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MULTI-OBJECTIVE OPTIMAL SCHEDULING METHOD OF COMBINED COOLING, HEATING AND POWER SUPPLY MICRO-ENERGY NETWORK UNDER FEM-SPH COUPLING

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Abstract. To enhance the multi-objective scheduling capability of cogeneration microgrids, this study proposes a novel multi-objective optimal scheduling method based on FEM-SPH coupling. A coupling control model integrating physical energy storage and chemical energy storage is established for the combined cooling, heating, and power (CCHP) micro-energy network. By analyzing the rated power and energy efficiency of the micro-energy network, adaptive scheduling is achieved through decoupling analysis of stored energy and its associated power. Utilizing power and energy density characteristics, FEM-SPH coupling control is implemented for cogeneration microgrid scheduling. Based on grid load demand and self-contained energy storage analysis, a comprehensive operational cost control framework is developed for the multi-objective optimization process. The multi-objective optimal scheduling of the CCHP micro-energy network is realized by incorporating adaptive adjustments in power-to-gas conversion and gas turbine operation. Simulation results demonstrate that the proposed method exhibits superior energy matching, strong optimization capability, and high system reliability, while improving the operational efficiency of each unit. The application of this method effectively balances the load demand of the energy network.

Mathematics Subject Classification. 90C30.

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1. Introduction

The multi-objective scheduling of cogeneration micro-energy networks is formulated through operational cost analysis and dynamic parameter optimization [1–3], establishing a comprehensive operational framework that integrates parameter identification for optimal performance. In reference [4], a multi-objective optimal scheduling method for combined cooling, heating, and power (CCHP) micro-energy networks is proposed, incorporating stochastic scheduling of cooling/heating loads and renewable energy integration. Direct current (DC) technology plays a pivotal role in optimizing resource allocation in China while addressing energy and environmental challenges. The advancement of flexible DC technology enhances renewable energy integration, improves power

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Keywords. FEM-SPH coupling, combined supply of cold, heat and electricity, micro-energy network, multi-objective optimal scheduling.

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supply reliability, and overcomes technical limitations in DC transmission and AC grid interoperability. As relay protection constitutes the primary defense for power system stability, it remains a critical technical challenge in flexible DC system deployment. Following an overview of DC technology development, this study analyzes and summarizes the fault characteristics and protection requirements of flexible DC transmission lines. Subsequently, the research status of key line protection technologies in flexible DC systems is reviewed based on protection principles. Finally, while identifying gaps and future demands in DC line protection technology, prospects for further development are outlined, alongside cogeneration micro-energy network control applications. However, this method exhibits limited adaptability and stability in micro-energy network scheduling. Reference [5] presents a CCHP microgrid scheduling model based on mixed-integer linear programming (MILP) control. This investigation focuses on fault traveling wave propagation characteristics in ring-type DC networks, revealing amplitude disparities between forward and reverse waves in faulted *versus* healthy lines. A novel fault identification method is developed by calculating the forward-to-reverse wave amplitude integral ratio within a post-fault time window, while a bipolar flexible DC system fault pole selection criterion is established. Integrating these with catastrophe theory-based initiation criteria, a boundary-element-free pilot protection scheme is proposed to optimize dispatch models. PSCAD/EMTDC simulations demonstrate the scheme's reliable fault zone identification capability, with strong transition resistance immunity and noise rejection. Nevertheless, the method shows limitations in adaptive stability and error feedback, indicating areas for improvement. Reference [6] introduces a distributed data quality management and information fusion approach for CCHP microgrid optimal scheduling. Utilizing the least squares method, this approach identifies fault current trends by fitting sampled data curves, enabling rapid fault detection and multi-objective energy network scheduling. PSCAD/EMTDC simulations verify the method's effectiveness and reliability, though its scheduling capability remains suboptimal. Reference [7] proposes a microgrid scheduling method incorporating long- and short-term energy storage, constructing a wind-solar-hydrogen microgrid system with component-level scheduling models. Leveraging hydrogen storage for long-term energy retention and batteries for short-term supply, an economically optimized dispatch model is formulated as a mixed-integer linear programming problem solved *via* Yalmip/Gurobi. Simulation results demonstrate improved renewable energy utilization through cross-seasonal storage coordination, albeit with multi-objective scheduling constraints. Reference [8] develops a multi-agent reinforcement learning approach with attention mechanisms for microgrid energy trading and scheduling. Treating individual microgrids as autonomous agents, the method enables decentralized control with reduced communication overhead while preserving privacy. MATLAB R2020a simulations confirm operational cost reductions compared to conventional methods, though multi-objective scheduling performance remains limited. Reference [9] presents a supply chain marginal profit maximization model using data envelopment analysis, optimizing resource allocation based on energy and power loss reduction. While demonstrating potential for emission reduction and productivity growth, practical scheduling performance proves inadequate. Reference [10] proposes a resilience enhancement strategy for multi-microgrid systems through distributed energy scheduling and network reconfiguration. A hierarchical architecture with robust outage management is implemented, featuring pre-disturbance prevention *via* robust optimization and post-disturbance recovery through dynamic reconfiguration. Elasticity metrics quantify system resilience in modified IEEE 33-node tests, though adaptability requires improvement. Reference [11] introduces a multi-objective optimization task scheduling method for cognitive vehicular networks using edge computing. A particle swarm optimization-based energy-efficient scheduling algorithm balances energy consumption and execution time in MATLAB simulations, yet exhibits suboptimal scheduling efficiency.

To address these challenges, this paper proposes a multi-objective optimal scheduling method for micro-energy networks based on Finite Element Method-Smoothed Particle Hydrodynamics (FEM-SPH) coupling. Simulation results demonstrate the superior performance of this method in enhancing multi-objective optimal scheduling capability for combined cooling, heating, and power (CCHP) micro-energy networks. The key innovations include:

(1) Establishment of a coupled control model integrating physical and chemical energy storage for CCHP microgrid operation;

(2) Realization of adaptive scheduling through decoupling analysis of stored energy and power by evaluating the rated power and energy efficiency of cogeneration micro-energy networks;
(3) Implementation of the FEM-SPH coupling algorithm for real-time scheduling control in cogeneration systems;
(4) Development of a multi-objective cost control framework considering grid load demand and integrated energy storage characteristics for CCHP microgrid optimization;
(5) Achievement of optimal CCHP microgrid scheduling through adaptive power-to-gas conversion and gas turbine coordination.

2. Multi-objective optimal scheduling model and parameter configuration of micro-energy network

2.1. Multi-objective optimal scheduling model of micro-energy network under FEM-SPH coupling

FEM-SPH coupling integrates two distinct numerical simulation techniques: the Finite Element Method (FEM) and Smoothed Particle Hydrodynamics (SPH). FEM is a numerical technique for approximating solutions to boundary value problems involving partial differential equations. It discretizes a continuum into numerous interconnected finite elements through nodal connections, with the system solution obtained by selecting approximation functions within each element and determining the extremum of total potential energy variation. This method finds extensive application in solid mechanics, fluid mechanics, and heat transfer analysis. Smoothed Particle Hydrodynamics (SPH) represents a meshless Lagrangian particle method that solves complex fluid dynamics problems by discretizing continua into physical property-carrying particles, where interparticle interactions govern system dynamics. As a mesh-free approach, SPH effectively handles large deformations and fracture phenomena. The FEM-SPH coupling method combines these techniques to solve multiphysics problems involving both solid structures and fluid dynamics. The coupling process allows for either local or global integration of FEM and SPH domains according to specific problem requirements.

To achieve multi-objective optimal scheduling in combined cooling, heating, and power (CCHP) micro-energy networks and acquire real-time operational parameters, this study examines the integrated energy system comprising multiple energy sources:

(1) Electrical energy: supplied through grid connections, photovoltaic systems, and wind turbines;
(2) Thermal energy: generated by micro gas turbines and gas boilers for space heating and domestic hot water applications;
(3) Cooling energy: produced by absorption chillers and electric chillers to meet air conditioning and refrigeration demands;
(4) Natural gas: utilized as fuel for energy conversion equipment including micro gas turbines and gas boilers.

The micro-energy network (MEN), a concrete manifestation of the Energy Internet, integrates multiple energy forms including electricity, heat, cooling energy, and natural gas. Through comprehensive energy management and real-time dispatch, this system achieves localized energy production and consumption while improving overall efficiency and supply reliability.

A hybrid control model for combined cooling, heating, and power (CCHP) systems is established, integrating Line-Commutated Converter High Voltage Direct Current (LCC-HVDC) and Voltage-Source Converter High Voltage Direct Current (VSC-HVDC) technologies. The structural description of the operational control system for the CCHP micro-energy network is presented, with the corresponding system structure diagram shown in Figure 1.

Based on the system structure model depicted in Figure 1 and considering the stochastic fluctuations of user loads, a tower-type concentrated solar power (CSP) generation control model is developed using linear Fresnel solar thermal power generation technology. Through active power conversion control in solar thermal generation,

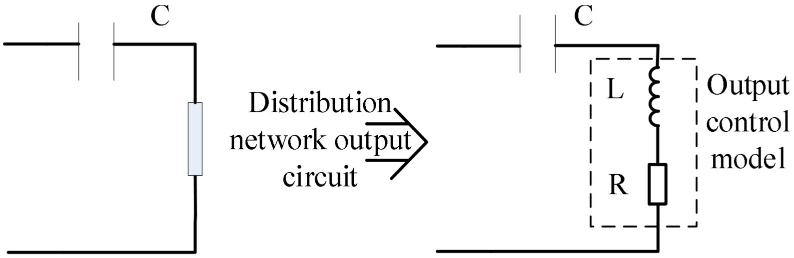


FIGURE 1. Micro-energy network structure diagram.

an integrated operational control model for the combined cooling, heating, and power (CCHP) micro-energy network is established, as described below:

$$M_n = u(t) \times \rho(t) \tag{1}$$

where, $u(t)$ represents the conversion voltage of the concentrated solar power (CSP) system, while $\rho(t)$ denotes the cooling/heating source parameter. During phase transitions of thermal/cooling media between solid, liquid, and gaseous states, the system temperature remains essentially constant. The fuzzy scheduling function for operational control of the combined cooling, heating, and power (CCHP) micro-energy network is expressed as:

$$\chi = \beta \times M_n \times d(t) \tag{2}$$

where, β represents the fan output power coefficient and $d(t)$ denotes the thermal storage dynamic parameter. Due to the discontinuous power output characteristics of the generation system and wind energy curtailment implemented by the control system, the fuzzy state characteristic objective function for operational control of the combined cooling, heating, and power (CCHP) micro-energy network is formulated as follows:

$$u = \chi \times k \tag{3}$$

where, k denotes the nodal distribution structural parameters of the combined cooling, heating, and power (CCHP) micro-energy network. Based on the transmission system's topological configuration and control strategy, the adaptive optimization function for photovoltaic power generation output adjustment is derived as follows:

$$F_j = \sum_{k=1}^{n} X_{kj}, \quad Q_j = \sum_{k=1}^{n} (X_{kj})^2 \tag{4}$$

where, X_{kj} represents the characteristic parameters disturbed by ambient temperature; n represents the number of characteristic parameters.

The relationship between power grids and microgrids exhibits three fundamental characteristics:

(1) Hierarchical structure where the main grid (macroscopic energy network) provides wide-area power supply while microgrids (local energy systems) function as complementary extensions;
(2) Complementary functionality whereby microgrids decrease main grid dependence through renewable generation and energy storage while enhancing system reliability by supplying emergency power during main grid failures;
(3) Dynamic interaction featuring bidirectional power exchange that enables energy flow between systems – microgrids purchase power during energy deficits and sell surplus power to the main grid.

The multi-objective optimal scheduling for combined cooling, heating, and power (CCHP) micro-energy networks primarily focuses on four key objectives:

(1) Economic efficiency through operational cost minimization by optimizing dispatch strategies that account for fuel consumption, maintenance requirements, and electricity procurement expenses;
(2) Environmental sustainability achieved by reducing carbon emissions and other pollutants while enhancing energy efficiency to promote green development;
(3) System reliability ensuring stable microgrid operation across diverse conditions to consistently meet multiple energy demands;
(4) Operational flexibility enhanced through improved adaptability to renewable energy fluctuations *via* integrated energy storage systems and demand response mechanisms.

Based on storage media differentiation within the alternating current (AC) voltage components of combined cooling, heating, and power (CCHP) microgrids, a hybrid doubly-fed configuration emerges that further classifies energy storage into electrochemical energy storage categories as follows:

$$x_i^{(k+1)} = (1-\omega)x_i^{(k)} \times \left(b_i - \sum_{j=1}^{n} a_{ij} x_j^{(k+1)} - \sum_{j=i+1}^{n} a_{ij} x_j^{(k)} \right) \tag{5}$$

where, ω represents the relaxation factor; $x_i^{(k)}$ denotes the steady-state characteristic value maintained throughout the scheduling cycle; b_i corresponds to micro-energy network emissions during islanded operation; a_{ij} signifies the operational cost parameter; $x_j^{(k)}$ indicates the homomorphic parameters of hybrid doubly-fed electrochemical energy storage. Under weak AC system conditions, the reactive voltage state distribution characteristics of the combined cooling, heating, and power (CCHP) micro-energy network are determined. By integrating these with islanded operation capabilities, a comprehensive multi-objective optimal scheduling model for micro-energy networks is achieved.

The microgrid and main grid maintain a tightly-coupled cooperative relationship requiring coordinated energy flow management and bidirectional power exchange to achieve system-wide optimization during operational scheduling. During microgrid energy shortages, user demand is supplemented through main grid dispatch support, while generation surpluses are fed back into the main grid through bidirectional power transfer. Additionally, the microgrid enhances grid stability by mitigating renewable energy intermittency through integrated energy storage systems and demand response mechanisms, thereby minimizing adverse impacts on the main grid. This synergistic interdependence facilitates efficient energy utilization while ensuring reliable operation across both networks.

2.2. Multi-objective optimal scheduling parameter configuration for micro energy networks

Through comprehensive analysis of rated power and energy efficiency characteristics in combined cooling, heating, and power (CCHP) micro-energy networks, adaptive scheduling is achieved *via* decoupling analysis of stored energy [12]. A dynamic parameter adjustment model is developed to optimize scheduling quality, energy distribution, and fusion characteristics within CCHP micro-energy networks. During frequency coupling processes, the autonomous disturbance characteristic state equation for the CCHP micro-energy network is expressed in equation (6):

$$\begin{cases} \sigma_1\left(\varphi_a, \dot{\varphi}_a\right) = \frac{1}{1+e^{-(\omega_{11}\varphi_a+\omega_{21}\dot{\varphi}_a)}} \\ \sigma_2\left(\varphi_a, \dot{\varphi}_a\right) = \frac{1}{1+e^{(\omega_{21}\varphi_a+\omega_{22}\dot{\varphi}_a)}} \\ \sigma_3\left(\varphi_a, \dot{\varphi}_a\right) = \frac{1}{1+e^{-d(\omega_{11}\varphi_a+\omega_{21}\dot{\varphi}_a)}}. \end{cases} \tag{6}$$

In equation (6), $-(\omega_{11}\varphi_a + \omega_{21}\dot{\varphi}_a)$ represents the power generation equipment parameter, $(\omega_{21}\varphi_a + \omega_{22}\dot{\varphi}_a)$ denotes the energy storage equipment parameter, and $-d(\omega_{11}\varphi_a + \omega_{21}\dot{\varphi}_a)$ corresponds to the cooling/heating source equipment parameter. During output control and power dispatch scheduling in the combined cooling, heating, and power (CCHP) micro-energy network, $d(\bullet)$ serves as the differential operator. Through terminal load stability control, the gradient function for optimal scheduling quality distribution and fusion feature security control is derived as $d(\bullet)$, where the second-order gradient is expressed as the k-th iteration value. For islanded CCHP microgrids operating without main grid support, a multi-objective optimization framework is developed using Smoothed Particle Hydrodynamics (SPH) methodology. By comparing single *versus* multi-objective parameters (including voltage deviation and frequency stability) and analyzing voltage disturbance/current response components, the resulting coupling state function meets operational requirements through autonomous control mechanisms.

$$g_k + A_k \Delta x_k = 0 \tag{7}$$

where, g_k represents the coupled state value exceeding corresponding minimum thresholds, Δx_k denotes the energy scheduling output gradient gain, and A_k indicates energy consumption. Through adaptive gain control, the proposed multi-objective scheduling method coordinates economic-environmental-reliability trade-offs in microgrid operation, achieving optimal multi-energy dispatch *via* coupled consumption optimization.

$$x_{k+1} = x_k - A_k^{-1} g_k. \tag{8}$$

By evaluating the satisfaction levels of each objective function and maximizing utilization of internal wind and photovoltaic resources, a fusion security control methodology yields a characteristic solution set m_{aggr}. This approach fully exploits the inherent characteristics of wind and photovoltaic generation, deriving an iterative function for optimal scheduling quality distribution in combined cooling, heating, and power (CCHP) microgrids:

$$x_{k+1} = x_k - \left[J^T(x_k)J(x_k) + \mu_k I\right]^{-1} J^T(x_k)\, v(x_k) \tag{9}$$

where, J represents the joint constraint parameter integrating power supply, heating, cooling, and gas distribution systems, while $v(x_k)$ denotes the membership function and μ_k corresponds to the mixed-integer linear programming characteristic quantity. Building upon these parameters, a multi-objective optimal scheduling configuration model for micro-energy networks is developed. Through comprehensive power-energy density characteristic analysis, the model implements Finite Element Method-Smoothed Particle Hydrodynamics (FEM-SPH) coupling control for combined cooling, heating, and power (CCHP) microgrid scheduling operations.

3. Multi-objective optimal scheduling model optimization for energy networks

3.1. FEM-SPH coupling control for scheduling of micro energy networks with combined cooling, heating and gas supply

The Finite Element Method (FEM) accurately models physical processes in combined cooling, heating, and power (CCHP) microgrids, including thermal transmission, power flow dynamics, and gas flow behavior [13]. Through construction of corresponding finite element models, key parameters including nodal/unit temperature, pressure, and flow rate can be computed, enabling comprehensive analysis and optimization of microgrid operational states.

While the Smoothed Particle Hydrodynamics (SPH) method is rarely employed directly in traditional combined cooling, heating, and power (CCHP) micro-energy network scheduling optimization, it can be effectively combined with other techniques to solve specific complex challenges [14, 15]. For simulating fluid dynamics or thermal energy transfer within micro-energy networks, the SPH method proves particularly valuable for detailed local simulations involving complex conditions such as large deformations or material fractures. The coupled Finite Element Method (FEM)-SPH approach synergistically combines their respective advantages, significantly improving simulation accuracy and computational efficiency.

The Finite Element Method-Smoothed Particle Hydrodynamics (FEM-SPH) coupling approach effectively addresses complex physical processes and system dynamics in multi-objective optimal scheduling of combined cooling, heating, and power (CCHP) micro-energy networks [16, 17]. For simulating fluid flow and heat transfer processes, FEM models solid structures and primary flow regions, while SPH handles localized simulations involving large deformations, fractures, or complex fluid interfaces [18,19]. This coupled methodology provides more accurate physical process characterization, delivering enhanced reliability for optimal scheduling decision-making.

When the microgrid cannot satisfy reverse power flow requirements under persistent disturbances, equation (10) provides the approximate Pareto-optimal solution for multi-objective scheduling optimization in combined cooling, heating, and power (CCHP) microgrids, derived through eigenvalue fusion analysis of operational quality distributions.

$$\theta = 2J^T(x)J(x) \tag{10}$$

where, $J(x)$ represents the electrical energy supplied from the energy storage power station. The dynamic parameters for microgrid operation connected to the energy storage station are configured [20], with the control objective function for microgrid scheduling defined as:

$$f_0(\mathrm{X}) = \frac{1}{\varepsilon} \times \theta \times x_{k+1} \times [P_1(\mathrm{X}) \times V_t(\mathrm{X}) \times C(\mathrm{X})] \tag{11}$$

where, ε represents a small constant, $P_1(\mathrm{X})$ denotes the charging/discharging power cost of the energy storage device, $V_t(\mathrm{X})$ corresponds to the generation unit output cost, and $C(\mathrm{X})$ indicates the operational cost. By equating the positive-sequence component of the energy-station-connected micro-energy network to its frequency-synchronized negative-sequence component, the corresponding liquidity function for inter-microgrid power exchange is derived [21], yielding the output synergy function $f_u(\chi)$ defined as:

$$f_u(\chi) = \frac{1}{1 + e^{-\sigma\chi}} \tag{12}$$

where, σ represents the power flow coupling coefficient among interconnected combined cooling, heating, and power (CCHP) micro-energy networks. The derived vector control state equation is expressed as:

$$C\frac{\mathrm{d}V}{\mathrm{d}t} = g_{Na} \times \alpha_m \times g_L \tag{13}$$

where, g_{Na} denotes the microgrid adjustment coefficient under shared power station operation, α_m represents the maximum charge/discharge power control coefficient for the energy storage station, and g_L signifies the damping inertia. Building upon this framework, a Finite Element Method-Smoothed Particle Hydrodynamics (FEM-SPH) coupling control model is developed for combined cooling, heating, and power (CCHP) micro-energy network scheduling. This model implements coordinated multi-microgrid control through joint scheduling strategies, with investment costs and operational maintenance expenses serving as primary evaluation metrics.

3.2. Energy regulation of electric to gas and gas generating units

Within the dispatch control center, distributed data management and cooperative control strategies are implemented to achieve targeted optimal scheduling and quality management for combined cooling, heating, and power (CCHP) micro-energy networks according to temporal operational requirements. For an energy storage station comprising N battery units, the network impedances during discrete time intervals are analyzed for both power-to-gas conversion systems and gas turbine units.

The total required capacity of energy storage stations for the microgrid system is calculated, and a shared energy storage approach is implemented to achieve multi-objective coordinated scheduling, yielding the following output feedback adjustment error:

$$S = C\frac{\mathrm{d}V}{\mathrm{d}t} \times (e_1 + e_2) \tag{14}$$

where, e_1 and e_2 represent multi-objective coordination coefficients. The internal capacity allocation parameters of the shared energy storage station are determined using individually configured storage capacities from each

Table 1. Parameter setting of micro energy network with combined heating and cooling.

Control parameters of feed lines in micro energy networks with combined heating and cooling	Value
N_p, N_s	16
f/kHz	22
$C_p, C_s/\mu$F	0.645
V_i/V	24.6
V_o/V	28
R_p, R_s	0.0177

micro-energy network as independent variables, enabling derivation of the combined cooling, heating, and power (CCHP) micro-energy network's operational control error as follows:

$$\dot{s} = 0. \tag{15}$$

Comparative analysis of combined cooling, heating, and power (CCHP) microgrid configurations with *versus* without energy storage systems facilitates optimal scheduling under integrated cooling/heating demand conditions.

Considering the minimal operational cost variations across multi-microgrid systems, frequency-synchronized component superposition generates a positive-sequence parameter regulation function for combined cooling, heating, and power (CCHP) scheduling optimization.

$$\frac{Y(s)}{R(s)} = G_m(s) \times U(s) \times \dot{s} \tag{16}$$

where, $G_m(s)$ is represents the weighted fuzzy eigenvalue while $U(s)$ denotes the energy storage capacity configuration component. Building upon this analysis, interference suppression is implemented during security control procedures for multi-objective optimal scheduling quality distribution and feature fusion in combined cooling, heating, and power (CCHP) micro-energy networks. The proposed framework establishes comprehensive operational cost control for CCHP micro-energy network scheduling by integrating grid load demand analysis with self-contained energy storage system evaluation, incorporating adaptive regulation of power-to-gas conversion and gas turbine coordination to achieve optimal multi-objective scheduling performance.

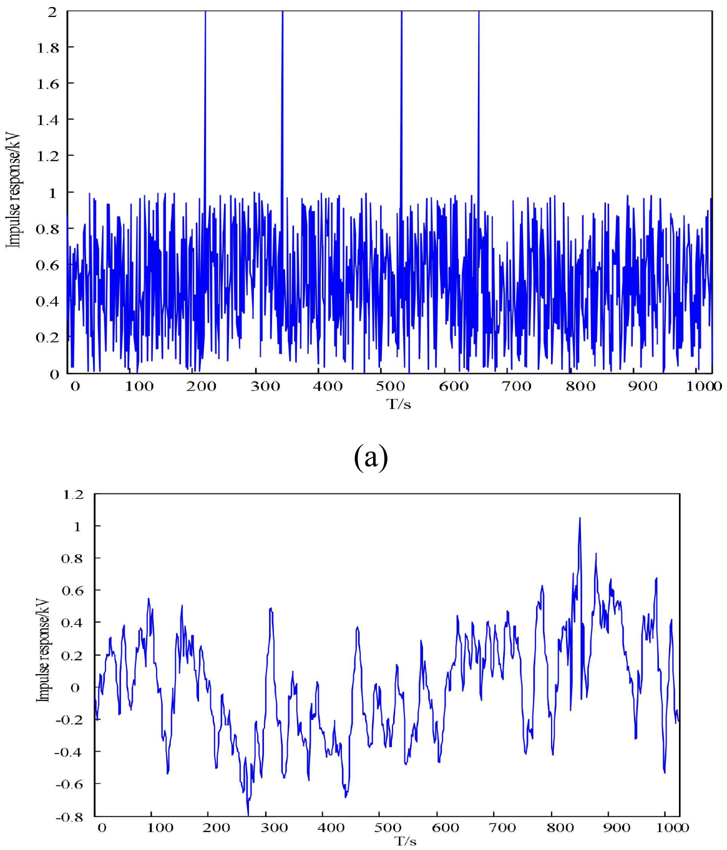
4. Simulation and test

Simulation results demonstrate the effectiveness of the proposed method in achieving multi-objective optimal scheduling for combined cooling, heating, and power (CCHP) microgrids. The experimental validation is performed using microgrid inverter power parameters of 0.45 MW, 0.28 MW, and 2.2 MW, with reactive power droop characteristics of 0.13, grid frequency of 50 Hz, and load parameters of 10 MW. Additional system parameters are provided in Table 1.

Using these parameter configurations, dynamic identification and scheduling operations are implemented for the combined cooling, heating, and power (CCHP) microgrid, with the resulting grid input characteristics shown in Figure 2.

Based on the energy storage response characteristics analysis from Figure 2, the proposed method implements optimal scheduling for the combined cooling, heating, and power (CCHP) micro-energy network, with the directional gain of this optimal scheduling process illustrated in Figure 3.

The analysis confirms that the multi-objective optimal scheduling method for combined cooling, heating, and power (CCHP) microgrids achieves a target power gain of 120 dB while significantly improving system



(a)

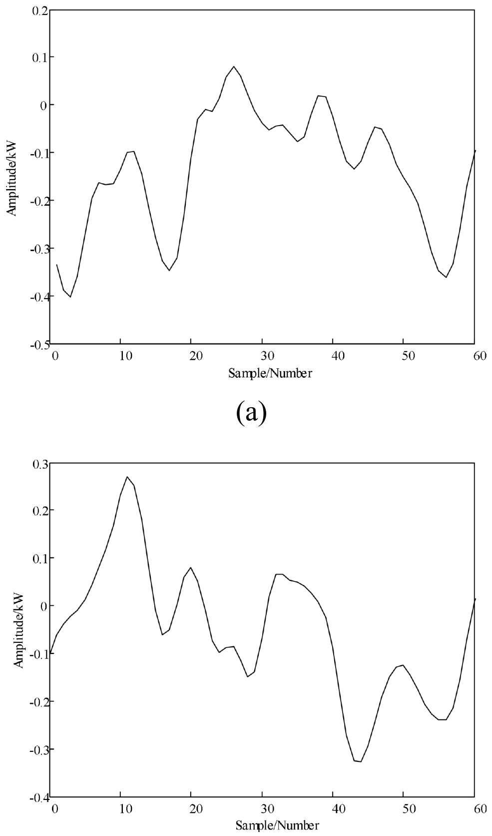
(b)

FIGURE 2. Characteristic amount of energy storage response of the power grid. (a) Cold channel. (b) Hot channel.

optimization capability, operational reliability, and unit efficiency. Comparative convergence testing of different microgrid scheduling methods reveals this method's superior performance, with detailed convergence results presented in Table 2 and demonstrating relatively lower convergence errors.

Figure 4 presents comparative experimental results of multi-objective optimal scheduling for combined cooling, heating, and electricity (CCHE) micro-energy network output power, demonstrating the performance differences between the proposed method, the reference [4] method, and the reference [5] method.

Analysis of Figure 4 reveals that none of the three methods – the proposed approach, reference [4]'s method, nor reference [5]'s method – achieve the 5000 kW maximum output power threshold for multi-objective optimal scheduling in the energy network, though all demonstrate competent energy scheduling capabilities. The proposed method exhibits superior performance with a narrower range between maximum and minimum output power values compared to both references [4,5] methods, indicating enhanced power curve stability. These results confirm that the proposed method effectively maintains the combined cooling, heating, and power (CCHP) micro-energy network's multi-objective scheduling output within a tighter operational range, optimally balancing load demands while preventing resource wastage.



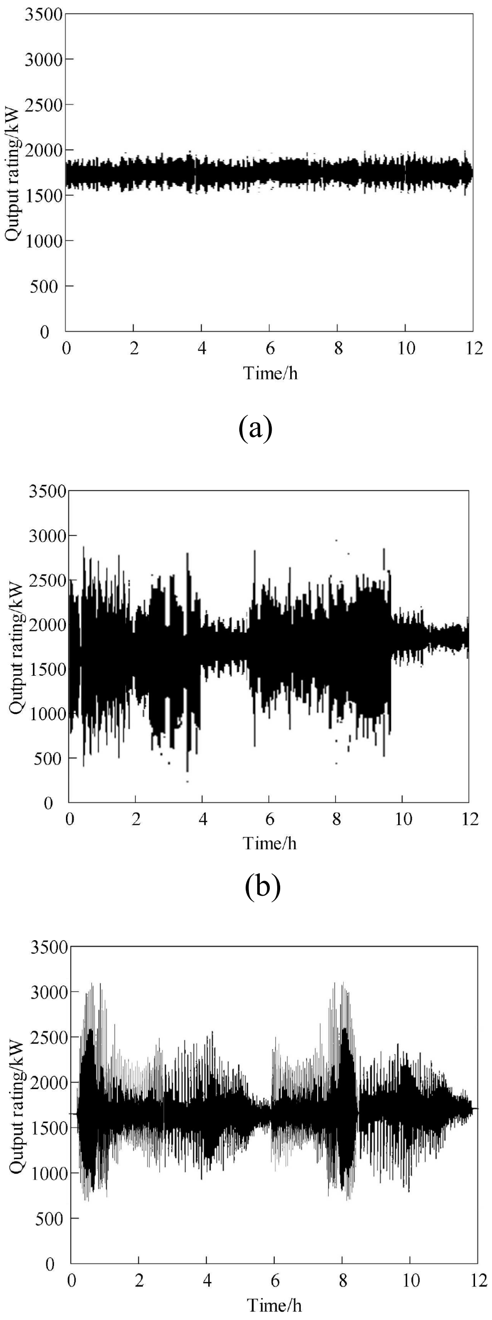
(a)

(b)

Figure 3. Targeted scheduling directional gain of micro energy networks with combined heating and cooling. (a) Cold channel. (b) Hot channel.

Table 2. Convergence error comparison test.

Iterations/Frequency	This method	Reference [4]	Reference [5]
10	0.081	0.252	0.227
15	0.057	0.292	0.164
20	0.082	0.222	0.135
25	0.056	0.314	0.244
30	0.055	0.306	0.140
35	0.029	0.219	0.121
40	0.026	0.352	0.208
45	0.084	0.261	0.188
50	0.097	0.398	0.171
55	0.088	0.285	0.253
60	0.079	0.290	0.113
65	0.028	0.224	0.205
70	0.058	0.237	0.232



(a)

(b)

(c)

Figure 4. Experimental results of multi-objective optimal scheduling output power for combined cooling, heating, and power (CCHP) micro-energy networks. (a) The method in this paper. (b) Reference [4] method. (c) Reference [5] method.

5. CONCLUSIONS

This study develops a Finite Element Method-Smoothed Particle Hydrodynamics (FEM-SPH) coupling-based multi-objective optimal scheduling method for combined cooling, heating, and power (CCHP) microgrids. By establishing comprehensive input-output relationships, the proposed framework enables intelligent microgrid control while significantly enhancing scheduling capabilities. The research first constructs a coupled control model integrating both physical and chemical energy storage systems within the combined cooling, heating, and power (CCHP) micro-energy network architecture. Through rigorous analysis of power and energy density characteristics, the implementation of FEM-SPH coupling control is successfully achieved for the scheduling processes in CCHP micro-energy networks. The developed energy-power decoupling analysis method effectively enables adaptive scheduling optimization in CCHP microgrid operations. Furthermore, a dynamic parameter adjustment model is established for target optimal scheduling of CCHP micro-energy networks, incorporating quality distribution fusion characteristics as fundamental parameters. The study employs advanced distributed data quality management and information fusion methodologies to execute precise target optimal scheduling operations for CCHP micro-energy networks. The experimental validation results conclusively demonstrate the method's superior effectiveness, exhibiting minimal convergence errors in target scheduling performance while simultaneously demonstrating robust system optimization capability and enhanced operational reliability that substantially improves overall unit operational efficiency.

CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest regarding the publication of this paper.

DATA AVAILABILITY STATEMENT

No new data/codes were created or analyzed in this study.

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