

Power Sharing Method for a Grid connected Microgrid with Multiple Distributed Generators

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Abstract – In this paper, a grid connected microgrid with multiple inverter-based distributed generators (DGs) is considered. DG in FFC mode regulates the microgrid as a controllable load from the utility point of view as long as its output is within the capacity limit. The transition mode causes a change in frequency of microgrid due to the loss of power transferred between main grid and microgrid. Frequency deviation from the nominal value can exceed the limit if the loss of power is large enough. This paper presents a coordinated control method for inverter-based DGs so that the microgrid is always regulated as a constant load from the utility viewpoint during grid connected mode, and the frequency deviation in the transition mode is minimized. DGs can share the load by changing their control modes between UPC and FFC and stabilize microgrid during transition.

Keywords: Microgrid, Distributed generator, Unit power control, Feeder flow control, Droop characteristic, Inverter control

1. Introduction

The increased penetration of distributed generators (DG) in distribution networks introduces great benefits to power system operators and consumers. First of all, DGs can integrate eco-friendly renewable energy resources such as solar cells, wind turbines, and fuel cells to distribution networks [1-3]. Second, because of the size and clean energy technology, DGs can be installed in close proximity to end-use consumers. Therefore, the installation and maintenance costs for generation and transmission facilities can be significantly reduced. In addition, because a portion of energy consumption of end-use consumers can be supplied by the local DGs, energy losses in transmission and distribution can be reduced and thus the voltage profile in distribution networks can be significantly improved. Third, the up-to-date power converters that integrate DGs to the grids can provide versatile auxiliary functions to power grids: for example, improvement of power quality, stability of the power grids as well as reliability [4-9].

Microgrids can be defined as autonomous small-scale power networks that contain multiple DGs and various critical loads, whose operation can be independent from the main grid. Microgrids can be either connected to the main grid or worked autonomously with respect to the grid connected and the island mode, respectively [10-13]. In the

grid connected operation mode, the microgrid is connected to the main grid at the point of common coupling (PCC) to deliver power to the load. DGs can operate in either the unit power control (UPC) mode or feeder flow control (FFC) mode. UPC and FFC control modes were firstly proposed by R. H. Lasseter in the CERTS microgrid concept [14-17].

From the utility's point of view, it is desirable if a portion of their networks consume constant electric power as scheduled or commanded. To make this possible, the FFC mode is set to the first DG (DG1 as shown in Fig. 1) which connects to the PCC, and thus, the grid would see a constant power demand from the microgrid [14, 15, 18]. However, DG1 can keep the feeder flow at PCC as long as its output is within the capacity limit. This depends on the feeder flow reference FL_{PCC}^{ref} , the limit of DG output, and the coordination between DGs in the microgrid. DG's capacity limit is normally fixed and depends on the manufacture and hardware installation therefore the FL_{PCC}^{ref} must be set at a value relevant with the DG's limit. If FL_{PCC}^{ref} increases the DGs have more reserve to remain the feeder flow unchanged. However the larger feeder flow, the larger frequency deviation in transition mode. Additionally, peak load conditions cause a higher burden to the utility grid therefore the feeder flow should be reduced by increasing the local DGs' output. On the contrary, if the FL_{PCC}^{ref} is low, the DGs have less reserve to maintain feeder flow unchanged, but the frequency change in transition mode will be reduced.

In order to deal with the two conflict objectives above, a control method for coordinating the controllable DGs (the uncontrollable DGs such as wind and photovoltaic power are considered as negative loads) in the microgrid is proposed so that the DGs operate in the predetermined

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control mode, UPC mode DGs' output is regulated to the predetermined reference power, and the DGs' output are mobilized during the peak load conditions to maintain the feeder flow unchanged. In addition, a reference value of feeder flow at the PCC, FL_{PCC}^{ref} , will also be suggested. With the proposed operation method with a suggested reference value of feeder flow, the microgrid will be always a constant load from the utility viewpoint, the feeder flow in the peak load conditions will be minimized by maximizing the DGs' output and thus the frequency deviation in the transition mode will be minimized.

2. System Configuration Description

Fig. 1 shows the simplified diagram of grid connected microgrid which comprises of multiple DGs. The microgrid connects with the main grid via a static transfer switch (STS). The DG1 operates in FFC mode to keep the power flow between the main grid and microgrid unchanged. The reference feeder flow of DG1 should be FL_{PCC}^{ref} . Other DGs, from DG2 to DGn, can operate in either UPC mode or FFC mode. Advantages of this microgrid configuration and the FFC mode were presented in [24].

Fig. 2 shows the detailed block diagram of the inverter-

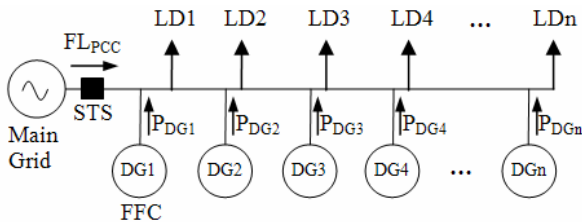


Fig. 1. Simplified grid connected microgrid with multiple distributed generators

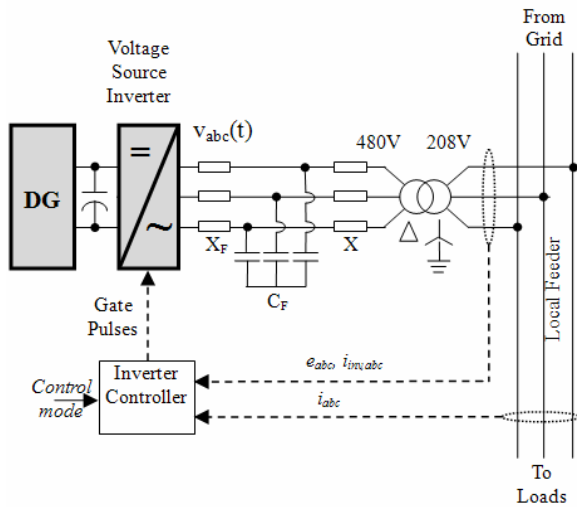


Fig. 2. Detailed three-phase diagram of an inverter-based distributed generators

based DG connected to the microgrid through a coupling transformer. The inverter converts the DC power generated by the DG to three-phase AC power. Because of fast switching power electronic devices, the inverter can flexibly control the magnitudes and phase angles of the output voltage and current. The DG output power and the local feeder flow are controlled by means of changing the control mode of the inverter controller.

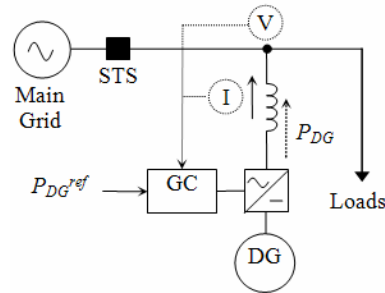
3. Control of a DG in Microgrid

In this section, the characteristics of the power control modes, i.e. UPC mode and FFC mode, of inverter-based DGs are described.

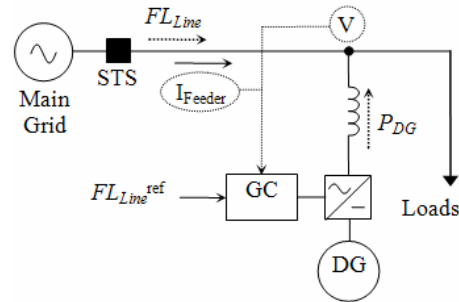
3.1 Unit power control mode

In UPC mode, the DG output power can be regulated at a constant level (P_{DG}^{ref}). In order to control the DG output, the voltage (V) at the interconnected point and the current (I) injected by the DG are measured as shown in Fig. 3(a). The active power injected by the DG (P_{DG}) is calculated from the measured voltage and current, and then fed back to the generator controller (GC).

When the microgrid is connected to the main grid, the DG can regulate its output power constantly regardless of load variation. If the load demand changes in the microgrid, the extra power can be supplied by the main



(a)



(b)

Fig. 3. Power-control mode of a DG: (a) Unit output power control (UPC); (b) Feeder flow control (FFC)

grid. On the other hand, when the microgrid disconnects from the main grid, which means the island mode, DGs must follow the load demand accurately. In previous studies, a power versus frequency (P - f) droop control has been adopted for DG power-sharing methods [11, 19-22]. This control uses the frequency of the microgrid as a common signal among the DGs to balance the active power generation of the system [11]. P - f droop-based power controllers have proven to be robust and adaptive to variation in the power system operational conditions, such as frequency- and/or voltage-dependent loads and system losses [11, 22].

3.2 Feeder flow control mode

The objective of FFC mode is to control the active power flow in the feeder where the unit is installed at a desired value (FL_{Line}^{ref}). In this mode, the DGs regulate the voltage magnitude at the connection point and the power flow in the feeder at connection point (FL_{Line}). The feeder current (I_{Feeder}) and voltage at the connection point (V) are measured in order to calculate the power as shown in Fig. 3(b).

Even during the grid connected mode, extra load demands are picked up by the DGs under FFC mode, and power supplied from the main grid remains unchanged regardless of the load variation within the microgrid. Thus the microgrid looks like a controllable load from the utility view point. On the other hand, in the island mode when the microgrid is disconnected from the main grid, the feeder flow versus frequency (FL - f) droop characteristic is used to share the load demand [14, 15].

4. Power Sharing Method for DGs in Microgrid

Microgrids include multiple DGs as depicted in Fig. 1. The control mode of DG1 should be always FFC mode because it can keep the power exchange between the microgrid and main grid unchanged. In this paper, we consider a microgrid including four DGs and it can be assumed without losing generosity that DG1 and DG3 are controlled in FFC mode whereas DG2 and DG4 are in UPC mode.

4.1 Conventional power sharing method

In general, the power generated by each DG depends on its control mode (UPC/FFC) and the droop characteristic [14, 15, 18]. In the grid connected operation mode, the features of the microgrid can be summarized as follows:

- The frequency is equal to the main grid frequency.
- Load variation can be matched by FFC-mode DGs or the main grid.
- The DG1 automatically follows the variation in the downstream loads and regulates the feeder flow at the

PCC point (FL_{PCC}) to a constant value, and thus the microgrid becomes a constant load from the main grid viewpoint as long as DG1's output is within its capacity limits. If the variation of loads exceeds the capacity of DG1, the microgrid needs extra power from the main grid so that the whole microgrid cannot act as a constant load anymore.

If the load LD3 and/or LD4 increases, DG3's output will increase in order to compensate the extra power, whereas the output of DG2 and DG4, i.e. the output of UPC-mode DGs, remains unchanged. If DG3 output reaches its maximum, DG1 will increase its output to supply the load instead of DG3 and regulate FL_{PCC} to a constant (i.e. FL_{PCC}^0). If DG1 output reaches its maximum, the extra power will be provided by the main grid and hence the feeder flow at the PCC point FL_{PCC} will be increased. Therefore, the microgrid is no longer a constant load from the utility view point.

If the main grid power is lost because of some events, e.g. voltage sags, faults, blackout etc., the microgrid can autonomously transfer to the island mode of operation. In this case, the frequency of the microgrid is controlled by the DGs based on the power versus frequency (P - f) droop characteristic [11, 14, 15, 20-23]. If the microgrid imported power from the grid before switching to the island mode, the DGs need to increase the power output to balance the power in the islanded microgrid. The frequency of the new operating point will be lower than the nominal value. On the contrary, if the system transfers to the island mode when exporting power to the grid, the new frequency will be higher than the nominal value. The feeder flow vs. frequency droop characteristic for FFC-mode DGs is shown in Fig. 4. The droop characteristics for DG1 and DG3 are shown in Fig. 4(a) and Fig. 4(b), respectively. In the grid connected operation mode, the frequency of the microgrid is equal to the main grid frequency of (f^0), the DG1 feeder flow is the power coming from the main grid FL_{PCC}^0 . If the microgrid transfers to island mode, the frequency of microgrid changes to f' due to the loss of

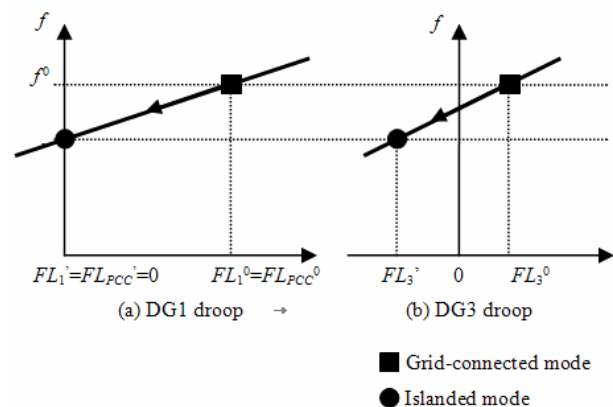


Fig. 4. Feeder Flow vs. Frequency Droop (DG1 & DG3: FFC mode).

power from/to the main grid (FL_{PCC} becomes zero). The change in the frequency of the microgrid during the transition mode can be calculated as follows:

$$\Delta f = f^0 - f' = K_1^F * FL_{PCC}^0 \quad (1)$$

where K_1^F is the droop constant of DG1. Eq. (1) shows that the frequency deviation depends on grid flow (FL_{PCC}^0). Therefore, the change of frequency in the transition mode can be out of its limits if $|FL_{PCC}^0|$ is high enough.

From the above expression, it can be seen that, in the conventional power sharing method, the microgrid can be seen as a variable load from the utility viewpoint and the deviation of frequency during a transition mode can exceed the limits.

4.2 Proposed power sharing method

In order to overcome the disadvantages of the conventional method, presented in section 4.1, a new power sharing method is proposed in which a proper feeder flow reference is determined and an algorithm for changing DGs' control mode is presented.

In order for the microgrid to be a constant load from the main grid viewpoint regardless of local load variation, the reference feeder flow of DG1, FL_{PCC}^{ref} , must be increased high enough. However, if the feeder flow at the PCC point is so high, the microgrid frequency can be beyond its limits during the transition mode. At the transition mode, the higher the feeder flow at the PCC (FL_{PCC}^0), the larger the deviation of frequency. Therefore, to minimize the change of the frequency in the transition mode, the reference value of DG1 feeder flow should be minimized. The proposed power sharing method is to deal with those two conflict objectives, and overcome the disadvantages of the conventional method.

As mentioned, UPC-mode DGs regulate their output to a constant and FFC-mode DGs compensate any change in load demand and keep the feeder flow constant at the reference value. The feeder flow at the PCC, FL_{PCC} , is calculated as follows:

$$FL_{PCC} = LD - \left(\sum_{i \in FFC} P_i + \sum_{j \in UPC} P_j^0 \right) \quad (2)$$

where:

$$LD = \sum_{i=1}^n LD_i \quad \text{: Microgrid load demand}$$

P_i : The output of the i^{th} DG which is in FFC mode.

P_j^0 : The reference output power of the j^{th} DG which is in UPC mode.

When the DG1 is operated in FFC mode and FFC-mode DGs outputs P_i are within their limits, the feeder flow can

be kept as the reference value (i.e., $FL_{PCC} = FL_{PCC}^{ref}$). Otherwise, the extra power need to be compensated by the main grid, and hence the FL_{PCC} cannot be constant. In order for FL_{PCC} to remain unchanged, the feeder flow reference (FL_{PCC}^{ref}) must be high enough so that the outputs of FFC-mode DGs do not reach their limits at the peak load. Therefore, from (2) we have:

$$FL_{PCC}^{ref} \geq LD^{\max} - \left(\sum_{i \in FFC} P_i^{\max} + \sum_{j \in UPC} P_j^0 \right) \quad (3)$$

where

$$LD^{\max} = \sum_{i=1}^n LD_i^{\max}$$

P_i^{\max} : The maximum capacity of the i^{th} DG

If FL_{PCC}^{ref} satisfies the inequality (3), the feeder flow will not change even if the load reaches its peak value.

Meanwhile, it is seen from (1) that the change of frequency (Δf), during the transition mode, is directly proportional to FL_{PCC} . Thus, in order to reduce the frequency variation during the transition mode, FL_{PCC}^{ref} should be minimized while satisfying (3), as follows:

$$FL_{PCC}^{ref} = LD^{\max} - \left(\sum_{i \in FFC} P_i^{\max} + \sum_{j \in UPC} P_j^0 \right) \quad (4)$$

In (4), FL_{PCC}^{ref} can be reduced further by increasing the power output reference of UPC-mode DGs (i.e., P_j^0). If the power references of UPC-mode DGs are set to their maximum (P_j^{\max}), FL_{PCC}^{ref} can be minimized:

$$\min(FL_{PCC}^{ref}) = LD^{\max} - \left(\sum_{i \in FFC} P_i^{\max} + \sum_{j \in UPC} P_j^{\max} \right) \quad (5)$$

Eq. (5) means that the feeder flow can be minimized if all DGs, including UPC-mode DGs, increase the output powers to their maximum when load demands reach the peak point. It is noted that the condition set in (5) corresponds to the positive value of FL_{PCC} and thus the direction of power is from the main grid to the microgrid. In case of the reversed direction the approach is similar. Even though the power references of UPC-mode DGs are not normally set at their maximum, and the load demand is not usually the peak value, (5) suggests that the two aforementioned conflicting objectives can be satisfied by changing the control mode of UPC-mode DGs when needed. In other words, when the load is heavy and other FFC-mode DGs reach their maximum limits, we can maintain the FL_{PCC} constant by changing the control mode of UPC-mode DGs to FFC mode. The algorithm for changing the control mode of UPC-mode DGs is shown in

Fig. 5. Similar to the case of conventional method, we also consider the microgrid system shown in Fig. 1 with assumption of four DGs, DG1 to DG4, where DG1 and DG3 are with FFC-mode, otherwise DG2 and DG4 are with UPC-mode.

The outputs of DG2 and DG4 are regulated unchanged, P_2^0 and P_4^0 , respectively, while the change in the load is matched by the two FFC-mode DGs (DG1 and DG3). Any variation in load demands LD1 and LD2 is firstly compensated by DG1. However, if DG1 output reaches its limit, the control mode of DG2 will be changed from UPC to FFC, and hence the output of DG2 can be increased more to match the load demand. As a result, the feeder flow at PCC will not change when DG1 output reaches its limit. The condition of DG2 mode change is that the DG1 output reaches its maximum.

In a similar manner, the change of load demands LD3 and LD4 are firstly matched by DG3. However, once DG3 output reaches its maximum, DG1 will then match the load demand. In the other words, the change of load demand is compensated for by FFC-mode DGs, in order from the nearest DG to the furthest DG (DG1). When the DG1 output reaches its maximum, the control modes of UPC-DGs are changed to FFC. For example, when DG1 output is maximized, the control mode of DG2 is changed to FFC mode, and DG2 participates in sharing the load together with DG1. Similarly, if the load keeps increasing and the outputs of DG1 and DG2 reach their limits, the control mode of DG4 will be changed to FFC mode. It can be seen that, the condition of changing the control mode of DG2 and DG4 is that the DG1 output reaches its maximum. However, DG4 only changes its control mode when DG2 is in FFC mode. In other words, UPC-mode DG will change its control mode to FFC mode if DG1 output reaches its maximum P_1^{\max} and UPC-mode DG in front of DG4 is in FFC mode, e.g. UPC-mode DG in front of DG4 is DG2. DG2 has no UPC-mode DG in front of itself so the condition that causes it to change its mode is only the status of DG1 output.

Changing the control mode of UPC-mode DGs to FFC mode allows the DGs to operate at maximum capacity, and hence the more load can be shared by UPC-mode DGs. It can be seen from (5) that changing the control mode of UPC-mode DGs allows the feeder flow reference at PCC (FL_{PCC}^{ref}) to be minimized, and it is set as follows:

$$FL_{PCC}^{ref} = LD^{\max} - \left(\sum_{i \in FFC} P_i^{\max} + \sum_{j \in UPC} P_j^{\max} \right) \quad (6)$$

Eq. (6) means that, the feeder flow at PCC can be minimized and always remained unchanged although the load reaches maximum, if the control modes of UPC-mode DGs are changed to FFC mode.

The algorithm of the control-mode change, as depicted in Fig. 5, shows that the DG will not change its control

mode to FFC mode if either the front UPC-mode DG is in UPC mode or DG1 output does not reach its maximum. In addition, UPC-mode DG will return to UPC mode if its output gets back to the reference power and the front UPC-mode DG is in FFC mode.

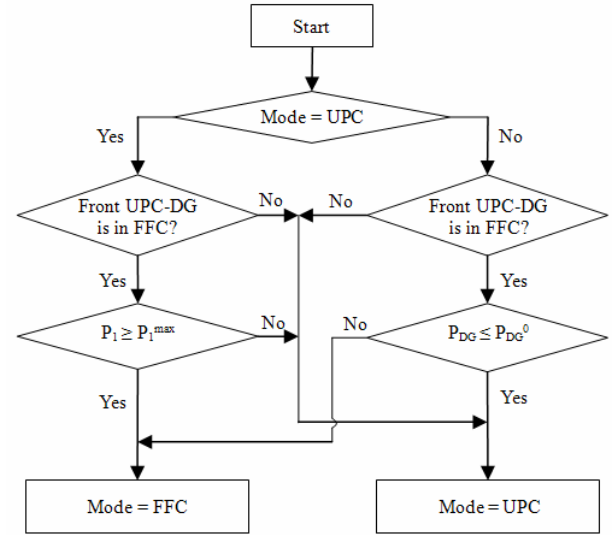


Fig. 5. Algorithm for changing the control-mode of DGs

5. Simulation Results and Discussion

5.1 Test system and simulation scenarios

To verify viability of the proposed power sharing method, a grid connected microgrid with three DGs and three-phase loads was simulated using PSCAD/EMTDC tool. The system configuration is shown in Fig. 6 and the system parameters are listed in Table 1.

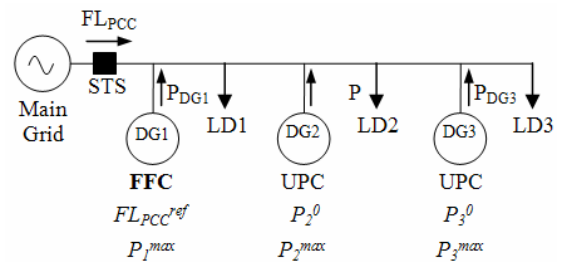


Fig. 6. Test system diagram

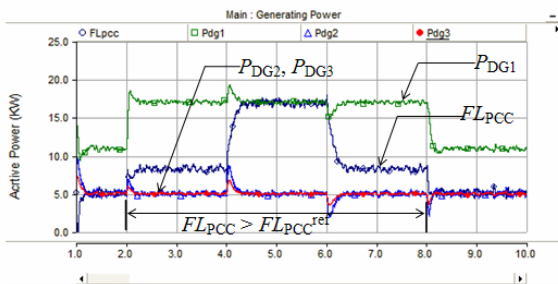
The control modes of DG1, DG2, and DG3 are set to FFC, UPC, and UPC modes, respectively. The feeder flow reference of DG1 is determined to 5 kW, based on (6) and the parameters shown in Table 1, and this value is used in all simulation cases, including conventional method and proposed method. LD1 and LD2 were not changed during the simulation, while the LD3 value was varied as follows. LD3 was initially 10 kW and changed to 20 kW, 27 kW, 20 kW, and 10 kW at 2 s, 4 s, 6 s, and 8 s, respectively (see Fig. 7(b)).

Table 1. The System Parameters

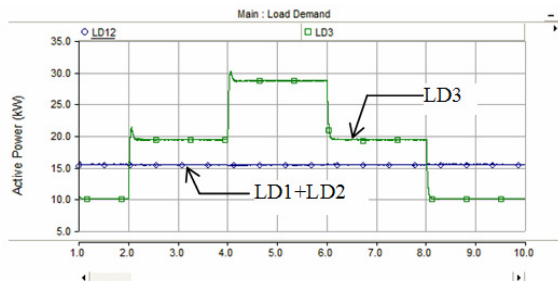
| Parameter | Value | Unit |
|------------------|-------|------|
| P_{DG1}^{max} | 17 | kW |
| P_{DG2}^{max} | 15 | kW |
| P_{DG3}^{max} | 9 | kW |
| P_{DG2}^0 | 5 | kW |
| P_{DG3}^0 | 5 | kW |
| FL_{PCC}^{ref} | 5 | kW |
| LD_1^{max} | 5 | kW |
| LD_2^{max} | 11 | kW |
| LD_3^{max} | 30 | kW |

5.2 Simulation results in the grid connected operation mode

This section describes the simulation results during the grid connected operation mode according to different power sharing method (conventional and proposed). Fig. 7(a) shows the simulation results for the conventional power sharing method. During the light loading condition (from 1 s to 2 s), the power from the main grid is regulated to the reference value (5 kW). At 2 s, DG1 increases its output to compensate for the increase of LD3. However, since DG1 reaches its maximum (17 kW), the remainder load is picked up by the main grid, and thus the FL_{PCC} is changed to 8 kW. Since the power output of DG2 and DG3 are fixed (control mode is not changed), between 2s and 8 s, the microgrid is no longer a constant load from the main grid viewpoint, as discussed in Section 4.1.



(a)



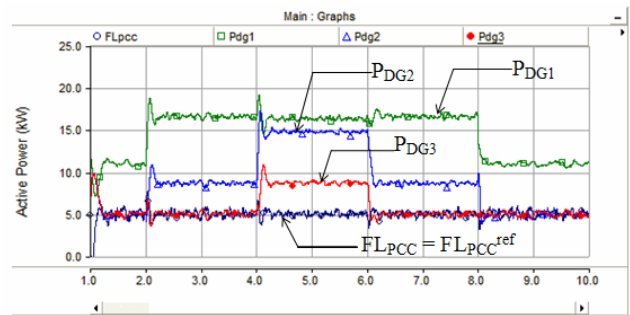
(b)

Fig. 7. Simulation results for the conventional method (Control mode of DGs are not changed): (a) Active power generation (FL_{PCC} changes during heavy load conditions); (b) Load demand (LD1,LD2 remain unchanged, LD3 changes).

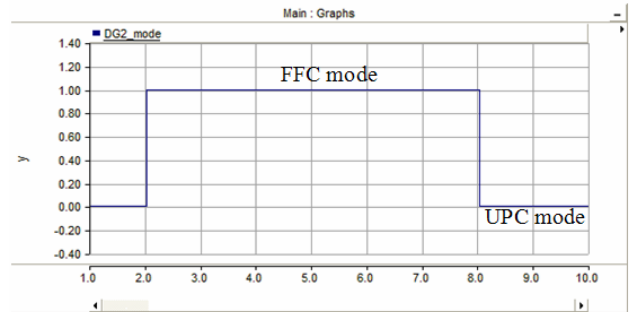
Fig. 8 shows the simulation results for the proposed power sharing method. The DGs power and/or flow references and the load demand are identical to those of the above case.

However, in the proposed method, the control mode of UPC-mode DGs are controlled according to the algorithm shown in Fig. 5. It can be seen from Fig. 8(a) that, by using the proposed method, the feeder flow at PCC (FL_{PCC}) remains unchanged although the load demand LD3 increases between 2 s and 8 s, FL_{PCC} is regulated to reference value (5kW). To accomplish this, the control modes of DG2 and DG3 are changed from UPC to FFC at 2 s and 4 s, respectively, as shown in Figs. 8(b) and 8(c).

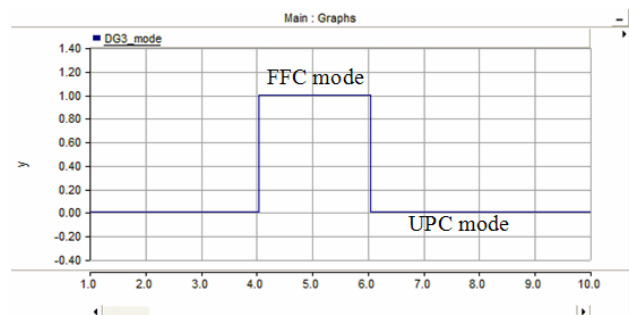
When LD3 increases to 19 kW at 2 s, DG1 firstly



(a)



(b)



(c)

Fig. 8. The simulation results for the proposed method: (a) Active power generation (FL_{PCC} remains unchanged); (b) DG2 control-mode change; (c) DG3 control-mode change.

increases its output, but the variation could not be compensated by DG1 within its limit. Therefore, DG2 changes its control mode to FFC mode, and increases its output until the load demands are matched. When LD3 increases further at 4 s, DG2 also reaches its maximum limit (15 kW). Accordingly, DG3 starts to increase its output by changing the control mode to FFC. When LD3 decreases at 6 s, DG3, which is the nearest DG upstream from LD3, firstly decreases its output. Since the DG3 output returns to its initial power reference (5 kW), the control mode is changed to UPC mode, and DG2 decreases its output. As LD3 decreases further at 8 s, the control mode of DG2 is also returned to UPC, and the DG1 output is decreased.

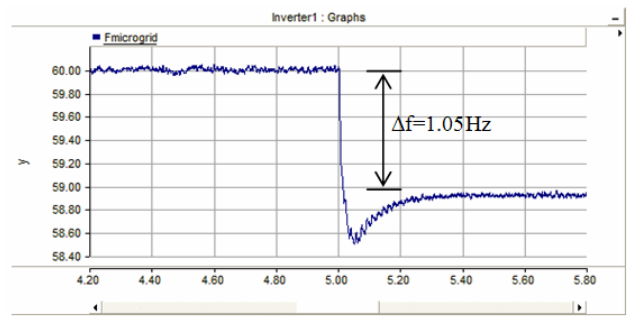
5.3 Simulation results in the transition mode

In this section, we investigate the advantage of the proposed method during the transition mode. To accomplish this, we simulated the intentional islanding, and observed the microgrid frequency during the transition mode. In order to investigate the effect of load level on the microgrid frequency, we simulated the islanding at 5 s and 7 s, respectively, for each power sharing method.

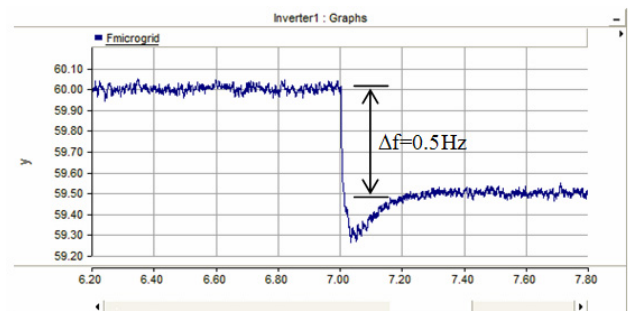
Fig. 9 summarizes the simulation results. It can be seen that the change of frequency in the proposed method is always constant since the feeder flow at PCC point is unchanged as depicted in Fig. 8(a). On the other hand, in the conventional method, FL_{PCC} depends on the load condition and it is no longer a constant if the first DG output reaches its maximum as shown in Fig. 7(a). Therefore, the change of frequency due to a disconnection from the main grid is not constant, but depends on the feeder flow power at which the disconnection occurred. Figs. 9(a) and 9(b) show the changes of frequency during the transition mode at 5s and 7s, respectively. The frequency change in case of disconnection at 5s (1.05Hz) is larger than that in case of disconnection at 7s (0.5Hz), since FL_{PCC} at 5s is larger than FL_{PCC} at 7s as shown in Fig. 9(a).

Additionally, during the transition mode between 2s and 8s, FL_{PCC} is larger than the feeder flow reference (5kW), and hence the change of frequency in the conventional method is always larger than the change in the proposed method. As depicted in Figs. 9(a) and 9(b), the changes of frequency in conventional method are 1.05Hz and 0.5Hz respectively, whereas that is 0.3Hz for the proposed method (see Fig. 9(c)).

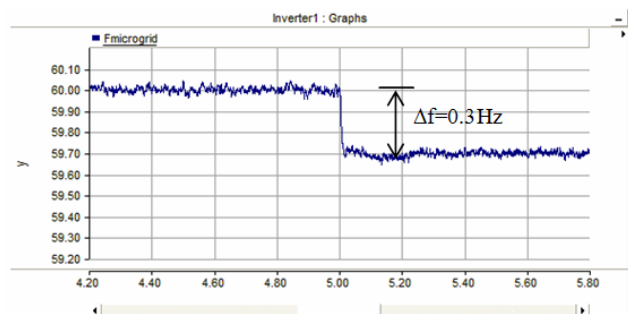
In summary, the simulation results show that the feeder flow is always kept unchanged in the proposed control algorithm whereas it changes significantly in the conventional method. In transition mode, the frequency change of the proposed method can be reduced compared to the conventional control method.



(a)



(b)



(c)

Fig. 9. Frequency change in the transition mode: (a) Conventional method, islanding at 5s; (b) Conventional method, islanding at 7s; (c) Proposed method, islanding at 5s.

6. Conclusion

A grid connected microgrid with multiple DGs is considered. The DGs can operate in either UPC mode or FFC mode. The DG1 with FFC mode regulates the microgrid as a controllable load from the utility point of view as long as its output is within the capacity limit. In this paper, a new control strategy for DG power sharing is proposed. The proposed control algorithm can bring several advantages such as 1) in grid connected mode, the microgrid can act as a controllable load from the utility point of view ; 2) during the peak loading condition, the DGs' output is stabilized and, therefore, it reduces the burden to the utility grid; 3) if the load in the microgrid is

not heavy, UPC mode DGs will work with the predetermined output power, and hence, DGs can work with high efficiency and/or low cost; 4) with the proposed reference value of the feeder flow, the burden to main grid during peak load conditions is minimized and, therefore, the frequency deviation will be minimized as the disconnection occurs.

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