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Exponential weighted method and a compromise programming method for multi-objective operation of plug-in vehicle aggregators in microgrids

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ABSTRACT

Distribution networks are undergoing radical changes due to the high level of penetration of dispersed generation and storage systems. This trend is strongly modifying the structure as well as the management of distribution networks, which are progressively approaching the new concept of microgrids (MGs). Also, the level of penetration of storage systems for plug-in electric vehicles (PEVs) is increasing significantly due to the significant potential that PEVs have for reducing both emission levels and transportation costs. The inclusion of these vehicles in MGs leads to a series of challenges in grid operation, especially ensuring the provision of services that can improve the operation of distribution networks. This paper deals with MGs, including renewable generation plants and aggregators of PEV fleets connected to the grid through power electronic devices. A multi-objective optimization model is presented for obtaining optimal, coordinated operation of MGs. A multi-objective model was solved using two different methods, i.e., the exponential weighted criterion method and a compromise programming method. Both of these methods appeared to be particularly suitable when computational time is an important issue, as it is in the case of optimal control. The effectiveness of the multi-objective approach was demonstrated with numerical applications to a low-voltage microgrid; other multi-objective model-solving algorithms also were assessed in order to compare their programming complexity and the computational efforts required.

1. Introduction

When the storage systems of plug-in electric vehicles (PEVs) are connected to the grid through power electronic devices, they can function as loads and as energy sources during the charging and discharging operations, respectively [1,2]. This characteristic provides the opportunity to furnish several services to the interconnected grid and several advantages can be derived in terms of the reliability and quality of electrical energy. The services are particularly suitable when a large number of vehicles (that compose a fleet) are plugged in to the grid simultaneously at the same connection point [3]; in this case, the grid interacts with vehicle fleets through so-called "aggregators," which provide appropriate control of all of the parked vehicles and their interaction with the grid [4,5]. Thus, the presence of PEV aggregators represents a highly interesting option in the microgrid (MG) context.

Analyses of the services that can be provided from PEV aggregators in MGs, including market opportunities, have been reported in [2,4]. The more suitable services are those that are characterized by high power value and rapid response. Peak power, spinning reserve, and regulation are examples of services that theoretically can be provided.

The potential revenue associated with peak power is limited, so interesting market opportunities in this area are expected only under some special circumstances [6,7]. However, spinning reserve and regulation offer much more promising market opportunities. Regulation requires devices to be available several times per day, a fast response (within a minute), and short duration of generation, so PEVs may be very well suited for this service, because they can respond very quickly. Also, since they can perform regulation both up and down, there is only a little net discharge of their batteries. A particularly interesting case of regulation is "smart charging," in which PEV aggregators (or even single vehicles) are considered to be controllable loads [4,8–10]. Currently, this service is of great interest, as shown in [4].

The smart-charging idea starts from the consideration that each PEV is usually driven only one or two hours a day on average and

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List of the symbols

I_l^r	current rating of the lth line
$I_{l,t}$	current of the lth line at time interval t.
N_{conv}	number of converters in the microgrid (including converter interfacing aggregators and DG units)
N_{ec}	number of equality constraints
N_{ic}	number of inequality constraints
$P^{sp}_{load\ dispatch,t}$	load dispatch command sent by the grid operator to the CCS at time step t.
$P_{loss,t}$	power losses at time interval t.
$P_{plug,r,t}$	active power at the rth aggregator
$P_{r,t}$	rth aggregator's active power at time step t.
$P_{r,max,t}$	rth aggregator's maximum admissible active power value at time step t.
$P_{r,min,t}$	rth aggregator's minimum admissible active power value at time step t.
$P_{s,t}$	active powers through the sth converter (of the aggregators and DG units)
$P_{1,t}$	active power through the interconnection bus at time interval t.
$Q_{s,t}$	reactive powers through the sth converter (of the aggregators and DG units)
$Q_{1,t}$	reactive power through the interconnection bus at time interval t.
$S_{S,C}$	size of the sth converter (of the aggregators and DG units)
$S_{1,T}$	MV/LV transformer rating
$V_{i,t}$	voltage amplitude at node i and time interval t.
$V^{sp}_{i,t}$	desired value of voltage amplitude at node i and time interval t
V_{max}	busbar voltage admissible maximum value
V_{min}	busbar voltage admissible minimum value
M	number of objective functions
n	number of microgrid nodes
p	selected parameter (used in the exponential weighted and compromise programming methods)
t	time interval code
v	number of aggregators
w_i	weight of the ith objective function (used in the weighted sum and objective sum methods)
Ω_l	set of microgrid lines
$\mathbf{x}$	vector of decision variables
$\mathbf{D}_t$	dependent variables vector (power losses and line currents) at time interval t.
$\mathbf{U}_t$	input vector (e.g. active and reactive load powers) at time interval t.
$\mathbf{Y}_t$	state vector (magnitude and argument of the unknown voltages) at time interval t.

reasonably can be expected to be plugged in for 10–15 h a day with only few hours needed to recharge [4]. The significant difference between the elapsed time needed for actual charging and the time that each vehicle is plugged in results in timing flexibility that can be used to provide grid services, while meeting the needs of the driver at the same time. That is what "smart charging" means. In practice, smart charging involves controlling the charging of the vehicle to meet both the needs of the vehicle's owner (i.e., to have the vehicle charged at a certain time) and the needs of the grid (i.e., matching generation and load, providing regulation, and avoiding overload in distribution networks due to the presence of many vehicles being charged at the same time). The PEV aggregator performs the smart charging service by determining how and when each vehicle is to be charged, thereby providing a demand-dispatch service to a utility or grid operator. To perform this service, the aggregator applies the appropriate mathematical models. Note that each aggregator can be characterized by a contracted capacity on an hourly basis [11]. There are different ways to guarantee the range of available capacity for each aggregator based on possible agreements with users and/or the presence of an auxiliary storage facility owned by the aggregator [12]. Models built from real travel data can also help to determine the aggregator contracted capacity [13]. These models should be implemented at the aggregator's architecture level, which is beyond the scope of this paper.

In the relevant literature, single-objective optimization models have been proposed, taking into account smart charging among the services that can be provided to a MG by PEV aggregators [8,9]. Recently, multi-objective (MO) optimization methods also have received attention [14]. In particular, in [14], an MO optimization model was proposed for the optimal operation of a low-voltage MG that included distributed generation (DG) units and PEV aggregators that performed the smart charging service. The MO model was solved by using the weighted-sum method and the objective-sum method. These methods were chosen because they allow reduced computational effort, which is an important issue in the case of smart charging where the control interval is just a few seconds.

This paper deals with the same MG structure of [14] and proposes the use of an exponential-weighted criterion and a compromise programming method to solve the MO model. This approach was based on the fact that a well-known survey of MO optimization methods for engineering applications showed that these methods can be used effectively when reduced computational effort is a strict requirement [15].

The new contributions of our research are: (i) the application of the exponential-weighted criterion and the compromise programming method as methods for solving the MO optimization model in this study and (ii) a comparison of the exponential-weighted criterion and compromise programming method with both the weighted sum method and the objective sum method proposed in [14] in terms of accuracy and computational requirements.

The proposed procedure allows for optimizing the performance of MGs characterized by the presence of demand response resources able to provide active and reactive power to the grid. This paper deals with the application of the proposed MO optimization approach to MGs characterized by the presence of plug-in vehicle aggregators and DG units.

The paper is organized as follows. Section 2 describes the MO optimization model briefly, and Section 3 illustrates the procedure used to acquire a solution. In Section 4, we present the results of numerical applications on a low-voltage MG and comparisons of the various methods used to acquire solutions. Our conclusions are presented in Section 5.

2. Formulation of the multi-objective problem

Let us consider a low-voltage (LV) MG with renewable generation units (in particular, solar and wind units) and PEV aggregators connected to the grid through power electronic converters (Fig. 1). The converter control systems receive reference signals of active and reactive power from a centralized control system (CCS). The signals are obtained by solving an appropriate optimization model that is able to guarantee specified MG internal and external services while meeting operating and technical constraints. The