Power Flow of Islanded AC Microgrids: Revisited

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***Abstract*—In this letter, a new methodology is proposed to extend the applicability of conventional power flow methods to islanded microgrids (MGs), operating with the droop control method. A slack bus is considered to be connected at a random MG node. The operational conditions of this slack bus as well as of the rest MG nodes are determined through an iterative procedure. The objective of this procedure is to force the active and reactive power flowing through the slack bus to zero, representing the islanded MG operation. The proposed approach has a similar accuracy with time-domain simulations, while it reduces significantly the required computational burden.**

***Index Terms*—Islanded operation, microgrid, power flow.**

I. Introduction

The increased penetration of distributed generation (DG) into the existing distribution grids has lead to the advent of microgrids (MGs). MGs can operate either in grid-connected or islanded mode, depending on technical and economical aspects. Considering grid-connected MGs, conventional power flow (CPF) methods can be readily applied for either deterministic or probabilistic steady-state analysis [1]. However, since these approaches require the existence of a slack bus, they cannot be applied for the analysis of islanded MGs [2].

Sophisticated techniques have been proposed to solve the power flow problem of islanded MGs. Nevertheless, these methodologies are characterized by limited performance, mainly suffering from convergence issues [3]. An alternative solution involves the detailed network modeling and the use of time-domain (TD) simulations. Although this approach can provide very accurate results, the corresponding computational complexity makes the applicability of TD simulations to real-scale MGs highly questionable.

Scope of this letter is to propose a novel solution for the power flow problem of islanded MGs. The proposed technique exploits the mathematical formulation of CPF methods and introduces an iterative procedure to accurately determine the equilibrium operating point of the islanded MG, as imposed by the droop characteristics of DG units. The proposed approach achieves a reduced computational burden against TD simulations, while also preserving the accuracy of the solution.

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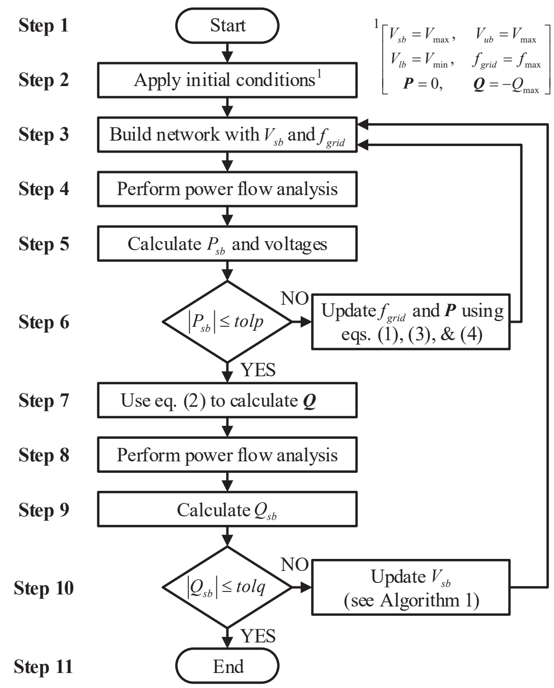

Fig. 1. Flowchart of the proposed method.

II. Islanded MG Operation

DG units in an islanded MG operate using the droop control, where the operating MG frequency f_{grid} and the voltage magnitude V_i at the output of the i-th DG unit are determined by the following equations:

$$f_{grid} = f_{\max} - m_i P_i \quad \forall i \in N_{dg} \tag{1}$$

$$V_i = V_{\max} - n_i (Q_i + Q_{\max,i}) \quad \forall i \in N_{dg} \tag{2}$$

where $f_{\max}$ and $V_{\max}$ are the maximum network operational limits of frequency and voltage, respectively. $Q_{\max,i}$ denotes the maximum reactive power capability of the i-th DG unit, while P_i, and Q_i are the active and reactive power of the i-th DG unit. Finally, N_{dg} denotes the number of the installed DG units, whereas m_i and n_i are the droop coefficients calculated as discussed in [4].

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III. Proposed Methodology

CPF methods introduce the concept of a slack bus used to absorb/provide the surplus/deficit of active and/or reactive power, representing the upstream utility grid. This slack bus operates at a constant voltage, imposing also the network frequency. However, in an islanded MG, the consideration of a slack bus, operating at fixed voltage and frequency is not valid, since the network operation is determined by the droop characteristics of (1) and (2). Therefore, to perform a power flow analysis for islanded MGs using CPF methods, the operational conditions of the slack bus must be available prior to the power flow solution. To address this issue, an iterative procedure is proposed. The objective is to properly adjust the voltage of the slack bus (V_{sb}) and f_{grid} in order to force active and reactive power flowing through the slack bus to zero, emulating this way the islanded operation of the MG and the disconnection of the upstream utility grid.

The proposed methodology consists of two nested loops, as presented in Fig. 1. The inner loop is used to calculate f_{grid}, while the outer loop defines V_{sb}. At the first step, the initial conditions are determined. Afterwards, line and load impedances are calculated at f_{grid} and a power flow analysis is performed. This power flow aims to calculate network voltages and the active power flowing through the slack bus (P_{sb}). If the absolute value of P_{sb}, i.e., $|P_{sb}|$, is greater than a predefined tolerance ($tolp$), DG units must adjust their injected active power by a ΔP_i amount. Following this approach, P_{sb} is allocated to all DG units in order to zero the active power flow through the slack bus. This is mathematically expressed by (3). Additionally, it is worth noticing that due to the use of the droop control mechanism of (1), ΔP_i amounts are mathematically described by (4).

$$\sum_{i=1}^{N_{dg}} \Delta P_i = P_{sb} \tag{3}$$

$$m_1 \Delta P_1 = ... = m_{N_{dg}} \Delta P_{N_{dg}} \tag{4}$$

Then, $\boldsymbol{P}$, which is the vector of active power injections of DG units is updated by adding the corresponding ΔP_i and the new f_{grid} is derived using (1). Subsequently, the procedure moves back to Step 3 and a new power flow analysis is conducted, using the updated values of f_{grid} and $\boldsymbol{P}$.

When $|P_{sb}|$ becomes lower than $tolp$, the inner loop terminates and the algorithm proceeds to Step 7 to calculate the vector of reactive power injections ($\boldsymbol{Q}$) of the DG units according to (2). Using $\boldsymbol{P}$, $\boldsymbol{Q}$, and f_{grid}, a power flow is performed to calculate the reactive power flowing through the slack bus (Q_{sb}). If $|Q_{sb}|$ is less than a predefined tolerance ($tolq$), the procedure terminates. Otherwise, a new V_{sb} must be defined. More specifically, a positive Q_{sb} indicates a deficit of reactive power in the MG. Therefore, according to (2), V_{sb} must be reduced to force DG units to increase their reactive power injection to cover reactive power needs of the MG. On the contrary, in case of negative Q_{sb}, V_{sb} must be increased. The new V_{sb} value is determined through a binary search method, as presented in Algorithm 1, and the procedure continues to Step 3. In Algorithm 1, V_{lb} and V_{ub} are the low and upper limits of the searching interval, while superscripts p and n denote the corresponding previous and new values.

Algorithm 1 Binary search of the slack bus voltage

if $Q_{sb} > 0$ **then**
  set V_{sb}^n to $V_{sb}^p - (V_{sb}^p - V_{lb}^p)/2$, V_{lb}^n to V_{lb}^p, V_{ub}^n to V_{sb}^p
else
  set V_{sb}^n to $V_{sb}^p + (V_{ub}^p - V_{sb}^p)/2$, V_{lb}^n to V_{sb}^p, V_{ub}^n to V_{ub}^p
end if

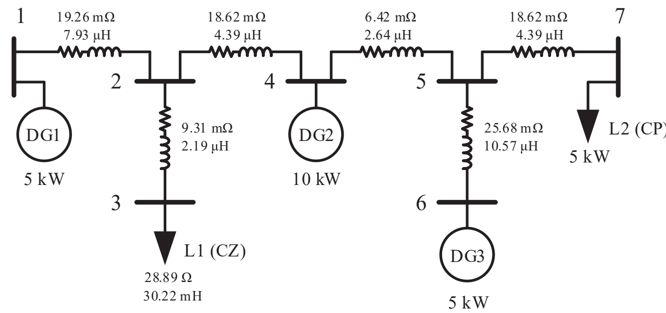

Fig. 2. Seven-bus test system.

TABLE I
Droop Coefficients m (Hz/kW) and n (V/kVAr)

m_1	m_2	m_3	n_1	n_2	n_3
0.400	0.200	0.400	12.924	6.462	12.924

TABLE II
Network voltages (V)

	Buses						
	1	**2**	**3**	**4**	**5**	**6**	**7**
PSIM	389.575	388.315	387.162	389.429	388.978	390.647	386.507
Proposed	389.510	388.252	387.098	389.364	388.914	390.581	386.446

TABLE III
Active (kW) and Reactive (kVAr) Power of DG Units

	P_1	P_2	P_3	Q_1	Q_2	Q_3
PSIM	2.44046	4.88086	2.44042	0.81238	1.64756	0.72951
Proposed	2.44034	4.88070	2.44035	0.81264	1.64791	0.72969

IV. Numerical Validation

The proposed methodology is demonstrated on the 0.4 kV islanded MG of Fig. 2, consisting of three DG units, a constant impedance (CZ), and a constant power (CP) load. The nominal power factor of the DG units is 0.85, while loads operate with inductive power factor equal to 0.95. All network elements operate at their nomimal power, while the droop coefficients of the DG units are presented in Table I assuming maximum and minimum operational limits, as defined in Standard EN50160 [5]. TD simulations are performed using PSIM software and the corresponding results are compared with those derived by the proposed method, assuming $tolp$ and $tolq$ equal to 0.1 W and 0.1 VAr, while the slack bus is randomly placed at bus 5. All simulations are performed using an Intel Core i7-930, 2.8 GHz, RAM 24 GB, personal computer.

The MG frequency calculated by both approaches is equal to 50.0238 Hz, while network steady-state voltages, active, and reactive power of DG units are presented in Tables II and III, respectively. In all cases a near-zero mismatch is observed. It is worth noticing that the proposed method yields identical results regardless the location of the slack bus. The superiority of the proposed method against TD simulations is verified by the corresponding execution times. More specifically, PSIM requires approximately 168 s to reach steady-state conditions, while the proposed method converges in 2.065 s, indicating its applicability for the power flow analysis of islanded MGs.

V. Conclusions

In this letter, a new methodology is proposed to accurately solve the power flow problem in islanded AC MGs. The distinct advantage of the method is its computational efficiency compared to the time-consuming TD simulations. Therefore, it can be a valuable tool for distribution system operators for close to real-time simulations of islanded MGs.

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