A microgrid scheduling method based on Evolutionary Game

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Abstract. In order to solve constrained scheduling problem in microgrid. A microgrid scheduling method based on evolutionary game is proposed in this paper. Furthermore, a renewable energy and traditional energy generators group with different cost functions was studied as an example. The results show that evolutionary game method proposed in this paper has higher accuracy and stability than the existing artificial fish swarm optimization algorithm (AFS). In the scheduling model of microgrid, the optimized cost of power supply has been reduced by 2%.

1. Introduction

Due to the uncertainty of renewable energy generation, it is difficult to schedule renewable energy generators with other distributed energy sources. The scheduling of microgrid generally starts from two aspects: model establishment and model solution. Scholars have made many achievements. Literature [1] proposed a cooperative market mechanism to define the energy transactions and market price in multi-microgrids which is formulated as a mixed integer linear programming and solved by GAMS software. Literature [2] using interval arithmetic backward forward sweep and particle swarm optimization with time varying acceleration coefficients based optimal power flow to solve the optimal power scheduling problem. Literature [3] used the energy hub concept to construct a scenario-based model for the optimal scheduling of electrical and using the probability distribution functions to quantify the benefits of implementing electrical and thermal demand response schemes.

In summary. There are also many methods of microgrid scheduling [4-6]. However, this kind of algorithms has the disadvantages of high computation complexity and long computation time. These disadvantages increase with the increase of optimization constraints. Therefore, this paper aims to propose a method based on evolutionary game theory to solve the constrained microgrid scheduling problems.

2. Power supply cost model of microgrid

In a microgrid, power equipment is mainly divided into renewable energy generation equipment, non-renewable energy generation equipment and storage battery. Let $S_{m,t}^{con}$ and $S_{n,t}^{res}$ denote the power supply of the m-th non-renewable energy generator and the n-th renewable energy generator in time $t$ respectively. Based on literature [7], the cost function of each power supply equipment is given as follows:

(1) Power supply costs of non-renewable energy sources:

$$C_{m,t}^{con} = \alpha \left( S_{m,t}^{con} \right)^2 + \beta \cdot S_{m,t}^{con} + \gamma \cdot U_{m,t}^{con} + \zeta_{m,t}^{const} + \eta_{m,t}^{const} + \zeta_{m,t}^{const}$$ (1)
\( C_{\text{con}}^{\text{m,t}} \) is the supply cost of the m-th non-renewable energy generation equipment in time t, the parameters \( \alpha, \beta, \gamma \) are obtained by querying the specific generator type information. \( c_{\text{m,t}}^{\text{constart}} \) is the maintenance cost when the m-th non-renewable energy generator starts up and \( c_{\text{m,t}}^{\text{constant}} \) is the maintenance cost when the m-th non-renewable energy generator shuts down. \( U_{\text{m,t}}^{\text{con}} \) and \( V_{\text{m,t}}^{\text{con}} \) are state vectors, which are expressed by vector 1 or 0 indicate opening or closing respectively.

(2) Power supply cost of renewable energy sources:

\[
C_{\text{n,t}}^{\text{res}} = W_{\text{n,t}}^{\text{res}} \cdot c_{\text{n,t}}^{\text{res}} \cdot S_{\text{n,t}}^{\text{res}} + U_{\text{n,t}}^{\text{res}} \cdot c_{\text{n,t}}^{\text{resstart}} + V_{\text{n,t}}^{\text{res}} \cdot c_{\text{n,t}}^{\text{resshut}} + c_{\text{n,t}}^{\text{resOM}}
\]

(3) Storage battery cost:

\[
C_{\text{i,t}}^{\text{stg}} = V_{\text{i,t}}^{\text{stg}} \cdot c_{\text{i,t}}^{\text{stg}} \cdot \eta_i \cdot S_{\text{i,t}}^{\text{stg}}
\]

(4) Power supply cost of grid:

\[
C_{\text{t}}^{\text{grad}} = c_{\text{t}}^{\text{grad}} \cdot S_{\text{t}}^{\text{grad}}
\]

In summary, the total cost of a microgrid can be recorded as a function of power supply \( f(S_{\text{x,t}}) \). Minimizing \( f(S_{\text{x,t}}) \) will be the primary goal of any independent microgrid operator. The microgrid optimization problem can be written as follows:

\[
\min \sum_{x=1}^{X} \sum_{t=1}^{T} f(S_{\text{x,t}})
\]

(5)

(6)

(7)

(8)

And the power balance constraint (1) is satisfied, \( L_t \) is the load of the microgrid in time t.

\[
\sum_{m=1}^{M} S_{\text{m,t}}^{\text{con}} + \sum_{n=1}^{N} S_{\text{n,t}}^{\text{res}} + \sum_{t=1}^{T} S_{\text{t,t}}^{\text{stg}} + S_{\text{t}}^{\text{grad}} = L_t
\]
3. Day ahead scheduling of microgrid based on evolutionary game

3.1. Scheduling method based on evolutionary game

In evolutionary game, the proportion of each species are denoted as $x_1, x_2, \cdots, x_n$ respectively, which meet the condition $\sum_{i=1}^{n} x_i = 1$. In the evolution process, the profit of the competition between species $i$ and species $j$ is denoted as $a_{ij}$, where $1 \leq i \leq n, 1 \leq j \leq n$. The profit matrix of the population is denoted as:

$$A = \begin{pmatrix} a_{11} & \cdots & a_{1n} \\ \vdots & \ddots & \vdots \\ a_{n1} & \cdots & a_{nn} \end{pmatrix}$$  \(10\)

The expected profit of species $i$ is:

$$E_i = \sum_{j=1}^{n} a_{ij} x_j$$  \(11\)

And the actual profit of the population is as follows:

$$E = \sum_{i=1}^{n} \sum_{j=1}^{n} x_i a_{ij} x_j$$  \(12\)

For the evolutionary mechanism of population, the dynamic evolution equation is as follows [8]:

$$\frac{dx_i}{dt} = x_i (E_i - E)$$  \(13\)

In this paper, every power supply equipment in the microgrid is regarded as a species, the power supply is the individual number of species, the load is the total individual number of population and the total group revenue is the daily operation cost of the grid. The goal is to minimize the population revenue. Then, the evolution equation of microgrid scheduling is:

$$\frac{dS_{x,t}}{dt} = -S_{x,t} \left( \sum_{x=1}^{X} \sum_{t=1}^{T} f(S_{x,t}) + \frac{\partial f(S_{x,t})}{\partial S_{x,t}} dt \right) - \sum_{x=1}^{X} \sum_{t=1}^{T} f(S_{x,t}) \right)$$ \(14\)

Where $S_{x,t}$ is the power supply of the $x$ power supply equipment in time $t$, including renewable energy generation equipment, non-renewable energy generation equipment and storage battery. And meet the following constraints:

$$\sum_{x=1}^{X} S_{x,t} = L_t - S_{t}^{grd}$$  \(15\)

3.2. Microgrid based on IEEE 33 node

In this section, a practical microgrid consisting of a solar photovoltaic panel (PV), a wind turbine (W), a fuel cell (FC), a diesel generator (DG), a micro-turbo-generator (MT) and a storage battery is considered, as shown in Figure 1. According to literature [7], the parameter $\alpha = 0.000007, \beta = 0.066, \gamma = 0.00454$; and the cost of purchasing power from external network is 0.572 Euros/kWh. The rest parameters of power equipment are shown in table 1[9]. In table 2[9], the constraints of power supply equipment are given. According to literature [9], the hourly load demand of microgrid and the predicted max available power per hour of renewable energy generators are given.
In the process of evolution, the following rules should be followed:

(a). When $\sum_{m=1}^{M} S_{m,t}^{\text{con, max}} + \sum_{n=1}^{N} S_{n,t}^{\text{res, max}} > L_t$, the power supply strategy of each equipment is adjusted by the dynamic evolution equation.

(b). When $\sum_{m=1}^{M} S_{m,t}^{\text{con, max}} + \sum_{n=1}^{N} S_{n,t}^{\text{res, max}} < L_t < \sum_{m=1}^{M} S_{m,t}^{\text{con, max}} + \sum_{n=1}^{N} S_{n,t}^{\text{res, max}} + \sum_{l=1}^{l} S_{l,t}^{\text{dch, max}}$, storage battery discharge.

(c). When $\sum_{m=1}^{M} S_{m,t}^{\text{con, max}} + \sum_{n=1}^{N} S_{n,t}^{\text{res, max}} + \sum_{l=1}^{l} S_{l,t}^{\text{dch, max}} < L_t$, storage battery discharges; meanwhile, insufficient power is purchased from the external network.

| Hour | MT (Euro/Kwh) | FC (Euro/Kwh) | PV (Euro/Kwh) | W (Euro/Kwh) | Bat (Euro/Kwh) |
|------|---------------|---------------|---------------|--------------|----------------|
| 1    | 0.0823        | 0.1277        | 0             | 0.021        | 0.1192         |
| 2    | 0.0823        | 0.1277        | 0             | 0.017        | 0.1192         |
| 3    | 0.0831        | 0.1285        | 0             | 0.0125       | 0.1269         |
| 4    | 0.0831        | 0.129         | 0             | 0.011        | 0.1346         |
| 5    | 0.0838        | 0.1285        | 0             | 0.051        | 0.1423         |
| 6    | 0.0838        | 0.1292        | 0             | 0.085        | 0.15           |
| 7    | 0.0846        | 0.1292        | 0             | 0.091        | 0.1577         |
| 8    | 0.0854        | 0.13          | 0.0646        | 0.11         | 0.1668         |
| 9    | 0.0862        | 0.1308        | 0.0654        | 0.14         | 0.1662         |
| 10   | 0.0862        | 0.1315        | 0.0662        | 0.143        | 0.1677         |
| 11   | 0.0892        | 0.1323        | 0.0669        | 0.15         | 0.1731         |
| 12   | 0.09          | 0.1315        | 0.0677        | 0.155        | 0.1769         |
| 13   | 0.0885        | 0.1308        | 0.0662        | 0.137        | 0.1692         |
| 14   | 0.0885        | 0.1308        | 0.0654        | 0.135        | 0.16           |
| 15   | 0.0885        | 0.1308        | 0.0646        | 0.132        | 0.1538         |
| 16   | 0.09          | 0.1315        | 0.0638        | 0.114        | 0.15           |
| 17   | 0.0908        | 0.1331        | 0.0638        | 0.11         | 0.1523         |
| 18   | 0.0915        | 0.1331        | 0.0662        | 0.0925       | 0.15           |
| 19   | 0.0908        | 0.1338        | 0             | 0.091        | 0.1462         |
| 20   | 0.0885        | 0.1331        | 0             | 0.083        | 0.1462         |
| 21   | 0.0862        | 0.1315        | 0             | 0.033        | 0.1431         |
| 22   | 0.0846        | 0.1308        | 0             | 0.025        | 0.1385         |
| 23   | 0.0838        | 0.13          | 0             | 0.021        | 0.1346         |
| 24   | 0.0831        | 0.1285        | 0             | 0.017        | 0.1269         |
Table 2. Characteristics of dispatchable power supply equipment.

| Type | Bus | Capacity (kW) | Max power(kW) | Min Power(kW) | Start up/shut down cost (Euro/kW) |
|------|-----|---------------|---------------|---------------|----------------------------------|
| W    | 14  | 600           | 20            | 0             | 0                                |
| PV   | 20  | 500           | 25            | 0             | 0                                |
| DG   | 8   | 600           | 20            | 0             | 0                                |
| FC   | 24  | 500           | 20            | 2             | 0.138                            |
| MT   | 31  | 500           | 20            | 6             | 0.107                            |
| Battery | 13 | 500 | 30 | Max SoC-100 | Min SoC - 30 |

3.3. Scheduling result analysis of evolutionary game

Based on the above optimization methods, table 3 gives the optimal results of microgrid scheduling. Figure 2 gives the hourly power supply of each generator in the microgrid and the hourly purchasing capacity of external network. Figures 3 and 4 give the charging and discharging capacity of the backup batteries and the charging capacity of the storage batteries respectively. It can be seen that the optimal results maximize the use of wind and solar renewable energy, and fully optimize the charging and discharging of storage batteries, avoiding purchasing power from the external network in the period of heavy load. The optimized results reduced the cost of power supply to 160.566 Euro.

Figure 2. Power supply of microgrid
In order to verify the effectiveness and superiority of the evolutionary game in microgrid scheduling, the particle swarm optimization [10] and artificial fish swarm optimization [7] are used to optimize the above microgrid mode. The optimization results of each method are shown in Table 4, and the mean and variance of the optimization results of each group of experiments are calculated respectively. It shows that evolutionary game has more accurate optimization results, which makes the scheduling cost of microgrid lower; the variance of 0.2097 shows that the evolutionary game has less volatility and its optimization results are more stable which improves the optimized results of the intra-day power supply cost of microgrid by 2%.
Table 3. Optimal scheduling results based on evolutionary game.

| Hour | $S_W$    | $S_{PV}$ | $S_{DG}$ | $S_{FC}$ | $S_{MT}$ | $S_{Grid}$ | $S_{Battery}$ | SoC   | L   |
|------|----------|----------|----------|----------|----------|------------|---------------|-------|-----|
| 1    | 16.0133  | 0        | 20       | 7.8890   | 20       | 0          | -             | 11.9023 | 30  | 52  |
| 2    | 16.0800  | 0        | 20       | 20       | 20       | 0          | -             | 26.0800 | 41.9023 | 50  |
| 3    | 16.1600  | 0        | 20       | 0        | 20       | 0          | -6.1600       | 67.9823 | 50  |
| 4    | 16.1733  | 0        | 20       | 0.0010   | 20       | 0          | -5.1743       | 74.1423 | 51  |
| 5    | 17.6800  | 0        | 20       | 0        | 20       | 0          | -1.6800       | 79.3166 | 56  |
| 6    | 16.1733  | 0        | 20       | 6.8267   | 20       | 0          | 0             | 80.9966 | 63  |
| 7    | 14.7333  | 0        | 20       | 15.2667  | 20       | 0          | 0             | 80.9966 | 70  |
| 8    | 14.5600  | 0.1      | 20       | 20       | 20       | 0          | 0.3400        | 80.9966 | 75  |
| 9    | 14.6533  | 0.59     | 20       | 20       | 20       | 0          | 0.7567        | 80.6566 | 76  |
| 10   | 13.1600  | 1.98     | 20       | 20       | 20       | 0          | 12.86         | 79.8999 | 88  |
| 11   | 11.6667  | 7.75     | 20       | 18.5833  | 20       | 0          | 0             | 67.0399 | 78  |
| 12   | 10.1467  | 9.8      | 20       | 14.0533  | 20       | 0          | 0             | 67.0399 | 74  |
| 13   | 11.6667  | 10.65    | 20       | 9.6833   | 20       | 0          | 0             | 67.0399 | 72  |
| 14   | 10.1460  | 9.7      | 20       | 12.1540  | 20       | 0          | 0             | 67.0399 | 72  |
| 15   | 14.7467  | 8.12     | 20       | 13.1333  | 20       | 0          | 0             | 67.0399 | 76  |
| 16   | 16.2133  | 4.95     | 20       | 18.8367  | 20       | 0          | 0             | 67.0399 | 80  |
| 17   | 16.1467  | 1.1      | 20       | 20       | 20       | 0          | 7.7533        | 67.0399 | 85  |
| 18   | 19.1333  | 0.1      | 20       | 20       | 20       | 0          | 8.7667        | 59.2867 | 88  |
| 19   | 17.5333  | 0        | 20       | 20       | 20       | 0          | 12.4667       | 50.5200 | 90  |
| 20   | 18.9467  | 0        | 20       | 20       | 20       | 0          | 8.0533        | 38.0533 | 87  |
| 21   | 19.0400  | 0        | 20       | 18.96    | 20       | 0          | 0             | 30       | 78  |
| 22   | 19.1067  | 0        | 20       | 11.8933  | 20       | 0          | 0             | 30       | 71  |
| 23   | 19.9333  | 0        | 20       | 5.0667   | 20       | 0          | 0             | 30       | 65  |
| 24   | 19.1467  | 0        | 20       | 0        | 16.8533  | 0          | 0             | 30       | 56  |

Table 4. Comparison of different scheduling methods.

|       | 1      | 2      | 3      | 4      | 5      | 6      | 7      | 8      | 9      | 10     | $\mu$ | $\delta^2$ |
|-------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|-------|-----------|
| PS    | 164.3  | 163.5  | 165.0  | 163.9  | 163.0  | 164.8  | 163.3  | 165.0  | 163.8  | 164.2  | 164.12 | 0.42      |
| O     | 25     | 62     | 05     | 56     | 88     | 65     | 56     | 38     | 65     | 21     | 81     | 84        |
| AS    | 162.2  | 163.2  | 161.9  | 162.2  | 163.5  | 163.2  | 164.0  | 162.2  | 162.8  | 163.3  | 162.89 | 0.42      |
| F     | 35     | 53     | 85     | 35     | 45     | 35     | 12     | 26     | 95     | 58     | 79     | 75        |
| EG    | 160.5  | 162.2  | 160.9  | 161.0  | 160.6  | 160.3  | 162.1  | 161.2  | 162.4  | 160.9  | 160.96 | 0.20      |
|       | 56     | 75     | 98     | 56     | 56     | 69     | 38     | 31     | 45     | 36     | 60     | 97        |

4. Conclusion
Based on evolutionary game theory, a microgrid scheduling method based on evolutionary game is proposed, and the evolution equation of microgrid daily scheduling is established. After that, the game model is modeled in the day-ahead scheduling optimization problem of microgrid. Compared with particle swarm optimization algorithm and artificial fish swarm optimization algorithm, the evolutionary game optimization method proposed in this paper has better adaptability and more accurate results. The total daily power supply cost of the microgrid described in this paper is reduced to 160.9660 Euro.
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