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Integrated management of cogeneration plants and district heating networks ☆

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ABSTRACT

Combined Heat and Power based District Heating Networks (CHP/DHN) systems represent nowadays one of the most efficient technologies, as an alternative to standard space heating solutions, leading to lower GHG emission in atmosphere. Dynamic modelling of district heating networks is of considerable importance in order to investigate suitable control strategies aimed to optimize the heat production and to manage the system transients following changes in the required heat. Through the analogous electrical systems modelling approach, a component software library has been developed for icon-based dynamic simulation of district heating networks, implementing the mathematical models in Matlab/Simulink environment. The calculation procedure that translates into practice the approach described above, complies with a main flow chart designed to allow for the simulation of the system operation in a quicker-than-real time, throughout the controlled time interval, while imposing the assumed duty and site conditions. The procedure's main body, as well as being utilized to assess the feasibility and to carry out the conceptual design, once the plant has started up, can be employed as a guide to the operator. Research activity has been focused on the development and integration of a code for dynamic simulation of heat distribution networks with a code for thermo-economics optimization of CHP systems, increasing the possibility of optimizing the matching between CHP plant and thermal users, through the exploitation of thermal storage capacity of the networks. A CHP-based district heating project in Northern Italy was considered as a test case. Results show that integrated management of cogeneration plants and district heating networks allows for the achievement of significant advantages both in terms of economic competitiveness and energy saving: in particular it has been highlighted that only through the support of an intelligent management system it is possible to maximize the potential benefits offered by the exploitation of district heating networks dynamic heat storage capacity.

1. Introduction

The combined production of heat and electrical energy allows for significant fuel savings, as the needed fuel is less than it would be necessary in case of separated generation of the same quantities of thermal and electrical energy [1–5]. Owing to modular configuration and "load following" operating condition, the feasibility study of cogeneration based district heating systems involves a highly complex constrained multi-variable optimization problem [6–12].

Given the large costs of installation (for cogeneration plant and network) and the tight energy saving constraints at which these plants are subjected, an incorrect predictive analysis can result in investment unsustainability either in economic or environmental terms [13–15].

For feasibility study purpose it is therefore deemed necessary to adopt an approach method based on a dynamic simulation, which takes into account the variability of the characteristic parameters of the system, aimed at finding the best performance obtainable from the matching between CHP and users, considering also the characteristics of interposed network.

In the past several methods of analysis of modular CHP plants based on the use of optimizers were introduced, showing the benefits obtained through the intelligent management of CHP/DHN systems, especially for small size plants [16–20].

This paper is presenting a typology of analysis, extended to large size CHP/DHN systems, integrating those methods with a simulation tool that allows a dynamic characterization of the heat distribution networks, highlighting in particular the advantages gained by using the networks as heat buffer. On the basis of above considerations a set of two combined calculation tools has been developed which, given a limited number of essential elements relevant to loads and networks inertias, allows to simulate typical

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Nomenclature

CHP	combined heat and power
COSPP	cogeneration and on site power production
DHN	district heating network
GHG	greenhouse gas
DHS	dynamic heat storage
i	initial hot pipe section node
$i+1$	intermediate hot pipe section node
$i+2$	final hot pipe section node
j	initial cold pipe section node
$j+1$	intermediate cold pipe section node
$j+2$	final cold pipe section node
p_i	pressure at pipe node i
p_{i+1}	pressure at pipe node $i+1$
p_{i+2}	pressure at pipe node $i+2$
p_{Li+1_i+2}	pressure at pipe node between resistance R_{i_i+1} and inductance L_{i_i+1}
F_{i_i+1}	flowrate from pipe node i to pipe node $i+1$
R_{HEi+1_j+1}	fluid resistance of heat exchanger between pipe node $i+1$ and pipe node $j+1$
R_{i_i+1}	fluid resistance of pipe segment i_i+1
L_{i_i+1}	fluid inductance of pipe segment i_i+1
C_{i_i+1}	fluid capacitance of pipe segment i_i+1
F_{i+1_i+2}	flowrate from pipe node $i+1$ to pipe node $i+2$
R_{i+1_i+2}	fluid resistance of pipe segment $i+1\_i+2$
L_{i+1_i+2}	fluid inductance of pipe segment $i+1\_i+2$
C_{i+1_i+2}	fluid capacitance of pipe segment $i+1\_i+2$
C_{i_i+1}	fluid capacitance of pipe segment i_i+1
F_{j_j+1}	flowrate from pipe node j to pipe node $j+1$
R_{j_j+1}	fluid resistance of pipe segment j_j+1
L_{j_j+1}	fluid inductance of pipe segment j_j+1
F_{Ci_i+1}	flowrate upstream of capacitance of pipe segment i_i+1
C_{j_j+1}	fluid capacitance of pipe segment j_j+1
F_{j+1_j+2}	flowrate from pipe node j + 1 to pipe node $j+2$
R_{j+1_j+2}	fluid resistance of pipe segment $j+1\_j+2$
L_{j+1_j+2}	fluid inductance of pipe segment $j+1\_j+2$
C_{j+1_j+2}	fluid capacitance of pipe segment $j+1\_j+2$
F_{Cj+1_j+2}	flowrate upstream of capacitance of pipe segment $j+1\_j+2$
F_{Cj_j+1}	flowrate downstream of capacitance of pipe segment j_j+1
F_{Ci+1_i+2}	flowrate downstream of capacitance of pipe segment $i+1\_i+2$
F_{i+2_i+3}	flowrate from pipe node $i+2$ to pipe node $i+3$
Δp_{Ri_i+1}	head losses in segment i_i+1 (expressed in pressure units)
Δp_{Ri+1_i+2}	head losses in segment $i+1\_i+2$ (expressed in pressure units)
Δp_{Li_i+1}	differential pressure across the fluid inductance of pipe segment i_i+1
Δp_{Li+1_i+2}	differential pressure across the fluid inductance of pipe segment $i+1\_i+2$
s	laplace operator
P_{i+1}, P_{j-1}	implicit calculation block output pressures
P_{i-1}, P_{j+1}	implicit calculation block input pressures
M^+_{i-1}, M^+_{j+1}	implicit calculation block output flowrates
M^+_{i+1}, M^+_{j-1}	implicit calculation block input flowrates
NPV	net present value (€)
IRR	internal rate of return
FESR	fuel energy saving ratio with respect to a non cogenerative case
ΔF	fuel saving with respect to a non cogenerative case (m^3/year)
ΔCO_2	carbon dioxide saving with respect to a non cogenerative case (kton/year)
T	temperature (°C)

dynamics of both CHP (working point vs. ambient and load conditions, electrical energy fares, fuel contracts, etc.) and heat distribution network (load penetration, heat distribution efficiency, heat storage capacity, inertias, etc.). The set of codes can therefore be a useful tool to perform a simulation engineering suitable to orient the selection of design parameters towards the optimized management of the CHP/DHN system.

2. Dynamic analysis method for CHP/DHN systems

As clarified in previous works [6,16,21,22], the adoption of CHP modular units featuring excellent rated nameplate performances is not sufficient to guarantee similar performances to the complete CHP/DHN system, since, due to the thermal load following operation, the prevailing effect is represented by the matching between CHP, relevant heat distribution network and final users.

Therefore the presently proposed method of dynamic analysis applied to CHP/DHN plants is based on the integrated management of two software developed and tuned to create a tool aimed to an accurate dynamic characterization of the system (CHP–networks–users) in order to get the best performance from the plant, as a result of optimized management of the cogeneration units following a given load curve required by the thermal island, thus linking the performance of the system to the energetic-economic context in which it is inserted.

In order to develop an analysis able to provide reliable results it is considered necessary to take into account the complex dynamics of many parameters characterizing the CHP/DHN system regarding the heat production and distribution plant, the demand for heat and power from users connected to the system and the trend of economic and financial scenario during the lifetime of the plant. In particular, with reference to heat and power production plant, one cannot neglect the way in which machine performance (efficiency, heat vs. work ratio) are affected by operating point and ambient temperature variations.

In view of what above the simulation tool shall be provided with the working map of each machine that will be used to correctly determine its time variant performance.

Considering the heat distribution system represented by the piping network carrying the hot fluid, it is necessary to evaluate dynamic parameters such as time delays, control logic and heat storage capacity (especially in the case of a large size network, it will be shown in the following how the network itself can be exploited as thermal storage, allowing to add a degree of freedom to the system by decoupling energy production and demand and achieving an even higher level of opimized management) [23–25].

Moreover it is of fundamental importance for a dynamic analysis to take into account the variations of the energy delivery efficiency of the network when varying the amount of transported heat [26,27]. This efficiency is a function of the thermal losses (which have to be dynamically evaluated through the network modelling) and of energy fed to the piping system and delivered to users [28].

Variations of network energy efficiency are strongly linked to the penetration curve of the system in the thermal basin, highlighting one of the most penalizing factors in development of district heating plant which, in the first realization phases, are forced to