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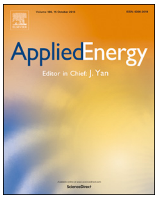

Flexible energy harvesting from natural gas distribution networks through line-bagging

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HIGHLIGHTS

- A novel method enabling flexible energy harvesting from natural gas distribution networks.
- Load shifting becomes possible without employing electrical storage.
- Gas bagging enables overnight charging of electric vehicles.
- Hazardous operations are avoided by employing model predictive control.
- A daily operational cost reduction of about 10% is achieved.

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ABSTRACT

In a swirling dynamic interaction, technological changes, environment and anthropological evolution are swiftly shaping the smart grid scenario. Integration is the key word in this emergent picture characterized by a low carbon footprint. Between the wide range of key actions currently pursued by European municipalities, the possibility of harvesting energy from natural gas distribution is being established in this context. Load matching is crucial for local energy exploitation and integration of renewable resources. In this paper, the authors introduce a novel management method to increase the flexibility of the energy harvesting process from gas distribution networks. This method, called gas bagging, enables one to shift energy production schedules by properly manipulating the downstream pressure of the pipeline system. The emerging system dynamics in gas bagging must be managed using a proper system control architecture. This is fundamental to avoid system-safety-constraint violations. From a relevant case scenario, the authors demonstrate that the energy load can be totally shifted to night hours without violating system-safety constraints. For this purpose, the implementation of model predictive control has revealed to be a strategic measure. In fact, this ensures safe and cost-effective operations enabling up to a 10% daily operational cost reduction. Results reveal gas bagging to be a strategic tool for energy production flexibility and carbon emission reduction using natural gas distribution networks integrated into a smart grid.

Nomenclature

D	pipeline, diameter (m)
$C_{\min}$	heat exchanger, minimum fluid heat capacity (J/kg K)
C_{steel}	boiler, stainless steel specific heat capacity (J/kg K)
C_{w}	boiler, water specific heat capacity (J/kg K)
$\mathrm{C_r}$	heat exchanger, heat capacity ratio
D_{Plug}	Joule-Thomson valve, plug diameter (m)
K_{G}	Joule-Thomson valve, flow coefficient (kg/s Pa)
c_{p}	hydraulic circuit, water specific heat capacity (J/kg K)
k	turbo-expander, natural gas heat specific ratio
L	pipeline, length (km)
$\dot{L}_{\mathrm{s}}$	hydraulic circuit, gas preheating thermal load (W)
m	hydraulic circuit, water mass (kg)
$\dot{m}_{\mathrm{in}}$	users, natural gas inlet mass flow rate (kg/s)
$\dot{m}_i$	header, *i*-th water stream mass flow rate (kg/s)
$\dot{m}_{\mathrm{out}}$	users, natural gas outlet mass flow rate (kg/s)
$\dot{m}_{\mathrm{w}}$	boiler, water mass flow rate (kg/s)

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$\dot{m}_{TE}$	turbo-expander, natural gas flow rate (kg/s)
$\dot{m}_{tot}$	user, natural gas total demand (kg/s)
M_{steel}	boiler, steel mass (kg)
M_{w}	boiler, water mass (kg)
P_{in}	Joule-Thomson valve, natural gas inlet pressure (Pa)
P_{out}	Joule-Thomson valve, natural gas outlet pressure (Pa)
P^{*}	Joule-Thomson valve, natural gas pressure at reference conditions (Pa)
P_{i}	pipeline, inlet pressure (Pa)
P_{o}	pipeline, outlet pressure (Pa)
$P_{out,TE}$	turbo-expander, outlet pressure (Pa)
q	Joule-Thomson valve, natural gas flow rate (kg/s)
$\dot{Q}_{b}$	boiler, thermal power output (W)
$\dot{Q}$	heat exchanger, power exchanged (W)
$\dot{Q}_{aux}$	hydraulic circuit, auxiliary heat gain (W)
R	gas constant (J/kg K)
s	Joule-Thomson valve, plug area (m^2)
T_{a}	hydraulic circuit, ambient temperature (K)
$T_{c,i}$	heat exchanger, cold fluid inlet temperature (K)
T_{del}	natural gas, delivery temperature at station level (K)
$T_{h,i}$	heat exchanger, hot fluid inlet temperature (K)
T_{in}	boiler, water inlet temperature (K)
T_{out}	boiler, water outlet temperature (K)
T_{out}^{header}	header, water outlet temperature (K)
$T_{out,TE}$	turbo-expander, natural gas outlet temperature (K)
T_{i}	header, *i*-th water stream temperature (K)
$T_{i,p}$	pipeline, average downstream temperature (K)
$T_{in,TE}$	turbo-expander, natural gas inlet temperature (K)
T_{s}	hydraulic-circuit water temperature (K)
T^{*}	Joule-Thomson valve, natural gas temperature at reference conditions (K)
T_{1}	Joule-Thomson valve, natural gas reference inlet temperature (K)
y	Joule-Thomson valve, actuator position (m)
W_{TE}	turbo-expander, mechanical power output (W)
V_{p}	pipeline, total volume (m^3)
$\dot{V}_{in}$	natural gas volumetric flow rate (m^3/h)

Greek letters

ΔT_{HE}	pre-heating heat exchanger (HE1), temperature difference (K)
ε	heat exchanger, effectiveness
κ	time instant
ρ^{*}	Joule-Thomson valve, natural gas density at reference conditions (kg/m^3)
η_{b}	boiler thermal efficiency
τ	time (s)
ρ	natural gas relative density (kg/m^3)
ζ	scaling factor

Abbreviations

BO	boiler
HE	heat exchanger
HP	high pressure
LP	low pressure
LPR	low pressure regulator
MP	medium pressure
MPC	model predictive control
NG	natural gas
TE	turbo-expander
VIGV	variable inlet guide vanes
NTU	number of transfer units
P	pump
PID	proportional, derivative, integral

1. Introduction

In the world's transition to a sustainable energy scenario, natural gas will keep playing a key role for residential and commercial sectors for most countries [1]. This issue has also been highlighted by Dieckhöner et al. in [2]. After being gathered and processed, the main phases for natural gas are transportation, storage, and distribution. Normally, the natural gas pressure is raised to 70 bars by means of compressor stations for a proper transportation through the transnational and national pipelines until the distribution nodes. At this stage, so-called pressure reduction stations are responsible for metering and reducing the gas pressure to the desired set-point for distribution purposes. Here, the natural gas pressure drop is normally induced by employing Joule-Thomson valves, thus, dissipating the gas energy. To prevent methane hydrates from being formed [3], the natural gas is normally preheated to temperatures that range between 40 °C and 60 °C depending on system operating conditions and the natural gas composition. In order to obtain a more sustainable process, a smart technological solution consists of the use of a turbo-expander (TE) instead of the Joule-Thomson valves, where the aim of the TE is to harvest energy from the gas pressure drop. In fact, Kostowski et al. analyzed the possibility of generating energy with a TE in [4] showing the engineering feasibility of such technology. Alparslan et al. presented an energy and exergy analysis of a pressure reduction station equipped with a TE in [5]. Furthermore, Borelli et al. presented a case study where a pressure reduction station is effectively integrated with other processes and users within the same district [6]. The performance analysis of the TE technology was conducted also in [7,8] where, in both cases, the energy sustainability of TE technology was demonstrated. In this case, for a given gas flow rate, the thermal energy required to prevent methane-hydrate formation would be up to 5 times higher than for the Joule-Thomson valve [9] because of the work extraction. This issue has stimulated researchers to seek for smart possibilities to reduce the carbon emissions linked to the energy-harvesting process. In fact, Kostowski et al. analyze the economic feasibility of cogeneration units in [10]. According to this study, the use of cogeneration units represents a good advantage compared with the use of boilers but low temperature heat sources might be required for gas pre-heating. In [11] an investigation of the performance of a hybrid turboexpander-fuel-cell system for power recovery at natural gas pressure reduction stations was presented. This is an interesting configuration but, economically speaking, the required initial investment might lead to a non-sustainable retrofit intervention. Other system configurations have been presented, such as in [12], where a comparative study between a pressure reduction station integrated with an internal combustion engine and an organic Rankine cycle was presented. In [13] a pressure reduction station integrated with a cogeneration system has been presented. Here, a new sizing optimization method was based on economic and thermal analysis as well. Similarly, in [14] the authors presented a novel optimization model for the optimal retrofitting of natural gas pressure reduction stations. According to this research, the use of cogeneration units tends to be economically not justifiable when the design and thus, the investment cost, is not properly defined. For this purpose, in [15], the technical criterion for economic justification of the use of cogeneration units in natural gas pressure reduction stations was presented. The authors demonstrated how only one of the eight case studies presented was suitable for cogeneration ensuring a payback period of less than eight years (which is a reasonable time length for an industrial project). Furthermore, with reference to the possibility reducing of fuel consumption for natural gas preheating by integration with renewable