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Optimal planning of Molten Carbonate Fuel Cell Power Plants at distribution networks considering Combined Heat, Power and Hydrogen production

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HIGHLIGHTS

- Propose a stochastic model for planning the location and operation of Molten Carbonate Fuel Cell Power Plants (MCFCPPs).
- Consider the effect of Combined Heat, Power, and Hydrogen (CHPH) simultaneously.
- Manage generation of thermal energy, and hydrogen, total emission of MCFCPPs and network.
- Consider uncertainties of the pressures of input hydrogen, oxygen, and carbon dioxide importing to MCFCPP.

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ABSTRACT

In this paper, a stochastic model is used for optimal planning of Molten Carbonate Fuel Cell Power Plants (MCFCPPs) in distribution network for producing Combined Heat, Power, and Hydrogen (CHPH). Total production costs of electrical energy, thermal energy, and hydrogen, emissions of MCFCPPs and network, and voltage deviation are considered in the objective function. In this paper, location and operation of MCFCPPs are taken into consideration while their investment cost is not taken into account. In this model, the uncertainties in forecasting the electrical and thermal loads, the pressures of hydrogen, oxygen, and carbon dioxide, and the indeterminacy of the nominal temperature of MCFCPP are considered using 2m + 1 Point Estimate Method (2m + 1 PEM). The problem of optimal planning of MCFCPPs as CHPH is of mixed integer nonlinear nature. So, a Self Adaptive Learning Bat-inspired Algorithm (SALBA) is employed for solving this problem. The problem is solved as a multi-objective one to achieve the best Pareto optimal set. A set of non-dominated solutions are saved in a repository and the proposed method is evaluated on a 69-bus distribution system.

1. Introduction

Power system deregulation encourages electrical companies to employ renewable energy resources [1]. Renewable energies could properly substitute the fossil fuels and noticeably reduce green house gases [2]. Molten Carbonate Fuel Cell Power Plant (MCFCPP) is a profitable renewable energy resource in which electro–chemical reaction between hydrogen and oxygen produces electricity, heat, and water [3], [4]. MCFCPPs have no rotating part, produce ignorable acoustic noise, and benefit from environment-friendly power production [5], [6]. They operate at high temperatures and are proper options for being used as CHPH [7]. In addition, as hydrogen is produced from methane, there is no need for direct sources of hydrogen [8].

Recently, many studies have addressed the operation of Distributed Generations (DGs) and renewable energy resources in distribution networks. Effects of DG locations on voltage stability margin in distribution networks are investigated in Ref. [9]. Moravej and Akhlaghi investigated the impacts of positioning of DGs on voltage profile improvements and power loss reductions using a novel approach based on cuckoo search [10]. Biswas et al. proposed a new formulation

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Nomenclature

V_{MCFCPP}	output voltage of MCFCPP
E_{eq}	equivalent cell potential
R	universal gas constant (8.3145 kJ kmol^{-1} K^{-1})
z	number of electrons transferred per molecule of fuel
P_{H_2}	pressure of hydrogen gas
P_{O_2}	pressure of oxygen gas
$P_{\text{H}_2\text{O}}$	pressure of water vapor
$P_{\text{CO}_{2,c}}$	pressure of carbon dioxide gas in cathode
$P_{\text{CO}_{2,a}}$	pressure of carbon dioxide gas in anode
Temp	MCFCPP temperature
i_{MCFCPP}	output current of MCFCPP
$-\Delta\overline{g}_f$	change in Gibbs free energy of the hydrogen reaction
F	Faraday constant
R_{ohmic}	ohmic cell resistance
η_{cathode}	the re-scaled cathodic over-potential
η_{anode}	the re-scaled anodic over-potential
A	active area cell
$I_{\max}$	maximum current density
P_{MCFCPP}	output active power of MCFCPP
X	decision variable
$t_{\max}$	total time
P_{Sub}^t	active power produced by the substation of network
C_{Sub}	cost of substation active power
C_{n1}	price of purchasing natural gas for FCPPs
N_{FCPP}	total number of FCPPs
$P_{\text{FCPP}j}^t$	active power generated by MCFCPP*j* during time *t*
$P_{H_{\text{FCPP}j}}^t$	equivalent electric power for hydrogen production during time *t*
$\eta_{\text{MCFCPP},j}^t$	efficiency of MCFCPP*j* during time *t*
C_{n2}	fuel price for thermal loads
N_{bus}	total number of buses
$L_{\text{th}i}$	thermal load demand of bus *i*
$P_{\text{th}i}^t$	heat produced by MCFCPP in bus *i* if there is a FCPP in this bus during time *t*
OM	operation and maintenance costs of FCPPs
C_{pump}	hydrogen pumping cost
$PH_{\text{FCPPUsage}}$	equivalent electrical energy of used hydrogen
C_{Hs}	hydrogen selling price
$PH_{\text{Save,FCPP}}$	equivalent electrical energy of saved hydrogen
H_{factor}	a conversion factor (kg of hydrogen/kW of electric power), where $H_{\text{factor}} = 1.05 \times 10^{-8}/v_{\text{cell}}$ and v_{cell} is the cell operating voltage, $v_{\text{cell}} = 0.6$ V.
h	number of objective function
locat$_n$	the location of MCFCPP$_n$
$N_\mu(X_i)$	normalized membership value of each particle in the repository
d	number of non-dominated solutions in the repository
T	total time
E_{grid}^t	emission produced by grid during time *t*
$E_{\text{FCPP},j}^t$	emission produced by MCFCPP*j* units during time *t*
$e_{\text{grid,SO}_2}$	emission coefficient of grid
$e_{\text{grid,NO}_x}$	emission coefficient of grid
$e_{\text{grid,CO}_2}$	emission coefficient of grid
$e_{\text{MCFCPP,SO}_2}$	emission coefficient of MCFCPP units
$e_{\text{MCFCPP,NO}_x}$	emission coefficient of MCFCPP units
$e_{\text{MCFCPP,CO}_2}$	emission coefficient of MCFCPP units
V_{ref}	nominal voltage
V_i^t	voltage magnitude of the bus *i* during time *t*
V_{Min}	lowest voltages of each bus
V_{Max}	highest voltages of each bus
$P_{\text{MCFCPP},j}^{t,\min}$	the minimum of active power produced by MCFCPP*j* during time t
$P_{\text{MCFCPP},j}^{t,\max}$	the maximum of active power produced by MCFCPP*j* during time t
Δt	step time
$P_{\text{Max,MCFCPP}}$	the maximum power of MCFCPP
$r_{\text{TE}j}$	the thermal energy to electrical energy ratio
$f_i^{\min}$	the lower bound of each objective function
$f_i^{\max}$	the upper bound of each objective function
$\mu_{fi(x)}$	membership function of each objective function
Iter$_{\max}$	maximum number of iterations
Iter	current iteration
A_m^k, r_m^k	Pulse loudness and emission rate for the *m*th bat in iteration *k*, respectively.
A_{mean}^k	Mean of the pulse loudness for all bats in iteration *k*.
$\mathbf{Gbest}^k$	Best compromise solution in iteration *k*.
f_m	Pulse frequency of the *m*th bat.
$f_m^{\min}, f_m^{\max}$	Minimum and maximum pulse frequency for bat *m*, respectively.
$\mathbf{Mean}^k$	Mean of the population positions.
$\mathbf{Pbest}_m^k$	Best position for bat *m* in iteration *k*.
$\mathbf{Worst}^k$	The worst solution among all bats in iteration *k*.
N_{Bat}	Number of bats
$\mathbf{Vel}_{\text{new},j}^k, \mathbf{Vel}_j^k$	new and old velocities of the *j*th bat, respectively
$\mathbf{X}_{\text{new},j}^k, \mathbf{X}_j^k$	new and old positions of the *j*th bat, respectively.
rand(.)	random number between 0 and 1
w_k	weight of *k*th objective function
η_{st}	hydrogen storage efficiency
η_{overall}^t	overall efficiency of MCFCPP

List of abbreviations

MCFCPP	Molten Carbonate Fuel Cell Power Plants
CHPH	Combined Heat, Power, and Hydrogen
SALBA	Self Adaptive Learning Bat-inspired Algorithm
DG	Distributed Generation
RWM	Roulette Wheel Mechanism
MCS	Monte Carlo Simulation
SD	Standard Deviation
CF	Constant Frequency
FM	Frequently Modulated
SALM	Self Adaptive Learning Mechanism
PEM	2m + 1 Point Estimate Method
PDF	Probability Distribution Function
DLF	Deterministic Load Flow
MOP	Multi-objective Optimization Problem

for placement of DGs using a combination of technical factors such as power loss minimization and voltage sag reduction and economical factors such as costs of maintenance and mount of DGs in the system [11]. Optimal placement and sizing of DGs using a multi-objective methodology are offered in Ref. [12]. El-Zonkoly studied the optimal positioning of new resources of energy in distribution networks considering different load models [13]. In Refs. [14], optimal placement and sizing of DGs are addressed based on fuel cost minimization, power loss reduction, and voltage profile improvement using a novel efficient population-based heuristic approach. Moradi and Abedini studied the problem of optimal placement and sizing of FCPPs using a combination of PSO and GA algorithms [15]. Niknam et al. formulated the optimal positioning of renewable energy sources in distribution networks in a Multi-objective Optimization Problem and used a modified honey bee mating optimization algorithm to obtain the solutions [16]. For location and size