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A multi-objective model for the day-ahead energy resource scheduling of a smart grid with high penetration of sensitive loads

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HIGHLIGHTS

- A multi-objective framework for smart grid management considering minimum reserve.
- The min. reserve is incorporated in the model in addition to the cost minimization.
- The day-ahead model for VPP aims to increase reliability and reduce uncertainty.
- Two-stage weighted sum approach using distributed and parallel computing.

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ABSTRACT

In this paper, a multi-objective framework is proposed for the daily operation of a Smart Grid (SG) with high penetration of sensitive loads. The Virtual Power Player (VPP) manages the day-ahead energy resource scheduling in the smart grid, considering the intensive use of Distributed Generation (DG) and Vehicle-To-Grid (V2G), while maintaining a highly reliable power for the sensitive loads. This work considers high penetration of sensitive loads, i.e. loads such as some industrial processes that require high power quality, high reliability and few interruptions. The weighted-sum approach is used with the distributed and parallel computing techniques to efficiently solve the multi-objective problem. A two-stage optimization method is proposed using a Particle Swarm Optimization (PSO) and a deterministic technique based on Mixed-Integer Linear Programming (MILP). A realistic mathematical formulation considering the electric network constraints for the day-ahead scheduling model is described. The execution time of the large-scale problem can be reduced by using a parallel and distributed computing platform. A Pareto front algorithm is applied to determine the set of non-dominated solutions. The maximization of the minimum available reserve is incorporated in the mathematical formulation in addition to the cost minimization, to take into account the reliability requirements of sensitive and vulnerable loads. A case study with a 180-bus distribution network and a fleet of 1000 gridable Electric Vehicles (EVs) is used to illustrate the performance of the proposed method. The execution time to solve the optimization problem is reduced by using distributed computing.

1. Introduction

1.1. Background

The main purpose for using Smart Grids (SG) is to deliver electricity efficiently, reliably, and securely from the sources to the end-users [1–3]. The integration of Distributed Energy Resources (DER), such as combined heat and power (CHP) units, fuel cells, micro-turbines, photovoltaic systems, small wind turbines, biomass, Energy Storage Systems (ESS), e.g. storage batteries, and Electric Vehicles (EVs) is facilitated in the SG context [4,5]. There are important economic and technical factors which must be considered regarding the increasing penetration of DERs in SGs. For instance, the intermittency of distributed renewable energy sources, the participation of small producers in the market, and the high maintenance costs are the challenges that must be overcome to take the advantage of an intensive use of DER [6]. The DER's aggregation yields to technical and commercial benefits. It attains higher profits by using a varied mix of generation technologies, and therefore can overcome the serious disadvantages of

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Nomenclature

Indices

I index of DG units
t index of time periods
b index of buses
L index of loads
S index of external suppliers
V index of EVs
E index of ESSs

Sets

Ω_{DG}^{d} set of dispatchable DG units
Ω_{DG}^{nd} set of non dispatchable DG units
Ω_{DG}^{b} set of DG units connected at bus b
$\Omega_{V}^{b,t}$ set of EVs at bus b during time period t
Ω_{E}^{b} set of ESS units at bus b
Ω_{S}^{b} set of external suppliers at bus b
Ω_{L}^{b} set of loads at bus b

Parameters

T number of time periods
N_b number of buses
N_{DG} number of DG units
N_L number of loads
N_S number of external suppliers
N_V number of EVs
N_E number of ESSs
$\eta_{c(V)}$ grid-to-vehicle efficiency when the vehicle V is in the charging mode (%)
$\eta_{d(V)}$ vehicle-to-grid efficiency when the vehicle V is in discharging mode (%)
$\eta_{c(E)}$ charging efficiency when the ESS E is in the charging mode (%)
$\eta_{d(E)}$ discharging efficiency when the ESS E is in discharging mode (%)
θ_b^{max} maximum voltage angle at bus b (rad)
θ_b^{min} minimum voltage angle at bus b (rad)
B_{bk} imaginary part of the element in y_{bk} corresponding to row b and column k (Ω^{-1})
$c_{Discharge(E,t)}$ discharging cost of ESS E in period t (m.u.)
$c_{Discharge(V,t)}$ discharging cost of EV V in period t (m.u.)
$c_{DG(I,t)}$ generation cost of DG unit I in period t (m.u.)
$c_{GCP(I,t)}$ generation curtailment power cost of DG unit I in period t (m.u.)
$c_{LoadDR(L,t)}$ demand response cost of load L in period t (m.u.)
$c_{NSD(L,t)}$ non-supplied demand cost of load L in period t (m.u.)
$c_{Supplier(S,t)}$ energy price of external supplier S in period t (m.u.)
G_{bk} real part of the element in y_{bk} corresponding to row b and column k (Ω^{-1})
$E_{BatCap(V)}$ battery energy maximum capacity of EV V (kW h)
$E_{MinCharge(V,t)}$ minimum stored energy to be guaranteed at the end of period t for the EV V (kW h)
MR_{min} minimum system reserve necessary (kW)
$P_{ChargeLimit(E,t)}$ maximum power charge of ESS E in period t (kW)
$P_{ChargeLimit(V,t)}$ maximum power charge of vehicle V in period t (kW)
$P_{DGMaxLimit(I,t)}$ maximum active power generation of DG unit I in period t (kW)
$P_{DGMinLimit(I,t)}$ minimum active power generation of of DG unit I in period t (kW)
$P_{DischargeLimit(E,t)}$ maximum power discharge of ESS E in period t (kW)
$P_{DischargeLimit(V,t)}$ maximum power discharge of EV V in period t (kW)
$P_{Load(L,t)}$ forecasted active power of load L in period t (kW)
$P_{LoadDRMaxLimit(L,t)}$ maximum reduce power from load L in period t (kW)
$P_{SupplierLimit(S,t)}$ maximum active power of upstream supplier S in period t (kW)
$Q_{DGMaxLimit(i,t)}$ maximum reactive power generation of distributed generator unit DG in period t (kvar)
$Q_{DGMinLimit(i,t)}$ minimum reactive power generation of distributed generator unit DG in period t (kvar)
$Q_{SupplierLimit(S,t)}$ maximum reactive power of upstream supplier S in period t (kvar)
S_{bk}^{max} maximum apparent power flow established in line that connected buses b and k (kVA)
$S_{TFR\_HV/MV(b)}^{max}$ maximum apparent power in HV/MV power transformer connected in bus b (kVA)
$S_{TFR\_MV/LV(b)}^{max}$ maximum apparent power in MV/LV power transformer connected in bus b (kVA)
S_{bk}^{max} maximum apparent power flow established in line that connected buses b and k (kVA)
V_b^{max} maximum voltage magnitude at bus b (p.u.)
V_b^{min} minimum voltage magnitude at bus b (p.u.)
y_{bk} admittance of line that connect buses b and k (Ω^{-1})
y_{Shunt_b} shunt admittance of line connected to bus b (Ω^{-1})

Variables

OC_{Total}^{D+1} Total operation cost for day-ahead (m.u.)
$\theta_{b(t)}$ voltage angle at bus b in period t (rad)
$E_{Stored(E,t)}$ energy stored in ESS unit E at the end of period t (kW h)
$E_{Stored(V,t)}$ energy stored in vehicle V at the end of period t (kW h)
$E_{Trip(V,t)}$ vehicle V energy consumption in period t (kW h)
MR^{D+1} Minimum reserve for day-ahead (kW)
$P_{Charge(E,t)}$ power charge of ESS unit E in period t (kW)
$P_{Charge(V,t)}$ power charge of vehicle V in period t (kW)
$P_{DG(I,t)}$ active power generation of DG unit I in period t (kW)
$P_{Discharge(E,t)}$ power discharge of ESS unit E in period t (kW)
$P_{Discharge(V,t)}$ power discharge of EV V in period t (kW)
$P_{GCP(I,t)}$ generation curtailment power in DG unit I in period t (kW)
$P_{LoadDR(L,t)}$ demand response active power reduced for load L in period t (kW)
$P_{NSD(L,t)}$ non-supplied demand for load L in period t (kW)
$P_{Supplier(S,t)}$ active power flow in the branch connecting to external supplier S in period t (kW)
$P_{TFR\_HV/MV(b,t)}$ active power in HV/MV power transformer connected in bus b in period t (kW)
$P_{TFR\_MV/LV(b,t)}$ active power in MV/LV power transformer connected in bus b in period t (kW)
$Q_{TFR\_HV/MV(b,t)}$ reactive power in HV/MV power transformer connected in bus b in period t (kvar)
$Q_{TFR\_MV/LV(b,t)}$ reactive power in MV/LV power transformer connected in bus b in period t (kvar)
$Q_{DG(I,t)}$ reactive power generation of DG unit I in period t (kvar)
$Q_{Supplier(S,t)}$ reactive power flow in the branch connecting to external supplier S in period t (kvar)
$Q_{Load(L,t)}$ forecasted reactive power of load L in period t (kvar)
$V_{b(t)}$ voltage magnitude at bus b in period t (p.u.)
$X_{(E,t)}$ binary variable of ESS unit E related to power discharge in period t
$X_{(V,t)}$ binary variable of EV V related to power discharge in period t
$X_{DG(i,t)}$ binary decision variable of DG unit I in period t
$Y_{(E,t)}$ binary variable of ESS unit E related to power charge in period t
$Y_{(V,t)}$ binary variable of EV V related to power charge in period t