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Optimal Scheduling of Plug-in Hybrid Electric Vehicles Operation in Distribution Networks Using Gravitational Search Algorithm

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ABSTRACT

In this paper, an optimal scheduling framework of plug-in hybrid electric vehicles (PHEVs) is introduced to address the issue with fluctuations of renewable resources and demand profile. The main purpose of the framework is to minimize the total power losses in distribution networks through the best locations and optimum number of PHEVs for charging and discharging. A heuristic optimization based on gravitational search algorithm (GSA) technique is used in the framework to solve the non-linear and non-convex problem. To showcase the framework effectiveness, two worst case scenarios are considered; low demand at high generation and high demand at no generation. The framework is tested on the modified 33-bus distribution network within MATLAB environment. The results show that the electricity can be transferred using PHEVs and give significant loss reduction in both cases.

Key words: Plug-in hybrid electric vehicle, gravitational search algorithm, network management, renewable energy.

1. INTRODUCTION

A huge-scale of renewable energy is expected to integrate in the distribution level as part of the energy transition from the conventional fossil-fuel plants to low/zero carbon emission energy resources (e.g., solar). The large amount of low/zero carbon emission energy resources in form of distributed generations (DGs) is being fed into the distribution networks can lead to enormous technical problems. The intermittent behavior of the DGs is one of the problems that limit the DG integration into the distribution power grid. The maximum amount of DGs could be absorbed in the power system under current conditions is generally between 20-25% [1]. The DG power curtailment is among several solutions that have been explored in order to increase the DG penetration level [2]. Although it helps, the amount of wasted energy will increase. Therefore, another solution is required to fully utilize the harvested energy and consequently, operate the power grid in more efficient and cost-effective way.

The concerns on greenhouse emissions have also received growing attention in the transportation sector to use electric vehicles (EVs) instead of the traditional internal combustion engine vehicles [3]. The market penetration of EVs is expected to reach 30% global market share by 2030 [4], motivated by the higher efficiency and lower gas emissions of EVs [5]. Plug-in hybrid EV (PHEV) is one type of the EVs in the market that can change the demand profile in power grids. Consequently, the integration of large-scale PHEVs into the existing power system leads to another challenge mainly due to the massive electricity demands from the emerging PHEV loads. Uncoordinated charging of large PHEV fleets in venues such as parking stations tends to impose significant risk on the power system operation in terms of voltage and thermal limits violation. Nevertheless, the PHEVs can be coordinated in such way using demand response scheme [6] to not only reduce the impacts of their charging operation but also the issue with fluctuation of the renewable resources.

Several studies on different aspects of EV implementations have been conducted including development of simulation tools [7], placement of charging stations [8-9] and impact on power quality [10]. However, the studies mainly focus on the charging operation and neglect the capability of PHEVs to supply power (i.e., discharge) and operate like mini-generator to help during the period of high demand using the concept of vehicle to grid (V2G) [11]. In other words, the PHEVs can operate in both way charging and discharging where this enables them to function as energy storage and deal with the issues of load fluctuations and the intermittent renewable resources [12]. Unlike other storage systems, the flexibility and mobility enable the PHEV to transport electricity from an area with high-generation to high-demand area when necessary. Thus, managing PHEVs in a highly coordinated manner is important to give maximum benefits to the power grid operation.

This paper aims to determine an optimal coordination of PHEV charging and discharging activities in distribution networks. This problem involves power flow calculation and identification best locations and number of PHEVs which is a non-linear and non-convex optimization problem. Among the used techniques, heuristic optimization technique has shown promising result in solving non-linear and non-convex problems [13]. Genetic algorithm (GA) is a well-known technique that uses heuristic algorithm to obtain a good solution in very short time [14-17]. In [18], the crossover operator of the GA is adopted in particle swarm optimization (PSO), another heuristic optimization technique, to overcome the pre-mature convergence issue. Meanwhile, gravitational search algorithm (GSA) is another type of heuristic optimization technique that has been reported has capability to provide a solution better than GA and PSO at certain problems [19]. Therefore, GSA is selected in this work to solve the optimal scheduling of PHEVs problem.

2. PLUG-IN HYBRID ELECTRIC VEHICLE MODEL

The PHEV in this work is considered to operate in either charging or discharging mode. From the network operation perspective, the PHEV can be modelled as motor (i.e., load) during charging and generator during discharging as shown in Figure 1 [20]. During discharging, power injection seen by the network to be less than the actual rated operating power, P_{rate} of the PHEV due to internal losses or efficiency, η. On the contrary, the efficiency does not affect the consumed power from the network during charging period instead less power to be delivered to the battery of the PHEV. Therefore, power injection at the PHEV connection point l can be calculated using the following expression:

$$P_l = \begin{cases} \eta P_{rate} & \text{, discharging} \\ -P_{rate} & \text{, charging} \\ 0 & \text{, otherwise} \end{cases} \tag{1}$$

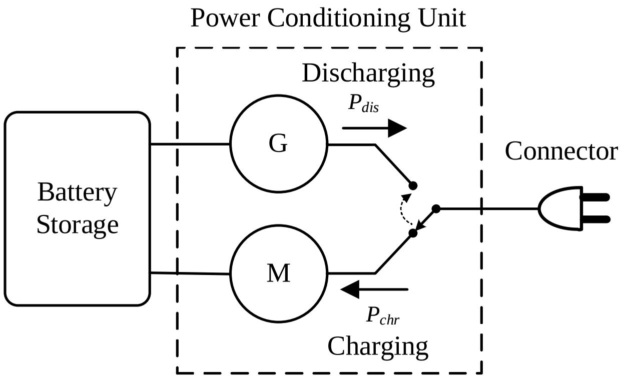

Figure 1: PHEV charging and discharging modes

In the conventional energy storage system modelling, state of charge is calculated as one of the operating constraints. In contrast, the PHEV state of charge in this study can be ignored because the PHEVs normally participate in V2G scheme (i.e., discharging mode) when their state of charge is adequate to do so. Likewise, the PHEVs will be charged when the state of charge at significant low level. Furthermore, the PHEVs are not restricted to the same vehicles and this makes them not bound to the previous status. Nevertheless, the total power injection at bus m is limited to the number of available PHEV connection points at that particular bus, N as given by:

$$P_m = \sum_{i=1}^{N} P_l \tag{2}$$

In this framework, the PHEVs are encouraged to be charged at the region of low demand and high generation or discharge otherwise. Therefore, a priority is given to PHEVs for either charging or discharging at certain bus according to their conditions. Consequently, a single mode of operation is expected at the selected bus. Hence, equations (1) and (2) can be simplified using the following expressions:

$$P_m = \begin{cases} \eta P_{rate} \times n & \text{, discharging} \\ -P_{rate} \times n & \text{, charging} \end{cases} \tag{3}$$

$$1 \le n \le N \tag{4}$$

where, n is number of PHEVs that engage in response to the provided incentive scheme.

3. GRAVITATIONAL SEARCH ALGORITHM

The gravitational search algorithm (GSA) is a probabilistic optimization technique introduced by Rashedi [21] to solve continuous domain problems. The search algorithm is based on the gravitational interaction metaphor of masses in the Newton theory. A j-th bit of agent i (x_{ij}) in the PHEV scheduling problem is represented by integer value where a combination of bits gives the agent i position. The GSA operators calculate agent's acceleration (a_{ij}) based on gravitational force and its mass in each iteration using the following equations:

$$G = G_0\left(1 - \frac{t}{T}\right) \tag{3}$$

$$F_{ij}^{k} = G\frac{M_i \times M_k}{R_{ik} + \varepsilon}(x_{kj} - x_{ij}) \tag{4}$$

$$F_{ij} = \sum_{k \in Kbest, k \neq i} rF_{ij}^{k} \tag{5}$$

$$a_{ij} = \frac{F_{ij}}{M_i} \tag{6}$$

where,

G_0 : initial gravity constant;
T : total number of iterations;
F : gravitational force action;
M : agent gravitational mass;

R_{ik} : Euclidian distance between i-th and k-th agent;
ε : small positive coefficient, 2^{-52};
r : uniform random variable in interval [0,1];
K_{best} : selection number of the best agent to apply on other agent and it decreases monotonously from $Kbest_{max}$ to $Kbest_{min}$ along the iteration t.

The agent's velocity (v_{ij}) is updated using its current velocity and its acceleration as:

$$v_{ij}^{t+1} = r v_{ij}^{t} + a_{ij}^{t} \qquad (7)$$

A new agent's position can be calculated using (8) but the obtained value is a floating number. In order to maintain the agent's position as integer variables, a new binary variable as expressed in (9) is introduced where $INT(x)$ denotes rounding function to the nearest integer and $\lfloor x \rfloor$ denotes floor function. Then, agent position is updated using condition in (10). This condition is necessary to give velocity more influence to the new agent position as suggested in [22].

$$x_{ij}^{new} = x_{ij}^{t} + v_{ij}^{t+1} \qquad (8)$$

$$x_{ij}^{bin} = INT\,(x_{ij}^{new}) - \lfloor x_{ij}^{new} \rfloor \qquad (9)$$

$$x_{ij}^{t+1} = \begin{cases} \overline{x_{ij}^{bin}} + \lfloor x_{ij}^{new} \rfloor & \text{, if } r < \tanh(v_{ij}^{t+1}) \\ INT\,(x_{ij}^{new}) & \text{, otherwise} \end{cases} \qquad (10)$$

4. OPTIMAL PHEV SCHEDULING FRAMEWORK

The goal of this work is to find suitable charging/discharging locations for PHEVs to help improving the distribution network operation in terms of the power loss reduction. In order to achieve the goal, an optimal PHEV scheduling framework using GSA technique is developed in MATLAB. The control variables are number of charging/discharging PHEVs and selected locations. Figure 2 shows a flowchart to obtain an optimal solution for the PHEV operation scheduling framework. Initial agent positions that carry all control variables are randomly generated within the pre-determined limits. The performance of each agent is then evaluated using MATPOWER [23] to calculate power flow based on given values. The obtained total power losses from the power flow calculation are used as a fitness value. Then, the worst and best agents can be identified to calculate each agent mass. The GSA operators manipulate the control variables using (3)-(10) to provide a new generation of agent positions. The process is repeated until it meets the stopping criterion. At this point, an optimal PHEVs operation is obtained.

5. RESULTS AND DISCUSSION

The proposed framework is applied on a modified 33-bus test system [24] to showcase its performance. The test system is a balanced 12.66 kV distribution network consisting of 33 buses that are interconnected by 32 lines. The total active and reactive power loads in the network are 3.715 MW and 2.3 MVar, respectively. There are 6 identical DG units in the test network at buses 6, 7, 13, 18, 28 and 33 with a capacity of 1 MW each unit to represent high penetration of renewable resources. This study aims to find the best two PQ buses for PHEV charging and discharging operation where each bus equipped with 20 connection points only. In this work, two worst case scenarios are considered; A) low demand (40%) at high generation (100%) and B) high demand (100%) at no generation (0%). Parameter settings for PHEV and GSA are given in the tables 1 and 2.

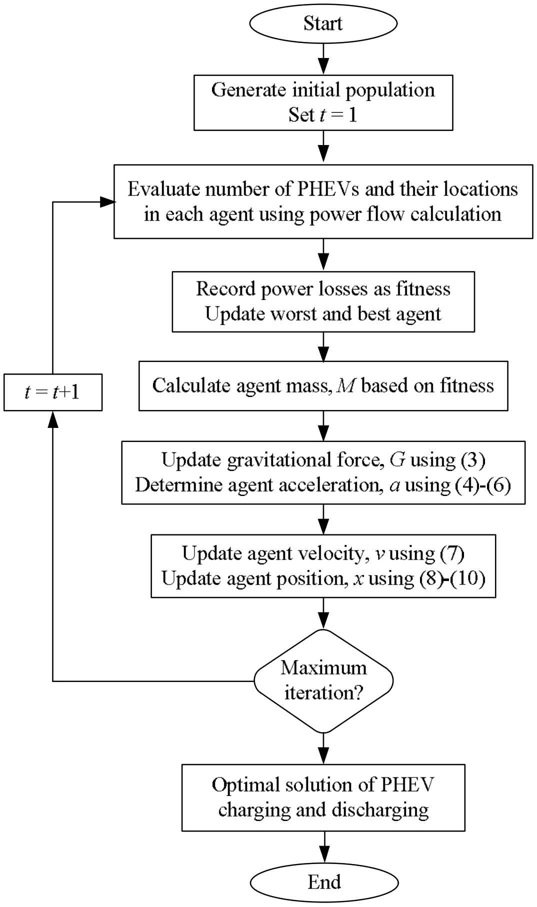

Figure 2: Optimal PHEV scheduling flowchart

Table 1: PHEV settings

PHEV Model	Rated operating power, Prate	Round-trip efficiency
Honda Accord [25]	6.7 kW	80%

Table 2: Optimization settings

Parameter	Settings
Population size	40
Maximum iteration	100
Initial gravity, G_0	100
$Kbest_{max}$ (Initial)	2.5%
$Kbest_{min}$ (Final)	100%

5.1 Optimization Performance

The performance of GSA to determine an optimal scheduling of PHEVs operation in the 33-bus system after performing 10 runs can be summarized in Table 3. The fitness value in the table is given in terms of power losses in kW. The GSA technique application has shown almost same performance in both cases which fewer tendencies to get best solution. The deviations from average value are 9 kW and 5 kW for Case A and B, respectively. Although the fitness is not impressive, the GSA converges fast roughly at 40 iterations in both cases. Figure 3 illustrates the characteristics of the GSA technique in getting the best solution for the case studies. As shown in the figure, GSA has capability to explore the search space and get good solutions at fast convergence rate. In overall, the GSA technique requires several runs in order to get a good solution and it is acceptable for this application.

Table 3: Performance of GSA on PHEVs scheduling

Case	Item	Worst	Average	Best
A	Fitness	404	399	390
	Iteration	73	42.9	14
B	Fitness	184	180	175
	Iteration	76	39.5	9

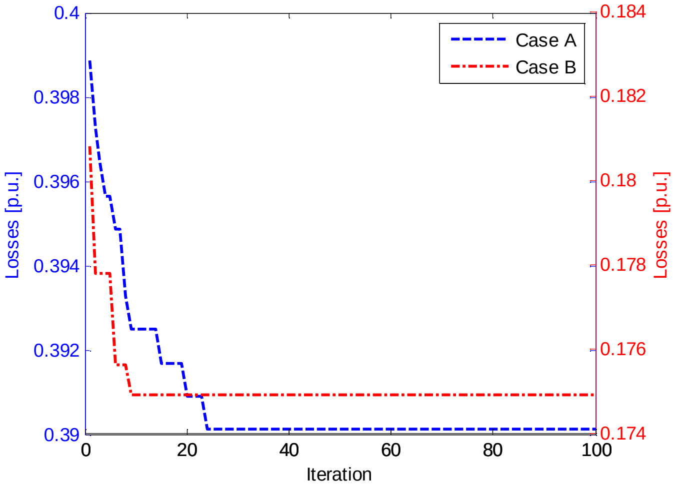

Figure 3: The GSA convergence characteristics

5.2 Improvement on Network Operation

The performance of network operation for both worst case scenarios is tabulated in Table 4. In Case A (low demand and high generation), most of PHEVs are required to charge in order to absorb the surplus generation from the DGs. Figure 4 illustrates the PHEV locations for charging (indicated by blue cars) and discharging (indicated by red cars) in the test network for the Case A. It clearly shows that PHEVs are suggested to be charged along the longest feeder with high DG installations (between bus 6 and 18). On the other hand, only one location for discharging is selected and it is near to the grid supply point. Since power generation in Case A is overwhelmed, power injection from PHEV discharging is not necessary. Nevertheless, it can be exported to external grid for profits (e.g., sell electricity) by directly connect to the grid supply point to reduce transmission losses. The optimal PHEV scheduling framework has demonstrated a significant improvement which able to achieve almost 10% power loss reduction or save more than 42 kW in Case A.

Table 4: Network operation at different worst case scenarios

Item	Case A		Case B	
	Chr	Dch	Chr	Dch
Location [bus]	15, 18	2, 28	5, 25	15, 33
No. of PHEV	17, 15	10, 0	0, 1	18, 20
Power losses [kW]	390.1		174.9	
Base case power losses [kW]	432.6		202.7	
Loss reduction	9.7%		13.7%	

Note: Chr = charging; Dch = discharging

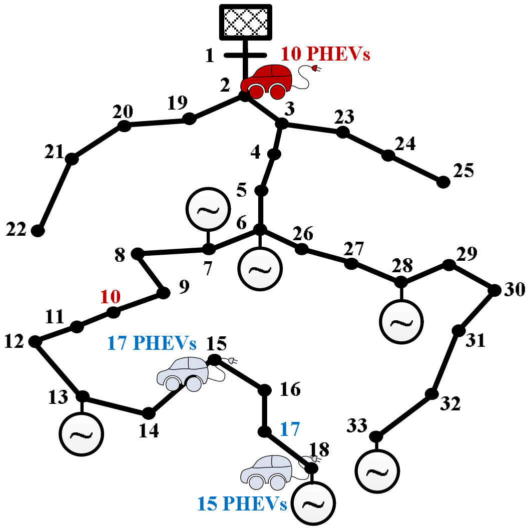

Figure 4: Optimal PHEV scheduling in 33-bus system during low demand at high generation (Case A)

Number of PHEVs charging for Case B (high demand at no generation) in Table 4 is relatively small as to avoid further demand increase during this period. Only one PHEV at bus 25 is suggested in Case B as shown in Figure 5. In this figure, all DGs are hidden to indicate no generation at this period. On the other hand, high volume of PHEVs is suggested to discharge at the end of the longest two feeders as can be seen in Figure 5. Buses 15 and 33 are locations near to the highest demand in the feeders from far end side. Therefore, discharging power from PHEVs will help the local demand to reduce dependency on the grid supply during this period and decrease overall system losses. It has shown more than 13%

power reduction in Case B when the PHEV scheduling scheme in place. From figures 4 and 5, the changing of PHEV mode of operation in the two case scenarios can be considered within local areas and therefore, the proposed PHEV scheduling scheme enables the mobility of electrical energy and improves the network operation with less implication to the existing infrastructure.

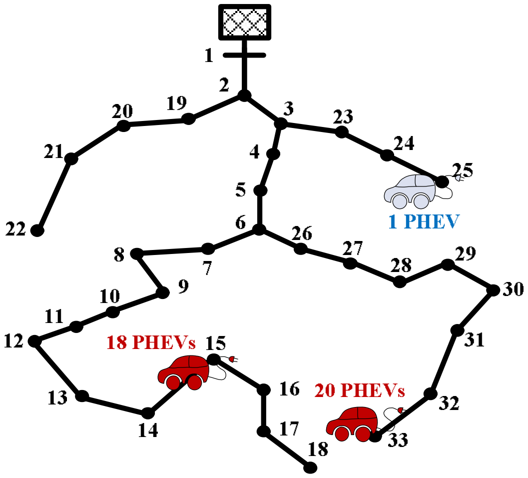

Figure 5: Optimal PHEV scheduling in 33-bus system during high demand at no generation (Case B)

6. CONCLUSION

This paper presented an optimal coordination framework of PHEV operation in a medium voltage distribution network. The optimization problem is addressed using GSA technique and has been tested on the modified 33-bus radial distribution network. The results show a significant power loss reduction in two worst case scenarios; low demand at high generation and high demand at no generation. Hence, this scheme can be used to achieve more efficient network operations.

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