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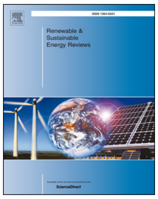

Probabilistic energy flow for multi-carrier energy systems

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ABSTRACT

This paper investigates energy flow of Multi-Carrier Energy Systems using Point Estimate Method and Monte Carlo simulation considering uncertainties, which may happen in the Electrical, Natural Gas, and District Heating Networks all together. These uncertainties could occur from the probabilistic behavior of loads or unforeseen faults. An innovative probabilistic energy flow of Multi-Carrier Energy Systems based on Point Estimate Method has been presented in this paper. Results for two different case studies are investigated and compared against those achieved from the Monte Carlo simulation. The results prove that the presented point estimate schemes have precise results, smaller computational burden, and time, comparing than Monte Carlo simulation method.

1. Introduction

Nowadays, by increasing the importance of utilization of cogeneration plants, which makes a strong coupling between the network industries such as Electrical, Natural Gas, and District Heating Networks (DHNs), the uncertainties in energy system, such as load variation, and faults of lines have been in great attention [1]. Therefore, the use of techniques able to account for uncertainty are requested to control and minimize the risks related to design and operation [2]. In this way, probabilistic methods are more appropriate for this purpose.

Several techniques such as Monte Carlo Simulation (MCS) method, analytical methods, and approximate methods have been studied to overcome problems under uncertainty [3,4].

MCS generates random values for uncertain input variables, and these values are applied to simulate a deterministic problem in each simulation [5]. This technique has been widely utilized in electrical network analysis to model uncertainty. The main drawback of the MCS is the excessive number of computation required to achieve convergence [6]. Thus to decrease the computational burden in solving Probabilistic Load-Flow (PLF) problem, several analytical approaches and approximate methods were suggested to simulate the load-flow solution distributions [7].

Analytical methods are computationally adequate, but they need some mathematical assumptions in order to simplify the problem. These techniques usually simplify the traditional PLF formulations and calculate the convolution of different probabilistic variables through their linear relationships [8]. Besides, the convolution techniques achieve a mathematical description of the behavior of output random variables (RVs).

Approximate methods such as Point Estimate Method (PEM) use deterministic process in order to simulate probabilistic problems by applying only some statistical moments of probability functions such as mean, variance, skewness, and kurtosis coefficients [9]. Hence, PEM overcomes the difficulties associated without perfect knowledge of the probability functions of stochastic variables [10]. The PEM in this approach is somehow better than MCS method because it has the less computational burden and consumed time since a smaller volume of data is requested [11,12].

This paper presented the point estimate method to solve the probabilistic energy flow of Multi-carrier Energy Systems (MES).

Various energy carriers such as electrical, natural gas, and DHN could be considered in an energy network. Electrical grids are the most favorite energy carriers employed in many countries [13]. Usually, an electrical grid is made up of electrical generation plants, which generate electric power by consuming suitable fuel such as gas, oil, and coal. Electrical loads are supplied by the generated electric power through transmission lines [14,15].

Natural gas is getting one of the most employed sources of energy in the world since the significance of its offer, market potential, adjustability, and smaller environmental issues in comparison to other effective fossil sources [16].

Natural gas supplies many commercial and residential consumers over the world by means of a vast and complex grid. A typical natural gas network is made up of one or more gas resources, numerous loads, pipelines, compressors, and other elements such as valves or regulators [17].

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Nomenclature

Subscript

E	electric
G	natural gas
H	heat
S	supply pipeline
r	return pipeline
g	ground

Superscript

hub	energy hub
gen	electric generator
chp	combined heat and power plant
boil	boiler
gs	natural gas source
shc	shunt capacitance
dem	demand
comp	compressor
pump	circulating pump
fuel	fuel
line	transmission line/pipeline
bus	electrical/gas/heat bus
min	minimum limit of a variable
max	maximum limit of a variable

Variables/parameters of the MES model

P	electric/gas/heat power (MW)
Q	reactive power (MVar)
S	apparent power (MVA)
f	natural gas flow (m^3/day)
$\dot{m}$	mass flow rate of water (kg/s)
V	voltage magnitude (p.u.)
θ	voltage angle (o)
π	natural gas pressure (bar)
T	temperature ($^\circ C$)
G	conductance of transmission lines (s)
B	susceptance of transmission lines or shunt capacitances (s)
TR	tap ratio of tap-transformers
H	compression ratio of compressors
C	constant of natural gas pipelines
D	diameter of natural gas pipelines (m)
L	total length of gas/heat pipelines (m)
τ	pump head of the district heating network(m)
η	efficiency of units
N	total number of units
a, b, c, d, e	heat rate coefficients of generators/characteristic coefficients of CHPs and boilers

Variables/parameters of the Point Estimate Method

$P_{l,k}$	Kth value of random variable P_l
$\omega_{l,k}$	weighting factor
μ	mean value
σ	standard deviation
ζ	standard location
k	total number of random variables
$Z(l, k)$	output random variables
$M_j(p_l)$	jth central moment of the random variable P_l
f_{pl}	PDF of random variable P_l
$\lambda_{l,j}$	coefficient of skewness
m	number of input random variables
ε^{RV}	error index of the random variable
ε_{MCS}	relative error of Monte Carlo method

Constants

ε	absolute rugosity of natural gas pipelines (0.05 mm)
z	natural gas compressibility factor ($z = 0.8$)
δ	density of natural gas relative to air ($\delta = 0.6106$)
c	specific heat capacity of water ($c_p = 4182$ J/kg K)
ρ	heat transition coefficient ($U = 0.455$ W/m K)
ψ, ξ	constants of compressors ($\psi = 0.167$ for turbo-compressor, $\psi = 0.157$ for a moto-compressor, and $\xi = 0.236$ for both types)
g	standard gravity constant ($g = 9.81$ m/s^2)

The International Energy Agency (IEA) declared that due to all energy consumption, heating, cooling estimated for about 46% of the entire global energy consumes in 2012, and about half of end use of energy in Europe is heat [18]. For that reason, DHNs have considerable ability in satisfying consumer's necessity. In addition, by using such a network, the environmental issues such as carbon dioxide emissions have been decreased sufficiently [19]. The effort of a DHN is to yield the consumers demand heat for its loads by applying sufficient heat production plants and a network of pipelines to transfer this produced heat power to the consumers. Hence, Shabanpour utilized a proper set of state-variables to optimize energy flow of electricity, natural gas, and DHN simultaneously [20]. Combined Heat and Power (CHP) plant is playing an indispensable role in producing the district heat by consuming natural gas. Thus, the entire fuel consumption can be diminished sufficiently.

Shabanpour proposed the modified teaching-learning based optimization method, which analyzed energy flow optimization in MES. The presented method, unlike conventional techniques, did not use any extra variable such as dispatch factors or dummy variables [21].

Geidl presented a general optimization technique, which studied energy flow optimization in multi-carrier energy systems [22]. He considered the possibility of conversion between electricity, natural gas, and DHN.

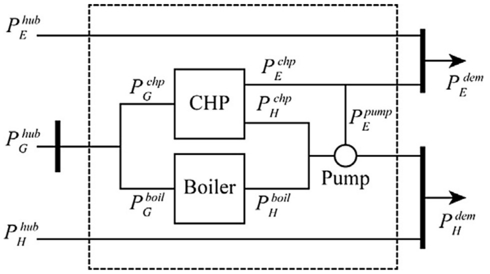

Fig. 1. An example for an energy hub.

Shabanpour presented the new approach based on teaching-learning algorithm, which analyzed multi-objective optimal energy flow problem taking into account the total fuel cost and total emission of the MES [23]. The proposed algorithm applies a self-adapting wavelet mutation technique. In addition, a fuzzy clustering approach is presented to reduce repository size besides a smart population selection for the next iteration.

Mohammadi presented a new point estimate scheme to solve the probabilistic power flow of electrical networks while he considered load variation and faults of lines [24].

Morales presented point estimate method to solve the probabilistic