Minimization of Queuing Time of Electric Vehicles at a Fast Charging Station

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Abstract— **Parallel developments in electric vehicles' battery technologies and the charging equipment is leading the transportation and logistics sector towards a new era. This paper focusses on the quick charging needs of passenger electric vehicles for their optimal charging in terms of total charging time and network capacity utilization. Power distribution network capacity is utilized in such a way that, charging power to each of the individual charging socket is assigned based on the state of charge of the connected electric vehicle to that particular charging socket. An algorithm has been designed to intelligently allocate the charging power to the individual sockets at the fast charging station to control the charging rate of electric vehicles. Each of the connected electric vehicle could be charged to a certain level of state of charge depending on the length of the queue to avoid congestion of the queue and give chance to other electric vehicles to begin their charging. Simulation results show the relation between available network capacity, number of charging sockets at the charging station and the queuing time of EVs.**

Index Terms — Battery, Charging, Electric Vehicle (EV), Fast Charging Station, Network Capacity

NOMENCLATURE

Abbreviations:

DC	Direct Current
DoD	Depth of Discharge
EVs	Electric Vehicles
SoC	State of Charge

Symbols:

b_m	Binary variable to identify status of priority socket as busy/idle
b_n	Binary variable to identify status of economy socket as busy/idle
C_m	Maximum rated charging power of priority socket (kW)
C_n	Maximum rated charging power of economy socket (kW)
C_{Rm}	Maximum allowed charging power of priority socket based on SoC of respective EV (kW)
C_{Rn}	Maximum allowed charging power of economy socket based on SoC of respective EV (kW)
m	Index of priority charging socket
M	Total number of priority charging sockets at the station
n	Index of economy charging socket
N	Total number of economy charging sockets at the station
q	Binary variable to check if there is a queue
P	Load on distribution substation from fast charging station at any time (kW)
P_m	Charging power of m^{th} priority charging socket at any time (kW)
P_n	Charging power of n^{th} economy charging socket at any time (kW)
P_T	Available capacity of the network (kW)
SoC_m	State of charge of EV being charged at m^{th} priority charging socket at any time
SoC_n	State of charge of EV being charged at n^{th} economy charging socket at any time
t	Time

I. INTRODUCTION

Unlike conventional gasoline vehicles which could be refuelled at a filling station to gain couple of hundred kilometers of mileage in just few minutes, the electrically powered vehicles require much more time to recharge them to gain the same number of kilometers. Conversely, Electric Vehicles (EVs) could be recharged not only at dedicated charging stations but also at home over the night. Problem arrives when EV is to travel longer distances where quick recharging is unavoidable due to the limitations of travelling duration and battery capacity. However, this issue could be resolved to some extent by enhancing the battery capacity to increase the mileage per recharge but it would incur addition capital cost of the EV, as main component in the EV price is the cost of its battery. This in turn requires the EV battery with the existing capacity to be charged quickly to avoid any additional trip delay while just waiting for EV recharging. Charging rate of EV's battery could be extended to some extent but charging speed is limited by the technical limitations of the batteries and the charger itself. There are a couple of studies available which have focussed on the charging control of EVs using different approaches [1]-[2]. For instance, auction based reservation of charging socket at the fast charging station is

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presented in [3] and game theory based concept has been utilized by [4] to navigate the charging of EVs at fast charging stations and communication based control is applied in [5] to manage the charging of EVs at the fast charging stations. Many research articles have studied the impact of fast charging of EVs on network voltage [6], loading [7]-[9] and power flow [10]. However, in this paper we have introduced a control algorithm to wisely allocate the charging power to each of the individual charging socket for the maximal usage of the network capacity based on the state of charge (SoC) of EVs being charged and also the minimization of the waiting time of EVs at the fast charging station.

The paper presents different available fast charging options to develop a business model for the fast charging station owner's to provide choice to the customers to select between different available options. We have introduced two options of fast charging for the customers, Economy charging with a nominal fast charging rate and Priority charge with ultrafast charging rate. This paper provides a clue for a business model for charging station owners that could be developed to offer the customers with a range of different price and charging speed packages. Customers are offered the value for waiting in the queue or pay more to avoid queuing and also charge at higher charging power to reduce the charging time itself. A scenario is simulated for two different cases of number of charging sockets and network available capacity to see their impact on the queuing time of EVs at the fast charging station.

This paper is organized into five different sections. After the introduction in Section I, the background information about the EV's battery specifications and available charging technologies is demonstrated in Section II. System model for the charging control algorithm is presented in Section III and the simulation results are discussed in Section IV and finally Section V concludes the work done in this paper and suggests the future topics relevant to this area.

II. Background

Charging of EVs' battery is not done at constant charging rate, rather the rate of charging varies with the gain in SoC of the battery. Each battery technology has dedicated charging protocol. Different options for charging of EV's batteries are available depending upon the need of charging. Slow charging could be done at home over the night, moderate charging is an option for charging EVs at relatively moderate charging currents to reduce the charging duration to some extent. DC fast charging is used for extra high charging power where the long wait for charging is not permissible. Charging levels for EVs could be broadly categorized into three major categories, Level-1 Charging, Level-2 Charging, DC Fast Charging as depicted in Fig. 1. Table I presents the three charging levels used for EV charging with the respective levels of voltages, charging currents, charging power depending on the need of individual EVs. Table II lists different maximum available capacities of EV batteries and the possible mileage range from few EVs manufacturers. Now-a-days batteries being employed in EVs are Lithium-ion based, because of higher performance and energy density, however, still some manufacturers are using Iron Phosphate based technology or some others.

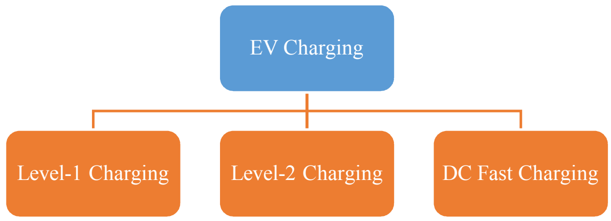

Fig. 1. Different charging levels of EVs

Table III presents the most advanced fast chargers currently available in the market from various manufacturers. For passenger cars, the highest power fast charger being deployed has rated charging power of 120 kW which is able to feed 100 km of mileage to an EV in just 10 minutes. However, the most frequently used fast chargers have rated charging power of 50 kW. This table gives an idea about the amount of time it will take to top-up an EV for 100 km based on different charging powers from various manufacturers. There are some technical limitations in increasing the charging current of the batteries due the chemistry and physical characteristics of the battery, for instance temperature control of the battery within the limits during charging. However, the advancements are being made to the battery technology and also the charging technologies to overcome these technical limitations in order to raise the charging power of the battery to a higher level. Chemical and physical processes involved in battery charging are beyond the scope of this particular research, however our goal is to have all this background information about the EV's battery in mind before we start to control the actual charging of the battery for limiting queuing and enhancing network capacity utilization. The following are the few important terms need to be defined for the charging and state of the EVs' battery:

C-rate: The rate of charging/discharging of a battery are measured by a parameter named as C-rate. It tells how fast a battery is being charged/discharged. C-rate of a battery is the measure of extent at which a battery charges/discharges in relation to its full capacity. For instance, C-rate of 1C indicates that the battery is fully charged/discharged in 1 hour. This parameter is mostly used to represent the rate of discharge of the battery.

Cut-off Voltage: It is the voltage which indicates the empty state of the battery and is the minimum permissible voltage for the normal operation of the battery.

Terminal Voltage: When the load is being applied on the battery, the voltage across the terminals of the battery is terminal voltage. The terminal voltage vary with the variation in SoC of the battery and also depends on the charging/discharging current.

Open-Circuit Voltage: When no load is applied on the battery, the voltage across terminals of the battery is the open-circuit voltage. Open-circuit voltage increases with the increase in SoC of the battery and vice versa.

Charge Voltage: It is the voltage between battery terminals when it is fully charged.

Charging Current: The amount of current at which the battery is initially charged until 70% of its SoC before switching to constant voltage charging mode.

III. SYSTEM MODEL

A fast charging system model has been developed in this paper in which different charging sockets are categorized as Economy Charging Socket and Priority Charging Socket. The maximum rated charging power for the economy charge is less as compared to maximum rated charging power for the priority charge. In our case, the two DC fast charging levels are considered in which maximum rated charging power for economy charge is C_n and other one is the superfast DC charging having maximum rated charging power for priority charge is C_m. Fig. 2 presents a model for the fast charging station, where a power distribution transformer feeds different fast charging sockets through a dedicated busbar. Economy charging sockets are marked with green color and Priority charging sockets with violet color. Some EVs are in the queue waiting for their turn to begin their charging.

Network Optimization Function:

Status bits are defined as:

$b_m = 1$, If EV is plugged-in at "m^{th}" priority socket

$b_m = 0$, If no EV is plugged-in at "m^{th}" priority socket

$b_n = 1$, If EV is plugged-in at "n^{th}" economy socket

$b_n = 0$, If no EV is plugged-in at "n^{th}" economy socket

q = 1, if there is a queue

q = 0, if there is no EV in the queue

C_m, Maximum power rating of priority socket

C_n, Maximum power rating of economy socket

Table I Technical specifications for different charging levels of EVs

Parameter	Level-1 Charging	Level-2 Charging	DC Fast Charging	DC Supercharging
Voltage (V)	230	230	400	400
Max. Current (A)	16	32	125	300
Current Type	Single Phase	Single Phase	DC	DC
Power (kW)	3.3	6.6	50	120
Top-up km/hour	16.5	33	250	600
On-board Charger Option	Possible	Possible	No	No
Application	Domestic	Domestic	Commercial	Commercial

Table II EV battery capacities and available range from different manufacturers

No.	Battery Type	Battery Capacity (kWh)	Range per Charge (km)
1	Lithium-ion (Li-ion)	100	506
2	Iron Phosphate (Fe)	80	402
3	Lithium-ion (Li-ion)	30	180
4	Lithium-ion (Li-ion)	33	200
5	Lithium-ion (Li-ion)	16	95
6	Lithium-ion (Li-ion)	24.2	190

Table III EV fast chargers and power ratings from different manufacturers

No.	Power Rating (kW)	Time to gain 100 km Mileage (minutes)
1	120	10
2	50	24
3	60	20
4	50	24
5	50	24
6	44	28

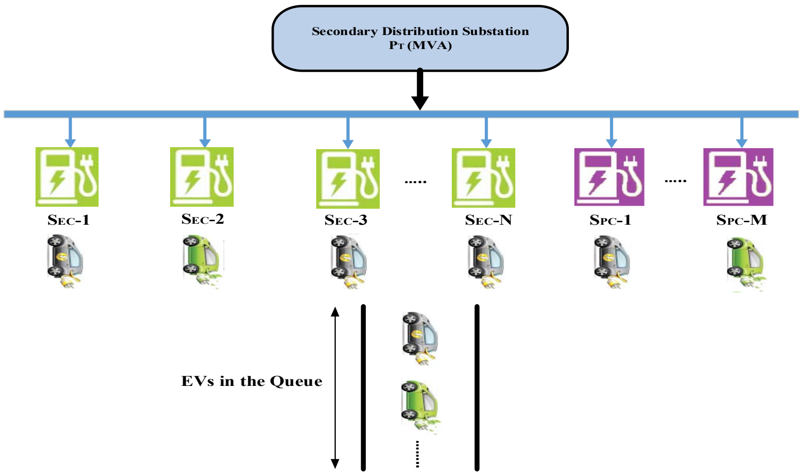

Fig. 2. Fast charging station model

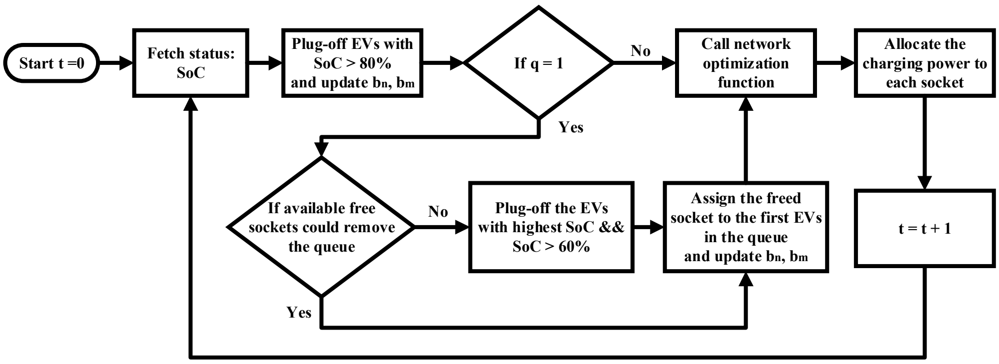

Fig. 3. Control algorithm

$$maximize\ [P] = \sum_{n=1}^{N} b_n \times P_n + \sum_{m=1}^{M} b_m \times P_m \qquad (1)$$

s.t.

$$P \le P_T \qquad (2)$$

$$0 \le P_n \le C_{Rn} \qquad (3)$$

$$if\ SoC_n \le 0.5, \gg\ C_{Rn} = C_n \qquad (4)$$

$$if\ 0.5 < SoC_n \le 0.6, \gg\ C_{Rn} = 0.8 \times C_n \qquad (5)$$

$$if\ 0.6 < SoC_n \le 0.7, \gg\ C_{Rn} = 0.6 \times C_n \qquad (6)$$

$$if\ 0.7 < SoC_n \le 0.8, \gg\ C_{Rn} = 0.5 \times C_n \qquad (7)$$

$$if\ 0.8 < SoC_n, \gg\ C_{Rn} = 0 \qquad (8)$$

$$0 \le P_m \le C_{Rm} \qquad (9)$$

$$if\ SoC_m \le 0.5, \gg\ C_{Rm} = C_m \qquad (10)$$

$$if\ 0.5 < SoC_m \le 0.6, \gg\ C_{Rm} = 0.8 \times C_m \qquad (11)$$

$$if\ 0.6 < SoC_m \le 0.7, \gg\ C_{Rm} = 0.6 \times C_m \qquad (12)$$

$$if\ 0.7 < SoC_m \le 0.8, \gg\ C_{Rm} = 0.5 \times C_m \qquad (13)$$

$$if\ 0.8 < SoC_m, \gg\ C_{Rm} = 0 \qquad (14)$$

Eq. (1) presents the optimization function to maximize the network capacity utilization by intelligently allocating the charging to each of the connected charging sockets at the fast charging station in which each of the priority and economy socket has minimum and maximum threshold level of charging power. The optimization function in eq. (1) is subject to constraints in eq. (2) through eq. (14). Constraint (2) limits the total charging demand of all the charging sockets at a particular fast charging station to be less than the power rating of respective feeding distribution transformer. Allowable charging power economy socket for different SoC levels of the connected EV is limited by the bounds (3) through (8). And allowable charging power priority socket for different SoC levels of the connected EV is limited by the bounds (9) through (14). Fig. 3 presents the proposed control algorithm for the charging control of EVs to maximize the utilization of power network capacity. We have considered one minute resolution, at the beginning of each minute the SoC level of all the connected EVs is checked. EVs with SoC already exceeding 80% of their respective full capacity, these EVs are forced to be plugged-off and the status bits of the respective charging sockets are triggered accordingly, i.e. from $b_n = 1$ and $b_m = 1$ (busy) to $b_n = 0$ and $b_m = 0$ (idle) state. Queue status is being

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checked, if q = 1 then it indicates that there is a queue, meaning that their some EVs waiting for their turn to begin charging, otherwise q = 0. If no EV is in the queue then it directly calls the network capacity optimization function to optimally allocate the charging to each of the individual charging sockets based on the current SoC of the respective connected EVs. After allocating the charging power it delivers the power the all busy/occupied charging sockets and increments the time counter by one minute and repeats the same procedure for the next time stamp, i.e. next minute.

However, if there is a queue, meaning that if there are some EVs being waiting for their charging then it checks if the available idle sockets could remove the queue. If so, it simply updates the status of respective charging sockets from idle to busy and assigns the particular sockets to the first EVs in the queue in order of their position in the queue. But if there is no idle socket or available idle sockets are not sufficient to accommodate all EVs in the queue then it plugs-off the EVs which have already gained a threshold level of SoC, for instance 60% of SoC by first plugging-off the connected EV with comparatively highest SoC until the queue is eliminated or the connected EVs have not gained the minimum threshold level of SoC. Then it assigns the freed charging sockets to the EVs in the queue in order of their position in the queue and triggers the status of respective charging sockets from idle to busy and calls the network optimization function to allocate the charging power during this minute and delivers the power and increments the time counter to next minute.

IV. SIMULATION SCENARIO AND RESULTS

A scenario is simulated to showcase the results obtained by the proposed algorithm of charging control of EVs at a fast charging station. Two cases are simulated for a single day with one-minute resolution of each time stamp. Different simulation parameters considered for the simulated cases are as follows: total number of charging sockets at the charging station are 50 for Case-1 and 100 for Case-2, maximum rated power of each socket is 120kW for both cases and available network capacity for the whole fast charging station is considered at maximum of 5000kW for Case-1 and 10000kW for Case-2. Traffic data is obtained from Finnish Transport Agency [11] and 20% EV penetration case is considered here which gives around 6500 EVs coming at this specific charging station over the day and the traffic pulse is presented in Fig. 4. Scenarios for other different parameters such as, battery capacities of EVs arriving at the charging station ranging from 25kWh to 50kWh, and initial SoC of EVs at the time of arrival at the charging station ranging from 5% to 40% are generated using Monte Carlo Simulations. In Fig. 5 we can see that for Case-1 the network capacity utilization follows the traffic pattern however, with the passage of time as more EVs are getting into the queue, the power demand from the charging station is at its maximum available capacity. In Case-2, due to more number of charging sockets less EVs are queued and the station only fetches the power at the maximum available capacity when there is a peak in traffic flow. Fig. 6 depicts the growth of the queue with the passage of time, due to less number of charging sockets it grows to around 1250 EVs at the peak of traffic pulse in Case-1 (i.e. 25 EVs per socket).

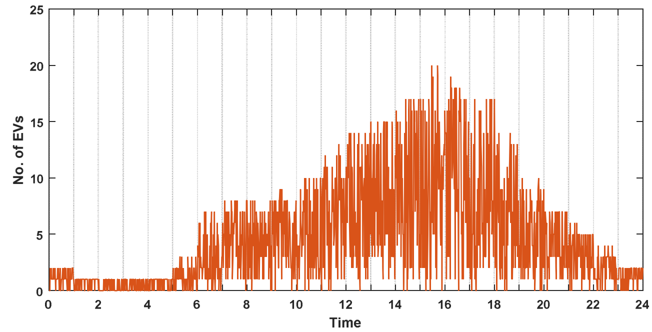

Fig. 4. EVs per minute coming at the fast charging station over the day

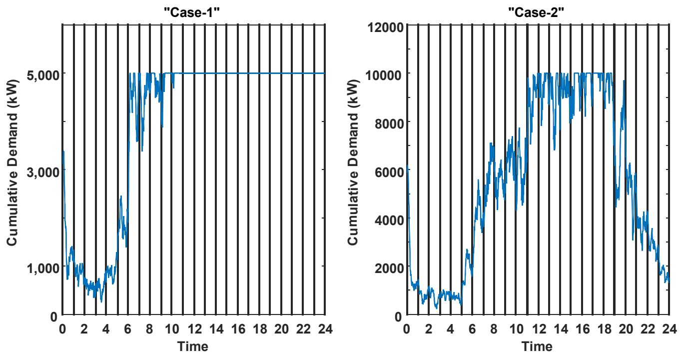

Fig. 5 Power demand on the network from all charging sockets over the day

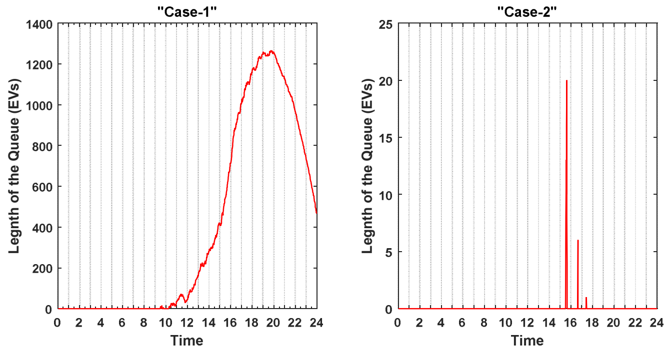

Fig. 6 Trend of queue growth for two different cases over the day

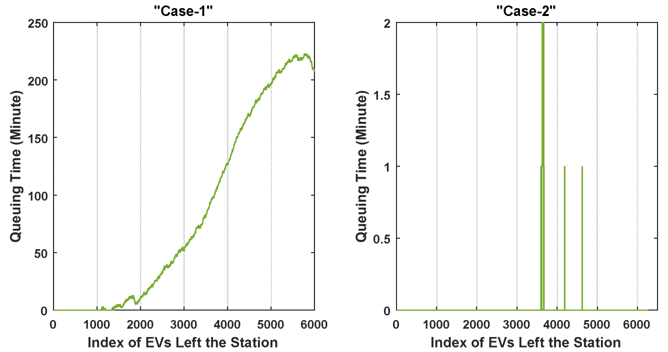

Fig. 7 Queuing time faced by each of individual EVs before starting charging

However, in Case-2 there are more available charging sockets so only few EVs are queued, a maximum being 20 EVs at a time (i.e. less than one per socket). The total number of EVs having to queue are 4984 in Case-1 and 27 in Case-2. The business case of optimizing the capacity of charging system could be based on the idea of dividing the customers into economy and priority groups. Actually even in Case-1, 23% of the EVs do not need to queue at all. This number of EVs could then be offered a priority lane against a higher payment. In Case-2 only 0.4% of the EVs need to queue, and it seems that the system is slightly over-rated. The optimal sizing of the capacity probably lies somewhere in between the two presented cases. However, according to the simulation performed, the capacity of the charging station is in good use also in Case-2. The number of EVs visiting each socket is 65 per day, which gives a sound basis for an investment.

Queuing time for each of the individual EVs is mapped in Fig. 7 for both cases. We could observe from Fig. 7 that the queuing time for each of the EV leaving the charging station after being charged and it is noted that in Case-1 the queuing time reaches to about 225 minutes at peak traffic hours and in Case-2 most of the EVs are able to avoid queuing and some have faced a queuing time of only 2 minutes. In Case-1, we observed that the queuing time is continuously increasing for EVs in the order they are arriving at the charging station.

In the simulations performed in this paper, the maximum charging power for both customer categories was the same, and it was only assumed that vacant sockets are first offered to priority customers. The different rated power of priority and economy sockets would decrease the charging time of priority customers and increase the charging time of economy customers, whereas the impact of this arrangement on the queueing times still remains a subject of further investigation. On the other hand, in the case of capacity congestion, the economy customers could be offered lowered charging power which in turn would enable more sockets being installed to the station within limits of the supply transformer. The EV owners would probably be more happy with shorter queuing times even if they come with the cost of correspondingly longer charging times.

V. Conclusions and Future Work

This paper has proposed a control algorithm for the charging of electric vehicles to maximize the utilization of network capacity and to avoid too long a queuing time of electric vehicles at the fast charging station. A business model for fast charging station owners is introduced in which customers could choose between the economical fast charging and priority fast charging for their EVs by paying price difference between two services. Two different cases of number of charging sockets and available network capacity are simulated to show their impact on length of the queue and the queuing time faced by each of the individual EVs. The results have shown how more number of charging sockets and available capacity of the network reduces the waiting time for EVs as well as the length of the queue. A suitable trade-off between charging capacity and queueing times could be found by a proper division of arriving EVs in two classes, where the higher fee is paid by customers who wish to avoid waiting times. In future, different pricing tariff for fast charging of EVs could be introduced based on charging rate, waiting time and maximum limitation for final SoC of the EV. The idea of dynamic price for fast charging of EVs considering various factors could be implemented to see its impact on charging cost and network capacity. How the value of long waiting time faced by the customer is compensated and how the customers avoiding the queue should be charged extra price is a subject of future research.

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