Optimal Configuration of Power Supply of Microgrid based on Bilevel Layer Programming with Renewable Energy Preferred

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Abstract. For the region where the renewable energy sources are more abundant and the requirement of load on power supply reliability is lower, a bilevel programming model giving priority to renewable energy is proposed, which takes environmental friendliness and economy into account. The lower level giving priority to renewable energy, which aims at maximizing the renewable energy power generation capacity, determines the size of renewable energy; The upper level ensuring the reliability of the system, which aims at minimizing the cost of the whole life cycle including the system initial investment, operation maintenance cost, fuel costs, environmental penalty cost and government subsidies, ultimately determines the optimal capacity configuration of different power sources in the system. Then a hybrid algorithm that combines the genetic algorithm with linear programming to solve this model is constructed. At last, by comparing the bilevel programming model with single layer and single target programming one, the validity and rationality of the model are fully verified, and the influence of the renewable energy penetration power limit, the cost of renewable energy units and the local climate factors on the optimization results are evaluated too.

1. Optimal Configuration of Microgrid Power Capacity with Renewable Energy Preferred

It’s significant issues to prioritize power and match up different forms of energy with load considering characteristics of power and importance of load[1-4]. Micro-grid power planning with renewable energy preferred is based on load curve of maximum load day, as shown in Figure 1, in which installed capacity means the part that can be utilized [5]. When power is kept well in balance, the total installed capacity is comprised by installed renewable capacity $C_{re}$ and conventional capacity $C_{ce}$, and its relationship with load suits for (1):

$$\sum C_{re} + \sum C_{ce} = P_{L_{max}}(1 + \gamma)$$

(1)

Where $P_{L_{max}}$ is peak load power; $\gamma$ is system reserve rate, generally 15% to 20%.

Renewable energy is given priority to, then installed renewable capacity could be calculated as:

$$\sum C_{re} = \lambda P_{L_{max}} = \min \{\lambda_{re}, \lambda_{limit}\} P_{L_{max}}$$

(2)
Where $\lambda_{re}$ is load rate of renewable energy, or the ratio of $C_{re}$ to $P_{Lmax}$, $\lambda_{limit}$ is renewable energy penetration limit which is introduced to avoid that large-capacity renewable energy could lower the quality of power.

![Diagram of micro-grid power capacity](image)

**Figure 1. Capacity of micro-grid power**

When the system power keeps in balance, the generation of renewable energy $E_{re}$ and conventional energy $E_{ce}$ are determined by total generation of the whole system:

$$
\sum E_{re} + \sum E_{ce} = E_d
$$

### 2. Micro source output model

#### 2.1. Wind Power Output Model

Wind speed model is developed using Weibull distribution model, and Weibull distribution parameters $k$ and $c$ is estimated by the average wind velocity and the standard deviation in which $k$ is shape factor in the range between 1.8 to 2.3, generally 2; $c$ reflects the annual average wind speed of area described. Affected by wind speed, output power of wind turbines fluctuates, hence is generally expressed by piecewise function [6] as follows:

$$
P_w(v) = \begin{cases} 
0, & v \leq v_{ci} \text{ or } v \geq v_{co} \\
\frac{P_{wtn}}{v_t - v_{ci}^3} v^3 - \frac{P_{wtn}}{v_r - v_{ci}^3} v_{ci}^3, & v_{ci} \leq v \leq v_{co} 
\end{cases}
$$

Where $P_w(v)$ is output power of wind turbine when wind speed reaches $v$, and $v_{ci}$, $v_{co}$, $v_t$ and $P_{wtn}$ are respectively cut-in speed, cut-out speed, rated speed and rated output power.

#### 2.2. Photovoltaic Power Output Model

PV system output power is related to ambient temperature and light intensity, and the latter within a certain time can be approximated as Beta distributions [7], so based on the random number generated $\chi$, output power of photovoltaic (PV) cell $P_v$ could be calculated as:

$$
P_v = \chi P_{pvn}
$$

Where $P_{pvn}$ is maximum power output of PV cells in predetermined time.

#### 2.3. Storage Model

Battery is charged when renewable energy is abundant enough, however, electricity can’t exceed the upper limit, and then the electricity $E_{soc}$ can be calculated as follows:

$$
E_{soc}(t+1) = \begin{cases} 
E_{socmax}, & E_{soc}(t) + \Delta E_t \geq E_{socmax} \\
E_{soc}(t) + \eta \cdot \Delta E_t \cdot \Delta t, & E_{soc}(t) + \Delta E_t < E_{socmax}
\end{cases}
$$

Conversely, battery is discharged when output can’t meet the current load, but electricity can’t fall below the lower limit, and then the electricity can be calculated as follows:
\[ E_{soc}(t+1) = \begin{cases} E_{socmin} + E_{soc}(t) \cdot \Delta E_t \geq E_{socmin} \\ E_{soc}(t) - \eta_d \cdot \Delta E_t \cdot \Delta t \geq E_{soc}(t) \cdot \Delta E_t < E_{socmin} \end{cases} \] (7)

Where \( E_{soc}^{max} \) and \( E_{soc}^{min} \) are respectively the upper and lower limit of battery capacity; \( E_{soc}(t) \) is electricity at \( t \); \( \eta_c \) and \( \eta_d \) are respectively the charge and discharge efficiency; \( \Delta E_t \) is the absolute difference between \( P_{re} \) and \( P_L \):

\[ \Delta E_t = |P_{re} - P_L| \] (9)

3. Optimal Configuration model of Microgrid Power Capacity Based on Bilevel Programming Giving Priority to Renewable Energy

3.1. Upper Programming Model

Renewable energy capacity which is determined by upper programming based on lower model considers energy storage and conventional installed capacity as decision variables, and the minimum lifecycle cost of energy (COE) as the objective function, the mathematical model is expressed as follows:

\[
\begin{align*}
\text{min } F_2 &= (F_0 \cdot CRF + F_{re} \cdot SFF + F_m + F_{fuel} + F_{env} + F_{sub}) / W \\
CRF &= \frac{r(1+r)^T}{(1+r)^T - 1} \\
SFF &= \frac{r}{(1+r)^h - 1} \\
\text{s.t. } R_{LOLP} \leq R_{max} \\
E_{socmin} \leq E_{soc} \leq E_{socmax}
\end{align*}
\] (10)

Where \( F_2, F_0, F_{re}, F_m, F_{fuel}, F_{env} \) and \( F_{sub} \) are respectively the COE, initial investment cost, replacement cost, annual operating and maintenance costs, annual fuel cost, annual environmental cost and government subsidies; CRF is the capital recovery factor convert present value to annual value, SFF is compensation fund factor, convert future value to annual value; The replacement cost is generally less than the initial investment, and is set at 80% of the latter in the paper; \( r, T \) and \( T_{re} \) are respectively discount rate, the system life cycle and the life of equipment, and \( r=5\%, T=20 \) in this paper [2]; Electricity shortage rate is introduced as the constraints of system reliability, \( R_{max} \) is the maximum probability of electricity shortage, and \( R_{max}=0.01 \) in this paper.

\( R_{LOLP} \) can be calculated as follows:

Based on annual output power of Monte Carlo model, power is balanced by hour. Renewable energy is give priority to supply power for system, and the total is \( E_{re} \). When the supply power could meet the power consuming of load, the difference \( \Delta E_t \) arises, then if the condition is satisfied, battery will be charged at this time and meet the (9). But when the supply power couldn’t meet the power consuming of load because of its randomness, battery will be discharged and meet the (10) if the condition is satisfied. And when the battery capacity can’t meet the power consuming, some conventional source else will be put into operation as the reserve to meet it to the most extent.

Non-critical loads will be shed if all conventional source still can’t meet the power consuming, and deficit at time \( t \) is denoted as \( E_{LOLP}(t) \), then annual probability of power shortage can be expressed as:

\[ R_{LOLP} = \frac{\sum_{t=1}^{8760} E_{LOLP}(t)}{\sum_{t=1}^{8760} E_d(t)} \] (11)
3.2. Lower Programming Model

Decision variables of lower level are installed capacity of all kinds of renewable energy whose objective function is maximum of the sum of renewable power. And it is expressed as follows:

\[
\begin{align*}
\max F_1 &= \sum_{T} \sum_{I} F_{re} \\
\text{s.t.} \sum_{C_{re}} &= \lambda R_{\text{max}} \\
X_i &\leq X_{i\text{max}}
\end{align*}
\]

(12)

Where \(X_i, X_{i\text{max}}\) are respectively the \(i\)th capacity, the \(i\)th maximum allowed installed capacity.

3.3. Optimization Model Algorithm

Considering the characteristics of optimal configuration of microgrid power supply, genetic algorithm and linear programming method are well combined to solve the bilevel programming model, whose steps can be expressed as follows:

1) According to actual data of wind speed and light intensity, sample model to acquire 8760hs’ data sequence utilizing the model in Section III.

2) Simulate output of wind turbines and PV cells in a year utilizing Monte Carlo, and get its average output and capacity factor.

3) Set genetic algorithm parameters, initialize population, and optimization variables are power supply capacity \(X_1, X_2, X_3, X_4\).

4) Solve the lower problem using linear programming method on the basis of the population of the upper levels: ① Form of a group of load rate of renewable energy; ② Compute ratio of \(X_1\) and \(X_2\) according to a certain load rate of renewable energy; ③ Obtain the optimal solution of \(X_1\) and \(X_2\) meeting the lower objective function; ④ Determine whether the calculation of all renewable energy power load rate is completed, if so, go to step 5), else turn to ②.

5) Obtain \(X_1, X_2\) by solving the lower problem, and iterate \(X_3, X_4\) of population. Simulate the output power of each power supply using Monte Carlo, obtain the reliability index and return it as a constraint, and finally find the optimum configuration of each power meeting the fitness function.

6) Determine whether meet the upper iteration termination condition, if so, output the optimal configuration, else go to step 3).

4. Analysis of Cases

4.1. Data of Cases

In this paper, an independent micro-grid in remote areas is set as an example to verify the effectiveness of the proposed optimization methods. According to the actual data of local wind speed and light intensity, sample model in section III to obtain 8760hs’ data sequence. The typical raw data of daily load in different quarters are shown in Figure 2, we assume changes of daily load within each quarter have a same tendency. System unit related data are shown in Table 1. Wind power, PV and diesel forced outage rate is given in [8]. Genetic algorithm parameters are set as follows: the number of population \(M=100\), the number of iterations \(T=300\), crossover rate \(P_c=0.5\), mutation probability \(P_m=0.01\), learning rate \(\text{eta}=0.8\).
Table 1. The cost and emission coefficients of the power source

| Type           | Single-machine Capacity (kW) | Life Span (a) | Initial Investment ($/kW) | Replacement Cost ($/kW) | Maintenance Cost ($/kW·a) | Fuel Cost ($/kWh) | NOx (g/kWh) | CO2 (g/kWh) | SO2 (g/kWh) |
|----------------|-------------------------------|---------------|--------------------------|-------------------------|---------------------------|------------------|------------|------------|------------|
| Wind Turbine   | 10                            | 20            | 6055                     | 0                       | 5.7                       | 0                | 0          | 0          | 0          |
| PV             | 0.083                         | 20            | 6675                     | 0                       | 14.3                      | 0                | 0          | 0          | 0          |
| Battery        | 50                            | 10            | 1300                     | 1040                    | 7                         | 0                | 0          | 0          | 0          |
| Diesel Engine  | 60                            | 10            | 864                      | 691.2                   | 26.5                      | 0.145            | 9.89       | 649        | 0.206      |

Figure 2. Typical day load in a year

4.2. Analysis of Optimization Results
To determine the system's optimal renewable energy power load ratio and corresponding ratio of power capacity, optimization calculations are made respectively when $\lambda_{re} = \{0.2, 0.3, 0.4, 0.5, 0.6\}$. Rate of wind turbines, PV cells and power supply under each renewable energy power load ratio can be seen as Figures 3 and 4 respectively. The optimal wind-solar-diesel-storage ratio and economical index obtained from upper and lower objective function is shown as Table 2. Single-level single-objective programming to minimize COE and maximize renewable energy power supply is shown as Table 2.

Figure 3. Capacity configuration of wind power and pv
Figure 4. Power supply under different capacity configuration of wind power and pv

Figure 4 and Figure 5 show that when $\lambda_{re} = 0.2$, power supply peaks if all wind turbines are installed. With the increase of $\lambda_{re}$, the total power supply is different when the ratio of renewable energy power is different; The mode utilizing wind turbine only has disadvantages, while wind-solar hybrid mode is optimal. Ratio of wind-solar capacity is related with parameters chose in the paper.

Table 2 shows that with the increase of $\lambda_{re}$, COE decreases first and then increases. When $\lambda_{re}=0.4$, the system is optimally economical, and corresponding wind-solar-storage-diesel capacities are respectively: 500, 237, 350, 360 (kW).

| $\lambda_{re}$ | Capacity Configuration (Wind, Solar, Storage, Diesel) | Renewable Energy Supply | COE (Yuan) |
|---------------|-----------------------------------------------------|-------------------------|------------|
| 0.2           | 380, 0, 100, 420                                    | 775012                  | 0.9491     |
| 0.3           | 520, 28, 250, 360                                   | 1091898                 | 0.9434     |
| **0.4**       | **500, 138, 300, 360**                              | **1294469**             | **0.9356** |
| 0.5           | 500, 237, 350, 360                                  | 1494125                 | 0.9402     |
| 0.6           | 550, 311, 450, 300                                  | 1716018                 | 0.9517     |

Table 3. Optimal capacity configuration under single layer and single objective programming

| Optimization Objective | Capacity Configuration (Wind-Solar-Storage-Diesel) | Renewable Energy Supply | COE (Yuan) |
|------------------------|----------------------------------------------------|-------------------------|------------|
| Minimum COE            | 310, 261, 150, 360                                 | 1186176                 | 0.9109     |
| Maximum Power Supply of Renewable Energy | 650, 358, 500, 300 | 1891943 | 1.0360 |

From the analysis of relation between power supply of renewable energy and COE in Table 2, it’s known that with the increase of renewable energy power supply, COE decreases first and then increases, which indicates that power supply of renewable energy and COE are conflicting.

From the comparison of Table 2 and Table 3, show that, it’s known that renewable energy power supply will be relatively low if COE is minimized, and the COE will be relatively high if renewable energy power supply is maximized, which indicates that single-objective programming will make the other index relatively unsatisfactory, while the model established in this paper can take both indexes into account.

5. Conclusions

Simulation results show that: From the comparison with single-level single-objective programming, it’s known that power supply of renewable energy and COE are conflicting, and single-objective programming will make the other index relatively unsatisfactory, while the model established in this paper can take both indexes into account.
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