voltage regulation and power tracking. The modelling and control design has been validated in detailed simulations and a sensitivity study has been also provided. The results show that the proposed controller provides good transient response to power reference changes even when individual converter references are updated with delays. The system is also found

to be stable under sudden disconnection of converters and the voltage and power tracking error is found to be small even when line impedances are not known accurately.

REFERENCES

- [1] O. Publishing, "World energy outlook 2017," Paris, 2017.
- [2] A. O. Rousis, I. Konstantelos, and G. Strbac, "A planning model for a hybrid ac-dc microgrid using a novel ga/ac opf algorithm," *IEEE Trans. on Power Systems*, vol. 35, no. 1, pp. 227–237, 2020.
- [3] B. Wunder, L. Ott, M. Szpek, U. Boeke, and R. Weiß, "Energy efficient dc-grids for commercial buildings," in *2014 IEEE 36th International Telecommunications Energy Conference (INTELEC)*, 2014, pp. 1–8.
- [4] T. Dragičević *et al.*, "DC microgrids—part i: A review of control strategies and stabilization techniques," *IEEE Trans. Power Electron.*, vol. 31, no. 7, pp. 4876–4891, 2016.
- [5] Y. Gu, X. Xiang, W. Li, and X. He, "Mode-adaptive decentralized control for renewable dc microgrid with enhanced reliability and flexibility," *IEEE Trans. Power Electron.*, vol. 29, no. 9, pp. 5072–5080, 2014.
- [6] X. Lu *et al.*, "Hierarchical control of parallel ac-dc converter interfaces for hybrid microgrids," *IEEE Trans. Smart Grid*, vol. 5, no. 2, pp. 683–692, 2014.
- [7] G. Liu *et al.*, "Power-based droop control in dc microgrids enabling seamless disconnection from upstream grids," *IEEE Trans. Power Electron.*, vol. 34, no. 3, pp. 2039–2051, 2019.
- [8] X. Lu *et al.*, "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, 2014.
- [9] M. Aragüés-Peñalba *et al.*, "Optimum voltage control for loss minimization in hvdc multi-terminal transmission systems for large offshore wind farms," vol. 89, pp. 54–63, 2012.
- [10] M. Nasir, H. A. Khan, A. Hussain, L. Mateen, and N. A. Zaffar, "Solar pv-based scalable dc microgrid for rural electrification in developing regions," *IEEE Trans. Sustain. Energy*, vol. 9, no. 1, pp. 390–399, 2018.
- [11] M. B. Pedersen, "Deconstructing the concept of renewable energy-based mini-grids for rural electrification in east africa," vol. 5, no. 5, pp. 570–587, 2016.
- [12] S. P. Engel *et al.*, "Comparison of the modular multilevel dc converter and the dual-active bridge converter for power conversion in hvdc and mvdc grids," *IEEE Trans. Power Electron.*, vol. 30, no. 1, pp. 124–137, 2015.
- [13] K. Zhang *et al.*, "Large- and small-signal average-value modeling of dual-active-bridge dc-dc converter considering power losses," *IEEE Trans. Power Electron.*, vol. 32, no. 3, pp. 1964–1974, 2017.
- [14] Y. Gu, W. Li, and X. He, "Passivity-based control of dc microgrid for self-disciplined stabilization," *IEEE Trans. on Power Systems*, vol. 30, no. 5, pp. 2623–2632, 2015.
- [15] E. Prieto-Araujo *et al.*, "DC voltage droop control design for multiterminal hvdc systems considering ac and dc grid dynamics," *IEEE Trans. Power Del.*, vol. 31, no. 2, pp. 575–585, 2016.