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# Optimal distribution of Plug-In-Electric Vehicle's storage capacity using Water Filling Algorithm for load flattening and vehicle prioritization using ANFIS

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ABSTRACT

Ever increasing Plug-In Electric Vehicles (PEVs) can be considered as mobile storage units and can be exploited for grid ancillary services such as frequency support, voltage regulation and to support to intermittent renewable sources. However, available PEV power is limited by battery State-of-Charge (*SoC*) and customer flexibility. Smart charging control strategies are required in order to maximize PEV storage utilization. In this article, a new control strategy is developed to achieve flat load profile and to minimize the cost of charging. Both utility and customer benefits are given equal importance while utilizing PEV's storage for load flattening. Water Filling Algorithm (WFA) is used to distribute available PEV energy which in turn helps in the effective day-ahead scheduling of PEVs. Minimization of the cost of charging and maximization of PEV power usage has been accomplished by Adaptive Neuro-Fuzzy Inference System (ANFIS). ANFIS is trained to prioritize vehicles based on both utility and customer perspectives simultaneously. The impact of ANFIS prioritization on aggregate PEVs power availability and load flattening at a given time is studied. Also, the role of WFA in the prior scheduling of PEVs on load flattening is analyzed. Danish power grid data is used to implement the proposed control strategy in a residential distribution network. Due to the active power transactions between PEV and grid, the bus voltages are maintained within limits without using additional control for voltage regulation.

## 1. Introduction

The uncoordinated PEVs charging load on the distribution network creates severe problems mainly by overloading the transformers and voltage deviations [1,2]. The advantage of PEVs is that the PEV's battery storage can be exploited for the grid support/services that include demand-side management, frequency and voltage regulation and spinning reserve reduction. The probability of PEV staying at home during mid-day is 0.9 and the probability of PEVs staying at home is 0.5 during weekdays and weekends [3] and hence PEV's storage can be flexibly exploited for grid support with help of smart charging strategies. PEV battery cost and range (key economic factors) have shown positive signs towards cost reduction and range improvement that led to a drastic rise in PEV market growth [4]. Solar PVs that are installed at home will cause reverse power flow and voltage rises due to its maximum power generation during mid-day period during which residential load will be less. PEV's battery storage can be utilized to support solar PVs and to avoid money spending on energy storage systems. Impact of a huge number of PEVs simultaneous charging on the residential transformer is studied in Ref. [5]. PEVs charging leads to transformer losses, peak load demand, lower voltages and harmonics due to converter setup [6]. The advantages of PEVs scheduling is studied in Ref. [7] with multiple stakeholders and charging fleets. Vehicle-to-Grid (V2G) brings bi-directional power flow in electric networks and hence it complicates the system operation [8]. Authors have proposed different PEV control strategies in order to utilize PEV storage for grid support. Voltage control is achieved with the coordination of static capacitors and PEVs in [9]. An optimal PEV control strategy is developed in Ref. [10] for charging where *SoC*, battery lifetime degradation, the voltage at the bus and trip schedule as key parameters. Battery lifetime and revenue maximization are given priority while using PEVs as mobile storages units [11]. In Ref. [12], authors have presented different PEV charging control strategies for solar PV systems assisted with PEV's storage. In Ref. [13], coordination of PEVs with static energy storage systems is used as secondary frequency regulation support along with convention primary frequency regulation support. In Ref. [14], trip requirements are considered while PEVs are scheduling for frequency regulation support. Authors have not considered the

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**Nomenclature**

*Abbreviations*

| | |
|---|---|
| ANFIS | Adaptive Neuro-Fuzzy Inference System |
| CDF | Cumulative Distribution Function |
| G2V | Grid-to-Vehicle |
| NTS | National Transport Survey |
| PDF | Probability Distribution Function |
| PEV | Plug-In-Electric Vehicle |
| V2G | Vehicle-to-Grid |
| WFA | Water Filling Algorithm |
| WFEDA | Water Filling Energy Dispatch Algorithm |

*Indices*

| | |
|---|---|
| $\gamma$ | Mileage of PEV (kWh/mile) |
| $\eta$ | PEV battery efficiency |
| $\lambda$ | Lagrange multiplier |
| $\Delta P$ | Deviation in grid power (kW) |
| $\Delta t$ | The time span of each interval |
| $\Delta V$ | Deviation in bus voltage (p.u) |
| $DoD$ | Depth-of-Discharge |
| $L$ | The total length of a trip (miles) |
| $t$ | $t^{th}$ time interval |

*Variables*

| | |
|---|---|
| $C_t^i$ | Cost of PEV charging during $t^{th}$ interval |
| $C_{L,i}$ | Cost of PEV battery replacement |
| $C_{t,c}^e$ | Electricity price during $t^{th}$ interval |
| $C_t^i$ | Cost of PEV charging at $t^{th}$ interval |
| $C_{L,i}$ | Cost of PEV battery replacement |
| $C_{t,c}^e$ | Electricity price during $t^{th}$ interval |
| $C_{pev,i}^{bdc}$ | Battery degradation cost |
| $C_{b,i}$ | Cost of the battery |
| $\mathrm{C_{L,i}}$ | Battery replacement cost |
| $DoD_i$ | Depth-of-Discharge if $i^{th}$ PEV |
| $DoD_i$ | Depth-of-Discharge if $i^{th}$ PEV |
| $E_{need}^{t,grid}$ | The total need of energy for $t^{th}$ interval |
| $E_{need}^{t,pev}$ | Energy need from PEVs for $t^{th}$ interval |
| $E_{spec}^{grid}$ | Specified energy from the grid |
| $E_{pev}^{i,cap}$ | PEV battery capacity |
| $E_{pev}^{i,t}$ | Energy charged/discharged during the interval $t^h$e interval |
| $\mathrm{E^t_{wfeda}}$, $\mathrm{P^t_{wfeda}}$ | Optimal energy and power dispatched for $t^{th}$ interval by WFEDA |
| $L_{C,i}$ | Life cycles of PEV battery |
| $L_{pev}^{i,t}$ | Laxity of $i^{th}$ PEV at $t^{th}$ interval |
| $P_{spec}^{grid}$ | Specified grid power |
| $P_{need}^{t,grid}$ | Power need from the grid during $t^{th}$ interval |
| $P_{solar}^t$ | Solar PV power during $t^{th}$ interval |
| $P_{load}^t$ | Load power during $t^{th}$ interval |
| $P_{pev}^{t,ch}$ | Charging requirement for all PEVs during $t^{th}$ interval |
| $P_{rate}^{i,t}$ | Power rate of $i^{th}$ PEV during $t^{th}$ interval |
| | Reference power rate setting for PEV for voltage regulation |
| $PEV_{avail}^{t,i}$ | Availability of $i^{th}$ PEV at home during $t^{th}$ interval |
| $SoC_{min}^i$ | Minimum $SoC$ of $i^{th}$ PEV |
| $SoC_{pev}^{i,t}$ | SoC of $i^{th}$ PEV at interval $t^{th}$ interval |
| $SoC_{max}^i$ | Maximum $SoC$ limit |
| $SoC_{depart}^{i,t=t_d}$ | $SoC$ requirement before departure |
| $SoC_{i,pev}^{new}$ | $SoC$ after arrival from a trip |
| $SoC_{i,pev}^{old}$ | $SoC$ level before departure for a trip |
| $t_d^i$ | Time of departure of $i^{th}$ PEV |
| $\mathrm{T^i_{ch}}$ | The time required to charge PEV to target $SoC$ |

requirement of power for grid ancillary support (frequency/voltage) during upcoming hours and also the effect on PEV power availability due to the time of PEV usage.

PEVs are used for frequency regulation in a distribution network with wind power plant [15] while another objective is to utility operating cost and network losses. The solar PV effect on bus voltage at midday period is mitigated with optimal usage of PEVs by adjusting the charging rate [16]. Dynamic programming method is used in frequency regulation with PEVs support by taking *SoC* and customer profit as the key factors [17]. Water Filling Algorithm (WFA) which used in communication channel power allocation [18] is used in Ref. [19] for load flattening by using PEVs storage with consideration of target *SoC* and trip schedules. A two-layer optimization of PEV scheduling for grid support with RES is proposed in Refs. [20,21]. Multi-stage modeling of PEV's aggregators is carried out in day-ahead electricity markets [22].

Revenue obtained by PEV owner through the participation in grid support is one of the key factors that encourage the customer to participate in grid support. In Ref. [23], it has been demonstrated that the uncoordinated PEVs charging causes peaks in load demand during evening times in residential areas, during morning hours in workplaces and during mid-day hours at commercial places. In view of customer revenue maximization, it will be more economical if the PEV is charging during time zones of lower electricity prices [24]. Customer revenue maximization, network loss minimization, and system reliability maximization are considered as objectives in Ref. [25] while scheduling PEVs for grid support. Another important factor is the flexibility of PEV usage in grid service that depends on target *SoC* for the trip. Prioritizing PEVs while using for grid support is an important task to maximize exploitation of PEVs storage without creating inconvenience to the customer. In Ref. [26], authors have implemented PEVs prioritization where battery capacity and power rate are the decision variables but the customer revenue aspects are not considered. Cost of electricity along with target *SoC* is used for prioritization [27] and *SoC* is taken as the key factor while deciding priority [28]. In Refs. [27,28], authors have not considered the vehicle Laxity (PEV's flexible time duration for participation grid ancillary support) which decides the vehicle flexibility to use in grid support. The existing works of literature have not considered the time amount of energy/power requirement for load flattening and time of PEV battery usage during the day ahead scheduling of PEVs for grid support. Also, the prioritization of vehicles is not carried out based on both customer (economical) and utility (technical) perspectives simultaneously while PEVs are being exploited for grid support. Also, the advantage of vehicle prioritization in effective utilization of battery power/energy is not studied thoroughly.

In this work, an attempt is made to confront the drawbacks mentioned above. The whole day is sliced into uniform time intervals (15 min duration each). The zones of energy need for load flattening has been identified using forecasted load demand including solar PV generation and PEV charging for the trip purpose. The available PEV storage capacity is estimated using the PEV mobility model. Day-ahead optimal energy distribution among the time intervals in each zone is accomplished with WFA. Aggregate PEV energy available at starting of each zone is considered as the main constraint and the available PEV power is taken as power constraint in each time interval. WFA helps in pre-scheduling of PEVs on the previous day itself. However, forecast errors in power demand and PEV's status in real time cause adjustments in the day-ahead schedule. Here, ANFIS prioritization helps in slightly shifting the PEV's day ahead of the scheduled time horizon to another flexible time zone.

ANFIS based prioritization strategy is developed to maximize PEVs