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Smart microgrid energy and reserve scheduling with demand response using stochastic optimization

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ABSTRACT

Demand side participation is one of the important resources that help the operator to schedule generation and consumption with lower cost and higher security. Customers can participate in both energy and reserve operational scheduling and earn benefit from reducing or shifting their consumption. In this paper, a novel stochastic energy and reserve scheduling method for a microgrid (MG) which considers various type of demand response (DR) programs is proposed. In the proposed approach, all types of customers such as residential, commercial and industrial ones can participate in demand response programs which will be considered in either energy or reserve scheduling. Also, the uncertainties related to renewable distributed generation are modeled by proper probability distribution functions and are managed by reserve provided by both DGs and loads. The proposed method was tested on a typical MG system comprising different type of loads and distributed generation units. The results demonstrate that the adoption of demand response programs can reduce total operation costs of a MG and determine a more efficient use of energy resources.

Introduction

Intelligent electrical grids with renewable energy sources have attracted increasing public attention in recent years. Green (solar and wind in particular) energy production is supposed to increase significantly in the next years. Microgrids (MGs) can be key solutions for integrating renewable and distributed energy resources, as well as distributed energy-storage systems [1,2]. According to the United States Department of Energy (DOE) definition, a MG consists of a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries. A MG acts as a single controllable entity with respect to the grid and can connect and disconnect from the grid in order to operate in both grid-connected and islanded mode [3]. The MG concept has been essentially introduced in order to support a better renewable energy penetration into the utility grid, to respond to some grid issues, such as peak shaving, and to reduce energy costs [4–6]. So, MG can be located in LV or MV level base on distribution networks configurations and voltage levels. A MG can be at LV or MV level, however, in most of studies and projects, MGs are usually LV networks and are interconnected to the MV distribution network [7–9]. In order to achieve the full benefits from the operation of MGs, it is important that the integration of the distributed resources into the LV grids, and their relation with the MV network upstream, contribute to optimize the general operation of the system [9].

On the other hand, a huge penetration of renewable energy sources may affect reliable and secure operation of the MG due to the intermittent nature of these resources [10]. So, the microgrid operator (MGO) usually faces renewable generation uncertainty as well as load demand uncertainty. This increased uncertainty must be considered when determining the requirements for spinning reserve (SR) in order to protect the power system against sudden load and renewable generation changes [11]. In some approaches, the total amount of reserve requirement of the grid is determined before the energy scheduling and without considering the probabilistic behavior renewable resources. This method is named deterministic energy and reserve scheduling [11–14]. On the other hand, in the stochastic method, the uncertainties related to renewable generation and load demand are modeled by scenarios and the reserve scheduling is carried out based on the probabilities of scenarios [15,16]. Some studies evidenced that the stochastic method has lower operational costs if compared with the deterministic ones [11,17].

In [7], a smart energy management system (SEMS) was presented to optimize the operation of the MG. The paper also considered photovoltaic (PV) output in different weather conditions as

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Nomenclature

Indices

t	index of optimization period, $t = 1, 2, \ldots, 24$
i	index of industrial customers, $i = 1, 2, \ldots, I$
b	index of commercial customers, $b = 1, 2, \ldots, B$
h	index of residential customers (home), $h = 1, 2 \ldots, H$
ty	index of shiftable appliances
k	index of steps in load reduction offer, $k = 1, 2, \ldots, K$
n, m	index of buses, $n = 1, 2, \ldots, N$
j	index of non-renewable DGs, $j = 1, 2, \ldots, J$
s	index of scenarios, $s = 1, 2, \ldots, S$
w	index of wind turbines, $w = 1, 2, \ldots, W$
pv	index of PV units, $pv = 1, 2, \ldots, Pv$

Variables

Binary variable

$u(j,t)$	on/off status (1/0) of the non-renewable DG j in period t
$us(j,t,s)$	on/off status (1/0) of the non-renewable DG j in period t and scenario s
$d(t,h,ty)$	on/off status (1/0) of home appliances ty at home h and in period t
$Y(t)$	1 if battery starts charging in period t and 0 otherwise
$X(t)$	1 if battery starts discharging in period t and 0 otherwise

Continuous variable

$Ecost$	total expected cost ($)
l_k^i	accepted load reduction of industrial customer i in step k of price-quantity offer package (kW)
$IC^E(i,t)$	total scheduled load reduction quantity prepared by the industrial customer i in period t (kW)
$IC^s(i,t,s)$	required load reduction quantity prepared by the industrial customer i in period t and scenario s (kW)
$IP^E(i,t)$	cost due to load reduction provided by industrial customer i in period t ($)
$IC^R(i,t)$	scheduled reserve provided by industrial customer i in period t (kW)
$IP^R(i,t)$	cost due to committing reserve provided by industrial customer i in period t ($)
$IP^s(i,t,s)$	cost due to load reduction provided by industrial customer i in period t and scenario s ($)
$CC^E(b,t)$	scheduled load reduction provided by commercial customer b in period t (kW)
$CC^s(b,t,s)$	required load reduction provided by commercial customer b in period t and scenario s (kW)
$CC^R(b,t)$	scheduled reserve provided by commercial customer b in period t (kW)
$CP^E(b,t)$	cost due to load reduction provided by commercial customer b in period t ($)
$CP^R(b,t)$	cost due to committing reserve provided by commercial customer b in period t ($)
$CP^s(b,t,s)$	cost due to load reduction provided by commercial customer b in period t and scenario s ($)
$RC^E(h,t)$	scheduled load reduction provided by residential customer h in period t (kW)
$RC^R(h,t)$	scheduled reserve provided by residential customer h in period t (kW)
$RP^E(h,t)$	cost due to load reduction provided by residential customer h in period t ($)
$RP^R(h,t)$	cost due to committing reserve provided by residential customer h in period t ($)
$RP^s(h,t,s)$	cost due to load reduction provided by residential customer h in period t and scenario s ($)
$P_{grid}(t)$	scheduled purchased energy from the main grid in period t (kW)
$C_{DG}(j,t)$	hourly fuel cost of non-renewable DG j in period t ($)
$Cs_{DG}(j,t,s)$	hourly fuel cost of non-renewable DG j in period t and scenario s ($)
$P_{DG}(j,t)$	scheduled active output power of non-renewable DG j in period t (kW)
$Ps_{DG}(j,t,s)$	active output power of non-renewable DG j in period t and scenario s (kW)
$R_{DG}(j,t)$	scheduled spinning reserve provided by non-renewable DG j in period t (kW)
$ENS(s,t)$	the amount of involuntarily load shedding in period t and scenario s (kW)
$Po_w(t)$	scheduled wind power of wind turbine w at hour t (kW)
$Po_{pv}(t)$	scheduled solar power of PV unit pv at hour t (kW)
$Loss(t)$	total network losses in period t (kW)
$SU(j,t)$	start up cost of non-renewable DG j in period t ($)
$P_B^+(t)$	scheduled battery discharge power in period t (kW)
$P_B^-(t)$	scheduled battery charge power in period t (kW)
$\lvert V(n,t)\rvert$	voltage amplitude at node n and in period t, p.u.
$\delta(n,t)$	voltage angle at node n and in period t
$P_{inj}(n,t)$	net injected active power to node n and in period t, p.u.
$Q_{inj}(n,t)$	net injected reactive power to node n and in period t, p.u.

Parameters

$P_L(t)$	total hourly demand of MG in period t (kW)
l_k^i	price offer of industrial customer i in step k ($/kW)
$q^{I,r}(i,t)$	reserve price of industrial customer i for being in standby in period t ($/kW)
L_{Max}^i	maximum quantity of load reduction offered by industrial customer i in period t (kW)
$CC_b^{max}(b,t)$	maximum quantity of load reduction offered by commercial consumer b in period t (kW)
$q^{C,E}(b,t)$	price offer of commercial customer b for energy reduction in period t ($/kW)
$q^{C,R}(b,t)$	price offer of commercial customer b for committing reserve in period t ($/kW)
$RC^{Max}(h,t)$	maximum quantity of load reduction offered by residential customer h in period t (kW)
$q^{R,E}$	price offer of residential customer h for energy reduction in period t ($/kW)
$q^{R,R}$	price offer of residential customer h for committing reserve in period t ($/kW)
$HDA(t,h,ty)$	power consumption of shiftable appliances ty at home h that turn on in period t ($\tau s \leqslant t \leqslant \tau e$), (kW)
$HDA^{Max}(h,ty)$	nominal power of shiftable appliance ty at home h (kW)
$f_w(v)$	Rayleigh probability distribution function
v	wind speed (m/s)
$f_b(\phi)$	beta probability distribution function
ϕ	solar irradiance (kW/m^2)
$P_{pv}(\phi)$	PV output power (kW) for irradiance ϕ
η^{pv}	efficiency of PV (%)
S^{pv}	total area of PV (m^2)
$P_w^s(s,t)$	wind turbine w output power in period t and scenario s (kW)
$P_{pv}^s(s,t)$	PV pv output power in period t and scenario s (kW)
$Ta_g^E(t)$	hourly electricity price ($/kW)
$C_{DGj}^R(j,t)$	reserve price of non-renewable DG j in period t ($/kW)
$VOLL(t)$	value of lost load in period t ($/kW)