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Interactive energy management of networked microgrids-based active distribution system considering large-scale integration of renewable energy resources

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HIGHLIGHTS

- Energy management of microgrids-based active distribution system is built.
- Expanded energy storage system is defined and applied into the energy system.
- Interactive energy game matrix describes operational interaction of energy systems.
- Technical operating performances are fully considered in the energy management.
- Impact of the large integration of renewable energy resources is considered and analyzed.

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ABSTRACT

Recently, large-scale renewable energy resources have been widely integrated into power systems. To optimize large-scale integration of these resources and improve the operation performance of the distribution system, this paper proposes a novel dynamic energy management strategy with the cooperative interaction of an energy system: a multi-grid connected microgrids (MGs)-based active distribution system (ADS). A bi-level multi-objective optimization problem of the strategy is formulated with the active distribution network (ADN) in the upper level and MGs in the lower level. The interaction can be classified into two categories: the one between MGs and the ADN and the other one among MGs. The former is described by bi-level programming; the latter is innovatively explained by an interactive energy game matrix (IEGM) defined in this paper. The concept of the expanded energy storage system is defined and applied to the IEGM for the optimal operation of ADSs. The optimal operation includes improved technical performances in terms of power quality, energy utilization, adaptability and autonomy. The optimization problem is solved with a hybrid algorithm of Rough Set Theory–Hierarchical Genetic Algorithm–NSGA-II. Case studies of an ADS with different MGs and a real system would validate the efficiency of the proposed methodology. Results show that the proposed EM strategy can accurately quantify and guide the energy interaction among MGs and that between MGs and the ADN. Moreover, those technical performances of the ADS are improved.

1. Introduction

Renewable energy resources (RERs, e.g., solar and wind) have drawn the attention of researchers since they are the solution to the future energy and environment crisis [1–3]. To make a more efficient and convenient use of these RERs, large amounts of different renewable energy plants have already been connected to power systems [4].The Energy Internet will be built on those infrastructures [5]. As a promising framework, multiple MGs can be connected with an ADS to integrate large-scale DERs on local conditions [6]. This framework can also improve system operation, reliability, environmental friendliness and economic benefits [7]. The ADS, which can control power flow and DERs actively, is a proper modern energy system integrating DERs into power systems [8]. As a kind of energy hubs of DGs, local loads and ESSs, MGs can directly combine different energy resources and manage them with hybrid energy systems [9], so they are proper bridges between DERs and ADSs [10–12]. However, due to the intermittency and uncertainty of RERs, large-scale integration of them has great impact on the overall system [13–15]. It is also a problem

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Nomenclature

Acronyms

RER renewable energy resource
EM energy management
MG microgrid
ADS active distribution system
ADN active distribution network
IEGM interactive energy game matrix
EESS expanded energy storage system
RST Rough Set Theory
HGA Hierarchical Genetic Algorithm
NSGA-II Non-dominated Sorting Genetic Algorithm II
DG distributed generator
FC fuel cell
MT micro turbine
SB storage battery
PV photovoltaic generator
WT wind turbine
REG renewable energy generator
PCC point of common coupling
DER distributed renewable energies
EES energy storage system
EMS energy management system
MGCC microgrid central controller

Sets/maximums

L set of nodes in ADN
L_N set of nodes connected to MGs in ADN
L_{DG} set of nodes connected to DGs in ADN
T sum of scheduling period t
N set of MGs in ADS
D game set of decision variables (d_i) of single MG
U_n set of types of DGs in MG $n, u = 1, 2, 3, 4$ and 5 denote FC, MT, SB, PV and WT, respectively
R_n set of types of REGs in MG $n, r = 1$ and 2 denote PV and WT, respectively
H_n set/sum of types of dispatchable DGs (MT and/or FC) in MG $n, h = 1$ and 2 denote FC and MT, respectively
I_n set/sum of MGs connected with MG n
N_1 sum of MGs including FC
N_2 sum of MGs including MT

Matrixes

$E^{\mathrm{EX}}_{n,t}$ IEGM of MG n
$C^{\mathrm{EX}}_{n,t}$ matrix of total cost of $E^{\mathrm{EX}}_{n,t}$
$P^{\mathrm{DGEX}}_{n,t}$ matrix of $a_{h,i,t}\ P^{\mathrm{DGEX}}_{h,i,t}$ in MG n
$P^{\mathrm{SBEX}}_{n,t}$ matrix of $b_{h,i,t}\ P^{\mathrm{SBEX}}_{i,t}$ in MG n

Variables

$U_{l,t}$ voltage at node l
$P_{l,k,t}$ line power flow from l to k
P^{LOSS}_{t} power loss of ADN
$P^{\mathrm{PCC}}_{l,t}$ PCC power exchange of MG connected to node l
$Q^{\mathrm{PCC}}_{l,t}$ reactive PCC power exchange of MG connected to node l
$P^{\mathrm{PCC}}_{n,t}$ PCC power exchange of MG n
$Q^{\mathrm{PCC}}_{n,t}$ reactive PCC power exchange of MG n
$P^{\mathrm{DG}}_{l,t}$ output of DG connected to node l
$Q^{\mathrm{DG}}_{l,t}$ reactive power of DG connected to node l
$\theta_{l,k,t}$ phase angle between l and k
d_i same type i of decision variable of MG n
d_1 REG of MG n
d_2 controllable DGs and SB of MG n
d_3 virtual capacity of FC and MT in other MGs
d_4 dispatchable capacity of SB in other MGs
x_i 0–1 variable of d_i
x_i' secondary 0–1 variable of d_i
$P^{\mathrm{DG}}_{u,n,t}$ output of DG u in MG n
$Q^{\mathrm{DG}}_{u,n,t}$ reactive output of DG u in MG n
$P^{\mathrm{MGPE}}_{n,t}$ total power exchange between MG n and other MGs
$Q^{\mathrm{MGPE}}_{n,t}$ total reactive power exchange between MG n and other MGs
$P^{\mathrm{Re}}_{r,n,t}$ actual output of REG r in MG n
$P^{\mathrm{CUR}}_{r,n,t}$ power curtailment of REG r in MG n
$x_{n,t}$ 0–1 variable of $P^{\mathrm{DGEX}}_{n,t}$ to determine whether $P^{\mathrm{DGEX}}_{n,t}$ is carried out
$y_{n,t}$ 0–1 variable of $P^{\mathrm{SBEX}}_{n,t}$ to determine whether $P^{\mathrm{SBEX}}_{n,t}$ is carried out
$P^{\mathrm{DGEX}}_{h,i,t}$ dispatchable capacity of DG h supporting MG n in MG i
$P^{\mathrm{SBEX}}_{i,t}$ dispatchable capacity of SB supporting MG n in MG i
$a_{h,i,t}$ secondary 0–1 variables of $P^{\mathrm{DGEX}}_{h,i,t}$ to determine whether $P^{\mathrm{DGEX}}_{h,i,t}$ is carried out
$b_{i,t}$ secondary 0–1 variables of $P^{\mathrm{SBEX}}_{i,t}$ to determine whether $P^{\mathrm{SBEX}}_{i,t}$ is carried out
$E^{T}_{n,t}$ transition state of charge capacity of SB in MG n
$E_{n,t}$ final state of charge capacity of SB in MG n

Parameters/constants

$P^{L}_{l,t}$ load at node l
$Q^{L}_{l,t}$ reactive load at node l
θ power exchange level
λ economy parameter
$P_{l,k,\max}$ maximum line power flow from l to k
$G_{l,k}$ conductance between l and k
$B_{l,k}$ susceptance between l and k
$P^{\mathrm{PCC}}_{\max}$ maximum PCC power exchange
$P^{\mathrm{PCC}}_{\min}$ minimum PCC power exchange
$P^{\mathrm{DG}}_{\max}$ maximum output of DG connected to ADN
$P^{\mathrm{DG}}_{\min}$ minimum output of DG connected to ADN
$Q^{\mathrm{PCC}}_{\max}$ maximum reactive PCC power exchange
$Q^{\mathrm{PCC}}_{\min}$ minimum reactive PCC power exchange
$Q^{\mathrm{DG}}_{\max}$ maximum reactive output of DG connected to ADN
$Q^{\mathrm{DG}}_{\min}$ minimum reactive output of DG connected to ADN
$P^{\mathrm{DG}}_{h,n,\max}$ maximum output of DG h in MG n
$P^{\mathrm{DG}}_{h,n,\min}$ minimum output of DG h in MG n
$Q^{\mathrm{DG}}_{h,n,\max}$ maximum reactive output of DG h in MG n
$Q^{\mathrm{DG}}_{h,n,\min}$ minimum reactive output of DG h in MG n
$U_{l,\max}$ maximum voltage at node l
$U_{l,\min}$ minimum voltage at node l
C^{GRID} sale/purchase price of grid
C^{DG}_{u} generation cost of DG u in MGs
C^{DG} generation cost of DG connected to ADN
C^{RE}_{r} fine per power curtailment of REG r
$P^{\mathrm{RE}}_{r,n,t,\max}$ maximum output of REG r in MG n
$P^{\mathrm{MGL}}_{n,t}$ load of MG n
$Q^{\mathrm{MGL}}_{n,t}$ reactive load of MG n
R_t spinning reserve of ADN
$E_{n,\max}$ maximum capacity of SB in MG n
$E_{n,\min}$ minimum capacity of SB in MG n