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Future distributed generation: An operational multi-objective optimization model for integrated small scale urban electrical, thermal and gas grids

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ABSTRACT

A multi-objective optimization model for urban integrated electrical, thermal and gas grids is presented. The main system consists of a retrofitted natural gas pressure regulation station where a turbo-expander allows to recover energy from the process. Here, the natural gas must be preheated in order to avoid methane hydrates. The preheating phase could be based on fossil fuels, renewable or on a thermal mix. Depending on the system configuration, the proposed optimization model enables a proper differentiation based on how the natural gas preheating process is expected to be accomplished. This differentiation is addressed by weighting the electricity produced by the turbo-expander and linking it to proper remuneration tariffs. The effectiveness of the model has been tested on an existing plant located in the city of Genoa. Here, the thermal energy is provided by means of two redundant gas-fired boilers and a cogeneration unit. Furthermore, the whole system is thermally integrated with a district heating network. Numerical simulation results, obtained with the commercial proprietary software Honeywell UniSim Design Suite, have been compared with the optimal solutions achieved. The effectiveness of the model, in terms of economic and environmental performances, is finally quantified. For specific conditions, the model allows achieving an operational costs reduction of about 17% with the respect to thermal-load-tracking control logic.

1. Introduction

The whole Natural Gas (NG) supply chain is composed by different subparts: compressor stations, transportation, storage, Pressure Regulation Stations (PRSs) and distribution. The role of PRSs is to guarantee a certain NG pressure drop between transmission and distribution nodes. Here the NG arrives at a pressure level, which usually ranges between 70 and 20 bars depending on the user location. Commonly, the NG pressure regulation is achieved by means of throttling valves. However, it is possible to upgrade this process enabling energy recovery by implementing Turbo Expander (TE) technology. In this case, the NG preheating process, which is fundamental to avoid methane hydrates [1,2], will require higher thermal energy due to the extraction of work from the thermodynamic transformation.

Considering the increasing NG demand forecasted by the International Energy Agency [3] and other studies [4,5], Waste Energy Recovery (WER) from NG distribution infrastructure seems to offer great opportunities. In fact, Tavakkoli estimated a WER potential of about 610 T J/day in the U.S. territory in [6]. Neseli et al. proposed a WER case study for a site located in Turkey in [7]. Here, an annual average energy recovery of about 6.3 GW h has been estimated. Kostowski et al. conducted a thermo-economic assessment of a PRS integrated with a cogeneration unit in [8]. Daneshi discussed the issue of implementing TE as distributed generation technology in [9]. Poživil made a simple analysis for a TE application in [10]. However, referring to this study, it is worth pointing out that the electricity produced should not be considered as "green" i.e. absolutely free of carbon emissions. Indeed, there is still a certain quantity of CO_2 embedded in the electricity produced by the TE since the NG has been (in most cases) compressed by using non-renewable resources. Moreover, in the majority of cases, the NG pre-heating process is accomplished by using conventional gas fired boilers and/or Combined Heat and Power (CHP) systems. This means that higher carbon emission would be associated with the WER process. Mansor and Mansor aim to incentivize TE installation for electricity production in Bangladesh in [11]. Kostowski et al. define a thermodynamic and economic analysis of TE application

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Nomenclature

$b(t)$ national incentive value [€/tep]
$C_{b,i}(i,t)$ thermal unit i, operational cost [€/h] at time t ∈ T
$C_{chp,j}(j,t)$ cogeneration unit j, operational cost [€/h] at time t ∈ T
$C^{el}_{grid}(t)$ electrical grid, operational cost [€/h] at time t ∈ T
$C^{th}_{grid}(t)$ thermal grid, operational cost [€/h] at time t ∈ T
$C_{incentive,j}(j,t)$ incentive value [€/h] at time t ∈ T
$C_{te,k}(k,t)$ energy recovery unit k, operational cost [€/h] at time t ∈ T
$C_{vlv,s}(s,t)$ expansion valve s, operational cost [€/h] at time t ∈ T
$E_{chp}(j,t)$ cogeneration unit j, active power in cogeneration asset [MW] at time t ∈ T
$E_{npn_{chp}}(j,t)$ cogeneration unit j, active power in non-cogeneration asset [MW] at time t ∈ T
$e_{b,i}(i,t)$ thermal unit j, environmental carbon emissions [kg/h] at time t ∈ T
$e_{chp,j}(j,t)$ cogeneration unit j, environmental carbon emissions [kg/h] at time t ∈ T
$e_{te,k}(k,t)$ energy recovery unit k, environmental carbon emissions [kg/h] at time t ∈ T
$e_{vlv,s}(s,t)$ expansion valve s, environmental carbon emissions [kg/h] at time t ∈ T
$e^{el}_{grid}(t)$ national electrical grid, environmental carbon emissions [kg/h] at time t ∈ T
$e^{th}_{grid}(t)$ thermal grid, environmental carbon emissions [kg/h] at time t ∈ T
$F_{chp}(j,t)$ cogeneration unit j, fuel consumption in cogeneration asset [MW] at time t ∈ T
$F_{non_{chp}}(j,t)$ cogeneration unit j, fuel consumption in non-cogeneration asset [MW] at time t ∈ T
$H_{chp}(j,t)$ cogeneration unit j, thermal power in cogeneration asset [MW] at time t ∈ T
$H_{non_{chp}}(j,t)$ cogeneration unit j, thermal power in non-cogeneration asset [MW] at time t ∈ T
i generic thermal unit
j generic cogeneration unit
k generic turbo expander
K correction factor
LHV lower heating value [MW/kg]
$\dot{m}_{fuel}(j,t)$ cogeneration unit j, total fuel mass flow [kg/h] at time t ∈ T
$N_{te}(k,t)$ energy recovery unit k, delivered NG [kW] at time t ∈ T
$N^{min}_{te,k}$ technical deliverable NG minimum of unit k [kW]
$N^{max}_{t,ke}$ technical deliverable NG maximum of unit k [kW]
$N_{vlv}(s,t)$ expansion valve s, delivered NG [kW h] at time t ∈ T
$N^{min}_{vlv,s}$ technical deliverable NG minimum of unit s [kW]
$N^{max}_{vlv,s}$ technical deliverable NG maximum of unit s [kW]
PES primary energy saving index
PES(t) Primary energy saving index at time t ∈ T
$P_{chp}(j,t)$ cogeneration unit j, power [kW] at time t ∈ T
$P_{te}(k,t)$ energy recovery unit k, power [kW] at time t ∈ T
$P^{min}_{te,k}$ technical power minimum of unit k [kW]
$P^{max}_{te,k}$ technical power maximum of unit k [kW]
$P_{withdrawal}(t)$ power withdrawal [kW]
$Q_b(i,t)$ thermal unit i, thermal power [€/h] at time t ∈ T
$Q^{min}_{b,i}$ technical thermal power minimum of thermal unit i [kW]
$Q^{max}_{b,i}$ technical thermal power maximum of thermal unit i [kW]
$Q_{chp}(j,t)$ cogeneration unit j, thermal power [kW] at time t ∈ T
$Q^{preheating}_{te}(k,t)$ energy recovery unit k, pre-heating thermal power at time t ∈ T
$Q^{preheating}_{vlv}(s,t)$ expansion valve s, pre-heating thermal power at time t ∈ T
RISP(t) energy saving [MW] at time t ∈ T
s generic throttling valve
T set of time intervals considered in the daily period
t single time interval length
WC number of incentives accumulated [tep]
$w_j(t)$ cogenerated electricity tariff at time t ∈ T
$w_k(t)$ recovered electricity tariff at time t ∈ T
$w_{k1}(t)$ recovered electricity tariff (fully renewable) [€/kW h] at time t ∈ T
$w_{k2}(t)$ recovered electricity tariff (fully fossil fuel) [€/kW h] at time t ∈ T
$w_r(t)$ conventional thermal power tariff [€/kW h] at time t ∈ T
$w_t(t)$ cogenerated thermal power tariff [€/kW h] at time t ∈ T
$w(t)$ national electricity cost factor [€/kW h] at time t ∈ T

Greekletters
$\varepsilon_{HE,s}$ expansion valve s, heat exchanger effectiveness
$\varepsilon_{HE,k}$ energy recovery unit k, heat exchanger effectiveness
$\eta_{el,rif}$ average electrical national grid efficiency
$\eta_{th,rif}$ average thermal national grid efficiency
ρ_k NG/ power correlation factor unit k
$\sigma^{el}_{grid,j}$ cogeneration unit j, electrical weight
$\sigma^{el}_{grid,k}$ recovery unit k, electrical weight
$\sigma^{th}_{grid,j}$ cogeneration unit j, thermal weight
$\sigma^{th}_{grid,i}$ thermal unit i, thermal weight
$\sigma^{th}_{grid,n}$ thermal unit n, thermal weight
σ energy policer decision weight

Abbreviations
CHP combined heat and power
DHN district heating network
NG natural gas
TE turbo expander
WER waste energy recovery

providing an interesting case study in [12]. Sung et al. provided a thermodynamic analysis of a PRS where the thermal production is provided by means of a heat pump [13]. A pilot project, undertaken in Romania, has been presented by Andrei et al. in [14]. Finally, Borelli et al. present a case study of TE application in [15]. The successful project undertaken, incentivized by the EU, will serve as a reference for further applications and replications. PRSs are normally located in industrial areas or city gates. For this reason, PRSs thermal integration potential is an important aspect to be considered during retrofits interventions. Energy systems integration plays an important role in distributed generation efficiency. An example of system integration is provided by Borelli et al. in [16]. Here, authors used a numerical dynamic model to study the transients of the integrated system made of a CHP unit coupled to a district heating network (DHN).

Some visions of potential future energy systems have been provided by Manfren et al. in [17]. As clearly stated by the authors, there are some key elements that future energy systems will have. More precisely, they should be integrated, interactive, optimized, resilient, adaptive and predictive in order to minimize Green House Gas (GHG) emissions and operational costs. WER and thermal integration opportunities for PRSs lead to the concept of