Electric Power Components and Systems
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/uemp20

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Published online: 03 Aug 2015.

To cite this article: Alireza Raghami, Mohammad Taghi Ameli & Mohsen Hamzeh (2015) Online Droop Tuning of a Multi-DG Microgrid Using Cuckoo Search Algorithm, Electric Power Components and Systems, 43:14, 1583-1595, DOI: 10.1080/15325008.2015.1048907
To link to this article: http://dx.doi.org/10.1080/15325008.2015.1048907

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Online Droop Tuning of a Multi-DG Microgrid Using Cuckoo Search Algorithm

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Abstract—This article presents an intelligent strategy to achieve appropriate real power sharing among distributed generators in a microgrid. The presented strategy employs two droop-based control methods and automatically adjusts their parameters. The first method is unit power control, which has specifications similar to the conventional droop method, and the second is feeder flow control, showing significant characteristics in both grid-connected and islanded modes operation of a microgrid. A combination of unit power control and feeder flow control methods is used for a multi-distributed generator microgrid. The microgrid operation mode passes from the grid-connected to the islanded through a transition. A new evolutionary algorithm called cuckoo search is employed to coordinate the power management of distributed generators within an on-line droop tuning. In comparison to the predecessor evolutionary algorithms, the cuckoo search algorithm represents more effective random processes with fewer parameters. Using the proposed control strategy, while the distributed generators contribute to load demand provision based on their rated powers, their powers are optimized in terms of overshoot and settling time. Digital time-domain simulation studies are carried out in the MATLAB/SIMULINK (The MathWorks, Natick, Massachusetts, USA) environment to verify the performance of the proposed control system.

1. INTRODUCTION

Microgrids are able to harmonize rapid penetration of distributed generators (DGs) in the power system. This harmonization is dependent on proper policymaking, which can establish superiority of microgrids in comparison to the conventional power system. A part of these policies is made by representing powerful control strategies that guarantee a desirable power quality during operation modes of a microgrid. This comprises grid-connected mode, islanded mode, and transition between them [1].

The DGs connection in an AC-microgrid requires voltage source inverters (VSIs). VSIs enable different prime-mover technologies to be operated at a single frequency while they are flexibly controlled by suitable strategies [2]. The droop-based control methods are prevalent among the power-sharing
control strategies in microgrids. When DGs of a microgrid system are controlled based on the droop methods, the system stability significantly depends on the droop controller parameters [3–8]. However, an increase in the number of DGs turns the tuning of droop-controller parameters into a cumbersome trial-and-error process [9]. All approaches presented in [9–17] addressed the previously mentioned tuning as an optimization problem.

In [14], the colonial competitive algorithm (CCA) is employed to optimally design controllers where interaction among DGs, energy storage systems, and loads is emulated by a cooperative game theory. Frequency and voltage are controlled in a favorite range. There, the controlling signals are made by artificial neural network working as microgrid central controller (MGCC). In [15], a particle swarm optimization (PSO) technique is used to schedule the droop and proportional–integral (PI) controller parameters of DGs of a microgrid. A combination of fuzzy logic and PSO techniques was applied in [9] to regulate the frequency of an autonomous microgrid. The frequency deviation is the input of the PSO algorithm, which adjusts the fuzzy function, and the PI controller parameters are the output of fuzzy controller. In [10], the differential evolution (DE) technique was used to ensure the stability of a system with two inverter-interfaced DGs. In [11], the PSO algorithm was employed to regulate the PI controller parameters of two VSIs in an autonomous microgrid. A central controller was employed in [12] to determine the droop and PI controller parameters of dispatchable DGs of an autonomous microgrid. The bacterial foraging optimization (BFO) method is used to adjust the controller parameters. Generally, in [9–13], controllers were utilized with a search technique to minimize an error cost function.

This article proposes an on-line control strategy which coordinates the real power sharing in a microgrid with multiple dispatchable inverter-based DGs. DGs are configured in multiple series and parallel feeders to resemble a practical microgrid. Two droop methods, namely unit power control (UPC) and feeder flow control (FFC) strategies, are employed for power management in the microgrid. The article puts forward a strategy to adjust FFC and UPC controller parameters. In this respect, multiple FFC-controlled DGs with series configurations has been investigated in [18]. Their analysis demonstrates that the change of operating mode from grid-connected to islanded condition can challenge the objective of the FFC method. They met the challenge by redefining FFC droop gains.

In this article, the droop-controller parameters are determined within a real-time self-tuning optimization approach. Using the proposed control strategy, while the DGs contribute to load-demand provision based on their rated powers, their powers are optimized in terms of overshoot and settling time. A new evolutionary algorithm is employed, namely cuckoo search (CS), to handle the optimization problems. The CS algorithm enjoys the advantage of fewer set parameters compared with the predecessor evolutionary algorithms. The CS algorithm has strong search capacity by means of more effective random processes. Since the stability of a microgrid is highly dictated by the power-sharing controller [19], meticulous research has been launched on the small-signal analysis of the microgrid [20]. In this article, the small-signal stability of the microgrid has been certified around a unique range of droop gains that are addressed as the constraints of the optimization problem.

The remainder of this article is organized as follows. The UPC and FFC methods are described in details in Section 2. Section 3 represents the structure of the proposed control strategy and the specifications of the CS algorithm as compared to the renowned metaheuristic algorithms. Then a test system is employed in Section 4, followed by time-domain numerical simulation results to validate the capability of the proposed strategy. Finally, in Section 5, the remarkable points of this study are outlined.

2. UPC AND FFC METHODS

The Consortium for Electric Reliability Technology Solutions (CERTS) introduced UPC and FFC methods in [21, 22]. Figures 1(a) and 1(b) illustrate the structure of a simple microgrid for which the DG is controlled via the UPC and FFC method, respectively. The droop characteristic of the DG with the UPC method is expressed as [22]

\[ \omega' = \omega^0 - K^U (P' - P^0), \]  

where \( \omega^0 \) and \( \omega' \) are the frequency of the DG unit in the initial and new operating points, respectively. \( P^0 \) is the set-point of DG real power, and \( P' \) is its value at the new operating point. \( K^U \) is the droop gain of the UPC method, which is defined as follows:

\[ K^U = \frac{\Delta \omega}{P_{\text{max}}}, \]  

In Eq. (2), \( \Delta \omega \) is the permissible frequency deviation, deemed to be about 1% of the rated frequency, and \( P_{\text{max}} \) is the maximum power of the DG [23]. In the grid-connected mode, the main grid guarantees constancy of the frequency, and according to Eq. (1), the output power of the DG is held steady at the set-point. Following the transition to the islanded mode, the new operating point is a function of the previous operating point of the microgrid. Based on the power exchange status of grid-connected operation, there are two different
FIGURE 1. Simple microgrid with DG controlled using: (a) UPC method and (b) FFC method.

situations, as shown in Figure 2(a) [22]. Any changes in the island load would be supplied following a frequency change.

The feeder flow ($F_L$) and microgrid frequency ($\omega$) in the FFC method are related by

$$\omega' = \omega^0 - K_F (F_L' - F_L^0),$$  \hspace{1cm} (3)

where $K_F$ is the droop gain of the FFC method. $F_L^0$ is the desired value of the feeder flow, and $F_L'$ is its value in the new operating point. As can be seen in Figure 1(b), the load demand ($P_{loads}$) is equal to the sum of the feeder flow ($F_{line}$) and the DG power ($P_{DG}$):

$$F_{line} + P_{DG} = P_{loads}$$  \hspace{1cm} (4)

It can be concluded from Eqs. (1), (3), and (4) that $K_F$ and $K_U$ are equal in absolute value, whereas there is a minus sign as difference:

$$K_F = -K_U.$$  \hspace{1cm} (5)

In grid-connected operation, the FFC-controlled DG adapts its output to regulate the power exchange with the main grid at the desired value, while the frequency is preserved by the main grid [22]. Once the microgrid shown in Figure 1(b) becomes islanded, the new operating point depends on the power exchange with the main grid in the grid-connected operation. Figure 2(b) demonstrates the different conditions of the transition. According to Eq. (3), the frequency is preserved constant during the islanded operation in the FFC method.

Figure 3 depicts the flowchart of the UPC and FFC methods for the microgrids of Figure 1. In Figure 3, $\delta_V$ is the voltage angle of the DG terminal. The highlighted blocks emphasize the main differences of the methods. In grid-connected operation, when the FFC method is applied, the power exchange of the microgrid and the main grid can be desirably regulated. If the microgrid operation alters to the islanded mode, the frequency is kept at a fixed value.

It is worth mentioning that the basic UPC and FFC methods are categorized as the primary real power-frequency control and cannot restore the microgrid frequency. Another important point is the cooperation of the dispatchable DGs. Once the UPC and FFC methods are implemented, the FFC-controlled DG undertakes any load change in its downstream feeder. The previously mentioned characteristic is unlike control strategies in which all DGs take part in responding to a load demand [24].
As recommended by CERTS scientists [21, 22], the UPC method suits nurturing applications of the DGs in the combined heat and power (CHP) systems where DG electricity generation obeys the timely heat demands. In fact, the function of the UPC-controlled DGs is complemented by FFC-controlled DGs, which supply the electrical load variation [18]. The subject of this article is enhancing the combinatory application of the UPC and FFC methods to prevent real power oscillation.

3. PROPOSED CONTROL STRATEGY

The proposed structure of the controller is depicted in Figure 4. In Figure 4(a), the MGCC gathers the DGs local information via the low-pass filters (LPFs) and sends back orders complied with the boundary limits. The proposed controller is based on an optimization plan.

As illustrated in Figure 4(b), the DG output power and the flowing power in the DG’s upstream feeder are the controller inputs and the angular frequency is the output. Moreover, a frequency feedback forms the other input of the control system. For each DG of the microgrid, either Eq. (1) or Eq. (2) is implemented through the droop-control module, as shown in Figure 4(b). The output limit control module is designed to enforce the DG rated power. The most prominent part of the proposed strategy is the droop-tuning module for which the inputs are the DG real power and the frequency. Once the FFC method is employed, $K_F$ is the output of the module, whereas with the UPC method, $K_U$ is the output. The droop-controller parameters are decision variables of an optimization problem. The power quality issues and the power sharing cri-
terion are considered in the cost function of the optimization problem.

Numerous decision variables and non-uniform sample space of the microgrid operations demand a global search technique. Therefore, the CS algorithm, which is a free derivative algorithm, is useful for this application. It should be noted that the CS algorithm outshines its renowned rivals in the realm of metaheuristic algorithms. Genetic algorithms (GAs) and PSO algorithms have been its rivals.

3.1. CS Algorithm

The capability of metaheuristic algorithms comes from imitating outstanding nature behaviors as a result of a long time evolution. The CS algorithm has been inspired from the breeding behavior of cuckoo birds and the flying pattern of some animals in 2009 [25]. Cuckoos are fascinating birds, not only because of their beautiful sound but also they have a strange aggressive breeding behavior. Some of them, such as the Ani and Guia species, lay their eggs in other birds’ nests. Consequently, some host birds come into conflict with the intruding eggs. It is possible to throw away the eggs that are not identical to their own or totally leave their nest and build a new nest somewhere else [26].

Two specifications of metaheuristic algorithms are intensification and diversification. Intensification works around selecting the best candidates and searching around the best. Diversification guarantees to effectively search the sample space. Random processes play an important role in these specifications. The basics of random processes are random movement. Famous distribution of stochastic and probability are applied to implement the random movement. In this article, random movement is based on levy distribution [27]. Many birds and monkeys search for foods according to Levy flights [28, 29]. The variance of Levy flight is expressed as

\[ \sigma^2(t) \sim t^{3-\beta}, \]

where \( 1 \leq \beta \leq 2 \) is an index typically set to 1. Unlike any other statistical method with linear variance, rapid growth of Eq. (6) enables the CS algorithm to effectively search large and unknown sample spaces [27]. Generating random numbers by Levy flight is comprised of selecting direction and generating steps. Uniform distribution and Mantegna distribution are usually employed for generating direction and steps, respectively [30]. It yields a symmetric and effective Levy distribution. Step length is calculated as

\[ s = \frac{u}{|v|^{1/\beta}}, \]

here, \( u \) and \( v \) can be obtained from the normal distribution as follows:

\[ u \sim N \left( 0, \sigma_u^2 \right), \quad v \sim N \left( 0, \sigma_v^2 \right) \]

where

\[ \sigma_u = \left\{ \frac{\Gamma(1+\beta) \sin(\pi \beta/2)}{\Gamma((1+\beta)/2) 2^{(\beta-1)/2}} \right\}^{1/\beta}, \quad \sigma_v = 1. \]

For a cuckoo nest with index \( i \), the Levy distribution is applied to generate the new answer \( x_i^{(t+1)} \) from the former generation \( x_i^{(t)} \):

\[ x_i^{(t+1)} = x_i^{(t)} + \alpha \oplus \text{Levy}(s), \]

where \( \alpha \) is a multiplier set based on the problem scale. The essence of Eq. (10) is random movement for which the next position is a function of the initial point and the position alteration rate.

3.2. Cost Function

All design concerns and challenges are addressed in the cost function. With an increase in the excellence of the cost function, its value is proportionally decreased. In the grid-connected operation, while the local load is provided based on the specifications of the UPC and FFC methods, the favorite value of the power exchange with the main grid must be preserved. Within the islanding transition, DGs are loaded up to compensate the previously imported power from the main grid. The loading change of each DG should adapt DGs’ relative rated power. From then on, the total load of the autonomous microgrid must be provided.

Once a load change occurs in the microgrid, the overshoot and the settling time of DGs’ power should be controlled in the reasonable ranges. Therefore, the following criteria are considered:

- the output power of DG units should be effectively controlled and
- the frequency should be regulated at the permissible ranges.

To satisfy these criteria, following indices are taken into account: (1) fast reaction of FFC-controlled DGs to the flow fluctuation of the upstream feeder, (2) power sharing among DGs in the mode transition period, and (3) load tracking and power sharing during the autonomous operation.

Error integrating function is the most related cost function. It can be implemented in four ways: (1) by the integrating time square error (ITSE), (2) by the integrating square error (ISE), (3) by the integrating absolute error (IAE), and (4) by the integrating time absolute error (ITAE). Based on previous studies [31, 32], the ITAE is the most appropriate, employed.
here as

\[
F = 4 \sum_{i=1}^{4} t^i f^i + \sum_{i=1}^{4} x (t - t^i_0) (st^i) + y \Delta f \\
+ 3 \sum_{i=1}^{3} z (t - t^i_0) [loading^i - loading^{i+1}]
\]

Subject to: 49.5 \leq f \leq 50.5

\[
\text{Min}_i \leq P_{DGi} \leq \text{Max}_i (1 \leq i \leq 4)
\]
\[
\text{min} \leq Droop_{DGi} \leq \max (11)
\]

where \( F \) is a function of time \( t \) to consider both the transient and the steady-state responses of the microgrid. Here \( i \) is the index term of the DG units. \( t^i_0 \) and \( t^i_f \) are the start and the stop times of the cost function calculation, respectively. \( w, x, y, \) and \( z \) are used as the weighting coefficients to emphasize a special term of \( F \). \( os^i \) and \( st^i \) represent the overshoot and the settling time of the DGs power, respectively. \( \Delta f \) introduces the maximum frequency deviation, which results from the transition to the islanded operation. The last term of \( F \) minds the proper loading of DGs during islanding. Furthermore, the frequency deviation is permitted to be around 1% by the power quality constraints [33]. The DG power limitation is implemented by the output limit control module in Figure 4. The feasible range of the droop gains is dictated by the stability studies.

3.3. Termination Criteria

When metaheuristic algorithms are employed to figure out an optimization problem, the termination criteria should be set to bring the repetitive solving process to a halt. Some studies take a maximum time duration for the process into account, and others define an acceptable error between the two consecutive values of the cost function [31]. In this article, a maximum value of the cost function and a maximum number of the iteration are employed as the termination criteria.

The flowchart of the applied CS algorithm is depicted in Figure 5. The CS algorithm can be described using three idealized rules: (1) each cuckoo lays one egg in any generation and dumps it in a randomly chosen nest, (2) the best nest with the highest quality eggs will be carried over into the next generation, and (3) the number of host nests is fixed and the alien cuckoo eggs might be found and thrown away with a probability of \( pa \).

Any egg in each nest represents a solution (every nest in Figure 5 consists of \( d \) eggs, which are decision variables of the optimization problem). Cuckoo eggs are supposed to be the superior solution, and they are applied to replace the inappropriate eggs. Finally, the eggs of the best nest would represent the optimized values of the decision variables.

![Flowchart of the applied CS algorithm](image)

Recent studies illustrate that the CS algorithm can outperform the previous metaheuristic algorithms in the sense of an identical optimization problem [32]. The relative merits of the CS algorithm are weighed up versus the GA and PSO algorithms in what follows [31–34].

1. The CS algorithm uses a kind of population-based elitism similar to the harmony search algorithm. CS is more immune to metaheuristic algorithms sensitivities, including sensitivity to the starting point selection and the sensitivity to the set parameters adjustment. The CS algorithm’s convergence with high-quality solutions is certainly certified compared to the GA and PSO algorithms.

2. Employing Levy distribution in the CS algorithm leads to more effective random processes. Consequently, the
FIGURE 6. Studied microgrid with four dispatchable electronically coupled DG units.

likelihood of getting trapped on the local optimum is noticeably decreased as compared to GA. Moreover, by means of Levy, the CS algorithm benefits from a faster searching process comparing to the PSO algorithm.

(3) Despite its predecessors, the CS algorithm has just two set parameters: population size ($n$) and nest percentage to be destroyed ($p_a$). The set parameters number turns to six for the GA and PSO algorithms. Turning fewer parameters saves time.

4. SIMULATION RESULTS AND ANALYSIS

To investigate the effectiveness of the proposed control strategy, the microgrid system of Figure 6 is simulated in the MATLAB/SIMULINK (The MathWorks, Natick, Massachusetts, USA) environment. The test system presented in [18] is slightly modified to gain a more practical microgrid system. The microgrid consists of four local RL loads and four DGs. Energy storage devices with fast responses are utilized on the DC side of the DG inverters. Accordingly, the inverters switching and the primary source dynamic can be exempt without any inaccuracy in the succeeding models [24]. Such energy storage assures swift absorption and generation of power surplus and power shortage, respectively, in the autonomous microgrid [14].

DG2 and DG3 are installed on a single feeder with a series configuration, and DG4 is installed on another single feeder in parallel with the former feeder. The result of the two parallel feeder is installed in series with DG1 on the last feeder. DG1 and DG3 are equipped with the FFC method, while DG2 and DG4 are equipped with the UPC method. $F_{lref}$ of DG1 and DG3 are set to 100 and 43 kW, respectively. The initial power references of DG2 and DG4 are set to 34 and 15 kW, respectively. The microgrid is initially operated in the grid-connected mode. At $t = 3.0$ sec, the microgrid is disconnected from the main grid. Each DG has a droop gain for which sample space is considered between 0.01 and 100 Hz/MW to assure system stability.

4.1. Simulation Results without the Optimized Droop Gain Scheduling

Using Eqs. (2) and (5), $K_F^*$ values are set to $-8$ and $-10$ Hz/MW, respectively, for DG1 and DG3. $K_U^*$ values are set to 6.7 and 10 Hz/MW, respectively, for DG2 and DG4. These values are employed for the DG controllers; however, they have not been adapted to the dynamic response of the microgrid.

The DG real power, feeder flowing power, and microgrid frequency are illustrated in Figure 7. As shown, the neglected droop adaptation adversely affects the response time of DGs. In the grid-connected mode, the UPC-controlled DGs (i.e., DG2 and DG4) slowly reach their reference power (34 and 15 kW,
FIGURE 7. Results of droop gain scheduling without optimization: (a) real power of DGs, (b) flowing power in the feeders, and (c) microgrid frequency.

respective). Moreover, the FFC-controlled DGs (i.e., DG1 and DG3) fail to regulate their feeder flows (100 and 43 kW, respectively). At $t = 3$ sec, the inter-tie breaker is opened. Afterward, a steep fall and rise of the frequency is observed between $t = 3.05$ to 3.1 sec; this is due to the reaction of the output limit module to the violation of DG1’s rated power (62.5 kW). As shown in Figure 7(c), the frequency of the islanded microgrid is regulated at 49.85 Hz by the FFC droop controller of DG1. However, the DG powers of the islanded microgrid fluctuate, and they are in deep trouble of instability. In fact, the power sharing is not proportional to DG rated powers during the operation mode transition. Although the DG1 rated power is greater than the DG3 and DG4 rating, after the transition, the DG1 generation is lowered, while the DG3 and DG4 generations are raised.

FIGURE 8. Sensitivity analysis of CS algorithm: (a) number of nests variation ($n$) and (b) variation of destruction probability ($pa$).

<table>
<thead>
<tr>
<th>Best CS algorithm parameter</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Destruction probability of alien eggs ($pa$)</td>
<td>0.2</td>
</tr>
<tr>
<td>Number of nests ($n$)</td>
<td>10</td>
</tr>
</tbody>
</table>

TABLE 1. Applied CS algorithm parameters
4.2. Simulation Results with the Optimized Droop Gain Scheduling

For determining $n$ and $pa$ parameters of the CS algorithm, a kind of sensitivity analysis is performed through testing various numbers of nests ($n = 5, 10, 20, \text{and} 40$) and different destroying probabilities ($pa = 0.1, 0.2, 0.3, \text{and} 0.4$). As shown in Figure 8, the CS algorithm sensitivity to the parameters changes is low; therefore, there is no need for fine tuning. Table 1 summarizes the CS algorithm parameters leading to the best result.

From the viewpoint of cost function convergence, Figure 9 lends credible support for the CS algorithm selection compared to the GA and PSO algorithms (i.e., the rivals). To implement the rivals, the guidelines in [31] have been employed. Parameter values of Table 1 are used for the CS algorithm in Figure 9, and the rivals have benefitted from the finest parameters tuning. These values are presented in Table 2, and some points are worth mentioning here.

First, a larger number of the tuning parameters besides more sensitivity makes the rival algorithms tuning more time consuming compared to the CS algorithm. Second, close scrutiny of Figure 9 reveals that GA gets trapped in local optimum. In addition, although the PSO algorithm reaches in the vicinity of the CS algorithm optimum point, the CS algorithm outshines with faster convergence. Table 3 presents the global optimum values obtained by the CS algorithm.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>GA</th>
<th>PSO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crossover probability (normal)</td>
<td>0.8</td>
<td>Initial velocity</td>
</tr>
<tr>
<td>Crossover probability (mathematical)</td>
<td>0</td>
<td>Minimum inertia constant</td>
</tr>
<tr>
<td>Mutation probability (elimination)</td>
<td>0.7</td>
<td>Maximum inertia constant</td>
</tr>
<tr>
<td>Mutation probability (normal)</td>
<td>0.5</td>
<td>Cognitive coefficient</td>
</tr>
<tr>
<td>Mutation probability (the most suitable)</td>
<td>0.5</td>
<td>Cognitive coefficient</td>
</tr>
<tr>
<td>Population size</td>
<td>10</td>
<td>Population size</td>
</tr>
</tbody>
</table>

**TABLE 2. Parameters values of the applied GA and PSO algorithms**

**FIGURE 9.** Performance evaluation of various solving algorithms.

**FIGURE 10.** Trend of CS algorithm performance with $pa = 0.2$ and $n = 10$: (a) cost function changes and (b) control parameter changes.
TABLE 3. Global optimum values of the control parameters

<table>
<thead>
<tr>
<th>Control parameter</th>
<th>Droop gain values (Hz/MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Droop gain of DG1</td>
<td>20</td>
</tr>
<tr>
<td>Droop gain of DG2</td>
<td>69</td>
</tr>
<tr>
<td>Droop gain of DG3</td>
<td>79</td>
</tr>
<tr>
<td>Droop gain of DG4</td>
<td>98</td>
</tr>
</tbody>
</table>

Figure 10 shows the process of the parameters convergence toward the global optimum values. The results of the time-domain simulation are depicted for the microgrid using the proposed control strategy in Figure 11. In the grid-connected mode, DG1 and DG3 successfully regulate their under control feeders flow at 100 and 43 kW, respectively. Furthermore, DG2 and DG4 produce the favorable values of 34 and 15 kW, respectively.
When the islanding occurs at \( t = 3 \) sec, all DGs increase their power to compensate the power reduction resulting from the separation of the main grid. The ratio of real power changes of DG2:DG1:DG3:DG4 is 1.6:1.25:1:1:1, which is almost the same as the ratio of DG rated powers (1.5:1.25:1:1). The dynamic responses of the DGs are totally free of overshoot and demonstrate swift adaptation. The frequency of the islanded microgrid remains within the permissible limits of 1%, because DG1 is controlled by the FFC method.

4.3. Robustness of the Proposed Control Strategy Against Load Variations

To demonstrate the robustness of the proposed control strategy in terms of variation in operating conditions, two abrupt changes in Load3 are considered. The whole operation process is the same as previous cases except for two load change contingencies.

Because of using the FFC method for DG1, the power exchange of the microgrid and the main grid is preserved at the set-point of 100 kW. At \( t = 2.5 \) sec, Load3 is suddenly decreased from the initial demand of 65 kW and 30 kVar to 45 kW and 20 kVar. As shown in Figure 12, the load changes are responded to by DG3, which is controlled based on the FFC method. Another change occurs at \( t = 3.5 \) sec, when the microgrid is operated as an islanded system. At this time, Load3 is increased to 60 kW and 25 kVar. Consequently, DG3 generates more power and prevents other DG intervention. In the islanded mode condition, DG1 preserves the microgrid frequency at 49.68 Hz, which is within the permissible range.

5. CONCLUSION

This article presents a novel intelligent power sharing strategy for a multi-DG microgrid. The UPC and FFC methods are employed to control the real power of DGs with combined series and parallel configurations. A complete operation mode is studied, including grid-connected, islanded, and the transition between them. Findings of this research can be itemized as follows.

- The FFC method is more advantageous for the main grid and the microgrid compared to the UPC method. In the FFC method, the DG matches the demand variation of downstream loads to regulate the neighbor feeder flow at the desired value. If an FFC-controlled DG is employed at the inter-tie breaker point, the power exchange of the microgrid and the main grid can be favorably regulated.
- Simulation results demonstrate the merits of the droop-based power sharing methods as a function of values of the droop parameters. A powerful on-line droop tuning can successfully figure out the values as demonstrated in this article.
- The CS algorithm has been used at the droop-tuning module. Fewer tuning parameters, lower sensitivity to the parameter alteration, and stronger converging ability make the CS algorithm the superior choice among metaheuristic algorithms. The obtained results prove this assertion.
- The power management objectives are addressed in an optimization process. Acceptable overshoot and settling time were accounted for DG power, while each DG was playing part in the microgrid generation capacity according to its relative rated power. Constraints were considered to keep the microgrid operation in the stable region.
- The proposed control strategy can effectively share the real power among DGs, even in a microgrid with complicated configuration, while the frequency is preserved within the permissible range. In fact, the presented strategy is more accurate and practical than other methods that employ linearized models of microgrids, since the controller parameters directly participated in the simulation of the non-linear models.

REFERENCES


**BIOGRAPHIES**

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