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The Charging Station for Fast-Charging Batteries of Two Electric Vehicles

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Abstract

The charging station for fast charging of lithium-ion batteries electric vehicles is considered. It contains two power units. The results of studying showed that it cannot simultaneously charge completely discharged batteries of two electric vehicles. An optional third power unit is proposed. The study showed that it reduces the waiting period for a second electric car battery to charge by 29%, which is positive factor for the owner of electric vehicles. Thus, the proposed three-unit CS can contribute to the improvement of the environmental situation in the world, especially in densely populated cities through the development of a network of efficient charging stations for EVs.

1 Introduction

Every year, the number of electric vehicles (EVs) on our roads is increasing significantly. This opens up great opportunities for improving the environmental situation in the world, especially in densely populated cities. However, studies have shown that one of the main obstacles to the use of EVs is the lack of a developed network of charging stations.

At present, the network of filling stations for vehicles with internal combustion engine (ICE) satisfies all the requirements of vehicle owners. They are available almost anywhere in the any country. As a result, motorists can easily find a competitively priced gas station and avoid queuing for more than a few minutes. The network of EVs charging stations should look exactly the same.

Charging EVs batteries should be as easy and convenient as refueling an ICE vehicle. Therefore, the efficiency of charging stations for EVs should be ensured by reducing the waiting period for the end of the battery charge and increasing the number of connection points for EVs.

A key aspect of any EV is the battery.

The lead-acid battery is the earliest and still widely used type of battery. It was designed by French physicist Gaston Plante in 1860 [1]. However, lead-acid batteries are not widely used in EVs due to their relatively low specific energy and lower energy density.

In 1991, Sony company mastered mass production of lithium-ion batteries. After that, these batteries began to be widely used in EVs. Compared with other batteries, lithium-ion batteries have significant advantages in terms of specific energy and energy density, which determines their relatively small size and lightweight [2]-[4]. Accordingly, EV with a lighter battery can travel a greater distance before the next recharge. Also, lithium-ion batteries have an unnoticeable memory effect and long cycle life. Because of this, BMW i3, Tesla, Nissan Leaf, BYD and other EVs use lithium-ion batteries.

Each type of lithium-ion battery [3]-[7] has its own advantages and disadvantages. At the same time, for all types of these batteries, the charging algorithm sets the process of an electrochemical reaction [8], [9], which determines how much heat will be released and what pressure will occur in the battery. Both of these factors affect the charging speed, life and reliability of lithium-ion batteries. In this regard, the choice of the type of charging algorithm is of great importance.

On the other hand, the type of charging algorithm determines the peak value of the current that is consumed from the city network. Therefore, it is advisable to choose a type of lithium-ion batteries charging algorithm that will provide a compromise between the allowable power consumption from the city network and the short charge time of the EV battery.

This article discusses the choice of a compromise between the power consumption from the urban network and the short charging time of the EV battery.

2 The Constant Current - Constant Voltage Charging Algorithm

The Constant Current-Constant Voltage (CC/CV) charging algorithm is the most used for fast-charging of lithium-ion batteries [10]-[12]. It has three stages that

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are shown in Fig.1, where the solid curve is the voltage (u_c) on the battery; dashed curve – current i_c) flowing through the battery; U_{0c} and I_{0c} – the initial voltage and current values on the battery; U_{cutoff} – accepted working minimum voltage value; U_{set} – a set value of the battery charge voltage.

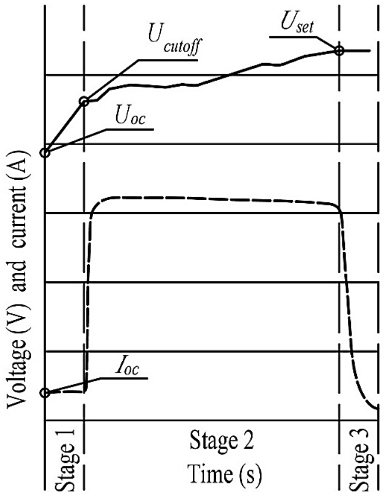

Fig. 1. An example of voltage and current at CC/CV

The first stage (Stage 1) of CC/CV is used when the initial value of the U_{0c} voltage on the battery is below the accepted working minimum value (U_{0c}<U_{cutoff}). This circumstance usually occurs due to self-discharge during long storage of the battery. At the first stage, due to the small current i_c, CC/CV provides a gradual output of the active electrode materials of the battery to the adopted U_{cutoff} level, at which they can be charged normally. In this case, the charge current of lithium-ion batteries is usually set equal to 0,1*C*, where *C* is the battery capacity. Also, the first stage of CC/CV is used in the “heating” of the battery’s electrode mass at low ambient temperatures.

At the second stage (Stage 2) of CC/CV, the battery charge is carried out with a stabilized i_c current of 0,5-3,2*C* ($i_c - const$), the value of which is determined in the specification of the specific lithium-ion battery. On the one hand, the higher the i_c current at the second stage, the faster the battery charges. On the other hand, due to the internal resistance, the u_c voltage on the battery at a higher i_c current will reach the U_{set} value faster. Accordingly, the less time is required to charge the battery at the second stage. At the same time, the higher the i_c current at the second stage, the greater the heating has a battery, which negatively affects the service life of lithium-ion batteries. The second stage of CC/CV ends when the u_c voltage becomes equal to U_{set}.

At the third stage (Stage 3) of CC/CV, the u_c is maintained equal to U_{set} ($u_c = U_{set} - const$). In this case, the current i_c is gradually reduced as shown in Fig. 1. The third stage of CC/CV ends either when the specified minimum i_c is reached, which is usually 0,1-0,05*C*, or when the specified maximum charge time is reached.

This algorithm is used in the charging station "EV DUAL Charge 50" (Fig. 2).

Fig. 2. The charging station "EV DUAL Charge 50"

This charging station (CS) has an input three-phase voltage of 400V, 50Hz and two output channels with maximum voltage of 500VDC [12]. The total output power of such CS is 50kW. The power circuit of the CS contains a control and protective switching unit (CPS), two power units (AC/DC1 and AC/DC2), four output contactors (K1-K4) and two output connectors (X1 and X2). It is shown in Fig. 3.

CPS controls the current consumption and connects the CS under consideration to the external three-phase network 400VAC, 50Hz. It also performs short circuit and overload protection functions. CPS can control the operate by both ways of remote automatic control and local manual control. It makes it possible to set the time-current protection, control and operation after the short circuit.

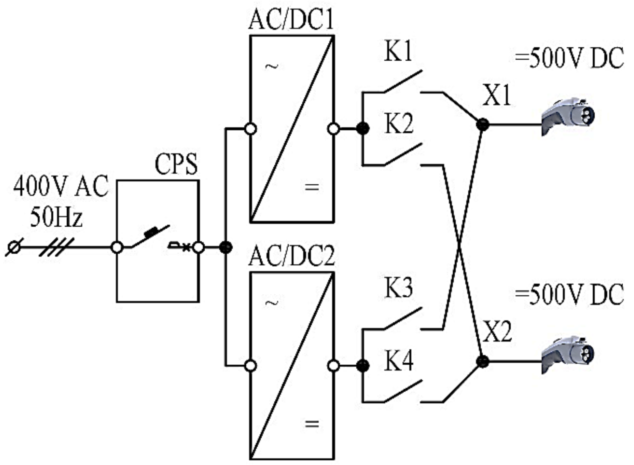

Fig. 3. The block diagram of a two-unit CS

The AC/DC1 and AC/DC2 power units convert a 400V, 50Hz three-phase input voltage into a DC output voltage that is set according to CC/CV. Each AC/DC1 and AC/DC2 contains an input controlled three-phase rectifier and a single-phase bridge inverter with an output transformer and an uncontrolled rectifier. Power units are developed taking into account technical solutions and recommendations [13]-[16]. Each AC/DC1 and AC/DC2 power units has an output power of 25kW.

Output contactors K1-K4 are designed to connect AC/DC1 and AC/DC2 to output connectors X1 and X2. They distribute the load, which is the batteries of the connected EVs, between the AC/DC1 and AC/DC2 power units.

It is assumed that the output contactors K1 and K2 cannot be closed at the same time, i. e. the AC/DC1 power unit cannot charge two batteries at the same time. Similarly, the output contactors K3 and K4 cannot be closed at the same time. Given this circumstance, Table I gives the possible combinations of the closed (*On*) and open (*Off*) states of the output contactors K1-K4, where P_{X1} and P_{X2} are the output power of connectors X1 and X2; *P1* and *P2* are output power of AC/DC1 and AC/DC2 power units; $\sum P_{in}$ is the total maximum power consumption CS; P_{inm} is the maximum power consumption of one power unit.

As output connectors X1 and X2, a connector of the CHAdeMO type or CCS2 type or both of these types can be used, depending on the requirements of the Customer.

In general, thanks to the presence of two power units AC/DC1 and AC/DC2, four output contactors K1-K4 and two connectors X1 and X2, the developed CS has the ability for fast-charging two EVs simultaneously. This circumstance potentially increases the throughput of the CS under consideration. However, any CS is limited by the level of peak power consumption, which is determined by the input three-phase network of a particular infrastructure [17]-[19]. Accordingly, the CS cannot always charge the batteries of two EVs at the same time.

Table I POSSIBLE STATE COMBINATIONS OF THE OUTPUT CONTACTORS

	Output contactor status				P_{X1}	P_{X2}	$\sum P_{in}$
	K1	K2	K3	K4			
1	*On*	*Off*	*Off*	*Off*	*P1*	*0*	P_{inm}
2	*On*	*Off*	*On*	*Off*	*P1+P2*	*0*	$2P_{inm}$
3	*On*	*Off*	*Off*	*On*	*P1*	*P2*	$2P_{inm}$
4	*Off*	*On*	*Off*	*Off*	*0*	*P1*	P_{inm}
5	*Off*	*On*	*On*	*Off*	*P2*	*P1*	$2P_{inm}$
6	*Off*	*On*	*Off*	*On*	*0*	*P1+P2*	$2P_{inm}$
7	*Off*	*Off*	*Off*	*Off*	*0*	*0*	*0*
8	*Off*	*Off*	*On*	*Of*	*P2*	*0*	P_{inm}
9	*Off*	*Off*	*Off*	*On*	*0*	*P2*	P_{inm}

In this regard, it became necessary to finalize the charging station "EV DUAL Charge 50" for simultaneous charging of two EVs.

3 Two-unit CS Study

We investigated the possibility of the two-unit CS, shown in Fig. 3, to charge the batteries of two EVs at the same time. And we considered the case when both batteries are of the same type and are completely discharged.

For clarity of the study results, we introduced the following parameters:

- relative battery charging time (t^*), calculated as the ratio of the current time to the reference battery charging time;

- calculated relative power consumption ($P^*_{in1}(t^*)$ and $P^*_{in2}(t^*)$), when charging the battery of the first and second EVs, which are defined as the ratio of the current power consumption when charging the first and second EVs to the allowable specified power consumption of CS.

In this case, the boundary relative value of the specified power consumption $P^*_{max\sum}(t^*)$ of CS, which is limited by the input three-phase infrastructure network, is equal to 1. At the same time, each $P^*_{in1}(t^*)$ and $P^*_{in2}(t^*)$ have a maximum value of 0.5.

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Using empirical data and models [20], [21], we calculated $P_{in1}^*(t^*)$ and $P_{in2}^*(t^*)$, during CC/CV (taking into account the absence of Stage 1). We then calculated the relative total power consumption of a two-unit CS as:

$$P_{\Sigma}^*(t^*) = P_{in1}^*(t^*) + P_{in2}^*(t^*). \quad (1)$$

Taking into account the condition that the CS under consideration immediately starts charging two identical batteries, then

$$P_{\mathrm{in1}}^*(t^*) = P_{\mathrm{in2}}^*(t^*), \quad (2)$$

and

$$P_{\Sigma}^*(t^*) = 2P_{in1}^*(t^*). \quad (3)$$

As a result, in Fig. 4, we plotted the relative power consumption $P_{in1}^*(t^*)$, when charging the battery of the first EV (a dotted line), the total relative power consumption $P_{\Sigma}^*(t^*)$, when charging the battery of the first and second EVs (a solid line), and the allowable specified power consumption $P_{max\Sigma}^*(t^*)$ of CS, which is marked with diamonds, depending on the relative time t^* of the battery charging.

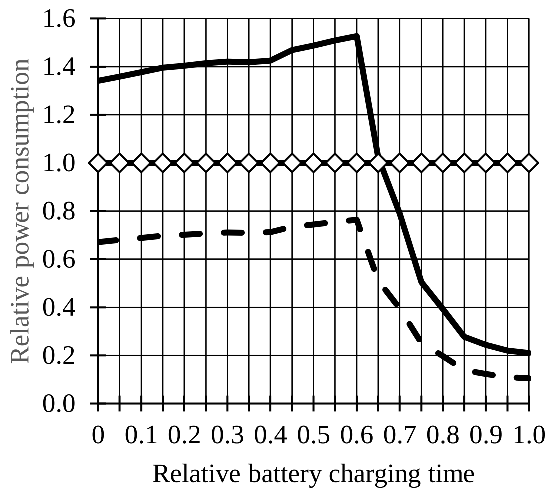

Fig. 4. Curves of relative consumption powers

It should be noted, a dual-unit CS can charge the batteries of two EVs at once under the following conditions:

$$\begin{cases} P_{\Sigma}^*(t^*) \le P_{max\Sigma}^*(t^*) \le 1; \\ P_{in1}^*(t^*) \le \frac{1}{N}; \\ P_{in2}^*(t^*) \le \frac{1}{N}, \end{cases}, \quad (4)$$

where *N* is the number of units in CS.

In this case, the relative time t^* of the battery charging changes from 0 to 1.

The first condition of (4) states that $P_{\Sigma}^*(t^*)$ cannot exceed the allowable specified power consumption of CS. This condition is due to the possibility of the infrastructure to which the CS is connected.

The second and third conditions of (4) establish that $P_{in1}^*(t^*)$ and $P_{in2}^*(t^*)$ cannot exceed the allowable power consumption of AC/DC1 and AC/DC2 power units. These conditions are based on the fact that only one unit connected to each EV: AC/DC1 or AC/DC2.

Analysis of the curves presented in Fig. 4 showed that the first condition of (4) is not met. In this regard, we concluded that in this case, a two-unit CS cannot immediately charge the batteries of two EVs. Obviously, this is a negative factor for the consumer and for the two-unit CS, accordingly.

Then we investigated, at what the relative time delay ΔT^* of the second EV it would be possible to charge the batteries of two EVs. In this case, the first condition of (4) takes the following form:

$$\begin{cases} P_{in1}^*(t_1^*) \le 1; \\ P_{in1}^*(t_2^*) + P_{in2}^*(t_2^*) \le 1; \\ P_{in2}^*(t_3^*) \le 1, \end{cases} \quad (5)$$

where t_1^* is from 0 to ΔT^*;

t_2^* is from $\Delta \mathrm{T}^*$ to T_1^*;

t_3^* is from T_1^* to T_2^*;

T_1^* and T_2^* are the relative charging completion times for the battery of the first and second EVs.

The analysis showed that condition (5) is satisfied if we charge the battery of the second EV with relative time delay $\Delta T^* = 0.73$ from the start of charging the battery of the first EV.

At the same time, the second and third conditions of (4) take the following form:

$$\begin{cases} P_{in1}^*(t^*) \le \frac{1}{N} = 0.5, \ t^* = [0, T_1^*]; \\ P_{in2}^*(t^*) \le \frac{1}{N} = 0.5, t^* = [\Delta \mathrm{T}^*, T_2^*]. \end{cases} \quad (6)$$

Unfortunately, this condition is not met. In this case, even charging one battery requires more output power than the output power of one power unit.

Thus, the dual-unit CS under consideration cannot simultaneously charge completely discharged batteries of two EVs, which is a negative factor for the consumer.

4 Three-unit CS study

To fulfill condition (6), we proposed to use three power units AC/DC1-AC/DC3 in the CS. In addition, each power unit has an output power equal to 16.5kW. Accordingly, the output power of such a CS does not exceed the output power of a two-unit CS. Also, we have added two output contactors K5 and K6 in the

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three-unit CS. In this regard, each of the three AC/DC1-AC/DC3, by means of already six output contactors K1-K6, can be connected to the output connectors X1 and X2. The power circuit of the proposed CS is shown in Fig. 5.

As in the previous CS, one power unit cannot charge two batteries at the same time. Accordingly, any pair of output contactors (K1-K2, K3-K4, K5-K6) cannot be closed at the same time. With this in mind, the three-unit CS has 27 possible combinations of closed and open states of the output contactors K1-K6, through which the AC/DC1-AC/DC3 power units are connected to the output connectors X1 and X2. As a result, the CS can charge batteries at an output power of 16.5kW or 33.0kW or 49.5kW.

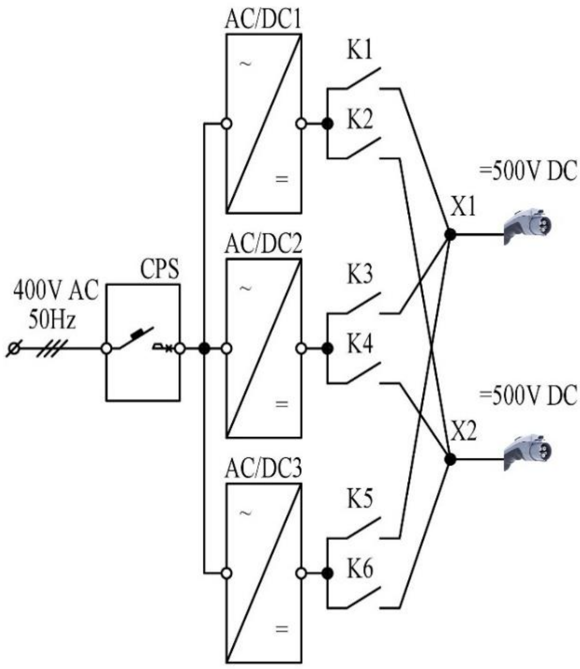

Fig. 5. The block diagram of three-unit CS

We assumed, at first the second AC/DC2 together with the first AC/DC1 can add output current to the first connector X1, and then it can add output current to the second connector X2 together with the third AC/DC3. In this case, the states of the output contactors K1-K6 are shown in Table II, where P1-P3 is the output power of the AC/DC 1-AC/DC 3.

The K2 and K5 are designed to be reserved in case of failure of some power unit AC/DC 1-AC/DC 3.

The study showed that condition (5) is satisfied if we charge the battery of the second EV with a relative time delay $\Delta T^* = 0.71$ from the start of charging the battery of the first EV. This case corresponds to the transition of the output contactors K1-K6 from line 1 to line 2 according to Table II.

Table II EXAMPLE OF THE STATUS OF OUTPUT CONTACTORS

	Output contactor status				P_{X1}	P_{X2}	$\sum P_{in}$
	K1	K3	K4	K6			
1	*On*	*On*	*Off*	*Off*	*P1+P2*	*0*	$2P_{inm}$
2	*On*	*On*	*Off*	*On*	*P1+P2*	*P3*	$3P_{inm}$
3	*Off*	*Off*	*On*	*On*	*0*	*P2+P3*	$2P_{inm}$

With a three-unit CS (*N*=3), the second and third conditions (5) take the following form:

$$\begin{cases} P^*_{in1}(t^*) \le 2\frac{1}{N} = 0.67, t^* = [0, \Delta \mathrm{T}^*]; \\ P^*_{in1}(t^*) \le \frac{1}{N} = 0.33, t^* = [\Delta \mathrm{T}^*, T^*_1]; \\ P^*_{in2}(t^*) \le 2\frac{1}{N} = 0.67, t^* = [\Delta \mathrm{T}^*, T^*_2]. \end{cases} \quad (7)$$

We have found that conditions (7) are satisfied if $\Delta T^* = 0.71$. This means that a three-unit CS can charge the battery of the second EV with a relative time delay $\Delta T^* = 0.71$ from the start of charging the battery of the first EV. Thus, under the conditions found, the three-unit CS can simultaneously charge the batteries of two EVs, which increases its throughput by 29% and reduces the waiting period for battery charging of the second event.

5 Conclusion

1 Any CS is limited by the level of peak power consumption, which is determined by the input three-phase network of the infrastructure. This factor limits the use of CS for fast-charging the batteries of several EVs at the same time.

2 The two-unit CS used does not allow the fully discharged batteries of two EVs to be charged at the same time.

3 The developed three-unit CS provides a fast-charging of fully discharged batteries of two EVs, provided that the battery of the second EV is charged after a relative time delay $\Delta T^* = 0.71$ from the start of charging the battery of the first EVER.

4 The proposed three-unit CS provides a 29% increase in throughput compared to a two-unit CS, which is a positive factor for the CS owner.

5 On the other hand, the developed three-unit CS reduces the waiting period for battery charging of the second EV by 29%, which is a positive factor for the EV owner.

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These factors increase the efficiency of the designed CS by reducing the amount of time a motorist waits for the battery to finish charging and by increasing the number of EVs connection points.

Thus, the proposed three-unit CS can contribute to the improvement of the environmental situation in the world, especially in densely populated cities through the development of a network of efficient charging stations for EVs.

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