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Power Management for Private and Semi-Private EV Charging

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Abstract

The aim of this paper is to propose a concept of smart charging equipment [1] and algorithms which can be used to fulfil different requirements of electric vehicle users and the power grid. Two different aspects are considered: private charging (charging at home, multi-dwelling buildings or business premises) and semi-private charging (in front of supermarkets etc.) on clusters of charging stations. The technical concept of the suggested smart charging solution is presented in detail.

Keywords: charging, load management, optimization, power management, smart grid

1 Introduction

Past experience and studies on the behaviour of EV users indicate that a large majority of EV charging will take place on private (home, work, multi-dwellings) or semi-private (supermarkets, park&ride) locations. This is one of the main reasons why a special emphasis should be placed on the optimization of private and semi-private charging.

As a result of higher levels of EV penetration (> 10 %) [2], EV charging can cause problems in local grids, especially in less developed grids and in areas with higher-than-average EV penetration levels, where an extra load on specific substations is expected. The grid operators will have to upgrade any bottlenecks and at the same time try to influence the EV users' charging behaviour to optimize the grid performance. The technical solutions should balance user expectations and grid requirements already in their initial development phase.

Private charging is characterized by a smaller number of EVs that are charging on the private network behind the grid connection point/energy metre. The main issue in this case is the limited nominal power of the connection, which must cover all other consumers, connected to the building's electrical installation.

Semi-private charging is characterized by the charging of several EVs on a cluster of public or semi-private charging stations under the control of a Charging Station Operator (CSO). The CSO can optimize the peak EV charging demand on its cluster(s) by managing the power according to the conditions of the grid and its contracts with other business entities.

1.1 Private charging (home charging, multi-dwelling buildings, business premises and other private parking areas)

Electric vehicle is a new type of electricity consumer that brings about the issues of grid's physical limitations, economics of charging and safety. A single EV with average consumption can use a considerable share of the maximum capacity of the grid connection point. The maximum capacity can be achieved in terms of contracted maximum power or in terms of physical limitation of the grid connection point. In the former case, the user can revise his contract with the distribution company and contracts higher power, but with higher associated fixed costs. In the latter case, the limitation is a result of a limited capacity of the internal (home) network or the external limitation of the low-voltage distribution network and is definitive as such and requires an upgrade to the grid.

The economics of EV charging is related to the amount of energy consumed and its price, which can change statically or dynamically. The user wishes to reduce his or her costs (with the use of favourable tariffs, planned charging, ...) while enjoying a high level of service. The cost of regular charging can be significant, especially compared to other typical consumers in an exemplary household network.

The final customer for electricity has a direct business relation with the electricity supplier and an indirect relation with the electricity distribution company. The motivation of the electricity supplier company to influence EV charging lies in the optimization of its portfolio of consumers. The distribution company on the other hand is motivated to influence charging when the part of the grid where the EV charging is taking place is experiencing higher loads.

1.2 Public and semi-private parking areas (Charging Station Operator)

Compared to private charging scenario, two new entities are present in public and semi-private charging scenarios: Charging Station Operator (CSO) and Electromobility Service Provider (EMSP) [3]. The CSO can either own the EVSE (electric vehicle supply equipment; hereafter charging stations) or make a deal with the owner of semi-private locations and manage only the installation and maintenance of charging stations. The EMSP offers only the charging services to EV users and does not have to actually own or maintain any charging stations. CSO's additional interest can be to offer system services to smart grid operators.

The CSO is faced with different issues related to power management of charging stations which are publicly accessible. CSO is managing a portfolio of charging stations or clusters of charging stations that are considered as end consumers of electricity. The CSO's strategy is to define a price policy with flat rates or dynamic tariffs, optimize the utilization of existing infrastructure and expand the charging infrastructure based on usage trends.

On semi-private EVSE-equipped parking lots, the total nominal output power of all installed charging stations may exceed the maximum connection capacity. In addition to this constraint there might be other consumers at the same grid connection point, for example at a supermarket with a few charging stations for visitors or an employee EV parking lot. In these cases, the number of cars that are actually charging is usually lower than the total number of cars parked at the charging stations at any given time. Increasing maximum connection capacity is expensive and should be avoided when possible. Power management algorithms allow us to handle times of peak consumption without resorting to such measures.

Without smart charging infrastructure and remote management of power, it is practically impossible to optimize the portfolio and stay competitive in the long run. The CSO can manage charging power on two levels:

- Through local optimization of charging power in individual clusters of charging stations,
- Through a central DSM system, which determines the charging power for individual clusters of charging stations based on the demand of portfolio optimization or system services.

2 Smart charging station solution

The different levels of private and semi-private charging entail different processes with a number of business entities with sometimes contradictory interests. The presented concept of smart charging station and algorithms can cover the needs of all involved actors.

2.1 Communication is key

Communication links between individual systems are essential for power management:

- Between the charging station and the vehicle:
    - IEC 61851 standard,
    - the coming ISO 15118 standard, which will be essential for precise power management;

- between the charging station and the user:
    - the desired charging duration,
    - current state of charging,
    - configuration of charging power optimization,
    - reports;
- between charging stations in a cluster:
    - the distribution of power among the charging stations in the cluster;
- between the charging station/cluster and the CSO (for public charging infrastructure):
    - information on the availability of charging stations and connected vehicles,
    - power management based on the output of the Demand Side Management (DSM) algorithm,
    - online diagnostics of the charging stations,
    - reservation of charging stations;
- between the charging station and the distribution's smart grid system:
    - priority management of charging power.

2.2 Local power management algorithms

The power management takes place on the level of individual charging stations or a cluster of charging stations. Power management can be performed in several modes, which can be enabled simultaneously; however, only the mode with the highest priority at any given time is actually performed.
The supported modes are:

- fast charging with the maximum power of the charging station (according to settings),
- manually planned charging on individual charging station (e.g. delayed to adjust to other consumers or to lower tariffs),
- optimal charging in a cluster of charging stations, where the limitations are defined in the configuration of the cluster,
- optimal charging in a cluster of charging stations based on the measured load of installation (and grid connection point).

2.2.1 Optimal charging in a cluster of charging stations

Not all EVs on EVSE-equipped parking lots will be charging all the time, for example due to following reasons:

- the EV will be parked for longer than the battery needs to be fully charged,
- the battery is almost full upon arrival,
- the user doesn't plug in the charger for some reason, etc.

Not all EVs that will be charging at any given moment will use all available power from the connected charging station. For example, the charging station might allow three-phase charging at 32 A per phase, but the EV with a single-phase charger may only draw 20 A on one phase. If we add to this the fact that other (non-EV) consumers at the same grid connection point could also be changing their consumption, we see that the charging stations operate in a very dynamic environment and there is a lot of potential to optimize their charging behaviour.

The IEC 61851 standard allows the EV to signal to the charging station how much current it is able to receive. Additionally, it allows the station to signal to the EV how much power it may draw at any one moment. The idea behind cluster optimization is that if we can make charging stations exchange this data among themselves and at the same time gather some more data from EV users, we can use it to optimize the charging levels across the whole EVSE-equipped parking lot, which would allow the owner/operator to use up most of the power available on grid connection point without paying extra when the demand would exceed the contracted capacity.

As a solution we envisioned a self-organizing cluster of charging stations that communicate with each other over the local network combined with an installation load measurement device that measures power consumption of all consumers at the grid connection point in real time. One of the stations has the role of the »master« station and hosts the mathematical algorithm that enables an optimal distribution of power among the stations in the cluster. The mathematical algorithms can operate in two regimes:

- priority treatment of fair distribution of power among the connected users (algorithm 1),
- priority treatment of optimal utilization of total available charging power (algorithm 2).

2.3 Upper level power management algorithms

The algorithm for the distribution of power within the cluster operates locally. The CSO controls and manages its infrastructure through the control centre software. One of the modules of the control centre is DSM, which enables remote management of the charging power. [4]

The DSM module perfoms online calculations for individual clusters, based on the current state of the infrastructure and demands (optimization of portfolio, system services, ...). These calculations are distributed to the local level via communication pathways. In response to any change, the DSM algorithm sends a new charging plan to the cluster. The cluster tries to conform to the received charging plan, with the priority treatment of local limitations.

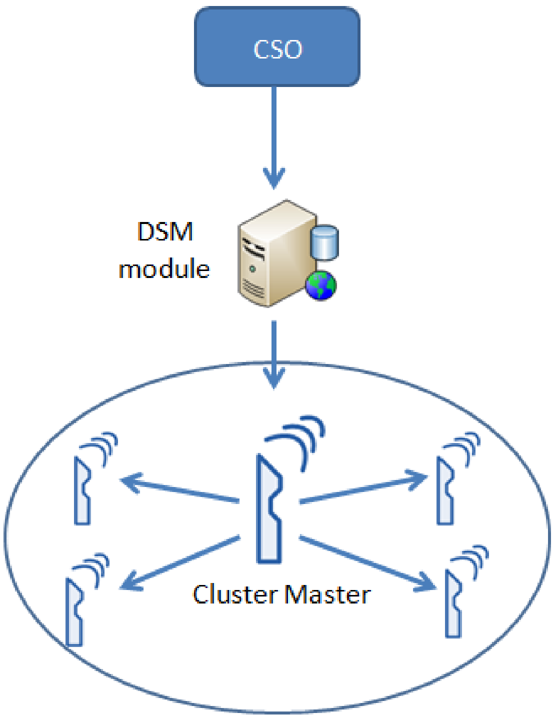

Figure 1: CSO-controlled power management

3 Charging cluster and its optimization

The cluster of charging stations is formed simply by distributing a list of local IP addresses of the charging stations that are part of the cluster. The software in charging stations selects the station that will act as the master. Alternatively, the role of the master could be given to a separate device in the network, but this configuration would be less resilient as it would create a single point of failure. In the event of master failure, the charging stations would not be able to calculate power distribution by themselves.

Our solution was therefore to make each charging station both master and slave and have a master election algorithm choose which role will be performed by the station at any one time. In the event that the charging station which is currently the master stops working or requires maintenance, the master election algorithm automatically chooses a new station as the master. Even in a hypothetical situation when the network would split in two and the resulting two groups of stations would not be able to communicate with each other, the algorithm would form two separate clusters with the knowledge that there might be another cluster that is unreachable and would regulate power consumption accordingly.

The master station is responsible for gathering data from other stations, for example:

- is there an EV currently charging on the station,
- when did the EV start charging,
- what is the minimum and maximum current with which the EV can charge,
- does the EV have a single-phase or a three-phase charger,
- what is the battery status,
- when would the user like to have the EV charged and ready to go.

If there is enough power to charge all the cars at the full capacity of their chargers then all the master does is confirm charging plans. It is when the power is limited when the interesting things happen.

In such case the above information is used to prioritize among EVs. We normally favour those that need to be charged faster and/or those that need more energy, but the exact criteria is not important in this discussion as it can be defined by the owner/operator of charging stations.

As we have mentioned before, we have two algorithms for power management within the cluster. Algorithm 1 assumes that users are the happiest when the EV is fully charged by the time they specified and we adjust the algorithm so that there are only a few cases in which the EV is not yet fully charged at that time. Algorithm 2 on the other hand maximizes the power consumption and enables those users with more powerful chargers to hit the road sooner.

Our solution can operate in either mode and can switch between them at any time.

3.1 Algorithm 1: Maximizing the number of EVs that are fully charged by the appointed time

After the master station prioritizes the cars according to the selected criteria, it calculates the so called "fair current" for all vehicles - this is the current that the EV would be assigned if its charger would have no restrictions. At this current, the car that would need to be full by 1 PM would always be full before the car that needs to be full by 2 PM. But since EV manufacturers do set some restrictions, both in minimum and maximum current that can be drawn by the EVs, it can happen that one EV's fair current is lower than what the EV manufacturer allows while another EV's fair current is more than its charger can draw. In such cases the master needs to adjust the current and redistribute the remaining current among other vehicles.

This would be a relatively straightforward problem to solve in a world where only single-phase or three-phase chargers would exist, but most charging areas will need to deal with a mix of both in the same cluster.

Our goal is that single-phase and three-phase chargers get an equal amount of power if all other variables like charging time, amount of energy needed, minimum and maximum power, etc., are equal. Therefore the current we calculate for three-phase chargers is generally 3 times lower than the current for single-phase chargers. To get the fair current for three-phase chargers, we calculate it on all three phases and take the lowest value.

Usually we will not be able to assign fair current to the chargers because of minimum and maximum current limitations of those chargers. Each EV is assigned at least the minimum current that is allowed by the EV manufacturer (i.e. no EV is left waiting without charging). There are also cars that get a "fair current" that is higher than what they can use, so we try to redistribute that current in a way that those cars that need to be charged sooner (or need more energy) will get more. To that end, we calculate a priority factor for each EV and distribute the remaining current according to it.

Since all our calculations are done per-phase, we can correctly distribute power in an environment where there are other single-phase consumers and where we might not have the same amount of current available on all three phases.

3.2 Algorithm 2: Maximizing cluster power

In this mode the goal is to use up as much of the available power as possible, while staying within limitations of the local power network. For this reason the algorithm favours three-phase vehicles (if any) as they consume power on all three phases.

First the maximum current of all three-phase chargers combined is calculated (M3), as well as the minimum current of all single-phase chargers (m1). If the combined current (M3 + m1) is greater than the available current, the maximum current of three-phase chargers is adjusted accordingly. On the other hand, if the combined current is lower than the available current, more current is given to single-phase chargers.

The calculated target current is distributed among single-phase and three-phase chargers in separate calculations. The relative priority of charging is calculated in the same way as in algorithm 1.

3.3 Algorithm comparison

The easiest way to understand the effects of both power distribution algorithms is to take a look at some examples. In this section we present cases in which algorithms give very different results, however there are also many cases in which results from both algorithms are similar. For example, if all EVs have three-phase or single-phase charging, both algorithms will return identical results.

3.3.1 Example 1

This example shows the allocated current for three EVs, two of them with single-phase chargers and one with a three-phase charger. We will assume that they all arrived at the same time and that each needs 8 kWh to fill their batteries; however, the desired charging time and charger power are different for each EV. Let us say the cluster has 32 A available on each phase for EV charging, so it is impossible to charge all three EVs at their full capacity. The table below shows the effect of algorithms 1 and 2 on charging time. (DoC = duration of charging)

Table 1: Example 1

Car	**1**	**2**	**3**
Charger	Three-phase	Single-phase (L1)	Single-phase (L2)
Max current (A)	32	20	16
Desired DoC	2:00	2:00	3:00
Ideal DoC*	0:22	1:44	2:10
Algorithm 1 DoC	0:45	1:45	2:40
Algorithm 2 DoC	0:28	2:22	2:45

*Ideal conditions are those in which the EV can be charged at its charger's full capacity.

Algorithm 1, which maximizes the number of EVs charged on time, managed to charge all three EVs in the allotted time, but since EV 2 uses only phase 1 and EV 3 uses only phase 2, phase 3 was used only at 12 A throughout the time of charging of EV 1. Maximum consumption by phase was 32 A / 28 A / 12 A.

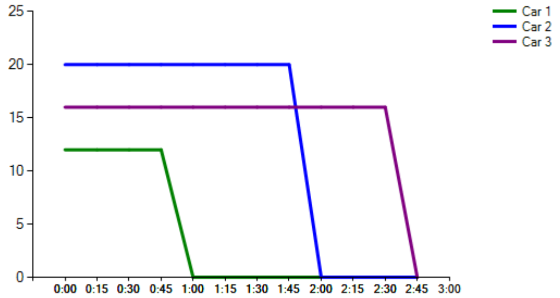

Figure 2: Algorithm 1 - consumed current by EV

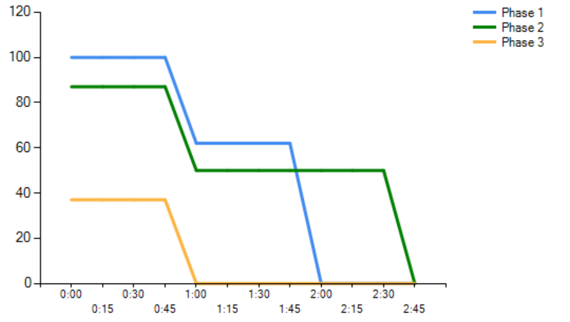

Figure 3: Algorithm 1 - percentage of available current used

Algorithm 2 maximized the cluster power which resulted in EV 1 drawing 26 A on all three phases for its entire charging time (28 min), while EVs 2 and 3 each drew 6 A on phases 1 and 2, respectively. The maximum consumption by phase was therefore 32 A / 32 A / 26 A. But this came at the expense of EV user 2, since the EV had to charge for 22 minutes longer than desired.

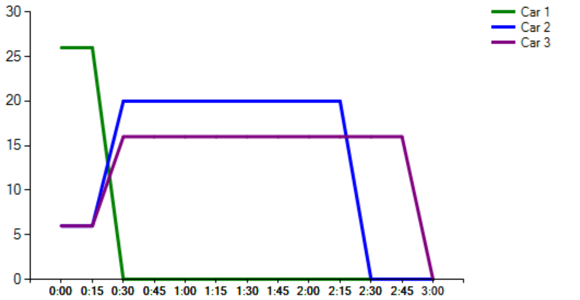

Figure 4: Algorithm 2 - consumed current by EV

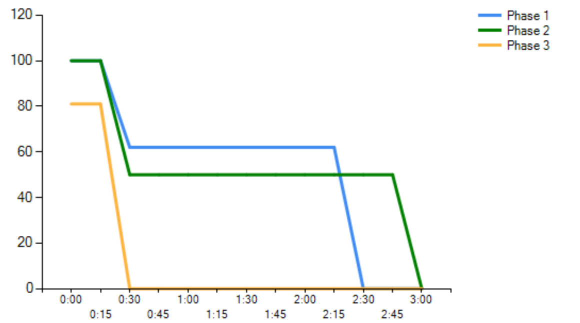

Figure 5: Algorithm 2 - percentage of available current used

3.3.2 Example 2

In this example we have three EVs again, one with a single-phase charger and two with three-phase chargers. Each needs 10 kWh and the cluster has 32 A available on each phase throughout the duration of charging. There is enough time and power available to charge all of their batteries using either of the two algorithms.

Table 2: Example 2

Car	**1**	**2**	**3**
Charger	Three-phase	Three-phase	Single-phase (L1)
Max current (A)	20	20	32
Desired DoC	2:00	2:00	4:00
Ideal DoC*	0:43	0:43	1:21
Algorithm 1 DoC	1:48	1:48	2:15
Algorithm 2 DoC	1:00	1:00	2:15

Algorithm 1, which maximizes number of cars charged on time (but does not guarantee the fastest charging possible), needed 48 minutes longer to charge the three-phase EVs than algorithm 2, while the single-phase EV was charged at the same time in both instances.

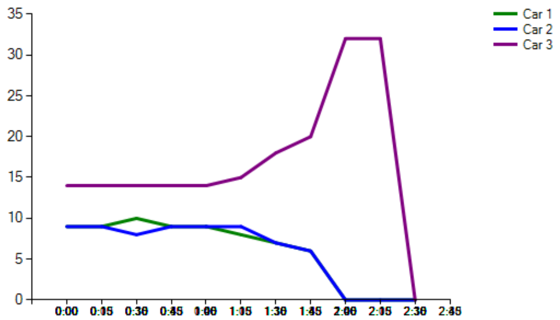

Figure 6: Algorithm 1 - consumed current by EV

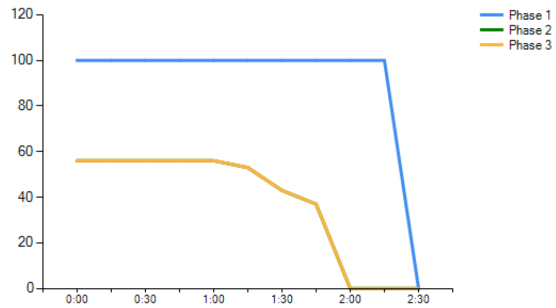

Figure 7: Algorithm 1 - percentage of available current used

Algorithm 2 maximized the cluster power which in this example resulted in a much better overall performance of the cluster.

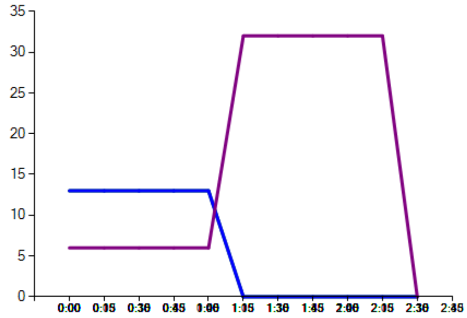

Figure 8: Algorithm 2 - consumed current by EV

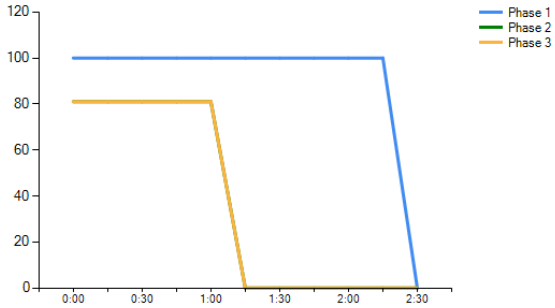

Figure 9: Algorithm 2 - percentage of available current used

The cluster master is able to calculate effects of these two algorithms in real time and switch between them as necessary to ensure high quality of service. Alternatively, the owner/operator of charging stations can select the algorithm to be used.

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