A Unified Interface Library Open-IES-Sim Platform

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Abstract. In the future, integrated functions and energy internet will become the direction of smart energy development. This puts forward requirements for power flow calculation and simulation of combined heat and power supply and unified modeling. Due to the complexity of the tespy heat network equipment model, the lack of node modeling corresponding to the power flow calculation model brings difficulties to the simulation modeling of the unified power and power flow calculation. Therefore, it is necessary to unify the interface of thermal network and power flow calculation model. Based on the tespy and pandapower libraries, this paper unifies the interface functions of heat network and power grid power flow calculation modeling, constructs a unified interface library Open-IES-Sim platform and builds a coupled power flow calculation process method and corresponding visualization results display program. The corresponding open source example is given. It is convenient for the future use of scientific research workers who need thermal and electrical coupling modeling and the demonstration research in education and teaching.

1. Introduction

In recent years, the integrated energy system and energy internet have become the direction for smart energy development [1]. In general, researchers believe that the energy internet is a distributed system which is built on top of the power system network infrastructure and consists of electrical energy, renewable resources, natural gas, transportation, heating and other systems [2]. This paper will present the unified modelling interface library Open-IES-Sim platform which is derived by reconstructing the original tespy and pandapower libraries. Such platform is mainly used for the modelling and calculation of an integrated electrical and thermal network.

1.1. Tespy and Pandapower

Tespy stands for Thermal Engineering System in Python, which is a powerful simulation toolkit for thermal power plants including power plants, regional heating systems or heat pumps. It is an extended external module in the Open Energy Modelling Framework and can be used as a standalone package. With regard to the power system, pandapower is a grid calculation program based on the data analysis library pandas and the power flow solver Pypower that can solve and compute the power flow. The combination of tespy and pandapower makes it possible to process unified power and thermal flow.
1.2. Necessity for Unified Modelling Interface for Power and Thermal Networks

Tespy contains abundant and complicated models for thermal network equipment, which could be inconvenient to use. There is also a lack of node modelling associated with power network calculation. Thus it is challenging to model and simulate a unified electrical and heat system and it is critically essential to unify the modelling interfaces of thermal network and power network. Based on the equipment models within the tespy and pandapower libraries, this paper unifies the interface functions for computing the power and thermal flow, aiming to make the unified model easy to use, learn and calculate. First of all, the definition of nodes in the network under computation is unified since both heat and power networks have their own node models. Secondly, the interface of connection lines among various nodes is also unified. Last but not least, the computing results of the thermal and power flow are displayed in a unified format on the graphical user interface, which can facilitate further development of unified thermal and power network modelling as well as educational demonstration and research.

1.3. Research Review on Power Network and Thermal Network Modelling

The principle of power network calculation and comparison of general power flow simulation and computation software were presented in [1] where the conditions of power flow convergence and the precautions during simulation were also discussed. [1] also showed the constraint equations for the power flow calculation.

The modelling and calculation of thermal network were introduced in [2]-[4]. More specifically, contents related to the modelling of a regional thermal network including the network topology constraint equations and component constraint characteristics were described in [4]. Geidl M. et al in [3] established a static thermal network model suitable for various network scales (i.e. distribution and transmission) considering the heat delay and loss. The principle and methods for the modelling of heat source, heat exchanger and other equipment were depicted in [4]. The aforementioned studies focused on either the power network or the thermal network and subsequently established the calculation models and parameters for the flow computation.

By contrast, various models and methods were proposed in [5]-[13] to compute the unified flow of the integrated energy system. A mixed-integer linear programming (MILP) model was used in [5] to determine the optimal capacity and operation for seven combined cooling, heating and power (CCHP) systems in the heating and cooling network of a residential area (Shahid Beheshti Town). Martin Geidl derived the general optimality conditions used for the optimal scheduling of multiple energy carriers and compared this method with the standard used for power system [6]. A modelling and optimisation method for energy hub schedule was established in [7], considering the random load and supply status (such as wind energy, electricity price, electricity load requirements). H. Lund proposed a modelling and optimisation method for the power flow calculation of the multi-energy system [8], whilst in [9], the flow problem of the merged system involving the natural gas and electricity was optimised. Xu X studied the dynamic characteristics of multi-energy controlling, including the number of control levels, the structure of the control system and the coordination strategies for different pairs of control levels [10]. The modelling and simulation method for the energy hub system including wind turbine, photovoltaic, gas turbine and electrolyser was given in [11] and the aim was to simulate the economic and environmental benefits when using a gas power plant instead of a coal power plant. Employing the multi-agent genetic algorithm, a method to solve the optimal power flow problem based on the energy hub model was proposed in [12] and this method could guarantee itself to converge and obtain the global optimal value. Henggeler Antunes C established a new model of regional thermal system and also elaborated the optimised planning of regional heating and cooling network surrounded by distributed power generation [13].

1.4. Purpose and Framework to Conduct Research for Unified Modelling

There is no existing open source simulation tool that can account for the electrical and thermal load as a whole, coordinate the network node requirements of the power and heat systems, unify the
modelling interface and calculate the joint energy flow. The paper will present a simulation program that provides a unified modelling interface, a unified simulation framework and result visualization and analysis to model and compute the combined power and heat flow. Certain open source examples will also be provided to facilitate subsequent learning and use.

Section II mainly focuses on the specific network modelling process of power, heat and combined heat and power as well as the related theory behind the energy flow calculation. Details of the program library containing the unified modelling interface of power and heat are showed in Section III. In Section IV, an example network consisting of 10 nodes with coupling equipment on each node is implemented using the unified modelling interface library with the results presented. Section V presents the summary and the direction for the future research and development of the library.

2. Network Modelling

2.1. Modelling of Power Network

When solving the power flow problem, the primary task is to calculate the voltage magnitude and phase angle of each power grid node as well as the distribution of power, according to the given operating parameters such as node injected power and node load. The power flow calculation is in fact to compute and solve the node power equations which are constrained by the following equations [3]:

\[ P_{Gi} - Re(P_i(V, \theta)) = P_{Li}; \forall i \in N_B \]  \hspace{1cm} (1)
\[ Q_{Gi} - Im(P_i(V, \theta)) = Q_{Li}; \forall i \in N_B \]  \hspace{1cm} (2)
\[ V_{limin} \leq V_i \leq V_{limax}; \forall i \in N_B \]  \hspace{1cm} (3)
\[ |P_{ij}(V, \theta)| \leq P_{ij,max}; \forall i, j \in N_B \]  \hspace{1cm} (4)
\[ P_{Gimin} \leq P_{Gi} \leq P_{Gimax}; \forall i \in N_G \]  \hspace{1cm} (5)
\[ Q_{Gimin} \leq Q_{Gi} \leq Q_{Gimax}; \forall i \in N_G \]  \hspace{1cm} (6)

Equation (1)-(2) represent the balance of active and reactive power whilst equation (3) ensures that the node voltage does not exceed the threshold. Equation (4) keeps the active power flow within the limit. Equation (5)-(6) ensure that the capacity of active and reactive power of the generator is within the limits. \( P_{Gi}, P_{Li} \) represent the actual generation and load of the active power of the node respectively; whilst \( Q_{Gi}, Q_{Li} \) denote the actual generation and load of the reactive power of the node, respectively. The voltage amplitude and the phase angle are marked as \( (V, \theta) \) and the upper and lower voltage limit of node \( i \) are represented by \( V_{limin}, V_{limax} \). \( P_{ij}(V, \theta) \) characterizes the power transferred over the transmission line with \( P_{ij,max} \) denoting the upper limit. The upper and lower limit of active power generation are expressed as \( P_{Gimin}, P_{Gimax} \) respectively. Similarly, the limit of reactive power generation are represented by \( Q_{Gimin}, Q_{Gimax} \). \( N_B \) illustrates the total number of nodes whilst \( N_G \) shows the number of nodes with generator installed.

The realization of the aforementioned power flow calculation theory is achieved by using the pandapower library to model the network and solve the equations. The pandapower library contains 13 basic elements commonly seen in a power grid and integrates the panda library for data analysis and the power flow solver Pypower.

2.2. Modelling of Thermal Network

The regional thermal network can be divided into a primary transmission network consisting of hot water pipes and a secondary supply network for the users. These two subnetworks are connected by the heat exchangers. This paper focuses on the heat flow of the secondary supply network where the hot water is used as the carrier to distribute the thermal energy to the users. The thermal flow can be modelled by equations expressing the balance of node flow, balance of pressure loss, heat flow, node temperature fusion, as shown below. When the network constraints are satisfied, the temperature of each node can be derived based on the known thermal load and flow requirement of specific nodes.

\[ \sum_{k \in S_{ps,t}} q_{ps,k,t} \xi_{ps,k,t} = \sum_{k \in S_{ps,t}} q_{ps,k,t} \forall i \in S_t, t \in S_t \]  \hspace{1cm} (7)
(8) \[ \sum_{k \in \mathcal{E}_{pr}} q_{pr,k,t} = \sum_{k \in \mathcal{E}_{ps}} q_{ps,k,t} \quad \forall i \in \mathcal{S}_{nr}, t \in \mathcal{T}_t \]

(9) \[ \Delta P_{ps,k,t} = \mu_p \cdot q_{ps,k,t} \quad \forall k \in \mathcal{S}_{ps}, t \in \mathcal{T}_t \]

(10) \[ \Delta P_{pr,k,t} = \mu_p \cdot q_{pr,k,t} \quad \forall k \in \mathcal{S}_{pr}, t \in \mathcal{T}_t \]

(11) \[ Q_{ps,k,t} = q_{ps,k,t} \cdot C \cdot T_{ps,k,t}/\lambda \quad \forall k \in \mathcal{S}_{ps}, t \in \mathcal{T}_t \]

(12) \[ Q_{pr,k,t} = q_{pr,k,t} \cdot C \cdot T_{pr,k,t}/\lambda \quad \forall k \in \mathcal{S}_{pr}, t \in \mathcal{T}_t \]

The node flow balance is described by equation (7)-(8) whilst the balance of pressure loss by equation (9)-(10), Equation (11)-(14) indicate the relationship between the water flow and the heat flow and expression (15)-(16) are the node temperature fusion equations. Constraints associated with the node temperature are listed in expression (17)-(22). \( q_{pr,k,t}, q_{ps,k,t} \) denote the flow rate (kg/h) in the kth water supply/return pipeline at time t, respectively. The collection of pipelines ending at node i are represented by \( S_{pr,i} \) and those starting from node i are marked as \( S_{ps,i} \). \( T_{ns,i,t}, T_{nr,i,t} \) denote the collection of nodes on the water supply/return pipelines and \( S_t \) is the set of multiple scheduling time periods. The pressure loss (m) on the kth water supply/return pipeline at time t is denoted as \( \Delta P_{ps,k,t}, \Delta P_{pr,k,t} \) with \( \mu_p \) as the pressure loss factor (m/(kg²/h²)). \( T_{ps,k,t}, T_{pr,k,t} \) represent the heat power (kW) at the entry/exit point of the kth water supply pipeline at time t and correspondingly \( T_{ps,k,t}, T_{pr,k,t} \) as the temperature at the entry/exit point of the kth water supply pipeline at time t. The symbol C signifies the heat capacity of water whilst \( \lambda \) is the unit conversion factor. \( T_{ns,i,t}, T_{nr,i,t} \) represent the temperature of the ith node connecting to the water supply/return pipeline at time t (°C).

### 2.3. Modelling of Combined Power and Thermal Network

In order to establish the combined heat and power network model for flow calculation, the concept of energy hub is introduced. More specifically, the energy hub is modelled using the load supply balance equations of the coupled devices and thus the nodes employing coupled devices will be represented by energy hub models. The load supply balance equation can be expressed as below.

\[ L = C \cdot P \]  

(23)

The following equation (24) shows the details.

\[
\begin{bmatrix}
L_{e1} \\
L_{h1} \\
L_{e2} \\
L_{h2} \\
\vdots \\
L_{en} \\
L_{hn}
\end{bmatrix}
= 
\begin{bmatrix}
C_{ee1} & 0 & \cdots & 0 \\
0 & C_{eh1} & \cdots & 0 \\
\vdots & \vdots & \ddots & \vdots \\
0 & 0 & \cdots & C_{en}
\end{bmatrix}
\begin{bmatrix}
P_{e1} \\
P_{h1} \\
P_{e2} \\
P_{h2} \\
\vdots \\
P_{en} \\
P_{hn}
\end{bmatrix}
\]

(24)

Where \( L_{e} \) is the electrical load demand of the node whilst \( L_{h} \) is the thermal load demand of the node. \( P_e \) and \( P_h \) denote the supply electrical power and thermal power of the node, respectively.
energy conversion relationship among the coupled devices can be represented by matrix $G_{ee}$ and $C_{eh}$, which are depicted in expression (25).

\[
\begin{bmatrix}
L_{ei} \\
L_{hi}
\end{bmatrix} = \begin{bmatrix}
C_{e} \\
C_{h}
\end{bmatrix} \cdot \begin{bmatrix}
P_{ei} \\
P_{hi}
\end{bmatrix} = \begin{bmatrix}
1 - \alpha_i \\
(\sum_{i=1}^{n} COP_i * \beta_i)
\end{bmatrix} \cdot \begin{bmatrix}
P_{ei} \\
P_{hi}
\end{bmatrix}
\]

(25)

Where $\alpha_i$ presents the first layer distribution coefficient (i.e. the mount of electrical power allocated for heat production). $\beta_i$ is the second layer distribution coefficient which is used to indicate the proportion of electrical power used by various combined heat and power devices such as heat pump, air conditioner, electric heater and electric boiler. $COP_i$ marks the energy efficiency ratio of the thermoelectric coupling which is defined by equation (26).

\[
COP_i = \frac{p_h}{p_e}
\]

(26)

To simplify the modelling of the energy hub, the energy efficiency ratio of the thermoelectric coupling is defined as a constant and the system typically operates in the FTL mode as described in [8]. In this specific mode, the amount of electrical power consumed at a node is determined by the thermal load. If the thermal demand exceeds the supplying capability of the thermal network, the deficit will be covered by the combined heat and power devices.

3. Unified Modelling Interface Library

The unified modelling interface library is implemented through object proxy. In principle, the underlying creation approaches and attributes of any thermal or electrical element are wrapped in the class, which can be called by the proxy object when the element is used. When an element is created, its category (i.e. thermal or electrical) can be specified. The modelling interface supports simultaneous creation of multiple networks and addition of low level elements but temporarily does not support the automatic creation of proxy objects using low level approach. Detailed classes within the library are described below in table 1.

**Table 1** Interface and usage of the detailed classes

| Class   | Interface                                                                 | Usage                                                                                       |
|---------|---------------------------------------------------------------------------|--------------------------------------------------------------------------------------------|
| Element | Kind, name, model                                                         | Kind specifies the element category (i.e. thermal or electrical).                            |
|         |                                                                           | name specifies name of the element.                                                        |
|         |                                                                           | model specifies the particular component encapsulated in bottom layer based on tespy or pandapower |
| Node    | Nodekind (Ele_Node_BUS, Heat_Node_LO, Heat_Node_HC) attributes            | The prefix Ele indicates a power network node whilst Heat represents a heat network node.   |
| Line    | Line_Ele, Line_Heat_PipeH, Line_Heat_Connection, Line_Heat_Bus, Line_Heat_Ref | The prefix Ele indicates a power network line whilst Heat represents a heat network line.   |
| Calculate | net.get_result(), nw.get_result()                                      | net is used for power flow calculation whilst nw for thermal flow calculation.          |
| Plot    | net.plot(), nw.plot()                                                     | net and nw are used to automatically obtain and visualise the power and thermal flow results, respectively. |
and electrolyser whilst the power network elements are infinite grid, generator, transformer, capacity and etc.

3.2. Node
With regard to the Node class, there is no such element class in the original tespy library which can be used to calculate the heat flow. The unified modelling, on the other hand, wraps the Node class based on tespy but this is not from the 13 types of elements whose basic models are established in tespy. Calling the Node class can specify the amount of required heat load and temperature at a specific thermal network node. Moreover, there are two variants for the heat network nodes encapsulated based on tespy: the connection node and the termination node.

3.3. Line
For the Line class, tespy uses the pipe as the connection for heat network flow computation whilst pandapower uses the electrical transmission line (i.e. known as Line) as the connection for the power flow calculation. When modelling the connection lines, the electrical connection link contains the attribute which directly specifies which two nodes are connected. This is different from the thermal connection link where the connection relationship needs to be configured in addition to specifying the attributes.

3.4. Calculate
The Calculate class encapsulates two internal solvers and the flow computing procedures are denoted by the calculation functions shown in table 1. The functions can be called once the network parameters and the connection relationship attributes are specified.

3.5. Plot
In the final step, the Plot class can visually display the results upon the completion of the calculation. The Plot class can automatically retrieve part of the flow calculation results, select which indicators of the results should be shown, and display them in divergent bar charts. The result visualisation is simple to achieve by calling the function interfaces as depicted in table 1.

The process of inheritance and reconstruction of the aforementioned unified modelling interfaces is summarised in the following Figure 1. The detailed modelling and calculation procedure is illustrated in Figure 2.

![Figure 1. Steps of inheritance and reconstruction process of interfaces.](image-url)
4. Case Study

4.1. Information of Example Case

The example network consists of 10 nodes and each node contains combined heat and power devices. The node information is given in table 2.

Table 2: Node Information

| Node Number | Node Name               | Thermal Demand (mw) |
|-------------|-------------------------|---------------------|
| 1           | housing_area1 (bus4)    | 5                   |
| 2           | industrial_area(bus2)   | 6                   |
| 3           | sport_center(bus7)      | 8                   |
| 4           | housing_area2(bus9)     | 9                   |
| 5           | housing_area3(bus11)    | 9                   |
| 6           | housing_area4(bus10)    | 13                  |
| 7           | housing_area5(bus3)     | 4.5                 |
| 8           | housing_area6(bus5)     | 9                   |
| 9           | housing_area7(bus6)     | 22                  |
| 10          | housing_area8(bus8)     | 22                  |

The heat network is modelled with a single heat source and each node employs devices such as heat exchanger, control valve, separator, combiner, egress pipe and ingress pipe. There are 8 Residential nodes, 1 Industrial node and 1 Commercial node in the example network. The schematic diagrams of the simulated heat network and electrical network are shown in Figure 3 and Figure 4.
The simulated electrical network is mostly supplied by an infinite grid but some of the nodes are also supplied by distributed generators. In Figure 2, Grid represents an infinite system supplying the AC power to Bus 1 at 220 kV. A 220/110 kV transformer with rating of 100 MVA is used between Bus 1 and Bus 2 whilst generators of various capacity are connected at Bus 3, Bus 7 and Bus 9. Models of all these devices are originated from pandapower.

During the modelling of combined heat and power network, all nodes include the coupling devices by default and the associated information are listed in Table 3.

### Table 3 Information of coupling devices at each node

| Node Name          | Name of Device1 | COP of Device1 | Name of Device2 | COP of Device2 |
|-------------------|-----------------|----------------|-----------------|----------------|
| housing_area1(bus4) | Heat Pump       | 5              | Air Conditioner | 3.5            |
| industrial_area(bus2) | Electric Boiler | 0.9            | Electric Heater | 1              |
| sport_center(bus7)  | Air Conditioner | 3.5            | CHP Unit        | 0.68           |
| housing_area2(bus9) | Heat Pump       | 5              | Electric Heating | 1              |
| housing_area3(bus11) | Heat Pump       | 5              | Air Conditioner | 3.5            |
| housing_area4(bus10) | Heat Pump       | 5              | Air Conditioner | 3.5            |
| housing_area5(bus3)  | Heat Pump       | 5              | Electric Heating | 1              |
| housing_area6(bus5)  | Heat Pump       | 5              | Air Conditioner | 3.5            |
| housing_area7(bus6)  | Heat Pump       | 5              | Air Conditioner | 3.5            |
| housing_area8(bus8)  | Heat Pump       | 5              | Air Conditioner | 3.5            |

The coupling devices can be modelled using the following equation:

\[ L_{hi} = P_{ei} \cdot (\alpha_i \cdot \sum_{j=1}^{n} COP_j) \cdot \beta_i + P_{hi} \]  \hspace{1cm} (27)

This equation can represent the electricity to the thermal energy conversion process of heat pump, electric boiler, air conditioner, electric heating and electric heater. It should be noted that this is also the expression after the matrix expansion. For the CHP unit which can produce both heat and electricity, the COP should be replaced by the thermostatic ratio. After calculating the supply electrical power of the node in the same way, the consumed electrical load by the CHP operation shall not be added to the Pe value of the node. Instead, only the electrical demand of all other coupling devices at this node shall be considered. The expression is shown below.

\[ P_{ei} = \frac{L_{hi} - P_{hi}}{\alpha_i \sum_{j=1}^{n} COP_j \cdot \beta_j} = \frac{\eta_c \cdot P_{h, chpi}}{\eta_h} \]  \hspace{1cm} (28)

Where \( \eta_c \) is the electricity production efficiency of the CHP and \( \eta_h \) denotes the heat production efficiency. The supply heat power of the node with CHP is indicated by \( P_{h, chpi} \).

According to the capacity of the heat network and the calculation results of the original heat network flow, the supply electrical power of a node (i.e. Pe) can be computed using the energy hub.
load supply balance equation, provided that the node supply heat power is $P_h$. The process of calculating the node supply electrical power $P_e$ after simplifying the energy hub load supply balance equation can be expressed as:

$$P_e = \frac{L_{hi} - P_{hi}}{\alpha_i \sum_{j=1}^{n} COP_f \beta_j}$$  (29)

Where $n$ is the total number of coupling devices at the node. The values of the supply electrical power on each node are inserted as the electrical demand in the power flow calculation model. If the network constraints are met, the flow calculation results will be released. If the network constraints are violated, the corresponding node will be identified and its attributes will be configured as the upper limit. The overall thermal load at the user side will then be adjusted in order to balance the entire energy network.

When solving the equations following the previous process, the first layer distribution coefficient $\alpha_i$ is determined by the supply capability of the heat network and the heat flow calculation results whilst the second layer distribution coefficient $\beta_i$ is determined by the energy efficiency ratio of each coupling device. Such an equation solving process can also apply to the operation mode FEL and FHL, in addition to the FTL mode. These two operation modes will be further studied in future research and will not be covered in this paper.

4.2. Simulation Results of Example Case

The simulation results of the example combined heat and power network operating in FEL mode are presented in Figure 5 and Figure 6.

![Figure 5. Voltage amplitude and phase angle of each node in the power network](image-url)
The results are displayed in divergent bar charts, where a reference value is specified. If a value is larger than the reference value, the exceeding part will be displayed in a horizontal green bar. On the contrary, the part that is smaller than the reference value will be displayed in a horizontal red bar. Such displaying approach can clearly indicate how significantly the value of a node can differ from the reference value. If the value of a specific attribute exceeds the threshold, the corresponding node will be flagged and the value of this particular attribute will be fixed at the limit (upper or lower), which will facilitate the subsequent flow calculation.

All diagrams are drawn by the Plot class in the unified modelling interface library. Various network reference values are defined. For the power network, the reference value of the node voltage is specified as the average value of the network voltage and the node phase angle is 0 degree. In terms of the thermal network, the reference value of the node temperature is defined as the average temperature at the user side.

5. Summary and Future Work
This paper presents a unified modelling interface library for flow calculation of the combined heat and power network, based on the pandapower and tespy libraries. The proposed unified library is relatively easy to use and its modelling process is simple. Furthermore, it is capable of computing both thermal and power flows and visualising the results in a user-friendly format. All of these features make the unified library advantageous in the scientific development, learning and education demonstration of the combined heat and power flow research topic. The unified library already solves the energy flow when the combined network is operated in the FTL mode and the future work will further develop the library so that it can be used in the network running in the FEL and FHL mode. For the result visualisation, other types of charts such as bar chart and line chart can be added in addition to the existing divergent bar chart. Further development will also be conducted so that the connection diagram of the network elements can be automatically generated and the flow calculation results of a specific node can be shown when the mouse pointer hovers on that node. These new capabilities will be included in the library.

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