POWER FLOW INCORPORATING COST-BASED DROOP CONTROL STRATEGIES FOR AC AUTONOMOUS MICROGRIDS

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(Received June 18, 2020; Accepted August 5, 2020)

Abstract - Several methods of power flow analysis for autonomous microgrids have been suggested; however, the implementation of these methods is challenging because of the lack of a swing bus and droop control characteristics. This paper puts forward an innovative technique for the load flow study of microgrids that autonomously operate according to droop control strategies incorporating cost rather than traditional droop schemes. This approach aims to extend the application of conventional power flow methodologies. In this approach, the incremental cost that is derivative of the fuel cost curve with respect to power output is embedded in droop schemes. The proposed approach deploys the iterative procedure to impose complex power that injects through the swing node to zero, which represents the autonomous operation of microgrids. Test results validate that this approach is exact and straightforward to implement; therefore, it can be highly beneficial for operating and planning microgrids.

Key words - Microgrid (MG); autonomous operation; power flow; distributed generation (DG); droop control strategies incorporating cost.

1. Introduction

Distributed generation penetrating increasingly into electrical distribution networks has resulted in the arrival of microgrids. These microgrid systems are likely to operate to be grid-connected or autonomous, which is dependent on technical and economic characteristics. In interconnected modes, the control on frequency and voltage magnitude of microgrids is performed by major electricity grids; however, these parameters are inconstant in stand-alone modes. The description of the hierarchical control methods for the operation of microgrids is comprehensively presented in [1].

Power flow that plays an essential role in the planning and operation of the power systems has been studied by numerous researchers since the 1960s. There are several developed power flow methods such as Gauss-Seidel, Newton-Raphson, and Fast Decoupled Power Flow versions, in which the most popular method in power system analysis is Newton-Raphson. These conventional power flow (CPF) algorithms are valid in the case of grid-connected microgrids because there is at least a slack bus, and system frequency is fixed. However, the system frequency is not constant in autonomous microgrids, which leads to the dependence of reactance on the frequency. Additionally, the real power, reactive power, and the voltage of droop buses at which distributed energy resources are connected are not predefined and are dependent on power system specifications; therefore, classifying the droop buses as slack, PV or PQ is invalid [2].

Some state-of-the-art techniques have been developed to deal with load flow problems for microgrids that operate independently. The droop characteristics of DGs are taken into account in these methods. A modified Newton-Raphson method incorporating the droop schemes of DGs to solve the power flow for islanded microgrids is proposed in [2]. Furthermore, in this paper, the authors also consider three different droop approaches. Authors in [3] introduced the concept of virtual impedance in the droop model to analyze normal steady-state operation for low-voltage Alternating Current (AC) and Direct Current (DC) microgrids. In this paper, a nonlinear system of equations that is employed to describe the steady-state operation of microgrids incorporating droop nodes is resolved using a procedure based on the Newton-trust region with global convergence. A novel power flow algorithm based on modified Newton-Raphson methods is proposed in [4], in which symmetrical sequence component models rather than phase-coordinate models of microgrid elements are adopted. In [5], a complex power compensation approach, which is based on sensitivity equations via Wirtinger calculus, is put forward. In [6], the enhanced microgrid power flow is devised to integrate hierarchical control effects. Despite the high degree of accuracy of the above methods, they are sophisticated and challenging to exploit for electrical system applications.

The method of Direct Backward/Forward Sweep (BFS) developed in [7]-[8], and Modified Backward/Forward Sweep presented in [9] are specifically designed for radical and weakly electrical distribution systems. Authors in [10] suggested the three-phase power flow method, which combines the conventional Newton-Raphson iterative approach with a Backward/Forward sweep algorithm for loop-based microgrids. A technique based on the implicit Zbus technique and the concept of virtual impedance for balanced and unbalanced distribution systems considering the effect of a multi-grounded neutral conductor is proposed in [11]. Nonetheless, the performance of these approaches is limited due to some problems relating to convergent characteristics. Modeling the elaborate network combined with applying time-domain simulation is also an alternative solution. Results from this approach are very accurate; however, it is computationally complex, which makes the real-scale application of time-domain simulations to microgrids highly questionable.

This paper aims to introduce a new technique to handle the load flow problems of autonomous microgrid systems. The presented method takes advantage of traditional power flow equations, and the steady-state operation points of independent microgrids are accurately determined using a repetitive strategy.

The main contributions of this paper are twofold:

- The iteration procedure employing traditional load flow studies with a view to determining the equilibrium operating point of the stand-alone microgrids is proposed;

- The droop control strategies integrating costs rather than the traditional droop schemes are considered.

The structure of the paper includes six sections as follows: Section 2 presents the formulation of the economic dispatch and the optimal dispatch rule. Section 3 describes the droop control strategies incorporating costs. The developed independent microgrid power flow methodology integrating the cost-based droop control strategies is presented in Section 4. Numerical results are given in Section 5, and the conclusions are drawn in Section 6.

2. The Optimal Dispatch Principle

First, this section mathematically describes economic dispatch formulation for independent microgrids, which intends to minimize the total cost of real power generation. Furthermore, the Lagrange method is used to solve this problem. Then, the optimal dispatch principle is derived.

2.1. Economic Dispatch Formulation

The objective of the economic dispatch in a power system with *n* generators committed is to determine the output power of generation units at minimum cost

$$\min C_T = \sum_{i=1}^{n} C_i \quad P_{Gi} \tag{1}$$

while satisfying power balance constraints and power bounds on generating units

$$\sum_{i=1}^{n} P_{Gi} = \sum_{j=1}^{m} P_{Dj} + P_L = P_D + P_L \tag{2}$$

$$P_{Gi}^{\min} \le P_{Gi} \le P_{Gi}^{\max} \qquad i = 1, 2, ..., n \tag{3}$$

Where, P_{Gi} is the active power output of DG$_i$, $C_i\left(P_{Gi}\right)$ is the operating cost function of DG$_i$, P_D is the aggregate of loads in the microgrid, P_L is the total real power losses, $P_{Gi}^{\min}$ is the minimum real power of generating unit *i-th* DG, and $P_{Gi}^{\max}$ is upper bound of the real power output of the *i*-th DG. It is noted that the active power losses usually account for nearly 5% of the aggregate demand in the microgrid.

2.2. The Optimal Dispatch Rule

A classical approach for dealing with the problem of optimum economic dispatch defined in (1)-(3) is deploying the Lagrange multipliers. When using this method, the corresponding Lagrange equation can be written as follows [12]

$$\tilde{C}_T(P_{G1}, P_{G2}, ..., P_{Gn}) = \sum_{i=1}^{n} C_i\left(P_{Gi}\right) + \lambda\left(P_D + P_L - \sum_{i=1}^{n} P_{Gi}\right) + \sum_{i=1}^{n} \mu_i^+\left(P_{Gi} - P_{Gi}^{\max}\right) + \sum_{i=1}^{n} \mu_i^-\left(P_{Gi}^{\min} - P_{Gi}\right) \tag{4}$$

where, λ is the Lagrangian multiplier of (2), μ_i^+, μ_i^- are Lagrangian multipliers of (3).

The conditions for the first-order optimality are

1. $$\frac{\partial \tilde{C}_T}{\partial P_{Gi}} = \frac{dC_i\left(P_{Gi}\right)}{dP_{Gi}} - \lambda + \mu_i^+ - \mu_i^- = 0 \quad for\ i = 1...n \tag{5}$$

2. $$\frac{\partial \tilde{C}_T}{\partial \lambda} = P_D + P_L - \sum_{i=1}^{n} P_{Gi} = 0 \tag{6}$$

3. $$\frac{\partial \tilde{C}_T}{\partial \mu_i^+} = P_{Gi} - P_{Gi}^{\max} \le 0 \quad for\ i = 1...n \tag{7}$$

$$\frac{\partial \tilde{C}_T}{\partial \mu_i^-} = P_{Gi}^{\min} - P_{Gi} \le 0 \quad for\ i = 1...n \tag{8}$$

4. $$\left.\begin{array}{l} \mu_i^+\left(P_{Gi} - P_{Gi}^{\max}\right) = 0 \\ \mu_i^-\left(P_{Gi}^{\min} - P_{Gi}\right) = 0 \\ \mu_i^+ \ge 0,\ \mu_i^- \ge 0 \end{array}\right\} for\ i = 1...n \tag{9}$$

Case 1: If $P_{Gi}^{\min} < P_{Gi} < P_{Gi}^{\max}$, according to (9), it yields

$$\mu_i^+ = \mu_i^- = 0 \qquad for\ i = 1...n \tag{10}$$

To apply equations (10) into (5), we have

$$\lambda = \frac{dC_i\left(P_{Gi}\right)}{dP_{Gi}} = IC_i \qquad for\ i = 1...n \tag{11}$$

where $IC_i = dC_i\left(P_{Gi}\right)/dP_{Gi}$ is the slope of the fuel-cost curve or so-called incremental cost (IC_i) of DG$_i$.

Case 2: If $P_{Gi} = P_{Gi}^{\max}$, according to (5) and (9), it yields

$$\begin{cases} \mu_i^+ \ge 0 \\ \mu_i^- = 0 \\ \lambda = \left.\dfrac{dC_i\left(P_{Gi}\right)}{dP_{Gi}}\right|_{P_{Gi}=P_{Gi}^{\max}} + \mu_i^+ \ge \left.\dfrac{dC_i\left(P_{Gi}\right)}{dP_{Gi}}\right|_{P_{Gi}=P_{Gi}^{\max}} = IC_i \end{cases} \tag{12}$$

Case 3: If $P_{Gi} = P_{Gi}^{\min}$, according to (5) and (9), it yields

$$\begin{cases} \mu_i^+ = 0 \\ \mu_i^- \ge 0 \\ \lambda = \left.\dfrac{dC_i\left(P_{Gi}\right)}{dP_{Gi}}\right|_{P_{Gi}=P_{Gi}^{\min}} - \mu_i^- \le \left.\dfrac{dC_i\left(P_{Gi}\right)}{dP_{Gi}}\right|_{P_{Gi}=P_{Gi}^{\min}} = IC_i \end{cases} \tag{13}$$

In conclusion, the solution to the problem (1)-(3) can be achieved according to the same incremental cost rule, and it is expressed as (14):

$$\begin{cases} IC_i = \lambda & P_{Gi}^{\min} \le P_{Gi} \le P_{Gi}^{\max} \\ IC_i < \lambda & P_{Gi} = P_{Gi}^{\max} \\ IC_i > \lambda & P_{Gi} = P_{Gi}^{\min} \end{cases} \tag{14}$$

The optimal dispatch principle in (14) denotes that the minimization of the cost of generating electricity in the microgrids is found out if all generators operating at neither lower limits nor upper bounds are operated at an equal incremental cost.

3. Droop schemes incorporating cost

First, conventional linear droop strategies are briefly summarized. After that, we carefully consider the deployment of quadratic fuel cost equations to derive droop schemes incorporating costs.

3.1. Conventional Droop Strategies

In microgrids operating independently with droop-based characteristics, the operating frequency at the power output of the *i*-th generating unit is calculated according to the equation as follows:

$$f_i = f_{\max} - \frac{f_{\max} - f_{\min}}{P_{Gi}^{\max}} P_{Gi} \tag{15}$$

where $f_{\max}$ = 51 Hz and $f_{\min}$ = 49 Hz are the upper and lower limits of operating frequency in the microgrids, respectively [13].

3.2. Droop schemes incorporating cost

The fuel cost of *i*-th generating unit can be expressed with a quadratic equation as follows

$$C_i\left(P_{Gi}\right) = \alpha_i + \beta_i P_{Gi} + \gamma_i P_{Gi}^2$$

where $\alpha_i, \beta_i, \gamma_i$ are cost coefficients.

Moreover, the incremental cost for *i*-th generating unit can be derived as the following forms:

$$IC_i = \frac{dC_i\left(P_{Gi}\right)}{dP_{Gi}} = 2\gamma_i P_{Gi} + \beta_i \tag{16}$$

The first step of establishing the droop schemes incorporating cost with the aim of minimizing the total generation cost is converting the formula for conventional droop diagrams expressed in (15) into (18) in which the incremental cost is introduced [14].

$$f_i = f_{\max} - \left(f_{\max} - f_{\min}\right).\left(2\gamma_i P_{Gi} + \beta_i\right) \tag{17}$$

Then, to guarantee the operational stability of the microgrids, the addition of a parameter *h* to the droop characteristic integrating incremental cost in (18) results in the following equation:

$$f_i = f_{\max} - \left(f_{\max} - f_{\min}\right).h..\left(2\gamma_i P_{Gi} + \beta_i\right) \tag{18}$$

Because the frequency of microgrid at the equilibrium operating point is identical, the total cost of generating electricity is minimum regarding the same incremental cost rule.

The droop schemes integrating incremental costs have some advantages related to solving the economic dispatch problem in comparison with other methods, such as consensus algorithms in [15]. The first advantage is that they not only do not require sophisticated mathematical models, but they can also be performed easily, which makes them advisable for practical purposes. Additionally, because of the full decentralization, they do not require communication links among DGs, which helps the reliability of microgrids to be improved. Last but not least, these schemes can plug-and-play. Consequently, the impact of the disconnected and connected properties of DGs on the effectiveness of the control strategies can be insignificant.

4. Autonomous Microgrid Power Flow Method

In the section, a novel approach with the combination of the droop schemes incorporating cost and the traditional load flow analysis is proposed.

A swing bus is mandatory in a conventional load flow study, which represents major power systems. The role of this bus is to either inject or withdraw when the real and reactive powers are inadequate or redundant. The operational voltage at the slack bus is constant, which also imposes the operating frequency. Nevertheless, in autonomous microgrids, since the droop control strategies can considerably affect the power networks, the voltage and frequency of the slack bus are not considered to be fixed. Therefore, the operating states of the swing bus have to be determined before conventional power flow methodologies are used to implement power flow analysis for autonomous microgrids. In this paper, a repetitive procedure for adjusting the voltage of the slack bus (V_{sb}) and the network frequency (f) is proposed, which forces the flow of complex power through the voltage reference bus to zero. This technique accurately imitates the stand-alone microgrids.

The developed approach, which is formed from two nested loops, is shown in Algorithm 1. The network frequency is determined using the inner loop, and the outer loop is exploited to calculate the voltage of the slack bus.

4.1. Initial conditions

In this step, a slack bus is randomly selected. The upper and lower limits of initial operational voltage at the slack bus, and the initial voltage of slack bus are determined as follows:

$$V_{ub}^{(0)} = V_{\max},\ V_{lb}^{(0)} = V_{\min},\ V_{sb}^{(0)} = V_{\max} \tag{19}$$

Where, $V_{\max}$ and $V_{\min}$ are the highest and lowest operating voltage, respectively. Additionally, V_{ub} and V_{lb} are the lower and upper bounds of the voltage in the searching interval, respectively.

Initially, the real power and reactive power output generated by the *i*-th generating unit are calculated according to expressions as follows:

$$P_{Gi}^{(0)} = 0,\quad Q_{Gi}^{(0)} = -Q_{Gi}^{\max} \tag{20}$$

where $Q_i^{\max}$ is the upper limit of reactive power provided by the *i*-th generating unit.

4.2. Inner loop: Frequency droop

At this stage, the series impedance of the line connecting different nodes *I* and *k* is calculated at the grid frequency as follows:

$$Z_{ik} = R_{ik} + jX_{ik}\frac{f^{(r+1)}}{f^{(r)}} \tag{21}$$

Where, R_{ik} is the resistance of branch *i-k*; X_{ik} is the inductive reactance of link *i-k;* $f^{(r)}$ is the grid frequency at the *r*-th iterative step and $f^{(r+1)}$ is the power system frequency at (*r+1*)-th step. Then, a load flow study is implemented. This power flow is for computing the real power that flows through the voltage reference node (P_{sb}) and network voltages. If the absolute value of P_{sb} is higher than a predetermined tolerance (*tolp*), the active power generated by DG units has to be adjusted by the amount of ΔP_{Gi}. In this paper, the allocation of P_{sb} to droop control generating units is not only to equal zero the real power generated by the swing node but also to operate microgrids at minimum cost. The expressions of this approach are shown as follows:

$$\sum_{i=1}^{N_{DG}} P_{Gi}^{(r+1)} = \sum_{i=1}^{N_{DG}} P_{Gi}^{(r)} + P_{sb}^{(r)}$$
$$2\gamma_1 P_{G1}^{(r+1)} + \beta_1 = \ldots = 2\gamma_{N_{DG}} P_{GN_{DG}}^{(r+1)} + \beta_{N_{DG}} \quad (22)$$

where N_{DG} is the number of generating units in a microgrid.

Then, the updated system frequency is determined using (19). The termination of the inner loop occurs when the absolute value of P_{sb} is not higher than *tolp*.

4.3. Outer loop: Voltage droop

The outer loop begins with the calculation of the reactive power injected by DG units using the equation described by (24).

$$V_i = V_{\max} - n_i\left(Q_{Gi} + Q_{Gi}^{\max}\right) \qquad \forall i \in N_{DG} \quad (23)$$

where n_i is the droop coefficient calculated as in [16].

The subsequent step is using the vector of active power (***P***) and reactive power (***Q***) injected of DG units and the system frequency to carry out load flow study for determining the reactive power that flows through the voltage reference bus (Q_{sb}).

If $\left|Q_{sb}\right| \le tolq$, the algorithm has converged. If not, a V_{sb} has to be updated. In particular, if Q_{sb} is positive, there is a shortfall in the reactive power of microgrid. Therefore, V_{sb} has to be decreased, which imposes generating units to increase the provision of their reactive powers. This helps deal with the microgrid reactive power requirement. A half-interval search technique is utilized to calculate the new approximations of V_{sb}, V_{ub}, *and* V_{lb} as follows:

$$V_{sb}^{(r+1)} = V_{sb}^{(r)} - \frac{V_{sb}^{(r)} - V_{lb}^{(r)}}{2}, V_{lb}^{(r+1)} = V_{lb}^{(r)}, V_{ub}^{(r+1)} = V_{sb}^{(r)} \quad (24)$$

However, V_{sb} must be raised if Q_{sb} is negative, which decreases the reactive power injected by distributed generation units. The equations for updating the latest values of V_{sb}, V_{ub}, *and* V_{lb} using the half-interval search technique are expressed as (26):

$$V_{sb}^{(r+1)} = V_{sb}^{(r)} + \frac{V_{ub}^{(r)} - V_{sb}^{(r)}}{2}, V_{lb}^{(r+1)} = V_{sb}^{(r)}, V_{ub}^{(r+1)} = V_{ub}^{(r)} \quad (25)$$

Algorithm 1: Autonomous Microgrid Power Flow Method

```
Initialize: V_sb, V_ub, V_lb, f, P_Gi, Q_Gi
Repeat
    Update   V_sb        Equations (25), (26)
    Repeat
        Update   f, P_Gi    Equations (19), (23)
        Form the electrical network using V_sb, f
        Execute   Power Flow Analysis
        Update   P_sb, V_i
    Until |P_sb| <= tolp
    Update   Q_Gi     Equation (24)
    Execute  Power Flow Analysis
    Update   Q_sb
Until |Q_sb| <= tolq
Result: P_Gi, Q_Gi, V_i, f and the branch power flow
```

5. Results and discussions

The single-line diagram developed by PSS/ADEPT software for the test system adopted in this work is shown in Figure 1 [17]. The microgrid includes essential DG sources in which DG_1 is batteries, DG_2 is microturbine, DG_3 and DG_4 are fuel cells, DG_5 is photovoltaics, and DG_6 is the wind turbine. Table 1 provides the maximum and minimum active power of the DG sources. Moreover, because the real power output of wind turbine generators and solar energy is inconstant and heavily dependent upon climate change, these generating units are operated at maximum power output extracted. In other words, the load flow analysis does not influence the real power output of these DGs. The cost coefficients of dispatchable DG units are listed in Table 2. The choice of the reactive droop slopes is determined as in [18], and these coefficients are shown in Table 3. Additionally, PSCAD software is deployed to carrying out time-domain simulations, and we have made a comparison between results obtained by both approaches.

Table 1. *Technical characteristics of installed DG sources*

DG	P_{min} (kW)	P_{max} (kW)	Q_{max} (kVAr)
DG_1	0	45	27,888
DG_2	0	30	18,592
DG_3	0	40	24,789
DG_4	0	45	27,888
DG_5	0	10	0
DG_6	0	10	0

Table 2. *Cost coefficients of quadratic cost functions*

DG	α	β	γ
DG_1	2.78	1.22	0.094
DG_2	1.63	3.41	0.078
DG_3	2.16	2.53	0.105
DG_4	3.39	4.02	0.082

It is assumed that predetermined tolerance values are equal to 0.1 kW and 0.1 kVAr, and bus 1 is aimlessly selected as the voltage reference bus. The microgrid frequency calculated by the proposed approach equals 49.544 Hz, and voltages, real power, and reactive power of DG units at equilibrium condition are revealed in Table 4. It is noticing that the different locations of the swing node all yield the same outcomes when applying the approach developed in this paper. Furthermore, the results of active power output attained by power flow incorporating droop control strategies integrating incremental cost are similar to those from the economic dispatch problem. Moreover, the calculated results using the proposed method closely match the results extracted using PSCAD software.

Table 3. *Droop coefficients m (V/kVAr)*

m_1	m_2	m_3	m_4
0.7	1.0497	0.7875	0.7

Table 4. *Voltages, Active and Reactive power of DG units*

DG	DG_1	DG_2	DG_3	DG_4
V (V)	369.8	365.4	367.1	361.3
P (kW)	32.221	24.792	22.067	19.863
Q (kVAr)	15.154	14.169	16.788	27.197

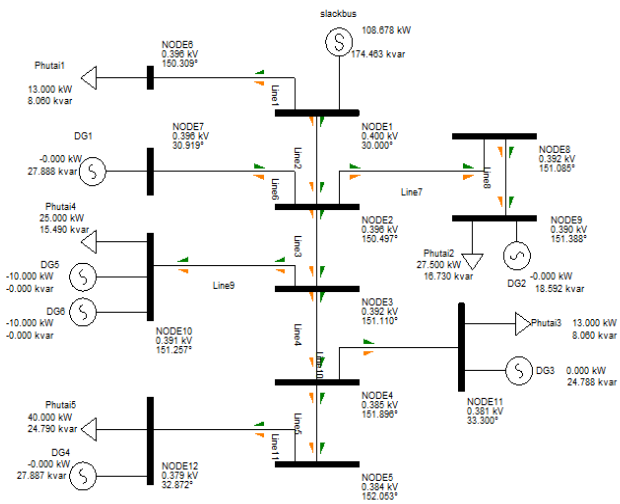

Figure 1. *A benchmark low voltage network for microgrid power flow study*

6. Conclusion

An efficient method proposed in this paper is leveraged to cope with the power flow problems for stand-alone microgrids that operate according to droop schemes incorporating cost using conventional power flow approaches. The proposed technique considers the absence of the slack bus in an autonomous microgrid and formulates the generator buses as the droop buses. This method is validated on a test system. A good agreement of the results indicates that the proposed method is accurate. The distinct advantage of the presented method is that it is very straightforward because it relies on conventional power flow methods. This characteristic helps the proposed approach to integrate into a piece of software for power system analysis easily, and it can be one of the beneficial tools for Distribution System Operators (DSOs) to operate independent microgrids.

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