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C6-207

CIGRE 2012

Toward Ultrafast Charging Solutions of Electric Vehicles

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SUMMARY

The paper is devoted to the problems arising from the ultrafast (≤ 10 min) charging of an electric vehicle (EV). An ultrafast charging station (UFCS) must provide high power output with minimal influence on the electricity transmission system, which can only be achieved by the application of energy storage acting as an additional buffer between the vehicle and the grid. Besides storage, interfaces between a fast charging station and the outside environment (vehicle, utility grid) must be designed to fulfil a set of requirements.

The main challenge is to be found within the specification of parameters for the design of future energy supply systems, providing for fast charging of the vehicle batteries while avoiding solicitations of the local distribution system which exceed its instantaneous power capabilities. The possible impact of an UFCS on the power distribution system is analysed with the stochastic approach, based on the utilisation of such a station. The general aspects of highly variable load profile clearly include the use of energy storage means that must be specified regarding both the energy storage and the instant power capabilities. Different technologies are analysed in terms of performances and costs.

In conclusion, one of the important problems facing electric vehicles is the possibility of short-time charging, both as seen from the EV battery itself as well as from the local supply system. In this context, large load variations as seen from the local power system, at multiple levels, must be carefully assessed with special attention to feasible load changes at the coupling points. By addressing these technical issues as well as the financial constraints, the research aims at providing viable solution for broad ultrafast charging systems integration into the power distribution infrastructure.

KEYWORDS

Electric vehicle - energy storage - load management - power converters

INTRODUCTION

In the quest of gaining more popularity for the electric vehicles (EV), one of the questions is how to charge an EV battery within a time frame comparable to tanking gasoline. The easiest and most widespread way to charge EVs still relies on the household outlets; however, they are limited in power (for the one-phase systems in Europe up to 3.6 kW and for three-phase connections 11 kW, respectively). Moreover, the 16 A given as the standard for household sockets is not a continuous rating, but rather foreseen for periodic maximums. Therefore only 10 A is permanently available from a standard household outlet and charging a 16 kW·h battery in domestic conditions takes approximately 7 hours, after which the car is able to cover up to 150 km, as stated by the vendors [1]. As an average daily mileage for a car is estimated to be only 38 km [2], this charging method would satisfy the needs of the bulk of the drivers; however, for the drivers segment often using long-stretch highways, a faster charging option to overcome the “range anxiety” must be guaranteed. In addition, promoting individual domestic charging is problematic in densely populated areas, where it is unthinkable to imagine extension cords hanging out from apartment windows – a fact limiting the EV market segment to house owners, unless tanking-equivalent charging is accessible.

An inherent problem is that, whilst comparing liquid fuel tanking with the flow rate of 35 l/ min and consumption of 7 l/ 100 km, the corresponding transfer power at an average EV energy consumption of 15 kW·h / 100 km would be as much as 4.5 MW, which is unthinkable from the power system viewpoint. Even when speaking of lower charging rates between five to ten minutes, a strong grid connection is a prerequisite if the battery’s ability to admit high charging power is neglected. The situation becomes even more aggravated if several EVs are being charged simultaneously; in this case the charging station must have a medium voltage (MV) grid connection. As a fast charging station is not always operational with full power, an energy storage unit helps to draw from grid only power near to the average value. The power electronics modules inside the charging station also affect the power quality by causing electromagnetic interference, which is another issue to be addressed. In following, the ultrafast charging issues are based on the utilisation scenarios from 20 EV/day to 200 EV/day, from rather conservative to very optimistic estimations [3].

1. STATE-OF-THE-ART OF THE EV BATTERY CHARGING

The usual “slow” charging procedure is split into two distinct periods: during the initial constant current (CC) period, the battery is charged to ~80 % of its rated capacity, while the following constant voltage (CV) stage lasts much longer [4] [5]. The transition between those two stages is due to the need to limit the battery terminal voltage, which is presently the main criterion to avoid overcharging. Thus, an ideal ultrafast charging spot should provide:

1) Charging the battery as quickly as possible.
2) Charging the battery as fully as possible.
3) No jeopardizing of the battery lifetime

In terms of the state-of-the-art, these three requirements are contradictory. However, there is some on-going research on enhancing the battery absorption capabilities and improved state-of-charge (SoC) estimation, which is a built-in feature of the battery management systems (BMS). The latter must be considered as the key component in terms of sustainable EV battery utilisation, which is as well responsible for the data communications between the battery and the charger [6]. The standards for EV charging and interfacing are largely still in the draft phase, concerning fast charging, IEC61851-23 and its practical implementation by the CHAdeMO consortium are of the most relevance [7] [8].

Taking into account the battery rated voltage of 330 V, as common to small cars [1], the maximal CHAdeMO method charging power, limited mainly by the connector’s maximum current of 120 A, could be as much as 50 kW. IEC 61851-23 has however drafted a 400 A/330 V dc charging mode which could bring that power up to 132 kW in the future. This means that, by using the latter, a 16 kW·h battery could be recharged in approximately 8 minutes. It is evident that the present state of standardisation does not foresee charging at higher rates enough to replenish the battery of an average EV within the objective 5 minutes.

2. LOAD PROFILE ESTIMATION

Specifying technical requirements for an UFCS in terms of managed power flows is based on several statistical assumptions on input data like:

1) objective charging time;
2) rated battery capacity;
3) efficiencies of energy conversion stages;
4) UFCS utilisation.

The utilisation of an UFCS can be determined based on traffic data, provided in Switzerland by the Federal Office of Statistics [9]. This data is processed to get presumable load diagrams. Fig. 1 shows typical traffic density distribution values for highway (tunnel Pomy near Yverdon) and urban conditions (Chauderon in Lausanne). The load generation procedure below is based on stochastic approach, applied in similar situations [10] [11].

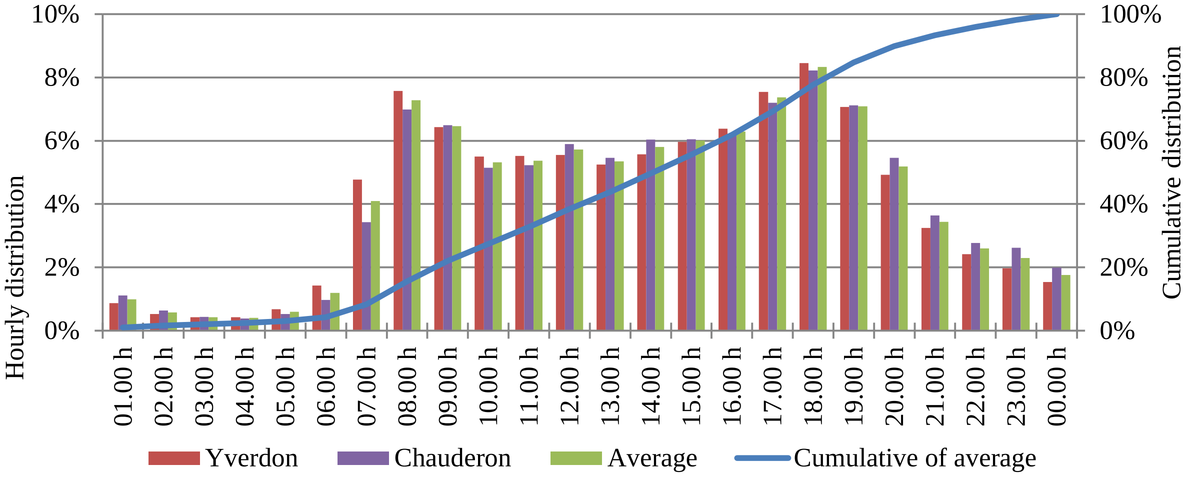

Fig. 1. Typical daily traffic density distribution

2.1 *Load curve generation procedure*

The load curve is deducted from the objective number of EVs to be charged during a day. For next, following steps are performed:

1. Hourly distribution of charged vehicles according to Fig. 1.
2. Assignment of arrival times within the specified hour. A vehicle can arrive at any minute of the given hour, so the minute is generated randomly.
3. Assignment of the initial state-of-charge SoC_i and rated battery capacity E_{bat} to each EV.
4. Generating charging curve for each EV based on the objective.
5. Superimposing single charging curves to obtain the sum values.

2.2 *Assumptions and considerations*

The EV battery rated voltage $U_{bat,N}$ = 330 V has been considered independent of the vehicle type.
The EV battery resistance is considered reciprocal to its capacity and has a base value of R_{int}(16 kW·h) = 70.4 mΩ, taken from a datasheet [12].

2.3 *Load simulations*

The simulations are carried out for 20, 50, 100 and 200 vehicles charged per day. The EV battery values are subjected to normal distribution (left-truncated for the capacity).

1) $E_{bat} \in$ [16 kW·h; 55 kW·h] (Fig. 2);
2) $SoC_i \in$ [0; 50 %] (Fig. 3);

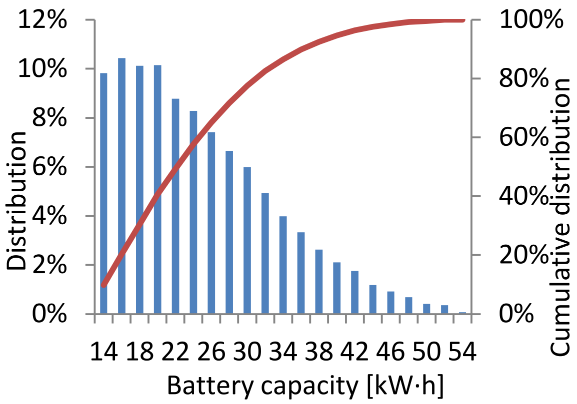

Fig. 2. EV battery capacity distribution

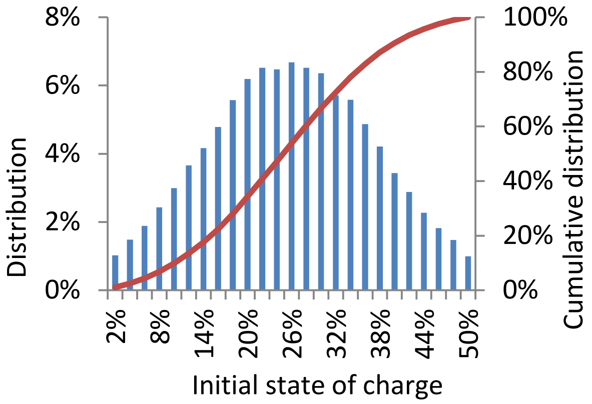

Fig. 3. EV battery initial SoC distribution

In all the simulations, the charging time t_{ch} = 5 min was kept constant independently of the SoC_i and E_{bat} values, meaning variable charging power. For every objective number of charged vehicles per day, 10 000 Monte Carlo iterations were made. In case of overlaps (multiple EVs charging simultaneously) the charging power sums up (Table 1).

Table 1. Values for t_{ch} = 5 min

	Power at EV input [kW]		Transferred energy [kW·h]			EVs at station		
EV/day	Per EV	Station max	Mean	Median	Max	Mean	Median	Max
20	Mean: 230 Median: 214 Max: 697	1193	362	361	496	1	1	3
50		1421	908	907	1113	2	2	5
100		1733	1850	1850	2220	3	3	6
200		2218	3652	3651	4061	5	4	8

3. UFCS LOAD LEVELLING AND SHIFTING

To decrease the UFCS impact on a utility grid, the load must be at least partially decoupled from the mains. This is done by implementing energy storage elements, which act as buffer between the EV and the grid (Fig. 4) [13]. The prospective UFCS comprises low power charger LPC for charging the storage buffer from the grid, storage buffer B and high power charger HPC for charging the EV both from the buffer and the grid. Each stage is characterised by power level P_{LPC}, P_B, P_{HPC} and conversion efficiency η_{LPC}, η_B, η_{HPC}. It is worth mentioning that the same buffer-based principle has recently been used in pneumatic energy transmission for compressed air propelled vehicles [14].

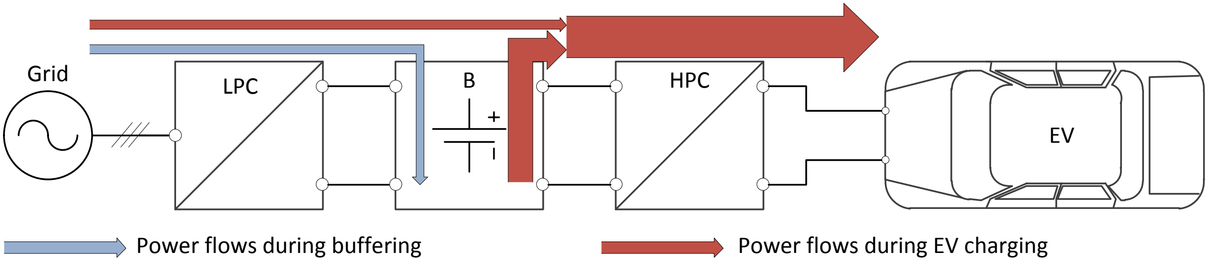

Fig. 4. Buffered UFCS topology

To spare writing space, calculation formulae are omitted in the following design considerations. The basic principle is to keep the system's overall energy balance over a specified time, allowing estimating instantaneous, mean and maximum power values and storage capacity based on the instantaneous storage power integration. Two main partial decoupling strategies are observed:

1. Load levelling – an ultrafast EV charging station is supposed to draw moving average charging power from the grid, the average is in the studied case taken over an hour and the strategy itself is based on the discrete low-pass filter analogy.

2. Load shifting – to an ultrafast EV charging station, more power is allocated during nighttime and less power during the grid peak hours, so the buffer absorbs energy when the grid overall load is minimal and releases energy for EV charging when the grid is more heavily loaded. In current example, load shifting, is performed by allocating hourly grid set point values as mirror inverted to the vehicle hourly distribution (Fig. 5).

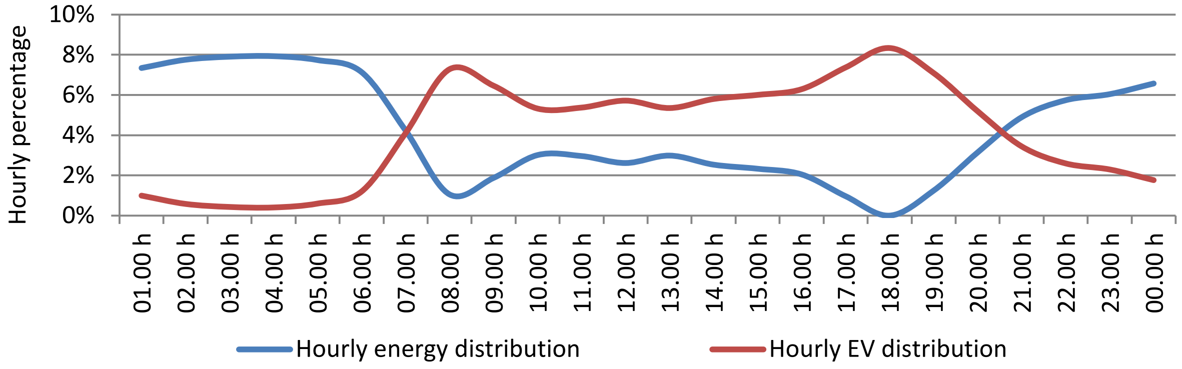

Fig. 5. Load shifting explication: hourly distributions for the vehicles and transferred energy from grid

Load shifting helps to decrease the necessary grid tie, but requires more capacity and transfer power for the intermediate storage than levelling (Table 2). The buffer instantaneous power is set by the number of simultaneously charged vehicles, i.e. the number of EV charging ports. It becomes evident, that the buffer charging power, limited by the objective grid load can be several times smaller than the discharging power into the EV battery. Moreover, it comes out that with buffering, the grid connection can even be made on the low-voltage side and in the proximity of a distribution substation. Thus, the input current for a buffered station charging 200 EV/day can be reduced to 630 A at a standard three-phase, 230 V/400 V connection. A sample curve 200 EV/day is shown in Fig. 6.

Table 2. Grid and storage parameters for load levelling and shifting at t_{ch} = 5 min, without queuing

EV/day	1 h levelling			Shifting		
	P_{LPC} [kW]	E_B [kW·h]	P_B [kW]	P_{LPC} [kW]	E_B [kW·h]	P_B [kW]
20	64	76	427	33	248	456
50	112	144	730	84	639	761
100	196	218	733	157	1155	874
200	426	334	1381	322	2281	1637

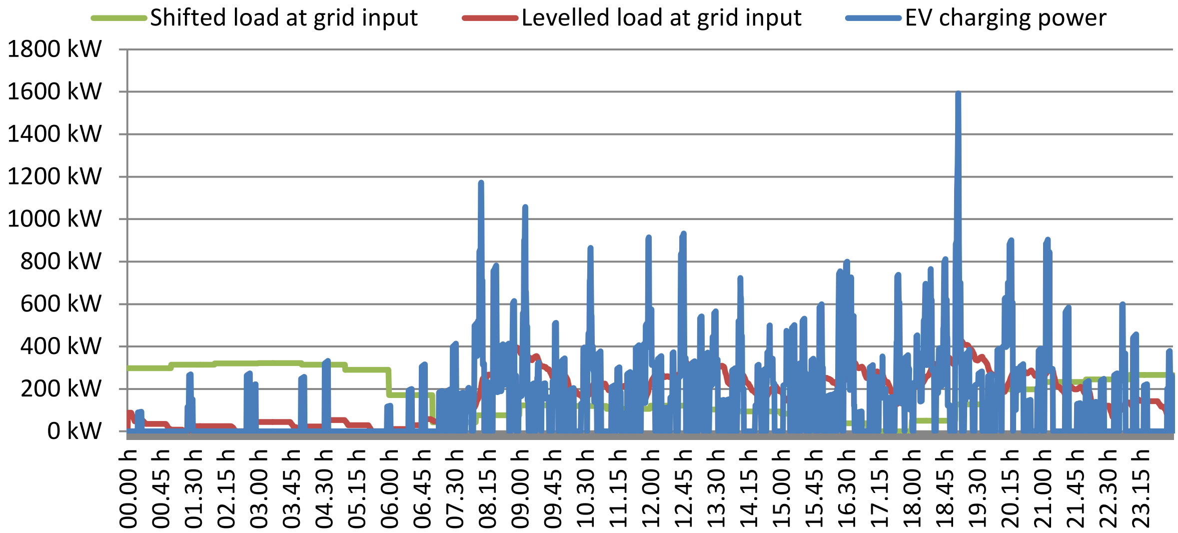

Fig. 6. Load curves for 200 EV/day (example without queuing)

4. ENERGY STORAGE SELECTION

4.1 Storage media and interfaces

Each storage technology can be assessed by basic descriptive data, which allows comparing them in respect of the objective task. Besides the physical limitations on the storage medium, the overall characteristics are defined by the transmissibility of the power interface. A comprehensive list of qualifying parameters is given in [15], of which following are of most relevance:

1. Specific energy (energy density) - relationship of usable energy to mass (gravimetric m_E) or volume (volumetric V_E).
2. Specific power (power density) - relationship of usable power to mass (gravimetric m_P) or volume (volumetric V_P).
3. Power loss - sum of recharge-discharge losses and auxiliary loads per time unit (self-discharge).
4. Calendar lifetime - expected lifetime.
5. Cyclic lifetime - maximum number of recharge-discharge cycles during calendar lifetime.

In Table 3, the basic energetic data of different storage units is given together with a load shifting example for 200 EV/day (Table 2). Taking into account the financial considerations in terms of price per energy, power and cycle [16], a conclusion may be drawn that if the installation space and weight are not critical, as it is the case for stationary storage, compressed air would be a feasible solution. The indicative mass and volume is comparable to an eight-axis tank wagon, which can be placed underground.

Table 3. Comparison of energetic characteristics of storage media [15] – [20]

Technology	Energy density		Power density		For 200 EV/day		Lifetime
	[W·h/kg]	[W·h/l]	[W/kg]	[W/l]	*m* [t]	*V* [m³]	[cycles]
Lead-acid	30	74	100	250	76	31	$\sim 10^3$
Li-ion high-energy	200	630	220	650	11	4	$\sim 10^4$
Li-ion high-power	80	140	750	1400	29	16	$\sim 10^4$
Supercapacitor	6	7.6	5900	7400	380	300	$\sim 10^5$
Flywheel	11	18	800	1300	207	127	$\sim 10^6$
Compressed air (CAES)	23	24	23	24	99	95	$\sim 10^5$
Redox flow batteries (RFB)	23	30	60	80	99	76	$\sim 10^4$

5. MARKET POTENTIAL

Drivers' elasticity with respect to fuel cost is proven to be extremely high [21] [22]. In the case of electric vehicles however the potentially cheap electricity, leading to lower expenses per kilometre, is often presented as one of the main advantages. In fact higher acquisition costs, lower autonomy and uncertainty about the battery lifetime represent high barriers for costumers.

In order to represent a valid market case, the price of a charge at an UFCS will have to be low enough to still appear attractive, while allowing a reasonable return on investments (ROI) for the UFCS owner.

Based on the results presented in Table 1, the average energy sold each day amounts to about 3600 kW·h, while the storage system needs to be able to store approximately 2200 kW·h (see Table 2). Given the current low price of electricity, the investments (civil infrastructure, electric converters, storage system) will have the biggest impact on the final price, followed by maintenance and operational costs.

The costs related to the infrastructure (i.e. land, building, electric components, wires …) are likely to be significantly higher than those of the storage system itself. Based on current market prices [16] several technologies (lead-acid, CAES and redox-flow batteries) require less than \$2M of investment for the storage system. Lithium-ion batteries are significantly more expensive (at least \$5M would be required for both high-energy and high-power batteries) but remain cheaper than supercapacitors and flywheels which would represent an investment of $10M or more.

Although the ROI rate depends on a large number of factors (number of years of operation considered, storage system technologies, infrastructural costs, price charged to the customers, etc.), it appears that a double digit one can be achieved in less than 10 years by choosing the cheapest storage technologies. Considering the current state of risk and technological readiness of redox-flow based technologies, CAES and lead-acid batteries appear much more attractive. In fact if the “second-life batteries” market is considered, substantial benefits can be made thanks to the very low acquisition cost those battery have.

A more thorough analysis has to be performed in order to establish the optimal parameters of this analysis (in particular the price to be charged to the customer has to be determined through survey) but the preliminary results show that there would be a business case and that the limitation is currently situation on the EV side (number of EVs in circulation too low, on-board battery and charging system forbidding ultra-fast charging) rather than on the charging station one.

6. CONCLUSIONS AND FUTURE WORK

The research conducted so far and presented in this paper yields following key conclusions:

1. Charging an EV during a few minutes causes peaks in power distribution systems, especially during most loaded hours. In the worst case, the peaks cumulate when several vehicles are charged simultaneously.
2. The impact of ultrafast charging on the power system can be alleviated by the application of intermediate energy storage. There exist two main buffering strategies: levelling and shifting. The buffering has more effect at lower utilisation rates in terms of station input power relationship to EV charging power. Load shifting, while being desirable from the overall grid management, needs more storage capacity than levelling.
3. The load-side management would help to decrease the power levels even further thanks to the avoidance of overlaps. In practice it means that the drivers must accept some waiting queues and longer charging times, as the station design is based on the average values.
4. A buffered station can be connected to a low voltage network even at an utilisation rate of 200 EV/day, provided the transformer substation is nearby.
5. With present technology and cost constraints, the optimal energy storage would be that of compressed air. This, however, requires sufficient installation space.
6. An UFCS has preferably a modular architecture, making the future extensions possible.

This paper thoroughly presents a methodology aimed at estimating the UFCS utilisation, calculating the storage parameters and criteria for the storage selection.

The next research step consists in building an experimental downscaled UFCS, capable of recharging a commercial EV. This hardware model, which shall be realised in the upcoming two years, will be fed from a conventional three-phase household outlet, should be able to recharge an EV for the next 100 km.

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