Research and Application of Multi-energy Complementary Comprehensive Energy Distributed Measurement and Control System

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Abstract. Multi-energy complementary integrated energy system has the problems of complex equipment operation, incomplete operation data monitoring and multi-time scale characteristics. In order to solve these problems, the operation state data of power, gas, cooling, heating network and distributed power supply as well as the operation state parameters of various networking energy consumption equipment at the load side were collected and monitored. This paper was optimized the system data collection and transmission method through multi-time scale data modeling and ultra-lightweight stream encryption algorithm, and the system operation multi-index evaluation system was constructed from three aspects of economy, technology and environmental protection. In this paper, the rationality and reliability of the scheme of stream encryption and the method of multi-index comprehensive evaluation were verified through the analysis of application examples. From multiple time scales, the system can monitor and control the change of heterogeneous energy stream, such as cooling, heating and electricity, and also can realize the high reliability data acquisition and real-time communication of multi-energy stream. It provided a data source for the real-time scheduling and control decision-making of the follow-up integrated energy system.

1. Introduction

With the depletion of traditional energy sources such as oil and coal and the aggravation of environmental pollution, the problems of environment and energy are becoming more and more serious. The proportion of renewable energy power generation is increasing, so if we want to build a clean and low-carbon modern energy system of sustainable development, we must improve the comprehensive utilization efficiency of energy. As a new regional energy supply system, the comprehensive energy system breaks the existing independent planning, design and operation mode of cold, heat, electricity, gas and other energy supply systems[1,2]. It can improve the utilization rate of

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renewable energy by coordinating and optimizing the distribution, transformation, storage and consumption of all kinds of energy. Multi-energy complementary integrated energy system has become an important research direction in the field of energy at home and abroad.

At present, scholars at home and abroad have done some research on multi-energy complementary integrated energy system, but they focus more on the concept, idea and basic theory of multi-energy complementary[3,4,5]. In China, the research on energy complementarity of integrated energy system started late. Although some pilot demonstration projects of integrated energy system have been implemented successively, there is still a lack of efficient control strategy and operation optimization scheme of multiple energy complementary system. The data measurement and control system with complete function and reasonable design is the premise and foundation of the research on the efficient control and optimization strategy of multi-energy complementary integrated energy system. As a complex system including different parts such as chiller module, generator module, waste heat recovery and utilization module, there are a large number of measurement units. Some devices without time calibration function make the measurement data of the system not in the same time section, and there are differences between intermittent energy and traditional energy equipment in data sampling frequency and optimal control time length, which makes the time scale of each link of the system source network load present diversified characteristics. The traditional measurement and control method based on single time scale is unable to meet the measurement and control requirements of integrated energy system. At the same time, there are still some problems, such as lack of data transmission confidentiality protection, centralized evaluation system on the power grid evaluation side and one-sided index setting, which require the measurement and control system to meet the requirements of multi-scale, comprehensive, real-time and intelligent.

In order to realize the real-time data acquisition, transmission and monitoring requirements of complete and high-performance heterogeneous energy stream, this paper used multi-time scale data modeling and data transmission encryption scheme suitable for advanced metering infrastructure to improve the existing measurement and control methods. Then, a multi-index comprehensive evaluation system which can comprehensively measure the economic benefits, reliable operation, energy and environmental protection, wind and power consumption, conversion efficiency and other characteristics of the comprehensive energy system was constructed. Finally, combined with practical engineering application, the distributed measurement and control system of multi-energy complementary comprehensive energy was designed and developed. The system greatly improved the comprehensiveness of the real-time state information collection and the accuracy of the measurement data processing of cooling and heating power system, and realized the multi energy stream high reliability data collection and real-time communication. It also provided strong technical support for joint simulation and efficient regulation of comprehensive energy system.

2. Theoretical basis of multi-time scale data acquisition, transmission and comprehensive evaluation method

2.1. Construction of uplink information model for multi-time scale data

The operation parameters of the energy equipment in the multi-energy complementary integrated energy system include constant parameters and periodic parameters, and the sampling period of the system measurement data is diverse, which does not match the control period of the equipment. So the data of both sides are not in the same time section, which increases the control difficulty of the measurement and control system. To solve this problem, we build an information model to solve the problem of data time section inconsistency. The information model is built as a mapping from the data of the lower layer to the upper layer[6,7].

The input $X_D$ of the lower sensing layer is the relevant parameter with time scale, and the output $Y_C$ is the data of the same time section required by the information processing algorithm of the upper monitoring layer, which is mapped as follows:

$$Y_C = T_{D-C} \cdot X_D$$  \hspace{1cm} (1)
Where $T_{D-C}$ is the mapping function in the time scale transformation matrix from input $X_D$ to output $Y_C$. In the mapping function, $E_P$ and $F_Q$ are determined by different types of input data, which are respectively $P$ constant type input data $x_c$, $Q$-P sampling time $t_i$ and sampling period $T_i$ periodic measurement data $x_{Q,T_i}$.

The mapping function $E_P$ of the constant class input data $x_c$ is the same dimension unit matrix as $y_{1,c}$ and $x_{1,c}$.

For the periodic measurement data with nonuniformity of time section, the mapping relationship between the $q$-th input data $x_{q,T_i}$ and the corresponding output control time $t$, the output $y_{q,T_i}$ of control period $T$ is:

$$y_{q,T_i} = \begin{cases} x_{q,T_i}, & \text{if } t = t_i \\ f(x_{q,T_i})x_{q,T_i}, & \text{other} \end{cases} \quad (3)$$

Where $f(x_{q,T_i})$ is a fitting function based on the historical data of the input data $x$, and the symbol $|$ indicates that the period $T$ is an integral multiple of the period $T_i$.

### 2.2. Stream encryption scheme based on ultra lightweight

The security of stream cipher depends on the unpredictability and randomness of key stream. In the stream cipher algorithm, the encrypting party and the decrypting party use a pair of keys. Each time, the plaintext data is encrypted in sequence with the key stream to obtain the ciphertext stream[8-11].

The key of the encryption party consists of the measurement unit ID and the string key generated by the decryption party.

The encrypting party uses the encryption algorithm to encrypt the hash value of the key stream $K_i$ and the explicit stream $M_i$ by xor operation to obtain the ciphertext stream $C_i$, and sends the ciphertext stream to the data decrypting party for analysis. The specific encryption algorithm formula is as follows:

$$k_i = C_i \oplus \text{Hash}(M_i \oplus \text{Key})$$

$$C_i = \text{Hash}(K_i) \oplus M_i \quad i=1,2,\ldots,n \quad (4)$$

The measurement unit first collected the plaintext stream data $M_i$ of the heterogeneous energy stream of the measured equipment, and then judge whether the last ciphertext stream $C_i$ exists. If not, namely $i=1$, bring $C_0 = \text{Hash}((\text{ID}, \text{Key}) \oplus \text{Hash}((\text{Key}, \text{ID}))$ and $M_0 = \text{Hash}((\text{ID}, \text{Key}) \oplus \text{Hash}((\text{Key}, \text{ID}))$ into the formula to calculate the key stream $k_i$, and do the sha256 hash operation on it. Finally, the ciphertext stream is obtained by exclusive or with plaintext stream. If it exists, namely $i > 1$, the cipher stream $C_{i-1}$ and the plaintext stream $M_{i-1}$ sent by the encrypting party in the previous time are substituted into the formula.

### 2.3. Operation multi index comprehensive evaluation system

Because there are many indexes used in the multi-energy complementary integrated energy system, the indexes are treated in layers[12,13]. The construction and operation of multi-index comprehensive evaluation system structure are shown in Table 1. Firstly, it constructs dimensions from three aspects
of economic benefits, technical performance and environmental value, and sets 6 first level indicators, 14 second level indicators and 6 third level indicators.

Table 1. Operation multi-index comprehensive evaluation system.

| Dimension       | First level indicators          | Second level indicators                | Third level indicators                                                                 |
|-----------------|---------------------------------|----------------------------------------|----------------------------------------------------------------------------------------|
| Economic benefits | Equipment economy               | Equipment utilization                  | Average power loss time of electric energy                                               |
|                  | Benefits                         | Equipment maintenance cost saving      | Average power loss time of thermal energy                                                 |
|                  |                                  | Heating profit                         | Average power loss time of cold energy                                                  |
|                  |                                  | Power supply profit                    |                                                                                         |
| Technical performance | Reliability                    | Average power loss time                |                                                                                         |
|                  |                                  | Power supply reliability              |                                                                                         |
|                  |                                  | Electric energy loss rate              |                                                                                         |
|                  |                                  | Cold energy loss rate                  |                                                                                         |
|                  |                                  | Thermal energy loss rate               |                                                                                         |
| Energy efficiency | Network loss                   | Distribution network loss rate         |                                                                                         |
|                  |                                  | Heat loss rate of pipe network         |                                                                                         |
|                  |                                  | Cold loss rate of pipe network         |                                                                                         |
| Environmental value | Environmental protection | Carbon emissions                       |                                                                                         |
|                  |                                  | Emission of gas pollutants            |                                                                                         |
|                  |                                  | Low carbon energy substitution ratio   |                                                                                         |

3. Design and construction of distributed measurement and control system of multi-energy complementary comprehensive energy

3.1. Overview of the overall architecture

Based on the advanced metering infrastructure, this paper designs and constructs a distributed measurement and control system suitable for multi-energy complementary integrated energy system. Figure 1 shows the overall architecture of the system. The whole system consists of three parts: the field sensing layer, the open network layer and the remote measurement and control platform.

The distributed measurement and control system of multi-energy complementary comprehensive energy is divided into two levels. The first level is deployed in the remote control center, which is constructed by encryption machine, key server, database server group, automatic data collection server group, measurement data processing server group, and Web server, and so on. It has 3D visualization, remote operation control, full situation awareness, accurate operation state evaluation, real-time data monitoring and other functions. The second level is deployed in the data acquisition nodes of the cold, hot, electric, gas networks and the operation equipment on the load side of each area. The wireless multi-energy stream measurement network is composed of numerous distributed micro measurement units. It is responsible for data sensing, synchronous acquisition, real-time transmission, analysis and processing, while the distributed measurement and control network is responsible for the control operation of all remote control equipment.

The distributed micro measurement unit in the field sensing layer synchronously collects the operation state data of electricity, gas, cooling and heating networks as well as the operation state parameters of all kinds of networking energy consumption equipment at the load side. The unit unifies the time section by means of multi-time scale data modeling, and collects the measurement data to the intelligent data collection route through the wireless multi energy stream measurement network. The open network layer uses 4G wireless network to encrypt and upload the data of distributed micro measurement unit to the remote measurement and control platform for analysis, processing and
evaluation. According to the operation state of the calculated comprehensive energy system, the user can send the execution command to the distributed measurement and control network to control and adjust the field devices.

![Figure 1. Overall system architecture diagram.](image)

3.2. System functional characteristics
The integration of multi-energy complementary integrated energy distributed measurement and control system has realized functions such as 3D panoramic visualization[14], remote equipment control management, data processing and state evaluation, accident early warning and security situation awareness, online data exchange and sharing. The specific functions are as follows:

1. Integrated energy system can be visualized by 3D panorama. Through the laser scanning modeling and visual rendering technology, a 3D digital model of the operation equipment of the multifunctional complementary integrated energy system is established, and the specific situation of the system is displayed with visual graphics to realize the 3D scene browsing and interoperability.

2. Equipment can be controlled and managed remotely. The platform generates an effective operation scheme, which can perform remote control and lifting operations on the equipment. The system automatically counts the total number of remote controls and the number of successful remote controls, and records the specific content of the operation process, including the operator, time, content, results, and so on.

3. Data processing and status assessment. The measurement data processing service group comprehensively processes and analyzes the large capacity real-time data monitored on site, and online evaluates the real-time operation status of the comprehensive energy system. The system has
the functions of automatically generating physical examination reports of all devices in the system, outputting data statistical reports and chart analysis.

(4), The system realizes accident early warning and security situation awareness. The data obtained by the measurement data processing service group would be analyzed on a year-on-year basis and a month-on-month basis, and the overall security situation of the integrated energy system would be further calculated. After the situation prediction results were obtained, the failure warning would be issued according to the warning classification and priority.

(5), Data can be exchanged and shared online. The monitoring data of the system has been processed in a hierarchical and systematic way, and output to the outside through the Web mirror phase server isolated outside the monitoring system in a standardized form. By this way, data sharing with the joint simulation and control system support platform was carried out.

4. Analysis of system application and performance

4.1. Examples of System application
The multi-energy complementary integrated energy distributed measurement and control system has been put into operation and tested in the demonstration project of distributed energy system - Sino German ecological park on the west coast of Qingdao in January 2020. The park is equipped with 1082kW distributed photovoltaic system, two 772.8 kW ground source heat pump host supporting outdoor buried pipe system, as well as a set of natural gas cooling and heating cogeneration system composed of two 400 kW natural gas internal combustion engines, two 0.3t/h flue gas waste heat boilers, two 470 kW steam hot water LiBr units, one 40 kW screw ORC expansion generator unit and one 1200kW direct fired absorption heat pump.

Figure 2-Figure 4 shows the real-time monitoring of parameters, dynamic 3D visualization and situation awareness, and remote control interface during system operation. At present, the system runs stably, the data measurement is real-time and reliable, and it can accurately monitor and control the change of heterogeneous energy stream, such as cooling, heating and electricity. It has accumulated a
lot of data for the research of the optimization control method, energy complementary strategy and economic operation mode of the multi-energy complementary integrated energy system.

4.2. Security analysis of data transmission

In order to verify the data transmission security of the multi-energy complementary integrated energy distributed measurement and control system, this paper sets the attack mode as intercepting information in the communication process. After that, the impact of the key information loss of the measurement unit on the key information of the remaining measurement unit after the fall of the sensor layer data acquisition node between the literatures [8,11] and this encryption scheme was analyzed. Literature [8] may expose the ID corresponding to the vector group and the key after being attacked and fallen; in literature [11], discrete logarithm and pairwise key function values may be exposed; in this paper, column vector, ID value and key value may be exposed after the node is fallen, but the attacker cannot get pairwise key information. In the attack test of the same intensity, the relationship between the number of fallen measurement units of the three schemes and all the key of the system is shown in Figure 5.

![Figure 5](image-url)

It can be seen from Figure 5 that the number of fallen measurement units has the smallest impact on this scheme. In the face of attack, with the increase of the number of fallen measurement units in literature [11], the number of keys obtained by the attacker increases significantly. However, although the number of as-obtained keys in reference [8] is less than that in reference [11], the probability is still higher than that in this paper. This proves that the super lightweight stream encryption scheme proposed at present has better security in the process of data transmission.

4.3. Effectiveness analysis of multi index comprehensive evaluation of system operation

In order to verify the rationality of the operation multi-index comprehensive evaluation system proposed in this paper, the distributed micro measurement unit installed on the site of the ecological park is used to collect the operation status data of the system. After that the actual evaluation and analysis of the operation status of the system are carried out based on the weight and scoring results of each index in the index system.

Single evaluation method has one sidedness. Thus, in order to make the index weight as objective and accurate as possible, this paper combines analytic hierarchy process and entropy method to determine the index weight [15,16,17]. It is assumed that the upper level index dominates the next level index $D_1, D_2, \ldots, D_n$, the judgment matrix $D$ is constructed according to the degree of relative importance:
### Formula

1. 
   
   \[
   D = D_{ij} = \begin{bmatrix}
   D_{11} & D_{12} & \cdots & D_{1n} \\
   D_{21} & D_{22} & \cdots & D_{2n} \\
   \vdots & \vdots & \ddots & \vdots \\
   D_{n1} & D_{n2} & \cdots & D_{nn}
   \end{bmatrix}
   \]  
   
   \[D_{ij}\] is the important value of factor i and factor j relative to the index.

2. 
   
   The initial weight coefficient \(W_j\) is calculated through 
   
   \[
   W_j = \sqrt[\sum n \prod M_j]{\sum n \prod M_j}^{-1}
   \]  
   
   \(M_j\) is the product of each row element of judgment matrix \(D\).

3. 
   
   The entropy value \(E_j\) of each index is used to get the correction coefficient \(\sigma_j\) through 
   
   \[
   \sigma_j = \left(1 - E_j \right) \left(\sum n \prod E_j \right)^{-1}
   \]  
   
   and the objective weight coefficient \(\mu_j\) is obtained after the initial weight coefficient \(W_j\) was modified by entropy weight method through 
   
   \[
   \mu_j = \sigma_j \left(\sum n \prod W_j \right)^{-1}
   \]

4. 
   
   The subjective and objective weight important coefficients \(\alpha_j\) and \(\beta_j\) of each index are calculated:
   
   \[
   \begin{align*}
   \alpha_j &= W_j \left(\mu_j + \mu_j\right)^{-1} \\
   \beta_j &= \mu_j \left(\mu_j + \mu_j\right)^{-1}, 1 \leq i \leq n
   \end{align*}
   \]  
   
   Combining the weight coefficients \(W_j\), \(\mu_j\) and the subjective and objective weight important coefficients, the combined weight factor \(W^o_j\) is obtained:

   \[
   W^o_j = (\alpha_j W_j + \beta_j \mu_j) \left(\sum n \prod (\alpha_j W_j + \beta_j \mu_j)\right)^{-1}
   \]

According to the above methods, the weight of each index is calculated. Due to the limited space, only the calculation results of index weight are shown in the paper, and the specific weight factors are shown in Table 2.

### Table 2. Weight factors.

| First level index  | Weight | Second level index | Weight | Third level index | Weight |
|--------------------|--------|--------------------|--------|------------------|--------|
| Equipment economy  | 0.2892 | Equipment utilization | 0.1753 |                   |        |
|                    |        | Equipment maintenance cost saving | 0.1139 |                   |        |
| Benefits           | 0.1385 | Cooling benefits    | 0.0229 |                   |        |
|                    |        | Heating benefits    | 0.0405 |                   |        |
|                    |        | Power supply benefits | 0.0751 |                   |        |
|                    |        | Average power loss time of electric energy | 0.0437 |                   |        |
|                    |        | Average power loss time of thermal energy | 0.0106 |                   |        |
|                    |        | Average power loss time of cold energy | 0.0094 |                   |        |
| Reliability        | 0.2264 | Power supply reliability | 0.1125 |                   |        |
|                    |        | Energy failure rate | 0.0502 |                   |        |
|                    |        | Electric energy loss rate | 0.0092 |                   |        |
|                    |        | Cold energy loss rate | 0.0291 |                   |        |
|                    |        | Thermal energy loss rate | 0.0119 |                   |        |
| Energy efficiency  | 0.2021 | Distribution network loss rate | 0.0198 |                   |        |
| Network loss       | 0.1342 | Heat loss rate of pipe network | 0.0641 |                   |        |
|                    |        | Cold loss rate of pipe network | 0.0503 |                   |        |
| Environmental      | 0.1096 | Carbon emission    | 0.0501 |                   |        |
The combined weight of the multi-index comprehensive evaluation system is synthetically operated. The weighted least square method [18] is used to solve the state estimation problem, and the Lagrangian function \( L(x, \lambda) \) is constructed as follow:

\[
L(x, \lambda) = \frac{1}{2} [z - h(x)]^T W [z - h(x)] - \lambda^T c(x)
\]

(8)

Where \( \lambda \) is the Lagrange coefficient, \( z \) is the scalar, \( x \) is the state variable, \( h(x) \) is the index function, \( W \) is the weight matrix, and \( c(x) \) is the equality constraint. In order to solve the running state of the system, Newton iterative method is used to form the iterative equation, which is iterative until the equation converges. At the same time, in the process of iteration, the residual detection method is used to eliminate the measurement data with large measurement error, so as to reduce the impact of measurement error and measurement bad data on the evaluation results. The comparison between the state estimation method in this paper, the fuzzy evaluation method and the actual value is shown in Table 3.

| Method of calculation | Economic benefits | Technical performance | Environmental value | Total score |
|-----------------------|------------------|-----------------------|---------------------|------------|
| Fuzzy evaluation      | 87.156           | 47.521                | 29.499              | 57.723     |
| This paper            | 86.991           | 42.135                | 35.173              | 60.857     |
| Actual value          | 86.988           | 42.017                | 34.987              | 60.392     |

From Table 3, it can be seen that compared with the results of data processing and correction by using fuzzy evaluation method, the deviation between the method in this paper and the real value is smaller, which can more truly reflect the operation state of the system.

5. Conclusions

Multi-energy complementary integrated energy system is a complex system with multiple energy streams, including cold, heat, electricity, gas and so on, and its devices are complex and diverse. What's more, it has the characteristics of information data diversity and multi-time scale. The data measurement and control system with complete functions and reasonable design are the premise and foundation of the research on multi-energy complementary integrated energy system. In view of the diversity of information data and the characteristics of multiple time scales in the multi-energy complementary integrated energy system, this paper designed a distributed micro measurement unit with data uplink information model, and a super lightweight stream cipher encryption scheme and a multi-index comprehensive evaluation method were also constructed. Finally, we constructed a multi-energy complementary system with panoramic visualization, full situation awareness, remote control of equipment and other functions integrated energy distributed measurement and control system. The reliability and effectiveness of the encryption scheme and the comprehensive evaluation method were verified through the analysis of the system application examples. The design and successful application of the distributed measurement and control system had accumulated a lot of data for the research on the efficient optimization strategy of the multi-energy complementary integrated energy system. The system also provided a system platform and technical basis for the research on the active management mechanism of the system "source-network-load". This is of great significance for State Grid Corporation to develop the comprehensive energy business on a large scale and build a clean and efficient modern energy system.

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