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Smart microgrid hierarchical frequency control ancillary service provision based on virtual inertia concept: An integrated demand response and droop controlled distributed generation framework

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ABSTRACT

Low inertia stack, high penetration levels of renewable energy source and great ratio of power deviations in a small power delivery system put microgrid frequency at risk of instability. On the basis of the close coupling between the microgrid frequency and system security requirements, procurement of adequate ancillary services from cost-effective and environmental friendly resources is a great challenge requests an efficient energy management system. Motivated by this need, this paper presents a novel energy management system that is aimed to coordinately manage the demand response and distributed generation resources. The proposed approach is carried out by constructing a hierarchical frequency control structure in which the frequency dependent control functions of the microgrid components are modeled comprehensively. On the basis of the derived modeling, both the static and dynamic frequency securities of an islanded microgrid are provided in primary and secondary control levels. Besides, to cope with the low inertia stack of islanded microgrids, novel virtual inertia concept is devised based on the precise modeling of droop controlled distributed generation resources. The proposed approach is applied to typical test microgrid. Energy and hierarchical reserve resource are scheduled precisely using a scenario-based stochastic programming methodology. Moreover, analyzing the results verifies the impressiveness of the proposed energy management system in cost-effectively optimizing the microgrid ancillary service procurement.

1. Introduction

Economic-environmental motivations to provide the ever-increasing energy demands in a secure and reliable framework lead the power system operators to utilize Distribute Energy Resources (DERs) more than ever [1]. On the other hand, individual uncoordinated operation of the DERs particularly Renewable Energy Sources (RESs) may have deteriorative impacts on the power system stability, sustainability and power quality indices [2]. In this regard, microgrid idea as an active and controllable infrastructure have been introduced as a reliable ground to aggregate various DER technologies and loads together in a small distribution power system [3]. Microgrids have also a high potential to facilitate the active participation of the end-user consumers in the light of the Demand Response (DR) programs [4]. Microgrid central controller (MGCC) can exploit the DR programs in order to not only reduce energy costs but also to provide the high level reliability and security requirements [5].

Microgrids are met with new complicated challenges stem from more complex components and higher degrees of uncertainty in a small region of power system. The challenges are more critical in the islanded mode and directly threaten the microgrid frequency security. In other words, unlike the synchronous generators, most of the DER units require static Voltage Source Inverter (VSI) units to connect to the grid in a sustainable manner. As a result, arisen from the lower inertia of the VSIs, not only the loadability and stability capabilities of the microgrid are reduced [6] but also the control system complexity is strengthened [7]. Besides, the intermittency of the RES units produces an uncertain operational environment for the islanded microgrids. The power fluctuations arise from the unpredictable load consumption also augments the degree of the uncertainty [8]. Thus, the control and management of the microgrid frequency security, particularly in the islanded mode, is a great challenge which should be investigated

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Nomenclature

Acronyms

DER	Distributed Energy Resource
DG	Distributed Generation
DR	Demand Response
DRP	Demand Response Provider
ELNS	Expected Load not supplied
EMS	Energy Management System
MCS	Monte Carlo Simulation
MGCC	Micro-Grid Central Controller
MILP	Mixed Integer Linear Programming
PV	Photovoltaic
RCF	Rate of Change of Frequency
RES	Renewable Energy Source
RWM	Roulette Wheel Mechanism
TEF	Total Expected Frequency
TOC	Total Operation Cost
TOE	Total Operation Emission
VSI	Voltage Source Inverter
VOLL	Value Of Lost Load
WT	Wind Turbine

Indices

i	index of VSI based DG from 1 to Ng
w	index of wind turbines from 1 to Nw
v	index of photovoltaic panels from 1 to Nv
d	index of demand response providers from 1 to Nd
s	index of random scenarios from 1 to Ns
h	index of hours from 1 to Nh
l	index of frequency control level could be pri (primary) and *sec* (secondary)
ud	index of scheduled reserves could be *up* or *down*

Parameters and Constants

$m_{p,i}$	frequency droop control gain of i-th VSI-based DG
f_{ref}	microgrid reference frequency
$\Delta f_l^{\max}$	maximum allowable microgrid frequency excursion limit during control level l
$\mathrm{ROCOF}_{\mathrm{MG}}^{\max}$	maximum allowable microgrid rate of change of frequency limit
$\mathrm{ROCOF}_i^{\max}$	maximum allowable rate of change of frequency limit associated to i-th DG
a_i	fixed operation cost of i-th VSI based DG
b_i	first-order operation cost of i-th VSI based DG
$H_{V,i}$	virtual inertia constant of i-th VSI based DG
$\omega_{c,i}$	low-pass filter cut-off frequency of i-th VSI based DG
$\rho_{i,l,ud}^R$	cost of up/down reserve of i-th VSI based DG in control level l
$\alpha_{d,m}^E$	cost of energy offer of m-th block in d-th DRP price-demand curve
$\alpha_{d,l,ud}^R$	cost of up/down reserve of d-th DRP in control level l
ρ_w	cost of operation of wind turbine w
ρ_v	cost of operation of photovoltaic panel v
E_i^g	CO_2 emission rate of i-th VSI based DG
$P_i^{\max}$	upper level of active power generation of i-th VSI based DG
$P_i^{\min}$	lower level of active power generation of i-th VSI based DG
$P_{L,h}$	forecasted load consumption at hour h
$P_{w,h}$	forecasted active power output of wind turbine w at hour h
$P_{v,h}$	forecasted active power output of photovoltaic panel v at hour h

Variables

π_s	probability of scenario s
$\Delta f_{l,h}^s$	microgrid frequency excursion in scenario s, control level l and at hour h
$\Delta P_{i,l,h}^s$	active power deviation of i-th VSI based DG in scenario s, control level l and hour h
$\Delta P_{w,l,h}^s$	active power deviation of wind turbine w in scenario s, control level l and hour h
$\Delta P_{v,l,h}^s$	active power deviation of photovoltaic panel v in scenario s, control level l and hour h
$\Delta P_{\mathrm{ref},i,l,h}^s$	reference power deviation of i-th VSI based DG in scenario s, control level l and hour h
$P_{i,h}$	active power output of i-th VSI based DG at hour h
$D_{L\cdot l,h}^s$	frequency elasticity of microgrid loads in scenario s, control level l and hour h
$P_{\mathrm{ref},i,h}$	reference power set point of i-th VSI based DG at hour h
$R_{i,l,ud,h}$	scheduled up/down reserve of i-th VSI based DG in control level l and hour h
$u_{i,h}^l$	binary variable indicating commitment state of i-th VSI based DG at hour h and control level l
$u_{i,h}$	binary variable indicating commitment state of i-th VSI based DG at hour h
$\Delta f_{l,h}^s$	microgrid frequency excursion in scenario s, control level l at hour h
$\mathrm{ROCOF}_{\mathrm{MG},h}^s$	rate of change of frequency of microgrid in scenario s at hour h
$\mathrm{ROCOF}_{i,h}^s$	rate of change of frequency of i-th VSI-based DG in scenario s at hour h
$P_{d,h}^m$	offered load reduction corresponding to m-th block of d-th DRP at hour h
$P_{d,l,h}^{s,m}$	offered load reduction corresponding to scenario s of m-th block of d-th DRP at hour h
$P_{d,h}$	aggregated offered load reduction corresponding to d-th DRP at hour h
$P_{d,l,h}$	aggregated offered load reduction corresponding to d-th DRP at hour h in control level l
$R_{d,l,ud,h}$	scheduled up/down reserve of d-th DRP in control level l and hour h
$P_{i,l,h}^s$	active power output of i-th VSI based DG in scenario s, control level l and hour h
$P_{\mathrm{ref},i,l,h}^s$	reference power of i-th VSI based DG in scenario s, control level l and hour h
$P_{w,l,h}^s$	active power output of wind turbine w in scenario s, control level l and hour h
$P_{v,l,h}^s$	active power output of photovoltaic panel v in scenario s, control level l and hour h
$P_{L,l,h}^s$	microgrid load consumption in control level l and hour h
$P_{L,l,h,f}^s$	microgrid load contribution in according to natural load-frequency dependency in control level l and hour h at static frequency f
$\mathrm{LSH}_{l,h}^s$	load to be shed unwillingly in scenario s, control level l and hour h

in-depth. Frequency is a common control variable which directly reflects the microgrid security [9]. Improper management of the frequency excursions not only queers the microgrid sustainability but also biases its economic and environmental targets. The interdependent coupling between the microgrid frequency and precise energy and reserve scheduling leads the MGCC to devise an