A Novel Control Strategy for Power Sharing Enhancement of an Inverter-Based Microgrid

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Abstract

An innovative power sharing strategy is put forward for active power-frequency management of a couple of inverter interfaced distributed generators encompassed in a microgrid. The presented strategy employs two cutting-edge droop based methods called unit power control (UPC) and feeder flow control (FFC). FFC outperforms UPC in terms of both grid-connected and islanded operation of microgrid. These methods are modified to enrich the transient response of distributed generators concurrent with the steady state behavior. A combination of these methods is applied to control generators of a microgrid where results of numerical time domain simulations substantiate the superiority of the enhanced edition control strategy.

Keywords: Feeder Flow Control (FFC); Unit Power Control (UPC).

I. Introduction

Technical pros, environmental constraints in addition to burgeoning body of economic incentives push boundaries of power industry toward growing employment of distributed generators (DGs). Although undeniable growth of DGs has reduced the need for development of the costly monopole traditional power systems, controlling a great number of small scale generators has become a delicate problem. Fortunately, promising concept of microgrids has recently emerged to cope with these problems. A microgrid is a part of distribution system including a number of DGs and local loads. Normally, it is operated connected to the main power grid system; however, it is able to be operated as an autonomous island due to contingencies or pre-planned sessions. The latter characteristic facilitates microgrids to perfectly promote power quality standards according to smart grids horizons responding to the growth of sensitive loads [1].

Many ongoing investigations introduce microgrid as a system with great uncertainties. In islanding operation, lack of main grid supportive role makes the microgrid really vulnerable to instability or even obligatory island cut off. Due to the aforementioned, microgrid operation needs a suitable control strategy coordinating generators and guaranteeing power quality independent of load variation and other uncertainties. In addition, the strategy should be based on plug-and-play structure that likely microgrid expansion does not urge substantial revision of the control infrastructure. Droop based methods are prevalent among these power sharing strategies [2-5].

II. Research Objectives and Methods

This paper puts forward a novel control strategy coordinating real power sharing in a microgrid with multiple dispatchable inverter based DGs. Power management strategy is implemented using two droop methods namely unit power control (UPC) and feeder flow control (FFC). First, UPC and FFC methods are described in details. While these methods demonstrate favorable response in the steady state power sharing, an enhanced structure is proposed to coincidently promote the steady state and transient power sharing among DGs.

A. Basics of Control Strategy

UPC and FFC methods are firstly investigated by Consortium for Electric Reliability Technology Solutions (CERTS) [6]. A straightforward structure of a typical microgrid whose DG is controlled using UPC and FFC methods is depicted in figures 1(a) and 1(b) respectively. Based on the UPC method, real power of a DG unit is related to frequency according to the below equation [6]:

$$\omega' = \omega^0 - K^U.(P' - P^0) \qquad (1)$$

Here P^0 is set point of the DG real power, and P' is its value in the new operating point. ω^0 and ω' are voltage frequency of the DG unit in initial and new operating points, respectively. Droop coefficient of the UPC method is represented by K^U :

$$K^U = \frac{\Delta\omega}{P_{\max}} \qquad (2)$$

Dividend of (2) is permissible frequency deviation (Δω) supposed to be 1 percent of nominal frequency and the divisor demonstrates maximum power of the DG unit in long term operation ($P_{\max}$) [2],[6]. In grid-connected mode, main grid assures rated frequency, thus due to (1), output power of the DG stays at the set point. Following the islanding process, any demand variation of the island load would be responded, however according to the (1), it causes a linear frequency change in turn [6].

Based on the FFC method, feeder flow (*FL*) is related to frequency (ω) according to the following expression:

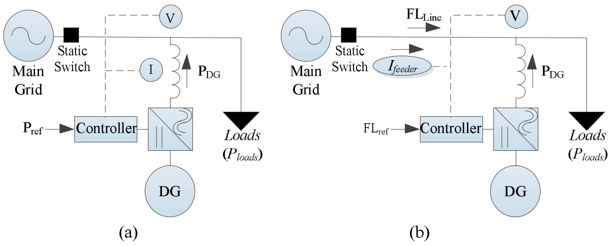

Figure 1: Straightforward microgrid whose DG is controlled via (a) UPC method. (b) FFC method.

$$\omega' = \omega^0 - K^F(FL' - FL^0) \tag{3}$$

Here FL^0 is favorite value for the flow of under control feeder and FL' is its value in new operating point. ω^0 and ω' are voltage frequency of the DG unit in initial and new operating points, respectively. K^F is droop gain of the FFC method. Since in figure 1(b):

$$FL_{line} + P_{DG} = P_{loads} \tag{4}$$

Combining the equations (2), (3) and (4) leads to the:

$$K^F = -K^U \tag{5}$$

To regulate the favorite value for the power exchange with the main grid, the FFC controlled DG adapts its output power in grid-connected operation, nevertheless, frequency is set at rated value by main grid [6].

When microgrid of figure 1(b) becomes islanded, since power exchange with the main grid cuts off, according to (3), frequency remains constant during the whole time.

The flowchart of UPC and FFC methods applied to the microgrids of figure 1 is illustrated in figure 2 where δ is voltage angle of the DG. Colored blocks stress the two advantages of FFC over UPC. First, if FFC method is employed for a DG neighboring the point of common coupling (PCC), power exchange of microgrid with main grid can be regulated desirably in grid-connected operation. Second, if operation of such a microgrid goes to islanded mode, frequency will be preserved intact.

However, analyses in [7] have demonstrated that attaining the advantages of FFC method can be restricted by series configuration of FFC controlled DG units (likewise the configuration of microgrid test system in the following simulations and analyses chapter). There, the challenge was met by redefining the FFC droop gains as a function of DG unit distance from the PCC, as:

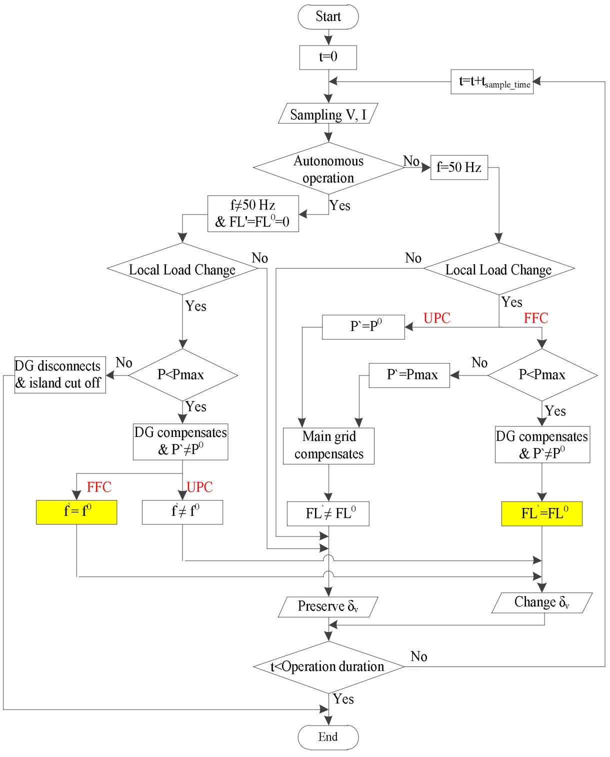

Figure 2: Flowchart of UPC and FFC methods

$$\frac{1}{K_i^F} = -\sum_{g=i}^{n} \frac{1}{K_g^U} \tag{6}$$

Here n is the total number of FFC controlled DG. It implies that in the chain of DG units, the furthest DG from PCC (i=n) has the least absolute value of droop gain.

B. Refinement of the Control Strategy

The below equations point out the output active and reactive power of the equivalent power circuit of an inverter interfaced DG unit:

$$P = \frac{R}{R^2 + X^2}(V_s^2 - V_s V_0 \cos\delta) + \frac{X}{R^2 + X^2}(V_s V_0 \sin\delta) \tag{7}$$

$$Q = \frac{X}{R^2 + X^2}(V_s^2 - V_s V_0 \cos\delta) - \frac{R}{R^2 + X^2}(V_s V_0 \sin\delta) \tag{8}$$

In these equations, X and R respectively present the inductive and resistive portion of output impedance of the inverter, δ is the phase difference between output voltage of inverter and voltage of the DG connection point [5]. V_0 and V_s are voltage magnitudes of inverter output and the DG connection point orderly. Combining the equations (7) and (8) and calculating the time variation of power phase result in:

$$\frac{d\delta}{dt} = \frac{1}{(V_s)^2 \cos\delta}\left(X\frac{dP}{dt} - R\frac{dQ}{dt}\right) \tag{9}$$

While (10) is the other expression for relation between phase difference and angular frequency of voltages:

$$\delta_0 - \delta_s = \int(\omega_0 - \omega_s)dt \tag{10}$$

Here ω_0 and ω_s orderly are angular frequency of inverter voltage and voltage of DG connection point. With insertion of (10) in (9), it is concluded that:

$$\omega_0 - \omega_s = \frac{1}{(V_s)^2 \cos\delta}\left(X\frac{dP}{dt} - R\frac{dQ}{dt}\right) \tag{11}$$

The outcome implies that in steady state, ω_0 and ω_s are equal. However, with initiation of load variation, owing to change in active and reactive powers, a difference is emerged between angular frequency of inverter and DG connection point. In addition, it is inferable that changes of DG active power and changes of DG reactive power happen in opposite direction. In fact, transient power fluctuates because of variation of inverter output phase. It can be envisaged that minimizing the inverter output phase variation can prevent power fluctuation. To accomplish this, a negative feedback is employed to attenuate variation of output phase times by a suitable gain within the basics of FFC and UPC droop methods. So (1) and (3) can be rewritten as follows:

$$\omega' = \omega^0 - K^U.(P' - P^0) + K_d^U \times \frac{d\delta}{dt} \tag{12}$$

$$\omega' = \omega^0 - K^F(FL' - FL^0) + K_d^F \times \frac{d\delta}{dt} \tag{13}$$

Insertion of (9) in later equations causes:

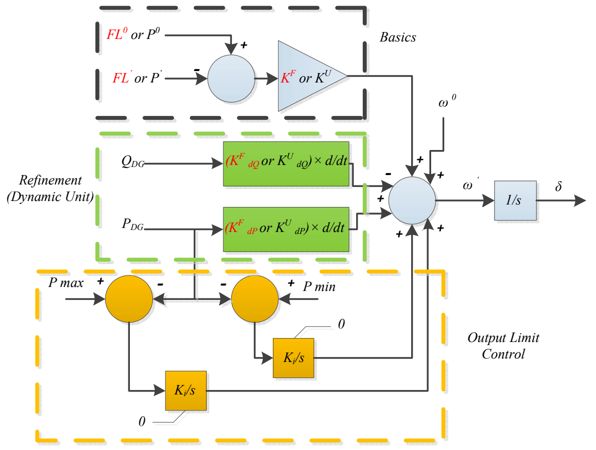

Figure 3: The proposed control strategy

$$\omega^{'} = \omega^0 - K^U.(P^{'} - P^0) + K^U_{dP} \times \frac{dP}{dt} - K^U_{dQ} \times \frac{dQ}{dt} \qquad (14)$$

$$\omega^{'} = \omega^0 - K^F(FL^{'} - FL^0) + K^F_{dP} \times \frac{dP}{dt} - K^F_{dQ} \times \frac{dQ}{dt} \qquad (15)$$

Here, $K^U_{dP}, K^U_{dQ}, K^F_{dP}$ and K^F_{dQ} are read as dynamical gains (versus static gains of K^U and K^F) and their values are:

$$K^U_{dP} = K^U_d \times \frac{X}{V_s^2 \cos\delta} \quad or \quad K^F_{dP} = K^F_d \times \frac{X}{V_s^2 \cos\delta} \qquad (16)$$

$$K^U_{dQ} = K^U_d \times \frac{R}{V_s^2 \cos\delta} \quad or \quad K^F_{dQ} = K^F_d \times \frac{R}{V_s^2 \cos\delta} \qquad (17)$$

Figure 3 summarizes the proposed strategy. The output limit control is just activated when the output power of the controlled DG goes beyond the DG's rating. This function emulates the physical limitations of the DG capacity.

III. Simulations and Analyses

Effectiveness of the proposed control strategy is evaluated through time domain numerical simulation of microgrid test system with single line diagram illustrated in Figure 4. This three DG units microgrid is connected to the main power grid via a static switch and is adopted from [7] while slightly modified. The rated frequency is 50 Hz and voltage of the main bus of microgrid measures 1.3 kV whereas DG units have a nominal voltage of 380 V. The units rated power measure 62.5, 75 and 50 kVA respectively for DG1, DG2 and DG3, besides they are controlled based on FFC, UPC and FFC methods orderly.

In all simulation processes, the amounts of FL^0 are set equal to 83, 43 kW for DG1 and DG3 respectively and the amount of P^0 is set equal to 34 kW for DG2. Therefore, DG1, DG2 and DG3 initially produce 47, 34 and 21 kW during which 83 kW power ($FL_{section1}$) is imported from main power system (parallel operation). At 3.0 s, Load 1 demand is reduced from 70 kW and 22.5 kVAr to 50 kW and 15 kVAr while DGs power sharing is tracked on close inspection. Afterwards, the static switch is opened at 5.0 s and microgrid operation changes to islanding mode. At last to assess the performance of the control strategy in islanded operation, Load 3 is raised from 65 kW and 30 kVAr to 80 kW and 40 kVAr at 9.0 s.

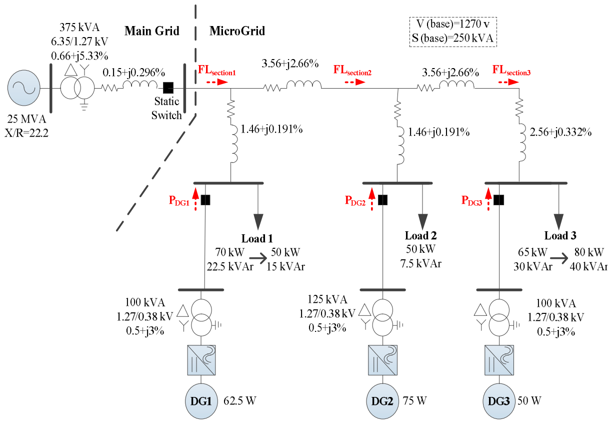

Figure 4: Microgrid consisting of three dispatchable electronically coupled DG units

Two scenarios are studied. First, the static droop gains are tuned using (2) and (5), so we have -0.05, +0.04 and -0.06 Hz/kW for DG1, DG2 and DG3 respectively. Then, the static droop gains are tuned using (2) and (6), thus DG1, DG2 and DG3 works with -0.05, +0.04 and -0.016 Hz/kW orderly. In each scenario, the effect of presence of dynamic unit in the control strategy is monitored.

Controlling DG1 with FFC method makes the frequency of autonomous operation of all case studies being preserved at 49.34 Hz which can be calculated via (3). At 3.0 s, with decrease in Load 1 demand, DG1 reduces its output to 27 kW to preserve imported power at 83 kW.

In first scenario (figure 5), after islanding, DG2 and DG3 produce their maximum available power respectively 75, 50 kW while P_{DG1} turns into 39 kW. Comparatively speaking, it is crystal clear that islanding process put a great deal of stress on DG3 which is the furthest DG unit from PCC and is controlled by FFC method. As the section c of figure 5 shows, employing the dynamic unit relieve the power overshoot of DG units considerably. This change for DG2 is a reduction from 40% in section (a) of figure 5 to 6.7% in section c of the figure. Although Load 3 demand increment at 9.0 s should be responded by DG3, since following the islanding transition, DG3 has reached to its generation limit (50 kW), DG1 raises its output from 39 kW to 54 kW.

In second scenario (figure 6), when values of the FFC static droop gains are assigned via (6), the situation of parallel operation does not differ. However, the greatest outcome is obtained during the transition to the islanding operation. When 83 kW imported power is cut at 5.0 s, DG1, DG2 and DG3 produce new amount of 56, 66 and 42.5 kW. Per unit output increment of DGs (1.49:1.29:1) becomes almost equal to the ratio of their rated power. Prevention of overloading of the DG3, keeps it ready to rise up its generation at 9.0 s when Load 3 demand increases and there is no need for intervention of other units. Although with new gain values there is no noticeable overshoot in generation alteration, the presence of dynamic unit in the structure of control strategy offers smoother generation changes in second scenario.

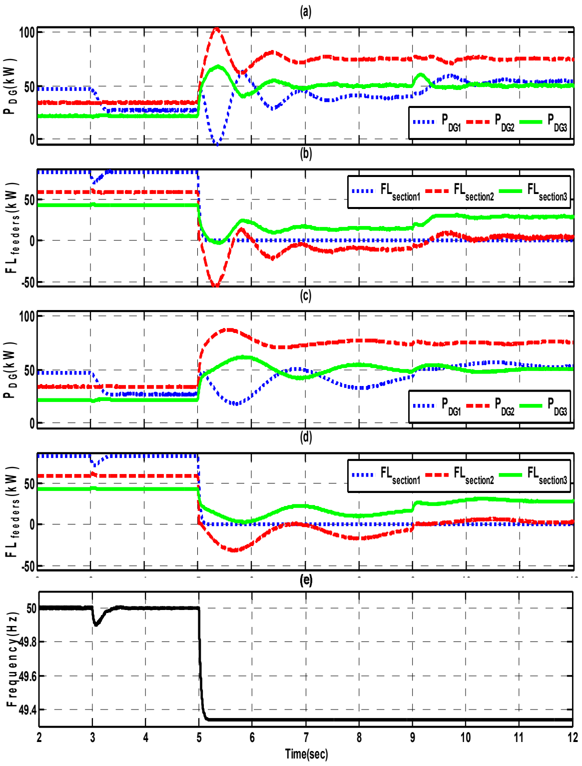

Figure 5: Static droop gains are -0.05, +0.04 and -0.06 Hz/kW for DG1, DG2 and DG3. Without dynamic unit: [(a) DGs output power (b) Feeder flows]. With dynamic unit: [(c) DGs output power (d) Feeder flows]. (e) Frequency

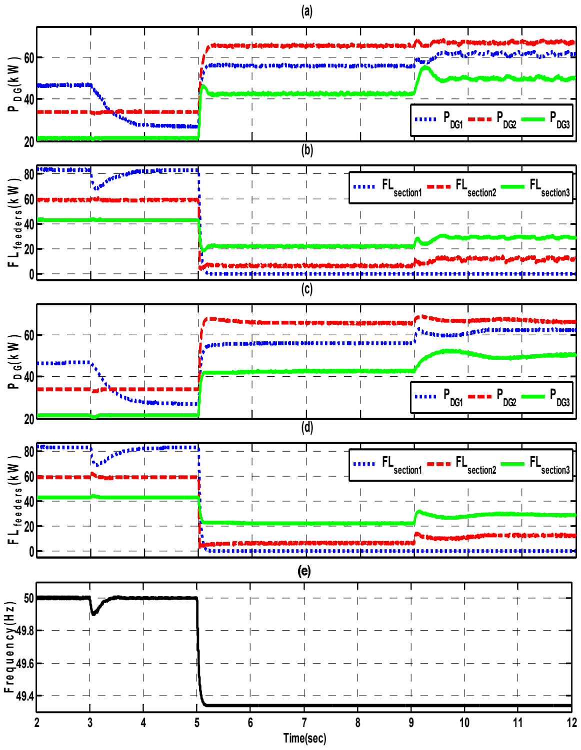

Figure 6: Static droop gains are -0.05, +0.04 and -0.016 Hz/kW for DG1, DG2 and DG3. Without dynamic unit: [(a) DGs output power (b) Feeder flows]. With dynamic unit: [(c) DGs output power (d) Feeder flows]. (e) Frequency

IV. Discussion

Two droop based methods were discussed namely UPC and FFC to accomplish power sharing of DG units. FFC method was considered as the superior option due to capability of regulating power flow of the neighbor feeder where its host DG unit is located. Besides, it stably offers a fixed frequency within islanding operation. A remedy was explained in the form of droop gains reconsideration to handle the problem of unsuitable loading of FFC controlled DG units with series configuration happened during islanding transition process. Although FFC controlled DG units with the modified static gains are able to represent appropriate steady state power sharing, a dynamic unit was analytically proposed in the structure of control strategy to guarantee transient changes of DGs' output power to be smooth. It is worth mentioning that due to our analyses (equations 16, 17), dynamical gains should have a certain proportion equals to the fraction of inductive and resistive part of DG output impedance. Although worthwhile experiments have cross-checked bottom-up concepts of basics methods in [8], interested researchers are encouraged to cross-check fruitfulness of the refined control strategy via practical implementation.

V. References

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