Coordinated Operation and Control of Combined Electricity and Natural Gas Systems with Thermal Storage

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Abstract: As one of the most effective approaches in dealing with the energy crisis, combined electricity and natural gas systems have become more and more popular worldwide. To take full advantages of such hybrid energy networks, a proper operation and control method is required. In this paper, a novel approach coordinating combined heating and power generation is proposed. First, state excursion rate, a criterion describing the deviation of system operation, is defined for system state evaluation. Then, thermal energy storage is allocated to provide more and better operation modes for combined generation. By investigating the state excursion rate of hybrid energy systems, the optimal operation mode is chosen through an analytical strategy. Case studies on hybrid energy networks show that all state variables, including voltages in electric systems and pressures in gas networks, are adjusted to follow proper operation constraints by the implementations of the proposed strategy. In addition to providing sufficient auxiliary services for hybrid systems, it is also possible to maintain the economic and energy-efficient benefits of energy supply. This study provides an effective method to utilize the regulation capability of combined heating and power generations, which is a technical basis of energy internet.

Keywords: combined heating and power generation; energy optimization; hybrid energy flow; integrated energy systems; smart operation strategy

1. Introduction

Energy internet, which is envisioned to be the architecture of future automated and flexible electric power distribution systems, has drawn wide attention in both academic and industrial fields [1]. With the integration of multiple energy sources, the upcoming energy internet will evolve to be a hybrid energy system with diverse generation sources, transmission media, and consumption terminals, leading to the interconnection of electric power networks, natural gas networks, and traffic road networks. This kind of integration can effectively improve energy use efficiency from the perspective of total energy consumption, which is a potential approach dealing with the global energy crisis [2].

Based on this background, studies focusing on the design and operation of hybrid energy systems have emerged worldwide. Destro et al. presented an optimal design and management strategy for the tri-generation system composed by a photovoltaic plant, a diesel CHP engine, a reversible heat pump and a boiler in [3], where various energy types, including power, heating, cooling and water, are considered. One typical hybrid energy unit, the distributed energy system in a hotel, is investigated by Zhou et al. in [4], and an effective planning approach based on a two-stage stochastic

programming model is proposed to manage the allocation of diverse devices. Considering the micro combined heating and power generators (micro-CHP) rated between 1 kW and 5 kW, Kopanos et al. [5] established a linear mixed integer programming framework to coordinate the operations of multiple micro-CHPs and optimize the interchanges of heating within subgroups of the micro-grids. Beside academic research, the hybrid energy systems have also been projected and constructed in actual industrial applications. Borelli et al. reported that the Genoa demonstrator, consisting of a turbo expander and an internal combustion combined heat and power unit, is able to recover wasted mechanical energy and serve heating and power demand [6]. This study is a part of the European Combined Efficient Large Scale Integrated Urban Systems (CELSIUS) project, which aims at supporting any European city to maximize the utilization of its primary and secondary energy resources. The idea of using renewable energy to drive combined generation systems is proposed by Ju et al. and verified in Guangzhou Higher Education Mega Center (GHEMC) [7]. The results show that such implementation will enhance performance of combined generation systems remarkably. Falke et al. [8] proposed a multi-objective optimization and simulation model considering various distributed heat and power generation units, storage systems, energy-saving renovation measures, and district heating networks. The developed model is applied to a residential district in Lampertheim, a town in Hesse, Germany, and demonstrated to be effective for real hybrid energy system modeling.

As reviewed above, hybrid energy systems with different energy forms and diverse driving devices have been explored. Considering the fast development of distributed natural gas networks, distributed gas turbines (GT) have been highlighted as a satisfying energy hub in recent years, which is able to convert energy from different systems, i.e., electric power networks and natural gas networks, to energy consumers. Aiming at different types of energy demand, GT-based energy hubs can evolve to be a combined heating and power (CHP) generation system or a combined cooling, heating and power (CCHP) generation system via installation of ancillary devices [9]. From practical applications in China, cooling load demands in summer are supplied by air-conditioning systems, which are commonly electricity driven. Heating load demands are mostly supplied by central heating systems, so CHP systems are more widespread in utility facilities and attract more research attention in the industry [10]. By making use of waste heat released from turbines for thermal supply, CHP systems help improve overall energy efficiency of generators from 30% to almost 80% [11]. Beside the remarkable enhancement of energy efficiency, the connection of electricity networks and natural gas systems provides mutual support for both energies, significantly improving the reliability of total energy supply. Hence, there has been a strong push globally for the CHP system and consequently it is often prioritized from an urban planning perspective [12].

Though with higher efficiency and reliability, CHP systems still face many challenges, of which determining the optimal operation mode is considered to be most fundamental. Following the electric load (FEL) and following the thermal load (FTL) are currently the most common strategies in the industry worldwide. Jalazadeh-Azar has compared the thermodynamic performance of FEL- and FTL-based CHP system operations, whose results demonstrated that a CHP system with FTL operation mode is superior from the first-law thermodynamic standpoint [13]. Three criteria, i.e., primary energy consumption (PEC), operation cost and carbon dioxide emissions (CDE), were introduced by Mago et al. [11] to evaluate the performance of CHP systems operations under different strategies and climates. The results show that FEL-based CHP systems always increase the PEC, while FTL-based CHP systems achieve reductions of PEC, CDE, as well as operation cost. In addition to simple FEL and FTL operations, some smart strategies of CHP systems are also discussed in the literature. Fang et al. proposed an optimal operational strategy based on an integrated performance criterion (IPC), which achieved an effective switch between FEL operating mode and FTL operating mode while taking PEC, CDE, and operation cost into consideration [14]. Considering the integration of photovoltaic (PV) power, Brahman and Jadid allocated both electrical energy storage (EES) and thermal energy storage (TES) in a cogeneration system to mitigate the impact of mismatch between electricity demand and thermal demand, achieving both energy cost and CDE reductions [15]. A nonlinear model

called TOOCS-off, which is a shortened form of techno-economic optimal operation of cogeneration systems—off, was developed by Reza in [16] to control the electrical energy flow and the thermal energy flow on the load side, showing the optimal energy management of CHP energy systems. Cascio et al. proposed a multi-objective optimization model for urban integrated electrical, thermal and gas grids, which achieves an operational cost reduction of about 17% with the respect to thermal-load-tracking control logic [17]. Targeting the maximization of owners' profits, a discrete operation optimization model for CHPs in real-time markets is proposed by Gu et al. in [18], and the potential operating strategy is pre-developed based on the forecasted prices and modified by dynamic modification process. An operation strategy following a hybrid electric-thermal load (FHL) is proposed by Li et al. in [19] to manage hybrid energy systems to achieve overall benefits of primary energy saving, exergy efficiency enhancement and CDE reduction.

However, current researches on operation strategies of CHP systems are all from the customer's perspective. That is to say, the analyses are based on local sites of residence or commerce. Even new indices, such as source primary energy consumption, is just a conversion between source and site for equivalent energy performance evaluation [20]. The interactions between CHP units and hybrid energy networks are commonly ignored, while the impact may be remarkable and cause severe problems for grid operators. For example, although FTL operation mode of CHP system is proved to have more economic benefits and higher energy efficiency [11,13], such operation strategy makes CHP system a random generation source or uncertain electric load from the view of electric power network, leading to remarkable uncertainties in electricity networks. This kind of stochastic feature may cause severe risks in electric distribution networks, especially considering the integration of distributed generations (DG). On the other hand, gas turbine-based generation systems are expected to interact with the electric power grid to provide auxiliary services, such as spinning reserve, peak shaving, and demand response, and then to improve the capability of renewable resource penetration [21]. Therefore, a desired operation strategy of CHP system should provide regulation services for network operation instead of uncontrollable effects. The same requirements exist in natural gas networks. Additionally, the inconsistent features of hybrid energies from diverse transmission systems should also be handled. Generally, gas networks are not as flexible and responsive as power networks, indicating much more restraints in operation. To realize the unified state evaluation of combined electricity and natural gas networks, Geidl and Andersson have presented an optimal power flow approach to deal with coupled power flows of hybrid energy systems in [22], which is verified in a 3 electric nodes and 3 natural gas nodes coupled system. However, the computational difficulties might be expected for realistically sized problems as stated by the authors.

In the framework of energy internet, the operating states of hybrid energy networks, both electricity systems and natural gas systems, should be simultaneously considered and controlled while formulating the optimal coordination of the hybrid energy systems. To the best of the authors' knowledge, the system states of hybrid energy networks are treated as constraints in the existing studies. As a further step, it is desired to involve the CHP systems in hybrid system control, i.e., utilizing the CHP unit to address the network abnormality. Hence, the coordination of the hybrid energy systems should consider the benefits of both grid operators and CHP owners other than only one aspect, which is rarely researched in the reviewed literature. With these concerns, a proper operation strategy should take the following requests into consideration. Firstly, the sufficient economic and energy benefits should be maintained. Then the negative impact of CHP unit on the connected networks, including electricity systems and natural gas systems, should be mitigated. Lastly, the regulation capability of CHP unit should be utilized to guarantee that both electricity networks and natural gas systems are in normal conditions, like the utilization of auxiliary services for power systems. This is a progressive guideline on the optimal control of hybrid energy systems, which is also the technical basis of energy internet construction and application.

In this paper, a novel operation and control strategy of combined heating and power systems is proposed. The operation states of hybrid energy systems, including both electric power networks

and natural gas networks, are considered as new criteria, which are indexed by state excursion rate (SER). By analyzing SERs of electricity systems and gas systems, the optimal operation mode of CHP generation is shifted based on modified FEL and FTL strategies. In order to achieve flexible and sufficient controls with the proposed method, the thermal energy storage is allocated in CHP systems. By implementations of the proposed control method, the CHP systems not only operate in an economic and energy-efficient way, but also contribute to network regulations of both energy systems. The operation of hybrid energy networks is improved greatly.

The remainder of this paper is organized as follows: Section 2 elaborates on the modelling of hybrid energy systems with CHP generation as an energy hub. The criterion and strategy of the proposed operation and control method are presented in Section 3. Section 4 describes the case studies and discussions. Conclusions are drawn in Section 5.

2. Modeling of CHP Based Hybrid Energy Systems

With combined heating and power generation as the energy hub, the typical framework of hybrid electricity and natural gas systems is shown in Figure 1. As can be seen, the whole energy internet can be divided into three parts based on the physical connections: power networks, gas networks and energy hubs. Power networks are connected with natural gas networks through CHP systems.
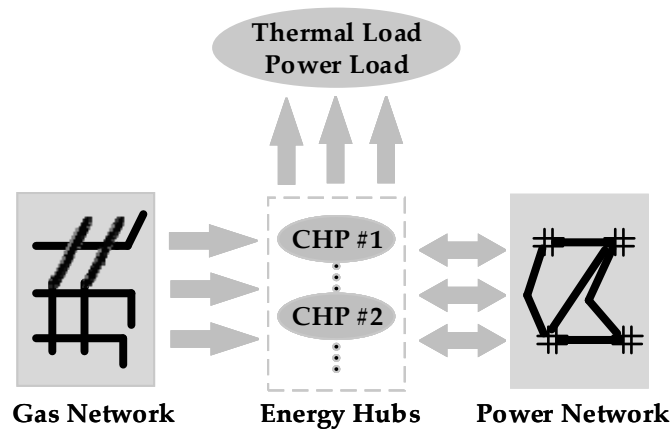

Figure 1. Framework of CHP based hybrid energy networks.

2.1. Natural Gas Network Formulation

In hybrid energy systems, the modelling of natural gas systems is simplified for specific research purpose. Generally, the primary elements considered in a gas network are pipelines, compressors, sources, and loads [23]. Like the nodal voltage in electric power systems, nodal pressure is the main state variable to determine energy flow in gas networks.

2.1.1. Pipelines

For pipeline k from node i to j, the flow rate (in standard SCF/h) can be expressed as [24]:

$$f_k = f_{kij} = S_{ij} M_k \sqrt{S_{ij}\left(\pi_i^2 - \pi_j^2\right)} \tag{1}$$

$$S_{ij} = \begin{cases} +1, & \pi_i - \pi_j \geq 0 \\ -1, & \pi_i - \pi_j < 0 \end{cases} \tag{2}$$

where M_k is a constant parameter related to internal diameter, length and friction of pipeline as well as temperature and compressibility factor of gas, and π_i is the pressure at node i, and S_{ij} reflects the gas flow direction of the kth pipe.

2.1.2. Compressors

Compressors are installed in natural gas networks to transport gas and compensate for the loss of energy and pressure. Compressors require a significant amount of energy, such as natural gas, steam or electricity, to operate. Since natural gas-driven compressors show remarkable economic benefits in gas network operations, they are widely used. The structure of this type of compressor is shown in Figure 2.
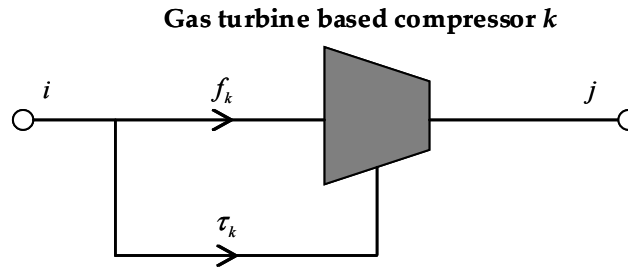

Figure 2. Compressor driven by a gas turbine.

Given a specific gas turbine based compressor, the actual adiabatic compressor horsepower follows the calculation [25]:

$$H_k = H_{kij} = B_k f_k \left[\left(\frac{\pi_j}{\pi_i} \right)^{Z_k} - 1 \right] \tag{3}$$

where H_k is the horsepower required to operate compressor k, f_k is the gas flow rate through compressor k, B_k is a constant parameter determined by temperature and efficiency of the compressor, and Z_k is a constant parameter related to compressibility factor. Based on (3), the gas consumption by compressor k can be approximated as:

$$\tau_k = \alpha_{c,k} + \beta_{c,k} H_k + \gamma_{c,k} H_k^2 \tag{4}$$

where $\alpha_{c,k}$, $\beta_{c,k}$, and $\gamma_{c,k}$ are parameters of energy conversion efficiency of kth compressor.

2.1.3. Gas Energy Balance in Gas Networks

The mass-flow balance equation at each node can be written as:

$$w_i = \sum_{pk \in i} A_{i,pk} f_{pk} + \sum_{ck \in i} (U_{i,ck} f_{ck} + T_{i,ck} \tau_{ck}) \tag{5}$$

where w_i is the gas injection at node i, pk stands for the indices of pipelines connected to ith node and ck denotes the indices of compressors connected to ith node. $A_{i,pk}$, $U_{i,ck}$, and $T_{i,ck}$ are parameters with following definitions:

$$A_{i,pk} = \begin{cases} +1, & \text{if pipeline } pk \text{ leaves node } i, \\ -1, & \text{if pipeline } pk \text{ enters node } i. \end{cases} \tag{6}$$

$$U_{i,ck} = \begin{cases} +1, & \text{if compressor } ck \text{ leaves node } i, \\ -1, & \text{if compressor } ck \text{ enters node } i. \end{cases} \tag{7}$$

$$T_{i,ck} = \begin{cases} +1, & \text{if the } ck^{\text{th}} \text{ compressor gets gas from node } i, \\ 0, & \text{otherwise.} \end{cases} \tag{8}$$

2.2. CHP System Formulation

　　As seen in Figure 1, CHP system is the energy hub connecting energy sources and customers. It draws natural gas from gas networks, exchanges electricity with power networks and provides heating and power for energy users.

2.2.1. Modeling of GT Based Generators

　　According to the heat rate curve, the relationship between natural gas flow and power output based on gas fired turbines' generators is as follows [23]:

$$HR_k = \alpha_{g,k} + \beta_{g,k}P_{g,k} + \gamma_{g,k}P_{g,k}^2 \tag{9}$$

$$w_{con,k} = \frac{HR_k}{GHV} \tag{10}$$

where HR_k is the input heating value of kth GT based generator, $P_{g,k}$ is the output electric power by kth generator, $\alpha_{g,k}$, $\beta_{g,k}$, and $\gamma_{g,k}$ are coefficients decided by heat consumption curve of kth generator, $w_{con,k}$ is the equivalent gas consumption by kth generator, and GHV is the gross heating value.

　　Along with electric power, thermal energy is also produced at the output of GT based generators. Power to heat ratio is the criterion calculating the proportion of generated electrical energy to the useful heating energy, which is defined as [26]:

$$C = \frac{E_{CHP}}{H_{CHP}} = \frac{\eta_e}{\eta_h} \tag{11}$$

$$\eta_e = \frac{E_{CHP}}{F_{input}} \tag{12}$$

$$\eta_h = \frac{H_{CHP}}{F_{input}} \tag{13}$$

$$\eta = \eta_e + \eta_h \tag{14}$$

where C is the power to heat ratio of the CHP unit, E_{CHP} is the electric energy produced by CHP unit in a certain period of time, H_{CHP} is the useful heat produced in the same period of E_{CHP}, F_{input} is the fuel energy used by CHP system, η_e and η_h are the efficiency of cogeneration unit for producing electric power and heating energy, respectively, and η is the total energy efficiency of the CHP system following $\eta \leq 1$.

　　According to reports provided by U.S. Department of Energy [27], CHP systems with low power to heat ratio, typically $C \leq 0.75$, are currently cost effective in many markets and applications. In China, the typical technical parameters of representative gas turbine based CHP systems are shown in Table 1 [28], whose power to heat ratios are all below 0.75.

Table 1. Typical technical parameters of representative gas turbine based CHP generation system.

	Power/kW	Heating/kW	C	η_e (%)	η (%)
1	250	341	0.733	29.99	70.88
2	610	1733	0.352	18.88	72.52
3	1435	3202	0.448	23.59	76.23
4	2825	6411	0.441	23.22	75.92
5	5265	9298	0.566	28.91	79.96

2.2.2. Loading Curves

　　Combined heating and power systems are commonly allocated for energy supply of both electric and thermal loads. Based on design principles of CHP generation systems for the East Asia region [29],

a typical 24 h loading data for a hotel powered by a CHP system can be concluded as Figure 3. The consumption proportion in the *y*-axis stands for the proportion of hourly energy consumption to the daily amount.
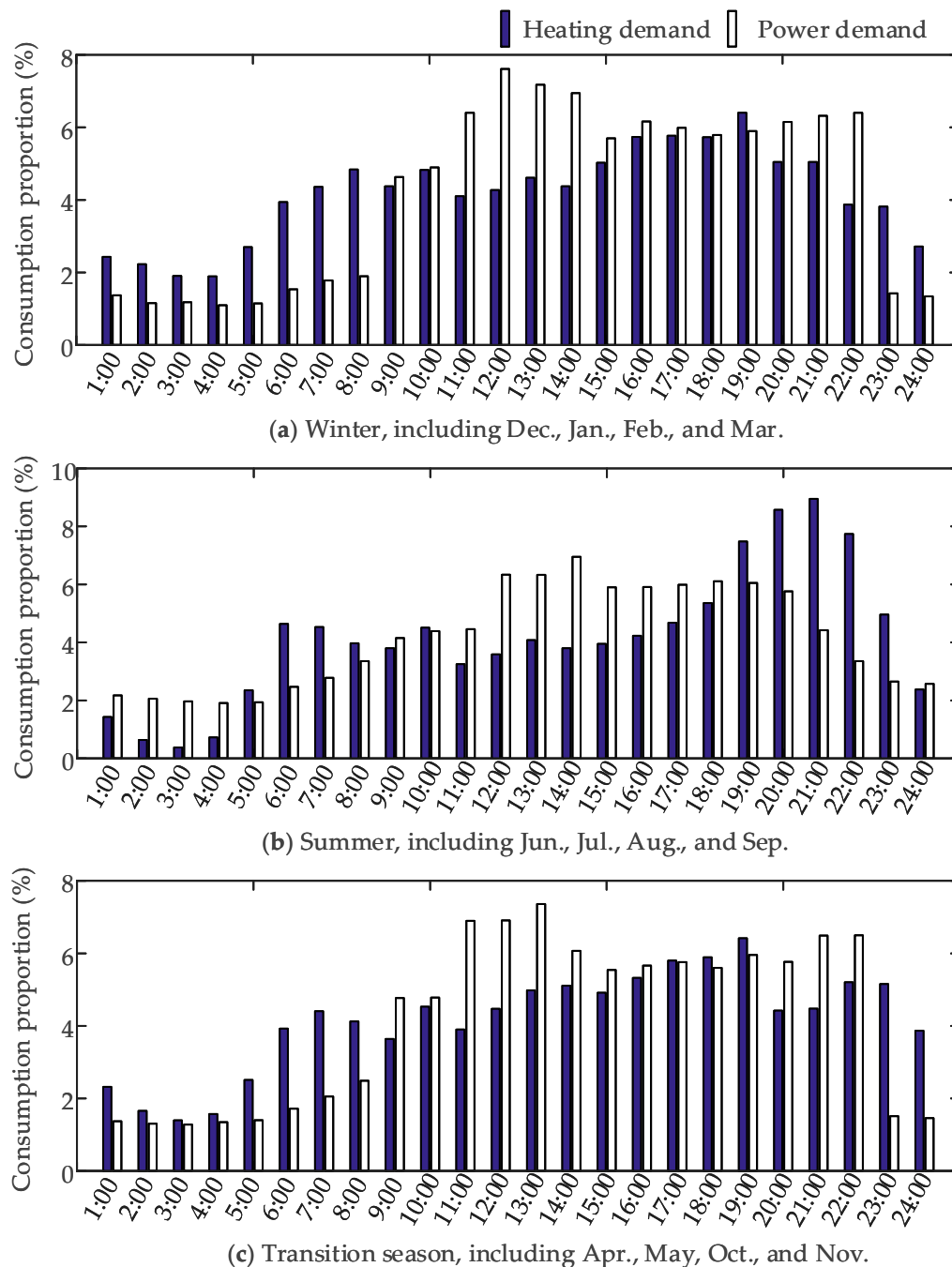

(**a**) Winter, including Dec., Jan., Feb., and Mar.

(**b**) Summer, including Jun., Jul., Aug., and Sep.

(**c**) Transition season, including Apr., May, Oct., and Nov.

Figure 3. 24 h energy consumption proportion. (**a**) Winter; (**b**) Summer; (**c**) Transition season.

2.2.3. Thermal Energy Storage

CHP systems combined with thermal energy storage have shown remarkable benefits for various commercial building types [30]. It is a trend to install TES in CHP generation systems, and therefore the operation of cogeneration systems is affected. Details of these impacts are further discussed and utilized in Section 3.2.

From the view of system operation, the thermal storage operation can be formulated as:

$$S_{TES}(t + \Delta t) = S_{TES}(t) + \int_{t}^{t+\Delta t} P_{TES}(x)\mathrm{d}x \tag{15}$$

where $S_{TES}(t)$ is the total thermal amount stored in TES at t moment, and $P_{TES}(t)$ is the thermal storing (positive value) or releasing (negative value) rate of TES at t moment.

Obviously, based on the physical restraints of energy storage devices, following constraints should be considered.

$$0 \le S_{TES}(t) \le S_{TES,\max} \tag{16}$$

$$\begin{cases} P_{TES}(t) \le P_{TES,\mathrm{maxc}} \text{ if } P_{TES}(t) > 0, \\ |P_{TES}(t)| \le P_{TES,\mathrm{maxd}} \text{ if } P_{TES}(t) < 0. \end{cases} \tag{17}$$

where $S_{TES,\max}$ is the capacity of the thermal storage, and $P_{TES,\mathrm{maxc}}$ and $P_{TES,\mathrm{maxd}}$ are the maximal thermal storing and releasing rate of devices, respectively.

2.3. Unified Gas and Power Flow Analysis

The power flow in electric power networks can be expressed as:

$$\begin{cases} \Delta P_i = P_{gen,i} - P_{load,i} - V_i \sum_{j \in i} V_j \left(G_{ij} \cos \theta_{ij} + B_{ij} \sin \theta_{ij} \right) = 0 \\ \Delta Q_i = Q_{gen,i} - Q_{load,i} - V_i \sum_{j \in i} V_j \left(G_{ij} \sin \theta_{ij} - B_{ij} \cos \theta_{ij} \right) = 0 \end{cases} \tag{18}$$

where ΔP_i and ΔQ_i are respectively the active and reactive power unbalance at node i, $P_{gen,i}$ and $Q_{gen,i}$ are respectively the active and reactive power generation at node i, $P_{load,i}$ and $Q_{load,i}$ are respectively the active and reactive load at node i, V_i is the voltage magnitude at node i, j stands for the indices of all nodes connected to ith node, G_{ij} and B_{ij} are respectively the real and imaginary part of the elements in the node admittance matrix, and θ_{ij} is the phase difference between node i and node j.

Since the natural gas networks and electric power networks are connected through CHP systems, the whole energy conservation equations for unified gas and power flow analysis are listed as follows:

$$w_i(t) - w_{i,CHP}(t) = \sum_{pk \in i} A_{i,pk} f_{pk}(t) + \sum_{ck \in i} \left(U_{i,ck} f_{ck}(t) + T_{i,ck} \tau_{ck}(t) \right) \tag{19}$$

$$w_{i,CHP}(t) \cdot GHV = \alpha_g + \beta_g P_{g,e}(t) + \gamma_g P_{g,e}(t)^2 \tag{20}$$

$$P_{g,e}(t) / P_{g,h}(t) = \eta_e / \eta_h \tag{21}$$

$$P_{g,h}(t) - P_{l,h}(t) = P_{TES}(t) \tag{22}$$

$$P_{g,e}(t) - P_{l,e}(t) = P_{EPN}(t) \tag{23}$$

$$P_{gen,i}(t) + P_{EPN}(t) - P_{load,i}(t) - V_i(t) \sum_{j \in i} V_j(t) \left(G_{ij} \cos \theta_{ij}(t) + B_{ij} \sin \theta_{ij}(t) \right) = 0 \tag{24}$$

where $w_{i,CHP}(t)$ is the gas consumption rate by CHP system at ith node at time t, $P_{g,e}(t)$ and $P_{g,h}(t)$ are respectively the electric power and heating energy generated by CHP system at time t, $P_{l,e}(t)$ and $P_{l,h}(t)$ are the electric and heating load demand in CHP system at time t, respectively, and $P_{EPN}(t)$ is the power that CHP system exchanges with electric power networks. If $P_{EPN}(t) > 0$, CHP system is an equivalent generator in power networks; if $P_{EPN}(t) < 0$, CHP system is an equivalent load.

3. Criterion and Control Strategy of CHP Generations

From (19) to (24), it is observed that the operation mode of CHP systems has influences on system states of both gas networks and power networks. Though current control strategies of CHP systems

are majorly focused on the cogeneration systems themselves, the interactions with connected grids should be seriously considered. Therefore, how to evaluate this impact is required at the first place, and then mitigation of these undesired impacts on the system operation is needed.

3.1. State Excursion Rate

System states would vary from time to time due to the change of loads, distributed generations, as well as CHP system operations. In order to give a proper and simplified evaluation of abnormal system states, the state excursion rate (SER) is defined as:

$$Bias(x) = \begin{cases} \frac{(x_{min} - x)}{x_{min}} \times 100\% & , x < x_{min} \\ 0 & , x_{min} \leq x \leq x_{max} \\ \frac{(x - x_{max})}{x_{max}} \times 100\% & , x > x_{max} \end{cases} \tag{25}$$

where x stands for the system state variable, such as nodal voltage in power system or nodal pressure in gas networks, and x_{max} and x_{min} are the upper and lower bounds of state variable, which are stipulated by local utilities or industrial standards.

Obviously, SER is an index representing the degree of system running out of normal operation. Because SER is capable of describing both electric power networks and natural gas systems, it is adopted in this paper for system state evaluation.

Considering the multiple uncertainty sources in networks, the system state would deviate to some extent even under regular operations. Based on SER given above, three constraints are defined to ensure both gas and power system operations are within proper states.

$$\max(Bias(x_i)) \leq \sigma_1 , i = 1, 2, 3, \ldots\ldots \tag{26}$$

$$\text{Average}(Bias(\mathbf{x})) \leq \sigma_2 \tag{27}$$

$$\text{Duration}(Bias(x_i) > \sigma_3) \leq t_1 , i = 1, 2, 3, \ldots\ldots \tag{28}$$

where (26) describes the permissible maximum bias of each state variable, (27) represents the allowable average bias of all interested state variables, and (28) is a constraint from the time domain, indicating the maximal duration of specific bias should be limited. σ_1, σ_2, σ_3, and t_1 are respectively the threshold values. x_i denotes the ith state variable, and x is the state variable vector.

3.2. Optimal Control of CHP Generation

Considering the installation of thermal energy storage, the CHP system operation modes are modified and extended based on conventional FEL and FTL modes.

- Following the electric load with thermal energy storage absorbing heat (FEL-TESA).
  CHP generation follows the electric demand of the load. The thermal energy produced is more than required, and the excess energy is stored in the thermal storage devices.
- Following the electric load with thermal energy storage releasing heat (FEL-TESR).
  CHP generation follows the electric demand. The thermal energy produced cannot meet the heating requirement of load, and the lacking part is supplemented by thermal storage.
- Following the electric load without thermal energy storage operation (FEL-TESO).
  CHP system follows the electric demand, while the thermal generation exactly matches the heating requirement. Thermal energy storage devices are out of working at the moment. This mode is activated only when the power to heat ratio of CHP system equals to the ratio of electric demand to heating requirement.
- Following the thermal load without thermal energy storage operation (FTL-TESO).

CHP generation follows the thermal demand of load and the thermal storage devices are out of working. The mismatch part of produced electricity, no matter redundant or insufficient, is handled by power networks.

- Following the thermal load with thermal energy storage absorbing heat (FTL-TESA).
  In order to make CHP system provide more generations, thermal storage operates at heat storing mode. Therefore, the total heating requirement becomes the summation of regular heating load and thermal storage. CHP generation follows the updated thermal demands.

- Following the thermal load with thermal energy storage releasing heat (FTL-TESR).
  In order to make CHP system produce less generations, thermal storage operates at heat releasing mode. Therefore, the heating requirement of load is partly supplied by thermal storage, and the request for thermal generation of CHP system is alleviated. CHP generation follows the lessened thermal demands.

A proper operation strategy of a CHP system should avoid the network running out of the constraints caused by either cogeneration itself or other factors such as distributed energy integrations. By implementing the proposed operation modes, the integrated energy system is able to operate at an economic and energy-efficient way, in addition to providing the auxiliary services in hybrid energy networks. The operation strategy of controlling CHP systems is shown in Figure 4, where CHP generation is shifted between the presented modes.
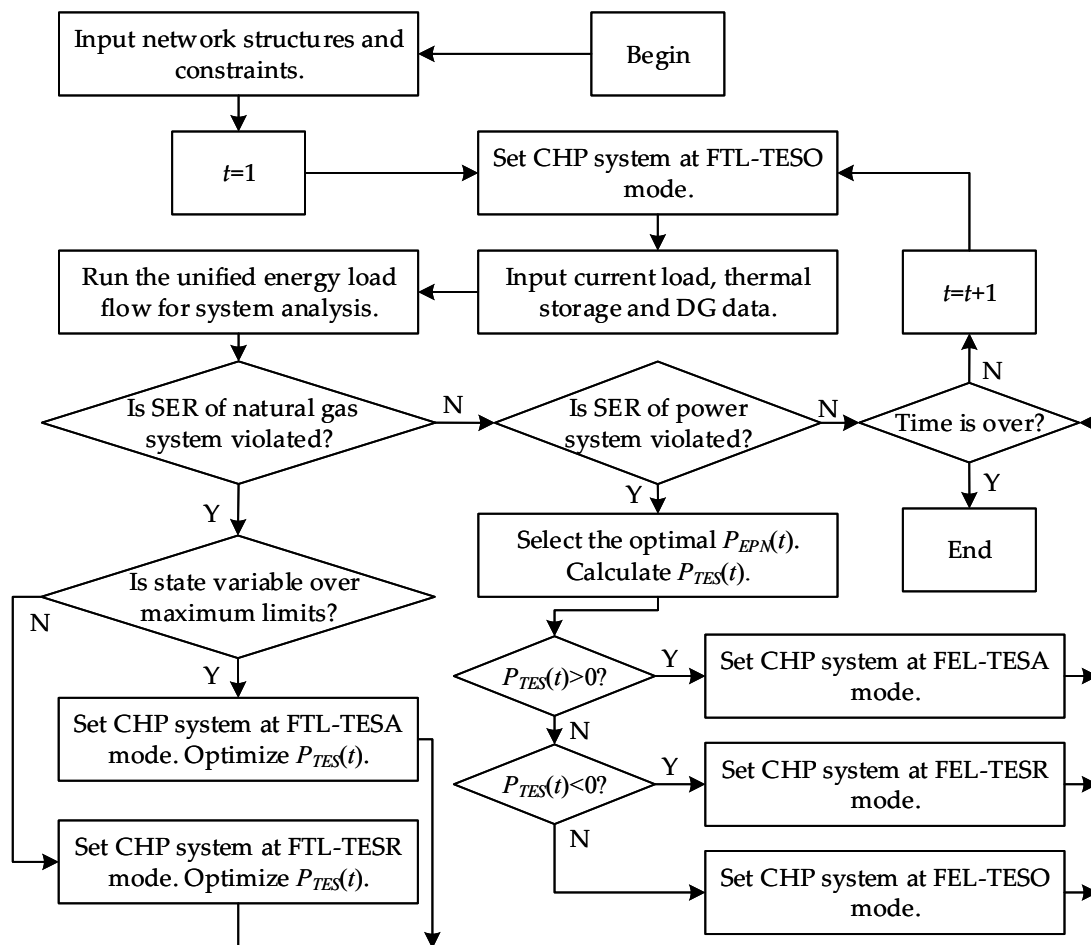

Figure 4. Coordinated operation and control strategy of hybrid energy system.

3.3. Coordination Control of Multiple CHP Systems

The proposed strategy shown in Figure 4 is directly adequate for operation control of hybrid energy systems with single CHP coupling. When it comes to the multiple CHP generations integrated in the hybrid energy systems, the proposed approach is still feasible to every individual CHP system, but the coordination between diverse CHP units are required. In order to address this concern, an optimization-based strategy coordinating multiple CHP units is proposed with the objective set as:

$$\min \sum_{i=1}^{N_{CHP}} |P_{TES,i}(t)| \tag{29}$$

where N_{CHP} is the total number of CHP generations coupling hybrid energy systems, and $P_{TES,i}(t)$ is the TES absorbing or releasing power in the ith CHP unit at t moment.

The objective function in (29) guarantees that the TES devices participate as little as possible in the system operation, leading to an increase of TES life span. Besides, this objective also tries to utilize the autonomy capability of CHP systems to achieve operation control, which eases the burden on infrastructure investment.

With (29) as the objective, the optimization are subjected to the constraints of both state excursion rate, i.e., (26)–(28), and thermal energy storage, i.e., (16) and (17). Based on these, the multiple CHP systems could be coordinated and therefore the control of the hybrid energy systems is effectively achieved.

4. Case Studies

The proposed control idea and strategy are tested on the hybrid energy systems, where the 14-node gas network [24] is coupled with the IEEE-57 bus test system. Loads of the CHP system follow the profiles shown in Figure 3. One 15 MW DG is installed in node 47 in the cases. The proposed control strategy is compared with conventional FEL mode and FTL mode of the CHP generations. Two cases, one with single CHP generation and another with two CHP coupling connections, are investigated and illustrated.

4.1. Hybrid Energy Systems with Single CHP Generation

In the first case, there is only one CHP unit coupling the electric power network and natural gas system. The CHP system installed in the hybrid systems connects node 3 of gas networks with node 46 of electric networks, whose rated power capacity is 20 MW.

4.1.1. Operation under Conventional FEL Mode

Under conventional FEL mode, the system states with different seasons are illustrated in Table 2, where major variables concerned in hybrid systems are listed.

Through Table 2, it can be found that under FEL mode, the electric power system is not under the influence of CHP generation, while the overvoltage problem always happens. The different profiles of power and heating demand in diverse seasons show more severe impact on the gas system, while under-pressure problem occurs in summer and transition seasons. The requirements for thermal energy storage devices, no matter capacity or operation rate, are also related to the power and thermal demands. Figure 5 illustrates the ratios of power to thermal loading requirements under different seasons. In summer, the loading power to heat ratios are mostly over 0.75, indicating that the thermal energy is always over-produced while the power to heat ratio of the CHP generator is set as 0.35, 0.55 or 0.75. Therefore, under these situations, the TES devices are always storing energy. So the requirement of TES capacity is very large, resulting in unpractical operation. Same circumstances happen in transition seasons. Comparatively, the power to heat ratios of loading demands in winter are between 0.17 and 0.81, which match the setting power to heat ratios of the CHP generator better. Hence the request for thermal energy storage is much less critical, especially while the power to heat

ratio of the CHP generator is 0.55. In conclusion, the CHP generator under FEL mode should be equipped with a proper power to heat ratio matching the loading demands well. As a result, the gas network is less impacted and TES devices can be less invested.

Table 2. System states under different power to heat ratio based CHP generations (FEL mode).

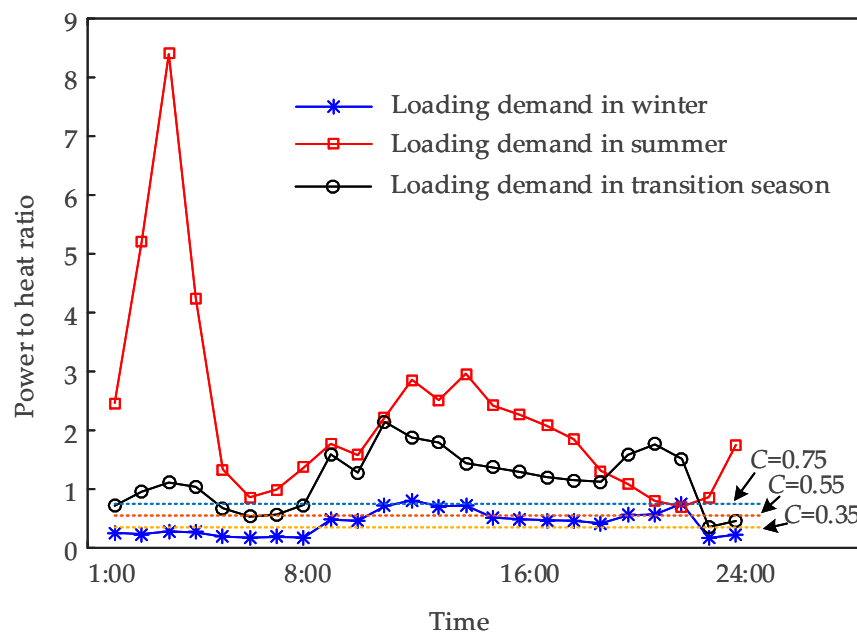| Season	State Variable	Power to Heat Ratio of GT Based Generator		
		0.35	**0.55**	**0.75**
Winter	Maximal voltage (pu)	1.0616	1.0616	1.0616
	Minimal voltage (pu)	0.9587	0.9587	0.9587
	Maximal pressure (psia)	1254	1254	1254
	Minimal pressure (psia)	604	604	604
	TES capacity required (MW·h)	70	30	65
	TES storing rate required (MW)	0.57	3.35	9.30
	TES releasing rate required (MW)	6.12	5.43	3.95
Summer	Maximal voltage (pu)	1.0616	1.0616	1.0616
	Minimal voltage (pu)	0.9587	0.9587	0.9587
	Maximal pressure (psia)	1350	1350	1350
	Minimal pressure (psia)	220	220	220
	TES capacity required (MW·h)	550	295	175
	TES storing rate required (MW)	42.95	25.24	16.97
	TES releasing rate required (MW)	/	/	0.75
Transition seasons	Maximal voltage (pu)	1.0616	1.0616	1.0616
	Minimal voltage (pu)	0.9587	0.9587	0.9587
	Maximal pressure (psia)	1225	1225	1225
	Minimal pressure (psia)	435	435	435
	TES capacity required (MW·h)	285	140	75
	TES storing rate required (MW)	23.80	13.11	8.41
	TES releasing rate required (MW)	/	2.11	3.14

Figure 5. Power to heat ratios of demands under different seasons.

4.1.2. Operation under Conventional FTL Mode

Under conventional FTL mode, the thermal energy is produced according to the consumption requirement of heating loads, so no TES devices are required. The system states under different operation conditions are illustrated in Table 3, where major variables concerned are listed.

Table 3. System states under different power to heat ratio based CHP generations (FTL mode).

Season	State Variable	Power to Heat Ratio of GT Based Generator		
		0.35	**0.55**	**0.75**
Winter	Maximal voltage (pu)	1.0611	1.0615	1.0620
	Minimal voltage (pu)	0.9588	0.9588	0.9589
	Maximal pressure (psia)	1246	1223	1208
	Minimal pressure (psia)	646	602	551
	Maximal power injection by CHP (MW)	1.38	2.99	4.59
	Maximal power consumption by CHP (MW)	3.26	1.84	0.42
Summer	Maximal voltage (pu)	1.0601	1.0606	1.0611
	Minimal voltage (pu)	0.9583	0.9583	0.9583
	Maximal pressure (psia)	1263	1260	1262
	Minimal pressure (psia)	625	564	456
	Maximal power injection by CHP (MW)	/	/	0.56
	Maximal power consumption by CHP (MW)	15.03	13.88	12.73
Transition seasons	Maximal voltage (pu)	1.0601	1.0604	1.0606
	Minimal voltage (pu)	0.9586	0.9586	0.9587
	Maximal pressure (psia)	1262	1251	1238
	Minimal pressure (psia)	654	634	605
	Maximal power injection by CHP (MW)	/	1.16	2.36
	Maximal power consumption by CHP (MW)	8.33	7.21	6.31

Through Table 3, it can be found that under FTL mode, the voltages in power networks and pressures in gas systems are all affected by CHP generation. In winter, because the power to heat ratio of loads and generations matches well, the electricity exchange between power networks and CHP systems is relatively small. However, the overvoltage problem seems more severe in this situation. This is due to the fact that overvoltage issues are caused by the DG injection and the effective way to mitigate the overvoltage is to consume more power in electric networks. Since the CHP system cannot afford high power consumption in winter, the power drawn from electric networks is limited. In summer and transition seasons, the overvoltage is alleviated remarkably. The reason is that in these seasons more electricity is required by CHP loads as shown in Figure 5, and the CHP generation following thermal demand cannot provide sufficient power. The electric system needs to supplement the lacking electricity. With more power consumed in power networks, the overvoltage problem is subsequently alleviated. The power exchanges between CHP systems and power networks are shown in Figure 6, where positive values denote power injection into electric systems and negative values refer to power consumption.

Combining Table 3 with Figure 6, it can be found that under FTL mode, higher power to heat ratio of CHP generation leads to more severe overvoltage problems in power electric networks. CHP systems with lower power to heat ratios generate less power under FTL mode and acquire more power from electric networks. Therefore, overvoltage issues are handled by extra power consumptions. As can be seen, the power to heat ratio of CHP generation significantly affects system states.

The CHP generation following electric loading expects the identical power to heat ratios of generation and loading demands. Meanwhile, the optimal power to heat ratio of CHP generation under FTL mode is constrained by the system states as well as loading demands. In both cases, the proportions of power and thermal demands are the pivotal concerns.
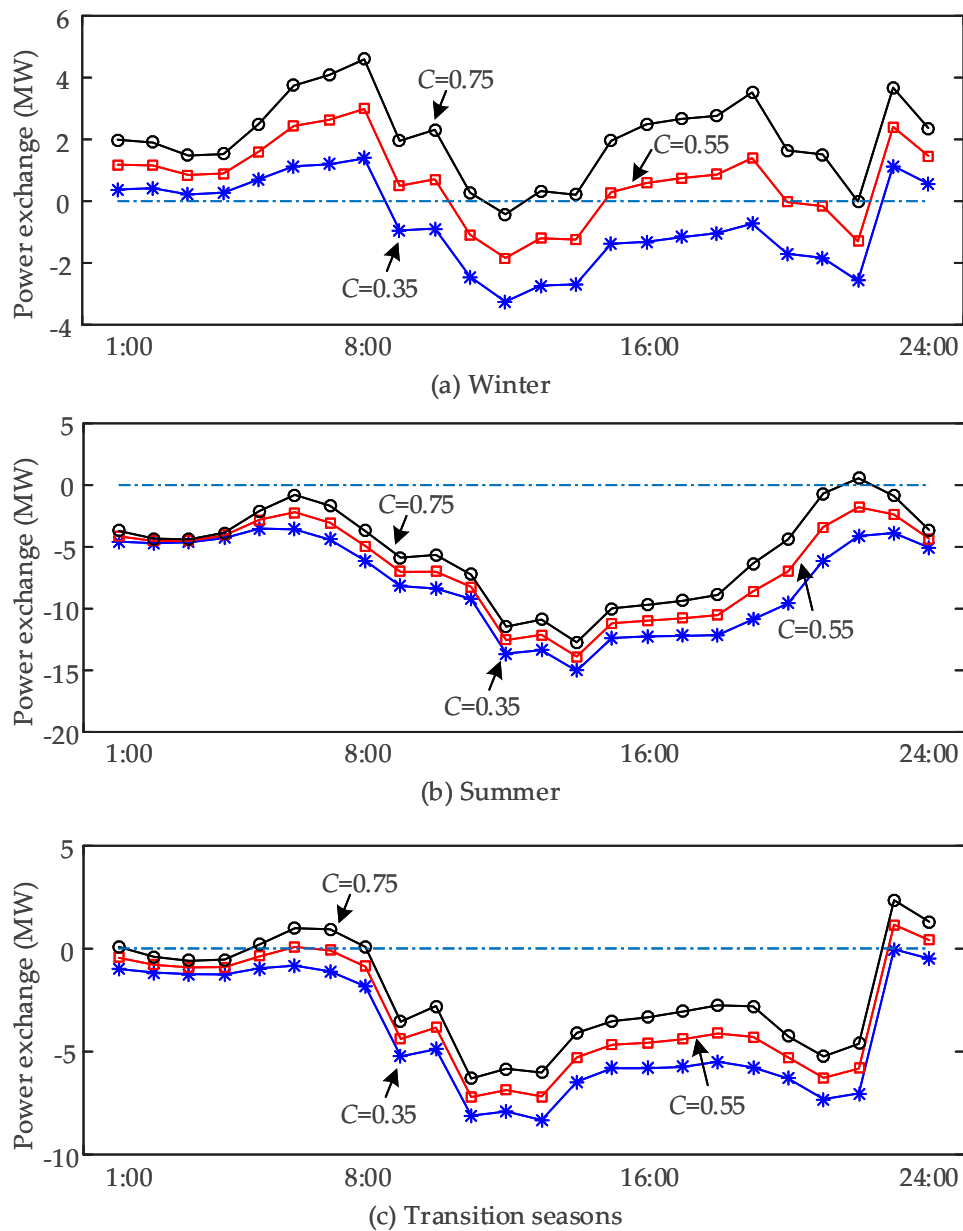
Figure 6. Power exchanges between CHP generation and power networks.

4.1.3. Operation under the Proposed Strategy

With the proposed strategy, the system states under different operation conditions are shown in Table 4. The proposed strategy prefers operating under conventional FTL mode, such as the case of summer with 0.35 power to heat ratio and transition season cases with 0.35 and 0.55 power to heat ratio. Under these situations, both the gas networks and electric systems are within proper operation states, so CHP generation is not required for auxiliary services. However, in other situations, either pressures in gas networks or voltages in electric systems are remarkably violated under conventional FTL mode. Hence the proposed strategy introduces new operation modes and the system operation is reset by coordinating with thermal storage devices. By implementing such policy, the under-pressure issues and overvoltage problems are all mitigated.

Table 4. System states under different power to heat ratio based CHP generations. (Following the proposed strategy).

Season	State Variable	Power to Heat Ratio of GT Based Generator		
		0.35	**0.55**	**0.75**
Winter	Maximal voltage (pu)	1.0605	1.0605	1.0605
	Minimal voltage (pu)	0.9588	0.9588	0.9589
	Maximal pressure (psia)	1278	1278	1277
	Minimal pressure (psia)	654	633	612
	TES capacity required (MW·h)	65	80	90
	TES storing rate required (MW)	/	/	/
	TES releasing rate required (MW)	7.88	8.89	9.37
	Maximal power injection by CHP (MW)	1.38	2.99	3.95
	Maximal power consumption by CHP (MW)	5.44	5.42	5.47
Summer	Maximal voltage (pu)	1.0601	1.0605	1.0605
	Minimal voltage (pu)	0.9583	0.9583	0.9583
	Maximal pressure (psia)	1263	1262	1265
	Minimal pressure (psia)	625	563	500
	TES capacity required (MW·h)	/	2	7
	TES storing rate required (MW)	/	/	/
	TES releasing rate required (MW)	/	1.20	3.95
	Maximal power injection by CHP (MW)	/	/	/
	Maximal power consumption by CHP (MW)	15.03	13.88	12.73
Transition seasons	Maximal voltage (pu)	1.0601	1.0604	1.0605
	Minimal voltage (pu)	0.9586	0.9586	0.9587
	Maximal pressure (psia)	1262	1251	1233
	Minimal pressure (psia)	654	634	621
	TES capacity required (MW·h)	/	/	4
	TES storing rate required (MW)	/	/	/
	TES releasing rate required (MW)	/	/	1.14
	Maximal power injection by CHP (MW)	/	1.16	2.36
	Maximal power consumption by CHP (MW)	8.33	7.21	6.31

Figures 7–9 illustrate the maximal voltages of all cases controlled by different strategies. When the CHP systems work under FEL mode, the electric networks always suffer from the overvoltage problems due to no effective interactions between the CHP generations and electric power networks. CHP systems under FTL mode do influence the system state of power networks, and this impact is related to the power to heat ratio of generation. Unfortunately, no matter which power to heat ratio is set, the overvoltage problem cannot be avoided in all seasons. The proposed strategy is activated for system management only when the abnormal conditions are detected. In summer and transition seasons shown in Figures 8 and 9, the maximal voltages in electric systems under FTL mode are mostly within constraints, so the curves of the proposed strategy are almost overlapped with these of FTL mode. In addition, in other cases, all maximal voltages are controlled within defined SER criterion by implementing the proposed strategy, so as to minimal pressures in gas networks. It is clearly seen that the auxiliary services of CHP generations are fully utilized by introducing the proposed strategy.
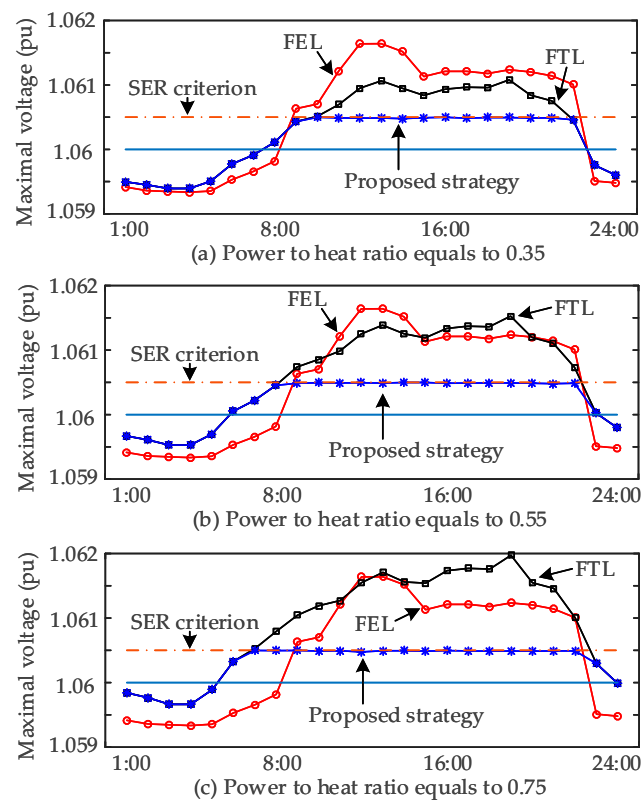
Figure 7. Maximal voltages under different control strategies in winter (power to heat ratio of CHP generation is set with diverse value, where (**a**) *C* = 0.35; (**b**) *C* = 0.55; and (**c**) *C* = 0.75).
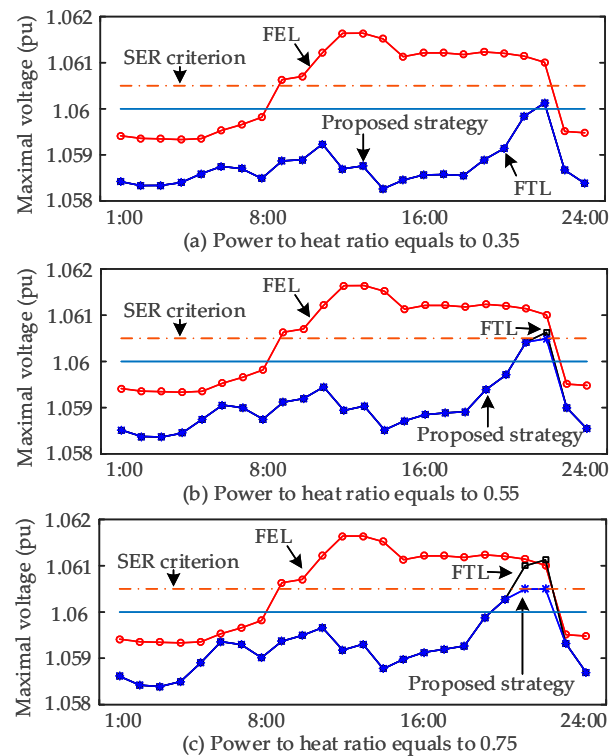

Figure 8. Maximal voltages under different control strategies in summer (power to heat ratio of CHP generation is set with diverse value, where (**a**) *C* = 0.35; (**b**) *C* = 0.55; and (**c**) *C* = 0.75).
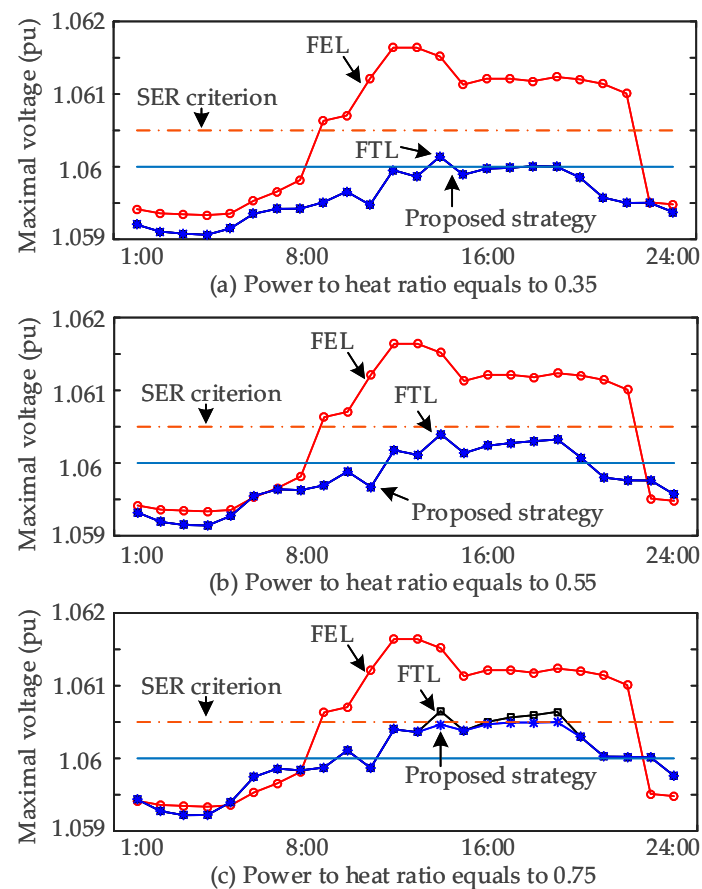
Figure 9. Maximal voltages under different control strategies in transition seasons (power to heat ratio of CHP generation is set with diverse value, where (**a**) *C* = 0.35; (**b**) *C* = 0.55; and (**c**) *C* = 0.75).

4.1.4. Comparisons and Discussions

In order to give a clear picture on how the proposed strategy works, detailed information of selected cases is extended. Here two cases are further studied. One is winter case with 0.55 power to heat ratio, where overvoltage is the main concern. The other is summer case with 0.75 power to heat ratio, where under-pressure and overvoltage are both included.
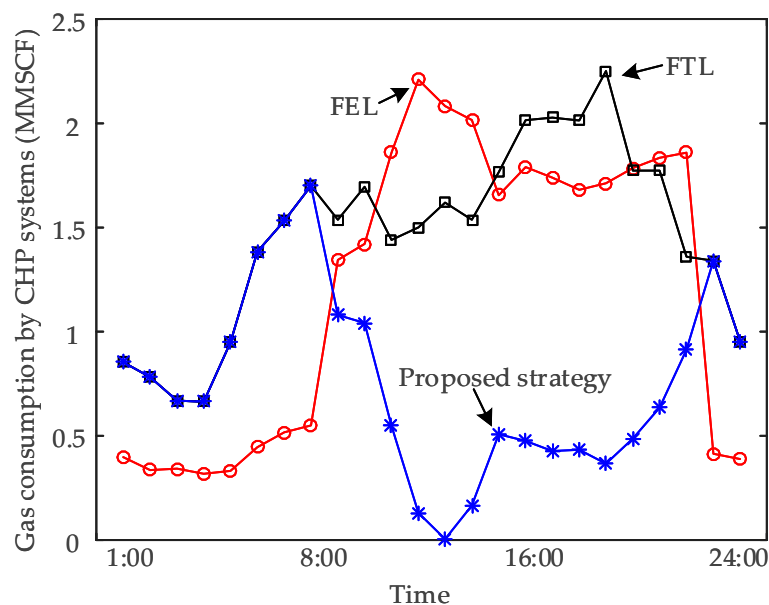
Case 1. Winter Case with 0.55 Power to Heat Ratio

Table 5 shows the one day CHP operation modes in winter case with 0.55 power to heat ratio. While there is no overvoltage detected in the system, CHP system operates under FTL-TESO mode, which is consistent with conventional FTL mode. As soon as overvoltage is detected, it is desired to consume more power in electric networks. Therefore, CHP systems stop injecting power into electric networks and start consuming. Meanwhile, the power generation of CHP systems is also lowed to match the power balance, so the CHP systems switch to FEL mode. Since there is a lack of thermal supply, TES devices are responsible for this part and hence releasing the stored heat. FTL-TESO mode is switched to FEL-TESR mode.

Table 5. CHP operation modes under the proposed control strategy in winter case (*C* = 0.55).

Time	1:00	2:00	3:00	4:00	5:00	6:00
Mode	FTL-TESO	FTL-TESO	FTL-TESO	FTL-TESO	FTL-TESO	FTL-TESO
P_{EPN} **(MW)**	1.18	1.16	0.85	0.90	1.60	2.44
Time	7:00	8:00	9:00	10:00	11:00	12:00
Mode	FTL-TESO	FTL-TESO	FEL-TESR	FEL-TESR	FEL-TESR	FEL-TESR
P_{EPN} **(MW)**	2.64	2.99	−0.68	−0.98	−3.40	−5.40
Time	13:00	14:00	15:00	16:00	17:00	18:00
Mode	FEL-TESR	FEL-TESR	FEL-TESR	FEL-TESR	FEL-TESR	FEL-TESR
P_{EPN} **(MW)**	−5.42	−4.80	−2.98	−3.41	−3.40	−3.24
Time	19:00	20:00	21:00	22:00	23:00	24:00
Mode	FEL-TESR	FEL-TESR	FEL-TESR	FEL-TESR	FTL-TESO	FTL-TESO
P_{EPN} **(MW)**	−3.49	−3.37	−3.11	−2.46	2.41	1.47

Figure 10 illustrates the gas consumption of the CHP system in winter case with 0.55 power to heat ratio. Under both FEL mode and FTL mode, the CHP systems consume remarkable quantities of natural gas while electric systems suffer from overvoltage issues simultaneously. These are unconscionable control strategies, resulting in abnormal system operation and primary energy wasting. Meanwhile, the gas consumption requirement by the proposed strategy is very small. The proposed strategy not only mitigates the overvoltage problems, but also saves the energy use in the hybrid energy systems, achieving desired benefits.

Figure 10. Gas consumptions following different control strategies (Winter, *C* = 0.55).

Case 2. Summer Case with 0.75 Power to Heat Ratio

Table 6 shows the one day CHP operation modes in summer case with 0.75 power to heat ratio. The CHP systems are mostly working under FTL-TESO mode, on account of the high ratio of power to heat demands. As seen in Figure 5, power demands in summer are very high, so the power produced by CHP generation following thermal loading cannot meet the electric loading requirement. The electric networks still supply a large amount of electricity and overvoltage is barely concerned. At 21:00, under-pressure issue is detected in hybrid systems, so the control mode is switched to FTL-TESR (Thermal energy releasing rate is 3.15 MW) based on the proposed strategy shown in

Figure 4. At 22:00, the under-pressure is gone, but overvoltage happens. So the operation mode is set as FEL-TESR (Thermal energy releasing rate is 3.95 MW). By introducing these two modes, the whole system operation is guaranteed to be normal.

Table 6. CHP operation modes under the proposed control strategy in summer case (*C* = 0.75).

Tim	1:00	2:00	3:00	4:00	5:00	6:00
Mode	FTL-TESO	FTL-TESO	FTL-TESO	FTL-TESO	FTL-TESO	FTL-TESO
P_{EPN} (MW)	−3.71	−4.33	−4.40	−3.86	−2.09	−0.79
Time	7:00	8:00	9:00	10:00	11:00	12:00
Mode	FTL-TESO	FTL-TESO	FTL-TESO	FTL-TESO	FTL-TESO	FTL-TESO
P_{EPN} (MW)	−1.67	−3.72	−5.88	−5.65	−7.25	−11.46
Time	13:00	14:00	15:00	16:00	17:00	18:00
Mode	FTL-TESO	FTL-TESO	FTL-TESO	FTL-TESO	FTL-TESO	FTL-TESO
P_{EPN} (MW)	−10.89	−12.73	−9.99	−9.69	−9.38	−8.90
Time	19:00	20:00	21:00	22:00	23:00	24:00
Mode	FTL-TESO	FTL-TESO	FTL-TESR	FEL-TESR	FTL-TESO	FTL-TESO
P_{EPN} (MW)	−6.34	−4.39	−3.04	−2.40	−0.87	−3.61

Figure 11 illustrates the TES energy exchange rate in summer case with 0.75 power to heat ratio, where positive values denote TES storing power and negative values denote TES releasing power. Since there is no TES involved in FTL mode, it is not illustrated. Under FEL mode, TES devices are frequently used, and the storing rate required is relatively high. Besides, high-frequency operations may reduce the service life of electric equipment. Under the proposed strategy, the TES devices are rarely operated. It indicates that the proposed strategy tries to control the system operations within the proper constraints by utilizing the features of the CHP generations themselves, rather than only depending on the additional equipment.
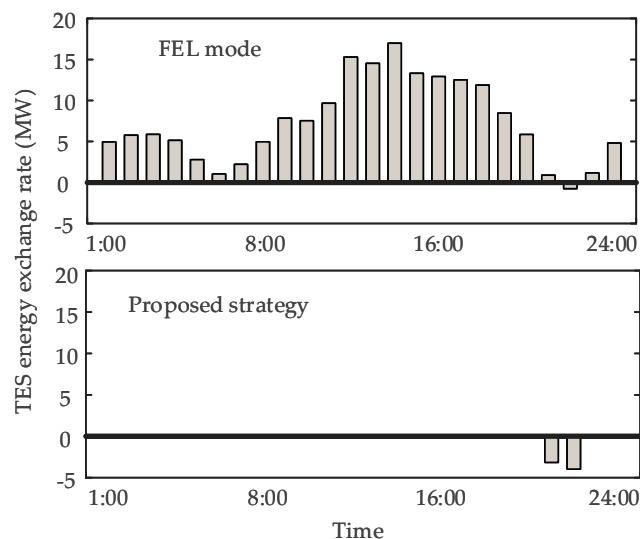

Figure 11. TES energy exchange in summer case with 0.75 power to heat ratio.

4.1.5. Impacts of Thermal Energy Storage

Based on studies shown above, further investigations on roles of thermal energy storage are conducted, while the TES capacities required in different scenarios are illustrated in Table 7. The proposed strategy requires some additional TES allocations compared with FTL strategy, but the amount of TES investment is very small in summer and transition seasons. Although TES requirement

is relatively high in winter, the overall economic efficiency is not that reduced due to the energy saving benefits shown in Figure 10. Besides, considering the auxiliary services achieved through allocation of TES devices, the installment of TES is both technical and economic desired.

Table 7. Thermal energy storage requirements in different scenarios (unit: MW·h).

Seasons	Control Mode	Diverse *C* Based GT Generator in CHP System		
		C = 0.35	*C* = 0.55	*C* = 0.75
Winter	FEL	70	30	65
	FTL	0	0	0
	Proposed strategy	65	80	90
Summer	FEL	550	295	175
	FTL	0	0	0
	Proposed strategy	0	2	7
Transition seasons	FEL	285	140	75
	FTL	0	0	0
	Proposed strategy	0	0	4

In the winter cases, the desired TES capacity for implementing the proposed strategy is 65, 80, and 90 MW·h, respectively. However, if the capacity of actual TES devices installed with CHP systems is limited, the proposed strategy still achieves reasonable voltage regulation effect. Assume that the installed TES capacity is respectively 90 and 45 MW·h, i.e., one is sufficiently allocated and the other is not. The voltage regulation results are shown in Figure 12. Though TES with 45 MW·h is not able to mitigate all overvoltage issues, it helps to shorten the overvoltage durations, e.g., from 12h to 5 h in *C* = 0.35 case, from 14 h to 6h in *C* = 0.55 case, and from 16 h to 8 h in *C* = 0.75 case. The proposed strategy shows universal effectiveness in providing auxiliary services.
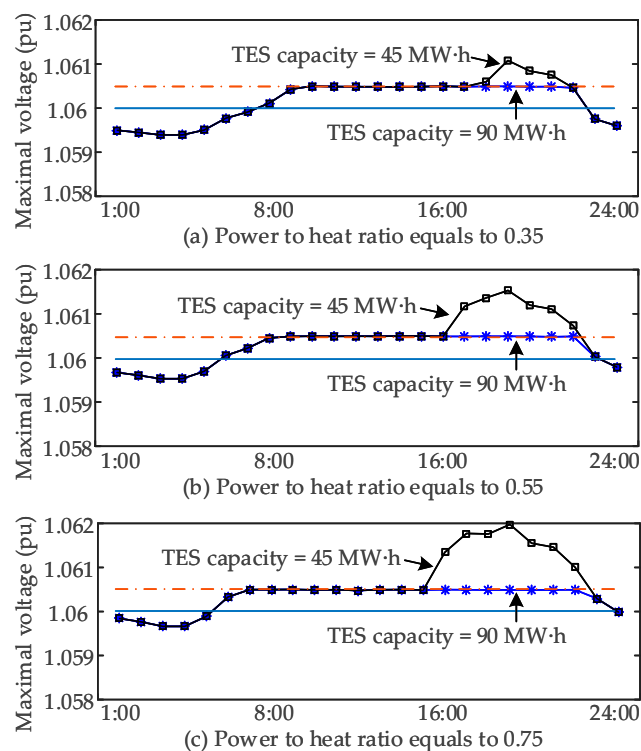

Figure 12. Impacts of TES capacity on voltage regulation (power to heat ratio of CHP generation is set with diverse value, where (**a**) *C* = 0.35; (**b**) *C* = 0.55; and (**c**) *C* = 0.75).

4.2. Hybrid Energy Systems with Double CHP Connections

In this case, two CHP systems are installed in the hybrid systems. One CHP unit connects node 3 of gas networks to node 46 of electric networks and is defined as CHP #1. The other CHP unit couples node 13 of gas networks to node 14 of electric networks, which is denoted as CHP #2. Since the impacts of power to heat ratio have already been investigated in previous subsection, in this part the power to heat ratio of CHP #1 is set as 0.75 while it is 0.55 for CHP #2. The rated power capacities of CHP units are both 20 MW. The optimization problem illustrated in Section 3.3 is solved by particle swarm optimization (PSO) to coordinate multiple CHP units.

4.2.1. General Control Performance

Based on diverse control strategies, the general system states are shown in Table 8. Under FEL mode, the CHP systems do not participate in the power network regulation and therefore overvoltage problem always exists. Besides, pressure abnormality happens in summer and transition seasons, when the power to heat ratio of loading demand is relatively high. Under FTL mode, overvoltage and under-pressure problems happen in both winter and summer. With the proposed strategy, the operation of the hybrid energy systems, including both natural gas networks and electric power networks, is always within proper constraints considering all season scenarios. Through the general results shown in Table 8, conclusion can be drawn that the proposed strategy is effective in the coordination of the hybrid energy system operations, ensuring the states of both subsystems within proper restraints.

Table 8. System states under different control strategy based CHP generations.

Season	State Variable	Control Strategy		
		FEL	FTL	Proposed Strategy
Winter	Maximal voltage (pu)	1.0616	1.0622	1.0605
	Minimal voltage (pu)	0.9587	0.9590	0.9590
	Maximal pressure (psia)	1400	1320	1320
	Minimal pressure (psia)	554	356	607
	TES capacity required for CHP #1 (MW·h)	65	/	75
	Maximal power injected by CHP #1 (MW)	/	4.22	3.04
	Maximal power consumed by CHP #1 (MW)	/	0.40	4.60
	TES capacity required for CHP #2 (MW·h)	30	/	25
	Maximal power injected by CHP #2 (MW)	/	2.64	2.42
	Maximal power consumed by CHP #2 (MW)	/	1.81	2.50
Summer	Maximal voltage (pu)	1.0616	1.0609	1.0605
	Minimal voltage (pu)	0.9587	0.9679	0.9579
	Maximal pressure (psia)	1580	1422	1429
	Minimal pressure (psia)	380	244	500
	TES capacity required for CHP #1 (MW·h)	175	/	5
	Maximal power injected by CHP #1 (MW)	/	0.56	/
	Maximal power consumed by CHP #1 (MW)	/	12.73	12.73
	TES capacity required for CHP #2 (MW·h)	295	/	15
	Maximal power injected by CHP #2 (MW)	/	/	/
	Maximal power consumed by CHP #2 (MW)	/	13.88	13.88
Transition seasons	Maximal voltage (pu)	1.0616	1.0602	1.0602
	Minimal voltage (pu)	0.9587	0.9586	0.9586
	Maximal pressure (psia)	1340	1390	1390
	Minimal pressure (psia)	252	612	612
	TES capacity required for CHP #1 (MW·h)	70	/	/
	Maximal power injected by CHP #1 (MW)	/	2.36	2.36
	Maximal power consumed by CHP #1 (MW)	/	6.31	6.31
	TES capacity required for CHP #2 (MW·h)	140	/	/
	Maximal power injected by CHP #2 (MW)	/	1.16	1.16
	Maximal power consumed by CHP #2 (MW)	/	7.21	7.21

4.2.2. Control Performance on the Electric Power Networks

In this and next subsections, the detailed performance analyses are expanded based on the winter case, where all the typical concerns are included. The results of summer and transition seasons cases are similar and therefore not presented due to space limit.

Figure 13 shows the maximal voltages in electric networks and the power exchanges between CHP units and power systems. By implementing the proposed strategy, both CHP systems start to inject less or draw more power from the view of electric networks, which is effective in mitigating the overvoltage problem. Comparing with CHP #2, the CHP #1 injects more power into electric networks under FTL mode, and therefore it is regulated more under the proposed strategy.
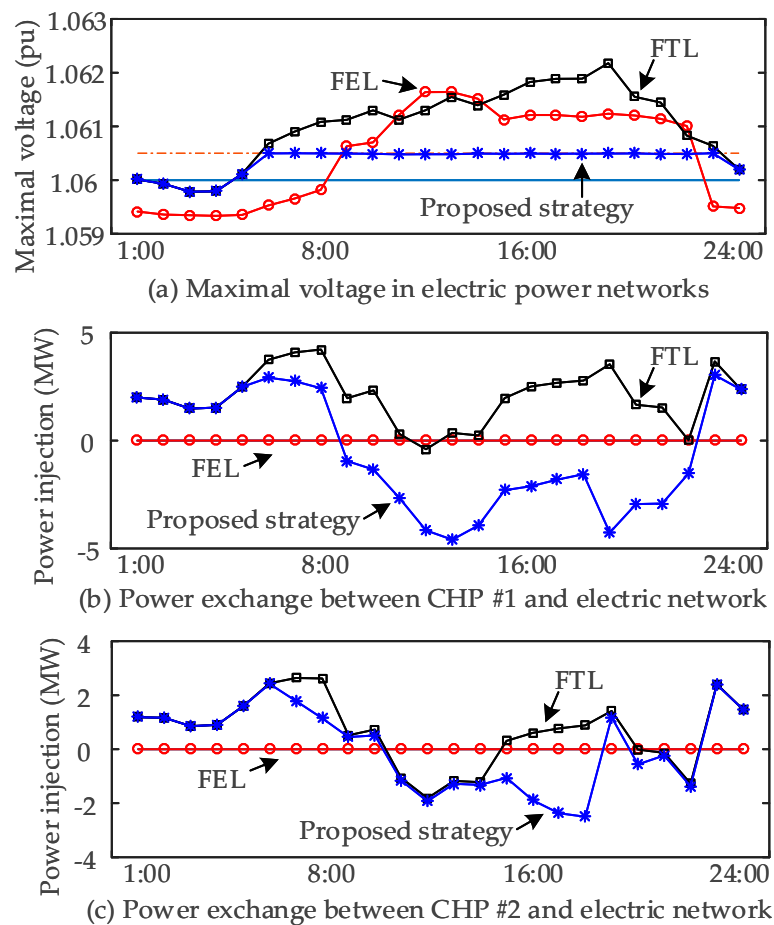

Figure 13. Control performance on the power electric networks ((**a**) Maximal voltage in electric power networks (**b**) Power exchange between CHP #1 and electric network (**c**) Power exchange between CHP #2 and electric network).

4.2.3. Control Performance on the Natural Gas Networks

Figure 14 shows the minimal pressure in natural gas networks and the gas consumption by two CHP units. Combined with Figure 13, following results can be obtained: (1) The gas pressure could be kept within proper ranges while the proposed strategy is implemented to mitigate the overvoltage issues, such as time period 6:00–18:00 and 20:00–23:00; (2) The proposed strategy is able to mitigate the pressure and voltage abnormality simultaneously, which is demonstrated at time 19:00; (3) Considering that the objective of coordination optimization is the minimum participation of TES, Figure 14b,c indicate that gas consumption of CHP units are decreased, resulting in energy saving achievements on the whole.
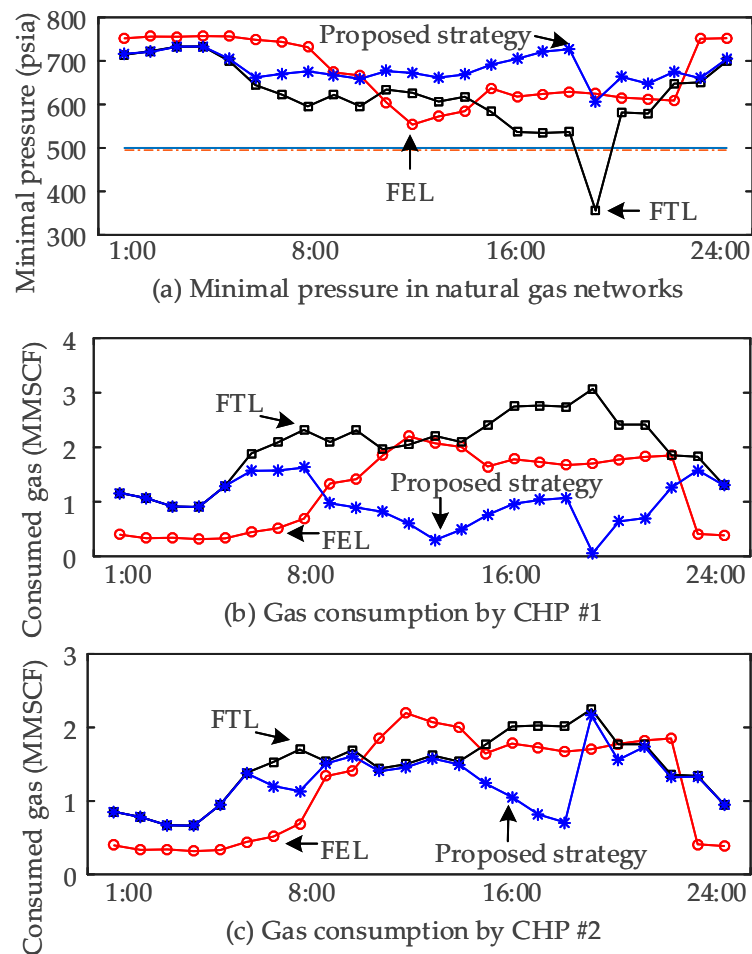
Figure 14. Control performance on the natural gas networks ((**a**) Minimal pressure in natural gas networks (**b**) Gas consumption by CHP #1 (**c**) Gas consumption by CHP #2).

5. Conclusions

This paper has presented a novel control approach for combined heating and power generation. Hybrid energy systems are modeled at the first place. Then the criterion, named as state excursion rate, is defined to address the abnormality of system operations. By introducing thermal energy storages, the operation modes of CHP systems are significantly extended, providing better choices for system operations. Based on SER index, the optimal operation mode of combined electricity and gas systems is chosen, forming the key of the proposed approach. Case studies are tested on the hybrid energy systems, and the results demonstrate the superiority of this study. The proposed ideas and methods are verified to be capable of providing auxiliary services for both natural gas networks and electric power network operations by utilization of CHP system features. Besides, the desired economic and energy-efficient benefits are also maintained, and diverse power to heat ratios of CHP generations are well handled.

From the view of energy internet, the proposed study has provided an effective solution to the design and operation problems of the hybrid energy systems. By installation of thermal energy storages and further following the proposed control strategy, the CHP systems in combined electricity and natural gas networks are able to first eliminate the negative impact of themselves on the grid operations and then to provide effective auxiliary services to address operation abnormality. Meanwhile, the economic and energy-efficient benefits of the whole system are simultaneously maintained. The role of CHP systems in this study is changed from a passive single device to be an active response

unit. The regulation capability of CHP systems is demonstrated in this paper as the first step, and the future work includes explorations of other types of energy hubs, integration of more energy forms and detailed economic analysis.

As an additional contribution to the energy internet, this study also provides a brand new visual angle dealing with hybrid energy issues, where benefits of all stakeholders are considered. Therefore, the proposed idea and approach are welcomed by grid operators, CHP owners, and even energy consumers, which makes the construction and application of energy internet more attractive to these interested parties.

Author Contributions: Yu Liu performed the experiments and wrote the paper; Shan Gao conceived the idea; Xin Zhao designed the experiments; Chao Zhang analyzed the cases; Ningyu Zhang contributed the test data.

Conflicts of Interest: The authors declare no conflict of interest.

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