Managing Residential-Level EV Charging Using Network-as-Automation Platform (NAP) Technology

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Abstract

The amount of power that can be provided for charging the batteries of the electric vehicles connected to a single neighborhood step-down transformer is constrained by the infrastructure. This paper presents a distributed and collaborative residential-level power grid management application to alleviate the need of costly infrastructure upgrade. The application is designed to be hosted in our in-house developed network-as-automation platform (NAP) technology where most of the control functionalities may be moved onto the networking devices. Moreover, we have adapted a service-oriented software engineering principle to achieve scalability, autonomous, and architecture agnostic properties for the residential-level EV charging. We demonstrate a functional prototype where off-the-shelf networking devices capable to host a Linux Operating system are used to showcase the NAP technology. Furthermore, we developed a web-based user interface that may be accessible from any standard computing device, e.g. iPhone, to monitor the runtime operation of this application.

1 Introduction and Related Work

It is already believed within the industry and the research community that Electric Vehicles (EVs)[1] are going to be a common scenario in the roads of North America, Europe, and Asia Pacific within this decade [2, 4]. It is already portrayed in various academic, industrial, and policy making forums that our natural reserve for fossil fuel is diminishing fast and also we are making our environment unlivable with *Green House Gas* (GHG) emissions. Therefore, to ensure the current civilization survivability and economic sustainability for the future, world leaders and organizations are taking various measures as an urgent need, e.g. promoting usage of renewable energy and thereby reducing dependency on fossil fuel, etc. [1, 5, 10]. In continuation of this effort, US President Obama called for one million EVs on the USA roads by 2015 in his 2011 State of the Union address [10].

In summary, the major driving forces for the EVs are the economical and environmental advantages over traditional gasoline-powered vehicles. However, charging the batteries required to drive the EV motors (single EV load can be as high as the rest of the household load) especially in a residential environment is a very challenging task. Currently, one of the major research challenges is: what level of infrastructure[2] upgrade/modification (both software and hardware) is required to accommodate the additional EV load? If it is required to build more fossil-fueled power plants to cover the additional EV load and significant modification in the power transmission and distribution grid (e.g. changing the transformers, circuit breakers, etc) then the economical and environmental advantages envisioned from the EVs will be mitigated. Therefore, the long-term success of this technology depends on the minimal excessive load and shift impact by the EVs on today's grid. Authors in [12, 13] have already shown that the additional EV load may be managed within the existing power grid if it is tackled more efficiently and collaboratively.

In the scope of this paper, a novel residential-level EV charging application deploying our in-house Network-as-Automation Platform (NAP) technology (networking devices are used for embedded computing and control) and a software/hardware prototype exploiting a service-oriented software engineering principle are presented.

The potential negative reliability and power quality impact on the distribution power grid due to the future EV penetration have been recently addressed in [5, 7]. These works are limited to examine the impact of charging EVs on the distribution power grid under different charging scenarios. Authors in [12, 13] have discussed the need of new algorithms to manage the EV loads in the grid. A centralized control system mounted on the poll besides the neighborhood step-down transformer has been envisioned to solve such a problem. Their approach is typically limited to those Utilities who are interested to provide such an additional control hardware. Moreover, these types of centralized architectures will suffer from known single-point computing bottlenecks. A control architecture to reduce the stress on the distribution power grid is presented in [11]. However, [11] fails to provide a distributed software-centric solution depending on the Utility regulations and available computing and communication platform. Moreover, work in [11] does not consider rest

[1] *Electric-cars* (e-car), *Electric Vehicle* (EV), *Plug-in Electric Vehicle* (PEV), *Plug-in Hybrid Electric Vehicle* (PHEV) are used interchangeably within the scope of this paper.

[2] This includes both power grid and residential infrastructure.

of the household loads, e.g. HVAC that may be scheduled together with the EV battery charging. In [8], authors suggest another control architecture using significant infrastructure upgrade to accommodate EV in the distribution power grid. This is the major limitation of [8], as infrastructure upgrade costs is not socially, politically, and economically desirable [6] in present situation. Considering all these limitations, we propose a novel residential-level EV charging application deploying our NAP technology (see Sec.4 for NAP details).
The rest of the paper is organized as follows. After presenting our novel contributions in 2, in 3 we describe the EV charging at residential neighborhood application. In 4 and 5, we explain our in-house developed NAP technology and service-oriented software engineering principle for the application, respectively. In 6, our proposed collaborative EV charging algorithm with its detailed computing and communication models is explained in detail. The developed prototyping case-study, as well as some additional analytical analysis of the collaborative algorithm are discussed in 7 with 8 concluding the paper.

2 Our Novel Contributions

Our novel contributions are as follows:
(1) A distributed algorithm to manage the residential-level power distribution grid in a collaborative way due to additional EV load penetration. The algorithm is able to find a schedule for all the requesting EVs to be charged intelligently and collaboratively.
(2) A distributed and networked embedded application hosting platform using our NAP technology. Within an NAP architecture, embedded computing (control) may be moved onto the networking devices, e.g. switch, router, etc. Service-oriented software engineering principle may be used to achieve loosely coupled architecture and platform agnostic computing on top of this NAP.
(3) A service-oriented design approach of the residential-level EV charging application. The application is architecture and platform agnostic and provides higher scalability and autonomy.
(4) A fully functional prototype to demonstrate the proposed algorithm and the NAP technology. Moreover, a web-based user interface to monitor the state of the residential-level EV charging application is presented. The user interface may be accessed from any standard computing system through wired/wireless connection, e.g. iPhone.

3 Residential-level EV Charging Application

A typical end-point power distribution system delivers power to a residential *Electric Vehicle Supply Equipment* (EVSE) from the neighborhood distribution pole equipped with a a transformer (neighborhood step-down transformer). Figure 1 presents an exemplary configuration of the power grid. The left side of the figure shows the power grid from the power generation to the neighborhood step-down transformer, while the right side of the figure shows multiple EVs with the respective EVSEs. The typical step-down trans-

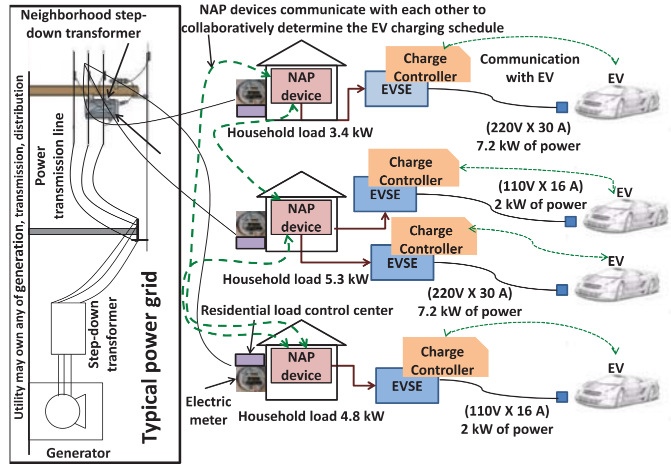

Figure 1: Electric vehicle in the distribution power grid

former has an upper limit representing the maximum load that can be supported from these neighboring houses altogether. In case the total load increases beyond the supported limit, the protection system (e.g. a circuit breaker) attached to the transformer gets activated automatically. Moreover, higher electric stress on the transformer reduces the performance and lifetime of the transformer. Depending on load sizes and types, neighborhood step-down transformers typically range in size from 25kVA to 75kVA per phase. A typical 25kVA transformer generally serves four to seven homes in a neighborhood [12].
A typical household can have the total load between 1.5 kW to 8 kW. Since the load of a single EV can be as high as 7.2 kW, either the circuit breaker connected to the house or the transformer will prevent EV loads overlapping with other large residential loads such as HVAC, which is typically 1 to 5 tons (3 to 20 kW). The scenario becomes even more complex when EV charging requests from neighboring residential units overlap in time, which has a high probability because typical EV users are likely to charge their EV batteries during off-peak hours (e.g., night time). Nevertheless, without proper management and control algorithms of plug-in requests, extensive infrastructure modifications may still be unavoidable in order to maintain power quality and mitigate power outages.
EV charging may contribute to an increase in peak demand and create various negative consequences, e.g. Utility customers will suffer far more frequent power outages, electric distribution operations would need to react to unplanned network upgrades, and call center personnel would experience a higher than normal number of complaints. The problem would not only result in the increased customer dissatisfaction, but also create a perception that the Utility company is incapable of supporting the roll-out of EVs which could, in turn, adversely impact EV penetration to the market. Moreover, all these accumulated issues would also result in the increased customer minutes of interruption and adversely impact related indices like *System Average Interruption Duration Index* (SAIDI), *Customer Average Interruption Fre-*

quency Index (CAIFI), etc [14]. To solve this problem, we present: a residential-level charge control algorithm to use the available power intelligently, a novel computing platform consisting of distributed and networked embedded systems of networking devices, and a service-oriented software engineering principle to make the system loosely coupled, scalable, autonomous, architecture and platform agnostic without any infrastructure upgrade.

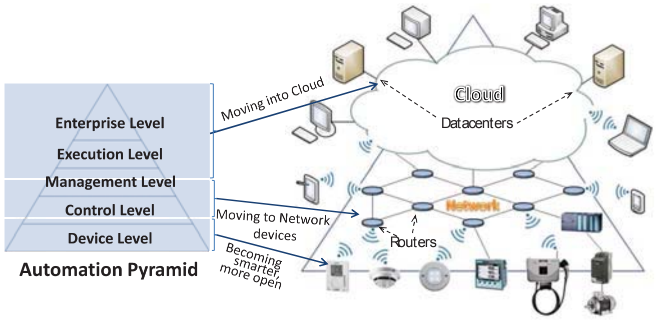

Figure 2: High-level overview of the NAP technology

4 Network as Automation Platform (NAP)

With the technology scaling in the semiconductor industries, today it is possible to integrate highly complex functionalities in the form of software pervasively within various components required for automation, e.g. sensors, actuators. Therefore, this technology scaling has allowed us to embrace another phase of evolution in the domain of embedded systems, termed as networked embedded systems. A networked embedded system is a collection of spatially and functionally distributed embedded devices interconnected by means of wired/wireless communication infrastructure. Within the system the interaction with the environment is done through sensors and actuators and some computing devices performing some control functions utilizing communication to achieve certain goals. Typically, these goals are some sort of automation, e.g. process automation, building automation, etc.
A typical automation pyramid (partitioned to different levels) that utilizes the networked embedded systems platform is shown in Figure 2. Typically, in a automation pyramid there are five levels (see Figure 2), where most of the lower levels may utilize networked embedded systems. In our NAP technology, we have envisioned the typical automation pyramid [16] to three levels. *Device level* may cover lots of functionalities of the *Control level* due to integrated software (intelligence) within the end devices e.g. sensors and actuators. *Control level* may take responsibilities of most of the *Management level* tasks. Finally, other top levels may be moved onto the cloud.
Technology trend clearly shows that the networking devices, e.g. routers, switches used for constructing this networked embedded systems platform are getting computationally powerful and moreover these networking device may host standard embedded operating systems. Therefore, most of the control functionalities shown in Figure 2 may be easily moved onto these networking devices. In the NAP technology, an automation system may be deployed and operated on such above mentioned networking devices, e.g. routers within a common network in a distributed manner. Automation services are deployed and operated on the networking devices in accordance with a service-oriented architecture model. At least one of the services may comprise a first instance of the service deployed on a first networking device and a second instance of the service deployed on a second networking device. Novel methods are developed within our research for deploying and operating the automation system on a multiple networking devices in the common network (this is out of the scope of this paper). Details of NAP technology may be found at [9].
For our residential-level EV charging application we have exploited this above mentioned technology to move the control functionalities onto the networking devices.

5 Service-Oriented Design for NAP

In the residential-level EV charging application, the embedded computing devices (the networking devices) for the control functionalities collaborate with each other only by sharing the local information (details will be discussed in Section 6). In addition, while monitoring and processing the information of other *NAP devices*, every *NAP device* makes the decision independently. Therefore, the communication between *NAP devices* can be loosely coupled so that only the interfaces of the services for information exchange are necessarily exposed. The autonomous but collaborative characteristics of the application fits exactly into the principles of *Service-Oriented Architecture* (SOA) [3]. Therefore, a framework based on SOA using Web Services, more specifically the *Device Profile for Web Services* (DPWS) [15] protocol suite is used in the residential-level EV charging application development. It is already discussed in early literature the advantages (e.g. scalability, loose coupling, autonomous behavior of the services, architecture and platform agnostic characteristics) of the SOA paradigm in the automation domain.

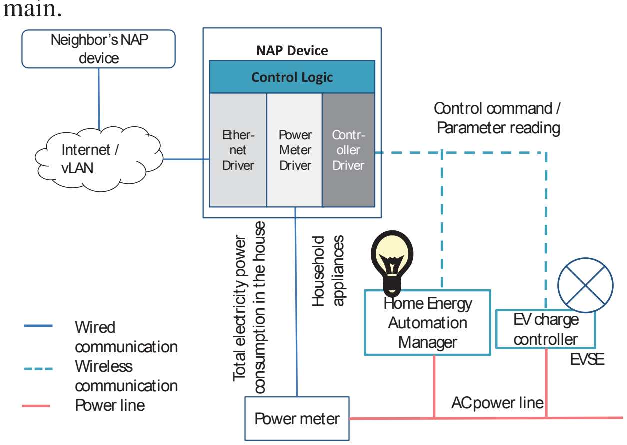

Figure 3: Single residence-level electricity power management in the presence of EV using NAP technology

6 Residential-level Power Grid Management

The proposed residential-level power grid management application that is executed on our NAP using a service-oriented software engineering principle is described below. Figure 3 has demonstrated a logical architecture among all the participating actors within a single house for the grid management in the presence of the EV. In this figure, within a single house one NAP device is wired connected to the *Power meter* and can read the power consumption of that house. The NAP device is also connected to the home energy automation manager (typically household appliance controller), as well as to the *EVSE* wirelessly, e.g. WiFi, ZigBee, ZWave. Therefore, the NAP device is able to communicate with the home energy automation manager and the EVSE utilizing control commands and parameters. All controllers, located inside or attached to the appliances/EVSE, are plugged into the *AC Power line* of the house through the *Power meter*, from where the power consumption of the entire house may be measured.

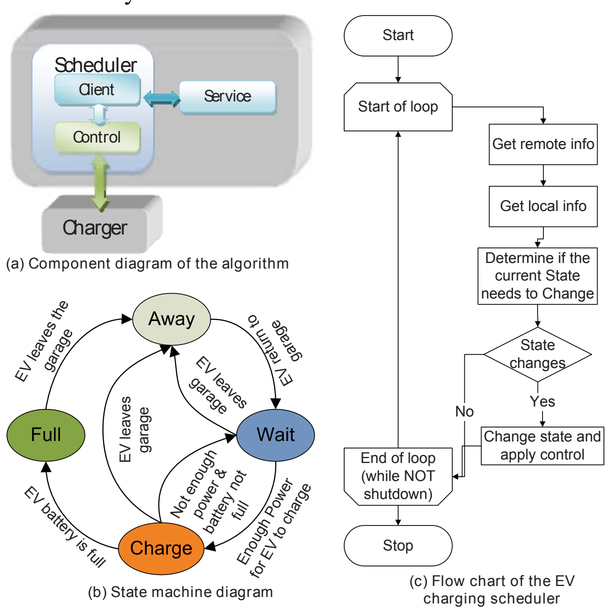

Figure 4: Residential-level distribution power grid management

One instance of the application running on each *NAP device*, situated in every neighboring houses, contains a service and a scheduler component. Moreover, the application communicates with the EVSE which is connected to the *NAP device*. The service provides: local household[3] and EVSE power consumption, as well as the EV state information (explained later) of the local *NAP device* to other *NAP devices*. The scheduler has a client which can connect to the services from all the *NAP devices* including itself, and a control component to decide EV state transition, as well as control and read status from its EVSE. The component diagram is shown in Figure 4(a).

There are four EV states associated with the residential-level EV charging: *Away*, *Wait*, *Charge*, and *Full*. The state diagram of this application is illustrated in Figure 4(b). *Away* means the EV is not in the garage, and the EVSE is turned `OFF`. While the EV is in the garage, it can be in one of the following three states:

- **Charge state**, when the EV is being charged and the EVSE is turned `ON`.
- **Full state**, when the battery of the EV is already full.
- **Wait state**, when the EV is waiting to be charged.

The transitions between states are controlled by the control component inside the scheduler (Figure 4(c)). The scheduler runs in an infinite loop within each of the *NAP devices*. In each loop, it uses the client component to collect remote information from the services running on other *NAP devices* (other neighboring houses), and the local information from its own service. The information includes household and EVSE power consumption, as well as the EV state of each *NAP device*. Based on the information from all the neighboring *NAP devices*, the control component in the scheduler decides if there should be a state change of the EV connected to this *NAP device* and control the EVSE accordingly. In the following, we assume that the limit of the neighborhood distribution power grid is P_{max}, the household and EVSE power consumption from the *NAP device* i are P_i^h and P_i^c, respectively. Moreover, each EV has a priority as Pr_i, where the higher the priority is, the earlier the EV is scheduled. The detailed conditions for the state transitions shown in Figure 4(b) are as follows:

- **From Wait to Charge**: While EV i is in *Wait* state, the condition to change to *Charge* state is given in Equation (1). It means the total available power from the neighborhood distribution power grid is enough for all household loads of the neighborhood, and all the EVs that have higher priority than the EV i to be charged, plus enough power to charge EV i.

$$P_{max} - \sum_{i} P_i^h - \sum_{j \neq i} I(Pr_j > Pr_i) P_j^c > P_i^{cmax} \quad (1)$$

  where $I(\bullet)$ is an indicator function and

$$I(Pr_j > Pr_i) = \begin{cases} 1 & \text{if } Pr_j > Pr_i, \\ 0 & \text{otherwise.} \end{cases} \quad (2)$$

  In our algorithm, the priority can be defined in various ways, e.g, time-based round-robin criterion.

- **From Charge to Wait**: When EV i is charging, once the condition in Equation (1) is no longer satisfied and the battery is not fully charged, EV i should stop charging and waits to be scheduled.

[3] Rest of the household loads and EV loads are treated separately within this paper.

- **From Charge to Full**: when the battery of the EV i is fully charged, EV i should stop charging.
- **From any other state to Away**: The EVSE is assumed to be able to send an interrupt signal to the scheduler to indicate whether the EV leaves the garage (unplugged from the EVSE). Once the scheduler receives the signal, it adjusts the EV state from any of the other three states to *Away* state regardless of the power information.
- **From Away to Wait**: When the EVSE sends a signal that the EV is back (plugged in to EVSE), the EV is first scheduled to be waiting and has the state *Wait*.

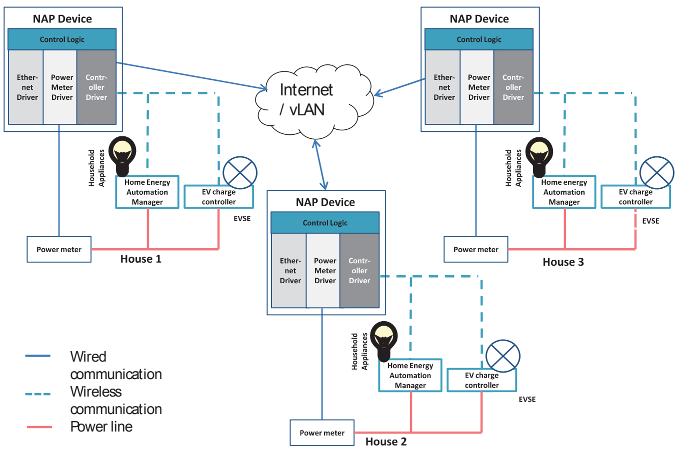

Figure 5: Neighborhood-level electricity power grid management in the neighborhood step-down transformer using NAP technology

All NAP devices (typically networking devices in nature) are connected to the Internet or to the *virtual LAN* (vLAN) and is able to communicate among themselves as described above. One such connected scenario is presented in Figure 5. In Section 7, the prototype of this scenario developed in our lab is presented.

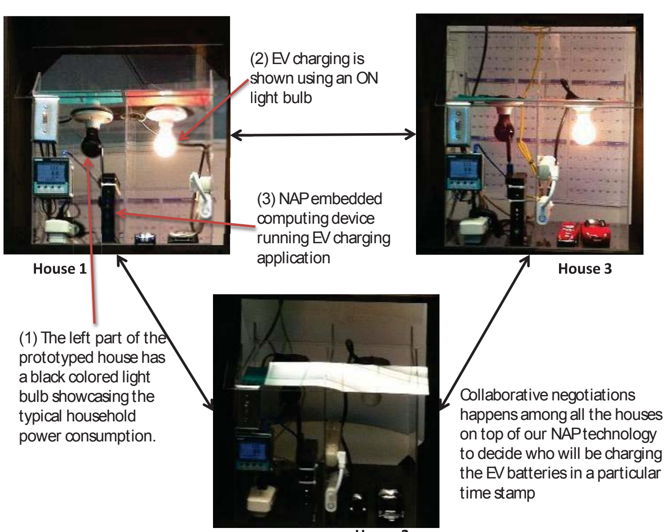

Figure 6: Prototype of our residential-level EV charging application

7 Results and Evaluation

The prototype[4] developed within the scope of this work assumes that three neighboring houses are served by a neighborhood step-down transformer (see Figure 6). We assume each house has two parts: the right side is the garage, where the light bulb indicates if the EV is charging and the left side indicates the rest of the house and the household loads are represented by the left light bulb. There is a *NAP device* in each house which is running the residential-level EV charging application collaboratively and finally all the *NAP devices* are connected through Ethernet.

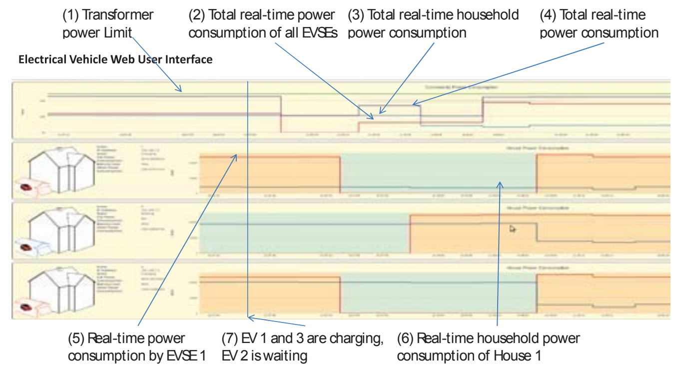

Figure 7: Web-based user interface for monitoring

Figure 7 shows the web-based user interface to monitor the application operation. As mentioned earlier, the user interface may be accessed from iPhone or any other devices. The four major sections from top to down show the total power consumptions and power consumptions of *House 1* to *House 3*, respectively over time. In the top section of the figure, Line 1 shows the total power limit constrained by the infrastructure, Line 2 shows the total real-time power consumption of all three EVSEs, Line 3 shows the total real-time power consumption of the three houses without EV consumption, and Line 4 shows the total real-time power consumption of the three houses. For these three houses, the power consumption of EVSEs and the rest of the household loads are shown for different time-stamps, e.g. the real-time power consumption of EVSE 1 is shown in Line 5, and the real-time household consumption is shown in Line 6.

Moreover, one time instance captured in Figure 6 is highlighted in Figure 7 at line 7, where EV 1 and EV 3 are charging while EV 2 is waiting. At this time-stamp, as the household consumption is relatively high, the transformer cannot serve enough power for all the three EVs to charge at the same time. Therefore, our schedulers enable two EVs instead of three EVs to be charging simultaneously.

We have also evaluated our residential-level EV charging using a separate simulation environment with an analytical model. Simulation parameters are: 4 neighborhood houses per transformer are considered, each house has a single EV, the power rating limit of the transformer is 25KVA (can accommodate at most 25 kW load), EV batteries are only

[4]Real lab-scale prototype of the logical representation of Figure 5.

charged between 5PM and 8AM (this is scenario specific), each EV requires 5 kW power to be charged fully, initial charge of each battery of the EV is 0%, it requires 10 hours to fully charge the batteries of the EVs, with full charge an EV may travel 100 miles, and next day commute for each of the EV users is on an average 50 miles and therefore at least 50% charged battery is required. We have compared our scheduling algorithm (Equation 1, Equation 2, and a round-robin based pririty criteria) with the typical charging approach (*First Come Full Charge* (FCFC)) where if an EV is allowed to start charging it will not be allowed to be pre-empted to share the electric power with others (this shows how we may maximize the total number of EVs to be charged given that all EVs do not require to be charged fully for next day commute).

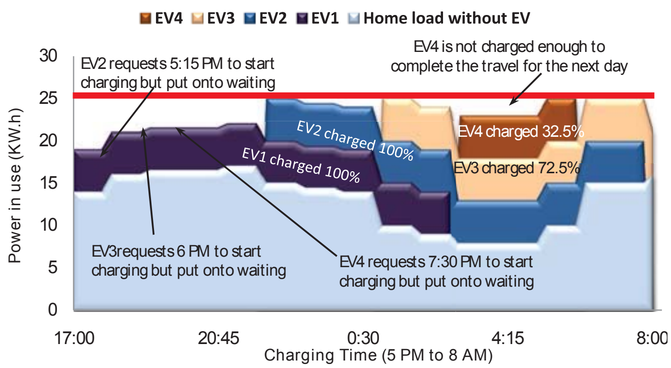

Figure 8: FCFC charge control without any collaboration

Figure 8 and Figure 9 are shown to compare our algorithm with *FCFC* algorithm.

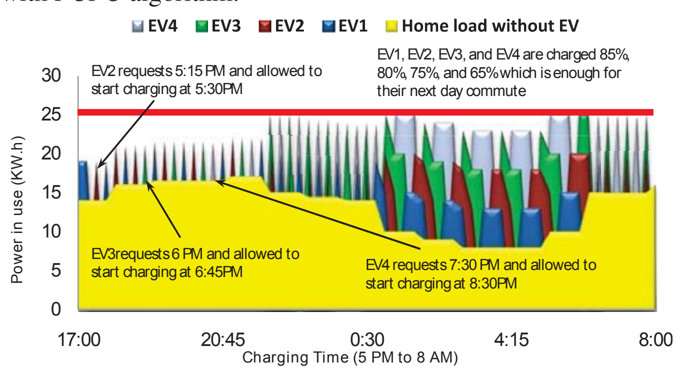

Figure 9: EV charging using our algorithm (a round-robin based priority criteria)

Figure 8 shows that EV1 requests to start charging at 5PM and is charged 100% finishing at 1:45AM. Therefore, EV1 is ready for next day travel. EV2 requests to start charging at 5:15PM but queued onto waiting as the *FCFC* algorithm is also not allowed to violate the maximum loading of the transformer. However, the EV2 charging request is accepted at 10PM and is charged 100% finishing at 7:45AM. Similarly, EV3, EV4 are charged 72.5% and 32.5% respectively. Therefore, in this scenario using *FCFC* algorithm EV4 will not be able to travel 50 miles (minimum 50% battery charging is required). However, our algorithm shown in Figure 9, for the same scenario, allows all the EVs to be charged in a collaborative way so that all the EVs may travel their required next-day distance. Using our algorithm, the batteries of the EV1, EV2, EV3, and EV4 are charged 85%, 80%, 75%, and 65% respectively.

8 Conclusion

We present a distributed and collaborative residential-level power grid management application to alleviate the need of costly infrastructure upgrades due to higher penetration of EVs. We demonstrate a functional prototype of this application using our in-house developed NAP technology and service-oriented software engineering principle. Moreover, in a separate simulation environment with an analytical model, we show that our collaborative negotiation algorithm is capable of meeting user requirements more intelligently and efficiently, e.g. by maximizing the total number of EVs to be charged in a given time stamp assuming that all EVs do not require to be charged fully for next day commute.

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