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Multi-dimensional signaling method for population-based metaheuristics: Solving the large-scale scheduling problem in smart grids

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ABSTRACT

The dawn of smart grid is posing new challenges to grid operation. The introduction of Distributed Energy Resources (DER) requires tough planning and advanced tools to efficiently manage the system at reasonable costs. Virtual Power Players (VPP) are used as means of aggregating generation and demand, which enable smaller producers using different generation technologies to be more competitive. This paper discusses the problem of the centralized Energy Resource Management (ERM), including several types of resources, such as Demand Response (DR), Electric Vehicles (EV) and Energy Storage Systems (ESS) from the VPP's perspective to maximize profits. The complete formulation of this problem, which includes the network constraints, is represented with a complex large-scale mixed integer nonlinear problem. This paper focuses on deterministic and metaheuristics methods and proposes a new multi-dimensional signaling approach for population-based random search techniques. The new approach is tested with two networks with high penetration of DERs. The results show outstanding performance with the proposed multi-dimensional signaling and confirm that standard metaheuristics are prone to fail in solving these kind of problems.

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1. Introduction

The advent of Smart Grid (SG) over the past few years is being possible due to major technological breakthroughs, namely in Information and Communications Technology (ICT) and increased penetration of Distributed Generation (DG) of several types [1]. These new resources require new methods for optimal management of resources in distribution systems. In this context new algorithms are needed for the SG, namely for addressing the Energy Resource Management (ERM) problems, which is the focus of this paper.

In the recent years, several studies have been focused on the ERM in SGs; moreover, the increasing number of Electric Vehicles (EVs) have gave rise to several research opportunities in the ERM field. The works reported in [2,3] present a unit commitment model with gridable EVs using Particle Swarm Optimization (PSO) to reduce costs and emissions in SGs increasing the security and reliability of utility grids. These works only use PSO to solve the optimization problem without comparing with other methods, namely other metaheuristics or deterministic approaches. Works reported in [4–6] present a PSO and a simulated annealing technique, respectively, to solve the day-ahead Distributed Energy Resources (DER) problem using a single-objective function. Both works compare the use of the metaheuristic with a conventional mathematical method demonstrating that the use of metaheuristics can be interesting to reduce the computational burden while preserving good solutions. The influence of the successive day on the day-ahead optimal solution is discussed in [7]. Authors in [8] develop an expert management system of a MicroGrid (MG) with the aim to minimize the operation costs and emissions of the MG operation by using a modified bacteria foraging algorithm. The model considers a simple load balance (active power) and does not consider the presence of EVs neither any type of Demand Response (DR). In [9] an intelligent energy management for a MG using intelligent techniques and linear-programming is presented. The model aims at minimizing operation cost and environmental impact. The formulation does not consider the network constraints, EVs, DR, and Energy Storage Systems (ESS), which may not sound realistic. In [10], an

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Nomenclature

Indices

I	DG units
t	time periods
b	buses
L	loads
S	external suppliers
V	EVs
E	ESSs
M	energy buyers

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
Ω_{M}^{b}	set of energy buyers 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
N_M	number of energy buyers
$\eta_{c(V)}$	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 (%)
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})
$c_{Discharge\ (V,t)}$	discharging cost of EV V in period t (m.u.)
$c_{DG(i,t)}$	generation price of DG unit i in period t (m.u.)
$c_{GCP\ (i,t)}$	generation curtailment power price of DG unit i in period t (m.u.)
$c_{LoadDR\ (L,t)}$	demand response program price for load L in period t (m.u.)
$c_{NSD\ (L,t)}$	non-supplied demand price 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 capacity of EV V (kWh)
$E_{MinCharge(V,t)}$	minimum stored energy to be guaranteed at the end of period t for the EV V (kWh)
$E_{Trip(V,t)}$	vehicle V energy consumption forecast in period t (kWh)
$MP_{Charge\ (E,t)}$	electricity charging price of storage unit E in period t (m.u./kWh)
$MP_{Charge\ (V,t)}$	electricity charging price of EV V in period t (m.u./kWh)
$MP_{Load(L,t)}$	electricity retail price for load L period t (m.u./kWh)
$MP_{Sell(M,t)}$	electricity selling price to market M in period t (m.u./kWh)
$P_{ChargeLimit(V,t)}$	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)
$P_{DischargeLimit(V,t)}$	maximum power discharge of EV V in period t (kW)
$P_{Load(L,t)}$	day-ahead active power load forecast of load L in period t (kW)
$P_{LoadDRMaxLimit(L,t)}$	maximum active power reduce permitted for 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)
$Q_{Load(L,t)}$	day-ahead reactive power load forecast of load L 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 to bus b (kVA)
$S_{TFR\_MV/LV(b)}^{\max}$	maximum apparent power in MV/LV power transformer connected to 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})
Δt	duration of time period t (h)

Variables

OC_{Total}^{D+1}	total day-ahead operation cost (m.u.)
I_{Total}^{D+1}	total day-ahead income (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 (kWh)
$E_{Stored(V,t)}$	energy stored in EV V at the end of period t (kWh)
$P_{Charge(E,t)}$	power charge of ESS 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 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 of DG unit I in period t (kW)
$P_{LoadDR\ (L,t)}$	active power reduction of load L in period t due to the demand response program implementation (kW)
$P_{NSD\ (L,t)}$	non-supplied demand for load L in period t (kW)
$P_{Sell\ (M,t)}$	sell to market M 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 to period t (kW)

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