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Metaheuristic optimization algorithms for the optimal coordination of plug-in electric vehicle charging in distribution systems with distributed generation

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ABSTRACT

This paper proposes three metaheuristic optimization techniques to solve the plug-in electric vehicle (PEV) charging coordination problem in electrical distribution systems (EDSs). Optimization algorithms based on tabu search, greedy randomized adaptive search procedure, and a novel hybrid optimization algorithm are developed with the objective of minimizing the total operational costs of the EDS, considering the impact of charging the electric vehicle batteries during a specific time period. The proposed methodologies determine a charging schedule for the electric vehicle batteries considering priorities according to the PEV owners charging preferences. A 449-node system with two distributed generation units was used to demonstrate the efficiency of the proposed methodologies, taking into account different PEV penetration levels. The results show that the charging schedule found makes the economic operation of the EDS possible, while satisfying operational and priority constraints.

1. Introduction

The future large-scale penetration of plug-in electric vehicles (PEVs) will bring both positive and negative consequences, depending on different points of view [1]. In the environmental context, PEVs reduce greenhouse gas emissions (CO_2, SO_2, and NO_x) by decreasing fossil fuel consumption [2]. On the other hand, PEVs benefit the transportation sector by providing low operational costs [3]. However, from the point of view of the electrical distribution system (EDS) operation, PEVs represent a significant new load that must be supplied efficiently by the system, fulfilling the final consumers needs [1]. Previous works have shown that the EDS operation is strongly affected when PEV charging is not properly coordinated [4]. Several problems, such as higher load peak, decrease in service quality, degradation of the voltage profile, overload of circuits, and increase in energy losses are consequences of PEV penetration [4–6]. Nevertheless, those impacts can be mitigated by using heuristic procedures to solve the PEV charging coordination (PEVCC) problem [4,7–10]. Charging strategies based on quadratic optimization models [6,11] and mixed-integer linear programming (MILP) [12,13] have been proposed. An MILP approach that minimizes the total daily cost due to EV charging to define the charging schedule in real-time was proposed in [13]. Other approaches based on decentralized PEV charging strategies have been investigated in [13–15]. In these latter works, each PEV is allowed to determine its own charging pattern, i.e., there is no central operator deciding when and at what rate each individual PEV will be charged.

On the other hand, centralized approaches have been considered for the PEVCC problem [10,16,17]. An algorithm for real-time smart load management applied to the PEVCC problem, which minimizes the total generation cost and the energy losses of the network, was developed in [10]. Furthermore, an evolutionary algorithm [16] and a metaheuristic method based on particle swarm optimization, genetic algorithms, and simulated annealing [17] were developed in order to provide quality solutions for the PEVCC problem.

The operation of the EDS, considering PEV charging and integration of DG sources, is a challenge for the EDS operator. Some authors have addressed this subject [8,10,18,19]. Ref. [18] proposed an online fuzzy coordination algorithm for the PEVCC problem that minimizes the total cost of energy generation and power losses, while maintaining the network's operational constraints and considering priority charging and DG resources. An optimization

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methodology for designing integrated PEV charging systems with multiple chargers, renewable DG, and storage units was proposed in [19].

Some other studies have considered the relationship between PEV charging and photovoltaic (PV) generation [20–22], as well as the relationship between PEV charging and wind power generation [23,24]. Likewise, the PEVCC problem, including DG operation in a three-phase generic LV distribution network, was investigated in [25]; nevertheless, control of the DG units was not considered. The management of DG units, demand response, and electric vehicles with V2G technology in a smart grid environment were considered in an optimization approach based on simulating annealing (SA) in [26]; additionally, a methodology based on mixed-integer non-linear programming (MINLP) was proposed to compare the results obtained with the SA approach, showing an important reduction in the computational times.

1.1. Contributions

Classical optimization techniques can be used to solve the PEVCC problem. However, in practice mathematical formulations for this problem, such as MINLP, are affected by scalability and convergence issues, due to the non-convex nature of the problem. The computational effort of the algorithms (e.g., non-linear branch and bound) used to solve this kind of problem is directly related to the number of binary variables. For the PEVCC problem, this number is proportional to the number of PEVs in the EDS. Therefore, the computational effort to solve the PEVCC problem increases with the penetration level of PEVs, as well as with the size of the network, making it hard to solve using classical optimization techniques. For this reason, the application of alternative optimization techniques, such as metaheuristics, should be investigated [18]. This work proposes novel optimization algorithms based on the metaheuristics Tabu Search (TS) [27] and Greedy Randomized Adaptive Search Procedure (GRASP) [28], to minimize the total operational costs of the EDS by finding the best possible PEV charging schedule that satisfies the PEV energy requirements, the priority charging conditions of the PEVs, and the operational constraints of the EDS. Also, a hybrid algorithm that, improves on the solutions found using the classical TS and GRASP algorithms is proposed. The performance of the proposed optimization methods was investigated in a 449-node EDS including medium and low voltage feeders.

The main contributions of this paper are as follows:

1. Novel metaheuristic algorithms for solving the PEVCC problem in EDSs, considering DG units, as well as the electrical and operational constraints of the system;
2. A procedure to obtain a suitable charging schedule for the PEVs with efficient computational behavior, which uses a sensitivity index for the variation of the energy costs related to the PEV charging.

2. Mathematical formulation of the PEVCC problem

The PEVCC problem can be formulated as an MINLP model in which the steady-state operation of the EDS is modeled based on [29,30]. The solution of this model provides the optimal charging schedule for the PEV batteries. In order to model the PEVCC problem, the following assumptions are considered:

1. The PEV batteries must be charged in a defined time period divided in time intervals, in which the charging process is executed;
2. The energy required by each PEV battery is known at the beginning of the time period;
3. The EDS operator controls the PEV charging process, i.e., the PEVs are equipped with communication devices that make it possible to control their charging state in each time interval;
4. Additionally, in each state of the charging schedule the operational constraints of the EDS must be satisfied.

2.1. Objective function

The main objective of the PEVCC problem is to minimize the total operational cost of the EDS (1). The objective function proposed in this work is formed by three components, calculated over the time period as the sum of the cost of the energy supplied by the substation and the DG units (2); a term that encourages the charging of PEVs with priority conditions (3); and the penalization costs associated with voltage limit violations, current limit violations, and non-charged PEV energy (4). The cost represented in (3) enables PEV charging with priority conditions, where ρ_t is a decreasing parameter that can be calculated by using the cost function defined by the equation $2^{[6+24H(t-18)-t]}$, and $H(t)$ is a Heaviside function. This term encourages the charging of priority PEVs as soon as possible over the charging of non-priority PEVs.

$$\min \beta+\gamma+\delta \tag{1}$$

where

$$\beta=\sum_{t\in T}\mu_t\Delta_t P^g_{SE,t}+\eta\sum_{t\in T}\Delta_t\sum_{j\in N}P^g_{j,t}\quad \forall j\in N, \forall t\in T \tag{2}$$

$$\gamma=-\sum_{j\in N}\sum_{t\in T}\kappa_j\rho_t P^v_{j,t}\quad \forall j\in N, \forall t\in T \tag{3}$$

$$\delta=\theta\sum_{j\in N}\max[(\underline{V}-V_j),0]^2+\sigma\sum_{ij\in L}\max[(I_{ij}-\bar{I}_{ij}),0]^2+\varphi\sum_{j\in N}\pi_j \tag{4}$$

A solution is only feasible when the penalizations related to the violation of voltage and current limits in (4) are equal to zero, which guarantees a feasible operation. Furthermore, the terms related to the PEVs in (3) and (4) indicate the charging preferences and the level of satisfaction of the PEV owners. Therefore, it is expected that all PEVs with priority charging conditions will be charged as soon as possible and that their energy requirements will be totally fulfilled, given that the system operates without limit violations.

2.2. Network constraints

Three types of constraints are considered in the proposed model:

- Active and reactive power balance constraints along with the voltage drop in the circuits, which represent Kirchhoffs laws and make it possible to calculate the steady-state operation of the EDS.

$$\sum_{ij\in L}P_{ij,t}-\sum_{jk\in L}(P_{jk,t}+R_{jk,t}I^2_{jk,t})+P^g_{j,t}=P^d_{j,t}+P^v_{j,t}\quad \forall j\in N, \forall t\in T \tag{5}$$

$$\sum_{ij\in L}Q_{ij,t}-\sum_{jk\in L}(Q_{jk,t}+X_{jk,t}I^2_{jk,t})+Q^g_{j,t}=Q^d_{j,t}\quad \forall j\in N, \forall t\in T \tag{6}$$

$$V^2_{j,t}-V^2_{k,t}=2(R_{jk}P_{jk,t}+X_{jk}Q_{jk,t})+Z^2_{jk}I^2_{jk,t}\quad \forall ij\in L, \forall t\in T \tag{7}$$

$$V^2_{k,t}I^2_{jk,t}=P^2_{jk,t}+Q^2_{jk,t}\quad \forall jk\in L, \forall t\in T \tag{8}$$

Eqs. (5) and (6) represent the active and reactive power balance and guarantee that all loads are supplied. Eqs. (7) and (8) represent the application of Kirchhoff's voltage law [31]. The set of Eqs. (5)–(8) is used to represent the steady-state operation of