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Intelligent optimization to integrate a plug-in hybrid electric vehicle smart parking lot with renewable energy resources and enhance grid characteristics

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ABSTRACT

Widespread application of plug-in hybrid electric vehicles (PHEVs) as an important part of smart grids requires drivers and power grid constraints to be satisfied simultaneously. We address these two challenges with the presence of renewable energy and charging rate optimization in the current paper. First optimal sizing and siting for installation of a distributed generation (DG) system is performed through the grid considering power loss minimization and voltage enhancement. Due to its benefits, the obtained optimum site is considered as the optimum location for constructing a movie theater complex equipped with a PHEV parking lot. To satisfy the obtained size of DG, an on-grid hybrid renewable energy system (HRES) is chosen. In the next set of optimizations, optimal sizing of the HRES is performed to minimize the energy cost and to find the best number of decision variables, which are the number of the system's components. Eventually, considering demand uncertainties due to the unpredictability of the arrival and departure times of the vehicles, time-dependent charging rate optimizations of the PHEVs are performed in 1 h intervals for the 24-h of a day.

All optimization problems are performed using genetic algorithms (GAs). The outcome of the proposed optimization sets can be considered as design steps of an efficient grid-friendly parking lot of PHEVs. The results indicate a reduction in real power losses and improvement in the voltage profile through the distribution line. They also show the competence of the utilized energy delivery method in making intelligent time-dependent decisions in off-peak and on-peak times for smart parking lots.

1. Introduction

With the advent of modernization and industrialization, rapid growth of hydrocarbon-based energy consumption has been one of the most significant challenges for the environment and human life. Air pollution, global warming, depletion of fossil resources and harmful emissions suggest the need to apply renewable energy to shift towards sustainable development, particularly for energy-intensive sectors. Almost 27% of total energy consumption and 33.7% of greenhouse gas emissions in the world were related to the transportation sector in 2012 [1]. Pollution costs induced by conventional transportation include but are not limited to health expenses, the cost of replanting forests devastated by acid rain, and the costs of monuments corroded by acid rain. Hence, development of high efficiency, clean and safe transportation has been amongst the most emphasized R&D activities in recent decades. Plug-in electric vehicles (PEVs), plug-in hybrid electric vehicles (PHEVs) and fuel cell vehicles are potentially not only environmental friendly and quiet but also cost-effective in terms of energy prices and operating costs compared to conventional vehicles [2]. Furthermore, electrified vehicles are controllable loads which can be utilized as distributed power storage and generation units to support the grid's energy in vehicle to grid (V2G) or vehicle to building (V2B) applications [3–5] and can also be used as spinning reserves in certain conditions [6].

Integration of hybrid renewable energy systems into electric vehicles and the electricity grid is a promising technique for addressing the environmental concerns, load shifting strategic problems, voltage instabilities, and net regulation costs simultaneously. In addition to the primary purpose of distributed generation (DG), which is energy injection, strategically placed and operated DG units can provide several other advantages to the grid such as voltage and load-ability enhancement [7], reliability improvement and network upgrade deferral [8]. Accordingly, appropriate site selection of optimized on-grid renewable-powered parking lots for electric vehicles could be helpful to

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develop power loss minimization through the grid. Utilization of on-grid hybrid renewable energy systems (HRESs) as a DG source for the mentioned case not only covers the uncertainties caused by the discontinuous nature of renewable energies in comparison with stand-alone systems, but also could degrade the stress on the grid caused by simultaneous charging of numerous vehicles. Therefore, reductions in the following items would be achievable [9]:

a. Severe voltage fluctuations.
b. Suboptimal generation dispatch.
c. Likelihood of blackouts due to network overloads.

Several studies are reported in the literature on optimal positioning, investigating a range of different placements [10] and sizing of decentralized electricity systems (not the components) [11], via utilizing classical optimization [12], meta-heuristics approaches [13–15] and analytical methods [16] to attain reduction in power losses or providing steady-state voltage profile through the grid [17,18].

The other types of studies related to the current paper discuss the integration of electric vehicles with renewable energy. Battistelli et al. [19] proposed a model to assess the contribution of V2G capable systems as a support for energy management considering renewable sources such as micro-grids. The efficiency of their developed model was validated via a realistic small electric energy system case study. Also, in a study performed by Bellekom et al. [20], wind power and electric vehicles in both integrated and single cases were evaluated to demonstrate the capability of EVs to level the nightly electricity demand via a load management charge regime. Turton and Mura [21] concluded that the global installed renewable energy capacity can be increased by 30–75% until 2020 by utilizing V2G capable EVs due to their capability to store discontinuous power and discharge it back to the grid when required.

However researchers acknowledge that V2G systems could positively affect performance of power grid. But, depending on the site and also the time that many vehicles are plugged-in to be charged, stability problems, equipment damages of overheating, and power quality degradation might occur due to simultaneous intensive charging load. To overcome such a challenge, various static (e.g. time-of-use pricing plans) and dynamic (e.g. intelligence-based techniques) solutions have been proposed, such as charging rate strategies in smart grid environment. An optimum charging policy must be able to balance constraints of the grid and users fairly. In previous studies, the superiority of smart charging to dumb charging and dual tariff charging have been demonstrated well. Vasirani and Ossowski [22] put forward an allocation mechanism inspired by a lottery scheduling method for allocating the available power to various simultaneous plugged-in PEVs. Su and Chow [23] employed swarm intelligence-based algorithms for optimal power allocation and performance evaluation of a PHEV parking station. The same authors utilized multi-objective optimizations and proposed an optimal energy strategy for a PHEV/PEV parking considering the peak demand, charging cost and the customer preference in [24]. They also evaluated and compared the performance of computational intelligence methods, such as estimation of distribution algorithm (EDA), particle swarm optimization, genetic algorithm (GA) and interior point method (IPM), for a similar case study [25].

Considering the current section and gathering the separated objectives of the mentioned studies, the definition of an optimized on-grid renewable-powered parking lot could be formed with the following characteristics:

a. It is placed in a well-situated site for optimal enhancement of the grid's voltage and minimization of the power losses as a distributed generation resource; it is grid-friendly.
b. To be a decentralized resource, it is integrated into an optimized renewable energy system; it is cost-effective and considers sustainable development.
c. It enjoys a time-variable charge allocation which considers the users satisfaction and the energy constraints of the grid simultaneously; it is intelligent.

The previous studies have considered the above items separately as the objectives of their case studies. The current paper considers all above items as fundamental design steps which must be considered before construction of an optimized parking lot equipped with distributed generation resources. First, optimal sizing and siting of the DG with the objective of power loss minimization and voltage improvement through the distribution system is achieved. After finding the best location for the parking lot, the DG size obtained in the previous step and load curve plus renewable energy potential of the studied region come into play for optimal sizing of the HRES components (as the DG source) via minimizing the energy costs. Ultimately a time-variable charging rate optimization for the parking lot is performed in 24-h considering the power limitations in time and the probable number of vehicles. Regarding smart and efficient charging facilities versus simultaneous charging of electric vehicles, potential technical challenges (of voltage profile and power losses) which threaten the power distribution system, besides the characteristics of the system suppliers (DGs), must also be addressed simultaneously. Accordingly, to clarify the correlation of the optimizations and how they are utilized to address one single issue, Fig. 1 illustrates the procedure of designed optimizations where the obtained results in each step are utilized as the input to the next optimizations.

For solving all three optimization problems, biologically inspired genetic algorithms are programmed in the MATLAB® environment.

2. Optimal sizing and siting of distributed generation

The objective of the current section is to find optimum size and site of the distributed electricity generation system (DES) to be installed for total power loss minimization over the line. Basically, adding a DES unit causes voltage disturbances and fluctuations throughout the line. For example, in a 20 kV medium voltage distribution grid, the voltage tolerance is approximately ±2% [17]. Hence, enhancement of the voltage profile and keeping it within allowed constraints (i.e. $0.95 \leqslant V_i \leqslant 1.1$ V.p.u) is also desired after power injection in this study. Efficient use of the DES could provide power loss degradation in transmission lines as well as voltage enhancement. The most significant advantage of DG is to support the power system and active power generation. Local active and reactive power generation affect a line's flow and could be supported by renewable energy systems or static devices respectively. Injection of active power into the optimum site can positively reduce the power losses for related buses and the line. The level of this degradation depends on the amount of injected power and the electricity demand in the related bus. In other words, it is directly influenced by the DG size. Implementation of DES near all buses is not feasible due to economic issues. Therefore, finding the optimum size and location for DG would be a promising solution to improve the power quality. A DES also has other benefits; it can be applied to support the power system in places that experience abrupt sizable loads at peak times. This could occur due to large electricity demands of entertainment centers if they get