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An extended energy hub approach for load flow analysis of highly coupled district energy networks: Illustration with electricity and heating

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HIGHLIGHTS

- An extended energy hub is proposed to model a general multicarrier energy network.
- The model is illustrated with coupled electricity and heating networks.
- A more realistic and flexible thermo-hydraulic model is implemented.
- A more accurate result is found in comparison to a recent work.
- Case studies with both radial and loop topologies are considered.

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ABSTRACT

Energy systems at district/urban level are getting more complex and diversified from time to time. Different energy carriers are coupled each other to meet various types of energy demands. The conventional way of analyzing energy networks independently does not reflect the true nature of the coupled networks. One of such a promising coupled multi-carrier energy system (MCES) is the combination of district heating and electricity networks. The coupling between these two networks is increasing due to the integration of co– and poly-generation technologies at the distribution networks. Recent literatures tried to address a load flow analysis for lightly coupled networks by formulating case-specific load flow models. This paper presents a more general and flexible tool developed using Matlab® which can be used to conduct the load flow analysis of highly coupled electricity and heating networks. An energy hub concept is extended further to formulate a general model in which local generations and detailed network parameters of MCES can be taken into account. Coupled heating and electricity networks are modeled in detail for illustration. The flexibility and generality of the model are then tested by considering case studies with different network topologies (tree and meshed). A comparison is also made with a model used in recent literature. The results show that the proposed model is more accurate. The main contribution of this paper can be summarized by the following five points: (1) Coupling matrices are used to relate network power flow equations of different energy carriers; (2) Hybrid hydraulic head and pipe flow equations are used to develop the hydraulic model which can be applied for both types of tree and meshed heating networks with the possibility of pumping units; (3) A general thermal model that relates steady state temperature drops and mass flow rates, even during change of flow direction, is developed for the heating network; (4) The electricity network is modeled with the possibility of tap changing transformers; (5) The overall system of equations are solved as a single problem using Newton-Raphson iterative method.

1. Introduction

The existing conventional (centralized) electricity grid consists of three main parts: generation, transmission and distribution systems. Although improvements have been made from time to time on these parts, there are still associated limitations such as: poor fuel to electricity conversion efficiency of conventional power plants; significant power loss in the transmission network; and significant amount of spinning reserve requirement to supply the rare peak demands [1]. Smart grids consisting of information and communication technologies (ICT), demand side management, distributed generations and energy storage facilities are proposed in recent literature to overcome those

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limitations of conventional power systems [2]. Distributed generation, as part of a smart grid, plays an important role in reducing carbon emission, improving power quality, decreasing power loss in the network and improving system reliability [3]. Combined Heat and Power (CHP) is one of such distributed generation options in which useful heat is generated in addition to the electricity by recovering the waste heat from conventional power plants which could otherwise be lost. Varieties of fuel types such as gas, biomass, waste and geothermal can be used as source of CHPs to produce both heat and electricity. Furthermore, the heat recovered from such plants can easily be fed into the local district heating networks.

A district heating network (DHN) is an interconnection of pipes which is used to transport heat using water as a medium. Lund et al. [4] described different generations of DHNs and their characteristics paying more attention on the future 4th generation DHNs. Some of the features of 4th generation DHNs are low temperature, flexible pipe material and capability to be integrated with smart electricity and gas networks. Altogether with these three types of energy networks (electricity, gas and heat networks), there are varieties of energy generation technologies and different types of energy demands at district level. The generation technologies include solar thermals, solar photovoltaics, wind turbines, heat pumps, fuel cells and poly-generation plants. Each energy demand can be met either from the same type of energy carrier or from another type of energy carrier using the energy conversion technologies. For example, a given heat demand can be met either through a heat exchanger, and/or a gas boiler (which converts gas into heat) and/or a heat pump (which uses electricity to transfer heat) and/or an electric boiler (which converts electricity to heat) and/or from a CHP (which converts fuel energy into electricity and heat). As the use of such energy conversion devices is increasing in district energy systems, the coupling between different energy carriers becomes stronger and stronger. Such an energy system which consists of varieties of energy resources and technologies is referred to as multi-carrier energy system (MCES)[5]. A smart energy system, which is an extension of a smart grid, deals with the interaction of different energy carriers through ICT, smart meters, demand side management, integration of distributed generations and energy storage technologies.

As it is common for uncoupled energy network, prefeasibility studies, load flow studies, optimization, contingency and reliability analyses are crucial for MCES to have a clear image of the energy network at the planning and operational phases. Prefeasibility studies deal with the techno-economic and environmental issues of the overall system and, hence, do not need the details of network parameters. Instead, an energy balance between aggregated demand and generation is considered to analyze the economical and emission parameters. Load flow and optimization studies, on the other hand, deal with the status of the energy network which require detailed modeling of the network parameters.

Levihn [6] presented the lessons learned from real energy networks in Stockholm where electric boilers and CHPs supply significant part of the heat demand. The results presented in the study are derived by investigating the correlation between the parameters under study and the historical data recorded in the network. For example, historical data is used to describe the relationship between outdoor temperature and output of distributed generations as a function of the energy market. Allegrini et al. [7], on the other hand, described the existing software tools that can be used to study urban energy systems. Some of the tools presented, such as EnergyPRO and EnergyPLUS, are used at the prefeasibility stage to do techno-economic analysis while others, such as TRNSYS, are used to do a detailed plant modeling at building/plant level. However, there is no tool suggested that can be used for modeling, simulation and operational optimization of district energy systems.

Geidl and Andersson [8] used an energy hub concept to model and optimize the conversion, transformation and storage relationships between different energy carriers. Electricity, heat and gas carriers are considered to illustrate the energy hub as a modeling concept for coupled networks. An alternating current (AC) power flow equations are used to represent the electricity network while hydraulic equations are assumed to represent any isothermal pipe flow networks. Three hubs that are interconnected with electricity and gas networks are considered for illustration. Any local generation associated to each hub is considered to be connected to the network outside of the energy hub. In addition, a unidirectional power flow into the hubs is assumed which implicitly limits the energy hub to act always as a consumer. This is not always true as there could be more production of a given energy carrier inside the hub than is required by the hub. The hub shall have a flexibility to inject the excess power back to the network. On the other hand, heating networks are not considered in their analysis and all the thermal demands are assumed to be met locally at each hub. Moreover, the proposed hydraulic equations are not sufficient enough to model thermal networks as the temperature of water in the heating pipe network is not in the isothermal state. Besides to that, the inlet and outlet temperatures of water at a given node (where the energy hub is connected) are generally different due to the mixing of water at different temperatures. This requires a separate treatment of the energy hub from the point of interconnection (node) which needs a modified representation of the energy hub. Wasilewski [9] used a modified energy hub concept and applied graph and network theory to study a MCES consisting of storage units, local generations and bidirectional energy flows. Although the approach described is more general than the original energy hub model proposed by Geidl [8], it fails to address the state of network parameters for each energy network.

Awad et al. [10] and Liu et al. [11] studied load flow problems of a MCES consisting of both heating and electricity networks taking the network parameters into account. In both cases, a complex representation of voltage and admittance values is used to formulate electricity power mismatch equations while node-loop equations with pseudo-dynamic temperature drop equations are used to represent temperature and heat mismatches.[1] However, the overall heat transfer coefficient is assumed to be constant for all mass flows, which is not always true in reality. Furthermore, the node-loop equations for hydraulic models needs assumption of pseudo-loop paths (the number of which depends on the network topology) in addition to the physical loops in order to have equal number of equations as the number of unknowns (the pros and cons of different hydraulic models are discussed in brief in Section 2.2.2 and more detailed discussion on the topic is found in [12]). As identification of pseudo-loops is not straight forward, it is difficult to develop a general algorithm for the models that are based on node-loop equations [12]. Moreover, both papers followed empirical approach to handle the coupling technologies unlike to the modular energy hub approach presented in [8]. In their case study, Liu et al. considered heating and electricity networks that are coupled through three CHP plants. All electrical demands and all CHP plants are assumed to be at unity power factor which is not always the case. There is also a requirement of reactive power to keep the voltage magnitude at the slack and PV hubs to a specified magnitude. However, no reactive power generation is considered in their case study [11].

Liu and Mancarella [5] extended the model presented in Liu et al. [11] into an energy system consisting of gas, electricity and district heating network. Shabanpour-Haghighi and Seifi [13] also reported a load flow study for similar MCES using empirical formulations rather than the energy hub concept. Both active and reactive power flows are considered in their case studies. However, lack of generality on the hydraulic models remained unsolved due to the use of the node-loop equations in their hydraulic models. They also assumed constant value of the overall heat transfer coefficients in their thermal models.

In a load flow study of a MCES, there are a number of equations for

[1] Mismatches refers to the tolerances in the system of equations that are solved in any numerical method such as Newton-Raphson.