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Complexity Measure and Operational Efficiency Evaluation of Electricity Engineering Market

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Abstract

With the continuous development of the electricity market, its character as a complexity system is increasingly revealed, which requires that we should integrate complexity theory into the evaluation of electricity market operation and should have the systems engineering way of thinking at the same time. This paper uses entropy to measure the complexity of the electricity market, then regards complexity as an indicator and integrates it into the index system of electricity market, after that a model which is modified based on entropy theory to evaluate the operation efficiency of the electricity market is established. Finally, the complexity and operational efficiency of the electricity market are evaluated by simulating data. Form consequence we can find that the complexity of the electricity market is higher than the general market, the efficiency of region 5 is relatively low, region 3 is the most efficient, other four regions are small in difference. The result shows that the entropy as a measure of the complexity of the electricity market is simple in calculation, it can also accurately reflect the complexity of the electricity market. The use of chaos optimization of entropy-random DEA model has good flexibility and feasibility for the evaluation of the operational efficiency of the electricity market.

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Keywords: Complexity; Electricity Market; Operational Efficiency; Entropy-random DEA; systems engineering

1. Introduction

Electricity market reform is an important part of power industry reform, the structure of the electricity market is becoming more and more complex, its components, degree of automation and regulatory power are increasing faster and faster, the power network constantly develops in the direction of extra high voltage, long-distance and large capacity, these factors lead to the complexity of electricity market becoming higher and higher. The complexity will directly affect the stability and development of electricity market. Therefore, we need to understand the complexity of electricity market, know how to measure it, based on it we can comprehensively evaluate the operational efficiency of the electricity market[1][2]. Obviously, evaluating its operational efficiency must be a complicated systems engineering because of the existence of the complexity in the electricity market.

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The current electricity market research mostly concentrates in the determined state of static market to research the reliability and economy. However, in recent years, some scholars have applied the theory of complexity to power system studies. Zhang Pinyi, Li Chunjie regarded electricity market as a complex system, used Haken model to evaluate its operational efficiency based on the principle of collaboration\(^4\); Zhou Jianguo, Wang Xiaowei used game theory and dynamic modeling approach to analyze power market and its complex behavior\(^5\). These scholars agreed that the complexity exist in the electricity market, but the research of complexity measurement and establishing the evaluation system from the concept of systems engineering are still blank. Based on these studies, using the method of systems engineering, this paper is committed to introduce the theory of complexity measure, and improve the evaluation method of the electricity market, through new ways and new perspective to explore the operational effectiveness of the electricity market, to improve the operational efficiency of the electricity market, and finally to provide more comprehensive policy recommendations to the electricity market supervision.

2. Complexity Measurement of The Electricity Market

2.1. Electricity market definition

The electricity market set in this paper is the intermediate links between plants producing electricity to customers consuming power, it’s a bridge connecting the power plant and electricity customers, which is composed by transmission and network, trading systems, scheduling systems, management information systems, technical support systems and so on. It’s a human integrated complex system.

According to the scope and characteristics of the electricity market, we can classify the complexity of electricity market into internal complexity and external complexity, combined with the flow of electricity in the power system, we form a complexity measure system of electricity market shown in Figure 1.

![Complexity of electricity market](image)

Fig. 1. the complexity measurement system of electricity market

We can also divide electricity market into three parts: power production side (the link that electricity market connected with power plant), power consumption side (the link that electricity market connected with electricity customers), and the internal link between them\(^7\)-\(^9\).

2.2. Entropy measure of the complexity of Electricity market

Electricity market exchanges all kinds of information with power plants, electricity customers and the market itself, entropy as a measure of the uncertainty of an event, can indicate the number and complexity of the information. Therefore, we can use entropy to measure the complexity of electricity market\(^10\).

According to the complexity measure system shown in Figure 2, the entropy of the electricity market also consists of three parts, as formula (1) shows.

\[
S = S_1 + S_2 + S_3
\]
In the formula: $dS$ - the total entropy of the electricity market, represents the whole market's degree of chaos; $dS_1$ - entropy caused by the uncertainty of power production side, for measuring the complexity of energy production; $dS_2$ - entropy caused by the uncertainty of power consumption side, for measuring the complexity of energy consumption; $dS_3$ - entropy caused by the interaction of market's internal factors, for measuring the complexity of energy transmission and distribution.

Therefore, the entropy of each part of the electricity market can be expressed as:

$$
d_iS = -\sum_{j=1}^{n_i} p(x_{ij}) \ln p(x_{ij}), \quad i=1,2,3, \quad j=1,2,…,n_i$$ \hspace{1cm} (2)

In the formula: $x_{ij}$ represents the $j$-th state of the $i$-th part; $n_i$ represents the number of states of $i$-th part. $p(x_{ij})$ represents the probability of state $x_{ij}$ occurs.

To calculate the entropy of electricity market, we need to divide the state of each part, and then calculate the probability of each state, finally according to formula (2) we can obtain the entropy. To simplify the calculation and facilitate the research, we can use the deviation of the planning value and the actual value to define the state variables, each part is divided into the same nine state, $n_i = n = 9$, $x_{ij} = x_j$, detailed division as table 1 shows.

<table>
<thead>
<tr>
<th>$x_j$</th>
<th>Dev.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$x_1$</td>
<td>-1~1</td>
</tr>
<tr>
<td>$x_2$</td>
<td>10~+∞</td>
</tr>
<tr>
<td>$x_3$</td>
<td>7~10</td>
</tr>
<tr>
<td>$x_4$</td>
<td>4~7</td>
</tr>
<tr>
<td>$x_5$</td>
<td>1~4</td>
</tr>
<tr>
<td>$x_6$</td>
<td>4~1</td>
</tr>
<tr>
<td>$x_7$</td>
<td>7~4</td>
</tr>
<tr>
<td>$x_8$</td>
<td>4~7</td>
</tr>
<tr>
<td>$x_9$</td>
<td>7~10</td>
</tr>
<tr>
<td>$x_{10}$</td>
<td>-10~7</td>
</tr>
<tr>
<td>$x_{11}$</td>
<td>-10~∞</td>
</tr>
</tbody>
</table>

Among them, the deviation of power generation side equals planned power production minus actual power production; the deviation of power consumption side equals planned power consumption minus actual power consumption; the deviation of power transaction side equals planned power transaction minus actual power transaction$^{[11]}$-$^{[13]}$. Calculate the probability of each state. Using the electricity market statistics, each period’s deviation can be obtained, classify the deviation into each state, we can get the frequency of each state occurs. Since the data is discrete finite sequence, the probability of each state can be approximated by their frequency. Take the probability into formula (2), the entropy can be obtained.

3. Evaluation of the Operational Efficiency

3.1. Evaluation index system of the operational efficiency of electricity market

Complexity can affect the operational efficiency of the electricity market, measure the complexity of the electricity market can reflect the operational status of electricity market. Therefore, the evaluation of the operational efficiency of electricity market cannot do without complexity indicators. This paper refers the evaluation index system of the operational efficiency of electricity market researched by the previous scholars$^{[14]}$-$^{[18]}$, then we add the complexity measure system into the evaluation system, forming a compound electricity market evaluation index system as shown in figure 2. Finally the evaluation index system include five classes.
In the figure, HHI index can be measured by the quadratic sum of suppliers’ market share; Top-m is the market share occupied by the largest supplier of m, generally take m=4; degree of N-1 principle implementation and transient stability are qualitative indicators, their level can be measured by the value between 0 to 5; LI value is an indicator responsive to market efficiency, equals the deviation of market marginal price MP and marginal cost MC divided by the marginal price MP; market social benefits consist of consumer surplus and supplier surplus.

Fig. 2. Evaluation index system of the operational efficiency of the electricity market

3.2. Entropy-Random DEA model

The evaluation of the operational efficiency of electricity market is a problem of multi-input and multi-output, Data envelopment analysis is simple and easy to use, particularly can deal effectively with problem of multi-inputs and multi-outputs[19].

In the evaluation index system of the electricity market operational efficiency, we define indicator which is the smaller the better as input indicator, which is the bigger the better as output indicators, therefore, each DMU has 6 input indicators: the complexity of energy production, the complexity of electricity consumption, the complexity of transmission and distribution, HHI index, Top-m, the line loss rate; and has 7 output indicators: degree of N-1 principle implementation, transient stability, reserve capacity, electricity supply and demand ratio, plant utilization, LI value, the market social benefits.

However, the randomness and complexity of the modern electricity market is increasing faster and faster. The demand of evaluating the operational efficiency of the electricity market is increasingly unable to be met by the existing DEA models. Therefore, it is necessary to improve the current model by adding random constraints into the model to meet the need of evaluating electricity market’s uncertainty, while integrating the entropy metrics into the model to meet the need of evaluating electricity market’s complexity[20]. The improved model called entropy - random DEA model is as follows:
\[
\begin{align*}
\min w^T X - u^T Y + k(\sum_{i=1}^{m} w_i \ln w_i + \sum_{r=1}^{s} u_r \ln u_r) \\
\text{s.t.} \sum_{i=1}^{m} w_i + \sum_{r=1}^{s} u_r = 1 \\
Pr\{R(X,Y) \geq \beta\} \geq \alpha \\
(X,Y) \in S \\
w_i > 0, u_r > 0 \\
i = 1, \cdots, m, \quad r = 1, s
\end{align*}
\]

In the formula: \(X = (x_1, x_2, \cdots, x_m)\), \(Y = (y_1, y_2, \cdots, y_s)\) respectively represent DMU's inputs and outputs; \(w^T = (w_1, w_2, \cdots, w_m)\), \(u^T = (u_1, u_2, \cdots, u_s)\) are the weights of inputs and outputs. \(Pr\{\cdot\}\) represents the probability of the event in \(\{\cdot\}\) occurs, \((X,Y)\) represents the operational state of power market; \(R(X,Y)\) represents the reliability of state \((X,Y)\); \(\beta\) is a certain standard that the reliability should be reached; \(\alpha\) is a confidence level of the constraints given in advance; \(S\) is the set of all state of electricity market.

The model belongs to non-linear stochastic programming, chaos optimization algorithm is a better global optimal method to solve this problem, its efficiency is superior to the traditional optimization algorithms.

3.3. Chaos optimization algorithm solve entropy-random DEA by matlab

Using Chaos optimization algorithm to optimize the model (6) needs to solve the problem of large space dimension, while matlab can deal with multi-dimensional vectors and matrices easily, so we will use matlab programming. First define the variables and function of model (6), the objective function can be defined as \(f = x^w + y^u + 0.3333 \cdot \text{dot}(w,\log10(w)) + 0.3333 \cdot \text{dot}(u,\log10(u))\).

Then write the procedure of chaos optimization algorithm. First define the initial value of chaotic sequences, then use a while loop for the first carrier, the coarse search, after that start a second carrier, the fine search. Last the optimal value can be obtained. The programming code is given in the appendix.

4. Analysis of Cases

4.1. Complexity measure case of electricity market

Use simulation data shown in Table 2, according to the calculation steps of the complexity measurement, we can compute the complexity of power market.

To \(d_iS\) for example, calculate the monthly deviation of planned energy production and actual energy production, classify the twelve deviations into each state in accordance with the range of each state, thus we can obtain the frequency of each state as followed in Table 3.
Table 2. Monthly planned value and actual value (Unit TWh)

<table>
<thead>
<tr>
<th>Month</th>
<th>Planned production</th>
<th>Actual production</th>
<th>Planned consumption</th>
<th>Actual consumption</th>
<th>Planned transaction</th>
<th>Actual transaction</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1759.58</td>
<td>1754.23</td>
<td>1606.39</td>
<td>1611.03</td>
<td>1746.74</td>
<td>1745.01</td>
</tr>
<tr>
<td>2</td>
<td>1797.71</td>
<td>1802.28</td>
<td>1631.36</td>
<td>1634.11</td>
<td>1796.47</td>
<td>1778.63</td>
</tr>
<tr>
<td>3</td>
<td>1841.51</td>
<td>1839.52</td>
<td>1633.65</td>
<td>1642.18</td>
<td>1837.92</td>
<td>1832.37</td>
</tr>
<tr>
<td>4</td>
<td>1858.9</td>
<td>1864.25</td>
<td>1669.25</td>
<td>1662.51</td>
<td>1854.89</td>
<td>1851.36</td>
</tr>
<tr>
<td>5</td>
<td>1892.78</td>
<td>1889.43</td>
<td>1735.42</td>
<td>1723.23</td>
<td>1873.75</td>
<td>1875.27</td>
</tr>
<tr>
<td>6</td>
<td>1899.02</td>
<td>1910.96</td>
<td>1730.35</td>
<td>1742.21</td>
<td>1905.20</td>
<td>1902.10</td>
</tr>
<tr>
<td>7</td>
<td>1964.37</td>
<td>1973.24</td>
<td>1779.91</td>
<td>1774.28</td>
<td>1906.39</td>
<td>1911.03</td>
</tr>
<tr>
<td>8</td>
<td>2011.43</td>
<td>1997.15</td>
<td>1781.25</td>
<td>1772.52</td>
<td>1931.36</td>
<td>1934.11</td>
</tr>
<tr>
<td>9</td>
<td>2023.03</td>
<td>2020.16</td>
<td>1798.39</td>
<td>1792.15</td>
<td>1933.65</td>
<td>1942.18</td>
</tr>
<tr>
<td>10</td>
<td>2027.67</td>
<td>2031.54</td>
<td>1814.27</td>
<td>1812.64</td>
<td>1969.25</td>
<td>1962.53</td>
</tr>
<tr>
<td>11</td>
<td>2055.71</td>
<td>2048.18</td>
<td>1843.64</td>
<td>1833.66</td>
<td>2001.32</td>
<td>1993.23</td>
</tr>
<tr>
<td>12</td>
<td>2068.65</td>
<td>2071.32</td>
<td>1861.46</td>
<td>1870.31</td>
<td>2010.32</td>
<td>2012.20</td>
</tr>
</tbody>
</table>

Table 3. The deviation range of each state

<table>
<thead>
<tr>
<th>$x_j$</th>
<th>$x_1$</th>
<th>$x_2$</th>
<th>$x_3$</th>
<th>$x_4$</th>
<th>$x_5$</th>
<th>$x_6$</th>
<th>$x_7$</th>
<th>$x_8$</th>
<th>$x_9$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

The probability equals frequency approximately, so we can obtain the value of $p(x_j) \ln p(x_j)$, sum them according to formula (2) and the entropy of energy production side is obtained, it’s 1.9792.

Following the same calculation we can obtain the value of $d_1S$ and $d_2S$, they are 2.02281 and 1.82008. Therefore, the total entropy of the electricity market $d = d_1S + d_2S + d_3S = 5.822085$. The result tells that the total entropy of the electricity market is high, and slightly higher than the general market, mainly because that electricity should keep balance constantly between production and sales, it’s delivered by a complex physical network, impacted greatly by the economy, environment, people’s custom and so on. The complexity of electricity consumption is the largest, the second is the complexity of power production, the smallest is the complexity within the electricity market, mainly because different kinds of power clients consume in different time and capacity, which led to the instability of electricity consumption; the complexity of power production side is decided by the fluctuation in the price of coal resources, difficulty of adjusting the generators, regulatory mechanism of power generating and bidding; the complexity of electricity market is relatively small.

4.2. Entropy-random DEA evaluation process

Assume six regional electricity market Region 1, Region 2, Region 3, Region 4, Region 5, Region 6 respectively represent six DMUs, use simulation data of each region to evaluate as shown in Table 4.

For simplicity, assume that the reliability of the electricity market meet the chance constraint, preprocessing the data, take the first DMU Region 1 Power Market for example, put its input and output matrix into the model (6).

Using chaos optimization algorithm and matlab programming to optimize the model, we can get the value of Region 1’s objective function, it’s 0.871, according to the same way the optimal objective function value of other five DMUs can be obtained, the results shown in Table 5.
Table 4. Data of evaluation index of operational efficiency of each region

<table>
<thead>
<tr>
<th>Region</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>power production entropy</td>
<td>1.747</td>
<td>1.816</td>
<td>1.832</td>
<td>1.783</td>
<td>1.82</td>
<td>1.857</td>
</tr>
<tr>
<td>power consumption entropy</td>
<td>1.813</td>
<td>1.839</td>
<td>1.753</td>
<td>1.844</td>
<td>1.79</td>
<td>1.821</td>
</tr>
<tr>
<td>power transaction entropy</td>
<td>1.835</td>
<td>1.786</td>
<td>1.834</td>
<td>1.865</td>
<td>1.822</td>
<td>1.798</td>
</tr>
<tr>
<td>HHI indicator</td>
<td>4012</td>
<td>3421</td>
<td>3632</td>
<td>4703</td>
<td>4352</td>
<td>5031</td>
</tr>
<tr>
<td>Top-m(%)</td>
<td>63.5</td>
<td>61.3</td>
<td>59.7</td>
<td>65.3</td>
<td>66.9</td>
<td>60.2</td>
</tr>
<tr>
<td>N-1 principle implementation</td>
<td>4.2</td>
<td>5</td>
<td>3.9</td>
<td>3.6</td>
<td>3.3</td>
<td>4.5</td>
</tr>
<tr>
<td>transient stability</td>
<td>5</td>
<td>4.6</td>
<td>4.2</td>
<td>3.5</td>
<td>3.7</td>
<td>4</td>
</tr>
<tr>
<td>reserve capacity(MW)</td>
<td>76.15</td>
<td>60.6</td>
<td>110.67</td>
<td>71</td>
<td>29.5</td>
<td>75.33</td>
</tr>
<tr>
<td>supply and demand ratio(%)</td>
<td>1.05</td>
<td>1.12</td>
<td>1.23</td>
<td>0.97</td>
<td>0.93</td>
<td>1.17</td>
</tr>
<tr>
<td>plant utilization(%)</td>
<td>7.67</td>
<td>7.23</td>
<td>5.5</td>
<td>5.59</td>
<td>5.83</td>
<td>5.24</td>
</tr>
<tr>
<td>line loss rate(%)</td>
<td>16.39</td>
<td>12.78</td>
<td>12.66</td>
<td>8.45</td>
<td>7.33</td>
<td>8.67</td>
</tr>
<tr>
<td>LI value</td>
<td>0.25</td>
<td>0.21</td>
<td>0.24</td>
<td>0.19</td>
<td>0.2</td>
<td>0.22</td>
</tr>
<tr>
<td>market social benefits(billion)</td>
<td>4.03</td>
<td>3.71</td>
<td>3.84</td>
<td>4.33</td>
<td>4.25</td>
<td>3.97</td>
</tr>
</tbody>
</table>

Table 5. The optimal value of each market

<table>
<thead>
<tr>
<th>regional market</th>
<th>Region 1</th>
<th>Region 2</th>
<th>Region 3</th>
<th>Region 4</th>
<th>Region 5</th>
<th>Region 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optimal value</td>
<td>0.871</td>
<td>0.846</td>
<td>0.921</td>
<td>0.827</td>
<td>0.717</td>
<td>0.845</td>
</tr>
</tbody>
</table>

The data shows that the electricity market efficiency of region 5 is the lowest, probably because the comprehensive production capacity of region 5 is low, and is supported by high energy-consuming industries, also sparsely populated, so the operational efficiency of the electricity market is low. In contrast, the highest is the electricity market of region 3, the other four regions are small in difference.

5. Conclusion

(1) This paper, based on the complexity science, establishes the evaluation index system of the operational efficiency of the electricity market, and adds the indicators of the complexity of the electricity market into the system, gives us a new perspective to reflect the information of evaluating objects.

(2) A new study of the complexity measurement of the electricity market has been done in this paper, entropy as a measure of the complexity of the electricity market, is simple in calculation and realistically reflects the complexity of the electricity market.

(3) The use of entropy - random DEA chaos optimization model has good flexibility and feasibility for the evaluation of the operational efficiency of the electricity market.

References


**Appendix A. Matlab programming code of chaos optimization algorithm**

```matlab
function f= fz(z)
  x=[x1, x2, x3, x4, x5, x6];
  y=[y1, y2, y3, y4, y5, y6, y7];
  s=sum(z);
  w=z(1:6)./s;u=z(7:13))./s;
  f=x*w+y*u+0.3333*dot(w,log10(w))+0.3333*dot(u,log10(u));
  clear all
  No1=10000;
  No2=1000;
  a1=0; b1=1;
```

a2 = 0; b2 = 1;
c1 = a1 * ones(1, 11); d1 = (b1 - a1) * ones(1, 11);
a = 0.003;
n = 2;
N = n + 1;
k = 0;
u1k(1) = rand(1, 1);
for i = 2:11
    u1k(i) = u1k(i - 1) + 0.001;
end
Y0 = 0;
while (k <= No1)
    ult = 4 * u1k.*(1 - u1k);
z1N = c1 + d1.*u1N; % x2N = c2 + d1.*u2N;
    Yk = fz(z1N);
    if (k == 0)
        Y0 = Yk;
z10 = z1N;
        % x20 = x2N;
    end
    if (Yk <= Y0)
        Y0 = Yk;
z10 = z1N;
    end
    k = k + 1;
    u1k = z1N;
    % u2k = u2N;
end
Y0
z10
k = 0;
z10 = z10;
while (k <= No2)
    u1N = 4 * u1k.*(1 - u1k);
z1N = u1k; % x2N = u2N;
z1k = z10 + a*(z1N - 0.5*ones(1, 11));
    YK = fz(z1k);
    if (YK <= Y0)
\[ Y_0 = Y_K; \]
\[ Z_{10} = z_{1K}; \]
end
K = K + 1;
u_{1K} = u_{1N};
end
Y_0
Z_{10}