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Probabilistic hydrogen, thermal and electrical management of PEM-fuel cell power plants in distribution networks

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ABSTRACT

This paper presents a Stochastic Multi-objective Optimal Operation Management (SMOOM) framework of distribution networks in presence of PEM-Fuel Cell Power Plants (FCPPs) and boilers. Operational costs, thermal recovery, power trade with grid and hydrogen management strategies are considered in this model. Furthermore, four objective functions has been considered as criteria for SMOOM, i.e. electrical energy losses, voltages deviations from their nominal values, total emissions emitted by CHP systems and grids, and total operational costs of CHP systems, as well as electrical energy cost of grids. A $2m+1$ Point Estimated Method is used to cope with the uncertain variables i.e. electrical and thermal loads, gas price of FCPPs consumption, fuel cost of residential loads, purchasing and selling tariff of electricity, hydrogen price, operation temperature of fuel cell stack, and the pressures of hydrogen and oxygen of anode and cathode, respectively. A new multi-objective Modified Firefly Algorithm (MFA) is implemented for minimizing the objective functions while the operational constraints are satisfied. Finally, a 69-bus distribution network is utilized to examine the performance of the proposed strategy regarding the rest.
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1. Introduction

The interest in Distributed Energy Resources (DERs) has increased because they are environmentally better than conventional power plants and their non-depleting energy sources [1]. Among various types of DERs, Fuel Cell Power Planets (FCPPs) are more noticeable; because they generate simultaneously electricity, heat, and hydrogen [2]. FCPPs can be utilised as dispatchable energy sources and their unused capacity can be employed for generating hydrogen, which in turn can be reused for generating electricity or be sold for profit [3]. Moreover, the waste heat from the onsite generation of electricity is used to meet the thermal demand [4]. Besides, their simple structure, high degree of modularity, high efficiency and low noise, fast reaction to load variations, their high cleanliness, and reliability are the other attractive characteristics of FCPPs [5,6]. Several articles have been developed in which FCPPs are used to generate electricity [7,8]. These literatures confirm that using FCPPs just by means of generating electrical energy is not efficient, and are more satisfactory when their produced thermal and hydrogen contribute to their economical model [8,9].

Here, the main barriers to use FCPPs are the uncertainties related to these units, such as costs; i.e. the cost of gas, hydrogen, and fuel, the cost for selling electricity to the grid, and purchasing from it; and also choosing a good strategy for controlling these units. There are also operational uncertainties such as operation temperature of the stack and pressures of hydrogen and oxygen at anode and cathode, respectively.

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Nomenclature

C_{FC}^{t}, C_{FC} Hourly and total operational cost of FCPPs, respectively, $

C_{n1}, C_{n2} Price of natural gas for FCPP and residential loads, respectively, $/kWh

C_{Hs} Hydrogen selling price, $/kg

C_{pomp} Cost of hydrogen pumping, $/kWh

C_{sub}^{t} Hourly and total cost of purchasing electricity from the substation, respectively, $

$C_{el,s}$ Selling tariff of electricity, $/kWh

$DOT_{i_{cap}}^{cap,max}$ Maximum allowable number of switching of the ith capacitor during the next day

$DOT_{i_{trn}}^{trn}$ Number of switching of the ith transformers taps during the next day

$DOT_{i_{trn}}^{trn,max}$ Maximum allowable number of changing of the ith transformer tap during the next day

E_{dir}^{t} Summation of direct and indirect emission from the FCPPs and the substation, respectively, kg

$E_{sub\_dir}^{t}$ Direct emission produced by the substation, kg

$E_{fuel\_onsite\_FC}^{t}$ Direct (onsite) emission produced by the FCPP, kg

$E_{fuel\_onsite\_boil}^{t}$ Direct (onsite) emission produced by the boiler, kg

$E_{i_{sub}}^{t}$ Direct emission factor of the substation, kg/kWh

$E\_onsite_{i_{FC}}^{t}$ Direct (onsite) emission factor of the FCPP, kg/kWh

$E\_onsite_{i_{boil}}^{t}$ Direct (onsite) emission factor of the boiler, kg/kWh

$E\_pre\_comb_{i_{FC}}^{t}$, $E\_pre\_comb_{i_{boil}}^{t}$ Indirect emission factor of the FCPP and boiler, respectively, kg/kWh

$F_{FC,iFC}$, $F_{boiler,iboil}$ Input fuel to FCPP and boiler, respectively

h^{t} Duration of tth time interval, h

$I_{FC}^{min(max)}$ Minimum (maximum) value for current density of FCPP, A/cm

k Number of objective functions

MDT Minimum down-time and up-time, respectively. (time interval)

n Number of decision variables

N_{bus}, N_{br} Number of network buses and branches, respectively

N_{cap}, N_{cap} Number of capacitors and FCPP, respectively

N_{sub}, N_{trn} Number of substations and transformers, respectively

OM Operation and maintenance cost, $

$P_{ij}^{br,max}$ Active power limit of line from bus i to bus j, kW

$P_{i_{sub}}^{t}$ Active power withdrawal of the ith substation, kW

P_{FC}^{t} Active power output of FCPP, kW

$\mathbf{P}_{h}$, $\mathbf{P}_{h,iFC}$ Vector of produced hydrogen by all reformers and ith reformer in all time intervals, respectively

$P_{h,i_{FC}}^{t}$ Produced hydrogen by ith reformers, kW

$\mathbf{P}_{h,u}$, $\mathbf{P}_{h,u,iFC}$ Hydrogen consumption vector of all and ith hydrogen reserve tanks in all time intervals, respectively

$P_{h,u,i_{FC}}^{T}$ Used hydrogen of ith hydrogen reserve tank, kW

PLR Ratio of electrical generated power to the maximum power

$P_{th,i_{FC}}^{t}$ Thermal power generated by the FCPP, kW

$\left|P_{ij}^{br}\right|$ Active power flow of line from bus i to bus j, kW

$Price_{i_{sub}}^{t}$ Tariff of purchasing electricity from the substation

$Pf_{i_{sub}}^{min(max)}$ Minimum (maximum) power factor of the ith substation

R_{ibr} Resistance of the ith branch, Ω

$R_{a\&f}$, $R_{i_{a\&f}}$ Vector of air and fuel ratio incoming to all and ith boiler in all time intervals, respectively.

$r_{TE,t}$ Thermal to electrical energy ratio

T Number of time intervals

$\mathbf{Tap}_{trn}$, $\mathbf{Tap}_{itrn}$ Vector of the tap positions of all and the ith transformer in all time intervals, respectively.

$Tap_{i_{trn}}^{min(max)}$ Minimum (maximum) tap position of the ith transformer

$\mathbf{U}_{cap}$, $\mathbf{U}_{icap}$ Vector that contains the status of all and the ith capacitor in all time intervals, respectively.

v_{cell} Cell operating voltage, V

V_{d}^{t} Voltage deviation from nominal, p.u.

V_{i}^{N} Nominal voltage of the ith bus, kV

$V_{i}^{min(max)}$ Minimum (maximum) voltage magnitude of the ith bus, kV

V_{i}^{t} Voltage magnitude of the ith bus, kV

U On/off status for the FCPP ($U = 0$ if it is off and 1 if it is on)

$\mathbf{X}$ Vector of control variables

ΔPD, ΔPU Lower and upper limit of the ramp rate, respectively

$\boldsymbol{\lambda}_{FC}$ Vector of water content of Nafion for all and the ith FCPP in all time intervals, respectively

$\lambda_{FC}^{min(max)}$ Minimum (maximum) value for water content of Nafion

η_{st}, $\eta_{i_{FC}}^{t}$, η_{boiler} Efficiency for hydrogen storage, FCPP and boiler, respectively

Subscripts

Bus, br, cap, trn, sub, FCPP Bus, branch, capacitor, transformer, substation and fuel-cell power plant, respectively

Interaction between FCPPs and thermal and electrical loads can be investigated regardless of the Distribution Networks (DNs) [7,10,11], but connecting FCPPs to the power systems can affect the technical aspects of these networks and a review of the affected issues is required. The main goal of Optimal Operation Management (OOM) is to minimise the predefined objective functions while regulating the voltage of the feeders and reactive power (or power factor) at substations using the Under Load Tap Changer (ULTC) transformers, as well as the shunt capacitors [12]. Connecting FCPPs to DNs is an opportunity for new control variables to improve the performance of the system. Several articles have been already developed with

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