A Unique Approach to Demand Side Management of Electric Vehicle Charging for Developing Countries

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***Abstract*—Increased penetration of electric vehicles (EVs) can lead to uncoordinated charging which can result in electrical distribution network overloads and possibly outages as well as increased peak demands. This can particularly occur in power systems with minimal and insufficient demand side management schemes. Such is usually characteristic of small Caribbean island power systems and their numerous distinctive policy, technical and infrastructural challenges. This manuscript documents a unique approach for EV charging (AC level 1 and 2) in Trinidad and Tobago with application to other Caribbean territories and developing countries. A prototype device is designed for connection to the EV that allows remote (IEEE 802.11 Standard) modification by the electrical utility of the pilot control signal of the J1772 charger. Technical and financial details of the prototype device are provided. The developed scheduling algorithm is provided and showcases the benefits of the optimized EV charging schedule.**

***Index Terms*—Transportation, Data Analytics, IoT, Sensors, Intelligent Electronic Devices, Optimization**

I. Introduction

Small island developing states in the Caribbean face numerous unique, legislative, technical and financial challenges associated with the mass integration of electric vehicles (EVs) into their respective transportation options. Understanding the macro level process beginning with EV importation to the deployment of public and private charging stations is crucial to formulating a strategic approach for sustainable long term growth of EV penetration. A suitable policy formulation process for small island developing states (SIDS) has been developed considering the roles and responsibilities of the various stakeholders. The process reviews the importation process, provides guidance on the local standard development/adoption process, reviews EV charging and EV charging interfaces, human safety and considers future V2G possibilities[1].

A previous study [2] based on real distribution network data in Trinidad and Tobago, highlighted that a 5% EV penetration can lead to feeder overloads as a result of residential AC level 2 charging. This study was classified as the worse case scenario with no diversity considerations and significant daily mileage driving, requiring daily battery charging in excess of 80% battery capacity. This confirms that the application of statistically distributed EV charging will yield greater margins for power consumption, supporting more residential electric vehicle charging. Continuing this research, applying machine learning to EV charging data can be used to optimize the utilization of existing aging distribution network infrastructure (transformers, overhead lines and cables), alleviating power system load flow congestion while delaying distribution network investments for upgrades particularly in a power system without a Time of Use (ToU) Tariff. With the exception of Barbados, Jamaica and Suriname, 75% of the countries in the Caribbean do not employ ToU tariffs [3]. At this time, there is no ToU tariff in Trinidad and Tobago.

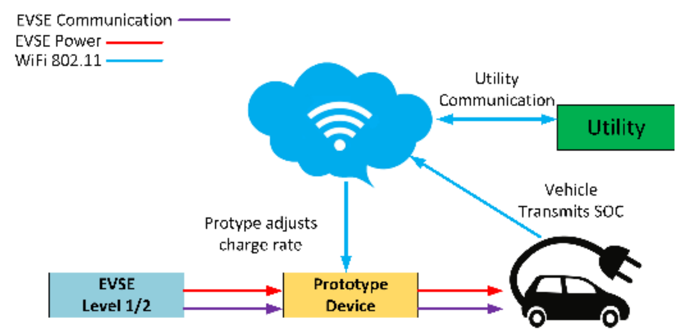

Fig. 1. System Concept

This manuscript documents a cost effective and practical approach that any SIDS utility can adopt to achieve alleviation of distribution network congestion as a consequence of EV charging in the absence of a ToU tariff. Details of the prototype operation and its development are documented with insight into the application of machine learning algorithms that can progress towards a smarter grid and complement smart city initiatives.

II. Methodology

A. Overview

In most communities there are environmentally conscious consumers of electrical energy. This documented approach will attract and encourage all EV owners to participate in an optional coordinated EV charging scheme. The utility can consider incentivizing participation through rebates based on deferred energy consumption over the billing cycle. Figure 1 shows the system operation concept.

B. Technical Approach

The method chosen employs the modification of pilot control signal in common Level 1/2 EV charge connectors. The choice for focus in this paper is the J1772 standard which is adopted in North America and Japan. This can also be applied to the IEC Type 2 (European) and the GBT connector (Chinese). The utility in Trinidad and Tobago employs Automated Meter Reading (AMR) [4] using the Itron family of smart meters. These smart meters transmit data to a communications control unit (CCU) via the use of ISM Bands 900-928 MHz [5]. The CCUs transmit to the utility via GPRS which is undedicated and subject to the cellular network geographical coverage, congestion and outages. In this approach timely feedback communication from the utility to the consumer is required. The simplest and most cost effective (avoids upgrading utility communication systems) communication solution is to use existing WiFi (IEEE 802.11) connections. The assumption therefore is that EV owners will have functional and secured accessible WiFi connections. This approach will only interface with the electric vehicle supply equipment (EVSE) not with the existing installed meters. This system will inherently be a “blackbox” that is connected to the output of a J1772 charger and will provide variable constant power output to the vehicle. The J1772 pin out diagram is shown in Figure 2. Three pins are used for the electricity supply (Line, Neutral and Ground) and the remaining two are used for the pilot control signal and proximity detection. According to the SAE J1772 Standard [6], the pilot signal requires a frequency between 900 and 1100 Hz.

The basis of the operation of the J1772 occurs in 3 main states which modify the magnitude of the pilot as follows [6]:

State A: 12V (EV is not connected)
State B: 9V 2.74$k\Omega$ (EV is connected/No charging)
State C: 6V 882Ω (EV is ready to charge)

The control of the charging is facilitated by modifying the duty cycle of the pilot control signal. For a current range of 6-51A this is governed by Equation 1[6]:

$$I = \frac{\text{Duty Cycle}}{0.6} \tag{1}$$

The prototype device will modify this duty cycle to allow for a coordinated charging environment controlled by the utility but can also be disengaged by the user based on circumstances. Figure 2 shows the concept layout of the prototype device. The prototype device is composed of two mutually exclusive functioning modules which communicate to each other and the utility. Module 1 is located load side of the charger. The progress so far, documented in this manuscript, is based on prototype development of module 1 and the supporting framework. Module 2 is housed in the vehicle and will be plugged into the EV on-board diagnostic system (ODB-II) port to monitor battery state of charge (SoC) and if needed give priority charging to users based on urgency. This overall solution is very scalable, as each prototype device will be link to an EV and connected to an AC level 1/2 charger. With clusters of EVs, algorithms can now be implemented to optimize charging with energy consumption via the use of machine learning. Table I shows an estimate for the cost of building such a prototype device.

TABLE I
Prototype Device Module 1 Financial Estimate

Item	Cost USD
Arudino MEGA 2560	$38.50
Arduino WiFi	$14.95
Electronic Accessories	$48.00
J1772 Connectors and Cables	$227.00
Total	$328.45

III. Dynamic Coordination of EV Charging

Since the time horzion for EV charging can be remotely controlled by the utility then ideally it would be best to spread the charging windows to alleviating the network overloads and curtailing peak load demand. This relaxes the requirement for increased power output from committed generating units and the requirement to commit additional generating units. Given all generating units on the power system are natural gas fired, this reduces fuel consumption, heat rate and financial impact. The prototype device described in the previous sections provides functionality to help realise these macro power system benefits. The dynamic coorindation is achieved as EV owners can use the prototype device to indicate a preferred window for EV charging. For example, if the EV owner arrives home at 7pm and the EV will remain at their home until morning then the EV owner can indicate that charging can be done (but must be completed) anytime between this broad window of 7pm and 6am. The utility then has the flexibility to spread EV charging across the network. The utility can incentivize their customers that are EV owners to provide wide window durations where and when possible to yield greater flexibility for dynamic coordination of EV charging.

A. Power Production and Consumption Models

In the model development, on the generation side, assume all households are served by a single power plant with a minimizing power generation cost objective and during peak periods additional generating units may have to be committed. Given there are associated startup and shutdown costs for committing generating units, the model must ensure that, if the load demand increases and now requires a generating unit to be committed, the duration for commitment must be financially acceptable. On the demand side, charging the EV battery is considered as a controllable load since the utility can decide when charging occurs and therefore when this load is present. All the other loads in a typical household are lumped and considered as uncontrollable. Typically the uncontrollable load can be predicted for short periods of time into the future. This prediction can be based on several features (see [7]).

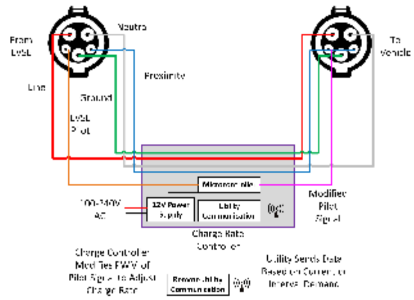

Fig. 2. Module 1 Prototype Simplified Schematic

One way to reduce peak demand is to spread the charging of each vehicle over the entire allocated window. However charging efficiency is higher at higher charging rates, as the the authors in [8] found that, with 10A charging current, the percentage loss was 17.22% but for the case of 40A the percentage loss was 12.38%. In light of this, it is technically beneficial to allow charging at the maximum rate and instead use scheduling to spread the load over time. Therefore, the objective of this solution is to determine when each EV should be charged at a maximum rate within the allowed window.

B. Scheduler

The scheduler is quite straightforward. Each time there is a request for EV charging the scheduler uses the allocated window, the SoC and the estimated time to charge the battery to determine the latest start time for charging to ensure that the battery is fully charged before the window closes. Let $\mathcal{W}$ represent the set of EVs presently waiting to be charged. For each $w \in \mathcal{W}$ let d_w represent the deadline for starting the charging process for EV owner w. If the charging begins after this time then the EV owner may not be able to have a fully charged battery when the car is ready to be used. On a periodic basis the scheduler carries out the following. The scheduler chooses the EV owner with the nearest deadline to serve next (i.e., the one with the smallest d_w). Let ρ denote the power plant utilization at that point in time, let G denote the capacity of the power plant and let p_w denote the generated power required to charge the car by EV owner w. If sufficient power is available (i.e., $(1-\rho)G > p_w$) then the the car is charged and the process is repeated. If insufficient power is available then we wait for the next scheduling instance.

C. Load Monitoring and Capacity Management

The utilization of the power plant can be easily monitored which is defined as the ratio of the total load to the total capacity. Ideally, the utilization should be as high as possible since the excess generated capacity is wasted. This can be achieved by carefully controlling the number of EVs being charged at any point in time. When the utilization is sufficiently low one or more generators can be brought off-line. However, such a change should not be done too rapidly. Therefore, periodic checks are done to determine if a sufficiently long time has elapsed since an increase was made before reducing the number of generators.

In order to determine when additional generators should be brought online imminent overloads need to be detected. Note that the plant will be running near capacity and hence utilization is not a suitable indicator. The values w_d can be used to detect load increases. As the number of EVs requiring charging increases or if the load due to the uncontrollable load increases then the metric

$$L(t) \equiv \min_{w \in \mathcal{W}} w_d - t \tag{2}$$

will decrease. In other words the probability of experiencing an event whereby an EV cannot be charged in time will increase. Therefore, this metric $L(t)$ will be used to determine load. Once this metric falls below some given threshold a generator is brought online. In Algorithm 1 a pseudo-code is provided for the scheduler and for capacity management.

Note that this procedure may not be fast enough to catch rapid changes in loading. In such case the load can be quickly reduced by decreasing the charging rate of all EVs currently being charged. This will be a short term solution and should not vastly affect the overall scheduling process.

D. Illustrative Example

TABLE II
SCHEDULER APPLICATION

Start Time	EVs	Start Time	EVs
7:00pm	2	8:30pm	4
7:30pm	4	9:00pm	4
8:00pm	4	9:30pm	2

Consider the following illustrative example. Assume there is a constant uncontrollable 8 kW load of and EV charging requests are received with the onset of the evening residential peak load. As shown in Table II each EV owner has specified the EV battery charge must be complete by 8am the next morning. Assuming identical initial SoC, each EV requires 0.1 kW for two hours. Figure 3 illustrates the load variation with time forimmediate charging and scheduled charging. Assuming that a another generating unit must be committed if the load exceeds 9 kW then for the case of immediate charging an additional generating unit must be brought online at 8:30pm

Algorithm 1 Scheduler Pseudo-Code

$R(t_1, t_2)$ = EVs requesting charge in interval $[t_1, t_2]$
$\mathcal{W}$ = set of EVs waiting to be scheduled
d_w = charging deadline for $w \in \mathcal{W}$
p_w = power generation required to charge EV w
ng = plant capacity given n generators
ρ = power plant utilization at time
τ = period of the scheduler
t_g = time of last change in number of generators
$t = 0$
μ = minimum time between generator removals
κ = minimum time to deadline before increasing capacity
loop
  $t \leftarrow t + \tau$
  $\rho =$ present value of plant utilization
  if $\{(1-\rho)ng > g\} \wedge \{(t - t_g) > \mu\}$ **then**
    $n \leftarrow n - 1$
    $t_g = t$
  end if
  $\mathcal{W} \leftarrow \mathcal{W} \cup R(t, t-\tau)$
  $w^* = \arg\min_{w \in \mathcal{W}} d_w$
  while $((1-\rho)ng > p_{w^*}) \wedge (|\mathcal{W}| > 0)$ **do**
    $\rho \leftarrow \rho + \frac{p_{w^*}}{ng}$
    Instruct w^* to start charging
    $\mathcal{W} \leftarrow \mathcal{W} - \{w^*\}$
    $w^* = \arg\min_{w \in \mathcal{W}} d_w$
  end while
  if $d_{w^*} - t < \kappa$ **then**
    $n \leftarrow n + 1$
    $t_g = t$
  end if
end loop

and can be taken offline at 10pm. However with scheduling no additional generaing units are needed.

IV. Conclusion

A unique approach to coordinated EV charging with application to SIDS particularly in the absence of ToU tariffs has been presented in this paper. The detailed methodology addressing the technical development (hardware and software) as well a preliminary financial assessment were provided. Functional and performance results are being collected and analyzed for the next update.

The prototype device conceptually showcased the benefits of an optimized EV charging schedule in the distribution network which can alleviate electrical distribution network overloads and prevent outages while deferring distribution network asset upgrade investments. The prototype device will be critical for the implementation of any strategic EV policy which can ***accelerate*** EV penetration.

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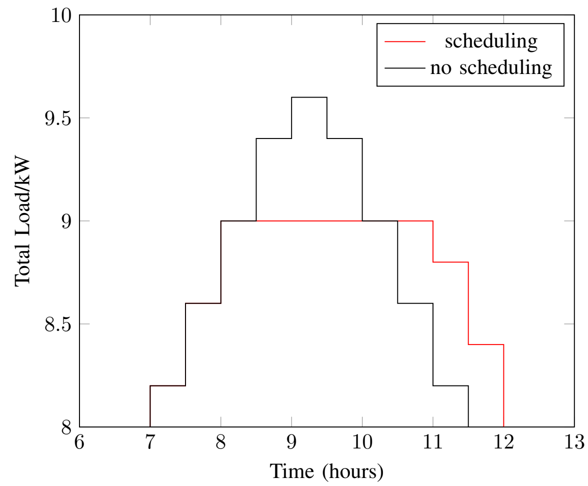

Fig. 3. Illustrative Example of Scheduler Benefit