Generalized Microgrid Power Flow

Lingyu Ren, *Student Member, IEEE*, and Peng Zhang, *Senior Member, IEEE*

***Abstract*—Power flow analysis for islanded microgrid is a challenging problem due to the lack of means to incorporate the hierarchical control effect. This letter bridges the gap by devising a generalized microgrid power flow (GMPF). The novelty of GMPF includes: 1) it introduces the generalized distributed generator (DG) bus and the adaptive swing bus to model the DGs' behaviors; 2) the droop-based power flow is used to initialize the secondary control adjustment; and 3) three types of secondary control modes are developed within a double loop framework. Test results validate the effectiveness and excellent convergence performance of GMPF.**

***Index Terms*—Generalized microgrid power flow (GMPF), adaptive swing bus, hierarchical control, secondary control.**

I. INTRODUCTION

MICROGRID has proved to be a promising paradigm to enable electricity resiliency. In August 2017, for instance, multiple microgrids have kept their local critical services up and running in the Houston area despite the enormous utility grid outages caused by Hurricane Harvey [1]. As the foundation of microgrid energy management system, reliable power flow analysis is critically important to unlock the potential of microgrids as primary resilience resources and enable situational awareness.

Power flow of islanded microgrid, however, remains an open problem. Not only the special characteristics of the low-voltage grid pose significant challenges on the derivative-based methods (e.g., Newton Raphson [2]), but none of the existing algorithms is able to incorporate the hierarchical control [3] effects in microgrids. An extended direct backward/forward sweep (DBFS) is developed for microgrids [4]. Similar with the distributed slack bus methods [5], [6], it uses adjustable generations to share power loss among multiple sources while differently it is a non-derivative method. However, it is unable to consider the secondary control which is a standard scheme for voltage and frequency regulation in islanded microgrid.

This letter bridges this gap by developing a generalized microgrid power flow (GMPF) that enables incorporating hierarchical control schemes into microgrid power flow. GMPF introduces an adaptive structure where the power outputs of DGs are adjusted incrementally until they satisfy the control objectives. Due to the clarity and popularity of DBFS, the GMPF framework is applied to DBFS in which the hierarchical control is incorporated.

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The authors are with the Department of Electrical and Computer Engineering, University of Connecticut, Storrs, CT 06269 USA (e-mail: lingyu.ren@uconn.edu; peng.zhang@uconn.edu).

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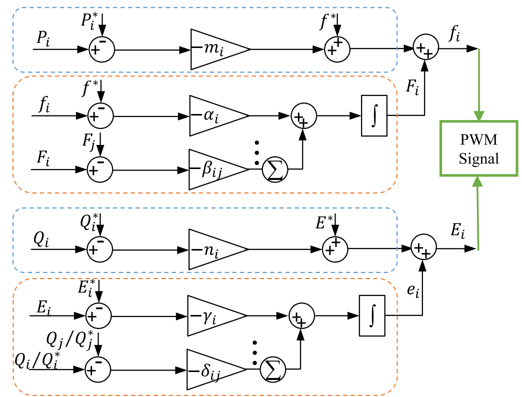

Fig. 1. Two-layered hierarchical control for invert-interfaced DGs (blue blocks: droop control; orange blocks: secondary control).

II. PRROBLEM STATEMENT

A. Direct Backward/Forward Sweep

For a conventional distribution grid, DBFS [7] is a matrix based BFS which requires only one matrix operation for backward sweep (BS) and another one for forward sweep (FS). Using the concept of bus injection to branch current matrix **BIBC**) and the branch current to bus voltage matrix (**BCBV**), the basic equations are:

$$\mathbf{I}_{\text{bus}} = (\mathbf{S}/\mathbf{U}_{\text{bus}})^* \quad (1)$$

$$\mathbf{I}_{\text{branch}} = \mathbf{BIBC} \cdot \mathbf{I}_{\text{bus}} \quad (2)$$

$$\Delta\mathbf{U} = \mathbf{BCBV} \cdot \mathbf{I}_{\text{branch}} \quad (3)$$

$$\mathbf{U}_{\text{bus}} = \mathbf{U}^0 - \Delta\mathbf{U} \quad (4)$$

Note: in Eq. (1), the slash symbol denotes the element-to-element division of two vectors. The BS and FS can be represented as Eq. (1-2) and Eq. (3-4), respectively [7]. The power injection of the swing bus ($S_1 = P_1 + jQ_1$) is calculated after the convergence of DBFS.

B. Hierarchical Control for Islanded Microgrids

In a microgrid case, E_i is used to denote the voltage magnitude (VM) of DG bus i. A two-layered hierarchical control structure is shown in Fig. 1, where the base layer is the P/F-Q/E droop controllers and the additive layer is the secondary control.

The P/F and Q/E droop coefficients are m_i, n_i, respectively. Three secondary control modes are defined [8] according to the selection of secondary control parameters (α_i, β_{ij}, γ_i, δ_{ij}):

1) *Reactive Power Sharing Mode (RPS):* Proportional reactive power sharing is targeted without voltage restoration ($\gamma_i = 0$). Define $R_{qi} = Q_i/Q_i^*$ as the reactive power ratio. It is the same for all DGs via RPS control.

2) *Voltage Regulation Mode (VR):* Voltage recovery of all DG buses is targeted assuming adequate reactive power support ($\delta_{ij} = 0$).

Algorithm 1: GMPF Algorithm

Initialize P_i^0, Q_i^0, F_1, E_1, R_{q1} (RPS, ST), E_{di}^0 (VR)
repeat
  Update ΔQ_i, $i \in \mathcal{G}$ **Eq. (5/6)**
  repeat
    Update ΔP_i, $i \in \mathcal{G}$
    Execute DBFS **Eq. (1-4)**
    Update ΔP_1, ΔQ_1
    Update F_1
  until F_1 *is constant*;
  Update E_1, R_{q1} (RPS, ST), E_{di}^k (VR) **Eq.(7)**
until R_{q1} *or* E_{di} *is constant*;

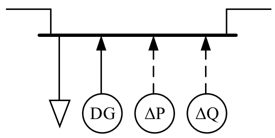

Fig. 2. A generalized bus-type to represent DG.

3) *Smart Tuning Mode (ST):* Proportional reactive powering is guaranteed with one leading DG that performs voltage restoration.

III. Generalized Microgrid Power Flow

A. Generalized DG Bus and Adaptive Swing Bus

Although, in a traditional BFS power flow there is one swing bus and all others are PQ buses, in islanded microgrids there is no swing bus to balance the power loss and the power gap caused by islanding. Instead, it is shared among all DGs according to the control mode. To capture this effect, a generalized PQ bus is introduced for modeling DG in microgrid (see Fig. 2), where adjustable active and reactive power injections, ΔP_i and ΔQ_i, are added for bus i.

To perform BFS, an adaptive swing bus is selected as bus 1 to update the secondary frequency adjustment F_1. The rule of thumb is to choose the DG bus with the smallest active power droop coefficients. Our finding is that small m_1 can guarantee a stable adjustment in ΔP_i by keeping a small updating step size and avoiding zigzag. One exception is that in the ST mode, the leading DG which acts as a voltage reference should be selected. The set of non-swing DG buses is defined as $\mathcal{G}$.

B. Generalized Microgrid Power Flow (GMPF) Algorithm

Algorithm 1 follows a double loop process. Here the *outer loop* is to update the reactive power until the secondary control objective (power sharing and/or voltage regulation) is reached, whereas the *inner loop* is to update the active power such that a unanimous F_i for all DGs is kept and a proportional active power sharing is achieved. The GMPF iterations are specified below.

GMPF is first initialized using the power flow results for droop controlled microgrid, specifically $F_1 = \Delta f_1$ (frequency deviation after droop control) and $R_{q1} = Q_1/Q_1^*$. Similar to [9] and [10], for VR mode, a dummy bus with a voltage E_{di} is created for DG bus i to determine the reactive power injection for voltage restoration, initialized as $E_{di}^0 = E_i$.

For all three modes, active power can always achieve accurate sharing by updating $\Delta P_i = -m_i \; F_1, i \in \mathcal{G}$ before DBFS and updating $F_1 = -m_1 \Delta P_1$ afterward (see algorithm table). This process is the *inner loop* with a stopping criterion $|\Delta F_1| < \epsilon_1$. The update of ΔQ_i and E_1, also the *outer loop*, depends on the secondary control modes, as described below:

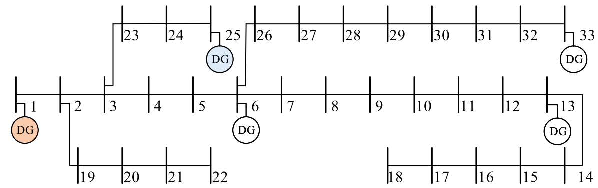

Fig. 3. 33 bus islanded microgrid with 5 local DGs.

1) For RPS mode, E_1 is updated following Q/E droop: $\Delta E_1 = -n_1 \Delta Q_1$ while ΔQ_i is updated by:

$$\Delta Q_i = R_{q1} \cdot Q_i^* - Q_i^0, \quad i \in \mathcal{G} \tag{5}$$

The convergence criterion is $|\Delta R_{q1}| < \epsilon_2$

2) For VR mode, E_1 is constant (E_1^*) while ΔQ_i is updated by:

$$\Delta Q_i = E_i^k \cdot (E_{di}^{k+1} - E_i^k)/Z_{di}, \quad i \in \mathcal{G} \tag{6}$$

$$E_{di}^{k+1} = E_{di}^k + E_i^* - E_i^k, \quad i \in \mathcal{G} \tag{7}$$

Here, Z_{di} is a virtual impedance between the dummy bus and the DG bus. It functions as the sensitivity of ΔQ_i to the voltage difference between the dummy bus and the DG bus. Define the maximum voltage magnitude error as $Er^k = max\{|E_i^* - E_i^k|, i \in \mathcal{G}\}$. The convergence criterion is then $|Er^k| < \epsilon_3$. Obviously, E_{di} is constant once convergence is reached.

3) For ST mode, E_1 is constant (E_1^*) while ΔQ_i is updated by Eq. 5 with the same stopping criterion as the RPS mode.

C. Limitations

The GMPF is an extension of DBFS considering the effect of the microgrid hierarchical controls. The convergence of the algorithm mainly relies on two factors: (1) the microgrid controllers much be stable [11] so that there exists at least one feasible power flow solution; (2) the admittance matrix should be adjusted to avoid ill-condition, normally caused by very short or very long lines [7]. To use GMPF, one prior assumption is that the concerned microgrid is radial or weakly meshed.

IV. Case Study

The effectiveness and efficiency of GMPF are tested on a 33-bus islanded microgrid with a base voltage of 12.66 kV and base power of 500 kW (see Fig. 3). In Case 1 (PF1), the microgrid settings in [4] is adopted, where 5 DGs are added at bus {1, 6, 13, 25, 33} respectively with corresponding droop coefficients: {0.05, 1, 0.1, 1, 0.2} (here the P/F and Q/E are assumed to have the same droop coefficients). Bus 1 is selected as the adaptive swing bus. The initial DG outputs before islanding, also the power references are 0.9+j0.9 p.u.. The parameters for GMPF are: $\epsilon_1 = 1e-3$; $\epsilon_2 = 1e-3$; $\epsilon_3 = 1e-4$; $Z_{di} = 0.1$. In Case 2, the droop coefficients are adjusted as {1, 1, 0.1, 0.05, 0.2} and bus 25 is the adaptive swing bus. All other settings are the same with Case 1 to show the impact of the adaptive swing bus and droop coefficients. GMPF is implemented in MATLAB and runs on a 2.1 GHz PC.

A. Voltage Magnitude Results

Fig. 4 and Fig. 5 illustrate the VM results from GMPF for Case 1 and Case 2, respectively. It is shown that: (1) In both cases, the VMs with only droop control (DP) have the lowest values due to the droop effect after islanding; (2) Under VR mode, both cases are able to recover their DG voltages to their reference values. Detailed analyses are omitted due to limited space.

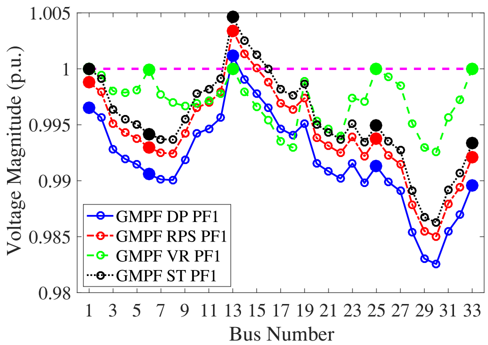

Fig. 4. Bus voltages for four control modes in Case 1.

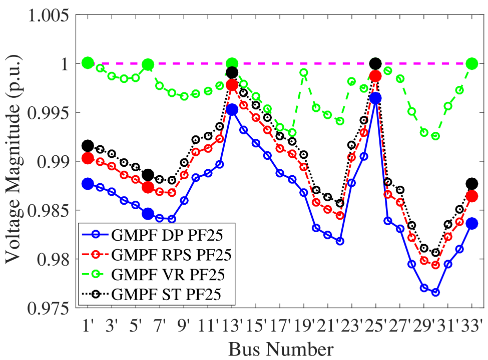

Fig. 5. Bus voltages for four control modes in Case 2.

TABLE I
POWER INJECTIONS OF DG BUSES

Bus No.	Active Power (p.u.)				Reactive Power (p.u.)			
	DP	RPS	VR	ST	DP	RPS	VR	ST
1	2.50	2.50	2.51	2.50	0.97	0.92	-0.9	0.92
6	0.98	0.98	0.98	0.98	0.90	0.92	2.94	0.92
13	1.70	1.70	1.70	1.70	0.93	0.92	0.02	0.92
25	0.98	0.98	0.98	0.98	0.90	0.92	1.56	0.92
33	1.30	1.30	1.30	1.30	0.92	0.92	1.00	0.92
1′	0.98	0.98	0.98	0.98	0.90	0.92	1.44	0.92
6′	0.98	0.98	0.98	0.98	0.90	0.92	2.74	0.92
13′	1.70	1.70	1.70	1.70	0.93	0.92	0.03	0.92
25′	2.50	2.50	2.50	2.50	0.97	0.92	-0.6	0.92
33′	1.30	2.30	1.30	2.30	0.92	0.92	1.00	0.92

TABLE II
CPU TIME AND ITERATION NUMBERS

	RPS1	VR1	ST1	RPS25	VR25	ST25
CPU Time	0.0316	0.0625	0.0156	0.0316	0.0625	0.0156
Iteration No.	9	173	9	9	171	9

B. DG Output Results

The DG outputs under each case are summarized in Table I. The active power is accurately shared among all 5 DGs in proportion with their droop coefficients. Meanwhile, the reactive power is evenly shared under RPS or ST mode. Under VR mode, the DG reactive power outputs show great diversity which is consistent with [8]. This indicates that VR mode is only feasible when microgrid has extra reactive power resources (such as shunt capacitor or D-STATCOM).

C. Convergence Results

Both cases show that GMPF has excellent convergence performance, shown in Table II. In RPS and ST mode, the *outer loop* (R_{q1}) is able to converge within 9 iterations.

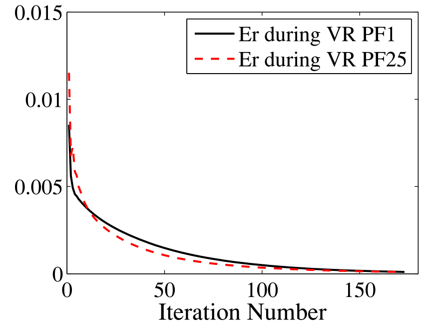

Fig. 6. Maximum voltage magnitude error during outer loop iterations.

However, in VR mode, it shows a long voltage recovery process as illustrated in Fig. 6. This is because, according to Eq. (6-7), the closer the VM is to the reference value the slower the update in reactive power injection.

V. CONCLUSION

A generalized microgrid power flow (GMPF) is devised to incorporate hierarchical control. Three implementations are developed for RPS, VR, and ST control modes. Test results show that GMPF can achieve accurate active power sharing in accordance with the droop coefficients while the reactive power sharing and voltage regulation determined by the control mode can also be accurately evaluated. Therefore, GMPF is a powerful tool for microgrid planning, control design, and energy management.

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