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Effects of district heating networks on optimal energy flow of multi-carrier systems

Amin Shabanpour-Haghighi, Ali Reza Seifi

School of Electrical and Computer Engineering, Shiraz University, Shiraz, Iran

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ABSTRACT

A multi-carrier energy network is a system consists of several energy carriers such as electricity, natural gas, heat, *etc*. Generally, each transmission network is optimized separately but it could overshadow the actual optimal operation of the whole energy network. An integrated viewpoint opens a new window on optimization analysis. Among various networks, district heating networks are very promising for energy saving and carbon emission reduction. In this paper, effects of utilizing this network on optimization of a multi-carrier energy system are shown. However, such a problem has a considerable number of variables that makes a non-linear, non-convex, non-smooth, and high-dimension optimization problem and the optimal solution cannot be achieved by conventional mathematical techniques. Therefore, it is better to use evolutionary algorithms instead. In this paper, the well-known modified teaching-learning based optimization algorithm is used to solve the problem. Various simulations on a typical system show the impacts of a district heating network in the multi-carrier energy system.

Contents

1. Introduction

Energy supply networks are usually considered as individual sub-networks with separate energy carriers such as electricity, natural gas,

E-mail addresses: shabanpour.amin@gmail.com (A. Shabanpour-Haghighi), seifi@shirazu.ac.ir (A.R. Seifi).

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and heat. An electrical network is the most popular transmission network utilized almost in all countries. Besides that, a natural gas network is another important system especially in recent days. In many countries around the world, the overall consumption of natural gas is growing. This fact should be maintained due to the great number of unexplored natural gas reserves, its low environmental impact and economic competiveness compared to other fossil fuels [1,2]. Another transmission network which is very promising for energy saving and carbon emission reduction is a district heating network (DHN) which is well-developed in a number of Northern European countries [3–8].

Generally, DHNs consist of some supply and return pipelines that deliver heat, in the form of hot water or steam, from the point of heat generation to consumers [9]. To work properly, heat exchangers need a certain pressure difference between the supply and return pipelines. This pressure difference is created and maintained by a central pump, usually located at the heat generation plant [10]. DHNs can accommodate heat from a wide range of sources such as fossil fuels, waste heat from industrial and electricity generation processes, renewable energy sources, *etc*. [11]. Combined heat and power (CHP) plants connected to DHNs are one of the most cost-efficient ways to generate heat and it has a proven track record in many countries [12,13]. CHPs usually consume natural gas to produce electricity and heat simultaneously. The surplus/deficit amount of the generated power by these plants should be transferred to/from the respected networks. Therefore, such a unit relates the natural gas network to the electrical and district heating networks that can affect energy flows in these systems and for optimization analysis, these interdependencies should be considered properly. On the other hand, restructuring of energy networks in several parts of the world has increased the interest in investigating how the state of each sub-network can affect the overall performance of the whole energy grid. The independent planning and operation of an energy network is unlikely to yield the overall minima, since synergies between different energy vectors cannot be exploited [14]. Hence, the most optimal operating regime of the system should be determined by considering all sub-networks together as a unified integrated system called multi-carrier energy network (MCEN).

An MCEN consists of several energy carriers related via a well-known concept called energy hubs [14,15]. An energy hub is an interface between participants and transmission systems that conditions, transforms, and delivers energy in order to cover the consumer needs [16].

Optimization problem of an MCEN is such a non-linear, non-convex, non-smooth, and high-dimension optimization problem that finding the global minima cannot be ensured using numerical techniques. Hence, an appropriate heuristic algorithm may be useful to solve the problem. The evolutionary technique used in this study is the modified teaching-learning based optimization which is fully described in [17] by the authors. Generally, teaching-learning based optimization algorithm is a parameter-free method and the performance of this technique is not affected by the parameters of the algorithm such as those in genetic algorithm, particle swarm optimization, *etc*. [17–20]. Adding a modified phase to this algorithm improves the convergence characteristic and provides great accuracy for the final result [17].

The aim of this paper is to find the effects of a DHN on minimizing the operational cost of an MCEN. To do so, a review on the MCENs are presented followed by reviewing the existing models of energy hubs and their shortcomings. Then the proposed approach is discussed and applied to a typical network. Results show impacts of the DHN on the MCEN and the ability of the DHN to reduce the operational cost of the MCEN is verified.

2. A review on MCENs

Multiple energy carrier systems [21] or hybrid energy systems [22] are referred to systems including various forms of energy such as gas, heat, electricity, *etc*. This integrated viewpoint opens a new window on research of synergies which can be available by the combination of electricity, natural gas, heat, and network infrastructures [23]. There are two main problems for these networks that should be solved: their power flow problem and their optimization problem. The former is discussed in several papers. For instance, a steady-state power flow equations for a combined natural gas and electrical network is proposed in [24] while in [25], a similar problem is solved for a combined district heating and electrical network. A detailed steady-state power flow analysis of an integrated gas, heat, and electrical network is proposed in [26]. It is well shown that these infrastructures are dependent and the power flow problem of MCENs cannot be decoupled. Another interesting problem of MCENs is how to find its optimal operating point. In the past, optimal power flow problems focused on systems employing only one form of energy. Various methods have been developed in particular for electrical networks [17,27,28], natural gas networks [29,30], and district heating networks [31,32]. More recently, the integrated modeling and analysis of the energy system as a whole is addressed in a number of publications. In this manner, several approaches have been developed and used for different aims. For example, an approximated flow model is utilized in [33] for optimizing power flows through an energy supply chain. In [14], the concept of energy hubs and its advantages to model and solve the optimal power flow problem of MCENs are discussed. The implemented method in that paper can be used only for a specific type of energy hubs where the total number of inputs should be equal to the total number of outputs. In other cases, a set of irregular equations is appeared. To overcome this shortage, an expanded model is proposed in [34]. The proposed solution uses dummy variables and virtual units but this would increase the difficulty of the optimization problem because of the additional variables and several supplementary constraints. As a matter of fact, a new approach is vital for solving optimization problem of MCENs which is developed in [35] by the authors. A novel method based on selecting an appropriate set of state-variables for the problem is proposed that eliminates the addition of any new variable to convert irregular equations into a regular set while the optimization problem is still solvable. Further analysis of such a technique is done in [36] and [37]. In the next section, a review on the existing methods to model the energy hubs is presented followed by some simulations by the proposed technique which aims to show the effects of DHNs on optimal energy flow of MCENs.

3. Energy hub concept

An MCEN consists of several energy carriers related via a well-known concept called energy hubs [14,15]. As shown in Fig. 1, an energy hub can be identified as a unit that provides the basic features input and output, conversion, and storage of different energy carriers [14]. In other words, an energy hub is an interface between participants and transmission systems that condition, transform and deliver energy in order to cover the consumer needs [16]. Some real facilities which can be modeled through the energy hub concept are big building complexes (airports, hospitals, and shopping malls), rural and urban domains, industrial plants (steel works, paper mills), and small isolated systems (trains, ships, aircrafts) [38]. Within the hub, energy is converted and conditioned using combined heat and power technologies, electrical transformers, power electronic devices, gas compressors, heat exchangers or boilers, and other equipments [39]. There are several ways to mathematically model an energy hub that are reviewed in this section.