Applied Energy 133 (2014) 388–402

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Self-adaptable hierarchical clustering analysis and differential evolution for optimal integration of renewable distributed generation

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HIGHLIGHTS

- We model a DG-integrated network accounting for uncertainties by MCS–OPF.
- We adopt DE to find optimal plans of renewable DG integration.
- We reduce the computational efforts during the DE searching process integrating HCA.
- We quantify the benefits of performing the HCDE in a controlled manner.
- We identify the time complexity limitations of the proposed HCDE framework.

ARTICLE INFO

Article history:
Received 1 May 2014
Received in revised form 21 July 2014
Accepted 22 July 2014

Keywords:
Distributed renewable generation
Uncertainty
Simulation
Optimization
Differential evolution
Hierarchical clustering analysis

ABSTRACT

In a previous paper, we have introduced a simulation and optimization framework for the integration of renewable generators into an electrical distribution network. The framework searches for the optimal size and location of the distributed renewable generation units (DG). Uncertainties in renewable resources availability, components failure and repair events, loads and grid power supply are incorporated. A Monte Carlo simulation–optimal power flow (MCS–OPF) computational model is used to generate scenarios of the uncertain variables and evaluate the network electric performance with respect to the expected value of the global cost (*ECG*). The framework is quite general and complete, but at the expenses of large computational times for the analysis of real systems. In this respect, the work of the present paper addresses the issue and introduces a purposely tailored, original technique for reducing the computational efforts of the analysis. The originality of the proposed approach lies in the development of a new search engine for performing the minimization of the *ECG*, which embeds hierarchical clustering analysis (HCA) within a differential evolution (DE) search scheme to identify groups of similar individuals in the DE population and, then, *ECG* is calculated for selected representative individuals of the groups only, thus reducing the number of objective function evaluations. For exemplification, the framework is applied to a distribution network derived from the IEEE 13 nodes test feeder. The results show that the newly proposed hierarchical clustering differential evolution (HCDE) MCS–OPF framework is effective in finding optimal DG-integrated network configurations with reduced computational efforts.

1. Introduction

Renewable distributed generation (DG) requires the selection of the different available technologies, and their sizing and allocation onto the power distribution network, considering the specific economic, operational and technical constraints [1–5]. This can become a complex optimization problem, depending on the size of the distribution network and the number of renewable DG technologies available, that can lead to combinatorial explosion [1,3,6–9]. Furthermore, for each renewable DG plan considered, the power flow problem needs to be solved to assess the response

Abbreviations: DE, differential evolution; DG, distributed generation; EA, Evolutionary Algorithm; EV, electric vehicle; GA, genetic algorithm; HCA, hierarchical clustering analysis; HCDE, hierarchical clustering differential evolution; MCS, Monte Carlo simulation; MS, main supply; OPF, optimal power flow; PSO, particle swarm optimization; PV, photovoltaic; ST, storage device; W, wind turbine.

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http://dx.doi.org/10.1016/j.apenergy.2014.07.086
0306-2619/

Nomenclature

$A_{i,i'}^{FD}$ ampacity of the feeder (i, i') (A)
$B_{i,i'}$ susceptance of the feeder (i, i') (1/Ω)
BGT available DG integration budget ($)
CCC cophenetic correlation coefficient
CCC_{th} cophenetic correlation coefficient threshold
CG global cost ($/h)
Ci total fixed investment and operation cost ($)
ci_j investment cost of the DG technology type j ($)
Co operating costs of power generation and distribution ($/h)
Coc crossover coefficient $\in [0, 1]$
Cop opportunity cost for kW h not supplied ($/kW h)
Cov_j^{PS} variable operating cost of the power source j
$Cov_{i,i'}^{FD}$ variable operating cost of the feeder (i, i')
D^{sp} matrix of linkage distances between groups at step sp
$\overline{D}^{sp}$ average of D^{sp}
$d_{p,q}^{sp}$ linkage distance between groups p and q
d_{CO} cutoff linkage distance
DG set of available types of distributed generation technologies
dg number of types of available distributed generation technologies
d_{min} minimum linkage distance
$d_{NC=4}$ linkage distance to form at least four clusters
ECG expected global cost ($/h)
ECG_{min} minimum expected global cost ($/h)
ep energy price ($/kW h)
ep_h energy price at highest total demand ($/kW h)
EV set of available types of EV
F differential variation amplification factor $\in [0, 2]$
FD set of feeders
G generations count index
G_{max} maximum number of generations
H matrix of HCA resultant linkage distances
$\overline{H}$ average of H
$h_{p,q}$ HCA resultant linkage distance between groups p and q
I_{MPP_j} current at maximum power point of PV technology type j (A)
I_{sc_j} short circuit current of PV technology type j (A)
k_{I_j} current temperature coefficient of PV technology type j (mA/°C)
k_{V_j} voltage temperature coefficient of PV technology type j (mV/°C)
L_i power demand at node i (kW)
$l_{i,i'}$ length of feeder (i, i') (km)
LS_i load shedding at node i (kW)
$mc_{i,j}$ mechanical state of PS type j at node i
$mc'_{i,i}$ mechanical state of feeder (i, i')
MS set of types of MS spots
ms number of types of MS spots
$M_{T_{i,j}}^{ST}$ mass of active chemical in ST type j at node i (kg)
N set of nodes in the distribution network
NS number of operating scenarios ϑ
n number of nodes in the distribution network
NFE number of objective function evaluations
N_{oT_j} nominal cell operation temperature of PV technology type j (°C)
NP population size
$op_{i,j}^{EV}$ operating state of EV type j at node i
p_j^- hourly probability distribution of EV type j charging state per day
p_j^0 hourly probability distribution of EV type j disconnected state per day
p_j^+ hourly probability distribution of EV type j discharging state per day
$Pa_{i,j}^{PS}$ available power in power source of type j allocated at node
p_{co} linkage distances cutoff level coefficient $\in [0, 1]$
$P_{i,j}^{MS}$ power supply of MS type j at node i (kW)
$P_{cap_j}^{MS}$ maximum capacity of the MS type j (kW)
$P_{R_j}^{EV}$ rated power of EV technology type j (kW)
$P_{R_j}^{ST}$ rated power of ST technology type j (kW)
$P_{R_j}^{W}$ rated power of W technology type j (kW)
$Pu_{i,j}^{PS}$ used power from the power source type j at node i
POP population
PS set of all types of power sources
PV set of solar photovoltaic technologies
ps number of all types of available power generation technologies
$Q_{i,j}^{ST}$ level of charge in ST type j at node i (kJ)
s_i solar irradiance at node $i \in [0, 1]$
SE_j^{ST} specific energy of the active chemical in ST type j (kJ/kg)
ST set of storage devices technologies
T_{a_i} ambient temperature at node i (°C)
t_d hour of the day (h)
th lifetime of the project (h)
TL total demand of power in the distribution network (kW)
TL_h highest total demand of power in the distribution network (kW)
$t_{op_{i,j}^{EV}}$ time of residence in the operating state $op_{i,j}^{EV}$ of EV type j at node i (h)
$t_{R_{i,j}}^{ST}$ upper bound of the discharging time interval of ST type j at node i (h)
V_{oc_j} open circuit voltage of PV technology type j (V)
V_{MPP_j} voltage at maximum power point (V)
V^{NET} voltage of the distribution network (kV)
W set of wind turbines technologies
w_{a_j} average wind speed of W type j (m/s)
ws_{ci_j} cut-in wind speed of W type j (m/s)
ws_{co_j} cut-out wind speed of W type j (m/s)
ws_i wind speed at node i
$X_{i,i'}^{FD}$ reactance of feeder (i, i') (Ω/km)

Greek symbols

α_i^{PV} shape parameter of the Beta probability density function of the solar irradiance at node i
β_i^{PV} shape parameter of the Beta probability density function of the solar irradiance at node i
δ_i voltage angle at node i
ϑ operating scenario
λ_j^F failure rate of power source type j (1/h)
$\lambda_{i,i'}^F$ failure rate of feeder (i, i') (1/h)
λ_j^R repair rate of power source type j (1/h)
$\lambda_{i,i'}^R$ repair rate of feeder (i, i') (1/h)
μ_i^L mean of the normal distribution of the power load at node i (kW)
μ_j^{MS} normal distribution mean of the MS type j at node i (kW)
Ξ configuration matrix of DG-integrated network
Ξ^{DG} DG part of configuration matrix of DG-integrated network
Ξ^{MS} MS part of configuration matrix of DG-integrated network