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Modelling and operation optimization of an integrated energy based direct district water-heating system

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ABSTRACT

This paper proposes a model of an integrated energy based direct district water-heating system, which makes joint use of wind energy, solar energy, natural gas and electric energy. The model includes a stand-alone wind turbine generator, heat producers, a water supply network and heating load. This research also investigates an optimal operating strategy in which the fossil fuel consumption of the system in daily operation is optimized. Based on the model, an objective function used to obtain the optimal control strategy is constructed with complex operating constraints. GSO (Group Search Optimizer) is used to trace the optimal set-point temperature of boilers and the optimal water flow of pumps to minimize fuels consumption while satisfying variable constraints. In order to verify the model and optimal operating strategy, simulation studies have been undertaken. The optimal operating strategy is evaluated in comparison with an unoptimized control strategy. The simulation results prove the validity of the model and show that the optimal operating strategy is able to make the system operation more energy efficient. The proposed system is also evaluated in comparison with a conventional natural gas heating system. The comparative results demonstrate the investment feasibility, the significant energy saving and cost reduction achieved in daily operation.

1. Introduction

Recently, the limited reserve of fossil fuels and global environmental problems have stimulated people to focus on the utilization of renewable energy sources. The combustion of fossil fuels has taken the main responsibility for the ever increasing emissions of greenhouse gases, and the amount of emissions has reached such levels that we need to take measures to prevent harmful effect caused by climate change [1]. Hence, it is necessary for an energy supply system to make efficient use of energy and/or to increase the share of renewable energy to reduce fossil fuel consumption and emissions. As an important type of energy supply system, a heating system is either based on individual heating or district heating. It is greatly important for a heating system to save primary energy, reduce environmental pollution and improve the quality of life for residents [2]. It has been proved that district heating is better than individual heating because it can reduce more primary energy consumption and emissions [1,3,4]. A considerable amount of research has been conducted on the model of district heating system [5–8]. Furthermore, studies show that the optimal heating floor area of a direct district heating system ranges between 50,000.00 and 250,000.00 m^2. If the heating area is greater than this range, an alternate heating system, which is called indirect district heating system, is recommended [9]. With the expansion of heating systems, how to reduce their fossil fuel consumption while meeting local heat demand has become a problem to be solved.

A variety of methods have been applied to reduce the fossil consumption of a heating system. Sperling and Möller [10] have investigated end-use energy savings and district heating expansion in a local renewable energy system. Marbe and Harvey [11] have analyzed opportunities for integration of biofuel gasifiers in natural-gas combined heat-and-power plants in district-heating systems. Roonprasang et al. [12] have conducted experimental studies of a new solar water heater system using a solar water pump. Østergaard and Lund [13] have developed a renewable energy system using low-temperature geothermal energy for district heating. Østergaard et al. [14] have investigated a renewable energy scenario for Aalborg Municipality based on low-temperature geothermal heat, wind power and biomass. It can be seen that the integrated utilization of renewable energies and

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Nomenclature

P_H	heat production (W)
η	efficiency
q_g	calorific value of natural gas (J/m^3)
B_g	natural gas consumption rate (m^3/s)
H_T	total solar flux incident on the tilted collector (W/m^2)
P	power (W)
C_p	power coefficient of a wind turbine
λ	tip speed ratio
β	blade pitch angle (deg)
ρ	density (kg/m^3)
v	wind speed (m/s)
A	area (m^2)
r	blade length (m)
Ω	turbine rotor speed (rad/s)
$\dot{m}_0$	mass flow rate of water flowing through heat units (kg/s)
m	mass (kg)
c	specific heat (J/(kg °C))
T_o	outlet temperature (°C)
T_i	inlet temperature (°C)
K	heat transfer coefficient unit area (W/(m^2 °C))
F	collector efficiency factor
α	absorptivity of the absorber plate for solar radiation
τ	over transmittance of glass cover
U_L	overall heat loss coefficient of a collector(W/(m^2 °C))
T_p	average plate temperature of a collector (°C)
p	pressure (Pa)
h	heat transfer coefficient unit length (W/(m °C))
l	length of a pipe (m)
$\dot{m}_p$	water mass flow of a pipe (kg/s)
Q	heat transfer rate (W)
T_a	ambient temperature (°C)
T_n	indoor temperature (°C)
T_s	supply temperature (°C)
T_r	return temperature (°C)
V	peripheral volume of a building (m^3)
n	the number of buildings
q_V	volumetric heat index of a building (W/m^3 °C)
T_{av}	average temperature of water flowing in a heating system (°C)
$\dot{E}$	input energy rate (kW)
$\overline{G}$	relative water flow ratio
N_{col}	the number of solar collectors at site
N_{WG}	the number of wind generators at site
L_d	the summation of the inductances of the wind generator on d-axis (H)
L_q	the summation of the inductances of the wind generator on q-axis (H)
R	resistance value (Ω)
f	frequency (Hz)
C	capital cost ($)
i	interest rate
A_{fac}	annuity factor
N	the lifetime of equipment (Year)

the efficient use of energies are two main approaches to achieving more energy savings for the heat supply and reducing pollution to environments. Compared with fossil fuels use, the utilization of renewable energies can make the heat supply sustainable, but the only use of renewable energy can not guarantee the quality of heating. Actually, the integrated utilization of energy resources, including both non-renewable energy and renewable energy, can make the heat supply sustainable and reliable concurrently. For district heating, multiple energy sources comprise fossil fuels, cogenerated heat, waste heat, and renewable energy including heat available from ground source heat pumps, solar thermal energy and biomass, etc. [15,16]. Actually, with the rapid development of wind turbine and photovoltaic technologies, wind and solar resources are utilized for electric power generation and heat production more widely. Moreover, the economic aspects of these technologies are promising to justify their use in small-scale stand-alone applications for residence or industry and many other social sectors [17,18].

Except from integrated utilization of energy resources, operation optimization of a heating system is also considered as a measure to reduce the fossil fuel consumption [9,19,20]. In order to investigate an optimal operating strategy for a particular system, an optimization algorithm is usually employed. EAs (Evolutionary Algorithms), which stem from the study of adaptation in natural and artificial systems, have been investigated comprehensively in last decades. GA (Genetic Algorithm) [21], PSO (Particle Swarm Optimization) [22] and other population-based optimization techniques [23] have been applied widely for optimization problem solving. Recently, GSO (Group Search Optimizer) was proposed by He et al. [24], which is inspired from group-living, a phenomenon of the animal kingdom. GSO especially concerns animal searching behaviour and utilizes the PS (Producer-Scrounger) biological model [25], which assumes group members search either for 'finding' (producer) or for 'joining' (scrounger) opportunities. An extensive discussion and intensive analysis of GSO can be found in Ref. [25], in which comprehensive comparison between GSO and other EAs on a range of single-objective benchmark functions has been reported. The performance of GSO is not sensitive to parameters such as maximal pursuit angle, which makes it particularly attractive for real-world applications. Actually, GSO has been applied to solve some real practical problems. He and Li [26] have investigated the application of a group search optimization based articial neural network to machine condition monitoring. Wu et al. [27] have developed optimal placement of FACTS devices by GSO with multiple producers. Liu et al. [28] have applied GSO on truss structure design. Silva et al. [29] have developed an evolutionary extreme learning machine based on group search optimization.

In this paper, integrated energy utilization and operation optimization are considered as joint measures to reduce the fossil fuel consumption of a direct district water-heating system while meeting a varying heat demand. The rest of the paper is organized as follows. Section 2 presents a model of a direct district heating system that makes joint use of wind energy, solar energy, natural gas and electric energy. Section 3 focuses on the operation optimization in which the fossil fuel consumption of the system in daily operation is optimized using GSO. In Section 4, the simulation studies of the proposed model and optimal control strategy are presented, including parameters settings, results analysis and the evaluation of the strategy. In Section 5, in order to analyze the investment feasibility, the energy saving potential and the running cost reduction potential of the proposed system, the system is evaluated in comparison with a conventional natural gas heating system. Finally, the paper is concluded in Section 6.