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An integrated tool for optimal energy scheduling and power quality improvement of a microgrid under multiple demand response schemes

Dimitrios Thomas[a,b,*], Gaspard D'Hoop[a], Olivier Deblecker[a], Konstantinos N. Genikomsakis[b], Christos S. Ioakimidis[b]

[a] Department of Electrical Engineering, University of Mons, 7000 Bd Dolez 31, Mons, Belgium
[b] ERA Chair 'Net-Zero Energy Efficiency on City Districts', Research Institute for Energy, 7000 Rue de l'Epargne 56, Mons, Belgium

HIGHLIGHTS

- Energy scheduling for optimal power dispatch and total system cost minimization.
- Financially incentivized flexibility services between microgrid and market operator.
- Framework which checks and mitigates power quality issues of the optimal solution.
- Power quality restored with a small number of iterations and additional system cost.

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ABSTRACT

This paper presents an integrated tool to mitigate power quality issues in a microgrid through coordinating the operating schedule of its generating resources and loads. Such a microgrid includes renewable and conventional distributed energy resources, electric vehicles, energy storage, linear and nonlinear loads, while it serves as an example small-to-medium scale residential and commercial buildings. The proposed tool operates on a sequential, two-stage basis: at the first stage the energy management system (EMS) ensures that the microgrid's generation resources and loads are dispatched at the minimum total system cost. In addition, it assesses the potential provision of flexibility services towards the system operator, relying on financially incentivized power signal requests. At the second stage, the power quality (PQ) framework evaluates whether the proposed optimal solution complies or not with several PQ standards applicable to the distribution level. The unique characteristic of the proposed tool is the self-triggered interaction between the EMS and the PQ framework, which identifies potential PQ violations, and restores the PQ indices to acceptable levels through an iterative process. Case studies have been performed with realistic model parameters to verify the performance of the proposed integrated tool. The obtained results demonstrate the effectiveness of the algorithm in managing voltage deviations, voltage unbalance, as well as harmonic distortions with a small additional cost for the total system.

1. Introduction

1.1. Background and motivation

A microgrid is a low-voltage power distribution system organized based on the control capabilities over the main network and it is characterized by distributed energy resources (DERs) and controllable loads. DERs comprise a variety of distributed generation (DG) units such as photovoltaics (PVs), distributed storage units (batteries, energy capacitors, etc.), wind turbines, and autonomous power stations (APS) which usually consume diesel or heavy oil (mazut) fuel. Controllable loads such as electric vehicles (EVs), heating, ventilation, and air-conditioning (HVAC) systems can be deferred or shed to balance supply and demand in the microgrid. Power flow in microgrids is controlled and monitored by an energy management system (EMS) ensuring that specific operational objectives (e.g., cost minimization) are met. To achieve this, an EMS adjusts the power imported from or exported to the main grid, the operation and dispatch of DERs, and the controllable loads [1].

Microgrids propose new features to electricity industry offering additional possibilities for multi-stage electrical power grid operation, control and management. Some of the new features comprise advanced

* Corresponding author.
E-mail address: dimitrios.thomas@umons.ac.be (D. Thomas).

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Nomenclature

$\alpha_{l,t}^{\Delta V,\text{lim}}$	parameter bounding $\alpha_{l,t}^{\Delta V}$ at each iteration
$\alpha_{l,t}^{\Delta V}$	artificial variable for restoring voltage deviation index
$\alpha_t^{\text{hd,lim}}$	parameter for bounding $\alpha_t^{\text{hd,lim}}$ at each iteration
α_t^{hd}	artificial variable for restoring voltage harmonic distortion index
$\alpha_t^{\text{unb,lim}}$	parameter for bounding $\alpha_t^{\text{unb,Ph}(\cdot)}$ at each iteration
$\alpha_t^{\text{unb,Ph}(\cdot)}$	artificial variable for restoring voltage unbalance index
λ^{hd}	sensitivity parameter related with the rate of change of α_t^{hd}
λ^{unb}	sensitivity parameter related with the rate of change of $\alpha_t^{\text{unb,Ph}(\cdot)}$
$\lambda_{\Delta V}$	sensitivity parameter related with the rate of change of $\alpha_{l,t}^{\Delta V}$
$\widetilde{\varepsilon}$	value of residual energy [$/kWh]
$\varepsilon_t^{\text{buy/sell}}$	day ahead electricity buy/sell price at time t [$/kWh]
$\xi_{(\cdot),t}$	auxiliary binary variable
$C^{\text{grid,react.}}$	penalty factor to restrict the reaactive power exhange with the grid [$/kVAR]
$C^{\text{EV,deg}}$	EV battery degradation cost [$/kWh]
$C^{\text{DER,react.}}$	penalty factor to restrict the reaactive power exhange among microgrid DERs [$/kVAR]
$C_r^{\text{DG,op}}$	operational cost for DG r [$/kWh]
C_r^{ST}	start-up cost for DG r [$]
$L_t^{\text{dem}(\cdot)}$	limit of demand-related active power alteration request at time t [kW]
$L_t^{\text{sup}(\cdot)}$	limit of supply-related active power alteration request at time t [kW]
$p_{k,t}^{\text{EV,ch/dis}}$	(dis) charging power of EV k at time t [kW]
$p_{l,ty,t}^{\text{load}}$	active power to serve load l of type ty at time t [kW]
$p_{r,t}^{\text{DG}}$	active power from DG r at time t [kW]
$p_{s,t}^{\text{ES,dis/ch}}$	(dis) charging power of storage s at time t [kW]
$p_t^{\text{grid,in/out}}$	active power drawn from/ injected to the grid at time t [kW]
$q_{l,ty,t}^{\text{load}}$	reactive power to serve load l of type ty at time t [kVAR]
$q_{s,t}^{\text{ES,gen/abs}}$	reactive power generated/absorbed from storage s at time t [kVAR]
$q_{r,t}^{\text{DG,gen/abs}}$	reactive power generated/absorbed from DG r at time t [kVAR]
$q_t^{\text{grid,in/out}}$	reactive power drawn from/ injected to the grid at time t [kVAR]
$R_t^{\text{dem}(\cdot)}$	reward for meeting demand-related request at time t [$/kWh]
$R_t^{\text{sup}(\cdot)}$	reward for meeting supply-related request at time t [$/kWh]
$soe_{k,t}^{\text{EV}}$	state of energy for EV k at time t [kWh]
$soe_{s,t}^{\text{ES}}$	state of energy for storage s at time t [kWh]
$z_t^{\text{dem}(\cdot)}$	total active power demand related with demand request alteration [kW]
$z_t^{\text{sup}(\cdot)}$	total active power supply related with supply request alteration [kW]

Acronyms

APS	Autonomous Power Station
DA	Day Ahead
DER	Distributed Energy Resource
DG	Distributed Generation
DHW	Domestic Hot Water
DR	Demand Response
DSO	Distribution System Operator
EMS	Energy Management System
ES	Energy Storage
EV	Electric Vehicle
HVAC	Heating Ventilation Air-Conditioning
IEEE	Institute of Electrical and Electronics Engineers
MILP	Mixed Integer Linear Programming
PCC	Point of Common Coupling
PF	Power Factor
PQ	Power Quality
PV	Photovoltaic
RMS	Root Mean Square
TC	Total Cost
THD	Total Harmonic Distortion
VOLL	Value of Lost Load
VUF	Voltage Unbalance Factor
WT	Wind Turbine
X/R	Reactance on Resistance ratio

smart metering, demand-side management systems and communication infrastructure providing real-time information for all system variables [2]. On the one hand and from a microgrid's point of view the aforementioned features combined with a demand-response (DR) strategy can decrease the total cost of energy supply, meeting at the same time microgrid's electricity and thermal demands. On the other hand, a microgrid can provide flexibility to a distribution system operator (DSO) in the form of ancillary services by responding to its signals for power supply/demand increase/decrease [3]. In addition, the accelerated development of microgrid has paved the way for the interconnection of multiple microgrids to provide regional power supply. As a result, the power exchange and the coordination of the DG units within the individual microgrids forming a multi-microgrid system is a complex problem that requires efficient and reliable energy management [4].

An important advantage of microgrids lies on their ability to remain operational even when the public power network encounters extensive blackouts. By taking advantage of their on-site distribution generation, microgrids can supply critical loads and keep crucial consumers in operation during blackouts in islanded mode. However, despite the aforementioned essential advantage, several reasons may prevent the uninterrupted and smooth islanded microgrid operation. The most frequent and significant reasons are: DG may not be able to regulate the voltage and frequency within the islanded system, fault contribution from DG may not be sufficient to allow satisfactory operation of protection systems, the parallel operation of DG units within the islanded mode may cause problems, etc. [5]. Therefore, it is important to determine the requirements for a safe and reliable microgrid operation which is able to overcome the above-mentioned challenges. Such an energy management framework which combines proactive and reactive approaches to efficiently address the uncertainties associated with generation and demand in islanded and interconnected microgrids is proposed in [6].

One of the primary operational challenges that arises in a microgrid, either it is related with its own EMS operation (in grid-connected or islanded mode), or with its action as an ancillary service to the DSO, is associated with power quality (PQ) management. Due to the usually small generation capacity, the physical operating characteristics of the microgrid's equipment and appliances can substantially affect the microgrid current, voltage and frequency resulting in harmful harmonic distortions. Thus, the microgrid's equipment operating characteristics must be sufficiently modeled taking into count both the fast time scales related with local controls and the longer time scales associated with energy scheduling.