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Optimal power flow based TU/CHP/PV/WPP coordination in view of wind speed, solar irradiance and load correlations

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ABSTRACT

This paper addresses a novel probabilistic optimisation framework for handling power system uncertainties in the optimal power flow (OPF) problem that considers all the essential factors of great impact in the OPF problem. The object is to study and model the correlation and fluctuation of load demands, photovoltaic (PV) and wind power plants (WPPs) which have an important influence on transmission lines and bus voltages. Moreover, as an important tool of saving waste heat energy in the thermoelectric power plant, the power networks share of combined heat and power (CHP) has increased dramatically in the past decade. So, the probabilistic OPF (POPF) problem considering valve point effects, multi-fuel options and prohibited zones of thermal units (TUs) is firstly formulated. The PV, WPP and CHP units are also modeled. Then, a new method utilizing enhanced binary black hole (EBBH) algorithm and $2m + 1$ point estimated method is proposed to solve this problem and to handle the random nature of solar irradiance, wind speed and load of consumers. The correlation between input random variables is considered using a correlation matrix. Finally, numerical results are presented and considered regarding the IEEE 118-busses, including PV, WPP, CHP and TU at several busses. The simulation and comparison results obtained demonstrate the broad advantages and feasibility of the suggested framework in the presence of dependent non-Gaussian distribution of random variables.

1. Introduction

1.1. Problem description and motivation

In the past decade, the rapid development and proliferation of photovoltaic (PV) units and wind power producers (WPPs) has extensively increased the uncertainties in power systems. These uncertainties affect power system planning and operation especially the optimal power flow (OPF) problem. For the OPF, an efficient and adequate evaluation of the input random variables (IRVs) can lead to superior management of congestion, bus voltages, line flows, active and reactive power generation of thermal units (TUs), transformer tap position and reactive power of shunt compensators. Probabilistic OPF (POPF) is an important probabilistic solver to analytically assess the random nature of the power grid variables. It plays an efficient role in maintaining the security and economy of the power network [1].

In earlier OPF approaches, the problem is formulated as a deterministic optimization problem neglecting the volatility of IRVs [2]. The problem of OPF was originally formulated in 1962 by Carpentier [3]. The OPF problem seeks to optimize an objective function (generally electrical energy cost) by adjusting a set of continuous and discrete control variables subject to equality and inequality constraints [4]. It is a highly non-smooth, non-convex, non-linear, large scale, static optimization problem with both discrete (transformer taps and switchable shunt devices) and continuous (generator voltage magnitudes and active powers) control variables.

The types of embedded power generation units that are explored in the power systems are mostly PVs and WPPs and combined heat and power (CHP) units [5]. For the aim of increasing the efficiency of TUs and producing heat power to satisfy heat load demand, the CHP unit as a cogeneration system is also considered in the OPF problem. The presence of non-convex feasible operating region (FOR) of CHP, non-convexity of prohibited operating zones (POZs) and multi-fuel options and non-smooth nature of valve-point effects of TUs further complicates the problem solution. Within this context, the motivation of this study is to provide an enhanced tool for the POPF problem including an appropriate treatment of the dependencies of the IRVs and all of the technical restrictions on PVs, WPPs, TUs and CHP units in transmission systems.

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Nomenclature

Indices

i, j, h, pv, w	thermal unit (TU), combined heat and power (CHP), heat-only, photovoltaic (PV) and wind power plant (WPP) unit indices, respectively
$iter$	iteration index of the proposed enhanced binary black hole (EBBH) algorithm
k, f	prohibited operating zone (POZ) and fuel type of TU indices, respectively
$l,\ g,\ cap,\ tran$	load bus, generator bus, reactive power compensator and transformer indices, respectively
n	star index

Constants

a_i, b_i, c_i, d_i, e_i	generation cost coefficients of ith TU
$a_{if}, b_{if}, c_{if}, d_{if}, e_{if}$	generation cost coefficients of ith TU with fuel type f
$a_j, b_j, c_j, d_j, e_j, f_j$	generation cost coefficients of jth CHP
a_h, b_h, c_h	generation cost coefficients of hth heat-only unit
c_w, c_{pv}	direst generation cost coefficients of wth WPP and pvth PV, respectively
f_{ξ_l}	probability distribution function of ξ_l
$G_{std,pv}$	reference solar irradiance for the pvth PV unit
$H^H_{h,\max}, H^{CHP}_{j,\max}$	heat capacity of heat-only unit h and CHP unit j, respectively (MWth)
$H^H_{h,\min}, H^{CHP}_{j,\min}$	minimum heat output of heat-only unit h and CHP unit j, respectively (MWth)
$iter_{\max}$	maximum number of iteration for the proposed EBBH algorithm
k, λ	shape and scale parameters of Weibull probability distribution function, respectively
m	number of input random variables
NP	number of stars in the population of EBBH algorithm
$NP_{absorbed}$	number of stars in the population of EBBH algorithm which absorbed to the black hole
$NCHP, NH, NPV, NTU, NW$	number of CHP, heat-only, PV, TU and WPP, respectively
$Nl, Ngen, Nload$	number of transmission lines, generator and load busses, respectively
$Ncap, Ntran$	number of reactive shunt compensators and transformers, respectively
N_{eq}	number of equality constraints
N_{iq}	number of inequality constraints
K_i	number of POZ relating to the ith TU
Nf_i	number of fuel options for ith TU
N_{bus}	number of total busses
nv	number of variables in each control vector.
$P^{TU}_{i,\min}, P^{CHP}_{j,\min}$	minimum active power output of the ith TU and jth CHP, respectively (MW)
$P^{TU}_{i,\max}, P^{CHP}_{j,\max}$	power capacity of the ith TU and jth CHP, respectively (MW)
P^L_{ik}, P^U_{ik}	lower and upper boundary of kth POZ for ith TU, respectively (MW)
P_{Gi}	active power generation of the ith bus (MW)
P_{Di}	active power demand of the ith bus (MW)
$\widehat{\mathbf{P}}^{WPP}, \widehat{\mathbf{P}}^{PV}$	expected power of WPPs and PVs vector, respectively (MW)
$\widehat{P}^{WPP}_w, \widehat{P}^{PV}_{pv}$	expected power of wth WPP and pvth PV, respectively (MW)
$P^{WPP}_{w,rate}, P^{PV}_{pv,rate}$	rated power of wth WPP and pvth PV, respectively (MW)
$P_{Line_l,\max}$	maximum real power flow through the lth branch (MW)
$\widehat{P}_{heat}$	forecasted heat load demand
Q_{Gi}	reactive power generation of the ith bus (MVAr)
Q_{Di}	reactive power demand of the ith bus (MVAr)
$Qc_{cap,\max}$	reactive power capacity of the capth shunt compensator (MVAr)
$Qc_{cap,\min}$	minimum reactive power output of the capth shunt compensator (MVAr)
$TP_{tran,\max}$	maximum tap setting of the $tran$th transformer
$TP_{tran,\min}$	minimum tap setting of the $tran$th transformer
$rand(\cdot),\ rand1(\cdot),\ rand2(\cdot)$	random function generators in the range [0,1]
$\mathbf{rand}_n(1, nv)$	Random vector with the dimension of $1 \times nv$ relating to the nth star.
$s_{1,w}, s_{2,w}$	slope of the first and second segment of the wth WPP, respectively
$T_{r,pv}$	temperature for standard testing conditions reference for the pvth PV unit
$T_{c,pv}$	temperature for the surface of pvth PV unit
$V_{i\max}, V_{i\min}$	maximum and minimum valid voltages for bus i, respectively
$v_{ci,w}$	cut-in wind speed of the wth WPP
$v_{co,w}$	cut-out wind speed of the wth WPP
$v_{1,w}, v_{2,w}$	breakpoint of the first and second segments of wth WPP, respectively
$v_{r,w}$	rated wind speed of the wth WPP
$w_{l,k}$	weighting factor k for $\xi_{l,k}$
ξ_l	value of the lth input random variable of the $2m+1$ point estimated method (PEM)
$\xi_{l,k}$	location parameter k for ξ_l
Y	output random variable of the $2m+1$ PEM.
α, β	parameters of beta probability distribution function
γ	maximum power correction for temperature of PV
$\lambda_{\xi_l,3}, \lambda_{\xi_l,4}$	skewness and kurtosis coefficients, respectively
$\chi_{l,k}$	standard location parameter k for $\xi_{l,k}$
$\mu_{\xi_l}, \sigma_{\xi_l}$	mean and standard deviation of ξ_l
μ_Y, σ_Y	mean and standard deviation of the Y, respectively
ξ	input set of uncertain variables of the $2m+1$ PEM

Variables

$Cost_{TU}(\mathbf{P^{TU}}), Cost_{CHP}(\mathbf{P^{CHP}}, \mathbf{H^{CHP}}), Cost_{Heat\text{-}only}(\mathbf{H^H}), Cost_{WPP}\left(\widehat{\mathbf{P}}^{WPP}\right), Cost_{PV}\left(\widehat{\mathbf{P}}^{PV}\right)$	TU, CHP, heat-only, WPP and PV generation cost (\$), respectively
F	electrical energy cost objective function (\$)
H^H_h, H^{CHP}_j	Heat output of hth heat-only and jth CHP unit, respectively (MWth)
$\mathbf{H}^H, \mathbf{H}^{CHP}$	heat-only and CHP heat outputs vector, respectively
P^{TU}_i, P^{CHP}_j	active power output of TU i and CHP unit j, respectively (MW)
P_{Line_l}	real power that flows through lth transmission line (MW)
$\mathbf{P}_G$	active power generations variables vector of OPF
$P_{slack}, \mathbf{V_L}, \mathbf{Q_G}, \mathbf{P_{Line}}$	slack bus active power, load bus voltage magnitude, reactive power of generators and active branch flow, respectively
$\mathbf{P}^{TU}, \mathbf{P}^{CHP}, \mathbf{P}^{PV}, \mathbf{P}^{WPP}$	TU, CHP, PV, and WPP active power outputs vector, respectively
$\mathbf{Qc}$	reactive shunt compensators variables vector of OPF
Qc_{cap}, Q_g	reactive power output of capth shunt compensator and gth generator, respectively (MVAr)
Q^{TU}_i	Reactive power output of TU i (MVAr)
$\mathbf{TP}$	Transformer tap settings variables vector of OPF
$\mathbf{U}$	Dependent variables vector of OPF
V_g, V_l	Voltage magnitude of gth generator bus and lth load bus, respectively (p.u.)
V_i	voltage amplitude of the ith bus (p.u.)