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Security-constrained optimal energy management system for three-phase residential microgrids

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ABSTRACT

This paper presents a mixed-integer linear programming (MILP) model for the optimal energy management of residential microgrids, modeled as unbalanced, three-phase, electrical distribution system (EDS). Initially, the problem is formulated as a mixed-integer nonlinear programming (MINLP) problem. Then, a set of linear approximations and equivalent mathematical representations are used to obtain a precise MILP model. The proposed formulation considers three-phase generation units (GU), single-phase photovoltaic (PV) resources, and single-phase energy storage systems (ESS), as well as load management. The aim of the proposed model is to minimize the final operational costs of the microgrid while considering operational constraints of the EDS and an unexpected outage of the main grid through a security-constrained set of equations. The optimal solution of the MILP model is found using commercial convex optimization solvers. The proposed model was tested in a residential, three-phase EDS. Results show that the proposed linearizations and approximations produce accurate solutions when compared with a nonlinear three-phase OPF formulation, with an error in the objective function near to 2% and a maximum error in the voltage near to 1%. Efficiency and flexibility of the proposed methodology are also discussed.

1. Introduction

Microgrids are supervised electrical networks used to energize low voltage loads in a limited, small-scale, geographic area. Besides regular networks, microgrids can be comprised of renewable/non-renewable generation units (GUs), energy storage systems (ESSs) and controllable loads. Thus, an energy management system (EMS) can be designed to efficiently control and dispatch all resources within the microgrid, in order to optimize active and reactive power injections, voltage profiles, operational costs, and others [1].

Since the management functionalities of a microgrid deal with issues from different technical areas, time scales and infrastructure levels, the hierarchical control scheme has been widely accepted as a standardized solution [2]. In general, the hierarchical control scheme comprises of three different levels: (i) the primary level, responsible for local control of the DERs units; (ii) the secondary level, which deals with primary deviations in variables as frequency and voltage, and (iii) the tertiary level, which is also known as the energy management system, which introduce intelligence to the system to manage and coordinate the operation of optimal power flows [3]. In terms of the structure of the EMS, there are two approaches commonly used in practical applications: centralized and decentralized schemes [4,5]. The difference between these approaches lies in the way they receive and process all the information from the different modules that comprise an EMS.

To provide an optimal schedule, the EMS formulates and solves an energy management (EM) problem, considering load consumption, renewable resources, the operational variables of the electrical distribution system (EDS), energy and thermal costs, and the charging/discharging features of the ESSs [6]. In general, the EM problem schedules the dispatchable generation and storage units in order to achieve economical operation, while guaranteeing that electrical and operational constraints of the system are satisfied. Thus, the EM problem falls into the category of mixed-integer nonlinear programming (MINLP) problems, in which the objective function includes nonlinear terms and binary decision variables, subject to a set of non-convex constraints that represent the EDS operation, and the commitment decisions of the GUs and the ESS.

Several works have addressed the EM problem using MILP and MINLP formulations [7]. In [8], the EM problem of a renewable-

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Nomenclature

Sets

F set of phases, F={A, B, C}
K set of outages of the main grid, $K = \{1, \ldots, \mathcal{T}\}$
L set of circuits
N set of nodes
T set of time intervals, $T = \{1, \ldots, \mathcal{T}\}$

Indexes

f, h phase $f \in F$, and phase $h \in F$
k outage $k \in K$ of the main grid
mn circuit $mn \in L$
n, m nodes $n \in N$ and $m \in N$
s sth binary variable used for the discretization of the SOC
t time interval $t \in T$
U main grid's node $U \in N$
y yth block used for the piecewise linearization of the GU's quadratic term
λ λth block used for the piecewise linearization of the squared circuit currents

Parameters

α_t cost of energy at time t
α_n^B investment cost for each ESS at node n
α^C load curtailment cost
α_0^G constant operational cost of the GU
α_1^G linear operational cost of the GU
α_2^G quadratic operational cost of the GU
Δ_t duration of each time interval t
$\bar{\Delta}_n^G$ discretization step used for the piecewise linearization of each GU's quadratic term at node n
Δ_n^S length of the interval used for the discretization of the SOC at node n
$\bar{\delta}_{mn}$ discretization step used for the piecewise linearization of each squared current at circuit mn
η^B efficiency of the ESS
Λ number of blocks used for the piecewise linearization of the squared circuit currents
$\sigma_{mn,\lambda}$ slope of the λth block used for the piecewise linearization of the squared current at circuit mn and block λ
θ_f reference phase angle
θ_1 maximum negative deviation of the phase angle
θ_2 maximum positive deviation of the phase angle
ζ load curtailment percentage
C^B nominal charge of the ESS
E_n^B nominal energy of the ESS at node n
$\bar{E}_n^B$ maximum charging/discharging energy rate of the ESS at node n
$\bar{I}_{mn}$ maximum current magnitudes at circuit mn
k^B, d^B parameters related to the costs of the ESS
$m_{n,y}^G$ slope of the yth block used for the piecewise linearization of the GU's quadratic term at node n
MDT_n minimum off-line time of the GU at node n
MUT_n minimum on-line time of the GU at node n
$P_{n,t}^{PV}$ active power supplied by the PV at node n, and time t
$P_{n,f,t}^D$ forecasted active demand at node n, phase f and time t
$\bar{P}_n^G$ maximum active generation of the GU at node n
$\underline{P}_n^G$ minimum active generation of the GU at node n
pf_n minimum power factor of the GU at node n
$Q_{n,f,t}^D$ forecasted reactive demand at node n, phase f and time t
$\bar{Q}_n^G$ maximum reactive generation of the GU at node n
$\underline{Q}_n^G$ minimum reactive generation of the GU at node t
$R_{mn,f,h}$ resistance of circuit mn between phases f and h
RD_n ramp-down constraint of the GU at node n
RU_n ramp-up constraint of the GU at node n
S number of auxiliary variables used for the discretization of the SOC
$\underline{SOC}_n$ minimum SOC of the ESS at node n
$\bar{SOC}_n$ maximum SOC of the ESS at node n
$\bar{T}_n^{G,\mathrm{ON}}$ maximum total on-line time of the GU at node n
$\mathcal{T}$ maximum time interval in the operational period
$V_{n,f,t}^{re*}$ real part of the estimated voltages at node n, phase f and time t
$V_{n,f,t}^{im*}$ imaginary part of the estimated voltages at node n, phase f and time t
$\underline{V}$ minimum voltage magnitude of the system
$\bar{V}$ maximum voltage magnitude of the system
$X_{mn,f,h}$ reactance of circuit mn between phases f and h
Y number of blocks used for the piecewise linearization of the GU's quadratic term

Continuous variables

$\delta_{mn,f,k,t,\lambda}^{im}$ imaginary part of the λth block used for the piecewise linearization of the squared current at circuit mn, phase f, outage k and time t
$\delta_{mn,f,k,t,\lambda}^{re}$ imaginary part of the λth block used for the piecewise linearization of the squared current at circuit mn, phase f, outage k and time t
$\Delta_{n,k,t,y}^G$ value of the yth block used for the piecewise linearization of the GU's quadratic term at node n, outage k, time t and block y
$\Phi_{n,t-1}^{\mathrm{CH}}$ variable used to represent the product between $b_{n,t}^{\mathrm{CH}}$ and $SOC_{n,t-1}$
$\Pi_{n,t}$ variable used to represent the product between $E_{n,t}^{\mathrm{DCH}}$ and $SOC_{n,t}$
$\Psi'_{n,k,t-1}$ variable used to represent the product between $T_{n,k,t-1}^{G,\mathrm{ON}}$ and $u_{n,k,t-1}$
$\Psi''_{n,k,t}$ variable used to represent the product between $T_{n,k,t-1}^{G,\mathrm{ON}}$ and $u_{n,k,t}$
$E_{n,t}^{CH}$ energy of the ESS at node n and time t in charging mode
$E_{n,t}^{DCH}$ energy of the ESS at node n and time t in discharging mode
$\tilde{E}_{n,t,s}^{\mathrm{DCH}}$ variable used to consider the sequential corrections of $E_{n,t}^{\mathrm{DCH}}$
$I_{mn,f,k,t}^{im}$ imaginary part of the current at circuit mn, phase f, outage k and time t
$I_{n,f,k,t}^{Dim}$ imaginary part of the current demanded at node n, phase f, outage k and time t
$I_{n,f,t}^{Bim}$ imaginary part of the current demanded/supplied by the ESS at node n, phase f and time t
$I_{n,f,k,t}^{Gim}$ imaginary part of the current supplied by the GU at node n, phase f, outage k and time t
$I_{n,f,k,t}^{PVim}$ imaginary part of the current supplied by the PV at node n, phase f, outage k and time t
$I_{U,f,k,t}^{Uim}$ imaginary part of the current supplied by the main grid at node U, phase f, outage k and time t