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A mixed integer linear programming model for the energy management problem of microgrids

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ABSTRACT

This paper presents a mathematical model for the energy management (EM) problem of a microgrid (MG) by means of a mixed integer linear programming approach. In the EM problem, the objective is to determine a generation and a controllable load demand policy that minimises, over a planning horizon, the operation cost subject to economical and technical constraints. We propose a detail modelling for microturbines (MTs) and fuel cells (FCs), where the constraints associated with such factors as the ramps, minimum up and downtime, and generation limits, represent various peculiarities that have not been adequately considered in literature. The proposed model also considers a detailed representation of critical, reschedulable and curtailable loads, which are important aspects in the MG concept. To analyse the proposed modelling, a MG is used along with a MT, a FC, a battery bank, wind and photovoltaic generators connected to the main grid. The results indicate that the model is adequate for the MG EM.

1. Introduction

The modern electrical energy industry addresses more affordable electronic technologies. The integration of small Distributed Energy Resources (DERs), such as Microturbines (MTs), Fuel Cells (FCs), batteries, wind and photovoltaic generators, is a trend that is currently in progress. The presence of the DERs and the demand management can reduce fossil fuel consumption, load peak shaving, as well as postpone investments in new transmission and distribution lines [1,2]. In this new paradigm, it is important to highlight the Microgrids (MGs), which are emerging as an additional element to maintain the growth and sustainability of the modern electric energy industry. Roughly speaking, a MG consists of a group of DERs and controllable and uncontrollable loads that operate either synchronised with the main grid or autonomously.

Despite several advantages of MGs, the new challenges are inherent, such as those related to DERs. In this context, a methodological challenge that supports the economic and technical operational issues of MGs is the energy management (EM) problem [3,4]. In general, solving this problem requires determining a generation and a controllable load demand policy that minimises, over a planning horizon, an objective function subject to economical and technical constraints. The policy is given by the on/off status, the respective output active power of each DER, the on/off status of the curtailable load demand (CLD) and the schedule of the reschedulable load demand (RLD). This strategy is used for the voltage and frequency control in MG real-time operation. Therefore, because it is necessary to minimise an objective function subject to constraints, the EM is usually performed based on the solution of an optimisation problem, although there are other possibilities, such as fuzzy logic and expert systems [5,6] and hierarchical and decentralised control [7,8].

The EM in [9] is performed for a MG with wind and thermal generations, aiming for the minimisation of the total operation cost and considering the stochastic behaviour of the wind. In [10], the EM addresses a MG composed of batteries and photovoltaic generation with connected operation with the main grid, which allows for the purchasing and selling of energy. In [11], the EM is performed for a MG composed of FC, wind, photovoltaic generation and batteries, considering a quadratic objective function for the cost. In [12], the EM is performed for a Microgrid with a MT, a FC, a diesel, a wind, and a photovoltaic generator and a battery, with a multi-objective approach to minimise the cost of operation and reduce

Abbreviations: CLD, curtailable load demand; DER, distributed energy resource; FC, Fuel cells; MG, microgrid; MILP, mixed-integer linear programing; MT, microturbine; RLD, reschedulable load demand; SOFC, solid oxide fuel cell.

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Nomenclature

Index/sets

- a index related to MTs ($a \in A$)
- b index related to SOFCs ($b \in B$)
- c index related to CLDs ($c \in C$)
- d index related to RLDs ($d \in D$)
- e index related to batteries ($e \in E$)
- i discretisation step index associated with the MTs and FCs ramps, RLD and CLD
- t index for the time step ($t \in ND$).

Variables

- dpf_{bt} absolute power output difference between $t-1$ and t stages of SOFC b (kW)
- eb_{et} energy of battery e (kWh) in step t
- pbc_{et} power charge of battery e (kW) in stage t
- pbd_{et} power discharge of battery e (kW) in stage t
- pdc_{ct} power of CLD c (kW) in stage t
- pdd_{dt} RLD d in stage t (kW)
- pde_t system deficit (kW) in stage t
- pex_t excess generation (kW) in stage t
- pf_{bt} power output of SOFC b (kW) in stage t
- pgb_t power purchased from the grid (kW) in stage t
- pgs_t power sold to the grid (kW) in stage t
- pt_{at} power output of MT a (kW) in stage t
- rb_{et} reserve of battery e (kW) in stage t
- ub_{et} binary variable that indicates whether battery e is discharging ($ub_{et}=1$) in stage t
- uc_{ct} binary variable that indicates whether CLD c is on ($uc_{ct}=1$) or off ($uc_{ct}=0$) in stage t
- ud_{dt} binary variable that indicates whether RLD d starts ($ud_{ct}=1$) in stage t
- uf_{bt} binary variable that indicates if an SOFC is on ($uf_t=1$) or off ($uf_t=0$) in stage t
- ug_t binary variable that indicates whether the MG is importing energy ($ug_t=1$) in stage t
- ut_{at} binary variable that indicates whether MT a is on ($ut_{at}=1$) or off ($ut_{at}=0$) in stage t
- yc_{ct} auxiliary binary variable for indicating the start of the load shedding in stage t of CLD c
- yf_{bt} SOFC b auxiliary binary variable for the start-up ramp rate in stage t
- yt_{at} MT a auxiliary binary variable of start-up ramp rate in stage t
- zf_{bt} SOFC b auxiliary binary variable for the shutdown ramp rate in stage t
- zt_{at} MT a auxiliary binary variable of shutdown ramp rate in stage t.

Parameters

- AT_{at}, BT_{at} constants associated with the fuel consumption function of MT a operating with a fixed ambient temperature, in (R$/h) and (R$/kWh), respectively
- BP_t energy purchase price in stage t (R$/kWh)
- CB battery e charge step ramp (kW)
- CC_c incremental cost during one hour of load shedding (R$/kWh) of CLD c
- CD load deficit incremental cost (R$/kWh)
- CE system excess energy incremental cost (R$/kWh)
- CF_b incremental operating cost of SOFC b (R$/kWh)
- DB battery e discharge ramp (kW)
- DC_{ct} forecast CLD c in stage t (kW)
- DDT_a number of stages of MT a's shutdown ramp rate
- D_t forecast critical load demand in stage t (kW)
- DT_a start-up cost of MT a (R$)
- $EB_e{}^F$ final energy of battery e (kWh)
- $EB_e{}^{max}$ battery e maximum energy (kWh)
- $EB_e{}^{min}$ battery e minimum energy (kWh)
- $EB_e{}^I$ initial energy of battery e (kWh)
- $EB_e{}^L$ energy lost in one time step of battery e (kWh)
- ED error associated with the demand (%)
- EF_b start-up cost of FC b (R$)
- EPV error associated with the photovoltaic generation (%)
- EPW error associated with the wind generation (%)
- FDD_d final stage where the RLD d load has to be fully supplied
- FT_a shutdown cost of MT a (R$)
- GF_b shutdown cost of FC b (R$)
- H horizon time (h)
- IDD_d initial stage where the RLD d could be turned on
- MFC_b maintenance incremental cost of FC b (R$/kWh)
- MTC_a maintenance incremental cost of MT a (R$/kWh)
- $NC_c{}^{max}$ maximum number of stages of load shedding for CLD c
- ND number of stages in the planning horizon
- $NDC_c{}^{st}$ maximum number of load shedding for CLD c
- $NF_b{}^{st}$ maximum number of start-ups of SOFC b
- $NT_a{}^{st}$ maximum number of start-ups allowed of MT a
- $P_a{}^{\max}$ nominal maximum output power of MT a (kW)
- PDD_{id} forecast RLD d in stage i (kW)
- $PF_b{}^{\max}$ maximum output power of SOFC b (kW)
- $PF_b{}^{\min}$ minimum output power of SOFC b (kW)
- PFU_{bi} output power in stage i of the SOFC b start-up ramp rate (kW)
- $PGB_t{}^{max}$ grid maximum power purchase in step t (kW)
- $PGB_t{}^{min}$ grid minimum power purchase in step t (kW)
- $PGS_t{}^{max}$ grid maximum power sell in step t (kW)
- $PGS_t{}^{min}$ grid minimum power sell in step t (kW)
- $PT_{at}^{\max}$ maximum output power of MT a operating with an ambient temperature of T_t (kW)
- $PT_a{}^{\min}$ minimum output power of MT a (kW)
- PTD_{ai} output power in stage i of MT a's shutdown ramp rate (kW).
- PTU_{ai} output power in stage i of MT a's start-up ramp rate (kW)
- PV_t forecast photovoltaic power in step t (kW)
- PW_t forecast wind power in step t (kW)
- RB number of time steps to the reserve of the system
- SP_t energy selling price in stage t (R$/kWh)
- Tc_a ambient temperature where the maximum output power of MT a decreases (°C)
- UDD_d number of stages in which RLD d is on
- UDF_b number of stages in the SOFC b start-up ramp rate
- UDT_a number of stages of MT a start-up ramp rate
- α_a constant for MT a (slope of the line, in kW/°C)
- $\eta_e{}^{bc}$ charge efficiency of battery e (%)
- $\eta_e{}^{bd}$ discharge efficiency of battery e (%)
- ξ_b incremental cost associated with the cycling operation of SOFC b (R$/kWh).

the greenhouse gas emissions, such as NO_x, SO_2 and CO_2. In [13], the EM is performed for a MG with thermal and wind generators and a battery, with a multi-objective approach to minimise the cost of operation and reduce the greenhouse gas emissions and energy capacity reserve. In [14], the EM is performed for a Micro-grid with thermal, wind and photovoltaic generators with batteries,