Unified Energy Circuit-based Integrated Energy Management System: Theory, Implementation, and Application

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Abstract—Due to their advantages in efficiency and flexibility, integrated energy systems (IESs) have drawn increasing attention in recent years. To exploit the potential of this system, an integrated energy management system (IEMS) is required to perform online analysis and optimization on coupling energy flows including electricity, natural gas, and heat. However, the complicated and long-term dynamic processes in natural gas networks and heating networks constitute a major obstacle to the implementation of IEMSs. In this article, a novel unified energy circuit (UEC) method that models natural gas networks and heating networks in the frequency domain with lump parameters, inspired by the electric-circuit modeling of electricity networks, is proposed. Compared with conventional time-domain modeling methods, this method yields fewer variables and equations under the same accuracy and thereby produces better computational performance. Based on the UEC models, the design and development of the IEMS with advanced applications of dynamic state estimation, energy flow analysis, security assessment and control, optimal energy flow, etc. are presented, which follows the numerical tests for validation. Finally, real-world engineering demonstrations of this IEMS on IESs at different scales are reported.

Index Terms—energy management, engineering demonstration, dynamic modeling, integrated energy system, unified energy circuit

I. INTRODUCTION

A. IES: the Physical Kernel of the Energy Internet

The “Energy Internet” is a new ecosystem that integrates energy systems (the physical layer) and the Internet (the cyber layer) to realize better openness and interconnection in energy production, transmission, and consumption [1]. Different from traditional energy systems, in which various energy sectors are operated separately, a key feature of the Energy Internet in its physical layer is that electricity networks, heating networks, natural gas networks, and other energy networks are integrated and coordinated to form so-called integrated energy systems (IESs) [2] or multienergy systems (MESs) [3], as illustrated in Fig. 1.

It is well recognized that IESs can release potential flexibility through shifting across different energy sectors [4], which reflects in (1) better energy supply reliability through multienergy complementation and switching [5], [6], (2) higher operational efficiency through the optimization of the multienergy infrastructure configuration [7] and energy cascade utilization [8], and (3) more renewable energy accommodation through the conversion of superfluous power into other energy sectors such as natural gas [9] and heat [10], which are convenient and inexpensive in terms of storage. O’Malley et al. evaluated the IES as a potential pathway to a low/zero-carbon future energy system [11].

However, these systems can also have drawbacks, as the deep couplings between energy networks complicate IESs, which makes the control and management of IESs more difficult and results in risks of cascading accidents across energy sectors. Some blackouts in electricity networks due to failures in natural gas networks that occurred in Texas [12], California [13], and Taiwan [14] have raised concerns.

B. IEMS: the Central Nervous System of the IES

To ensure the secure and economic operation of IESs, the integrated energy management system (IEMS), which is software that monitors and perceives IES states and then performs decision-making regarding IES dispatch and control,
comes into being. The precursor of the IEMS can be traced back to the energy management system (EMS), which is regarded as the central nervous system of electricity networks [15]. A brief review on the evolution history of EMSs is given as follows and is also visualized in Fig. 2.

Ever since human society entered the era of electrification, works to realize observable and controllable electricity networks have begun. From the mid-1950s to the late 1960s, EMSs gradually took shape and were equipped with supervisory control and data acquisition (SCADA) systems to gather real-time measurement data and simple automatic generation control (AGC) systems comprising load-frequency control (LFC) and economic dispatch (ED) to control the generation of power plants [16]-[17]. However, due to less consideration of security issues in the EMSs of that period, most decision-making in electricity network operations had to be performed manually and offline [18].

With the rapid development and wide interconnection of electricity networks, such a prototypical EMS cannot satisfy the needs of managing a complicated electricity network. In the 1970s, modern EMSs began to emerge based on the works about the security control systems of electricity networks proposed by Dy-Liaacco [18]-[19]. One main trend of EMSs at that time was the integration of advanced applications including state estimation, power flow calculation, contingency analysis, optimal power flow, etc. [20], which achieved a quantum leap in the automation level and intelligence level of electricity network management. In addition, different architectures of EMSs were proposed to support the increasing computational needs, benefitting from the rapidly developed digital computer technology during this period [21]. Up to the 1990s, most electric power control centers (EPCCs) all over the world employed EMSs to manage their electricity networks, such as those in Korea [22], Japan [23], and Canada [24].

With the dawn of the new century, renewable energy, which tends to be uncontrollable and strongly fluctuant, has been increasingly incorporated in electricity networks, resulting in curtailment issues [25]. Under these conditions, a traditional EMS that manages resources only on the supply side cannot provide sufficient flexibility for electricity networks to accommodate renewable energy. Consequently, more EMSs that cover all aspects of electricity network operation to involve more distributed flexibility resources were developed successively to form the EMS family [26], including the wind farm EMS [27], microgrid EMS [28], electrical vehicle (EV) EMS [29], building EMS [30], home EMS [31], etc. These EMSs are locally autonomous and achieve decentralized coordination by virtue of the information communication technology (ICT) to comanage a smart grid.

Naturally, IEMSs can be considered as a new type of EMSs: IES-oriented EMSs, whose management objects are expanded from the pure power flow in electricity networks to the multiple heterogeneous energy flows in IESs. For these energy flows, functions similar to those of traditional EMSs are required to be implemented in IEMSs, so as to perform online analysis, optimization, and control.
C. Challenges and Contributions

Although an IEMS has functions similar to those of a traditional EMS, its implementation is not a simple replication of the previous procedure because of the very large differences in the physical properties of the energy flows managed by the two systems.

Electric-power flow has a very fast propagation speed, so the dynamic processes in electricity networks occur on a short time scale, which means that a state adjustment on the supply side immediately causes a corresponding state change on the demand side. This decides the EMSs oriented to electricity networks are designed in a section\(^1\)-based manner that includes two key features: first, the current state is uniquely determined by the current boundary conditions; second, one section is enough to completely represent the future states until the next boundary condition change. However, the propagation speeds of other energy flows represented by natural gas and heat are so slow that the dynamic processes can last several hours and even days in large-scale IESs\(^2\). This characteristic means that the IEMS must be designed in a window\(^2\)-based manner that includes two key features different from those of the section-based manner: first, the current state is jointly determined by the historical states and current boundary conditions; second, multiple sections are needed to accurately represent the future states during the dynamic process. These distinctions are illustrated in Fig. 3.

To perform such a window-based analysis in an IEMS, the dynamic processes in natural gas networks and heating networks have to be formulated using partial differential equations (PDEs) with temporal and spatial derivatives, which are far more intractable than the algebraic equations of steady electricity networks. In current studies, the mainstream approach to analyzing these PDE models is the finite difference method (FDM), which approximates derivatives with differences in both spatial and temporal domains. Nevertheless, this method encounters the following challenges in the engineering practices of the IEMS: (1) The introduction of massive numbers of discrete points significantly increases the calculation complexity, which limits the applicable IES scales. (2) The determination of PDE solutions requires comprehensive initial conditions, including the initial states inside pipelines, which are difficult to obtain due to the lack of measurements. (3) With unsuitable temporal and spatial step lengths, the FDM calculation probably diverges or oscillates.

To address these challenges, works from the perspectives of theory, implementation, and application are presented in this article, corresponding to the following threefold contributions:

1) Inspired by the electric-circuit modeling of electricity networks, a unified energy-circuit (UEC) method that models natural gas networks and heating networks in the frequency domain is proposed. Compared with extant time-domain modeling methods, this method requires fewer variables and equations/constraints for calculation which yields higher computational efficiency. Moreover, this method is step length-free and does not require initial states inside pipelines.

2) Extensible architectures of software and function are designed for IEMSs. Then, based on the proposed UEC method, advanced applications of IEMS including dynamic state estimation, energy flow analysis, security assessment and control, and optimal energy flow are developed in a window-based manner. Numerical tests validate that the implemented IEMS is able to analyze and optimize city-scale IESs online.

3) In recent years, the implemented IEMSs have been successively deployed in several industrial parks and cities in China for engineering demonstrations, which has resulted in significant economic and environmental advantages. Their typical operation scenarios and overall benefits are reported and summarized.

The remainder of this article is organized as follows. Section II introduces the theory of the UEC modeling method in detail. In Section III, the implementation of IEMSs in architecture design and application development is presented. In Section IV, engineering demonstrations of IEMSs in China are reported. Finally, Section V concludes this article and presents an outlook on future IEMSs.

II. THEORY: UNIFIED ENERGY-CIRCUIT MODELING METHOD

Regarding the organization of this section, we first review the related works on the UEC method in subsection A. Then, the deduction process of the electric-circuit model for transmission lines is reviewed in subsection B, which provides intuition on energy circuits. Based on this, we dive into the energy-circuit modeling of gas flow and heat flow in pipelines in subsection C, which is the core content of this section. In subsection D, circuit models of transmission lines and pipelines are merged by topology constraints that describe connection relationships of branches to derive the UEC models of networks. Finally, more details are discussed in subsection E.

A. Related Works

Modeling is a perpetual topic in many studies since it

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\(^1\) A “section” refers to the state variables of the whole system at a certain moment. It can be interpreted as a snapshot of the system.

\(^2\) A “window” refers to the state variables of the whole system over a period of time. It can be interpreted as multiple “sections” with enough small intervals.
constitutes the basis of analysis and optimization, so as it is in the research of IESs.

The pioneering work of modeling an IES began in energy hub (EH) research [35], as an end-to-end model using a coupling matrix to describe the processes of multienergy conversion and delivery from supplies to consumption, first proposed by Andersson et al. in 2007 [36]. Next, techniques for coupling-matrix computation in EH models were proposed in [37] and [38], making EH models practical. Because an EH model does not model transmission lines/pipelines and the corresponding dynamic processes, the security concerns and flexibility resources inside multienergy networks are ignored, which makes the model more suitable for small-scale IESs.

IES models involving network characteristics have proliferated since 2016, such as those in [39]-[41]. The models in these works contain simultaneous equations for electricity networks, natural gas networks, heating networks, and coupling devices in a steady state, which successfully consider security concerns and incorporate tractable calculations. However, the flexibility from the large inertia of natural gas networks and heating networks is still omitted. Replacing the steady-state models with the dynamic PDE models of natural gas networks [42] and heating networks [43] after discretization by the FDM can solve this issue theoretically but not practically for large-scale IESs due to the massive computational burden.

Another approach to modeling natural gas networks and heating networks with dynamic characteristics involved performs from an electric circuit-analog perspective, which compares gas flow and heat flow to current. This is not a totally novel idea: Robertson and Gross designed an electric circuit for the dynamic simulation of transient heat flow in pipelines as early as 1958 [44]. In recent years, this idea has been reapplied in the digital simulation modeling of IESs. Chen et al. proposed a circuit-analog model for heat exchangers [45], [46] while Lan et al. proposed one for heat pipelines [47], and a similar model for natural gas networks is presented in [48]. These works still solve dynamic models in the time domain using the FDM, and the circuit-analog models included are mainly for illustration purposes and the reuse of electromagnetic transient programs (EMTPs). Other works map the circuit-analog models of natural gas networks [49], [50] and heating networks [51] into the complex frequency domain by Laplace Transform (LT) and thereby avoid finite difference discretization in the time domain. However, the intractable symbolic calculation that includes the Laplacian “s” in the complex frequency domain is not well addressed.

The proposed UEC model is a new circuit-analog model for IESs that fully draws on the deduction process of the electricity network model from the time domain to the frequency domain and from distributed parameters to lump parameters to eliminate the temporal derivative and spatial derivative, respectively. This model accurately reflects the dynamic processes in IESs and is tractable enough for calculation.

B. Review of the Electric-Circuit Modeling of Transmission Lines

The electromagnetic energy flow delivered by transmission lines obeys Maxwell’s equations, which constitute a field model. This field model is too complex to analyze the energy flow distribution in a transmission line, let alone that in a whole electricity network. For practical purposes, tractable circuit models are developed in three phases as follows.

1) TDDP Circuit Model

In 1965, Taylor et al. simplified the 3D electromagnetic field around transmission lines to the 1D voltage-current wave along the lines using Stokes’ theorem [52], which ultimately yielded the telegrapher’s equations [53]:

\[
\begin{align*}
\frac{\partial U(x,t)}{\partial x} + L \frac{\partial I(x,t)}{\partial t} + R' I(x,t) &= 0 \\
\frac{\partial I(x,t)}{\partial x} + C \frac{\partial U(x,t)}{\partial t} + G' U(x,t) &= 0
\end{align*}
\]

(1)

where \(x\) and \(t\) represent space and time, \(U\) and \(I\) are the voltage and current, and \(R'\), \(L'\), \(G'\), and \(C'\) are per-unit-length resistance, inductance, conductance, and capacitance.

The temporal-spatial PDEs (mathematical model) in (1) correspond to the time-domain-distributed-parameter (TDDP) circuit (physical model) shown in Fig. 4 (a).

2) FDDP Circuit Model

Steinmetz first employed the concept of a “phasor”, which converts a sine wave in the time domain to a complex vector in the frequency domain, to analyze AC electricity networks [54]. Using the phasor representation, (1) is equivalent to

\[
\begin{align*}
\frac{dU(x)}{dx} + (R' + j\omega L')I(x) &= 0 \\
\frac{dI(x)}{dx} + (G' + j\omega C')U(x) &= 0
\end{align*}
\]

(2)

where \(\omega\) is the angular frequency of AC electricity networks, \(U\) is the complex voltage, and \(I\) is the complex current, respectively.

The essence of the phasor representation is analyzing the circuit model in the frequency domain by Fourier transform (FT). Thus, the spatial partial differential equations (PDEs)
in (2) correspond to the frequency-domain-distributed-parameter (FDDP) circuit shown in Fig. 4(b).

3) FDLP Circuit Model

An equivalent two-port model of transmission lines is obtained by solving the ODE (2):

\[
\begin{bmatrix}
U(l) \\
j(l)
\end{bmatrix} = \begin{bmatrix}
\cosh \gamma l & -\sinh \gamma l \cdot Z_c \\
-(\sinh \gamma l) / Z_c & \cosh \gamma l
\end{bmatrix} \begin{bmatrix}
U(0) \\
j(0)
\end{bmatrix}
\]

(3)

where \(Z_c = \sqrt{(R' + j\omega L') / (G' + j\omega C')}\) is the characteristic impedance, \(\gamma = \sqrt{(R' + j\omega L') \cdot (G' + j\omega C')}\) is the propagation constant, and \(l\) is the length.

The algebraic equations in (3) correspond to the frequency-domain-lump-parameter (FDLP) circuit shown in Fig. 4(c), i.e., the famous pi-equivalent circuit of transmission lines [55]. Based on this circuit, the electricity networks are modeled by algebraic equations rather than PDEs, which provides significant computational savings for high-level analysis.

C. Energy-Circuit Modeling of Pipelines

Now, we turn to the energy-circuit modeling of gas flow and heat flow in pipelines, whose original models are formulated by PDEs. According to [42], the 1D gas model in natural gas pipelines obeys the equations of mass conservation and momentum conservation, as in (4). According to [43], the 1D heat flow in heat pipelines obeys the equations of energy conservation and enthalpy, as in (5).

\[
\begin{align*}
A \frac{\partial p}{\partial t} + c^2 \frac{\partial m}{\partial x} &= 0 \\
1 \frac{\partial m}{\partial t} + \frac{\partial p}{\partial x} + \lambda \rho v^2 / 2D + \rho g \sin \alpha &= 0 \\
m &= \rho v A \\
p &= c^2 \rho
\end{align*}
\]

(4)

where the constants \(A\), \(D\), \(\lambda\), \(\alpha\), \(g\), and \(c\) are the cross-sectional area, inner diameter, friction factor, dip angle, gravitational acceleration, and sonic speed, respectively; variables \(p\), \(m\), \(v\), and \(\rho\) are the pressure, mass flow rate, velocity, and density, respectively.

\[
\begin{align*}
\frac{c_p \rho A}{\partial t} + c_p m \frac{\partial T}{\partial x} + \rho \frac{\partial m}{\partial t} + \mu T &= 0 \\
h &= c_p m T
\end{align*}
\]

(5)

where constants \(c_p\) and \(\mu\) are the specific heat capacity and heat dissipation coefficient, respectively; variables \(T\) and \(h\) are the relative temperature (water temperature minus ambient temperature) and heat flow, respectively. In this article, we consider only the scenario in which heating networks are operated under quality regulation, i.e., the mass flow rate \(m\) of each pipeline is a known constant that is optimized in advance for typical operating conditions [56].

The above two PDE models are usually solved by the FDM with different calculation schemes and step lengths, as studied in [42] and [43]. From another perspective, the UEC method aims to extract common transmission laws of power flow, gas flow, and heat flow and thereby generalize the deduction process of circuit modeling for transmission lines to that for gas pipelines and heat pipelines, so as to equivalently convert their original PDE models (4) and (5) into FDLP-circuit models in the form of algebraic equations. Its methodology includes the following three steps.

Step 1) Circuit Analogy

First, the state variables describing different energy flows are given a unified representation as “potential” \(P\) and “flow” \(F\): the potential is defined as the amount of work needed to move a unit of matter from a reference point to a specific point against the electric/force/thermal field and corresponds to the voltage in electricity networks, pressure in natural gas networks, and temperature in heating networks; the flow is defined as the stream of electric charge/mass/energy passing through a surface per unit of time and corresponds to the current in electricity networks, gas flow in natural gas networks, and heat flow in heating networks. Then, circuit components, including resistance that resists flow, conductance that resists potential, inductance that resists flow changes, and capacitance that resists potential changes, are generalized from the electric circuit to the hydraulic circuit and thermal circuit, as summarized in TABLE I. Based on these circuit components, the PDEs of gas and heat pipelines can be reorganized into forms similar to the telegrapher’s equations of transmission lines, as in (6) and (7), which construct the TDDP circuits of pipelines shown in Fig. 5.

\[
\begin{align*}
\frac{\partial p(x,t)}{\partial t} + L_h \frac{\partial m(x,t)}{\partial t} + R_h m(x,t) + k_p p(x,t) &= 0 \\
\frac{\partial m(x,t)}{\partial t} + C_h \frac{\partial p(x,t)}{\partial t} &= 0
\end{align*}
\]

(6)

3 Though the hydraulic circuit is derived based on the natural gas network equations, it is applicable to other fluid networks such as water networks, petroleum networks, steam networks, and hydrogen networks with minor modifications.
TABLE I
CIRCUIT ANALOGY: FROM ELECTRIC CIRCUIT TO HYDRAULIC CIRCUIT AND THERMAL CIRCUIT

| Physical Object                              | Electric Circuit                               | Hydraulic Circuit                              | Thermal Circuit                               |
|---------------------------------------------|------------------------------------------------|------------------------------------------------|------------------------------------------------|
| Energy Circuits                             | Electric Circuit                               | Hydraulic Circuit                              | Thermal Circuit                               |
| Potential $\mathcal{P}$                     | voltage (V): $U$                                | pressure (Pa): $p$                              | temperature (K): $T$                           |
| Flow $\mathcal{F}$                          | current (C/s, i.e., A): $I$                     | gas flow (kg/s): $m$                            | heat flow (J/s, i.e., W): $h$                  |
| Resistance $R_x$; $R_y$                     | $R_x : U = R_x I$                               | $R_y : p = R_y m$                               | $R_y : T = R_y h$                              |
| Conductance $G_x$; $G_y$                    | $G_x : I = G_x U$                               | $G_y : m = G_y p$                               | $G_y : h = G_y T$                              |
| Inductance $L_x$; $L_y$                     | $L_x : U = L_x \frac{dl}{dt}$                  | $L_y : p = L_y \frac{dm}{dt}$                  | $L_y : T = L_y \frac{dh}{dt}$                 |
| Capacitance $C_x$; $C_y$                    | $C_x : I = C_x \frac{dU}{dt}$                  | $C_y : m = C_y \frac{dp}{dt}$                  | $C_y : h = C_y \frac{dT}{dt}$                 |

\[
\begin{aligned}
\frac{\partial T(x,t)}{\partial x} + L_x \frac{\partial h(x,t)}{\partial t} + R'_x h(x,t) &= 0 \\
\frac{\partial h(x,t)}{\partial x} + G_x \frac{\partial T(x,t)}{\partial t} + C'_x \dot{h}_x(x,t) &= 0
\end{aligned}
\]

(7)

The fourth term in the first equation of (6) represents a pressure-controlled pressure source (generalized from the voltage-controlled voltage source), and $k'_x$ is its parameter. The derivation from (4) and (5) to (6) and (7) is provided in Appendix A, as well as the parameter definitions of these circuit components.

**Step 2) Fourier Transform**

FT is employed to decompose the nonsinusoidal excitations in natural gas networks and heating networks into several sinusoidal components with different frequencies. For each frequency component, the TDDP circuits of pipelines can be mapped to the frequency domain through the phasor representation, which gives the FDDP circuits formulated in (8) and (9). Thus, for the hydraulic circuit and thermal circuit, there are a series of FDDP circuits corresponding to the TDDP circuit.

\[
\begin{aligned}
\frac{dp_x(x)}{dx} + (R'_x + j\omega_x L'_x) \dot{m}_x(x) + k'_x \dot{h}_x(x) &= 0 \\
\frac{dh'_x(x)}{dx} + j\omega_x C'_x \dot{p}_x(x) &= 0 \\
\frac{d^2T'_x(x)}{dx^2} + (R'_x + j\omega_x L'_x) \dot{h}_x(x) &= 0 \\
\frac{dh_x(x)}{dx} + (G'_x + j\omega_x C'_x) \dot{T}_x(x) &= 0
\end{aligned}
\]

(8)

where $\omega_x$, $\dot{p}_x$, $\dot{m}_x$, $\dot{T}_x$, and $\dot{h}_x$ are the angular frequency, complex pressure, complex gas flow, complex temperature, and complex heat flow corresponding to frequency component $\kappa$.

After obtaining the response of each frequency component by step (3), by mapping them back into the time domain using inverse Fourier transform (IFT) and then superposing, the desired time-domain response is acquired. This step is visualized in Fig. 6.

**Step 3) Two-Port Equivalence**

Given the boundary values at the beginnings of pipelines, the spatial ODEs of the $\kappa$-th FDDP hydraulic circuit and thermal circuit can be solved analytically, and the solutions obtained are given in (10) and (11).

\[
\begin{bmatrix}
\dot{p}_x(l) \\
\dot{m}_x(l)
\end{bmatrix} =
\begin{bmatrix}
A_{xx} & B_{xx} \\
C_{xx} & D_{xx}
\end{bmatrix}
\begin{bmatrix}
\dot{p}_x(0) \\
\dot{m}_x(0)
\end{bmatrix}
\]

(10)
\[
\begin{bmatrix}
T_e(l) \\
\dot{h}_e(l)
\end{bmatrix} =
\begin{bmatrix}
A_e & B_e \\
C_e & D_e
\end{bmatrix}
\begin{bmatrix}
T_e(0) \\
\dot{h}_e(0)
\end{bmatrix}
\]

(11)

The derivation from (8) and (9) to (10) and (11) is provided in Appendix A, as well as the definitions of transmission parameters \(A, B, C,\) and \(D\).

These solutions describe an algebraic relationship between the potential and flow variables on both ends of pipelines under frequency component \(\kappa\), based on which the \(\kappa\)-th FDLP hydraulic circuit and thermal circuit of pipelines are drawn in Fig. 7, as well as their branch impedance \(Z\), branch admittance \(Y\), and controlled source parameter \(K\).

![FDLP Circuit of Gas Pipelines](a) and (b) FDLP Circuit of Heat Pipelines

Now, the original field models of pipelines described by PDEs are transformed into a series of circuit models described by algebraic equations.

D. Energy-Circuit Modeling of Networks in IESs

1) Single-Network Model

Without loss of generality, in the derivation of this part, we assume that all excitations in energy networks are in same-frequency sinusoidal forms, which means that there is only one frequency component after FT. Therefore, we can omit the subscript that distinguishes different frequency components for the purpose of brevity.

A network is a connection formed by a set of branches according to a specific topological relationship, so its modeling requires formulating both its branch characteristics and topology constraints.

In the last two subsections, we modeled transmission lines, gas pipelines, and heat pipelines using pi-equivalent FDLP circuits, which all contain three branches composed of impedance and controlled sources. Thus, based on the UEC model, the branch characteristics of electricity networks, natural gas networks, and heating networks can all be represented by the following unified complex algebraic equation:

\[
\dot{F}_b = \mathcal{Y}_b(\mathcal{P}_b - \mathcal{K}_b \mathcal{P}_{bf})
\]

(12)

where \(\dot{F}_b\), \(\mathcal{P}_b\), and \(\mathcal{P}_{bf}\) are the flow variable, difference of potential variables on both ends, and potential variable on the “from” side of branch \(b\), respectively; \(\mathcal{Y}_b\) and \(\mathcal{K}_b\) are the admittance and pressure-controlled pressure source parameter of branch \(b\), respectively. Note that \(\mathcal{K}_b = 0\) always holds for branches in electricity networks and heating networks.

Listing the \(\dot{F}_b\), \(\mathcal{P}_b\), and \(\mathcal{P}_{bf}\) of all branches in vector form (represented by bold font) and the \(\mathcal{Y}_b\) and \(\mathcal{K}_b\) of all branches in diagonal-matrix form (represented by bold font), we obtain the branch equation in matrix form as follows.

\[
\dot{F}_b = \mathcal{Y}_b(\mathcal{P}_b - \mathcal{K}_b \mathcal{P}_{bf})
\]

(13)

For the topology constraints, we first introduce two matrices to indicate the network topology: node-branch incidence matrix \(\mathcal{A}\) and node-outflow-branch incidence matrix \(\mathcal{A}_1\), whose definitions are given below.

\[
\mathcal{A}(i, j) = \begin{cases} 
1, & \text{if branch } j \text{ flows from node } i \\
-1, & \text{if branch } j \text{ flows into node } i \\
0, & \text{otherwise}
\end{cases}
\]

(14)

\[
\mathcal{A}_1(i, j) = \begin{cases} 
1, & \text{if branch } j \text{ flows from node } i \\
0, & \text{otherwise}
\end{cases}
\]

(15)

where \(\mathcal{A}(i, j)\) and \(\mathcal{A}_1(i, j)\) are their entries at the \(i\)-th row and \(j\)-th column.

Based on these two matrices, the KCL and KVL constraints in electricity networks are generalized to the flow constraint and potential constraint in more energy networks. The flow constraint means that the difference between the outflow and inflow of a node equals its flow injection, as given in (16); the potential constraint correlates the branch potential and node potential, as given in (17) and (18).

\[
\mathcal{A}\mathcal{P}_b = \mathcal{P}_n
\]

(16)

\[
\mathcal{A}_1^T\mathcal{P}_b = \mathcal{P}_{bf}
\]

(17)

\[
\mathcal{A}_1^T\mathcal{P}_{bf} = \mathcal{P}_{bf}
\]

(18)

where \(\mathcal{P}_b\) and \(\mathcal{P}_n\) are the vectors of flow injection variables and potential variables of all nodes, respectively.

Substituting (16)-(18) into (13) yields a unified network equation for electricity networks, natural gas networks, and heating networks, as in (19). This equation is also unified for both steady-state calculation and dynamic-state calculation: the former requires only the frequency component of \(\omega = 0\), while the latter requires multiple frequency components.

\[
\dot{F}_b = \mathcal{Y}_b \mathcal{P}_b
\]

(19)

where \(\mathcal{Y}_b = \mathcal{A}\mathcal{Y}_b \mathcal{A}^T - \mathcal{A}\mathcal{Y}_b \mathcal{K}_b \mathcal{A}^T\) is named the generalized node admittance matrix.

Note that the frequency-domain network equation (19) for electricity networks is derived using the complex voltage (\(\bar{U}\)) and complex current (\(\bar{I}\)) as state variables. Due to the difficulty
in phase measurement, it is more common in practice to describe an electricity network by a power flow equation that uses the phase angle ($\theta$), voltage magnitude ($U$), active power ($P$), and inactive power ($Q$) as state variables. To cater to this custom, we can regard $\theta$ and $U$ as potential variables and $P$ and $Q$ as flow variables so that the DC power flow equation and linearized AC power flow equation [57] can be written in a form consistent with that of (19).

2) **Multinetwork Model**

At this point, we have established UEC models for single-energy networks of electricity, natural gas, and heat. To integrate these single-network models as an IES model, energy-conversion devices that physically couple different energy networks, such as gas turbines and electric boilers, should be modeled.

Considering that there are $m$ energy-conversion devices coupling an $N_e$-bus electricity network, an $N_g$-node natural gas network, and an $N_h$-node heating network, a converter characteristic matrix $C$ [38] that has $m$ rows and $N_e+N_g+N_h$ columns is employed to formulate the coupling relationships. Each row in this matrix represents a coupling equation, and each column represents an injection variable of a node in different networks. The converter characteristic matrix in (20) is an illustrative example of a gas-fired co-generation unit that couples the injections of bus 1 in a 3-bus electricity network ($\hat{P}_{1e}$), node 2 in a 3-node natural gas network ($\hat{P}_{2g}$), and node 3 in a 3-node heating network ($\hat{P}_{3h}$) with the equation:

$$\eta^e \hat{P}_{1e}^e + \eta^g \hat{P}_{2g}^g + \eta^h \hat{P}_{3h}^h = 0$$

Note that the flow injection of electricity networks ($\hat{P}_{1e}$) here is active/inactive power rather than current.

$$C = \begin{bmatrix} \eta^e & 0 & 0 & 0 & \eta^g & 0 & 0 & \eta^h \end{bmatrix} \quad (20)$$

We denote the columns in $C$ corresponding to the nodes of the electricity network, natural gas network, and heating network as $C^e$, $C^g$, and $C^h$, respectively. Then, we obtain the time-domain coupling equation in (21) and the frequency-domain coupling equation in (22).

$$C^e \mathbf{F}_{n,e}^e + C^g \mathbf{F}_{n,g}^g + C^h \mathbf{F}_{n,h}^h = 0 \quad \forall \tau \quad (21)$$

$$C^e \mathbf{F}_{n,e}^e + C^g \mathbf{F}_{n,g}^g + C^h \mathbf{F}_{n,h}^h = 0 \quad \forall \kappa \quad (22)$$

Combining the time-domain power flow equation of electricity networks, the frequency-domain network equations of natural gas networks and heating networks, the time-domain coupling equation, and the transformation equation between time-domain variables and frequency-domain variables yields the multinetwork UEC model of an IES comprising an electricity network, a natural gas network, and a heating network, as given in (23).

$$\begin{align*}
P F(\mathbf{F}_{n,e}^e, \mathbf{F}_{n,g}^g, \mathbf{F}_{n,h}^h) &= 0 \quad \forall \tau \\
\mathbf{F}_{n,e}^e &= \mathbf{Y}_{n,e}^e \mathbf{P}_{n,e}^e \quad \forall \kappa \\
\mathbf{F}_{n,g}^g &= \mathbf{Y}_{n,g}^g \mathbf{P}_{n,g}^g \quad \forall \kappa \\
\mathbf{F}_{n,h}^h &= \mathbf{Y}_{n,h}^h \mathbf{P}_{n,h}^h \quad \forall \kappa \\
C^e \mathbf{F}_{n,e}^e + C^g \mathbf{F}_{n,g}^g + C^h \mathbf{F}_{n,h}^h &= 0 \\
\{ \mathbf{F}_{n,e}^e \} \quad \forall \kappa &= FT(\{ \mathbf{P}_{n,e}^e \} \quad \forall \tau) \\
\{ \mathbf{F}_{n,g}^g \} \quad \forall \kappa &= FT(\{ \mathbf{P}_{n,g}^g \} \quad \forall \tau) \\
\{ \mathbf{F}_{n,h}^h \} \quad \forall \kappa &= FT(\{ \mathbf{P}_{n,h}^h \} \quad \forall \tau)
\end{align*} \quad (23)$$

where $PF(\cdot)$ refers to the power flow equation (either the DC model, linearized AC model, or original nonlinear AC model), $FT(\cdot)$ refers to the FT equation, and the superscripts of $e$, $g$, and $h$ distinguish the electricity network, natural gas network, and heating network.

Particularly, if the power flow equation is linear, i.e., DC power flow or linearized AC power flow, it can be mapped to the frequency domain along with the coupling equation so that the FT equation can be excluded, which yields the pure-frequency-domain multinetwork UEC model in (24). This model can be solved in parallel, which leads to better computational performance.

$$\begin{align*}
\mathbf{F}_{n,e}^e &= \mathbf{Y}_{n,e}^e \mathbf{P}_{n,e}^e \\
\mathbf{F}_{n,g}^g &= \mathbf{Y}_{n,g}^g \mathbf{P}_{n,g}^g \\
\mathbf{F}_{n,h}^h &= \mathbf{Y}_{n,h}^h \mathbf{P}_{n,h}^h \\
C^e \mathbf{F}_{n,e}^e + C^g \mathbf{F}_{n,g}^g + C^h \mathbf{F}_{n,h}^h &= 0
\end{align*} \quad (24)$$

**E. Discussion**

1) **Use Historical Boundary Values as Surrogate Initial Values**

Since the dynamic models of natural gas networks and heating networks involve temporal-spatial PDEs, the determination of their solutions requires both future boundary values (given values of some variables at all times) and initial values (given values of all variables at $t = 0$). However, the UEC method contains a step of discrete FT which implicitly performs a periodic extension. Consequently, initial values cannot be assigned explicitly in the UEC method.

To address this issue, an approach that utilizes historical boundary values as surrogate initial values is proposed based on the intuition that the state of a physical system at an arbitrary moment does not come out of nowhere but is a result of all

![Fig. 8. Approximation of the initial values at $T_0$ using the historical boundary values from $T_0-T_{\text{history}}$ to $T_0$.](image)
excitations before this moment. Considering the response decay of excitations, we can use the boundary values of a history window with limited length to approximate the state values at the end of this history window, as illustrated in Fig. 8.

Considering the difficulty involved in directly obtaining the initial values of the state variables inside pipelines due to measurement deficiencies, this equivalence approach is rather practical in engineering practice since the acquired historical boundary values are mostly the injection or potential variables of sources and loads that can be adequately measured.

Regarding the selection of the history window length, a basic principle is that the longer it is, the greater the accuracy of the surrogate is at the cost of a heavier computational burden. Another important lesson is that setting the sum of the history window length and future window length as an integer multiple of 24 hours can effectively decrease the error caused by the periodic extension because the operation of energy networks presents day-to-day regularity. For example, if we want to analyze the IES over the next 8 hours, then 16 hours is a good choice for the history window length.

2) Computational Complexity

Here, we discuss the computational complexities of analyzing a natural gas network or a heating network using the UEC method and FDM.

For a natural gas/heating network with \( N \) nodes, \( M \) pipelines that have \( L \) segments on average after finite difference, and \( T \) time steps whose FT result contains \( F \) frequency components, the UEC method produces \( F \) sets of equations, and each set contains \( N \) variables; therefore, its temporal complexity is \( O(N^2F) \), and its spatial complexity is \( O(N^F) \). Relatively, the traditional FDM \([42]-[43]\) produces \( T \) sets of equations, and each set contains \( LM \) variables; therefore, its temporal complexity is \( O(L^2M^3T) \), and its spatial complexity is \( O(L^2M^2T) \). Obviously, there is \( O(M) = O(N) \) and \( O(T) = O(F) \), which indicates that the UEC method has lower complexity than the FDM. In addition, different frequency components in the UEC method are independent and therefore can be calculated in a parallel manner, while the time steps in the FDM have to be calculated serially. This distinction further widens the performance gap between the two methods.

III. IMPLEMENTATION: DESIGN AND DEVELOPMENT OF IEMS

Regarding the organization of this section, we first introduce the designs of the software architecture and functional architecture for IEMSs in subsections A and B, respectively. Then, the introductions to four typical advanced applications in IEMSs, including energy flow analysis, optimal energy flow, dynamic state estimation, and security assessment and control, are successively presented in the following four subsections of C, D, E, and F. The introduction to each application includes the related works, UEC-based formulation, and numerical tests for validation.

A. Design of Software Architecture for IEMSs

Following the design ideas of openness, standardization, and modularization, hierarchical software architecture is designed for IEMSs, as visualized in Fig. 9. From a bottom-up perspective, this architecture contains five levels of operating system (OS), data, middleware, application, and front-end. A brief introduction to these levels is presented below.

(a) OS Level

The IEMS is developed based on off-the-shelf OSs. As a cross-platform software, it is compatible with Linux and Windows OS, which are the most commonly used in industries.

![Software Architecture of IEMSs](image)

(b) Data Level

Multiple storage methods, including real-time database (RTDB), SQL database, NoSQL database, and file storage, are integrated at the data level for different storage requirements. The RTDB responds to fast data-access requests during computation processes but has relatively small capacity, while the SQL and NoSQL databases undertake the function of large-capacity and persistent data storage, e.g., historical data and model data, but have relatively slow access speed. File storage is used for the purposes of program logs, data export, etc.

(c) Middleware Level

At the middleware level, three buses of data, service, and message and eight modules of log management, warning management, process management, application management, resource monitor, task dispatch, identity authentication, and security defense are designed to connect the low-level OS and data with high-level applications. The common services provided by these buses and modules greatly simplify the implementation and extension of advanced applications.

(d) Application Level

Various applications, including SCADA, dynamic state estimation, generalized load prediction, energy flow analysis, security assessment and control, and optimal energy flow, are developed at the application level, which provides the IEMS with functions covering the whole process of managing multiple energy flows. According to the user needs, more applications such as node price calculation and virtual power plants can be extended.
(e) Front-end Level
The front-end level provides a user interface that receives user commands to invoke the corresponding applications and displays the returned results. This user interface is implemented in three manners of local monitors, portable terminals (through a local area network), and remote web access (through a wide area network) to meet the requirements of diverse scenarios.

B. Design of Functional Architecture for IEMSs
Now, we discuss the applications in the IEMS. The functional architecture that organizes these applications is designed as shown in Fig. 10, and the corresponding timeline relationships are presented in Fig. 11. The specific details are expanded as follows.

![Functional Architecture for IEMSs](image)

**Fig. 10. Functional architecture of IEMSs.**

| Time Span | Description |
|-----------|-------------|
| $T_0$       | Historical Measurement Data |
| $T_0$       | Dynamic State Estimation |
| $T_i$       | Security Assessment and Control |
| $T_f$       | Optimal Energy Flow |
| $T_{max}$   | Generalized Load Prediction |

**Fig. 11. Timeline relationships of applications in IEMSs.**

1) **SCADA**
As the sensory organ of IEMSs, the SCADA collects real-time measurement data from physical systems and performs data management such as format regulation and indexed storage. Its detailed functions include data acquisition and processing, network topology coloring, event and alarm processing, automatic recording and printing, event recall and sequence recording, device remote control, etc. These functions constitute the fundament of the subsequent applications of analysis, dispatch, and control.

2) **Dynamic State Estimation**
The dynamic state estimation application serves as a data-cleaning machine in IEMSs. For the raw data of historical measurements and current measurements from the SCADA, this application filters measurement noise, detects and identifies bad data, and complements unavailable measurements with pseudo measurements according to known information, such as IES topologies, device parameters, and historical data, to provide consistent, complete, and reliable data for other applications. Its detailed functions include measurement filtering, bad data identification, pseudo measurement generation, network topology analysis, observability analysis, parameter recognition, etc.

3) **Generalized Load Prediction**
Based on historical data and other information such as weather and forecast day type, the generalized load prediction application forecasts multienergy loads and available renewable energy supplies in the future, which provides important references for other applications to formulate device schedules and assess security risk. The predictions are categorized into different time scales of middle-term, short-term, and super short-term according to different needs.

4) **Energy Flow Analysis**
Utilizing the processed historical measurement data from the dynamic state estimation and predicted future boundary conditions from the generalized load prediction, the energy flow analysis application calculates the temporal-spatial energy flow distributions in the whole IES from the present to a certain future. This application draws a comprehensive system picture for dispatchers and helps them perceive the trends of the system in advance. In addition, the calculated state is provided as a base state for further security assessment.

5) **Security Assessment and Control**
The application of security assessment and control works as a guard for IESs that prevents not only failures inside a single-energy network but also failures across different energy sectors due to stronger and tighter interdependencies and interactions between different energy flows. This application first generates a contingency set that comprises all failures of critical devices in different energy networks and then evaluates the consequence of each contingency by invoking the energy flow analysis application to detect potential security constraint violations. If the assessment reveals a security risk, either preventive control that pulls the IES back into a normal and secure state before the contingency or corrective control that maintains the IES security after contingency is adopted.

6) **Optimal Energy Flow**
The optimal energy flow application ensures the economic operation of IESs under the premise that security constraints are satisfied. For a scheduling span given predicted multienergy loads and available renewable energy supplies, this application formulates dispatch schedules for all controllable devices in
different energy networks to optimize the objective of operating costs, renewable energy accommodation, or energy supply efficiency. In this process, the multienergy complementation and system inertia of natural gas networks and heating networks are fully considered to obtain a better dispatch solution. According to different time scales, this application includes day-ahead, intraday, and real-time scheduling models.

In these functions, the SCADA and generalized load prediction are uncorrelated to the modeling of energy networks, so they can be developed in a manner similar to that in traditional EMSs, as in [58] and [59]. However, the remaining applications have to be implemented considering the long-time-scale dynamic characteristics of natural gas networks and heating networks, which results in a significant difference from the implementations of the same applications in traditional EMSs. In the next four subsections, these four advanced applications are successively developed based on the UEC method to consider the dynamics in IESs and meet the requirements for the online use of IEMSs.

C. Development of UEC-based Energy Flow Analysis

1) Related Works

As the coupling between electricity, natural gas, and heating networks deepens and complicates, there is a trend to calculate the energy flow distributions of different energy networks in a joint manner [39]-[41]. These works list steady-state models of various energy networks in simultaneous equations and derive a whole Jacobian matrix of all the variables so that they can be solved by Newton-Raphson iterations. Reference [60] improves the calculation performance by replacing the original Jacobian matrix with a diagonal and constant matrix that is generalised from the fast decoupled model in the power flow calculation of electricity networks. Furthermore, [40] and [61] utilize the fixed-point iterative method and holomorphic embedding method to decompose the joint model for privacy reservation and calculation acceleration. Considering the uncertainties in generalized loads, probabilistic integrated energy flows are analyzed by the Monte-Carlo simulation, interval calculation method, and point estimate method in [62], [63], and [64], respectively. However, the above works all formulate natural gas networks and heating networks by steady-state models, which ignore the dynamic process from one steady state to another steady state, resulting in calculation errors. In fact, large-scale natural gas networks and heating networks do not even enter a steady state under hour-level regulation, let alone minute-level regulation. In response to this situation, integrated energy flow calculations with dynamic models embedded are studied in [65]-[67]. However, the dynamic models used in these works are all algebraized by the FDM, which consequently brings a considerable computational burden.

2) UEC-based Energy Flow Analysis

For clarity, we first introduce the energy flow analysis of a single-energy network. Each node in this energy network owns two variables of potential and flow injection, and we assume that either one of these two variables is known while the other one remains unknown, so the nodes are categorized into fixed-potential nodes and fixed-injection nodes. Moreover, we define a history window with time periods of \( \tau_{\text{Th}} , \tau_{\text{Th+1}} , \ldots , \tau_{\text{Th}} \) and a future window with time periods of \( \tau_{0} , \tau_{1} , \ldots , \tau_{\text{Th-1}} \).

Therefore, we have the following six categories of node variables:

\[ \mathcal{P}_{n,p,t} \text{ and } \mathcal{F}_{n,f,t} ( \tau = \tau_{\text{Th}}, \tau_{\text{Th+1}}, \ldots, \tau_{\text{Th}} ): \text{potential variables of fixed-potential nodes and injection variables of fixed-injection nodes at historical time } \tau. \text{ They are known historical boundary conditions.} \]

\[ \mathcal{P}_{n,p,t} \text{ and } \mathcal{F}_{n,f,t} ( \tau = \tau_{0}, \tau_{1}, \ldots, \tau_{\text{Th-1}} ): \text{potential variables of fixed-potential nodes and injection variables of fixed-injection nodes at future time } \tau. \text{ They are known future boundary conditions.} \]

\[ \mathcal{P}_{n,f,t} \text{ and } \mathcal{F}_{n,f,t} ( \tau = \tau_{0}, \tau_{1}, \ldots, \tau_{\text{Th-1}} ): \text{potential variables of fixed-injection nodes and injection variables of fixed-potential nodes at future time } \tau. \text{ They are unknown state variables to be solved.} \]

The steps to obtain the energy flow distributions, including both node state variables and branch state variables in the future window, are as follows (illustrated in Fig. 6).

(a) Mapping from the time domain to the frequency domain

We use FT to map the time-domain boundary conditions \( \mathcal{P}_{n,p,t} \text{ and } \mathcal{F}_{n,f,t} \) to the frequency domain \( \mathcal{P}_{n,p,k} \text{ and } \mathcal{F}_{n,f,k} \):

\[
\mathcal{P}_{n,p,k} = \mathcal{F}(\kappa) \sum_{i=-\text{Th}}^{\text{Th}} \mathcal{P}_{n,p,t} e^{-j2\pi \kappa \text{Th+Tx}} / 2 (\text{25})
\]

\[
\mathcal{F}_{n,f,k} = \mathcal{F}(\kappa) \sum_{i=-\text{Th}}^{\text{Th}} \mathcal{F}_{n,f,t} e^{-j2\pi \kappa \text{Th+Tx}} / 2 \kappa = 0,1,\ldots, \text{Th+Tx}/2
\]

(b) Calculation in the frequency domain

We build the FDLP-circuit equations according to the current time-domain parameters:

\[
[\mathcal{Y}_{n,pp,k} \mathcal{Y}_{n,pf,k} \mathcal{Y}_{n,pf,k}] [\mathcal{P}_{n,p,k}) = [\mathcal{F}_{n,p,k}) \kappa = 0,1,\ldots, F (\text{26})
\]

where \( \mathcal{P}_{n,p,k} \text{ and } \mathcal{F}_{n,f,k} \) are the known excitations from step (a), \( \mathcal{Y}_{n,pp,k} \text{ and } \mathcal{Y}_{n,pf,k} \) are the unknown responses to be solved, \( \mathcal{Y}_{n,pf,k} \) and \( \mathcal{Y}_{n,pf,k} \) are the corresponding divisions to the generalized node admittance matrix, and \( F \) is the number of reserved frequency components that controls computational accuracy: \( F \leq \text{Th+Tx}/2 \). The solutions of the \( \kappa \)-th component are

\[
\mathcal{P}_{n,f,k} = \mathcal{Y}_{n,pp,k}^{1/2} (\mathcal{F}_{n,f,k} - \mathcal{Y}_{n,pf,k} \mathcal{P}_{n,p,k}) \mathcal{F}_{n,f,k} \mathcal{P}_{n,p,k} + \mathcal{Y}_{n,pf,k} \mathcal{P}_{n,p,k} \mathcal{F}_{n,f,k} \mathcal{P}_{n,p,k} (\text{27})
\]

Based on the node solutions, the energy flow distributions on
the branches are obtained:

$$\mathcal{F}_{v,k} = \mathcal{Y}_{v,k} \left( A^T \hat{\mathcal{P}}_{v,k} - \mathcal{K}_{v,k} A^T \bar{\mathcal{P}}_{v,k} \right)$$  \hspace{1cm} (28)

where $\hat{\mathcal{P}}_{v,k}$ is the concatenation of $\mathcal{P}_{v,p,k}$ and $\mathcal{P}_{n,f,k}$.

(c) Mapping from the frequency domain to the time domain

We use IFT to recover the frequency-domain responses back into the time domain:

$$\mathcal{P}_{n,f,i} = \sum_{k=0}^{F} \text{Re}(\mathcal{F}_{n,p,k} e^{\frac{2\pi}{Tn+Tx} k})$$

$$\mathcal{F}_{n,p,i} = \sum_{k=0}^{F} \text{Re}(\mathcal{F}_{n,p,k} e^{\frac{2\pi}{Tn+Tx} k})$$ \hspace{1cm} (29)

$$\mathcal{F}_{b,i} = \sum_{k=0}^{F} \text{Re}(\mathcal{F}_{b,k} e^{\frac{2\pi}{Tn+Tx} k})$$

where $\text{Re}(\cdot)$ means extracting the real part.

(d) Correction of the time-domain parameters

For electricity networks with a linear power flow model and heating networks, the solutions in (29) are the final results of energy flow analysis. For natural gas networks that establish the UEC model using Taylor expansion (see more details in Appendix A), we further check whether the error between the base value $x_b$ at the Taylor expansion point and the average variable value $x_v$ is within the given threshold $\varepsilon$: $\|x_v - x_b\| / \|x_v\| \leq \varepsilon$. If this criterion is satisfied, the solutions in (29) are output as the final results; otherwise, we update $x_b$ by (30), which further changes the time-domain parameters, and return to step (b) for a new iteration.

$$x_b \leftarrow (1 - \delta)x_b + \delta x_v$$  \hspace{1cm} (30)

where $\delta \in (0,1]$ is the step length.

It is recommended to first calculate only the zero-frequency component (i.e., steady energy flow analysis) to obtain a converged base value and then perform the calculation with all frequency components. This warm-start technology significantly reduces the computational burden for nonlinear energy networks.

For joint energy flow analysis of multienergy networks, there are two cases according to the different power flow models of electricity networks. If the power flow model is linear so that can be mapped into the frequency domain, then the above steps can be applied to joint energy flow analysis by replacing the single-network UEC equation (26) in step (b) with the pure-frequency-domain multinetowrk UEC equation (24); otherwise, we have to solve the multinetowrk UEC equation (23) that embeds a general electricity network model to obtain the joint energy flow distributions. It can be solved either in a centralized manner using the Newton method or in a decentralized manner by alternately solving single-frequency equations of the involved energy networks and updating boundary variables, in which the energy flow analysis of natural gas networks and heating networks can be performed using the above steps.

3) Case Study

We prepare two test systems for validation. The first one is a small-scale IES for illustrative purposes, which contains a 9-bus electricity network, a 7-node natural gas network, and a 6-node heating network, as shown in Fig. 12. In the electricity network, there are three power loads supplied by a wind turbine (WT), a combined heat and power (CHP) unit, and a gas turbine (GT). In the natural gas network, there are three gas loads supplied by two gas wells (GW). In the heating network, there are two heat loads supplied by a CHP unit and a gas boiler (GB). The three energy networks are coupled by the CHP unit, gas turbine, and gas boiler. The second one is a large-scale IES for performance verification, which contains a modified IEEE 118-bus electricity network, a 181-node natural gas network, and a 376-node heating network. The natural gas network and heating network in this test system are from two actual city-scale energy networks.

Fig. 12. Topology of the illustrative test system.

![Fig. 12. Topology of the illustrative test system.](image)

Fig. 13. Energy flow distributions in the illustrative IES: (a) transmission line power flow in the electricity network, (b) pipeline temperature in the heating network, (c) node pressure in the natural gas network, and (d) pipeline gas flow in the natural gas network. The solid lines are computed by the UEC method, and the dotted lines are computed by the FDM.

We calculate the energy flow distributions of this illustrative
IES for the next 24 hours with an interval of 5 minutes using the UEC method (specifically, pure-frequency-domain multinetwerk UEC model), in which the history window length is also chosen as 24 hours and all frequency components are reserved. Some results that are usually important to operators, including transmission line power flow in the electricity network, pipeline temperature in the heating network, and node pressure and branch gas flow in the natural gas network, are represented in Fig. 13 by solid lines. To validate the results, we further supplement the results computed by the FDM with the implicit upwind scheme and parameters used in [42]-[43] by dotted lines (the initial values are those in the results computed by the UEC method), which show high consistency. The average/maximum errors of the results in subfigures (a)-(d) are 0.001/0.021%, 0.208/1.639%, 0.025/0.133%, and 0.076/0.654%, respectively. With such accuracy, the elapsed time of the UEC method is only 0.34 s, which is far less than the 14.75 s of the FDM.

To further demonstrate the advantage of the UEC method in computational performance, the two methods are tested on a large-scale IES (their parameters remain consistent with those of the above test). For 24-hour energy flow analysis, under the same accuracy, the UEC method costs 1.30 s while the FDM costs 251.51 s. This result indicates that the UEC-based IEMS is able to perform online energy flow analysis on city-scale IESs.

D. Development of the UEC-based Optimal Energy Flow

1) Related Works

The main purpose of integrating different energy flows is to pursue more secure and economic operation of energy systems. As pioneering works, [68] optimizes the integrated power and gas flow for a secure purpose (e.g., to eliminate gas supply shortages for gas turbines), [69] optimizes the integrated power and heat flow for a lower operating cost (e.g., to mitigate wind power curtailment), and [70] does both. These works are realized using the steady-state models of natural gas systems and heating systems, which are replaced by dynamic models in [71] and [72] to utilize the inertias of these two systems as energy storage. Interpreted from mathematics, the latter works search for a better optimal dispatch schedule in a larger feasible region. Similar to the case of energy flow analysis, the dynamic models in most extant studies of optimal energy flow are algebraized by the FDM, and better computational performance can be obtained by switching to the UEC method.

In addition, more complex factors are considered in related studies. Considering privacy preservation, the joint optimization problem is solved in a decentralized manner with the topology and parameters of different energy systems unshared by the multiagent genetic algorithm [73], generalized Bender’s decomposition [74], and alternating direction method of multipliers [75]. Considering individual incentives, a Nash-Stackelberg game model [76] and a transfer payment strategy [77] are proposed for the optimal energy flow problem with energy systems managed by independent entities. Considering uncertainties, stochastic optimization [78], robust optimization [79], and distributionally robust optimization [80] are employed to give a deterministic dispatch schedule. Our proposed UEC method is compatible with these works.

2) UEC-based Optimal Energy Flow

In the optimal energy flow problem, the given potential and given flow injection of controllable devices (e.g., generators and boilers) are slacked so that the energy flow equations are underdetermined, i.e., with multiple solutions, in which the solution that optimizes the objective function and satisfies the given constraints is the target solution. The optimal energy flow problem embedding the UEC model is formulated as follows.

(a) Decision Variables

The decision variables in the UEC-based optimal energy flow problem contain four categories: time-domain flow variables, time-domain potential variables, frequency-domain flow variables, and frequency-domain potential variables, which are introduced as follows. Note that each complex variable in the frequency domain is decomposed into two real variables of the real part and imaginary part to ensure that all decision variables are in the real-number field.

\[ \mathcal{F}_{\ell,\kappa}: \text{flow injection variables of all nodes at time } \tau, \text{ which can be further divided into two categories of controllable one (}\mathcal{F}_{\ell,\kappa,\ell}, \text{ e.g., generators and boilers) and uncontrollable one (}\mathcal{F}_{\ell,\kappa,n}, \text{ e.g., loads and middle zero-injection nodes).} \]

\[ \mathcal{P}_{\ell,\kappa}: \text{potential variables of all nodes at time } \tau, \text{ which can also be divided into controllable one (}\mathcal{P}_{\ell,\kappa,\ell}) \text{ and uncontrollable one (}\mathcal{P}_{\ell,\kappa,n}). \]

\[ \mathcal{F}_{\ell,\kappa}^{\text{Re}} / \mathcal{F}_{\ell,\kappa}^{\text{Im}}: \text{real/imaginary part of the complex flow} \]

\[ \text{injection variables of all nodes in the frequency component } \kappa, \text{ which can also be divided into controllable one (}\mathcal{F}_{\ell,\kappa}^{\text{Re}} / \mathcal{F}_{\ell,\kappa}^{\text{Im}}) \text{ and uncontrollable one (}\mathcal{F}_{\ell,\kappa,n}^{\text{Re}} / \mathcal{F}_{\ell,\kappa,n}^{\text{Im}}). \]

\[ \mathcal{P}_{\ell,\kappa}^{\text{Re}} / \mathcal{P}_{\ell,\kappa,n}^{\text{Im}}: \text{real/imaginary part of the complex potential variables of all nodes in the frequency component } \kappa, \text{ which can also be divided into controllable one (}\mathcal{P}_{\ell,\kappa}^{\text{Re}} / \mathcal{P}_{\ell,\kappa,n}^{\text{Im}}) \text{ and uncontrollable one (}\mathcal{P}_{\ell,\kappa,n}^{\text{Re}} / \mathcal{P}_{\ell,\kappa,n}^{\text{Im}}). \]

(b) Objective

Usually, the objective is minimizing the total operating cost that is quadratic or linear to the flow variables of controllable devices, as in (31).

\[ \min \sum_{i=0}^{T_{x}-1} \mathcal{F}^T_{\ell,\kappa,n} \mathcal{Q}_{\ell,\kappa,n} + P^T_{\ell,\kappa,n} \mathcal{F}_{\ell,\kappa,n} + R_{\tau} \]  

(31)

where \( \mathcal{Q}_{\ell,\kappa,n}, P_{\ell,\kappa,n}, \text{ and } R_{\tau} \) are the corresponding quadratic, linear, and constant coefficients, respectively, and \( T_{x} \) is the number of dispatch periods.

(c) Constraints

The constraints include bound constraints in (32), coupling constraints in (33), FDLP network constraints in (34), time-domain-frequency domain (TD-FD) transformation constraints in (35), i.e., IFT, and historical boundary condition constraints in (36). In these constraints, (32) and (33) are the time-domain constraints that describe relationships outside the network, (34)
is the frequency-domain constraint that describes relationships inside the network, and (35) and (36) bridge the variables in these two domains.

\[
\begin{align*}
\mathcal{P}_n \leq \mathcal{P}_{n,f,i} \leq \mathcal{P}_n \\
\mathcal{F}_{n,f,i} \leq \mathcal{F}_{n,f,i} \leq \mathcal{F}_{n,f,i} & \quad i = 0,1,\ldots,Tx-1
d\end{align*}
\]

(32)

where \( \mathcal{P}_n \) and \( \mathcal{P}_n \) are the lower and upper bounds of the node potential that ensure secure operation; \( \mathcal{F}_{n,f,i} \) and \( \mathcal{F}_{n,f,i} \) are the lower and upper bounds of controllable node injections; and \( \mathcal{F}_{n,f,i} \) represents the predicted values of uncontrollable node injections.

\[
\mathcal{C} \mathcal{F}_{n,f,i} = 0 \quad i = 0,1,\ldots,Tx-1
\]

(33)

where \( \mathcal{C} \) is the converter characteristic matrix defined in (20).

\[
\begin{align*}
\mathcal{F}_{n,f,i}^\text{Re} &= \text{Re}(\mathcal{W}) \mathcal{P}_{n,f,i}^\text{Re} - \text{Im}(\mathcal{W}) \mathcal{P}_{n,f,i}^\text{Im} \\
\mathcal{F}_{n,f,i}^\text{Im} &= \text{Re}(\mathcal{W}) \mathcal{P}_{n,f,i}^\text{Im} + \text{Im}(\mathcal{W}) \mathcal{P}_{n,f,i}^\text{Re}
d\end{align*}
\]

(34)

where \( \text{Re}(\cdot) / \text{Im}(\cdot) \) refers to the extraction of the real/imaginary part and \( Th \) is the number of historical periods.

\[
\begin{align*}
\sum_{k=0}^{(Th+Tx)/2} \mathcal{P}_{n,k}^\text{Re} \cos\left(\frac{2\pi ki}{Th+Tx}\right) - \mathcal{P}_{n,k}^\text{Im} \sin\left(\frac{2\pi ki}{Th+Tx}\right) &= \mathcal{F}_{n,f,i} \\
\sum_{k=0}^{(Th+Tx)/2} \mathcal{P}_{n,k}^\text{Re} \cos\left(\frac{2\pi ki}{Th+Tx}\right) - \mathcal{P}_{n,k}^\text{Im} \sin\left(\frac{2\pi ki}{Th+Tx}\right) &= \mathcal{P}_{n,f,i} \\
\sum_{k=0}^{(Th+Tx)/2} \mathcal{F}_{n,k}^\text{Re} \cos\left(\frac{2\pi ki}{Th+Tx}\right) - \mathcal{F}_{n,k}^\text{Im} \sin\left(\frac{2\pi ki}{Th+Tx}\right) &= \mathcal{F}_{n,f,i} \\
\sum_{k=0}^{(Th+Tx)/2} \mathcal{F}_{n,k}^\text{Re} \cos\left(\frac{2\pi ki}{Th+Tx}\right) - \mathcal{F}_{n,k}^\text{Im} \sin\left(\frac{2\pi ki}{Th+Tx}\right) &= \mathcal{P}_{n,f,i} \\
i = 0,1,\ldots,Tx-1
\end{align*}
\]

(35)

where \( \mathcal{F}_{n,f,i} \) and \( \mathcal{P}_{n,f,i} \) \((i < 0)\) are the historical boundary conditions.

The above quadratic programming (QP) problem can be efficiently solved using off-the-shelf commercial solvers such as Gurobi [81] and CPLEX [82].

3) Case Study

We first test the above UEC-based implementation of optimal energy flow on the illustrative IES shown in Fig. 12. The test configuration includes a scheduled time of 24 hours (i.e., day-ahead schedule), a historical time of 24 hours, and an interval of 15 minutes. For validation, the same optimal energy flow problem is solved using the conventional steady-state model and the conventional FDM-based dynamic model. The results of the three methods are reported as follows.

Regarding the comparison between the UEC-based dynamic model and the conventional steady-state model, the results are summarized in TABLE II, and the detailed dispatch schedules of sources in the three energy networks are provided in Fig. 14. For the steady gas-network model, there is no feasible solution since the two gas wells cannot cover the peak gas load around 10:00. However, using the dynamic gas-network model, a dispatch schedule with mismatches between the gas load and gas supply is still feasible, which only results in acceptable pressure fluctuation due to the inflation and deflation processes indicated in Fig. 14. For the steady heating-network model, the heat supply follows the heat load plus the heat loss. Consequently, the CHP unit maintains high output during the night (00:00-04:00) due to the heavy heat load during this period, which squeezes the space for wind power.

![TABLE II](https://example.com/table2.png)

**TABLE II**

|                      | Dynamic Model | Steady Heat Model | Steady Gas Model |
|----------------------|---------------|-------------------|-----------------|
| Operating Cost ($)   | 346,597.50    | 357,088.27        | Infeasible      |
| Wind Power Curtail. (%) | 5.47         | 17.71             |                 |
| Heat Loss (%)        | 6.42          | 7.70              |                 |
| Natural Gas Demand (t)| 869.44        | 916.80            |                 |

![Fig. 14](https://example.com/fig14.png)

**Fig. 14.** Dispatch schedules obtained by (a) the UEC-based dynamic model and (b) the conventional steady-state model (only for the heating network).
accommodation through heat-power coupling. In addition, the low output of the CHP unit during the daytime (10:00-14:00) results in more power supplied by the gas turbine, which is more expensive than the CHP unit. In contrast, the dynamic heating-network model avoids the above two circumstances by shifting the peak load to the valley load and finally gives a dispatch schedule with less operating cost.

The FDM-based dynamic model calculates a dispatch schedule similar to that calculated by the UEC-based dynamic model, as compared in Fig. 15. The main difference comes from the different final states (temperature in the heating network and pressure in the natural gas network): the FDM-based model greedily consumes the existing stock as much as possible, so we add an extra constraint that the final state be no worse than the initial state, while the final state decided by the UEC-based model is influenced by the historical boundaries due to the periodic extension effect of FT. Nevertheless, this influence is extremely slight, and the two methods give optimal objectives with a difference of less than 0.1%. With almost the same optimality, the UEC method obviously outperforms the FDM from the perspective of efficiency: the optimization problem of the former method has nearly 95% fewer variables and constraints and is solved in roughly 75% less time than that of the latter method. Details are listed in TABLE III.

In the performance validation on the large-scale IES, the UEC method costs only 134 s to solve the day-ahead optimal energy flow, which is far less than the 1615 s of the FDM. This confirms the UEC-based IEMS is able to perform online optimization on city-scale IESs.

E. Development of the UEC-based Dynamic State Estimation

1) Related Works

State estimation that effectively improves measurement accuracy has been broadly applied in electricity networks for a long time [83]. With the increasingly tight coupling of different energy networks, related studies have expanded this method to IESs: [84]-[85], [86], and [87] develop state estimation models for integrated electricity and heat systems, integrated electricity and gas systems, and general IESs comprising electricity, natural gas, and heat, respectively. These models are established based on the weighted least square method. Considering the more complex factors in IESs, a weighted least absolute value-based state estimation model is investigated in [88], and another second-order conic programming-based state estimation model is formulated in [89]. Moreover, [90] proposes a decentralized state estimation method to address the privacy issue.

However, the above works have followed the section-based estimation manner adopted in electricity networks, i.e., using steady-state network models, which ignores the dynamic processes and results in obvious estimation error. This research gap is closed in [91]-[92] and [93]-[94], which develop dynamic state estimation models for heating networks and natural gas networks, respectively. In these works, historical measurement data are involved in the estimation of current measurement data, and the PDE constraints of the dynamic model are algebraized by the node method and FDM. The differences between these models and our UEC-based dynamic state estimation are twofold: 1) both historical and current measurement data are estimated to provide consistent historical boundary conditions for other applications; 2) the PDE constraints are algebraized by the UEC method, which yields fewer variables and constraints.

2) UEC-based Dynamic State Estimation

In the state estimation, there may be excess measurements so that the energy flow equations are overdetermined, i.e., with no solution due to conflicting constraints. The dynamic state estimation problem slacks all state variables with a penalty on deviation from measurement and picks the solution that obeys the dynamic model constraints and minimizes the deviation as the estimated state. The dynamic state estimation problem embedding the UEC model is formulated as follows.

(a) Measurement Data

According to the time scales of the dynamic processes in different energy networks, different measurement data are

![Fig. 15. Dispatch schedules obtained by (a) the UEC-based dynamic model and (b) the FDM-based dynamic model.](image-url)
adopted for estimation. For electricity networks, only current measurement data \((\tau = \tau_r)\) are used since the current state is not related to historical states. For natural gas networks and heating networks, both current measurement data and historical measurement data \((\tau = \tau_{-T_h:T_{h+1}}, \cdots, \tau_{-T_x})\) are estimated. In addition, further historical measurement data \((\tau = \tau_{-T_h:T_{h+1}}, \cdots, \tau_{-T_x})\) participate in the estimation to provide surrogate initial values.

We denote the above measurement data as follows.

\(z^{\tau_r}_{\tau} :\) the measurement vector of the electricity network at time \(\tau_r\), which includes the active/inactive power injection and voltage magnitude of buses and active/inactive power in transmission lines.

\(z^{\tau}_{\tau} (i = -T_x - T_h + 1, \cdots, 0) :\) the measurement vector of the natural gas network and heating network at time \(\tau_i\), which includes the flow injection \((z^{\tau}_{\tau})\) and potential \((z^{\tau}_{\tau})\) of nodes.

(b) Decision Variables

The electricity network is modeled by the conventional AC power flow model, yielding only time-domain variables as follows.

\(x^T_{\tau} :\) time-domain variables at time \(\tau_0\), as the estimated values of \(e^T_{\tau}\).

The natural gas network and heating network are modeled by the UEC model, yielding both time-domain variables and frequency-domain variables as follows.

\(x^T_{\tau} (i = -T_x - T_h + 1, \cdots, 0) :\) time-domain flow injection variables at time \(\tau_i\), as the estimated values of \(z^{\tau}_{\tau}\).

\(x^P_{\tau} (i = -T_x - T_h + 1, \cdots, 0) :\) time-domain potential variables at time \(\tau_i\), as the estimated values of \(z^P_{\tau}\).

\(x^{\tau,Re}_{\hat{\kappa}} / x^{\tau,Im}_{\hat{\kappa}} (\hat{\kappa} = 0, 1, \cdots, F) :\) real/imaginary part of the frequency-domain flow injection variables in the frequency component \(\hat{\kappa}\).

\(x^{P,Re}_{\hat{\kappa}} / x^{P,Im}_{\hat{\kappa}} (\hat{\kappa} = 0, 1, \cdots, F) :\) real/imaginary part of the frequency-domain potential variables in the frequency component \(\hat{\kappa}\).

(c) Objective

Usually, the objective for dynamic state estimation is minimizing the weighted sum of measurement residuals, as in (37).

\[
\min \left\| x^e_{\tau} - z^e_{\tau} \right\|_{W^e} + \sum_{i = -T_x - T_h + 1}^{0} \delta_i \left(\left| x^{\tau,Re}_{\hat{\kappa}} - z^{\tau,Re}_{\hat{\kappa}} \right|_{W^r} + \left| x^{P,Re}_{\hat{\kappa}} - z^{P,Re}_{\hat{\kappa}} \right|_{W^r} \right) \tag{37}
\]

where \(W^e\) is the covariance matrix of measurements in the electricity network; \(W^{r,h}\) is the covariance matrix of measurements in the natural gas network and heating network; and \(\delta_i\) is the weighting factor of the measurement at time \(\tau_i\).

Regarding the selection of \(\delta_i\), a recommended solution is setting \(\delta_i\) as 1 for \(i > -T_x\) and a relatively small value such as 0.01 for \(-T_x - T_h < i \leq -T_x\).

(d) Constraints

There are three constraints involved in the dynamic state estimation problem.

The first one is the AC power flow model of electricity networks, whose details can be found in \([83]\).

The second one is the UEC model of natural gas networks and heating networks, which consists of the frequency-domain network equation in (38) and the TD-FD transformation equation in (39).

\[
\begin{align}
\begin{bmatrix}
x^{\tau,Re}_{\hat{\kappa}} \\
x^{\tau,Im}_{\hat{\kappa}}
\end{bmatrix} &= \text{Re}(\mathcal{Y}_{\hat{\kappa}}) x^{P,Re}_{\hat{\kappa}} - \text{Im}(\mathcal{Y}_{\hat{\kappa}}) x^{P,Im}_{\hat{\kappa}} \quad \kappa = 0, \ldots, D \tag{38}
\end{align}
\]

\[
\begin{align}
x^{P,Re}_{\hat{\kappa}} &= \text{Re}(\mathcal{Y}_{\hat{\kappa}}) x^{\tau,Re}_{\hat{\kappa}} - \text{Im}(\mathcal{Y}_{\hat{\kappa}}) x^{\tau,Im}_{\hat{\kappa}} \\
x^{P,Im}_{\hat{\kappa}} &= \text{Re}(\mathcal{Y}_{\hat{\kappa}}) x^{\tau,Re}_{\hat{\kappa}} + \text{Im}(\mathcal{Y}_{\hat{\kappa}}) x^{\tau,Im}_{\hat{\kappa}}
\end{align} \tag{39}
\]

The third one is the time-domain coupling relationship between different energy flows, as in (40).

\[
C^e x^e_{\tau} + C^{r,h} x^P_{\tau} = 0 \tag{40}
\]

where \(C^e\) and \(C^{r,h}\) are the corresponding converter characteristic matrices.

The above nonlinear programming problem for joint state estimation of three energy networks can be efficiently solved using the primal-dual interior-point method. However, for the following two reasons, it is recommended to sequentially estimate the states of electricity networks and states of natural gas networks and heating networks, i.e., estimate the electricity network first and then estimate the natural gas network and heating network, in which the estimation results of the electricity network are regarded as pseudo measurements through the coupling relationship:

i) The electricity network requires more frequent state estimation than the other two networks because of its fast dynamic processes.

ii) Sequent estimation separates the nonlinear constraints of electricity networks and linear constraints of natural gas networks and heating networks, which improves the solving efficiency.

3) Case Study

The above UEC-based implementation of dynamic state estimation (DSE) is tested on the illustrative IES shown in Fig. 12. The test configuration is as follows: the estimated time is 24 hours, the historical time is 2 hours, the measurement interval is 5 minutes, the results from the energy flow analysis are set as the true values of states, and the measurement data are generated by superposing Gaussian noise whose amplitude is set as 0.01 p.u. on the true values. The estimation accuracy is
evaluated using the following index:

$$\xi = \frac{\|\hat{x} - \bar{x}\|^2}{\|z - \tilde{x}\|^2}$$

(41)

where $\hat{x}$ is the vector of estimated values, $\bar{x}$ is the vector of true values, and $z$ is the vector of measurement values. A smaller $\xi$ means higher estimation accuracy, and its limit is 0.

For comparison, the same tests of the conventional steady state estimation (SSE) method and FDM-based DSE method are supplemented. The estimation accuracy of the three methods is compared in TABLE IV, from which we observe that the average value of $\xi$ obtained by the SSE method is larger than 1 for both the natural gas network and heating network. This indicates that the estimated data of the SSE method are worse than the measurement data. In contrast, the average values of $\xi$ obtained by the DSE methods (both FDM-based and UEC-based) are less than 1, which validates their effectiveness in filtering noise. Particularly, the UEC-based DSE outperforms the FDM-based DSE because the limited frequency components in the UEC-based DSE method implicitly filter the high-frequency components of noise.

### TABLE IV
ACCURACY COMPARISON OF THE THREE ESTIMATION METHODS

|       | SSE | FDM-DSE | UEC-DSE |
|-------|-----|---------|---------|
|       | HN  | NGN     | HN      | NGN     | HN      | NGN     |
| Avg. $\xi$ | 1.67 | 2.07 | 0.22 | 0.41 | 0.02 | 0.07 |
| Max. $\xi$ | 8.91 | 10.21 | 0.63 | 0.92 | 0.21 | 0.66 |

* HN: heating network, NGN: natural gas network

Some typical estimation results of the SSE and UEC-based DSE are provided in Fig. 16, from which we can observe that the curves estimated by the SSE fail to track the dynamic processes and have many glitches (i.e., are unsmooth) due to less consideration of the couplings between adjacent sections. These phenomena explain why the SSE method produces a large $\xi$.

In addition to better estimation accuracy, the UEC-based DSE method spends 0.87 s on calculation, which is obviously less than the 4.38 s of the FDM-based DSE method.

### F. Development of the UEC-based Security Assessment and Control

#### 1) Related Works

Security assessment is a technology for recognizing potential security issues in systems. Ever since security assessment for electricity networks were proposed by Dy-Liacco in 1967, it has developed by leaps and bounds, as summarized in [95]. As the couplings between different energy flows tighten, researchers begin to explore security assessment for cascading failures across energy sectors in IESs. In [96] and [97], security assessments for IESs are implemented by calculating post-contingency energy flows for each failure in the contingency set. For faster online use, [98] and [99] propose an IES-security-region method, but it is rather conservative for practical use. The above works continue the custom of security assessment in electricity networks that focuses on the steady state after failure but ignores the dynamic process between the steady state before failure and that after failure. For IESs with large inertias, this process can last tens of minutes or even several hours, which is important information for IES operators. To provide this information, performing dynamic energy flow analysis in security assessment is necessary.

If a security risk is detected by assessment, the security control module regulates controllable devices to maintain system security. According to the timing of the control performed, security control is mainly divided into preventive control and corrective control: the former modifies device schedules before failure to ensure that the post-contingency state is still secure, whereas the latter modifies the device schedules after failure to maintain secure operation. These security control problems for electricity networks are investigated in [100], and similar works are implemented for IESs: [68] and [101] study preventive control, while [102] and [103] study corrective control. Nevertheless, the research gap of involving dynamic characteristics in the security control of IESs still remains.

#### 2) UEC-based Security Assessment and Control

The security assessment in IEMSs contains two steps of contingency set generation and post-contingency energy flow analysis. Regarding the first step, its implementation is similar to that in conventional EMSs, so we do not introduce it here. For the second step, we utilize the aforementioned UEC-based energy flow analysis (in subsection C) to obtain the temporal-spatial dynamic energy flow distributions after a given failure so that we can determine both whether the IES is secure after...
the failure and when the IES becomes insecure.

The failures in the contingency set can be divided into two categories: injection failures and topology failures. The former refers to the failures of sources (e.g., generators, boilers, and gas wells) and loads that influence the network injection; the latter refers to the failures of pipelines and transmission lines that influence the network topology. The energy flows with injection failures can be directly calculated by the UEC method as long as the node injection corresponding to the failure device is set to zero after the fault time. However, the UEC method cannot directly address the energy flow analysis with topology failures because two sets of topologies are involved in the time domain, which means a time-variant node admittance matrix is included, i.e., \( \mathbf{Y}(t) \), thereby invalidating the superposition theorem.

To solve this problem, an equivalent time-invariant transformation for topology failures is provided. Without loss of generality, we assume that there is a branch broken at time \( t_0 \). First, the energy flow without this failure (i.e., base state) is calculated to obtain the branch flow of the broken branch before \( t_0 \). Then, we remove the broken branch from the topology and add two imaginary node injections to the nodes connected by this branch: the injection at the inflow node is the branch-end flow before \( t_0 \) and zero after \( t_0 \), while the injection at the outflow node is the negative branch-beginning flow before \( t_0 \) and zero after \( t_0 \). This procedure is visualized by an illustrative example in Fig. 17. Through this transformation, the energy flow distribution in the transformed network, which can be efficiently calculated by the UEC method, is exactly the desired energy flow distribution in the original network.

According to the severity and rapidity of the consequences, preventive control or corrective control is applied for failures in the contingency set. Their UEC-based implementations are similar to the optimal energy flow application. The differences lie in the fact that the security control problem may have an objective other than minimizing operating costs, such as minimizing schedule deviations, and additional constraints reflecting failures (cutting planes or fixed flow injections). Referring to the UEC-based optimal energy flow problem, a corrective control problem that minimizes the schedule deviations is formulated as follows.

\[
\min \sum_{i=0}^{\tau_f-1} \left( \mathbf{F}_{n,c,t_i} / \hat{\mathbf{F}}_{n,c,t_i} - 1 \right)^2
\]

subject to

- bound constraints (32)
- coupling constraints (33)
- FDLP network constraints (34)
- TD-FD transformation constraints (35)
- historical boundary value constraints (36)

where \( \hat{\mathbf{F}}_{n,c,t_i} \) represents the original schedules of controllable devices at time \( \tau_i \). Compared with the constraints in the optimal energy flow problem, there is one more equality constraint in the bound constraints (32)* to assign the node injections correlated to the given failure.

Note that in the corrective control problem, the time \( \tau_0 \) is the fault time so that the devices follow the original schedule before the failure \( (\tau_{\tau_0} - \tau) \) and only the subsequent schedule after the failure \( (\tau_0 - \tau_{\tau_0-1}) \) is modified.

3) Case Study

There are 26 failures in the N-1 contingency set of the illustrative IES shown in Fig. 12. From this contingency set, we select an injection failure (gas turbine outage) and a topology failure (pipeline 2-3 in the natural gas network breaks) for security assessment, with the results shown in Fig. 18. The fault times are both set at 12:00.

For the first failure, although no overload or loss of load occurs in the electricity network, there is a load temperature exceeding the upper limit in the heating network consequently. The mechanism of fault propagation across energy sectors is as follows: the power mismatch induced by the gas turbine outage is all compensated by the only controllable CHP unit, which in turn increases the heat supply due to coupling. Finally, the over-supplied heat leads to a global temperature rise in the heating network. After 63 minutes, the nearest load 1 first touches the security limit of 120 °C. The detailed dynamic processes are given in subfigures (a) and (b) of Fig. 18. Note that only the curves under the security bound are reliable because the water explosively boils at that temperature and stops heating up.

The second failure ultimately results in the pressure of gas load 1 exceeding the lower limit. After the breakdown of pipeline 2-3, the gas supply path of load 1 is switched from “pipeline 3-4 > pipeline 2-3 > pipeline 1-2” to “pipeline 6-7 >
pipeline 2-6 > pipeline 1-2”. This significantly aggravates the gas flow on pipeline 6-7, which has already delivered the gas flow of load 3. As a consequence, the pressure loss on pipeline 6-7 increases, and the remaining pressure at load 1 and load 3 thereby decreases. Due to the large inertia of the natural gas network, this flow-shifting process lasts several hours, and the furthest load 1 first touches the security limit of 0.7 MPa after 202 minutes. The detailed processes are presented in subfigures (c) and (d) of Fig. 18. Because gas load 1 supplies the gas turbine, the low-pressure fault further trips the gas turbine and leads to another incident in the heating network (i.e., the first failure introduced above).

Another similar failure that causes severe inadequate gas supply pressure is the breakdown of branch 3-4, which is equivalent to the outage of gas well 1. The pressures of gas loads under the original schedules after this failure occurred at 12:00 are presented by the dashed lines in Fig. 19 (d), which indicate that the pressures of load 1 and load 3 exceed the lower limit at 15:16 and 16:28, respectively. To avoid such incidents, corrective control that minimizes schedule deviations to maintain state variables in security bounds is performed, and the modified schedules are shown in Fig. 19 (a), (b), and (c) by the solid lines. The corrective mechanism is as follows: raise the power and heat outputs of the CHP unit so that the gas turbine and gas boiler can decrease their outputs while maintaining a balance between the supply and demand. The reduction in gas consumed by the gas turbine and gas boiler alleviates the gas transmission congestion in the natural gas network, which consequently maintains the load pressure above the security lower bound, as shown in Fig. 19 (d).

IV. APPLICATION: ENGINEERING DEMONSTRATIONS IN CHINA

Regarding the organization of this section, we first report an overview of IEMS engineering demonstrations in China in subsection A, which follows a detailed introduction to the typical city-scale demonstration project in Jilin Province in subsection B.

A. Overview of IEMS Engineering Demonstrations

Since 2016, our developed IEMSs have been deployed onsite for engineering demonstrations. By the end of 2021, there have been a building-scale IES, 4 park-scale IESs, and a city-scale IES that are equipped with IEMSs, as well as 2 park-scale IESs and 3 city-scale IESs where IEMSs are under construction. A partial list of these engineering demonstrations is compiled in TABLE V.

These IESs cover the energy flows of electricity, natural gas, steam (for industrial heating purposes), heating (for residential heating purposes), and cooling. Through the joint operation of these energy flows, the IEMS produces significant benefits, including the primary benefits of reducing energy-using costs, reducing peak load, improving system security, and increasing renewable energy accommodation and secondary benefits of reducing or delaying energy supply facilities and reducing carbon emissions.

Throughout the development of IEMSs for these engineering demonstrations, the gradual expansion of the IES scale brought about two changes to the network modeling in IEMSs. In the first period, the demonstrations were performed in buildings or commercial parks whose pipeline networks are so small that the regulation on energy supply devices immediately changes the states on the demand side. Thus, we chose steady-state network models to model these small-scale IESs. In the second period, our IEMS began to manage the IESs of large industrial parks and towns, in which obvious dynamic processes in pipeline networks were observed. We found that the FDM-based
TABLE V
PARTIAL LIST OF IEMS ENGINEERING DEMONSTRATIONS IN CHINA

| Location          | System Scale | Construction State | Energy Sectors             | More Available Details                                                                 |
|-------------------|--------------|--------------------|---------------------------|----------------------------------------------------------------------------------------|
| Changchun, Jilin  | city         | implemented        | electricity heating       | A heating network with over 268 km of pipelines that supplies heat for a total area of 20 million m² is involved. After the IEMS is accessed, wind power curtailment decreases by 12.65%. |
| Zhejiang          | city         | under construction | electricity natural gas   | A natural gas network with over 1600 km of pipelines is involved.                         |
| Dehong, Yunnan    | city         | under construction | electricity natural gas   | A cross-border IES is involved.                                                          |
| Beichen, Tianjin  | park         | implemented        | electricity natural gas   | A town that covers an area of 20.3 km² and has abundant flexibility resources including CHP units, gas boilers, ground-source heat pumps, and energy storage devices is involved. After the IEMS is accessed, the daily operating cost decreases by 6.3%. |
| Conghua, Guangzhou| park         | implemented        | electricity steam         | An industrial park that covers an area of 12 km² and has a power load of 20 MW, a steam load of 50 t/h, and a cooling load of 15 MW is involved. After the IEMS is accessed, the peak power load decreases by 20% through demand response. |
| Beike, Beijing    | park         | implemented        | electricity natural gas   | A commercial park that covers an area of 70 acres and has a power load of 4 MW and a heating/cooling load of 5 MW is involved. |
| Huaneng, Jilin    | building     | implemented        | electricity heating/cooling| A building that has a total area of 16000 m² and a heating/cooling load of 1.5 MW is involved. After the IEMS is accessed, the daily operating cost decreases by 4.3%. |

dynamic network model worked well for these middle-scale IESs. For engineering practices on city-scale IESs, the FDM yields numerous discrete elements that severely slow the decision-making speed of IEMSs. Under such pressure, the UEC method was proposed to promote the development of IEMSs that manage large-scale IESs.

B. A Typical Demonstration in Jilin Province

A typical demonstration project of the IEMS in Jilin Province is reported as follows.

1) Project Background

Jilin Province is located in the northeast of China. By the end of 2017, the electricity network in this province included 97 220-kV substations, transmission lines of 12965 km, and a total installed capacity of 26860 MW. To utilize the rich wind resources in this province, wind turbines with a capacity of 5050 MW are installed, which equals 18.80% of the total installed capacity, 50% of the maximum load, and 123% of the minimum load. In 2017, the power generated by wind turbines reached 8.69 billion kWh. Due to its high latitude, this province has a 6-month heating season from October to April of the following year, and multiple district heating networks with pipelines of a total length over 28000 km have been built to supply heat for a total area of 611.5 million m². More than 70% of the heat load is supplied by CHP units operating with a heat-led strategy, which significantly limits the peak-shaving ability of these CHP units and squeezes the space for wind power accommodation. As a result, the annual wind power curtailment rates in Jilin Province were always above 20% and even 30% in 2017 and before, in which the curtailment during the heating season accounted for 80%-90%.

In response to this situation, a demonstration project supported by the Ministry of Science and Technology of China and the State Grid Corporation of China is carried out. This project contains two phases: the first phase mainly focuses on reducing wind power curtailment by coordinated dispatch of the electricity network and heating network (i.e., the optimal energy flow application of the IEMS), while the second phase mainly focuses on the comprehensive energy management of the two networks (i.e., the remaining applications of the IEMS). The goal of this demonstration project includes improving both wind power accommodation in the electricity network and operation management of the heating network.

2) Field-Site Deployment

The engineering demonstration is implemented in an area of Changchun, which is the capital of Jilin Province. In this demonstration area, 8 CHP units with an installed capacity of 1820 MW, 8 wind farms with an installed capacity of 1288 MW, and 2 electric-heating substations with an installed capacity of 46 MW are integrated to supply power and heat. The heat is delivered by a heating network that owns 400 heat-exchange stations and pipelines over 268 km (containing water of roughly 300 thousand tons) to a load of 20 million m².
The deployment relationships of the IEMS and these facilities are illustrated in Fig. 20: the sensor data of the electricity network and power-supply devices are collected by the data server in the EPCC, while those of the heating network and heat-supply devices are collected by the data server in the heat power control center (HPCC). These measurement data, as well as other necessary data such as topology and contingencies, are sent to the IEMS server that is located at the EPCC for calculations. The results are sent back to the data servers in the EPCC and HPCC, some of which are issued to devices to adjust their outputs and the other of which are stored for queries from the work stations in the control center.

The involved power and heat system in this demonstration project contains a 621-node-817-branch electricity network and a 376-node-508-branch heating network. Using the UEC-based implementation, the calculation performances of advanced applications in the IEMS all meet the online-use requirements. Specifically, the dynamic state estimation is executed every 5 minutes, and each execution is finished in 30 seconds (typical); the energy flow analysis is executed every 5 minutes, and each execution is finished in 5 seconds (typical); the security check is executed every 60 minutes, and each execution is finished in 20 minutes (typical); the day-ahead optimal energy flow is executed once a day, and each execution is finished in 3 minutes (typical); and the intraday-rolling optimal energy flow is executed every 4 hours, and each execution is finished in 3 minutes (typical).

3) Overall Benefits

The heat-storage characteristics of the massive amount of water in the heating network provides significant flexibility for wind power accommodation. A typical scenario is provided in Fig. 21, which is a screenshot of the developed IEMS on March 1\textsuperscript{st}, 2018. On this day, there was a large output of wind power from 00:00 to 05:00. To accommodate more wind power, the outputs of CHP units were decreased, which led to a 5°C drop in the water supply temperature. However, due to the large inertia of the heating network, little influence on the indoor temperature caused by this adjustment was observed. Through such a regulation, an extra wind power of 475 MWh was accommodated on this day.

During the demonstration period of the first-phase project in 2017, the wind farms in the demonstration area reduced wind power curtailment by 83.99 GWh, representing a decrease of 12.65% compared with that of the same period in the previous year. This is equivalent to a saving of 27756 tons of standard coal and a reduction of roughly 73000 tons of carbon dioxide emissions.

During the demonstration period of the second-phase project from 2020 to 2021, the daily operating cost of the heating network decreased by 4.87% compared with that of the same period in the previous year due to comprehensive energy management.

![Fig. 20. Deployment relationships of the IEMS and other facilities.](image)

![Fig. 21. System screenshot on March 1\textsuperscript{st}, 2018.](image)

V. CONCLUSION

A novel UEC modeling method for IESs is proposed in this article, based on which an IEMS that manages large-scale IESs is further developed.

The proposed UEC method models natural gas networks and heating networks in the frequency domain with lump parameters, analogous to the electric-circuit modeling of electricity networks. This method unifies the analyses of three heterogeneous energy networks on both steady-state and dynamic-state time scales in the same mathematical form. In addition, this method efficiently algebraizes the original PDE models of dynamic processes in natural gas networks and heating networks, which yields fewer variables and equations and thereby lower computational complexity. In numerical tests, performance improvement across orders of magnitude is observed in both analysis and optimization. Moreover, this method also has high parallel computing efficiency and no numerical convergence issues and does not require the initial conditions inside pipelines.

The developed IEMS is designed in a window-based manner to match the long-time-scale dynamic characteristics in IESs. This IEMS integrates various advanced applications including dynamic state estimation, energy flow analysis, security assessment and control, and optimal energy flow to cover the whole process of managing multiple energy flows. These advanced applications are implemented based on the UEC.
method to enable their online uses for large-scale IESs. Since 2016, this IEMS has been deployed at 6 sites, including buildings, parks, and cities, for engineering demonstrations, and more sites with larger-scale and more comprehensive energy systems are under construction of this IEMS. The economic and environmental benefits achieved in these actual demonstration projects provide sufficient empirical evidence for the promising application prospects of IEMSs and the computing advantages of the UEC method.

It is worth noting that the contents of IEMSs are far more than what is presented in this article. An outlook for the future IEMS is given as follows.

1) More energy flows

In addition to the energy flows of electricity, natural gas, and heating introduced in this article, there are varying degrees of coupling between the energy flows of steam, hydrogen, petroleum, etc., and even traffic flow because of the fast development of electric vehicles. Integrating these energy flows into the managing scope of IEMSs is promising for better coordination in wider areas.

2) More advanced applications

The advanced applications developed in this article cover the essential but not all functions of energy flow management. More applications can be customized to satisfy diverse requirements. For instance, an application that aggregates distributed flexibility resources in the IES to interact with the utility grid (similar to the concept of virtual power plants) and an application that determines energy prices for different energy sectors at different positions (similar to the concept of nodal price calculation) are both useful extensions.

3) More flexible architectures

In this article, we assume a centralized architecture for participants in an IES; i.e., all information of different energy networks is collected together for calculation. This sometimes causes privacy issues. A decentralized architecture, in which participants perform local calculations and exchange boundary information to converge to a globally consistent solution, is more flexible. To realize this architecture, efficient distributed algorithms and robust communication networks should be further studied.

APPENDIX

A. Derivation of the Hydraulic Circuit and Thermal Circuit

This appendix provides the derivation process from the original PDE models of pipelines to the TDDP-circuit models, then to the FDDP-circuit models, and finally to the FDLP-circuit models.

1) Hydraulic-Circuit Model for Natural Gas Pipelines

The PDEs (4) that describe the 1D gas flow in natural gas pipelines include four variables ($m$: mass flow rate, $p$: pressure, $\rho$: density, and $v$: velocity) and a quadratic term involving $v$. We first apply Taylor expansion to linearize the quadratic term at point $v = v_b$ (the value of $v_b$ is modified through iterations; see more details in Section III.B) and then eliminate $\rho$ and $v$ by substituting the last two equations into the first two, which finally gives the equation below.

\[
\begin{align*}
\frac{\partial p}{\partial x} + \frac{1}{A} \frac{\partial m}{\partial t} + \lambda m \frac{\partial m}{\partial x} + \frac{2 D g \sin \alpha - \lambda v^2}{2 D c^2} p &= 0, \\
\frac{\partial m}{\partial x} + \frac{A}{c^2} \frac{\partial p}{\partial t} &= 0
\end{align*}
\]

(43)

Then, based on the circuit analogy defined in TABLE I, the hydraulic-circuit components are extracted from (43):

\[
\begin{align*}
R'_b &= \lambda v_b / (AD) \\
L'_b &= 1 / A \\
C'_{h} &= A / c^2 \\
k'_b &= (2 D g \sin \alpha - \lambda v^2) / (2 D c^2)
\end{align*}
\]

(44)

The above symbols simplify (43) to (6), i.e., the TDDP hydraulic circuit of natural gas pipelines. There is no conductance in the hydraulic circuit, which indicates no gas leakage under normal conditions.

With the phasor representation of the hydraulic circuit in (45), the TDDP hydraulic-circuit model (6) is transformed into the FDDP model (8).

\[
\begin{align*}
L'_n \frac{d m(x, t)}{d t} &= j \omega L'_n \hat{m}(x) \\
C'_{d} \frac{d p(x, t)}{d t} &= j \omega C'_{d} \hat{p}(x)
\end{align*}
\]

(45)

Given the boundary values at pipeline beginnings as $m(0)$ and $\hat{p}(0)$, the solution of (8) is as follows:

\[
\begin{align*}
\hat{m}(x) &= e^{-k_b x/2} \left[ -\frac{2}{\sqrt{k'_b + 4 Z'_n}} \sinh \left( \frac{\sqrt{k'_b^2 + 4 \gamma'_n^2}}{2} x \right) \hat{p}(0) + \frac{k'_b \sinh \left( \frac{\sqrt{k'_b^2 + 4 \gamma'_n^2}}{2} x \right)}{\sqrt{k'_b^2 + 4 \gamma'_n^2}} \hat{m}(0) \right], \\
\hat{p}(x) &= e^{-k_b x/2} \left[ -\frac{2}{\sqrt{k'_b + 4 \gamma'_n^2}} \sinh \left( \frac{\sqrt{k'_b^2 + 4 \gamma'_n^2}}{2} x \right) \hat{m}(0) + \frac{\sqrt{k'_b^2 + 4 \gamma'_n^2}}{2} \hat{p}(0) - \frac{k'_b \sinh \left( \frac{\sqrt{k'_b^2 + 4 \gamma'_n^2}}{2} x \right)}{\sqrt{k'_b^2 + 4 \gamma'_n^2}} \hat{m}(0) \right]
\end{align*}
\]

(46)

where $Z_n = \sqrt{(R'_n + j \omega L'_n) / j \omega C'_{d}}$ and $\gamma'_n = \sqrt{(R'_n + j \omega L'_n) \cdot j \omega C'_{d}}$ are the characteristic impedance and propagation constant of natural gas pipelines.

After extracting the transmission parameters as in (47), the FDLP hydraulic-circuit model (10) is obtained.
2) Thermal-Circuit Model for Heat Pipelines

A similar derivation is performed to obtain the thermal-circuit model for heat pipelines. First, we rewrite the PDEs (5) that describe the 1D heat flow in heat pipelines as (48), from which the thermal-circuit components are extracted as in (49). Based on these components, the TDDP thermal circuit of heat pipelines is obtained in (7).

\[
\begin{align*}
\frac{\partial x}{\partial t} + \frac{\partial A}{\partial t} + \mu = 0 \\
\frac{\partial h}{\partial t} + c_p \rho A \frac{\partial T}{\partial t} + \mu T = 0 \\
R' = \rho / (c_p m^2) \\
L' = \rho / (c_p m^2) \\
G' = \mu \\
C' = \rho / (c_p m^2)
\end{align*}
\]

Then, combining the phasor representation (50) with the TDDP thermal circuit (7) yields the FDDP thermal circuit as (9), whose solution is given in (51) after assigning the boundary values at pipeline beginnings as \( h_0(t) \) and \( T_0(t) \).

\[
\begin{align*}
L' \frac{d(h(x,t))}{dt} &= j \omega L' h(x) \\
C' \frac{dT(x,t)}{dt} &= j \omega C' T(x) \\
h(x) &= -\sinh(\gamma x) T(0) / Z_h + \cosh(\gamma x) h(0) \\
T(x) &= -Z_h \sinh(\gamma x) h(0) + \cosh(\gamma x) T(0)
\end{align*}
\]

where \( Z_h = \sqrt{(R' + j \omega L')} / (G' + j \omega C') \) is the characteristic impedance and \( \gamma = \sqrt{(R' + j \omega L') (G' + j \omega C')} \) is the propagation constant of heat pipelines.

Finally, we obtain the FDLP thermal-circuit model (11) from (51), in which the transmission parameters are as follows.

\[
\begin{align*}
A_h = \cosh(\sqrt{k_h^2 + 4 \gamma_h^2} t/2) e^{-k_h t/2} - k_h' \sinh(\sqrt{k_h^2 + 4 \gamma_h^2} t/2) e^{-k_h t/2} / \sqrt{k_h^2 + 4 \gamma_h^2} \\
B_h = -2 \sinh(\sqrt{k_h^2 + 4 \gamma_h^2} t/2) e^{-k_h t/2} / \sqrt{k_h^2 + 4 Z_h^2} \\
C_h = -2 \sinh(\sqrt{k_h^2 + 4 \gamma_h^2} t/2) e^{-k_h t/2} / \sqrt{k_h^2 + 4 Z_h^2} \\
D_h = \cosh(\sqrt{k_h^2 + 4 \gamma_h^2} t/2) e^{-k_h t/2} + k_h' \sinh(\sqrt{k_h^2 + 4 \gamma_h^2} t/2) e^{-k_h t/2} / \sqrt{k_h^2 + 4 \gamma_h^2}
\end{align*}
\]

In fact, the derivation of the thermal-circuit model is a special case of the hydraulic-circuit model when the controlled source parameter \( k \) is zero; i.e., the pipeline is symmetric.

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