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Intelligent Energy Allocation Strategy for PHEV Charging Station Using Gravitational Search Algorithm

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Abstract. Recent researches towards the use of green technologies to reduce pollution and increase penetration of renewable energy sources in the transportation sector are gaining popularity. The development of the smart grid environment focusing on PHEVs may also heal some of the prevailing grid problems by enabling the implementation of Vehicle-to-Grid (V2G) concept. Intelligent energy management is an important issue which has already drawn much attention to researchers. Most of these works require formulation of mathematical models which extensively use computational intelligence-based optimization techniques to solve many technical problems. Higher penetration of PHEVs require adequate charging infrastructure as well as smart charging strategies. We used Gravitational Search Algorithm (GSA) to intelligently allocate energy to the PHEVs considering constraints such as energy price, remaining battery capacity, and remaining charging time.

INTRODUCTION

The vehicular network recently accounts for around 25% of CO_2 emissions and over 55% of oil consumption around the world. Several researchers have proved that a great amount of reductions in greenhouse gas emissions and the increasing dependence on oil could be accomplished by electrification of transport sector [1]. Indeed, the adoption of hybrid electric vehicles (HEVs) over the last decade has brought significant market success. Plug-in hybrid electric vehicles (PHEVs) which is very recently introduced promise to boost up the overall fuel efficiency by holding a higher capacity battery system, which can be directly charged from traditional power grid system, that helps the vehicle to operate continuously in “all-electric-range" (AER) [2]. Plug-in hybrid electric vehicles with a connection to the smart grid can possess all of these strategies. For this, the widely extended adoption of PHEVs could play a significant role in the alternative energy integration into traditional grid systems [3]. There is a need of efficient mechanisms and algorithms for smart grid technologies in order to solve highly heterogeneous problems with different objectives, having to interact within certain levels of dubiety and dynamism [4]. According to a statistics of Electric Power Research Institute (EPRI), about 62% of the entire United States (US) vehicle will comprise of PHEVs within the year 2050 [5]. Moreover, there is an increasing demand to implement this technology on the electric grid system. Several numbers of PHEVs have the capability to threaten the stability of the power system. For example, in order to avoid interruption when several thousand PHEVs are introduced into the system over a short period of time, the load on the power grid will need to be managed very carefully. One of the main targets is to facilitate the proper interaction between the power grid and the PHEV. For the maximization of

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customer satisfaction and minimization of burdens on the grid, a complicated control mechanism will need to be addressed in order to govern multiple battery loads from a numbers of PHEVs appropriately [6]. The total demand pattern will also have an important impact on the electricity industry due to differences in the needs of the PHEVs parked in the deck at certain time [7]. The proposed optimization focuses on the public charging station for plug-in vehicles because most of PHEV charging is expected to take place in public charging locations [8]. One of the important constraints for accurate charging is State-of-Charge (SoC). Charging algorithm can accurately be managed by the precise State of charge estimation. [9].

Wide penetration of PHEVs in the market depends on a well-efficient charging infrastructure. The power demand from this new load will put extra stress on the traditional power grid [10]. As a result, a good number of PHEV charging infrastructures with appropriate facilities are essential to be built for recharging electric vehicles, for this some strategies have been proposed by the researchers [11][12]. Charging stations are needed to be built at workplaces, markets/shopping malls and home. In [13], authors proposed the necessity of building new smart charging station with effective communication among utilities along with sub-station control infrastructure in view of grid stability and proper energy utilization. Furthermore, assortment of charging stations with respect to charging characteristics of different PHEVs traffic mobility characteristics, sizeable energy storage, cost minimization; Quality of Services (QoS) and optimal p of intelligent charging station are underway [14]. Thus, evolution of reliable, efficient, robust and economical charging infrastructure is underway. In this wake, numerous techniques and methods have been proposing for deployment of charging station for PHEVs [15].

An approximate graph of a typical Lithium-Ion cell voltage versus SoC is shown in Fig. 1. The figure indicates that the slope of the curve below 20% and above 90% is high enough to result in a significant voltage difference to be depended on by measurement circuits and charge balancing control [19] [20]. There is a need of in-depth study on maximization of average SoC in order to facilitate intelligent energy allocation for PHEVs in a charging station. GSA is one of the newest heuristic algorithms introduced by Rashedi et al. [17]. It is inspired by the well-known law of gravity and interactions between the masses, and implements Newtonian gravity and the laws of motion. Most of the previous research efforts studied only Genetic Algorithm (GA) [6], Particle Swarm Optimization (PSO) [7], and Estimation of Deferential Evaluation (EDA) [8] as an optimization technique for intelligent energy management for PHEVs. This paper will consider a new and effective optimization technique named Gravitational search algorithm (GSA).

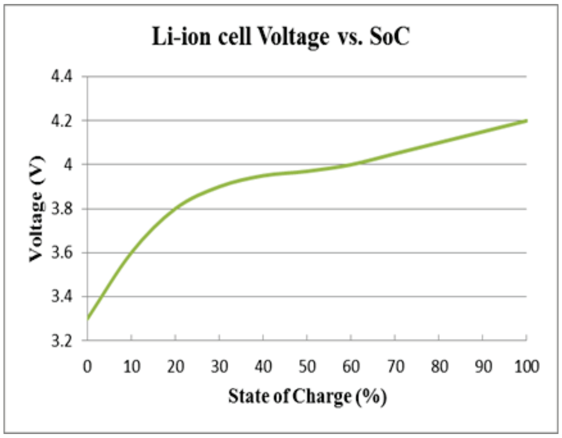

FIGURE 1. Li-ion cell voltage vs. State-of-Charge

GSA-based optimization has already been used by the researchers for post-outage bus voltage magnitude calculations, economic dispatch with valve-point effects, optimal sizing and suitable placement for distributed generation (DG) in distribution system, optimization of synthesis gas production [16], solving thermal unit commitment (UC) problem and finding out optimal solution for optimal power flow (OPF) problem in a power system [18]. Specifically, we are investigating the use of the Gravitational Search Algorithm (GSA) method for developing real-time and large-scale optimizations for allocating power.

The remainder of this paper is organized as follows: Next section will describe the specific problem that we are trying to solve. We will provide the optimization objective and constraints, mathematical formulation of our algorithm and review the GSA method as well as describe how the algorithm works for our optimization problems.

The simulation results and analysis of charging station scenarios are presented then. Finally, we summarize our paper and provide a brief discussion of future work.

PROBLEM FORMULATION

The idea behind smart charging is to charge the vehicle when it is most beneficial, which could be when electricity price, demand is lowest, when there is excess capacity, or based on some other metric.

The main aim is to allocate power intelligently for each PHEV coming to the charging station. The State-of-Charge is the main parameter which needs to be maximized in order to allocate power effectively. For this, the objective function considered in this paper is the maximization of average SoC and thus allocate energy for PHEVs at the next time step. The constraints considered are: charging time, present SoC and price of the energy.

The objective function is defined as:

$$\max J(k) = \sum_i w_i(k)\, SoC_i(k+1) \tag{1}$$

$$w_i(k) = f\left(C_{r,i}(k), T_{r,i}(k), D_i(k)\right) \tag{2}$$

$$C_{r,i}(k) = \left(1 - SoC_i(k)\right)^* C_i \tag{3}$$

where $C_{r,i}(k)$ is the battery capacity (remaining) needed to be filled for i no. of PHEV at time step k; C_i is the battery capacity (rated) of the i no. of PHEV; remaining time for charging a particular PHEV at time step k is expressed as $T_{r,i}(k)$; the price difference between the real-time energy price and the price that a specific customer at the i no. of PHEV charger is willing to pay at time step k is presented by $D_i(k)$; $w_i(k)$ is the charging weighting term of the i no. of PHEV at time step k (a function of charging time, present SoC and price of the energy); $SoC_i(k +$ 1is the state of charge of the i no. of PHEV at time step $k+1$.

Here, the weighting term indicates a bonus proportional to the attributes of a specific PHEV. For example, if a PHEV has a lower initial SoC and less charging time (remaining), but the driver is eager to pay a higher price, the system will provide more power to this particular PHEV battery charger:

$$w_i(k)\, \alpha \left[Cap_{r,i}(k) + D_i(k) + {}^{1}\!/_{T_{r,i}}(k) \right] \tag{4}$$

The charging current is also assumed to be constant overΔt.

$$\left[SoC_i(k+1) - SoC_i(k)\right].Cap_i = Q_i = I_i(k)\Delta t \tag{5}$$

$$SoC_i(k+1) = SoC_i(k) + I_i(k)\Delta t / Cap_i \tag{6}$$

Where the sample timeΔt is defined by the charging station operators, and $I_i(k)$ is the charging current overΔt.

The battery model is regarded as a capacitor circuit, where C_i is the capacitance of battery (Farad). The model is defined as:

$$C_i . \frac{dV_i}{dt} = I_i \tag{7}$$

Therefore, over a small time interval, one can assume the change of voltage to be linear,

$$C_i . \left[V_i(k+1) - V_i(k)\right] / \Delta t = I_i \tag{8}$$

$$V_i(k+1) - V_i(k) = I_i \Delta t / C_i \tag{9}$$

As the decision variable used here is the allocated power to the PHEVs, by replacing I_i (k) with P_i(k)the objective function finally becomes:

$$J(k)=\sum w_i\cdot\left[SoC_i(k)+\frac{2P_i(k)\Delta t}{0.5.C_i\cdot\left[\sqrt{\frac{2P_i(k)\Delta t}{C_i}+V^2{}_i(k)}+V_i(k)\right]}\right] \tag{10}$$

Power obtained from the utility ($P_{utility}$) and the maximum power ($P_{i,max}$) absorbed by a specific PHEV are the primary energy constraints being considered in this paper. The overall charging efficiency of a particular charging infrastructure is described by η. From the system point of view, charging efficiency is supposed to be constant at any given time step. Maximum battery SoC limit for the i no. of PHEV is $SoC_{i,max}$. WhenSoC_ireaches the values close to$SoC_{i,max}$, the i no. of battery charger shifts to a standby mode. The state of charge ramp rate is confined within limits by the constraint ΔSoC_{max} . The overall control system is changed the state when i) system utility data updates; ii) a new PHEV is plugged-in; iii) time periodΔt has periodically passed.

Energy allocation to PHEV charging station is subjected to various constraints as mentioned in the problem formulation section. Different constraints make the entire search space limited to a particular suitable region. So, a powerful optimization algorithm should be implemented in order to achieve high quality solutions with a stable convergence rate.

GRAVITATIONAL SEARCH ALGORITHM

GSA is a powerful optimization technique which has been introduced by Rashedi et al. in the year of 2009 [17]. In GSA, the specifications of each mass (or agent) are total four, which is mass (inertial), position, mass (active gravitational) and mass (passive gravitational). The position of the mass presents a solution of a particular problem, and masses (gravitational and inertial) are obtained by using a fitness function. GSA can be considered as a collection of agents (candidate solutions), whose masses are proportional to their value of fitness function. During generations, all masses attract each other by the gravity forces between them. A heavier mass has the bigger attraction force. Therefore the heavier masses which are probably close to the global optimum attract the other masses proportional to their distances.

The gravitational force is expressed as follows:

$$F_{ij}^d(t)=G(t)\frac{M_{pi}(t)\times M_{aj}(t)}{R_{ij}(t)+\varepsilon}\left(x_j^d(t)-x_i^d(t)\right) \tag{11}$$

Where M_{aj} is the active gravitational mass related to agentj, M_{pi} is the passive gravitational mass related to agenti, $G(t)$is gravitational constant at timet, ε is a small constant and $R_{ij}(t)$ is the Euclidian distance between two agents i and j.The $G(t)$is calculated as

$$G(t)=G_0\times\exp(-\alpha\times iter/maxiter) \tag{12}$$

Where α and G_0 are descending coefficient and primary value respectively, current iteration and maximum number of iterations are expressed as iter andmaxiter. In a problem space with the dimensiond, the overall force acting on agenti is estimated as following equation:

$$F_i^d(t)=\sum_{j=1,j\neq i}^{N} rand_j F_{ij}^d(t) \tag{13}$$

Where $rand_j$ is a random number with interval [0, 1]. From law of motion we know that, an agent's acceleration is directly proportional to the resultant force and inverse of its mass, so the acceleration of all agents should be calculated as follow:

$$ac_i^d(t)=\frac{F_i^d(t)}{M_{ii}(t)} \tag{14}$$

Where t is a specific time and M_{ii} is the mass of the object i.The velocity and position of agents are calculated as follow:

$$vel_i^d(t+1) = rand_i \times vel_i^d(t) + ac_i^d(t) \tag{15}$$

$$x_i^d(t+1) = x_i^d(t) + vel_i^d(t+1) \tag{16}$$

Where $rand_i$ is a random number with interval [0, 1].

In Gravitational search algorithm, all agents are initialized first with random values. Each of the agents is a candidate solution. After initialization, velocities for all agents are defined using (15). Moreover, the gravitational constant, overall forces, and accelerations are determined by equations (12), (13) and (14) respectively. The positions of agents are calculated using (16). At the end, GSA will be terminated by meeting the stopping criterion stated below.

TABLE 2. GSA parameter settings

Parameters	**Values**
Primary parameter, G_0	100
Number of mass agents, n	50 and 75
Constant parameter, α	20
Constant parameter,ε	.01

The stopping criteria used in this work was the maximum number of function evaluations (which was pre-defined to 200).

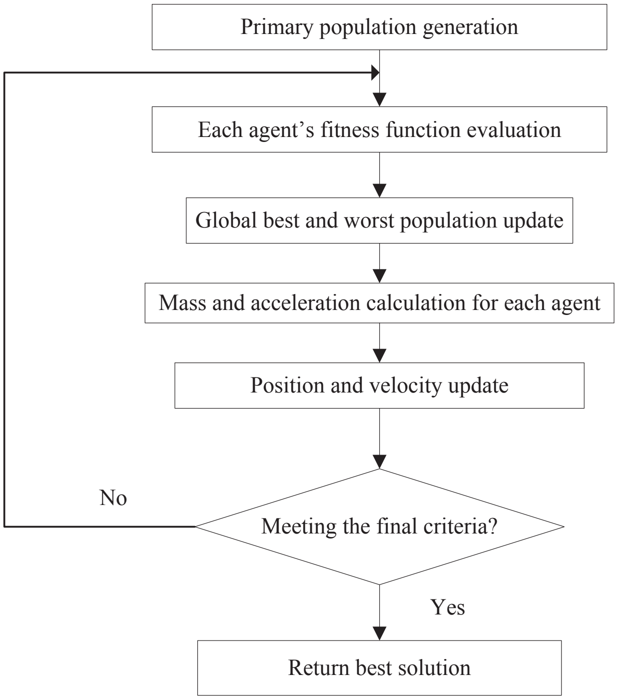

FIGURE 2. The GSA Algorithm

SIMULATION RESULTS AND ANALYSIS

The GSA algorithm was applied to find out global maximum solution of the objective function. All the calculations were run on an Intel (R) Core™ i3-3110M CPU@ 2.40 GHz, 4.00 GB RAM, Microsoft 64 bit Windows 7 OS and Matlab R2010a.

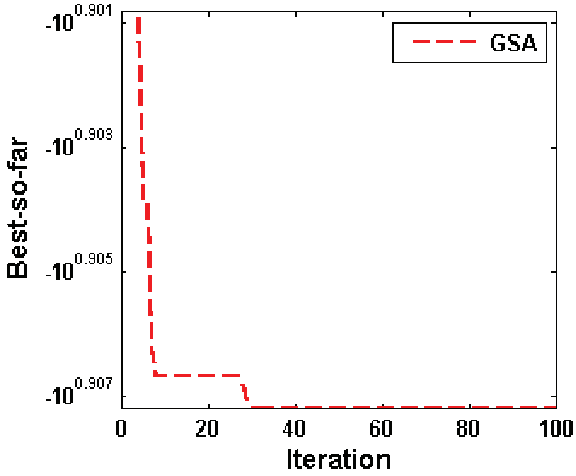

FIGURE 3. GSA implementation (for 50 mass agents)

The simulation was also performed for 75 mass agents and the result is as shown in Fig. 4. Here, the assumption was that the gravitational and inertia masses are the same. However, for some applications different values for them can be used. A heavier inertia mass provides a slower motion of agents in the search space and hence a more precise search [17]. On the contrary, a heavier gravitational mass causes a higher attraction of agents. This allows a faster convergence.

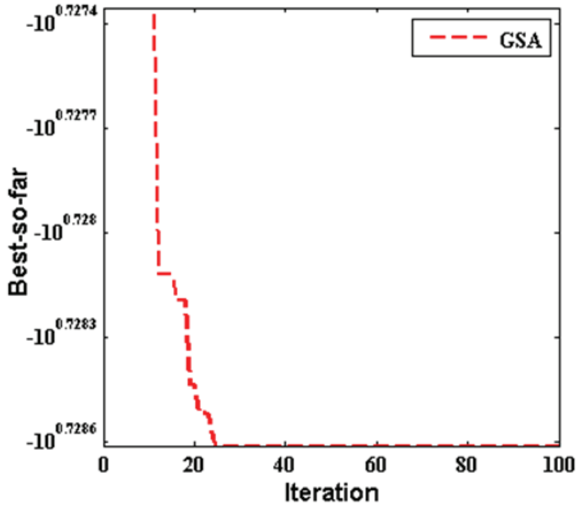

FIGURE 4. GSA implementation (for 75 mass agents)

For this experiment, the initial state of charge was expressed as a random number which is continuous uniform between 0.2 and 0.6. The sample time was set around 1200 seconds (20 minutes). The remaining charge time was defined as continuous random number between 0 and 6 hours.

CONCLUSION AND FUTURE WORK

In this paper, Gravitational Search Algorithm (GSA)-based optimization was performed in order to optimally allocate power to each of the PHEVs coming in the charging station. Here, total PHEVs are considered for Matlab Simulation. Simulation results show the GSA implementation for 50 and 75 mass agents respectively.

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