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Optimal distribution feeder reconfiguration for increasing the penetration of plug-in electric vehicles and minimizing network costs

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ABSTRACT

Appearance of PEVs (Plug-in Electric Vehicles) in future transportation sector brings forward opportunities and challenges from grid perspective. Increased utilization of PEVs will result in problems such as greater total loss, unbalanced load factor, feeder congestion and voltage drop. PEVs are mobile energy storages dispersed all over the network with benefits to both owners and utilities in case of V2G (Vehicle-to-Grid) possibility. The intelligent bidirectional power flow between grid and large number of vehicles adds complexity to the system and requires operative tools to schedule V2G energy and subdue PEV impacts. In this paper, DFR (Distribution Feeder Reconfiguration) is utilized to optimally coordinate PEV operation in a stochastic framework. Uncertainty in PEVs characteristics can be due to several sources from location and time of grid connection to driving pattern and battery SoC (State-of-Charge). The proposed stochastic problem is solved with a self-adaptive evolutionary swarm algorithm based on SSO (Social Spider Optimization) algorithm. Numerical studies verify the efficacy of the proposed DFR to improve the system performance and optimal dispatch of V2G.

1. Introduction

PEVs (Integration of Plug-in Electric Vehicles) will introduce demands and storage in distribution systems with distinctive feature of mobility. This feature of PEV fleets will impose additional operation constraints and introduce benefits for supplying critical system loads in specific locations and periods [1]. Increased penetration of these vehicles into the existing electric grid requires considerations as a result of their demand characteristics and mobile connection to grid. Congestion on transmission and distribution lines and transformers, increase in energy loss, decreasing the reliability and power quality are some of the technical challenges of using large number of vehicles in the grid [2–4]. It is reported in Ref. [5] that peak electricity demand hours coincides the hours during which the majority of vehicles are getting charged at a residential garage. Additionally, the stochastic behavior of PEVs will also add complexity to the optimal operation and management of the system. V2G (Vehicle-to-Grid) technology aims to minimize PEV impacts by providing energy and ancillary service to the grid. It should be noted that ancillary services provided by the V2G technology give electrical energy with better power quality from different viewpoints such as fast response and distribution in network [2]. V2G represents a system where power can be sold to the grid by plugging an idle PEV to the grid. Through V2G, grid operation costs will be reduced by taking advantage of the fact that the stored energy in PEVs can be transferred between locations without obeying power flow rules [1]. In this way, reference [1] tries to schedule the generation units of a power system using V2G technology. Discussion of V2G, its characteristics, advantages, weaknesses, economics, and technical specifications can be found in Refs. [6–9].

In the new smart distribution systems, optimal DFR (Distribution Feeder Reconfiguration) is a precious and significant strategy for the operator. DFR is defined as the process of changing the topology of the network using some remote switches such that all the network constraints are taken into account. The most basic constraint is that the radial structure of the system should be preserved [10]. Furthermore, the main focus and objective in DFR is to upkeep the situation of the grid by minimizing the total cost, total loss, voltage deviation and improving the load balance. Among these useful but conventional objective functions, most attention has been given to the active power losses. In this area, new methods based on ANN (Artificial Neural Network) [11], optimum flow pattern [12], graph theory [13], brute-force approach [14], heuristic

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Nomenclature

a,b Wöhler curve parameters
acm_s/acm_s^{ini} total/initial accumulation factor of sth strategy
$Cost$ total network cost
$C_{sub}^t/C_{loss}^t/C_v^t$ hourly energy price/loss cost/V2G price
C_{Bat} investment cost ($)
C_d^{total},C_d (total) degradation cost of PEV battery
DoD_i/DoD_f initial/final DoD in a discharge cycle
d_{ic}/d_{ib} cartesian distance to closest/best individual
E_{bat} usable energy of the battery (kWh)
$E_{D,v}^t$ energy for PEVs in fleet v to drive at time t
E_v^t available energy in batteries of fleet v at time t
E_v^{ini}/E_v^{fin} initial/final energy in PEV fleet v
E_v^{min}/E_v^{max} min/max energy in batteries of PEV fleet v
$f_i/f_b/f_w$ objective value of ith/best/worst individual
$Iter$ iteration counter
$Iter^{max}$ maximum number of iterations
$Lévy(.)$ Lévy flight function
M_w weighted mean of male spiders in the colony
N_c number of life cycles
N_{dis} number of discharge cycles
$N_l/N_{br}/N_{bus}$ number of loops/branches/buses of network
N_{mod} number of individuals which select a strategy
N_p population size
N_F/N_M number of female/male spiders in the colony
N_v total number of PEVs
n_v number of control variables
P_{sub}^t/P_{sub}^{max} hourly/max imported power from upstream grid
P_{loss}^t hourly active power loss of network
$P_{c,v}^t/P_{d,v}^t$ charging/discharging capacity of PEV fleet v
$P_{c,v}^{min}/P_{c,v}^{max}$ min/max charging capacity of PEV fleet v
$P_{d,v}^{min}/P_{d,v}^{max}$ min/max discharging capacity of PEV fleet v
P_v^t charge/discharge power rate of PEV fleet v at time t
P_i^t/Q_i^t hourly injected active/reactive power at bus i
$P_{attraction}$ attraction threshold
Prb_s normalized selection probability of sth strategy
r_m mating region
S_{ij}^t/S_{ij}^{max} hourly/max apparent power flow between bus i and j
$S_{strategy}$ set of modification strategies
SF_i success factor of ith individual
T planning horizon
t' time at which SoC is set to a specific value
U_v^t status of grid connection of fleet v at time t
$U_{c,v}^t/U_{d,v}^t/U_{i,v}^t$ indicator of fleet v in charge/discharge/idle mode
u_j/l_j upper/lower bound of jth control variable
V_i^t/δ_i^t voltage magnitude/phase of bus i at hour t
V_i^{min}/V_i^{max} minimum/maximum voltage at bus i
$w_i/w_c/w_b/w_F$ weight of ith/closest/best/closest female individual
X_c/X_c^F position of closest spider/closest female spider
$X_i/X_b/X_r$ position of ith/best/randomly selected individual
$X_{i,F}/X_{i,DM}/X_{i,NM}$ position of ith female/dominant male/non-dominant male spider
X_{mut} improved new individual based on mutation process
X_{Testi} ith test individual generated in modification strategy
Y_{ij}/θ_{ij} magnitude/phase of impedance between bus i and j
α_i, ρ_i ith random number between [0, 1]
β_{mut} mutation level
Δ random number in roulette wheel process
θ empirical constant factor

techniques [15], GA (Genetic Algorithms) [16–18], expert systems [19], and PSO (Particle Swarm Optimization) [20,21], have been studied. Meanwhile, other objectives such as improving load balance [22], voltage deviation [23] emission [24,25] and reliability indices [26,27] have been studied in the literature as well. In Ref. [28] multi-objective DFR problem considering load demand of PEVs is solved in a deterministic framework regardless of V2G capability of these vehicles. To the best of the authors' knowledge, the high capability of DFR strategy for increasing the penetration of stochastic V2G enabled PEVs in the future transportation fleet has not been studied yet. In response to this necessity, this paper proposes a stochastic DFR formulation to optimally schedule V2G provision and specify the most beneficial topology for network at the same time. The uncertainties associated with PEVs, energy price and active/reactive load demands were modeled with MCS (Monte Carlo Simulation) method. According to the high complexity and nonlinearity of the proposed optimization problem, a new self-adaptive optimization algorithm called MSSO (Modified Social Spider Optimization) algorithm is proposed to solve the problem. SSO (Social Spider Optimization) is a new bio-inspired optimization algorithm based on the cooperative behavior of social spiders to solve the non-convex constrained optimization problems [29]. The intelligent performance of social spiders to interact with each other in the colony is simulated to find the optimum solution in the search space. In order to improve the whole performance of the conventional SSO in realistic optimization applications, a new modification phase is proposed and added to the algorithm. The proposed methodology is applied to 69-bus IEEE distribution test system to corroborate the veracity of the procedure. It is shown that the proposed stochastic DFR strategy along with V2G reduces PEV impacts optimally and SSO is efficaciously able to minimize the proposed objective functions. The problem is solved in a stochastic framework and number of PEVs in each fleet, PEVs battery capacity, energy price and active/reactive load demand, departure and arrival time of PEVs and charge/discharge values are considered as uncertain parameters. The study utilizes DFR as a strategy to excel network situations respecting security constraints. Also, a novel self-adaptive SSO is presented for solving complex optimization problems. Therefore, the main contributions of this paper can be summarized as: 1) Investigating the effect of DFR strategy on the optimal operation and management of PEV Fleets considering V2G operation and battery aging, 2) Proposing a new sufficient optimization framework based on MSSO and MCS to solve the problem in a stochastic environment, 3) Introducing a new adaptive modification method for SSO algorithm to improve its total search ability for the optimization applications.

The rest of the paper is organized as follows: The proposed stochastic DFR problem is described and formulated in Section 3, where the objective function and main constraints are introduced. Basics of the original SSO and proposed MSSO are presented in Section 4 followed by the numerical simulation results in Section 5. Finally, the contributions and conclusions of the paper are summarized in Section 6.

2. Proposed stochastic DFR strategy

2.1. PEV fleet in electric grid

PEVs are dispersed and mobile probabilistic loads or generations in the distribution grid. Consequently, some assumptions should be