Power Sharing and Synchronization Strategies for Multiple PCC Islanded Microgrids

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***Abstract*—Most of researchers have already studied and discussed the power sharing and synchronization of several generation systems connected to a unique point of common coupling (PCC) to which the loads are also connected. A high penetration rate of distributed generation systems (DGs) based on renewable energies has for logic consequence the development and setting up of networked multi-PCC microgrids. In this paper an improved droop control method for synchronization as well as active and reactive power sharing of different DGs in multiple PCC islanded microgrids is proposed while the real characteristics of the line feeders are taken into account. The simulation results confirm the feasibility and effectiveness of the proposed strategies for synchronization and interconnection of different microgrid DGs, while insuring accurate sharing of the DGs active and reactive powers.**

***Index Terms*—Distributed generation units, droop control, microgrids, power sharing, synchronization**

I. Introduction

An efficient solution to reduce the greenhouse gas emissions, which is the principal responsible for global warming, is increasing the production of renewable clean energy using the distributed power generation units. Thanks to this evolution, the production of the renewable energy is on the rise [1]. These renewable energy generation systems are integrated either in an islanded microgrid or in the main grid. In microgrids with a high penetration rate of distributed generators, the intermittency of renewable energy may cause the instability of the microgrid or even the main grid when it is connected to the microgrid. The first challenging problem is to synchronize and connect either a distributed generator to an islanded microgrid (first mode), considered as unit, with the main grid (second mode) [2], [3], while insuring "plug and play" feature with the respect of active and reactive consumed power sharing between the different distributed generation units in both modes.

Currently most research works concern the development of power sharing and synchronization strategies in microgrids based on droop control [4]-[8]. However, the considered microgrids in these papers have only one point of common coupling (PCC) which is connected to all of the generation systems through controlled converter units and to the loads. In these cases, the application of the proposed synchronization and power sharing methods has been validated. But in a more networked microgrid, with different DG sources and loads connected randomly to the different PCCs, the usual synchronization methods as well as power sharing strategies are less efficient due to the interconnected PCCs by the line feeders for which the impedances cannot be neglected.

Few researches discussed solutions for power sharing, "plug and play" and the possibility of connection to the main grid which transforms islanded microgrid to a grid-connected microgrid, using both-way communication. Once a new DG unit decides to join the microgrid, a signal will be sent to the central control that will correct reactive power references correspondingly. Then the "plug and play" feature can be realized [9].

In this paper a networked microgrid with multiple DGs and loads interconnected with line feeders, modeled by RLC circuits and inspired from an IEEE 9bus test feeder Fig. 3 is considered. Adapted droop control and synchronization strategies are proposed to suit the complex microgrid in islanded mode to ensure accurate power sharing and "plug and play" feature with distributed control with no need to both-way communication. In islanded mode, the first DG connected to the microgrid imposes the voltage and frequency, then for every other DG to be connected to the microgrid, the proposed synchronization strategy is applied before its interconnection. During the synchronization interval, to not disturb the power sharing between DGs already connected to the microgrid, the droop control algorithms are improved to take into consideration the complex nature of the line impedances. The simulation tests and obtained results confirm the efficiency of the proposed

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strategies to secure successfully the power sharing in islanded mode and during synchronization interval using distributed control strategy.

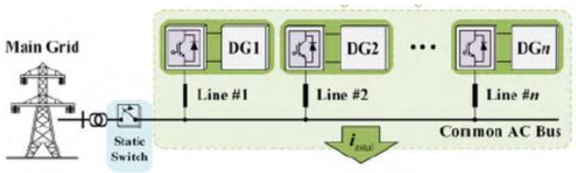

Fig. 1. Microgrid with one PCC [4].

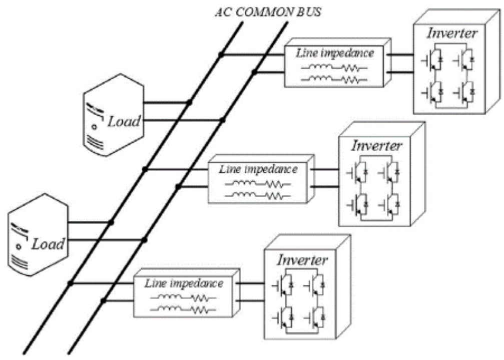

Fig. 2. Microgrid with one PCC [10].

II. Synchronization and Power Sharing Strategies in Islanded Microgrids

A. Traditional Droop Control

The traditional droop control strategy is mostly effective in microgrids with only one PCC Fig. 1 and Fig. 2 especially if not considering the impact of line impedances [4], [10].

In practice the real microgrids may have several PCC, interconnected by multiple line feeders with non-negligible impedances. In this paper to consider such a microgrid is inspired from an IEEE 9bus test feeder, composed of two DGs and three loads, interconnected by RLC power lines (Fig. 3). This microgrid have also the connection possibility to the main grid trough a controllable switch which is not activated in this study.

To highlight the difference between microgrids with one PCC (Fig. 1 or Fig. 2) and networked microgrids with multiple PCC (like the one in Fig. 3), the droop control strategy used successfully in literature for DGs power sharing and synchronization of a mono-PCC microgrid is applied for the same objectives in the considered networked multiple PCC microgrid. The classical active and reactive power sharing method is based on droop control that regulates for each DG the frequency and the voltage amplitude at the associated PCC based on relations (1) and (2) [11]:

$$\omega_i = \omega_n - m_i\left(P_i - P_{\text{in}}\right), \quad m_i = \Delta\omega / P_{\text{in}} \tag{1}$$

$$V_i = V_n - n_i\left(Q_i - Q_{\text{in}}\right), \quad n_i = \Delta V / Q_{\text{in}} \tag{2}$$

where P_i and Q_i are the measured values of active and reactive power of the i^{th} DG, P_{in} and Q_{in} are their rated values, ω_n and V_n are the rated values of frequency and voltage of the i^{th} DG, $\Delta\omega$ and ΔV are the frequency and voltage deviations, and m_i and n_i are the droop control coefficients as illustrated in Fig. 4 and Fig. 5.

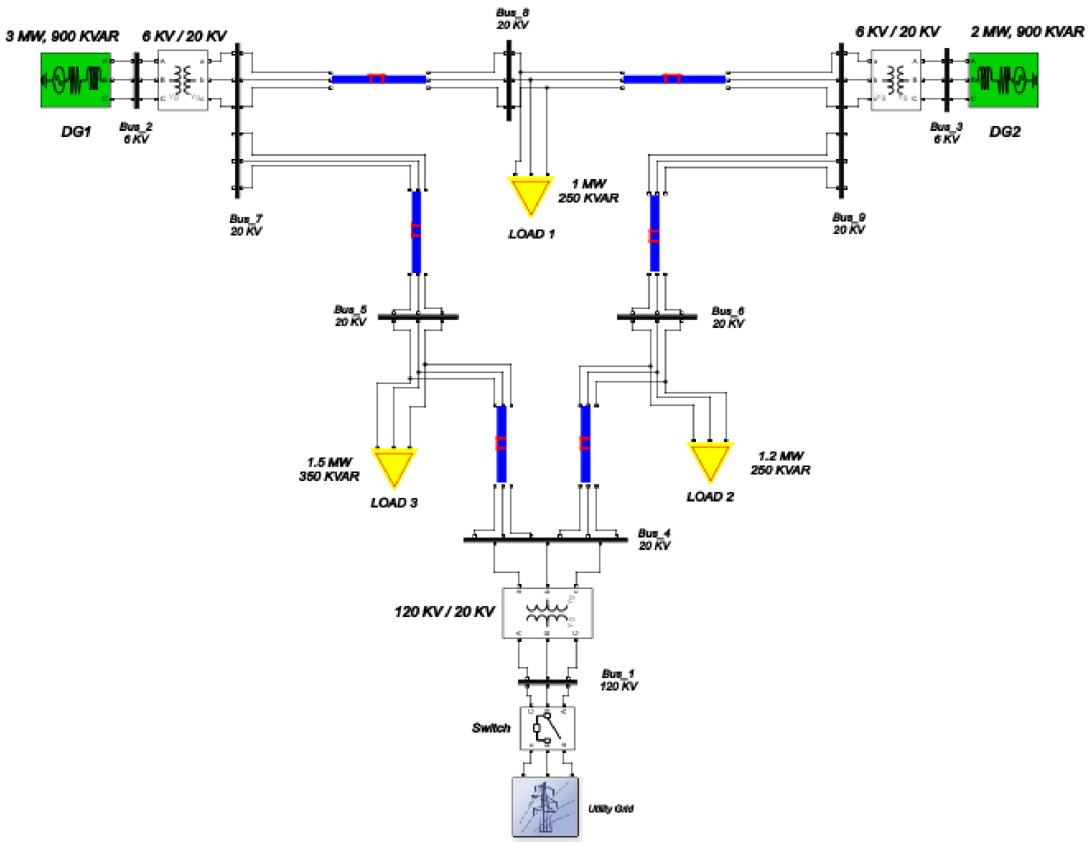

Fig. 3. IEEE 9bus test feeder.

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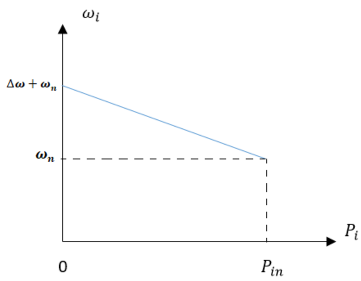

Fig. 4. Active power.

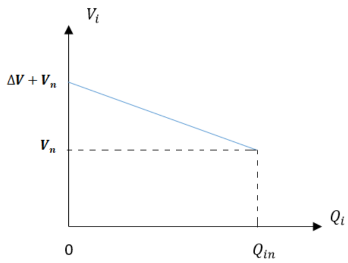

Fig. 5. Reactive power.

This classical droop control in (1) and (2) does not ensure an efficient reactive power sharing even in mono-PCC microgrids so a developed droop control strategy that was proved effective for active and reactive power sharing in mono-PCC microgrids [12]:

$$K_a\left(\delta_{\text{in}}-\delta_L\right)=m_i\left(P_i-P_{\text{in}}\right) \tag{3}$$

$$K_e\left(V_{\text{in}}-V_L\right)=n_i\left(Q_i-Q_{\text{in}}\right) \tag{4}$$

is the one applied to the complex multi-PCC microgrid in Fig. 3.

The proposed angle droop aims to indirectly control the voltage at the PCC to be equal to the rated values (i.e. V_{in} and δ_{in}). The added integrators can minimize the static error between the feedback signal and the corresponding rated values. If we choose K_a and K_e the same, which results in accurate real and reactive power sharing that is no longer depends on the system impedance and immune to numerical errors and disturbances.

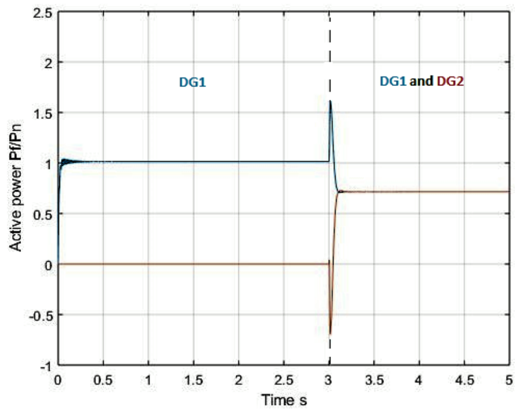

Fig. 6. Active power in the first scenario.

Fig. 6 and Fig. 7 show the simulation results concerning the power sharing in the multi-PCC microgrid of Fig. 3 when it operates in islanded mode knowing that the second DG is connected to the microgrid at 3 s. It can be remarked that the application of the classical droop method leads to a perfect active power sharing but at the moment of connection of the second DG a non-acceptable disturbing power peak occurs (Fig. 6). In addition, these classical strategies do not ensure an efficient reactive power sharing (Fig. 7) due to the line feeder's impedances [9], [10].

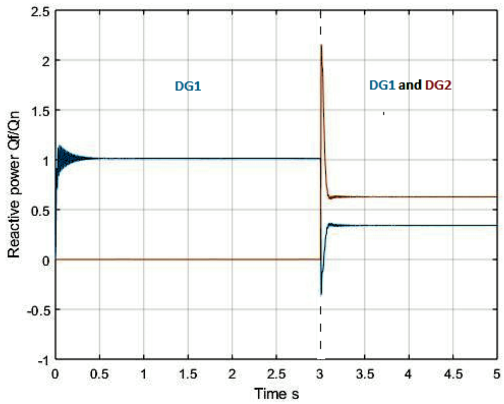

Fig. 7. Reactive power in the first scenario.

As a partial conclusion, the droop control strategy in (3) and (4) is not effective in networked microgrids which necessitates its modification. For this reason, in the next section a modified droop control strategy is proposed.

B. Modified Droop Control for Multi-PCC Microgrids

In networked multi-PCC microgrids, each line feeder connecting the i^{th} PCC to the j^{th} one has a non-negligible inductance $\lambda_{i,j}$ and resistance $\rho_{i,j}$. Due to this phenomenon, the line voltage drop between these two PCCs creates a coupling between exchanged active ($P_{i,j}$) and reactive ($Q_{i,j}$) powers, based on the next formula:

$$\Delta V=\rho_{i,j}I_{i,j}\cos\varphi+\lambda_{i,j}\omega I_{i,j}\sin\varphi=\frac{\rho_{i,j}P_{i,j}+\lambda_{i,j}Q_{i,j}}{V_i} \tag{5}$$

This coupling phenomenon causes also the circulating current in the complex microgrids [10] and leads to an inefficient power sharing of the DGs within the networked multi-PCC microgrids Fig. 7. In this simulation (Fig. 6 and Fig. 7), the first DG starts at 0 s and the second DG starts at 3 s.

To achieve an efficient power sharing in this type of multi-PCC microgrids, applying modifications to the classical droop control strategy is proposed, expressed by the equations (1) and (2), by adding a decoupling term in the equation (7) (the term: $-J_i(P_i-P_{\text{in}})$) remove the coupling phenomenon between active and reactive power expressed by relation (5).

$$\omega_i=\omega_n-m_i(P_i-P_n) \tag{6}$$

$$V_i=V_n-n_i\left(Q_i-Q_{\text{in}}\right)-J_i(P_i-P_{\text{in}}) \tag{7}$$

with

$$\begin{cases} J_i=K_p\varepsilon_i+K_I\int\varepsilon_i dt \\ \varepsilon_i=-\left(\dfrac{V_{\text{ref}}}{V_{\text{in}}}-1\right)-\left(\dfrac{Q_i}{Q_{\text{in}}}-1\right) \end{cases} \tag{8}$$

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The non-linear coefficient J_i varies with each operating condition and allows the primary control of the i^{th} DG voltage in case of a complex topology multiple PCCs AC microgrid. It is estimated by relation (8) using a PI controller. In steady state, when the error ε_i tends to zero, the reactive power sharing between DGs is ensured. V_{ref} in relation (8) is the voltage of one of the PCCs within the considered microgrid.

C. Synchronization Strategy in Multi-PCC Islanded Microgrid

Due to the complexity of the microgrid and the intermittency of renewable energy, the connection of each DG to the microgrid requires an efficient synchronization strategy without disturbing the power sharing between the DGs already connected. To realize the synchronization of the i^{th} DG to i^{th} PCC, the amplitude, frequency and phase of V_{DGi} (U_{DGi}, θ_{DGi}, ω_{DGi}) must be close enough to those of V_{pcci} (U_{pcci}, θ_{pcci}, ω_{pcci}) [2]. As explained in Introduction, the first DG establishes the frequency of the microgrid and imposes the voltages at different PCCs. To connect every other DGs to the microgrid it should synchronized.

To achieve the fast and efficient synchronization of the i^{th} DG to the microgrid, the errors between the frequencies, the amplitudes and the phases of both sides (the i^{th} DG and i^{th} PCC) are forced to zero by means of pure integrator controllers. For frequency and phase synchronizations the pure integrators are added only during the synchronization interval to the frequency droop control equation as shown in (9), and for the voltage synchronization the pure integrator is added only during the synchronization interval to the voltage droop control equation as shown in (10). Thanks to the coupled active and reactive power relationships term in (7) the power sharing that should be affected during the synchronization is maintained as efficient as possible.

$$\omega_i = \omega_n - m_i(P_i - P_n) + b_{SYi} \times \left[K_a \int \left(\omega_{pcci} - \omega_{DGi}\right)dt - K_b \int \left(\theta_{DGi} - \theta_{pcci}\right)dt\right] \quad (9)$$

$$V_i = V_n - n_i\left(Q_i - Q_{in}\right) - J_i(P_i - P_{in}) + b_{SYi} K_c \int \left(V_{DGi} - V_{pcci}\right)dt \quad (10)$$

where b_{SYi} is a binary variable which is equal to 1 during the synchronization of the i^{th} DG to the microgrid and 0 after its interconnection to the microgrid.

III. VALIDATION BY SIMULATION RESULTS

To validate the proposed strategies for synchronization and power sharing introduced in Section II, the considered networked multi-PCC microgrid (Fig. 3) is modeled using Simscape feature of Matlab/Simulation. DG1 and DG2 are formed with a controlled voltage source Fig. 8, connected to two distinguished PCCs and controlled with the modified droop methods. The main parameters are listed in Table I. All of the simulation results are in per unit (e.g. for active power P_i/P_{in}) to make noticeable the power participation of each DG.

The first simulations are realized to validate the efficiency of the proposed power sharing strategy based on relations (6), (7) and (8). The first DG imposes at 0 s the frequency of the microgrid as well as the voltages at different PCCs which depend also on the line feeder's parameters and the loads. The second DG is connected to the microgrid at 3 s without applying the synchronization procedure. Fig. 9 and Fig. 10 show respectively the evolution of the active power and reactive power. The active power and reactive power sharing is perfectly ensured in steady state and validate particularly the efficiency of the proposed voltage droop control method detailed by relations (7) and (8). However, an aggressive transitory state with high power peak occurs logically due to the absence of synchronization.

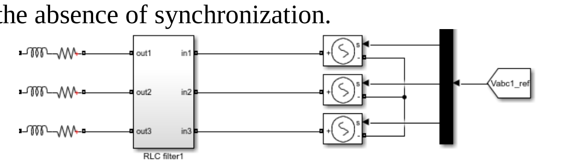

Fig. 8. Controlled voltage source with the filter.

TABLE I: PARAMETERS

Lines	Resistance (Ω)	Inductance (mH)	capacitance (μF)	Points of connections
Line 1	0.63	7.14	205	Bus 8- Bus 7
Line 2	2.55	11.4	230	Bus 5- Bus 7
Line 3	0.63	7.14	205	Bus 8- Bus 9
Line 4	2	7	180	Bus 9- Bus 6
Line 5	1.7	7.6	153.4	Bus 4- Bus 5
Line 6	1.7	7.6	153.4	Bus 4- Bus 6
Sources and loads	Active power (Mw)	Reactive power (Mvar)	Phase to pahse voltage (kV)	Point of connection
Source 1	3	0.9	6	Bus 7
Source 2	2	0.9	6	Bus 9
Load 1	1.5	0.35	20	Bus 5
Load 2	1.2	0.25	20	Bus 6
Load 3	1	0.25	20	Bus 8

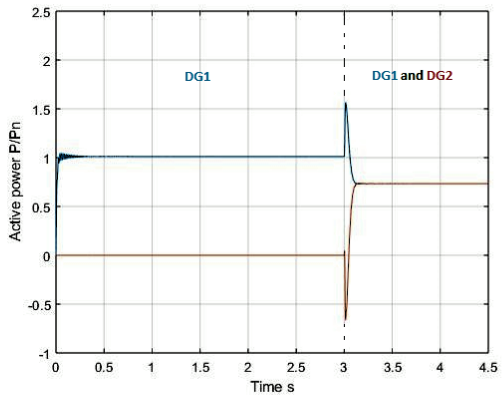

Fig. 9. Active power in the second scenario.

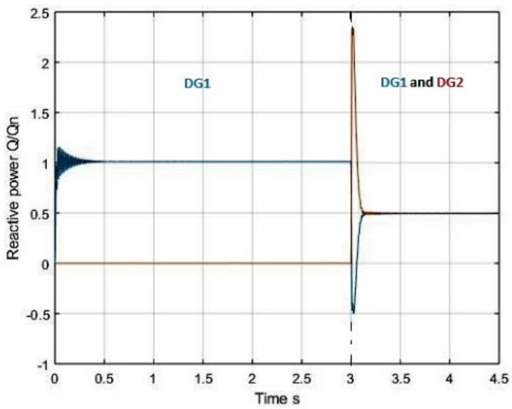

Fig. 10. Reactive power in the second scenario.

The second simulations are realized to validate the efficiency of the proposed synchronization and power sharing strategy based on relations (9) and (10). The first DG imposes at 0 s the frequency of the microgrid as well as the voltages at different PCCs. The second DG is synchronized during the interval [1 s ~ 3 s], and connected to the microgrid at 3 s. Fig. 11 and Fig. 12 show respectively the evolution of the active power and reactive power. The active power and reactive power sharing is perfectly ensured in steady state without being affected by synchronization procedure. In addition, thanks to the latter, the power peaks are cancelled during the transitory state after the second DG interconnection to the microgrid. It should be noted that these performances are maintained with higher number of DGs, even if the results are not presented.

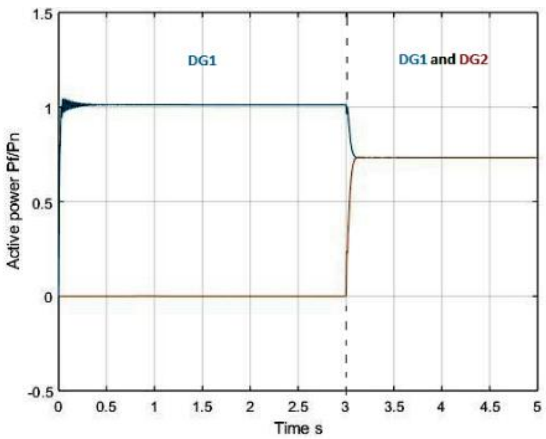

Fig. 11. Active power in the third scenario.

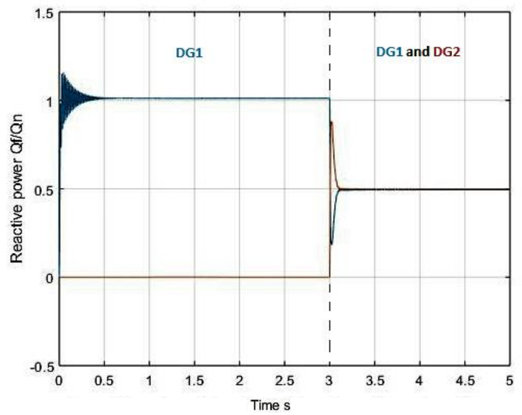

Fig. 12. Reactive power in the third scenario.

In order to verify the robustness of the proposed power sharing strategies with respect to the high load variations and disturbances, the third simulation tests have been realized. At 0 s the first DG establishes the frequency of the microgrid and the PCC's voltages while Load 1 and Load 2 are connected to their PCCs. Then the second DG is interconnected at 5 s to the microgrid after being synchronized from 1 s to 5 s. At 12 s the third load is also connected, applying a high positive load step to the microgrid. Finally, at 18 s, a high negative load step is applied to the microgrid by disconnecting Load 2.

Thanks to the modified droop control strategy given by (6), (7) and (8), the active power sharing and the reactive power sharing are ensured considering the results presented in Fig. 13 and Fig. 14. The convergence of the reactive power of the two DGs under different load conditions is convincingly verified.

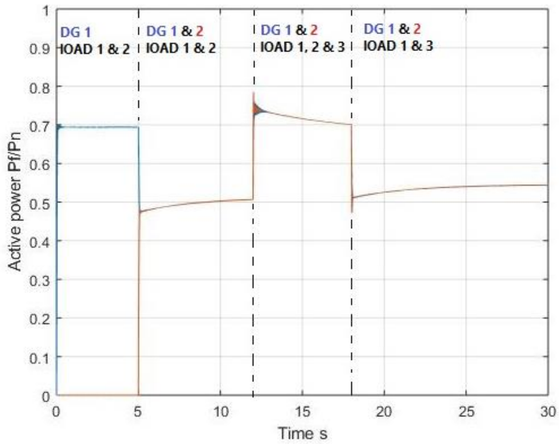

Fig. 13. Active power under multiple case of charge

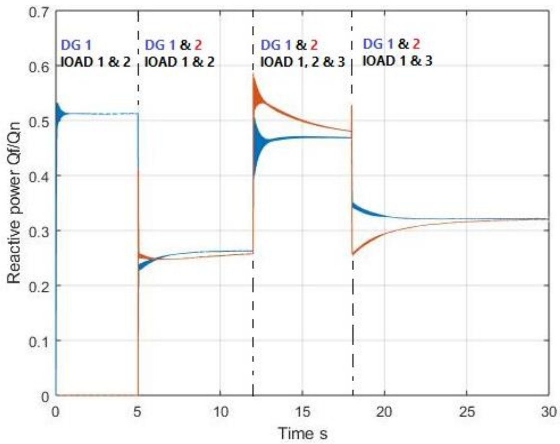

Fig. 14. Reactive power under multiple case of charge.

The behavior of the system after the connection of the second DG at *t*=5s shows the efficiency of the proposed synchronization strategy. Furthermore, the strategy of synchronization does not affect the power sharing properties obtained with the proposed droop control well adapted to multiple PCC microgrids with complex line feeder's impedances.

IV. Conclusion

In this paper, first the demonstration shows how the droop control strategies that properly insure power sharing in MONO-PCC microgrids. They are not able to control efficiently power sharing in networked multi-PCC microgrids. An improved droop control strategy is proposed which allows ensuring an equally sharing both for active power and reactive power in a complex microgrid with multiple PCCs. A synchronization control strategy is also proposed for connection of one DG to a networked multi-PCC microgrid. It allows a proper connection without large overshoot of powers during transient states. Moreover, the proposed droop control strategy with its synchronization strategy is compliant with the "plug and play" feature.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

All authors contributed in all phases of work by means of conception and modelling of the microgrid as well as the development of the new strategies. All authors read and approved the final version.

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