Energy Hub Scheduling Method with Voltage Stability Considerations

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***Abstract*—Energy Hub is expected to be one of the most effective methods to address the integrated system with multiple energy carriers. In this work, an Energy Hub scheduling method is proposed, which could not only meet various energy load demands but also address the transmission line loss and voltage stability influences. The proposed method is then evaluated by case studies, where the electricity network and thermal network are implemented on the Real Time Digital Simulator (RTDS). The proposed scheduling method is run online with real-time monitoring of the whole system operation status. Results show that the proposed Energy Hub scheduling method is able to reduce the hub operating cost while improving the overall voltage profile.**

I. INTRODUCTION

The growing energy demand has been foreseen in the near future, including both electricity and thermal energy consumptions. On one hand, the electricity network and thermal network are coupled in both industrial and residential areas, for example, the community heating and cooling has been common in urban areas where electricity network has almost been deployed to every corner. On the other hand, the Combined Heat and Power (CHP) generation technologies can be exploited to support both electricity and thermal demand [1]. Thus the study of this integrated multiple energy carrier system has drawn a lot of research interests, where Energy Hub has been expected to be one of the most promising methods.

Energy Hub is a concept to address the coupled system where multiple energy carriers are involved. The energy network may include the electricity network, thermal network and chemical network, while the energy carrier can be the electricity, natural gas or renewable energy. The objective of the Energy Hub is to optimise the energy network operation point to improve its performance in a system level. In [2], the optimal power flow was formulated and the coupling effect between the electricity and natural gas network was studied. In [3], the Energy Hub architecture was investigated, where an intelligent agent based structure was proposed. The carbon emission aspect was considered in [4], and the demand response program was used to optimise the Energy Hub operation. In [5], the Energy Hub probabilistic reliability was modeled to study the plan of electricity and natural gas interconnection infrastructure. A probabilistic energy management scheme was proposed in [6], where the distributed renewable energy, plug-in hybrid electric vehicle (PHEV) and heat storage were considered. However, existing literature assumes either perfect electricity network or the network power loss is linearly approximated, where the practical transmission line loss influence on the Energy Hub operation is less addressed.

The general goal of the Energy Hub is to meet the various energy demands. But in a practical electricity network, power quality is also critical for normal and steady power system operations. The voltage stability is one of the core power system performance indexes. If the voltage magnitude is out of the steady range, then it could damage the electrical appliance or even induce system level collapse [7]. The voltage profile is influenced by the operating point of the electricity network, which will be influenced by the scheduling of the Energy Hub. But in the existing literature, the influence of Energy Hub scheduling and operation on the voltage profile performance is still not fully studied, which is one of the main focuses and contributions in this work.

Another effort and contribution made in this work is to evaluate the proposed Energy Hub scheduling method in real-time. Instead of offline numerical simulations, we have implemented the considered electricity and thermal network on the Real Time Digital Simulator (RTDS). The optimal operating point is calculated using the proposed method, which is based on the real-time system status information. The RTDS and Matlab are interfaced with the Data Acquisition and Actuator module extended from [8], which will be detailed in Section III-B.

II. ENERGY HUB SCHEDULING

The energy services required by industrial, commercial and residential consumers vary in different forms, such as heat and electricity [9]. In the meantime, the energy carriers can come from multiple sources, such as natural gas, electricity and renewable energy. Thus the Energy Hub concept has been proposed in [2], which provides an integrated infrastructure to optimise the energy consumption and meet various load demands with heterogeneous energy inputs and outputs. An example of the considered Energy Hub is illustrated in Fig.1. The energy carriers can be conditionally used and converted to the different energy forms via conversion technologies such as CHP. The dispatch factors of different energy carriers for the Energy Hub components are optimised to meet the energy demand while improving the system overall performance, such as reducing the cost and increasing the stability.

The Energy Hub power flow can be modelled in a general form as $\boldsymbol{L} = f(\boldsymbol{P})$, where $\boldsymbol{L}$ denotes the energy outputs and $\boldsymbol{P}$ denotes energy carrier inputs. The Energy Hub network function $f(\cdot)$ is determined by several factors, including the

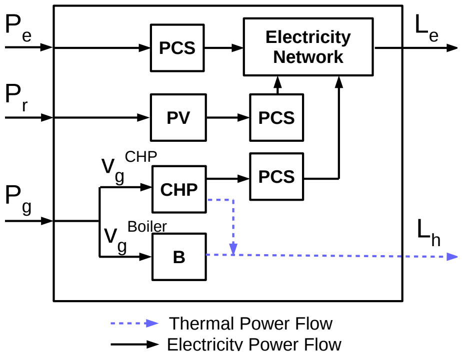


Fig. 1. An example of Energy Hub.

energy dispatch factors v_i, the energy conversion efficiency η_i for energy converter i and the power flow relations defined by the electricity network. In the example given in Fig. 1, the Energy Hub consists of Power Conditioning System, Combined Heat and Power Unit, Boiler and Photovoltaic Panels. The Energy Hub will scheduling the input amounts of the electricity, renewable energy and natural gas to optimise the outputs in the form of heat and electricity. These parameters will be detailed in the following parts.

A. Power Conditioning System

The Power Conditioning System (PCS) is a voltage source inverter, which is capable of independent and rapid control of active and reactive power [7]. The PCS units have shown great potential in grid modernization, especially with the trend of high penetration of variable renewable energies and responsive loads. Besides the conversion between different electric forms, for example AC from/to DC and different voltage level conversion, the PCS unit is able to provide an independent control to absorb or supply reactive power Q^{PCS} subject to the real power P^{PCS} and its apparent power capacity $S^{\text{PCS}}_{\text{max}}$, which can be modelled as follows.

$$(Q^{\text{PCS}})^2 + (P^{\text{PCS}})^2 \leq (S^{\text{PCS}}_{\text{max}})^2. \tag{1}$$

With the control of injected or absorbed reactive power at PCS, the Energy Hub is enabled to help improve the grid voltage stability performance. In this paper, it is assumed that the PV and CHP have installed with PCS units, and the apparent power capacity is larger than their maximum generation capacity.

B. Combined Heat and Power Unit

The natural gas CHP unit consumes natural gas to produce electric power, while the generated heat can be recovered to feed the heat load. The electrical and thermal energy outputs of CHP can be modelled as follows.

$$P^{\text{CHP}}_e = \eta^{\text{CHP}}_e \times P^{\text{CHP}}_{\text{g}} \tag{2}$$

$$P^{\text{CHP}}_h = \eta^{\text{CHP}}_h \times P^{\text{CHP}}_{\text{g}} \tag{3}$$

where P^{CHP}_e and P^{CHP}_h are the generated electricity power and heat, respectively. The consumed natural gas is represented by $P^{\text{CHP}}_{\text{g}}$. The electrical efficiency and thermal efficiency are η^{CHP}_e and η^{CHP}_h, respectively.

With the PCS unit as the inverter between the CHP and the grid, the real power of CHP P^{CHP}_e is bounded by the maximum apparent power capacity $S^{\text{CHP}}_{\text{e, max}}$ of the PCS units at the CHP bus as follows.

$$0 \leq P^{\text{CHP}}_e \leq S^{\text{CHP}}_{\text{e, max}} \tag{4}$$

In the meantime, the available reactive power Q^{CHP}_e for voltage stability control can be given by

$$-\sqrt{(S^{\text{PCS}}_{\text{e, max}})^2-(P^{\text{PCS}}_e)^2}\leq Q^{\text{PCS}}_e\leq\sqrt{(S^{\text{PCS}}_{\text{e, max}})^2-(P^{\text{PCS}}_e)^2}. \tag{5}$$

The heat power generated by CHP P^{CHP}_h is also bounded by its maximum heat capacity $S^{\text{CHP}}_{\text{h, max}}$ given as follows,

$$0 \leq P^{\text{CHP}}_h \leq S^{\text{CHP}}_{\text{h, max}}. \tag{6}$$

C. Boiler

The boiler is a pressure vessel, which consumes the natural gas to heat contained fluid, where water is generally used. The boiler is an efficient method to convert natural gas energy into heat form, whose efficiency is usually higher than CHP. If let η_{Boiler} denote the boiler's efficiency, then the heat power generated by the boiler P^{Boiler}_h can be given by

$$P^{\text{Boiler}}_h = \eta^{\text{Boiler}}_h \times P^{\text{Boiler}}_{\text{g}}, \tag{7}$$

where $P^{\text{Boiler}}_{\text{g}}$ is the gas input of the boiler. The heat power generated by the boiler is bounded by its maximum capacity $S^{\text{Boiler}}_{\text{h, max}}$, which can be given by

$$0 \leq P^{\text{Boiler}}_{\text{g}} \leq S^{\text{Boiler}}_{\text{h, max}} \tag{8}$$

D. Photovoltaic Panels

Photovoltaic Panels (PVs) are one of the most important renewable energy resources, especially on the demand side and customer domain. The PV panel converts solar energy into DC electricity, which is a clean energy source and important in meeting the increasing load demand in both industrial and residential scenarios. Let P_r denote the absorbed solar power by the PV with an efficiency η^{PV}_e, then the power generated by the PV P^{PV}_e can be given by

$$P^{\text{PV}}_e = \eta^{\text{PV}}_e \times P_r. \tag{9}$$

With the PCS to convert the electricity from DC to AC, the available reactive power of the PV unit Q^{PV}_e can be given by,

$$-\sqrt{(S^{\text{PV}}_{\text{e, max}})^2 - (P^{\text{PV}}_e)^2}\leq Q^{\text{PV}}_e\leq\sqrt{(S^{\text{PV}}_{\text{e, max}})^2 - (P^{\text{PV}}_e)^2} \tag{10}$$

E. Electricity Network and Reactive Power Compensation

The AC power flow model is considered for the electricity network in this work. When a power system is operating in the steady state, the summation of the power injected by generators, the power consumed by loads and the power exchanged between buses via transmission components should be zero [10]. For an N bus power system, the active power P_i and reactive power Q_i injected at bus i can be formulated by

$$
\begin{aligned}
P_i = & \sum_{j=1}^{N} V_i V_j \left(G_{ij} \cos(\theta_i - \theta_j) + B_{ij} \sin(\theta_i - \theta_j) \right) \\
Q_i = & \sum_{j=1}^{N} V_i V_j \left(G_{ij} \sin(\theta_i - \theta_j) - B_{ij} \cos(\theta_i - \theta_j) \right)
\end{aligned}
\tag{11}
$$

where V_i and V_j are the voltages at bus i and j, while G_{ij} and B_{ij} are conductance and susceptance of the admittance matrix, respectively.

In practical systems, the power loss due to the transmission components cannot be avoided. One major source is the line loss due to the transmission line. The line loss is subject to the current value on the transmission line resistance, which makes the line loss not linear to the power flow through the transmission line. In existing Energy Hub related studies In [2] – [6] [11], the electricity network is considered either perfect (no network or power loss) or the line loss is linearly approximated. In this work, instead of approximation, the exact line loss is estimated via Newton–Raphson's method in real-time, which will be considered during the Energy Hub scheduling procedure.

In electricity network, the voltage magnitude is one of the major power quality factors. If the voltage is too high or too low, it could reduce the lifetime of electrical appliances or induce system collapse. Thus it is desired that the voltage profile is stabilised and maintained within a bounded range, which can be given as follows

$$
V_{\text{min}} \leq V \leq V_{\text{max}}. \tag{12}
$$

The relation between the voltage and power system elements can be also given from the power flow equations (11). A common practice to improve the voltage stability is via the reactive compensation at certain buses [10]. In this paper, the reactive power injection or absorption is achieved through the control of PCS unit, whose operating point is determined by the proposed Energy Hub scheduling method to be detailed in the following part.

F. Energy Hub Scheduling Method with the consideration of voltage stability

As discussed above, the Energy Hub with an integration of multiple converters is able to schedule the consumption of different energy carriers to meet various load demands. In existing works, the power grid is assumed to be lossless or linearly approximated, while the loss due to power flow and its impact on the voltage stability performance is still under-addressed. In this part, an Energy Hub scheduling method is proposed, which considers the line loss and voltage stability influences while the hub operation cost is minimised.

The Energy Hub can adjust the natural gas dispatch factor v_g^{CHP} and v_g^{Boiler} for the CHP unit and the Boiler, which should satisfy the following constraints.

$$
v_g^{\text{CHP}} + v_g^{\text{Boiler}} = 1. \tag{13}
$$

TABLE I

PARAMETERS IN THE CASE STUDY

Parameter	**Description**	**Value**
η_e^{CHP}	CHP power generation efficiency	0.404
η_h^{CHP}	CHP thermal generation efficiency	0.566
η_h^{Boiler}	Boiler thermal efficiency	0.900
η_e^{PV}	PV electricity efficiency	0.165
$S_{\text{e, max}}^{\text{CHP}}$	Max. PCS apparent power at CHP bus	4MW
$S_{\text{e, max}}^{\text{PV}}$	Max. PCS apparent power at PV bus	4.5MW
$S_{\text{h, max}}^{\text{Boiler}}$	Max. thermal power at boiler unit	8MW

Let $C_e(\cdot)$ and $C_g(\cdot)$ denote the electricity price function and denote gas price function, respectively, the Energy Hub scheduling objective is to minimise its operation cost, which can be given as follows

$$
\begin{aligned}
\min_{P_e, P_g, v_g^{\text{CHP}}, v_g^{\text{Boiler}}, Q_e^{\text{CHP}}, Q_e^{\text{PV}}} \quad & C_e(P_e) + C_g(P_g) \\
\text{s.t.} \quad & (2) - (13)
\end{aligned}
\tag{14}
$$

By solving the above optimisation problem, the Energy Hub will decide the electricity P_e exchanged between the main grid, the natural gas P_g from the gas network, the dispatch factor v_g^{CHP} and v_g^{Boiler} as well as the injected reactive power of the PCS units Q_e^{CHP} and Q_e^{PV} at CHP and PV bus, respectively.

III. CASE STUDIES

The proposed Energy Hub scheduling method is evaluated in a real-time and online method. The considered system is integrated with the electricity network and thermal network, which is illustrated in Fig. 2. A modified 4-bus medium voltage distribution network is considered as the electricity network [10], where the PV and CHP are installed at bus 2 and 3, respectively. The bus 1 is the slack bus and the bus 3 is the conjunction of the electricity network and the thermal network, where a large boiler is installed.

In order to evaluate the performance of the proposed Energy Hub scheduling method, another method is used for comparison purpose, whose objective is to meet load demands but without considering the line loss and reactive power compensation, which is referred to as default method.

A. Data Models and Parameters

The aggregated hourly electricity loads and PV generation are scaled from the real history data in the UK provided by [12] and [13], with peak loads of 1.5MW and peak PV generation of 4MW. The aggregated heating load profile is from [14] with a peak load of 4MW. These load profiles are illustrated in Fig. 3.

The Energy Hub system parameters are given in Table I [3]. The electricity and price are £0.1487/kWh and £0.0365/kWh, respectively [15]. The electricity price is assumed the same for the Energy Hub to sell to or buy from the main grid. To maintain the voltage stability of the electricity network, the voltage lower and upper threshold for the Energy Hub optimisation are set to be 0.985 p.u. and 1.015 p.u., respectively.

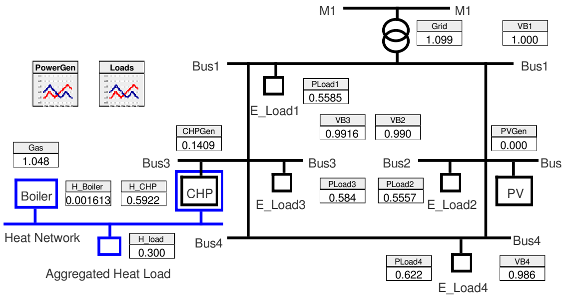


Fig. 2. The considered Energy Hub system architecture, which consists of a 4-bus electricity network and a thermal network.

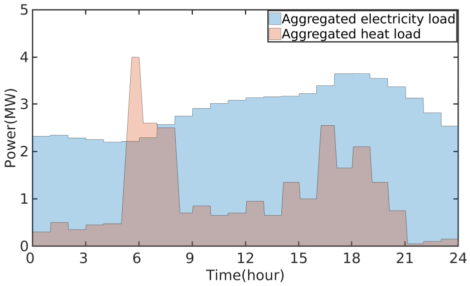


Fig. 3. Aggregated hourly electricity load and heat load.

B. Real Time Evaluation

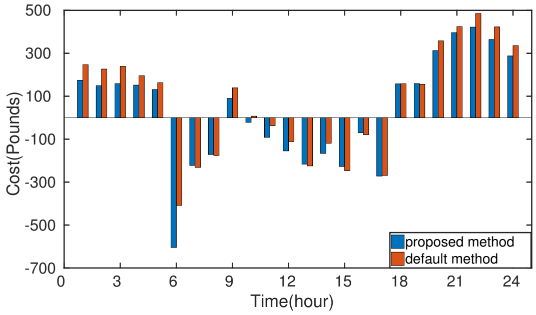
In order to test the performance of the proposed Energy Hub scheduling method, the considered system is implemented on the Real Time Digital Simulator (RTDS), which is illustrated in Fig. 4. The RTDS is the state-of-the-art power system and control system simulator, which is capable to provide real-time simulation with a time-step of $50\mu s$. The Energy Hub scheduling optimisation problem is solved using Matlab Optimisation Toolbox, while the Matlab and RTDS are interfaced using the Data Acquisition and Actuator (DAA) module. The DAA module is extended from the one used in [8], which emulates the smart meters and controllers.

Fig. 4. The real-time estimation setup with RTDS, Matlab and DAA module.

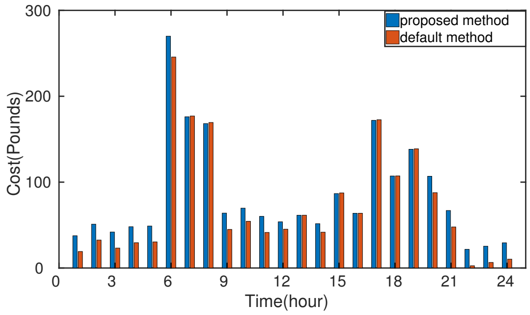
In the experiment, we have performed the online and real-time evaluation of the proposed Energy Hub scheduling method, where the Energy Hub collects the system status and computes the optimal dispatch factors v_g^{CHP} and v_g^{Boiler} to meet both electricity and heat demand, while the optimal reactive power for the PCS units at PV and CHP buses Q_e^{PV} and Q_e^{CHP} are calculated to improve the voltage stability. These control commands are conveyed through the DAA back to the RTDS, which are all run in real-time for a 24 hour period.

C. Operation Cost

The hourly operation costs of the Energy Hub for the proposed method and the default method are presented in Fig. 5a and 5b. It can be seen that with the proposed scheduling method, the Energy Hub spends less on the electricity while more on the natural gas in general. One major reason is that the proposed scheduling method considered the power loss due to power flow, which was compensated via CHP unit with increased natural gas consumption.



(a) Hourly electricity cost performance.



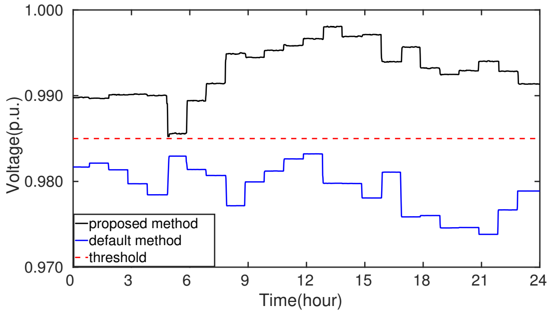
(b) Hourly gas cost performance.

Fig. 5. Hourly electricity and gas cost performance of the Energy Hub.

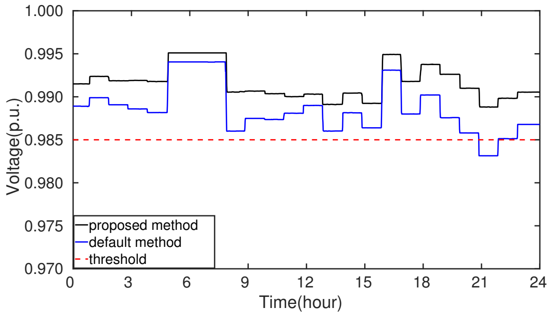
A further analysis of the electricity and natural gas cost in the 24 hours period shows that, the accumulated cost of the Energy Hub using the proposed method is £2757 and it is £3395 for the default method. The main reason is that the proposed method further reduced the cost by the increased revenue from selling the surplus electricity to the main grid, as can be indicated during 6hr to 12hr in Fig. 5a.

D. Voltage Magnitude Performance

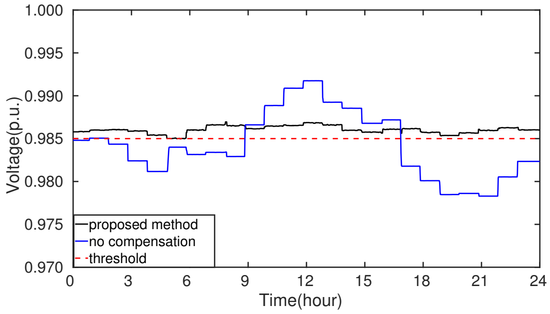
The voltage magnitude performance of bus 2-4 is illustrated in Fig. 6a–6c. The voltage fluctuated during the 24 hours due to the variation of the electricity loads, heating loads and the power generation performances. Due to the consideration of power loss and voltage stability, it can be seen that the proposed method is able to maintain the voltage magnitude on all buses within desired range, while the voltage magnitude dropped below the lower threshold for some time period, especially during the peak time of heat load (6hr–9hr and 16hr–21hr) and electricity load (16hr–21hr).



(a) Bus 2 voltage magnitude with v.s. without voltage control.



(b) Bus 3 voltage magnitude with v.s. without voltage control.



(c) Bus 4 voltage magnitude with v.s. without voltage control.

Fig. 6. Bus voltage magnitude performance improvement via the implemented voltage control system on the prototype.

A further analysis on the statistical performance of the whole 24 hour period is given in Table II. It shows that the standard deviations of the voltage profile for bus 3 and bus 4 are smaller compared the default method. This indicates that the proposed method improved the voltage profile by reducing the fluctuation during the 24 hour period. Although the proposed method achieved a less desired standard deviation performance, it was at the cost of maintaining the overall grid voltage profile in the desired range.

It should be also noted that all results were obtained in the real-time evaluation. Thus Fig. 6a–6c also indicate that the proposed Energy Hub scheduling method is able to improve the real-time voltage stability performance.

TABLE II
STATISTICAL PERFORMANCE OF THE VOLTAGE PROFILE

		Bus 2	Bus 3	Bus 4
Average Value (p.u.)	Proposed Method	0.9930	0.9916	0.9860
	Default Method	0.9792	0.9885	0.9842
Standard Variation	Proposed Method	0.0030	0.0019	0.0004
	Default Method	0.0027	0.0028	0.0038

IV. CONCLUSION

In this paper, the multiple energy carrier system was studied using the Energy Hub concept. An Energy Hub scheduling method was proposed, where the power loss due to the power flow and the voltage stability aspect were considered. The real-time evaluation was performed in the case study, where real-world data were used. The hourly operation cost for both electricity and natural gas and the voltage magnitude performance were analysed, where the proposed Energy Hub scheduling method showed potentials in reducing the cost while improving the overall grid voltage profile. In the future work, we will extend our work to study larger power grids with more distributed energy resources.

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