Applied Energy 191 (2017) 170–182

Contents lists available at ScienceDirect

Applied Energy

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

Minimizing unbalances in low-voltage microgrids: Optimal scheduling of distributed resources

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HIGHLIGHTS

- The paper deals with unbalanced low voltage microgrids.
- Unbalances are a critical issue as they can increase losses and heating effects.
- A strategy is proposed that reduces voltage unbalances and minimizes other objectives.

ARTICLE INFO

Article history:
Received 6 October 2016
Received in revised form 31 December 2016
Accepted 24 January 2017
Available online 1 February 2017

Keywords:
Microgrids
Dispersed storage and generation
Optimization methods
Control strategies
Scheduling

ABSTRACT

In this paper, a comprehensive strategy for the scheduling of unbalanced microgrids is proposed. The microgrids are characterized by the presence of a variety of distributed resources, such as data centers, electric vehicles, and distributed generation systems. The operation strategy is based on the solution of a multi-objective optimization problem, whose objective functions are related to specific services and requirements of the microgrid, such as cost minimization, power quality improvements, and energy savings. Particular attention is paid to the unbalances presence in the microgrid with the aim to outline how the proposed strategy is able to significantly reduce them taking contemporaneously into account other important economic and technical objectives. An analysis of the objectives and the different operational perspectives also is proposed, which allows us to exploit the effectiveness of the multi-objective approach. The results of numerical applications are presented to show the effects of the considered strategy in terms of achievable advantages.

1. Introduction

Microgrids (μGs) must meet several needs and expectations of customers and of the various stakeholders involved in the electrical energy chain [1]. This heterogeneity requires identifying a μG's operation policy so that it is able to address a variety of targets related to efficiency, power quality (PQ), resiliency, and affordability [2]. The operation policy should carefully take into account the presence of distributed energy resources (DERs), such as generating units and responsive loads that can have positive impacts in terms of the efficiency and sustainability of the system but also they can have negative effects in terms of PQ and the reduction of reliability. In fact, as is well known, the uncertainties of some types of generating units (i.e., those based on wind and solar energy sources) and of loads (e.g., plug-in electric vehicles, PEVs) are responsible for line overloading and critical voltage profiles. Moreover, unexpected peak power in load demand or in power generation could lead to problems in matching generation and loads [3,4]. In the low voltage (LV) μGs characterized by uneven distribution of single phase loads and generators and of unbalanced lines, the PQ problems are even more critical due to the unbalances [5,6]. The criticalities related to the unbalance presence have been widely discussed in the technical literature [6–14]. Unbalance in the phase voltages and the consequent flow of large unbalanced currents can increase losses as well as heating effects so compromising power electronic converters and induction motors [6]. In the case of LV μGs, typically made by four-wire circuit configuration, the presence of zero-sequence components in the currents flowing through the line and neutral conductors also can cause overloading of distribution feeders and transformers [7]. Moreover, when the μG includes micro-generation units equipped with synchronous generators such as wind turbines, micro-hydro plant and bio-diesel powered generators, unbalanced loading can cause excessive mechanical stress and noise due to a

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http://dx.doi.org/10.1016/j.apenergy.2017.01.057
0306-2619/

Nomenclature

B_{ij}^{pk} term of the susceptance matrix corresponding to the bus i with phase p and the bus j with phase k
C_E daily cost of the energy imported from the upstream grid
E_{bi}^{ch} battery SoC of the UPS at bus i at the beginning of the charging period
E_{bi}^{dch} battery SoC of the UPS at bus i at the beginning of the discharging period
E_{bi}^{max} battery's size of the UPS at bus i
E_{bi}^{min} minimum value of the energy to be stored in the UPS's battery at bus i
E_{loss} daily energy lost
G_{ij}^{pk} term of conductance matrix corresponding to the bus i with phase p and the bus j with phase k
$I_{l,t}$ phase current flowing through line l during the tth time interval
I_l^r ampacity of the phase current flowing through the lth line
$P_{1,t}$ three-phase active power imported from the upstream grid at the tth time interval
$P_{bi,t}$ power provided by the battery equipping the UPS at bus i, during the tth time interval
P_{bi}^{ch} maximum charging power of the battery of the UPS at bus i
P_{bi}^{dch} maximum discharging power of the battery of the UPS at bus i
P_D peak value of the daily imported power profile
$P_{EVC_{i,t}}^{ch}$ maximum power that the EVC can absorb from the grid at the ith bus, during the tth time interval
$P_{EVC_{i,t}}^{dch}$ maximum power that the EVC can supply to the grid at the ith bus, during the tth time interval
$P_{i,t}^{p}$ active power at bus i with phase p during the tth time interval
$P_{i,t}^{p,sp}$ forecasted active power at bus i with phase p during the tth time interval
$P_{li,t}^{sp}$ power requested by the privileged loads of the UPS at the ith bus, during the tth time interval
$Q_{1,t}$ three-phase reactive power flowing through the transformer during the tth time interval
$Q_{i,t}^{p}$ reactive power at the ith bus with phase p during the tth time interval
$Q_{i,t}^{p,sp}$ forecasted reactive power at bus i with phase p during the tth time interval
R_l resistance of line l
$S_{DC,i}$ rating of the UPS's converter at the ith bus
$S_{DG,i}$ rating of the DG's converter at the ith bus
$S_{EVC,i}$ rating of the EVC at the ith bus
S_{tr} size of the interconnecting transformer
$SE_{i,j}^{0}$ specified value of the energy stored in the battery of the jth PEV plugged-into the EVC connected to the ith bus at the arrival time
$SE_{i,j}^{exp}$ specified value of the energy stored in the battery of the jth PEV plugged-into the EVC connected to the ith bus at the departure time
$SE_{i,j}^{max}$ maximum value of the energy that can be stored in the battery of the jth PEV plugged-into the EVC connected to the ith bus
$SE_{i,j}^{min}$ minimum value of the energy that can be stored in the battery of the jth PEV plugged-into the EVC connected to the ith bus
SM daily mean value of security margin
Vd daily mean value of voltage deviation
$V_{i,t}^{(d)}$ positive sequence of the ith bus voltage during the tth time interval
$V_{i,t}^{(i)}$ negative sequence of the ith bus voltage during the tth time interval
$V_{i,t}^{p}$ magnitude of the ith bus voltage with phase p during the tth time interval
V_{max} maximum admissible value of the phase voltage
V_{min} minimum admissible value of the phase voltage
V^{slack} specified value of the voltage magnitude at slack bus
V^{sp} desired value of $V_{i,t}^{p}$
$a_{i,j}$ first time interval in which the jth PEV is plugged-into the ith EVC
$d_{i,j}$ last time interval in which the jth PEV is plugged-into the ith EVC
i bus index
j PEV index
kd daily mean value of unbalance factor
kd_{max} maximum value of unbalance factor
$kd_{i,t}$ unbalance factor at the ith bus during the tth time interval
l line index
n number of μG's busses
nt number of time intervals of the day
p phase index
t time interval index
Δt duration of time intervals
Ω_b set of busses where kd has to be minimized
Ω_{ch} set of time intervals in which the UPS's battery is allowed to charge
Ω_{dc} set of busses where data centers are connected
Ω_{dch} set of time intervals in which the UPS's battery is allowed to discharge
Ω_{DG} set of busses where DG units are connected
Ω_{EVC} set of busses where the EVCs are connected
Ω_{EVi} set of PEVs plugged-into the ith EVC
Ω_G set of the μG busbars
Ω_L set of load busses
Ω_l set of lines of the μG
$\Omega_{i,j}$ set of the time intervals where the jth PEV is plugged-into the ith EVC
Ω_t set of time intervals in which a day is divided
α_t price of energy during the tth time interval
η_{EVC} charging efficiency related to the EVC
η_{inv} efficiency of the UPS's converter operated as an inverter
η_{rect} efficiency of the UPS's converter operated as a rectifier
$\vartheta_{i,t}^{p}$ phase-voltage argument of the ith bus voltage with phase p during the tth time interval

double system frequency, so reducing the efficiency and life of the synchronous generator [8]. The solutions proposed to reduce unbalances vary depending on the specific application. In [11] a hierarchical control structure is proposed to reduce the effects of the power oscillations caused by grid unbalances on the converters used to interface distributed generation (DG) units. In [12] a control including primary, secondary, and tertiary levels is proposed to realize optimal unbalance compensation in islanded μGs by means of a genetic algorithm based procedure. Ref. [13] proposes a control algorithm for three phase inverters connecting DG units to domestic distribution systems. In [14] the improvement in terms of phase-balancing that can be obtained by using battery energy storage systems in LV feeders is analyzed. From the above considerations it clearly appears that unbalances must be limited in order to avoid abnormal operation of the μG and of its loads or curtailment of clean power production [15–17].