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Simultaneous integrated optimal energy flow of electricity, gas, and heat

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ABSTRACT

In this paper, an integrated approach to optimize electrical, natural gas, and district heating networks simultaneously is studied. Several interdependencies between these infrastructures are considered in details including a nonlinear part-load performance for boilers and CHPs besides the valve-point effect for generators. A novel approach 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. As a large optimization problem, the optimal solution cannot be achieved by conventional mathematical techniques. Hence, it is better to use evolutionary algorithms instead. In this paper, the well-known modified teaching–learning based optimization algorithm is utilized to solve the multi-period optimal power flow problem of multi-carrier energy networks. The proposed scheme is implemented and applied to a typical multi-carrier energy network. Results are compared with some other conventional heuristic algorithms and the applicability and superiority of the proposed methodology is verified.

1. Introduction

Recently, there is a challenge to find the optimal operating point of energy resources in such a way that a required objective is satisfied. Traditionally, common energy infrastructures such as electricity, natural gas and local district heating systems are mostly planned and operated independently [1–5]. The independent approaches applied in dealing with these energy carriers, however, could overshadow the optimal energy operation [5–7]. New studies suggest integrating these networks called multi-carrier energy networks [1,5,8–10]. The important reason of such a view is the increasing utilization of co-generation plants which makes a strong coupling between the mentioned networks [1]. On the other hand, the independent approaches applied in dealing with these energy carriers could overshadow the optimal energy operation [5]. The growth in utilization of co- and tri-generation plants along with the energy efficiency concerns create sufficient incentives to enhance energy service networks by coordinating various energy systems [11]. The interdependence of these industries naturally requires integrated optimization of combined energy networks. For example, a combined heat and power (CHP) unit consumes natural gas to produce electricity and heat [12]. Therefore, it relates the natural gas network to the electrical and district heating networks which would affect the energy flow in these systems. This example shows that sub-networks of an energy delivery system are strongly dependent and their power flows relate to each other. So, for an optimization procedure, these networks should be considered together as a unified system that creates the so-called multi-carrier energy network (MCEN). In response, some publications suggest an integrated view of energy networks and several concepts are presented [13–15]. A well-known concept called energy hubs is proposed in [1]. It opens a new window on modeling of an integrated energy network including various energy carriers such as electricity, natural gas, and heat.

From a system point of view, energy hubs are an interface between participants and transmission systems that condition, transform and deliver energy in order to cover the consumer needs [1,2,9]. Hence, the energy hub benefits from a number of prospective advantages over conventional decoupled energy supply, such as more flexibility in load supplying or peak shaving in prices [16].

There are various energy carriers that could be considered in an energy network. In this paper, three important networks are studied includes electrical, natural gas, and district heating networks. Electrical networks are the most popular transmission networks utilized almost in all countries. Generally, an electrical network consist of electrical generation plants that produce electric power by consuming appropriate fuel such as coal, oil, and gas. Electrical loads are supplied by the generated electric power with

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Nomenclature

Subscript

E	electric
G	natural gas
H	heat
s	supply pipeline
r	return pipeline
g	ground

Superscript

hub	energy hub
gen	electric generator
chp	combined heat and power plant
boil	boiler
gs	natural gas source
shc	shunt capacitance
dem	demand
comp	compressor
pump	circulating pump
fuel	fuel
line	transmission line/pipeline
bus	electrical/gas/heat bus
min	minimum limit of a variable
max	maximum limit of a variable

Variables/parameters of the MCEN model

P	electric/gas/heat power (MW)
Q	reactive power (MVar)
S	apparent power (MVA)
ϕ	consumed amount of fuel (m^3/day, ton/day)
f	natural gas flow (m^3/day)
$\dot{m}$	mass flow rate of water (kg/s)
V	voltage magnitude (p.u.)
θ	voltage angle (°)
π	natural gas pressure (bar)
T	temperature (°C)
G	conductance of transmission lines (s)
B	susceptance of transmission lines or shunt capacitances (s)
TR	tap ratio of tap-transformers
H	compression ratio of compressors
C	constant of natural gas pipelines
D	diameter of gas pipelines (m)
L	total length of gas/heat pipelines (m)
τ	pump head of the district heating network (m)
η	efficiency of units
u, v, w	cost coefficients of fuels
a, b, c, d, e	heat rate coefficients of generators/characteristic coefficients of CHPs and boilers
N	total number of units

Variables/parameters of the MTLBO algorithm

X	individual of the optimization problem
F	objective function
T	teacher of the algorithm
M	mean value of the found individuals
W	worst solution among all individuals
rand	a random number between [0, 1]
ξ	wavelet function
υ	central frequency of the wavelet function
ς	upper limit of the wavelet function
σ	constant illustrates shape of the wavelet function
φ	a random number between ±2.5 h
μ	fuzzy membership function
ω	weighting factor for objective functions
k	current iteration of the algorithm

Constants

ε	absolute rugosity of natural gas pipelines (0.05 mm)
z	natural gas compressibility factor ($z = 0.8$)
δ	density of natural gas relative to air ($\delta = 0.6106$)
c	specific heat capacity of water ($c_P = 4182$ J/Kg K)
ρ	heat transition coefficient ($U = 0.455$ W/m K)
ψ, ζ	constants of compressors ($\psi = 0.167$ for a turbo-compressor, $\psi = 0.157$ for a moto-compressor, and $\zeta = 0.236$ for both types)
g	standard gravity constant ($g = 9.81\ \text{m/s}^2$)

the help of transmission lines. 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 [17,18]. A typical natural gas network consists of one or more gas resources, several loads, pipelines, compressors, and other devices such as valves or regulators [19]. Besides, electrical and natural gas networks, local district heating networks have great potential in many parts of the world. They have proved to be more efficient because of combined production of heat and electricity by cogeneration units [20–23]. Hence, the total fuel consumption can be reduced significantly. Other interests of using such a network are mainly due to environmental issues, such as the necessity in reduction of carbon dioxide emissions [24]. The aim of a district heating network is to provide the required heat for its consumers by utilizing adequate heat generation plants and a network of pipelines to transmit this generated heat power to the loads.

In the past, the optimization problem is solved independently using particular algorithms for each network. There are some competitive advantages to optimize the integrated energy networks than to optimize each network separately for system operation and economic analysis. Recently, the integration of various energy networks are addressed in some publications. In [1], the optimal power flow problem of MCENs is analyzed considering electricity and natural gas and the concept of energy hubs. A unified framework for modeling and supporting multiple-energy delivery systems with the help of energy hubs are discussed in [11]. It is worthwhile to note that if the total number of inputs of an energy hub is larger than the total number of its outputs then a set of irregular equations is appeared. To deal with this problem, some dummy variables are utilized in [5] and these irregular equations are converted into a regular set and a multi-agent genetic algorithm is proposed for optimization. Although this approach can successfully solve the mentioned issue but several equality and inequality equations are added to the formulation that increase the complexity of the problem.

In this paper, a new approach based on selecting an appropriate set of state-variables for the problem is proposed that eliminates the addition of any new variable while the optimization problem is still solvable. This approach is used to solve a multi-period optimal power flow problem considering electricity, gas, and heat simultaneously. The proposed methodology can be applied to district areas and cities [25]. Generally, input–output relationships of units are modeled by a simple constant efficiency in literatures to