Asian Power Electronics Journal, Vol. 14, No. 1, April 2020

100kW Electric Bus Wireless Charging System with Calculating Method for Hybrid Energy Storage Capacity

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Abstract – For the application background of electric buses being wirelessly charged at the stopping locations on bus route, a 100 kW electric bus wireless charging system with supercapacitor (SC)-battery hybrid energy storage is designed. In addition, a calculating method for hybrid energy storage capacity is proposed to select the appropriate capacities of system hybrid energy storage devices and thus reduce the weight of bus. Firstly, the equivalent circuit model of the wireless power transfer (WPT) system with SC and battery being loads is analyzed. Then, for the dynamic change of SC equivalent resistance, the SC detection, the wireless data communication, and the power regulation are adopted in the system. Finally, the 100 kW wireless charging system designed in this paper is implemented and verified by experiments. When the transfer distance is 0.45 m, the output power can be 80.2 kW with 89.6% transfer efficiency. Moreover, according to the experimental results and the bus energy consumption survey, the energy storage capacity is calculated by the proposed calculating method.

Keywords – electric bus; wireless power transfer (WPT); supercapacitor (SC); hybrid energy storage

I. INTRODUCTION

Internal combustion engines will cause environmental problems, such as air pollution and global warming, while the operation of an electric motor is zero emission [1]. Therefore, compared with traditional buses, electric buses have more advantages. At present, the inconvenience of traditional wired charging mode and the energy storage problem limit the development of electric vehicles (EVs) including electric buses [2].

For the inconvenience of traditional wired charging mode, the applications of wireless power transfer (WPT) technology to EVs [3] and railway vehicles [4] have been studied in recent years. The wireless charging mode is convenient and without spark or electric shock danger. Therefore, in view of the inconvenience of electric bus traditional wired charging mode, wireless charging mode is a solution with prospects for development. As shown in Fig. 1, on bus route, there are some stopping locations such as bus stops and traffic lights intersections. The short stopping time can be used to charge the bus by wireless charging mode. On the premise of guaranteeing the required driving mileage, by frequent wireless charging, the capacity of energy storage device is reduced and the effective utilization of energy is improved. Electric energy can be conveniently and efficiently delivered to the bus by the wireless charging mode, meanwhile, the storage mode of the electric energy also needs to be considered.

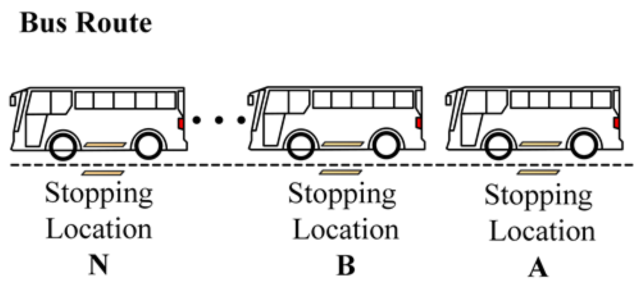

Fig. 1: Diagram of the stopping locations on bus route

For the electric energy storage problem, batteries are suitable to support the progress of EVs because of the high energy density and mobility of batteries [1]. However, the performance and life of batteries are usually rapidly degraded due to frequent high current charging and discharging. Compared with battery [5]-[6], supercapacitor (SC) has higher power density and longer lifetime [6]. Thus, SC is suitable for the frequent wireless charging such as the 3-kW wireless power transfer system for sightseeing car in [7]. In summary, for the electric bus being wireless charged frequently, there are drawbacks in using battery only. And combining the advantages and disadvantages of the above two energy storage modes, it is more appropriate to use the SC-battery hybrid energy storage mode for electric buses, which are heavy duty passenger vehicles [8]. For SC-battery hybrid energy storage mode, it is important to select their appropriate capacities. A calculating method for hybrid energy storage capacity is proposed in this paper. Moreover, the paper proposes the idea that electric buses could be wirelessly charged during the short stopping time at the stopping locations on bus route. However, in order to meet the demand, which is making electric buses fully charged at short notice, it is essential to increase the output power level of WPT system. Therefore, a 100kW WPT charging system is built in the paper.

The concept map of the electric bus wireless charging system with SC-battery hybrid energy storage in this paper is illustrated in Fig. 2. As shown in Fig. 2, after the power distribution, the transmitting coil is powered by the AC-DC-DC-AC power supply. Then the electric energy is transmitted to the receiving coil through electromagnetic coupling. The electric energy received by the receiving coil is used to charge the SC-battery hybrid energy storage device after the rectifying filter. The rest sections of this paper are organized as follows: Section II analyses the equivalent circuit model of the WPT system with SC and battery load. On the basis of the analysis of Section II, the electric bus wireless charging system with SC-battery hybrid energy storage is designed in Section III. The calculating method for hybrid energy storage capacity is also elaborated in Section III. Section IV implements the electric bus wireless charging system designed in Section III. By using the calculating method, the hybrid energy storage capacity is calculated according to the experimental results and the bus energy consumption survey. Finally, the conclusion is shown in Section V.

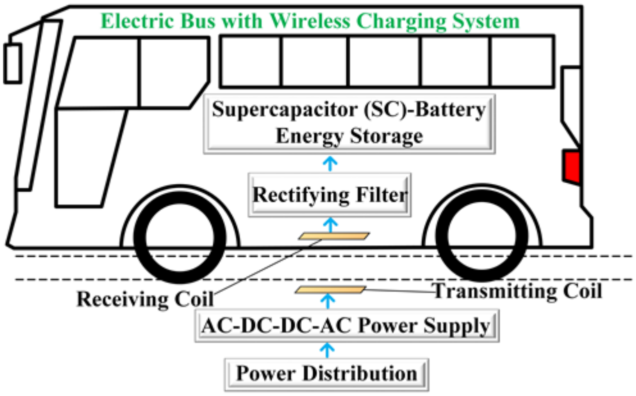

Fig. 2: The concept map of electric bus wireless charging system with SC-battery hybrid energy storage

II. Equivalent Circuit Model of the WPT System with SC-Battery Load

As shown in Fig. 3, by replacing the resistance load of the mutual inductance circuit model in [9] with the SC's classical equivalent circuit model [10] and the simplified battery model [11], the equivalent circuit model of the WPT system with SC and battery is obtained.

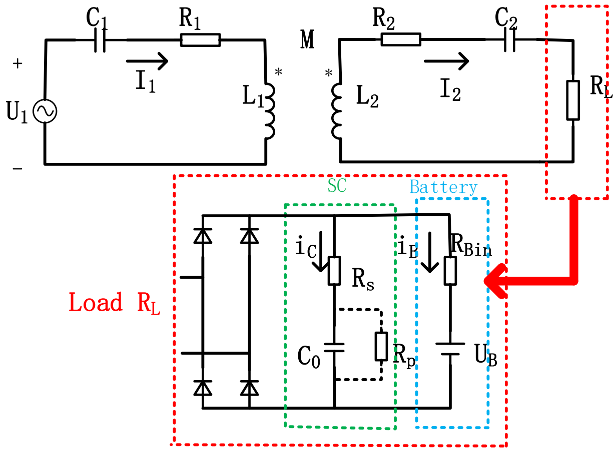

Fig. 3: The equivalent circuit model of the WPT system with supercapacitor (SC) and battery loads

In Fig. 3, u_1 is the voltage of high frequency AC power supply; U_o is the voltage of the load; i_1 and i_2 are the currents of transmitting and receiving coils, respectively; L_1 and L_2 are the inductances of transmitting and receiving coils, respectively; R_1 and R_2 are the equivalent series resistances of transmitting and receiving coils, respectively; series capacitances C_1 and C_2 are the resonant capacitances; M is the mutual inductance of transfer coils; R_s, C_o, R_p and u_{co} are the equivalent series resistance, the ideal capacitance value, the equivalent parallel resistance and the capacitance voltage of SC, respectively; u_B and R_{Bin} are the ideal battery voltage and the battery equivalent internal resistance, respectively; R_{CL} is the equivalent resistance of SC; R_{BL} is the equivalent resistance of battery; R_L is the equivalent resistance of SC-battery loads and rectifier circuit; i_C is the current flowing through the branch of SC; i_B is the current flowing through the branch of battery.

A. Mutual Inductance Circuit Model of WPT System

According to Kirchhoff's Voltage Law (KVL) and Fig. 3, the mutual inductance circuit relation formula of series resonant WPT system can be written into:

$$\begin{cases} u_1 = (R_1 + j\omega L_1 + \dfrac{1}{j\omega C_1})i_1 - j\omega M i_2 \\ j\omega M i_1 - (R_2 + j\omega L_2 + \dfrac{1}{j\omega C_2} + R_L)i_2 = 0 \end{cases} \tag{1}$$

where $\omega = 2\pi f$ with f being the resonant frequency.

When transmitting coil and receiving coil are identical, i.e. $L_1 = L_2 = L$, $R_1 = R_2 = R$, $C_1 = C_2 = C$, and the resonant angle frequency $\omega = 1 / (LC)$^(1/2), Equation (1) becomes:

$$\begin{cases} u_1 = Ri_1 - j\omega M i_2 \\ j\omega M i_1 - (R + R_L)i_2 = 0 \end{cases} \tag{2}$$

According to (2), input power P_{in}, output power P_{out} and transfer efficiency η can be written into:

$$P_{in} = u_1 i_1 = \frac{(R+R_L)u_1^2}{R(R+R_L)+(\omega M)^2} \tag{3}$$

$$P_{out} = i_2^2 R_L = \frac{u_1^2(\omega M)^2 R_L}{[R(R+R_L)+(\omega M)^2]^2} \tag{4}$$

$$\eta = \frac{P_{in}}{P_{out}} = \frac{R_L}{(R+R_L)[1+\dfrac{R(R+R_L)}{(\omega M)^2}]} \tag{5}$$

Unlike the pure resistance load in [16], R_L is the equivalent resistance of SC-battery load, thus R_L needs to be analyzed.

B. SC Load

The effects of the SC's equivalent parallel resistance R_p can be neglected for transient capacitor discharges on the order of a few seconds to a few minutes [10]. In this paper, the wireless charging system is designed to make use of the short time at each stopping location on bus route to charge the electric bus. Therefore, only the equivalent series resistance R_s and the ideal capacitance C_o are analyzed [7].

Assuming that the load voltage U_o is constant and the charging time is t, the current and the voltage of SC can be denoted by i_C(t) and u_{co}(t), respectively. By KVL, it can be obtained that:

$$U_o(t) = i_C(t)R_s + u_{co}(t) \tag{6}$$

The changes during the charging process can be expressed as:

$$\begin{cases} U_o(0) = i_C(0)R_s + u_{co}(0) \\ U_o(t) = i_C(t)R_s + u_{co}(t) \end{cases} \tag{7}$$

The change of the SC's voltage during the whole charging process (from 0 to t s) is denoted by ΔU_c, i.e. $\Delta U_c = u_{co}(t) - u_{co}(0)$. According to (7), $i_C(t)$ can be written into:

$$i_C(t) = i_C(0) - \frac{\Delta U_c}{R_s} \tag{8}$$

And another expression of $i_C(t)$ is:

$$i_C(t)=C_o\frac{du_{co}}{dt}=C_o\frac{\Delta U_c}{t} \quad (9)$$

According to (8) and (9), ΔU_c can be written into:

$$\Delta U_c=i_C(0)\frac{R_s t}{C_o R_s+t} \quad (10)$$

Therefore, according to (8) and (10), the SC's equivalent resistance, i.e. R_{CL} can be written into:

$$R_{CL}=\frac{U_o}{i_C(t)}=\frac{U_o}{i_C(0)}(1+\frac{t}{C_o R_s}) \quad (11)$$

The initial current $i_C(0)$ can be written into:

$$i_C(0)=\frac{U_o-u_{co}(0)}{R_s} \quad (12)$$

where $u_{co}(0)$ is the initial voltage of SC. By substituting (12) into (11), it can be obtained that:

$$R_{CL}=\frac{U_o}{U_o-u_{co}(0)}(R_s+\frac{t}{C_o}) \quad (13)$$

It can be seen from (13) that R_{CL} has a dynamic change t/C_o.

C. Battery Load

In Fig. 3, the current flowing through the battery branch, i.e. i_B can be written into:

$$i_B=\frac{U_o-u_B}{R_{Bin}} \quad (14)$$

Thus, the equivalent resistance of battery, i.e. R_{BL} can be written into:

$$R_{BL}=\frac{U_o}{i_B}=\frac{U_o}{U_o-u_B}R_{Bin} \quad (15)$$

where u_B is constant under ideal condition.

In summary, the equivalent resistance of SC-battery loads, i.e. R_L' can be written into:

$$R_L'=\frac{R_{CL}R_{BL}}{R_{CL}+R_{BL}}=\frac{U_o}{\frac{U_o-u_{co}(0)}{R_s+\frac{t}{C_o}}+\frac{U_o-u_B}{R_{Bin}}} \quad (16)$$

$$R_L=\frac{8}{\pi^2}R_L' \quad (17)$$

As shown in formula (17), the relationship between R_L and R_L' is remarkable, which is established with uncontrolled rectifier circuit. In R_L', there is a dynamic change caused by SC. According to (4), when R_L is known, the output power P_{out} can be adjusted by changing the value of u_1. Thus, the dynamic change should be taken into account in the subsequent wireless charging system design.

III. Design of the Electric Bus Wireless Charging System with SC-Battery Hybrid Energy Storage

A. Overall System Design

The design block diagram of the electric bus wireless charging system with SC-battery hybrid energy storage is illustrated in Fig. 4. The system is divided into two parts: the transmitting part and the receiving part. The transmitting part is installed at each stopping location on bus route. The receiving part is installed on the electric bus.

As shown in Fig. 4, the DC voltage U_{d1} obtained by rectifying filter is input into the DC chopper. The inverter converts the output DC voltage of the DC chopper into high AC frequency voltage. Then the high frequency AC voltage is input into the transmitter of magnetically coupled resonant circuit. The resonant capacitor C_1 and the transmitting coil L_1 form the resonant circuit of the transmitter. Electric energy is sent to the receiver by electromagnetic coupling. The resonant capacitor C_2 and the receiving coil L_2 form the resonant circuit of the receiver. By the high-frequency rectifying and filtering circuit, the electric energy is converted into the DC voltage, which is used to charge the SC-battery hybrid energy storage device.

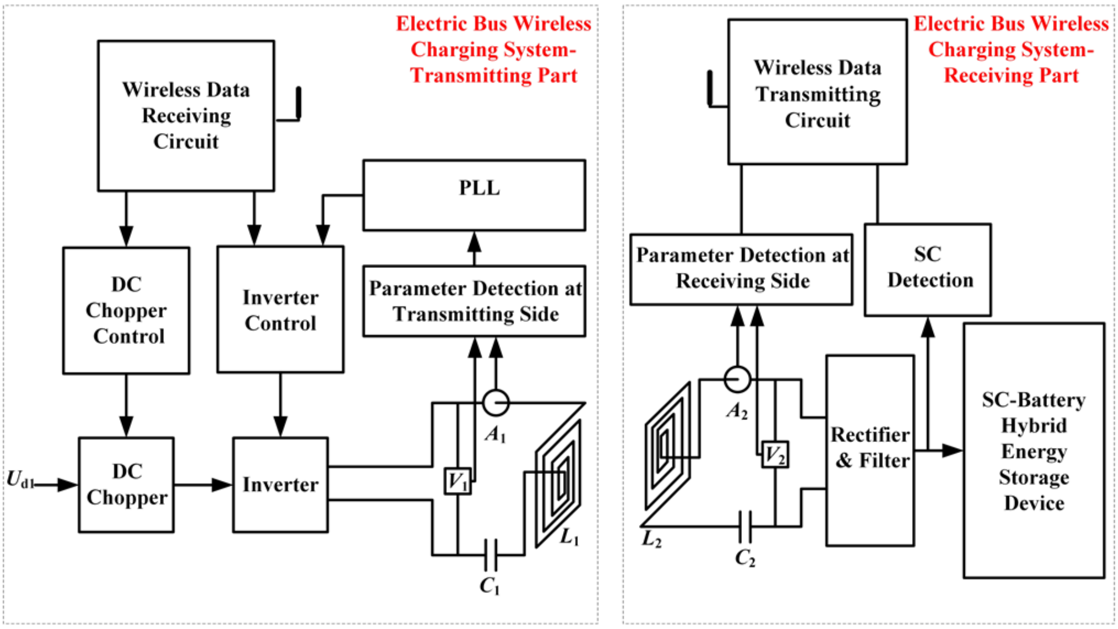

Fig. 4: The design block diagram of electric bus wireless charging system with SC-battery hybrid energy storage

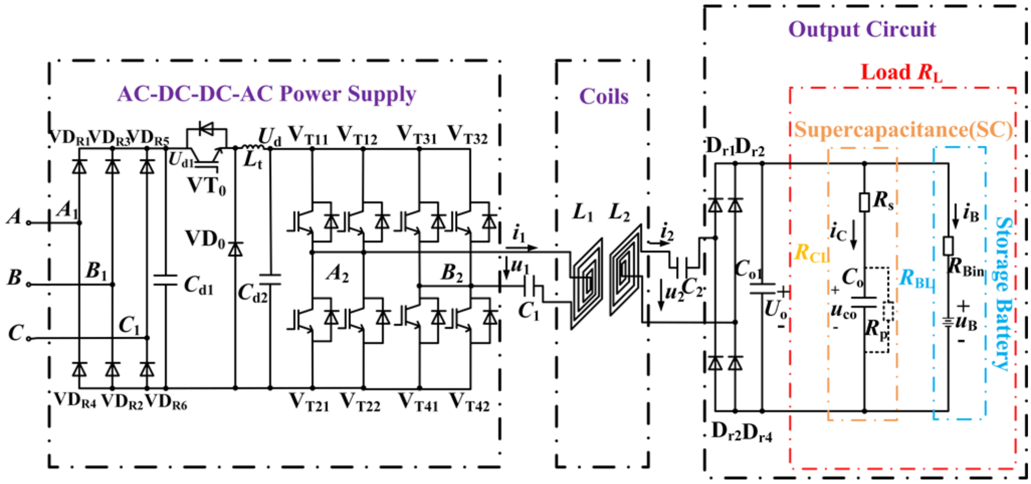

Fig. 5: Diagram of electric bus wireless charging system circuit

As shown in Fig. 4, the parameter detection at transmitting side is to detect inverter output voltage and current. The detected voltage and current will be used for PLL frequency tracking. The parameter detection of receiving side is divided into rectifier input voltage and current detection and SC detection. SC detection is used to obtain the required voltage and current of SC. The detected parameters of receiving side are sent to transmitting side by wireless communication circuit.

The system control includes DC chopper circuit control and inverter frequency tracking control. 1) DC chopper circuit control: In the circuit model analysis of Section 2, R_L has a dynamic change. Thus, the SC detection circuit is added to the system. After the SC detection, the detected data is sent to the wireless data receiving circuit by the wireless data transmitting circuit, and the received data is processed. According to the required voltage and current of SC, the output power is regulated by the control of the DC chopper circuit. 2) Inverter frequency tracking control: When the parameters of the resonant circuit are changed, the PLL frequency tracking circuit automatically tracks the resonant frequency.

B. Design of the Electric Bus Wireless Charging System Circuit

The system circuit is designed according to the overall system design. The diagram of electric bus wireless charging system circuit is illustrated in Fig. 5. The system circuit consists of three parts: 1) AC-DC-DC-AC power supply; 2) coils and related resonant circuits; 3) output circuit.

1) AC-DC-DC-AC power supply

The three-phase rectifier bridge (VD_{R1}-VD_{R6}) and the filter capacitor C_{d1} are used to convert A, B, and C three-phase AC voltage into the DC voltage U_{d1}. And U_{d1} is input into the Buck circuit (VT_0, VD_0, Cd_2). By the inverter circuit, the output voltage of Buck circuit, i.e. U_d is converted into the high frequency AC voltage, which corresponds to u_1 in Fig. 3. The power level of the wireless charging system in this paper is very large. In order to sustain the rated large current, IGBT parallel connection needs to be adopted.

2) Coils and related resonant circuits

The parameters of the symmetrical square coils used in this paper are as follows: the average side lengths of both coils are 0.85 m; the turn numbers of both coils are 10; the thickness of the magnetic conductor is 5 mm; the side length of the square magnetic conductor is 1.2 m.

To facilitate the design of the related resonant capacitors, finite element analysis software is used to simulate the coils. The coils simulation model is illustrated in Fig. 6. The self-inductance ($L_1 = L_2 = 4.5629 \times 10^{-4}$ H) and the mutual inductance ($M = 3.9156 \times 10^{-5}$ H) are obtained by the simulation.

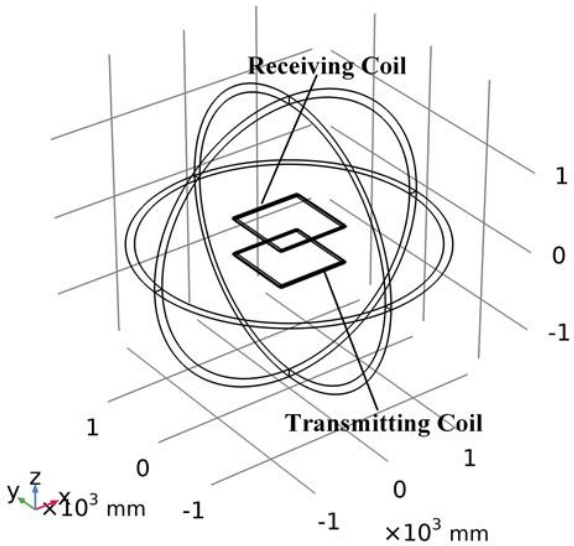

Fig. 6: The coils simulation model

3) Output circuit

By the high frequency rectifier (D_{r1}-D_{r4}) and the filter capacitor (C_{o1}), the high frequency AC output of the receiving coil is converted into the DC voltage, which corresponds to U_o in Fig. 3. And U_o charges the SC-battery hybrid energy storage device.

According to the above design of the system and the circuit, the electric bus wireless charging system can be implemented. But for the whole system, the capacity selection of hybrid energy storage device is equally important. Under the premise of continuous and reliable driving, determining the appropriate capacity of hybrid energy storage device can greatly reduce the cost of system.

C. Calculating Method for Hybrid Energy Storage Capacity

This calculating method is for the pure electric buses with SC-battery hybrid energy storage. The long-term storage device is battery, and the short-term storage device is SC.

The time for a bus going to and fro on its route one or more times is recorded as t_{all}. And the related data is recorded at a regular time interval Δt. Then the number of recording points n is $t_{all}/\Delta t$. The related data is recorded as follows:

There is wireless communication between the transmitting side and the receiving side of the wireless charging system designed in this paper. Therefore, historical WPT received power $P_{WPT}(t_i)$ can be recorded by analyzing the data of the system transmitting side installed at each stopping location on bus route. And historical actual demand power $P_{bus}(t_i)$ are recorded at each recording point, where i=1, 2, 3..., n. Historical supply-demand mismatch power $P_\Delta(t_i)$ and historical average supply-demand mismatch power $P_{\Delta avg}(t)$ are obtained by (18) and (19).

$$P_\Delta(t_i) = P_{WPT}(t_i) - P_{bus}(t_i) \tag{18}$$

$$P_{\Delta avg}(t) = \frac{\sum_{i=1}^{n} P_\Delta(t_i)}{n} \tag{19}$$

By $P_{WPT}(t_i)$, $P_{bus}(t_i)$, $P_\Delta(t_i)$, and $P_{\Delta avg}(t)$, the capacity of SC-battery hybrid energy storage device is calculated as follows:

1)Battery (long-term) energy storage capacity

Assuming that the maximum of the sum of any q consecutive $P_\Delta(t_i)$ is $\max(\sum P_\Delta(t_i))$, then the battery energy storage capacity E_1 is the time integral of the corresponding q consecutive $P_\Delta(t_i)$, where $1 \le q \le n$. Moreover, in order to protect the battery from over discharge and ensure the stability of power supply, it is necessary to keep E_1 larger than calculated value.

2)SC (short-term) energy storage capacity

Fast Fourier Transform (FFT): By FFT and historical supply-demand mismatch power $P_\Delta(t_i)$, historical supply-demand mismatch power of frequency domain, i.e. $P_\Delta(f_i)$ are obtained. Due to the character of FFT, only data within half of the sampling frequency are analyzed. Then $P_\Delta(f_i)$ are converted into periodic supply-demand mismatch power $P_\Delta(T_i)$, where i =1, 2, 3..., n / 2 and $T = 1 / f$.

Standardization: According to (20), total supply-demand mismatch power $P_{\Delta all}$ is obtained. Then according to (21), periodic supply-demand mismatch power $P_\Delta(T_i)$ is standardized.

$$P_{\Delta all} = \sum_{i=1}^{n/2} P_\Delta(T_i) \tag{20}$$

$$P'_\Delta(T_i) = \frac{P_\Delta(T_i)}{P_{\Delta all}} \tag{21}$$

where i = 1, 2, 3..., n / 2.

Accumulation: Accumulated value of supply-demand mismatch power, i.e. $P''_\Delta(T_k)$ are calculated as shown in (22).

$$P''_\Delta(T_k) = \sum_{i=k}^{n/2} P'_\Delta(T_i) \tag{22}$$

where k=1, 2, 3..., n/2. Then a continuous function curve of $P''_\Delta(T_k)$ is obtained.

Selection of critical percentage: In logarithmic coordinates, when the function value decreases from the maximum to $20\log(1/2)^{1/2}$ of the maximum, the function value corresponding to the continuous function is the critical percentage k_p. A corresponding $T_k(k_p)$ is obtained by finding the $P''_\Delta(T_k)$ closest to k_p. The period length less than $T_k(k_p)$ can be considered to be buffered by energy storage device.

Capacity calculation: The SC energy storage capacity E_2 is the product of the corresponding $T_k(k_p)$ and historical average supply-demand mismatch power $P_{\Delta avg}(t)$, i.e. $E_2 = P_{\Delta avg}(t) \times T_k(k_p)$.

IV. IMPLEMENTATION OF THE WIRELESS CHARGING SYSTEM

A. EXPERIMENT RESULTS OF THE WIRELESS CHARGING SYSTEM

In order to facilitate the power design of the wireless charging system and the calculation for energy storage capacity, the historical actual demand power $P_{bus}(t_i)$ of a bus were recorded. The $P_{bus}(t_i)$ is illustrated in Fig. 7.

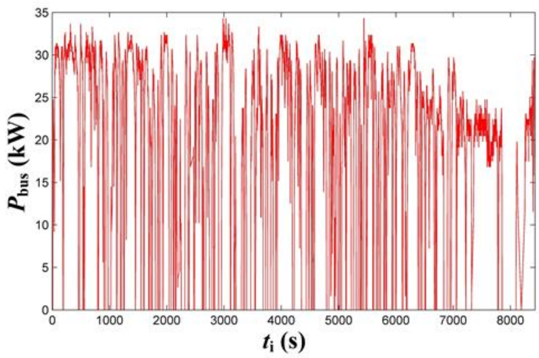

Fig. 7: Historical actual demand power $P_{bus}(t_i)$

As shown in Fig. 7, t_{all} is 8427 s, and the regular time interval Δt is 1 s. Then the number of recording points n is 8427. Within 8427 s, the bus consumes 42 kW·h. If the bus is charged at 80 kW when it stops ($P_{bus}(t_i)$ = 0 kW), the charging energy of the bus within 8427 s is 45 kW·h, which can meet the demand. Therefore, in consideration of system transfer efficiency, a wireless charging system with 100 kW input power is implemented as shown in Fig. 8.

Fig. 8: Diagram of the wireless charging experiment device with 100 kW input power

In Fig. 8, the frequency tracking range of the 100 kW high-frequency AC-DC-DC-AC power supply is 30–60 kHz. Both the transmitting coil and the receiving coil are square planar coils. And the average side lengths of both coils are 0.85 m.

The experimental results are shown in Table 1, where U_1 is the input voltage; I_1 is the input current; P_1 is the input power; U_2 is the output voltage; I_2 is the output current; P_2 is the output power; h is the transfer distance; f is the frequency of the power supply; η is the transfer efficiency.

As shown in Table 1, when the transfer distance h is 0.45 m, the output power P_2 can be 80.2 kW, which satisfies the power demand, at the efficiency of 89.6%.

Table 1: Experimental Result of the Wireless Charging System

U_1 (V)	I_1 (A)	P_1 (kW)	U_2 (V)	I_2 (A)	P_2 (kW)	h (m)	f (kHz)	η (%)
500.3	125.2	62.63	476.4	120.7	57.5	0.3	46.9	91.8
507.3	150.0	76.12	523.2	131.6	68.9	0.4	43.5	90.5
515.7	173.5	89.5	564.7	142.4	80.2	0.45	42.7	89.6

B. Calculation of the System Hybrid Energy Storage Capacity

According to the recorded $P_{bus}(t_i)$ and the design of Section III, a 100 kW wireless charging system for electric bus is implemented. On the basis of this wireless charging system, the SC (short term) and battery (long term) energy storage capacities are calculated by the calculating method proposed in Section III.

If the wireless charging system in this paper is used, the electric bus can be wirelessly charged with power of 80 kW at the stopping locations on bus route. In other words, when $P_{bus}(t_i) = 0$ kW, $P_{WPT}(t_i) = 80$ kW. According to Fig. 7, $P_{WPT}(t_i)$ can be obtained as shown in Fig. 9.

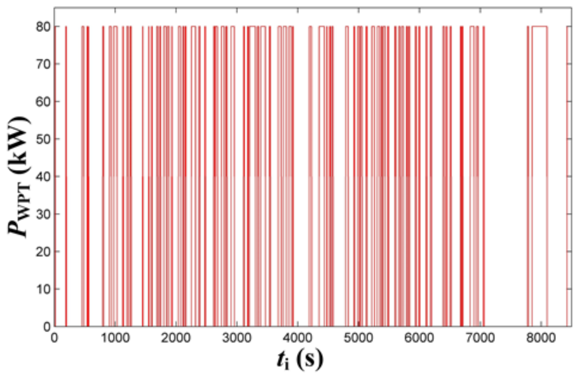

Fig. 9: Historical WPT received power $P_{WPT}(t_i)$

According to (19), Fig. 7, and Fig. 9, the historical supply-demand mismatch power $P_\Delta(t_i)$ can be obtained as shown in Fig. 10. And in Fig. 10, the maximum of the sum of any q consecutive $P_\Delta(t_i)$, i.e. max($\sum P_\Delta(t_i)$) is 36601 kW. The corresponding recording points n are 1682–5838 with q being 4157.

Therefore, the battery (long term) energy storage capacity E_1 can be written into:

$$E_1 = \int_{t_{1682}}^{t_{5838}} P_\Delta(t_i) \tag{23}$$

And E_1 is calculated to be 10.14 kW·h.

Next, the SC (short term) energy storage capacity E_2 is calculated. By FFT and the historical supply-demand mismatch power in Fig. 10, i.e. $P_\Delta(t_i)$, the historical supply-demand mismatch power of frequency domain, i.e. $P_\Delta(f_i)$ are obtained as shown in Fig. 11. In Fig. 11, only the data within half of the sampling frequency are analyzed. Then $P_\Delta(f_i)$ are converted into the periodic supply-demand mismatch power $P_\Delta(T_i)$ as shown in Fig. 12. In Fig. 12, to make the display more intuitive, the horizontal axis is transformed to logarithmic coordinates.

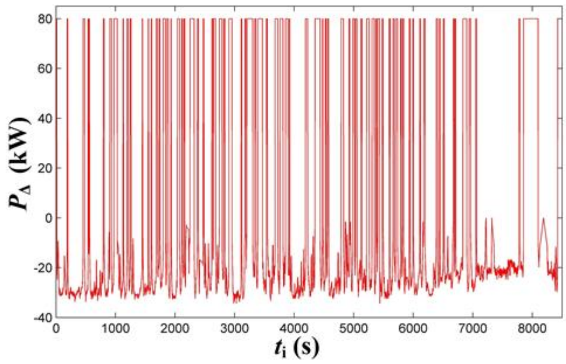

Fig. 10: Historical supply-demand mismatch power $P_\Delta(t_i)$

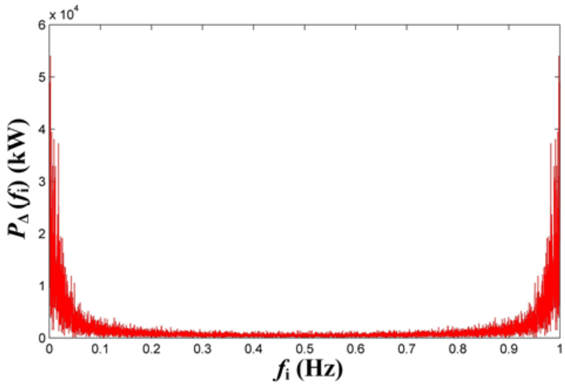

Fig. 11: Historical supply-demand mismatch power of frequency domain $P_\Delta(f_i)$

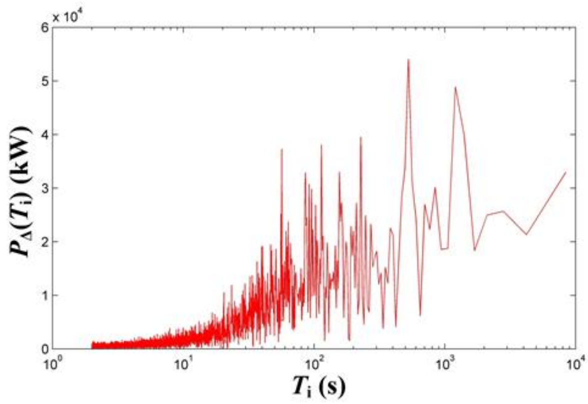

Fig. 12: Periodic supply-demand mismatch power $P_\Delta(T_i)$

According to (20), the total supply-demand mismatch power $P_{\Delta all}$ is obtained. And by $P_{\Delta all}$ and (21), $P_{\Delta}(T_i)$ is standardized.

Then, the accumulated value of supply-demand mismatch power $P''_{\Delta}(T_k)$ are calculated according to (22). The continuous function curve of $P''_{\Delta}(T_k)$ is obtained as shown in Fig. 13. the critical percentage $k_p = 0.293 \approx 0.3$. Then the corresponding $T_k(k_p)$ ($T_k(k_p) = 61$ s) is obtained by finding the $P''_{\Delta}(T_k)$ closest to 0.3. Therefore, the SC (short term) energy storage capacity $E_2 = P_{\Delta avg}(t) \times T_k(k_p) = 0.02$ kW·h.

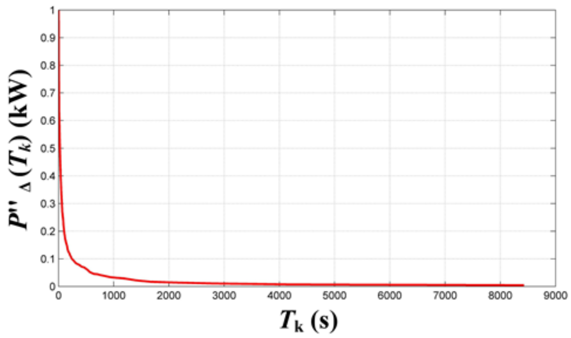

Fig. 13: Accumulated value of supply-demand mismatch power $P''_{\Delta}(T_k)$

V. CONCLUSION

In this paper, for the application background of electric buses being wirelessly charged during the short stopping time at the stopping locations on bus route, a set of 100 kW electric bus wireless charging system is designed and implemented. When the transfer distance h is 0.45 m, the output power P_2 can be 80.2 kW, which satisfies the power demand, at the efficiency of 89.6%. And the calculating method for hybrid energy storage capacity is used to calculate the capacity.

In this paper, considering the present experimental condition limit, SC-battery load is replaced by resistances. The charging problems of SC-battery, such as the different working voltage range and power distribution, will be taken into account in the further research using actual SC and battery and corresponding converters circuits. In the experiment of the further research, the SC and battery with the calculated energy storage capacity will be used and the system performance will be tested.

ACKNOWLEDGMENT

This research was funded by the National Natural Science Foundation of China (Grant No. 51407084), the China Postdoctoral Science Foundation (Grant No. 2017M610294) and the Jiangsu Planned Projects for Postdoctoral Research Funds (Grant No. 1701092B).

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