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Combined cooling, heating, and power system optimal pricing for electricity and natural gas using particle swarm optimization based on bi-level programming approach: Case study of Canadian energy sector

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ABSTRACT

Combined cooling, heating, and power (CCHP) systems are considered energy efficient and they can be economically rewarding only when the inter-dependencies of energy prices for electricity and natural gas (NG) are properly accounted for. The goal of this study is to determine the optimal hourly energy prices for electricity and NG for a non-autonomous CCHP system using particle swarm optimization algorithm based on bi-level programming approach. Based on optimal sizing and configuration of the CCHP system, the rewards for both the distribution utility and the industrial energy consumer are analyzed. For simulation purposes in this study, a CCHP system with known loads operated in Ontario, Canada, based on actual energy prices is examined. For a CCHP system with gas turbine (GT) as prime mover, the optimal energy prices for on-peak and off-peak periods for spring, summer, fall, and winter for electricity and NG are determined. It is found that for the on-peak period, if the electricity prices in winter are 1.16, 1.56, and 1.75 times greater than those in summer, fall, and spring, respectively, and if the NG prices in winter are 1.19, 1.64, and 1.86 times greater than those in summer, fall, and spring, respectively, the rewards for distribution utility and industrial energy consumer are guaranteed. Based on the simulation results, it is determined that, under the optimal hourly energy prices for electricity and NG, the industrial energy consumer meets in excess of 92% of its needed electricity by the CCHP system that is sized and configured optimally with capital recovery of 2–3 years.

1. Introduction

Combined heating and power (CHP) and combined cooling, heating, and power (CCHP) systems have experienced a favorable growth in recent years due to simultaneous efficient system operation and economical energy utilization (El-Khattam et al., 2004; Environmental Protection Agency (EPA)). Also, CHP and CCHP systems have been shown to provide a hedge against unstable energy costs, as their installation provides for avoiding transmission and distribution losses, (Lopez-Lezama et al., 2010; Moradi and Abedini, 2012; Tichi et al., 2010).

In the literature, numerous studies have been introduced that focus only on techno-economic feasibility of utilizing CHP and CCHP systems for various applications without regards for rewards for both distribution utility as energy supplier and energy consumer. For example, Huang et al. (Huang et al., 2004) examined genetic algorithm to develop an optimal operation strategy based on overall cost reduction that improves the competitiveness of cogeneration system in the power market. Osman and Ries (Osman and Ries, 2006) developed a mixed integer linear programming model to determine optimal operation of integrating cogeneration systems with power grid, where environmental criteria are considered. Oh et al. (Oh et al., 2007) used mixed integer linear programming to determine optimal configuration of a cogeneration system by considering annual electricity, heating, and cooling loads. In that study, it was determined that the optimal configuration of cogeneration plant is dependent on system type. Also, in that study, the economic evaluation for the optimal configuration system based on the fuel tariff system was conducted and it was found that the short payback period of2.8 years and a high internal rate of return (47%) are essential to adopt the cogeneration plant in hospitals and apartments and to guarantee the rewards for CCHP

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owner. Brujic et al. (Brujic et al., 2007) presented optimization model to determine optimal operation schedule for CHP systems with an auxiliary boiler and heat storage, where the CHP systems participated in electricity spot market and their optimal operation schedule was determined based on electricity spot prices and electricity demand forecast. In another study, Ren et al. (Ren et al., 2008) presented a mixed integer nonlinear programming model for optimal sizing of a residential CHP system, where the annual cost of the energy system served as the objective function. Tichi et al. (Tichi et al., 2010) presented a model to determine optimal configuration of CHP and CCHP systems based on various prime mover technologies. In that study, the objective function was the total cost of investment and operation of CHP and CCHP systems for an industrial energy consumer, under the conditions of selling and not-selling to distribution utility and, the effects of energy price policies are examined based on optimal configuration of the systems examined. Aghaei Meybodi and Behnia (Aghaei Meybodi and Behnia, 2011) presented a thermo-economic approach for optimal sizing of internal combustion engines as prime movers of a CHP system to develop operational strategy plans, where the criterion for making decision was the net annual cost. Boljevic and Conlon (Boljevic and Conlon, 2011) introduced a multiple linear regression model to determine optimal placement and sizing of a CHP system connected to a 15-bus distribution network. Wang et al. (Wang et al., 2011) introduced a model to optimize a CHP system, where the influence of the technical, economic, and environmental parameters on the result of optimization problem are analyzed and compared numerically.

1.1. Contributions

The review of available literature indicates that nearly all techno-economic studies on CHP and CCHP systems are developed and formulated to determine optimal size, configuration, and operation from the view point of energy consumer, as system owner. However, with the increasing utilization of CHP and CCHP systems, it is of interest to determine the benefits to be realized by distribution utilities and energy consumers, simultaneously, by means of optimal energy pricing, where parallel operation with the grid is accessible.

The goal of this study is to determine the optimal hourly energy prices for both electricity and NG for a non-autonomous CCHP system using particle swarm optimization (PSO) algorithm based on bi-level programming (BLP) approach. Based on optimal sizing and configuration of a CCHP system, the rewards for both the distribution utility and the industrial energy consumer, as the CCHP system owner, are analyzed. To examine the inter-dependencies of energy prices, in this study, an approach is presented to determine optimal hourly electricity and NG prices for a typical 24 h in each season of a year for a CCHP system that operates in parallel with the grid in Ontario, Canada. It is noted that the implication of non-autonomous operation is selling electricity to distribution utility, when the economics of such operation is justified.

Further, as cooling load usually coexists with heating and electric power needs, this study is focused on determination of optimal energy prices for a CCHP system and CHP system is not considered.

The organization of this study is as follows. Section 2 describes the CCHP system and the incentive policies are explained in Section 3. Section 4 formulates the BLP approach. The PSO algorithm used for optimization is explained in Section 5 and, the simulation parametric values are presented in Section 6. The simulation results are presented in Section 7. Finally, in Section 8, conclusions and recommendations for future work are given.

2. System description

The CCHP system in this study operates in parallel with electric utility distribution network and consists of prime mover, auxiliary boiler, and absorption chiller, as shown in Fig. 1. The prime mover utilizes NG to produce electricity and the resulting thermal energy is recovered by heat recovery steam generator for heating as well as cooling by absorption chiller which is intended to reduce peak electricity load. If the remaining recovered thermal energy is less than that needed for heating, an auxiliary boiler that operates with NG is used (Tichi et al., 2010). The CCHP system is to be used in an industrial energy consumer with known loads, as discussed later. If the power produced is more than the electricity load, the excess is sold to distribution utility, otherwise, the unmet electricity is purchased from distribution utility.

For the purposes of comparison, a conventional separate heat and power (SHP) system is considered for which the needed electricity is purchased from distribution utility including that required by a compression chiller, as an integrated component of SHP system. In the SHP system, a boiler that operates with NG is used to produce required thermal energy to supply heating load.

3. Incentive policies

Over the years, various incentive policies have been introduced to promote development of CHP and CCHP systems. Aside from tax exemption for fuels (COGEN Europe, 2001), various strategies have been implemented for increasing the use of CHP and CCHP system worldwide as discussed by Wu and Wang (2006) (Xiaoyi, 2007), namely, allowing the private power producer to sell electricity to utility, obligation for decreasing environmental pollutants, tax reduction on the use of NG for industrial CCHP systems, carbon tax exemption for CCHP systems, low interest loan, and investment subsidies.

While many countries have begun to encourage utilization of CCHP and CHP systems in their energy markets, the critical factors in development of CCHP system have been determined as energy prices for electricity and fuels (Wu and Wang, 2006).

In this study, the distribution utility is considered as the sole owner and operator of distribution network, where it supplies the required electricity and NG purchased from the wholesale market. It is also assumed that the distribution utility can purchase electricity from energy consumer as CCHP system owner. The electricity is sold by CCHP system based on the price offered by CCHP owner. It is noted that when electricity is supplied by CCHP system, the distribution utility purchases less electricity from wholesale market.

As mentioned earlier, the optimal hourly purchased electricity price from CCHP system and the optimal hourly NG price must be determined such that rewards for the distribution utility and the CCHP owner are guaranteed. Thus, to analyze the economic feasibility of CCHP system, in addition to determination of the optimal energy prices for electricity and NG, the optimal size, configuration, and operation of CCHP system must be determined.

In this study, the distribution utility receives an hourly price for electricity offered by the CCHP owner. Then, the optimal size, operation, and configuration of CCHP system are determined based on maximization of the distribution utility income and minimization of the power loss of distribution network. Therefore, the distribution utility determines the amount of electricity purchased from CCHP system and the CCHP owner must find the optimal prices that minimize its annual costs. If the CCHP owner offers a high price, the distribution utility will not purchase electricity from CCHP system, and conversely, if the CCHP owner offers too low of a price, its annual costs are not minimized (Lopez-Lezama et al.,