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Dynamic Economic Dispatch Solution for a Microgrid Using Improved Ant Colony Optimization

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Abstract

This paper presents a novel approach for dynamic economic dispatch in a MicroGrid by using the improved ant colony optimization (ACO). In order to satisfy the power balance and load demand, the mathematical model of economic dispatch is given to support the MicroGrid in both grid-connected and islanded mode. By means of ACO, the dynamic economic dispatch solution is proposed in combination with sequential quadratic programming (SQP), and the essential procedure is introduced. Simulation results demonstrate the feasibility and benefits of the proposed scheme.

***Keywords**: economic dispatch, microgrid, ant colony optimization, distributed generation*

1. Introduction

MicroGrid is an important part of smart grid, which can supply electricity and heat energy to the user by utilizing distributed generation units according to certain standards [1]. All kinds of distributed generation units, loads, energy storages, and control devices are combined into a single controlled unity and able to keep supplying power to the user in case of disconnecting to utility grid [2-3]. In MicroGrid, economic dispatch plays a crucial role and determines the optimal output of a great deal of micro generation units in a short term so as to satisfy the loads at the lowest possible cost [4-5]. However, since the renewable energy has the dynamical intermittency and sporadic randomness, it is challenging to perform economic dispatch in the MicroGrid.

The research of economic dispatch in MicroGrid has been carried out in the optimized management of both the supply side (for example, multi-objective approach for optimal control [6], load-sharing control strategy [7], and multi-agent system [8]), and energy storages (e.g., optimal operation of biomass combined heat and power [9], multi-objective operation management [10], and hierarchical agents [11]). Demand side management is also studied by introducing novel upcoming technologies [12-13]. In addition, swarm intelligence methods are emerging to be applied into economic dispatch for the MicroGrid in recent years [14-15], which have been proved to be a useful and effective way in traditional economic dispatch [16-17].

In this paper, we propose a dynamic economic dispatch solution for a MicroGrid based on the improved ACO. The goal is to find out the optimal composition of micro generation units to support the load and power balance, by means of ant foraging behaviour and probability selection skills according to the pheromone. We establish a mathematical model of economic dispatch under the running constraints of power exchange and micro generation units, in order to minimize the total cost of power generation. Combined with SQP, we improve ACO algorithm to solve the problem of

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dynamic economic dispatch in a MicroGrid, for ensuring the overall convergence while maintaining the local convergence. Simulations illustrate the feasibility and effectiveness of the proposed approach.

2. MicroGrid Structure

The MicroGrid structure studied in this paper is shown in Figure 1, which consists of photovoltaic (PV), wind turbine (WT), micro turbine (MT), fuel cell (FC), battery (BT), other distributed generation unites (DG) and loads with different capacities and characteristics.

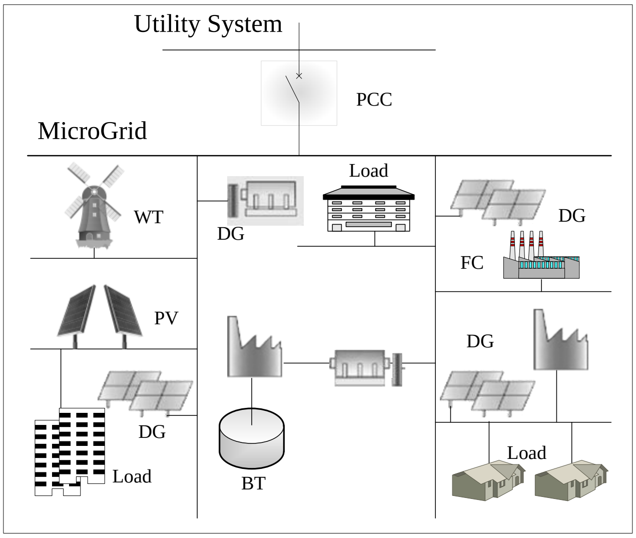

Figure 1. A Typical MicroGrid Structure with loads and Micro Generation Units

In this structure, there is an electrical connection point to the utility system named point of common coupling (PCC). When the PCC is in grid-connected mode, the MicroGrid can exchange the power with utility system. If the power in the MicroGrid cannot meet the loads and balance needs, the MicroGrid will purchase the electricity from the utility system. On the contrary, the MicroGrid will sell the surplus power to get some income from the utility system. When the PCC is in disconnected mode (islanded mode), the MicroGrid is operating by itself and the power are generated by the cooperation of micro generation units.

3. Mathematical Model of Economic Dispatch in MicroGrid

The target of dynamic economic dispatch in MicroGrid is to adjust the output power for the existing distributed generation units in order to meet power balance and load demand, while minimizing the emission. Since there are two modes of MicroGrid, we discuss the model from two different aspects, that is, grid-connected mode and islanded mode.

3.1. Proposed Objective Function

3.1.1. Grid-connected Mode: In this context, the MicroGrid is connecting to the utility system through the PCC and the difference between load demand and output power by micro generation units can be balanced dynamically. Therefore, the MicroGrid can buy some power from the utility system when the generated power is not enough to satisfy the load demand. The MicroGrid can also sell the spare power to the utility system to get the income. The objective function of operating cost is defined as:

$$F = \min\{\sum_{k=1}^{T}\Delta t_k[\sum_{i=1}^{N}(CF_i + COM_i) + CB_{i,k} - CS_{i,k}]\} \tag{1}$$

where T is the total operating time of MicroGrid, N is the total number of generating units and Δt_k is the duration of time interval k. CF_i means the fuel cost of the micro generation unit i while COM_i denotes the operation and maintenance cost of the micro generation unit i. $CB_{i,k}$ stands for the purchased electricity of the micro generation unit i in Δt_k if the load demand goes beyond the generated power, and $CS_{i,k}$ implies the income from sold electricity of the micro generation unit i in Δt_k if the generated power is too much for the load demand.

The fuel cost of CF_i is computed by:

$$CF_i = KF_{i,k} \times P_{i,k} \tag{2}$$

where $KF_{i,k}$ is the fuel coefficient ($/Kwh) of the micro generation unit i in Δt_k and $P_{i,k}$ is the generated power (Kwh) for the micro generation unit i in Δt_k.

The operation and maintenance cost of COM_i is calculated by:

$$COM_i = KOM_{i,k} \times P_{i,k} \tag{3}$$

where $KOM_{i,k}$ is the operation and maintenance coefficient ($/Kwh) of the micro generation unit i in Δt_k and $P_{i,k}$ is the same meaning as in Eq. 2.

The purchased electricity of $CB_{i,k}$ is computed by:

$$CB_{i,k} = KB_{i,k} \times PB_{i,k} \tag{4}$$

where $KB_{i,k}$ is the buying coefficient ($/Kwh) of the micro generation unit i in Δt_k and $PB_{i,k}$ is the bought power (Kwh) for the micro generation unit i in Δt_k.

The income from sold electricity of $CS_{i,k}$ is computed by:

$$CS_{i,k} = KS_{i,k} \times PS_{i,k} \tag{5}$$

where $KS_{i,k}$ is the buying coefficient ($/Kwh) of the micro generation unit i in Δt_k and $PS_{i,k}$ is the income (Kwh) for sold by the micro generation unit i in Δt_k.

3.1.2. Islanded Mode: Under this circumstance, the MicroGrid is disconnected to the utility system and controlled by MicroGrid itself as an islanded entity. No power is exchanged between MicroGrid and utility system through the PCC. Thus, the objective function of operating cost is defined as:

$$F = \min\{\sum_{k=1}^{T}\Delta t_k[\sum_{i=1}^{N}(CF_i + COM_i)]\} \tag{6}$$

where all the parameters are the same meanings as in Eq. 1 except removing the cost for purchasing power and the income for selling surplus power.

3.2. Equality Constraints

3.2.1. Grid-connected Mode: According to the charge-discharge of battery, there are two kinds of situations for power balance constraints, namely charging balance constraints and discharging balance constraints.

For charging battery, the power balance constraints are defined as:

$$P_{load} = \sum_{i=1}^{N} P_{i,k} - \alpha_{ch} P_{ch,k} + PB_{i,k} - PS_{i,k} \tag{7}$$

where P_{load} is the load power in MicroGrid, $P_{i,k}$ is the generated power (Kwh) for the micro generation unit i in k, $P_{ch,k}$ is the power for charging the battery, α_{ch} is charging efficiency coefficient, $PB_{i,k}$ and $PS_{i,k}$ are the same meanings as in Eq. 4 and Eq. 5.

For discharging battery, the power balance constraints are defined as:

$$P_{load} = \sum_{i=1}^{N} P_{i,k} - \alpha_{dis} P_{dis,k} + PB_{i,k} - PS_{i,k} \tag{8}$$

where all parameters are the same as in Eq. 7 except $P_{dis,k}$ is the power for discharging the battery and α_{dis} is discharging efficiency coefficient.

3.2.2. Islanded Mode

In islanded mode, MicroGrid cannot exchange any power with utility system, so it doesn' t need to consider purchasing power and selling power.

For charging battery, the power balance constraints are redefined as:

$$P_{load} = \sum_{i=1}^{N} P_{i,k} - \alpha_{ch} P_{ch,k} \tag{9}$$

where the parameters are the same meanings as in Eq. 7.

For discharging battery, the power balance constraints are redefined as:

$$P_{load} = \sum_{i=1}^{N} P_{i,k} - \alpha_{dis} P_{dis,k} \tag{10}$$

where the parameters are the same meanings as in Eq. 8.

3.3. Inequality Constraints

The constraints of micro generation units, buying and selling electricity, and charging and discharging battery constitute the inequality constraints in MicroGrid.

3.3.1. Inequality Constraints for Micro Generation Units

$$P_{i,k}^{\min} \le P_{i,k} \le P_{i,k}^{\max} \tag{11}$$

where $P_{i,k}^{\min}$ and $P_{i,k}^{\max}$ are the minimum and the maximum operating power of the micro generation unit i.

3.3.2. Inequality Constraints for Buying and Selling Electricity

$$PB_{i,k}^{\min} \le PB_{i,k} \le PB_{i,k}^{\max} \tag{12}$$

$$PS_{i,k}^{\min} \le PS_{i,k} \le PS_{i,k}^{\max} \tag{13}$$

where $PB_{i,k}^{\min}$ and $PS_{i,k}^{\min}$ are the minimum buying and selling electricity from/to utility system while $PB_{i,k}^{\max}$ and $PS_{i,k}^{\max}$ are the maximum buying and selling electricity from/to utility system.

3.3.3. Inequality Constraints for Charging and Discharging Battery

$$P_{bt,k}^{\min} \le P_{bt,k} \le P_{bt,k}^{\max} \tag{14}$$

$$E_{bt,k}^{\min} \le \left| E_{bt,0} - \sum_{k=1}^{j} P_{bt,k} T \right| \le E_{bt,k}^{\max} \tag{15}$$

where $P_{bt,\min}$ and $P_{bt,\max}$ are the minimum and the maximum charging/discharging efficiency. $E_{bt,k}^{\min}$ and $E_{bt,k}^{\max}$ are the minimum and the maximum battery capacity.

4. Dynamic Economic Dispatch Solution for a MicroGrid

The ACO algorithm is a heuristic method to look for the shortest path by imitating ant foraging behaviour [18]. By means of ACO algorithm, we explore the dynamic economic dispatch in MicroGrid in combination with SQP. In our approach, the ant path should be found out to describe a kind of micro generation unit composition that meets a certain operation state, and then the economic dispatch problem is solved by SQP.

4.1. ACO Algorithm

Through pheromone, ants can perform indirect communication with each other. Each ant drops the pheromone in the passing road and this behaviour has positive feedback of enhancement to make all the ants finally choose the shortest path. There are two critical factors to achieve such goal, that is, moving probability and pheromone update.

4.1.1. Moving Probability: Moving probability is used to express the probability that the ant moves to the next micro generation unit, defined as:

$$p_{ij} = \begin{cases} \dfrac{[\tau_{ij}(t)]^{\alpha}[\eta_{ij}(t)]^{\beta}}{\sum_{j \in N_n}[\tau_{ij}(t)]^{\alpha}[\eta_{ij}(t)]^{\beta}} & if \ j \in N_n \\ 0 & \end{cases} \tag{16}$$

where p_{ij} is the moving probability of the ant from the micro generation unit i to the micro generation unit j . N_n is the set of unvisited neighbour nodes. $\tau_{ij}(t)$ is the pheromone of the micro generation unit j . $\eta_{ij}(t)$ is the cost from the micro generation unit i to the micro generation unit j . α and β stand for the weights of different parameters.

It can be seen from Eq. 16 that the more the ants walked across the path, the more the pheromone will be in this path. And the solution performance is also improving dynamically. We use the roulette wheel type selection to decide where to go next for the ant to avoid local optimization.

4.1.2. Pheromone Update: We take the local and whole pheromone update mechanism here. On one hand, the local pheromone update ensures the pheromone in the path evaporating over time. On the other hand, the whole pheromone update keeps the shortest path accumulating more pheromone.

The passing path should be updated by local pheromone mechanism when one ant finishing a complete solution in an iteration process, defined as:

$$\tau_i(t+1) = (1-\rho)\times\tau_i(t), \ \ 0<\rho<1 \tag{17}$$

where $\tau_i(t)$ is the pheromone in the micro generation unit i at t moment and ρ is a coefficient of evaporation.

The local pheromone update is to let the following ants find out more different solutions in order to get a better solution for micro generation unit composition.

After all the ants in every iteration have established their own complete solution, the path with the optimal solution should be updated its pheromone once again (that is, a micro generation unit combination meeting a certain operation state), defined as:

(18) $$\tau_i(t+1) = \tau_i(t+1) + \frac{Q}{\min\{F_k, k \in N\}}$$

where Q is a parameter with positive value, N is the number of ants and $\min\{F_k, k \in N\}$ means the optimal composition of micro generation units in the iteration at t moment.

4.2. Combining ACO with SQP

SQP is one of the great solutions to handle the small and medium scale of nonlinear programming problem and has been used in many fields [19]. It generates the optimal solution by transforming the original problem into a series of quadratic programming. It can improve the approximation degree of the quadratic programming sub-problem and also be applied to strong nonlinear optimization problem.

The basic idea of the SQP method is to calculate the optimal solution by simplifying the original problem of nonlinear programming to a quadratic programming problem in some approximate solutions. If it has the optimal solution, then this solution will be considered as the optimal solution of the original nonlinear programming problem. Otherwise, repeat the process by replacing the current solution with a new approximate solution.

After each iteration, the economic dispatch is computed by SQP for each ant. Each path is a possible micro generation unit combination meeting a certain operation state. By SQP, the approach can not only have the overall convergence, but also ensure the local convergence.

4.3. Key steps of the improved Approach

According to the above analysis, we summarize the essential procedure of the proposed approach for dynamic economic dispatch in MicroGrid as below.

Step1: System initialization. Initialize pheromone for all the micro generation units and the related parameters.

Step2: Find out all the micro generation unit compositions that meeting the constraint conditions, and let the ants carry out their searching for optimal solutions.

Step3: Construct the complete initial solution by SQP.

Step4: Choose the next step for ants by moving probability and the roulette wheel type selection.

Step5: Repeat step 4 until all the ants have updated their next steps.

Step6: Compute the optimal solution for each ant by SQP.

Step7: Perform pheromone update, including the local and the whole pheromone update.

Step8: Stop when it meets the end condition. Otherwise, go to step 4.

5. Simulation Results and Discussion

To validate the feasibility and effectiveness of the proposed approach, two case studies are carried out for dynamic economic dispatch in a MicroGrid. One is based on grid-connected mode and the other is based on islanded mode. The MicroGrid is used to supply power for a factory in America, which encompasses PV, WT, MT, FC, and BT. We don't consider the start-up cost here due to its little influence on the results.

5.1. Parameter Setting

The characteristics of micro generation units in MicroGrid are given in Table 1. Natural gas is applied as the basic fuel for power generation with the fuel coefficient $KF_{i,k} = 0.06\$/Kwh$. The maximum buying electricity $PB_{i,k}^{\max}$ and the selling electricity $PS_{i,k}^{\max}$ with the utility system are limited within 200 Kw. The efficiency coefficients of α_{ch} and α_{dis} are set to 0.85. We choose some typical days in summer as the study objects and the prediction chart of PV, WT and load is shown in Figure 2.

Table 1. Characteristics of Micro Generation Units

Type	PV	WT	MT	FC	BT
Capacity (Kw)	50	200	200	200	150
OM cost ($/Kwh)	0.005	0.01	0.01	0.02	0.005

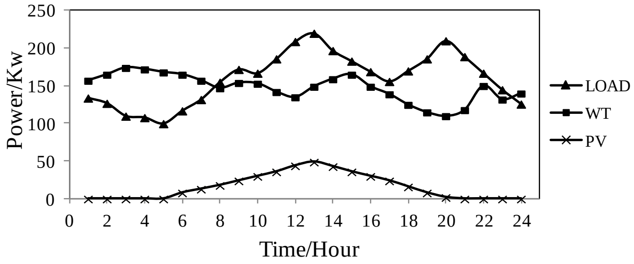

Figure 2. Prediction chart of PV, WT and Load

In our simulations, the time-of-use pricing is adopted to meet the supply and balance demand during time, in which the price is divided into three classes: on-peak, mid-peak and off-peak. The buying electricity price (B-price) and the selling electricity price (S-price) are different when the MicroGrid exchanging power with the utility system. Table 2 shows the time-of-use pricing in detail.

Table 2. Time-of-use Pricing ($/Kwh)

Time	07: 00-9: 00	9: 00-17: 00	17:00- 19:00	19: 00- 22:00	22: 00-07:00
Usage	Mid peak	On-peak	Mid peak	On-peak	Off-peak
B-price	0.07	0.13	0.07	0.13	0.04
S-price	0.05	0.09	0.05	0.09	0.026

By simulation work on this problem, we set $\alpha = 0.2$, $\beta = 0$, and $Q = 100$. The ant number is set to 10. The numbers of maximum iterations and maximum stagnations are set to 200 and 10.

5.2. Case 1: Optimization for Grid-connected Mode

At the beginning, we mimic the power balance by the strategy of charging and discharging battery in the grid-connected MicroGrid without using the optimization algorithm, as shown in Figure 3.

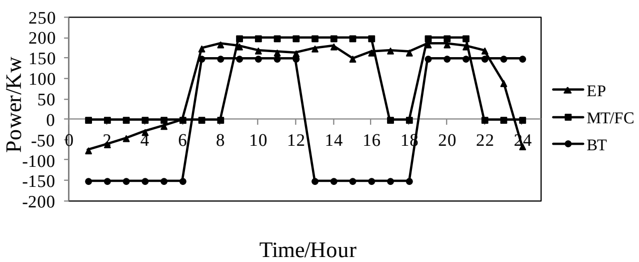

Figure 3. Power Balance in the Grid-connected MicroGrid without Optimization

Then, we perform a case study for power balance by the improved approach, aiming to ensure the minimum total cost by comprehensive consideration of the difference between the cost of buying and selling electricity. Figure 4 shows the results of power balance after optimization, where the exchanging power is positive when the MicroGrid selling electricity to utility system and negative when the MicroGrid buying electricity from utility system.

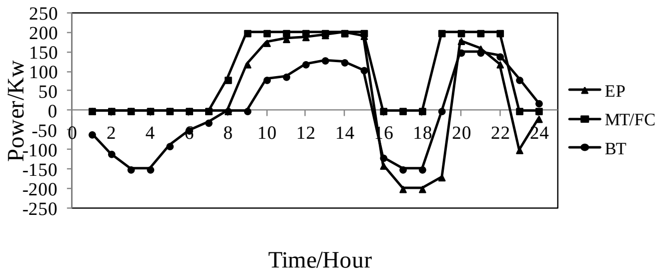

Figure 4. Power Balance after Optimization in the Grid-connected MicroGrid

It can be seen from Figure 4 that MT/FC starts running and generating power for MicroGrid during mid peak from 07:00 to 09:00. In this period, the cost of the micro generation units for generating electricity is cheaper than buying power from the utility system, so the MicroGrid is generating power by MT/FC. The charging process for battery is ended at 08:00. At 09:00, the whole grids are going into peak time. During the peak hours, the MicroGrid is selling the generated electricity by MT to the utility system, since the generating cost is cheaper than the power price in the utility system. The battery is discharging to support the load and balance demand. From 17:00 to 19:00, the MicroGrid is buying electricity from the utility system for charging the battery so as to prepare for the next peak hours. When going into 19:00, the battery is discharging its maximum power until no remaining power, to prepare for charging on the next day. At the same time, the micro generation units are running for selling electricity to the utility system until the peak time is over at 22:00. The price is off-peak from 22:00 to 7:00, so the MicroGrid is purchasing power from the utility system for supporting the load and balance need.

In Figure 5, it shows the comparison of total cost of daily power generation for no optimization and after optimization in the grid-connected MicroGrid. The average cost of daily power generation is $ 112.35 before optimization while it is $ 75.15 after optimization.

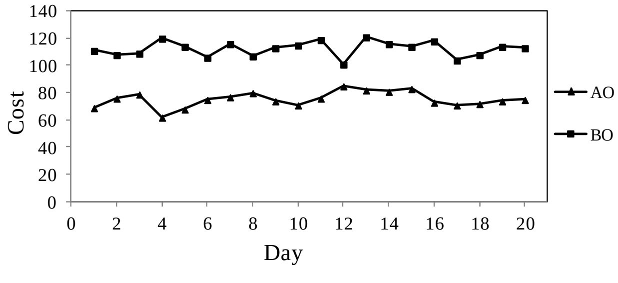

Figure 5. Comparison of Total Cost of Daily Power Generation in the Grid-connected MicroGrid

5.3. Case 2: Optimization for Islanded Mode

We also carry out the simulations for the islanded MicroGrid. Figure 6 shows the power balance by the strategy of charging and discharging battery without using the optimization algorithm and the result after optimization is shown in Figure 7.

It can be seen from Figure 7 that the micro generation units are running and generating power for MicroGrid during all the time when the power cannot meet the load and balance demand. From 16:00 to 19:00, the battery needs charging and it' s the time when the generated power by WT is decreasing. So other micro generation units have to contribute more power during this time.

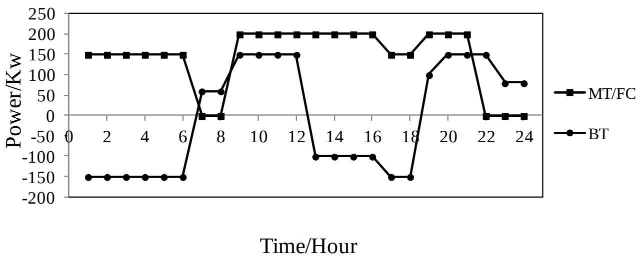

Figure 6. Power Balance in the Islanded MicroGrid without Optimization

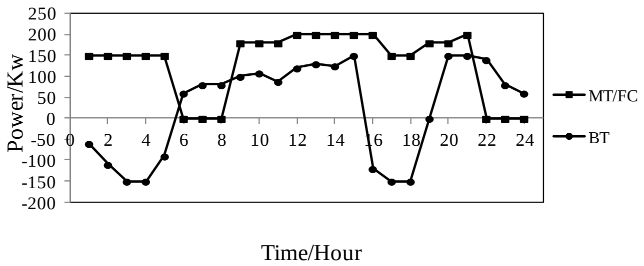

Figure 7. Power Balance after Optimization in the Islanded MicroGrid

Figure 8 shows the comparison of total cost of daily power generation for no optimization and after optimization in the islanded MicroGrid. The average cost of daily power generation is $ 151.65 before optimization while it is $ 125.45 after optimization.

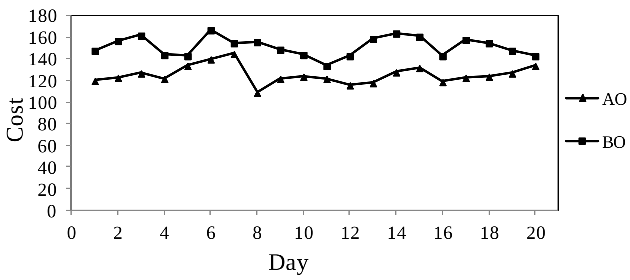

Figure 8. Comparison of Total Cost of Daily Power Generation in the Islanded MicroGrid

In addition, Figure 9 shows the evolution curve in solving the optimal investment problem of the micro generation unit composition by the improved ACO. It can be seen from Figure 9 that the cost is reduced with the increase of iteration times and a good solution can be obtained about 20 iterations.

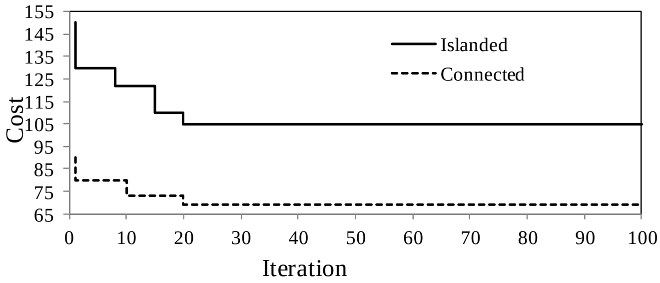

Figure 9. Evolution Curve of the improved ACO

Since the MicroGrid can sell the surplus power to the utility system in the grid-connected mode, the total expense is less than that in the islanded mode. According to the simulation results, it is feasible and effective to solve the dynamic economic dispatch in MicroGrid by the presented approach.

6. Conclusions and Future Work

In this paper, we presented a novel approach to solve dynamic economic dispatch for a MicroGrid, which based on the improved ACO. We established a mathematical model of economic dispatch in MicroGrid according to different modes of MicroGrid. Then, the traditional ACO was improved by SQP in order to discover the near-globally optimal solution. The key steps of the improved ACO for dynamic economic dispatch in MicroGrid were given and several simulations were carried out. The simulation results showed that the proposed approach significantly reduced the total cost of power generation, while meeting the load and balance demand required by the dynamic economic dispatch in the MicroGrid. It also proved that the proposed approach is feasible and effective for both the grid-connected and the islanded MicroGrid.

In future study, we will focus on the improvement of dynamic economic dispatch by combining hybrid intelligent algorithms. Moreover, an optimization of the dynamic economic dispatch method by considering the prediction error and the fault diagnosis of power generation and load information is a promising topic and needs further investigation.

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References

[1] I. Wasiak, “The concept of smart electrical power microgrids”. Przeglad Elektrotechniczny 87, no 6 (2011): 35–41
[2] Y. C. Wu, M. J. Chen, J. Y. Lin, W. S. Chen, and W. L. Huang, “Corrective economic dispatch in a microgrid”. International Journal of Numerical Modelling: Electronic Networks, Devices and Fields (2012)
[3] A. K. Basu, A. Bhattacharya, S. Chowdhury, and S. P. Chowdhury, “Planned Scheduling for Economic Power Sharing in a CHP-Based Micro-Grid”. Power Systems, IEEE Transactions on 27, no 1 (2012): 30–38
[4] Y. Che and J. Chen, “Research on Design and Control of Microgrid System”. Przeglad Elektrotechniczny 88, no 5B (2012): 83–86
[5] N. Augustine, S. Suresh, P. Moghe, and K. Sheikh, “Economic dispatch for a microgrid considering renewable energy cost functions”. In Innovative Smart Grid Technologies (ISGT), 2012 IEEE PES, 1–7, 2012
[6] M. Salani, A. Giusti, G. Di Caro, A. E. Rizzoli, and L. M. Gambardella, “Lexicographic multi-objective optimization for the unit commitment problem and economic dispatch in a microgrid”. In Innovative

Smart Grid Technologies (ISGT Europe), 2011 2nd IEEE PES International Conference and Exhibition on, 1–8, 2011
[7] Z. Zhang, X. Huang, J. Jiang, and B. Wu, "A load-sharing control scheme for a microgrid with a fixed frequency inverter". Electric Power Systems Research 80, no 3 (2010): 311–317
[8] T. Logenthiran, D. Srinivasan, and A. M. Khambadkone, "Multi-agent system for energy resource scheduling of integrated microgrids in a distributed system". Electric Power Systems Research 81, no 1 (2011): 138–148
[9] M. Pirouti, J. Wu, A. Bagdanavicius, J. Ekanayake, and N. Jenkins, "Optimal operation of biomass combined heat and power in a spot market". In PowerTech, 2011 IEEE Trondheim, 1–7, 2011
[10] A. A. Moghaddam, A. Seifi, T. Niknam, and M. R. Alizadeh Pahlavani, "Multi-objective operation management of a renewable MG (micro-grid) with back-up micro-turbine/fuel cell/battery hybrid power source". Energy (2011)
[11] B. Jiang and Y. Fei, "Dynamic Residential Demand Response and Distributed Generation Management in Smart Microgrid with Hierarchical Agents". Energy Procedia 12 (2011): 76–90
[12] M. Roozbehani, A. Faghih, M. I. Ohannessian, and M. A. Dahleh, "The intertemporal utility of demand and price elasticity of consumption in power grids with shifTable loads". In Decision and Control and European Control Conference (CDC-ECC), 2011 50th IEEE Conference on, 1539–1544, 2011
[13] A. Molderink, V. Bakker, M. G. C. Bosman, J. L. Hurink, and G. J. M. Smit, "A three-step methodology to improve domestic energy efficiency". In Innovative Smart Grid Technologies (ISGT), 2010, 1–8
[14] A. A. Moghaddam, A. Seifi, and T. Niknam, "Multi-operation management of a typical micro-grids using Particle Swarm Optimization: A comparative study". Renewable and Sustainable Energy Reviews (2011)
[15] M. D. Govardhan and R. Roy, "Artificial Bee Colony based optimal management of microgrid". In Environment and Electrical Engineering (EEEIC), 2012 11th International Conference on, 334–339
[16] J. B. Park, K. S. Lee, J. R. Shin, and K. Y. Lee, "A particle swarm optimization for economic dispatch with nonsmooth cost functions". Power Systems, IEEE Transactions on 20, no 1 (2005): 34–42
[17] M. A. Abido, "Multiobjective particle swarm optimization for environmental/economic dispatch problem". Electric Power Systems Research 79, no 7 (2009): 1105–1113
[18] M. Dorigo, M. Birattari, and T. Stutzle, "Ant colony optimization". Computational Intelligence Magazine, IEEE 1, no 4 (2006): 28–39
[19] F. E. Curtis and M. L. Overton, "A Sequential Quadratic Programming Algorithm for Nonconvex, Nonsmooth Constrained Optimization". SIAM Journal on Optimization 22, no 2 (2012): 474–500

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