An Intelligent Charging Control Method for Electric Vehicle Charging System

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***Abstract*—In this paper, an intelligent double closed loop controller for electric vehicle (EV) charging system in smart grid (SG) is proposed, in which it can perform seamless changeover from constant current (CC) to constant voltage (CV) charging stage. Moreover, it can perform CC and CV charging control separately without adding in an external logic. Experimental results will be provided in full paper submission in order to verify the proposed controller in comparison to the conventional one.**

***Keywords*—Constant Current (CC), Constant Voltage (CV), Battery Charger, Electric Vehicle**

I. INTRODUCTION

To reduce fuel usage and greenhouse emissions, electric vehicle (EV) application is growing more interest in nowadays [1] and so as in smart grid (SG). Thus, the EV battery charging system plays an important role in the development of EV because it strongly influences the quality, safety, convenience, and the life of the EV in use. As a result, an appropriate EV charging control strategy is necessary to be developed in order to enhance the charging system efficiency, effectiveness, reliability and safety. However, an EV charging system is unavoidably operating for different kinds of EV with different voltage rating, current rating and capacity rating. That means the running parameters of the EV charging system will vary from time to time, thus leading to a design challenge.

Different to the normal battery charging system, a general EV charging system will face to different kinds of EVs with different voltage rating, current rating and capacity rating. That means the running parameter of the EV charging system will vary time to time.

Another side, to maintain a good status of the battery and extend its operation life length, many battery-charge methods have been proposed, such as the constant-current (CC charging), constant-voltage (CV charging), CC-CV charging, pulse charging, and reflex charging [2][3], on the other hand a three stage charging strategy is always asked to completed in EV charging system. The first stage is a constant current (CC) charging progress, the second a constant voltage (CV) charging progress, and the third is a floating charging progress. This strategy demand that the control method should maintain the output current or voltage to stable in different stages. And the seamless handover from the CC control to the CV control should be achieved when the battery voltage is reach to its voltage limits [4].

To the regular control method, the inner loop is a current control loop and the outer loop a voltage loop. The output of the voltage loop controller act as a current reference to the inner current loop. The given voltage reference signal will be the key parameter which decide the output of the whole controller. To achieve the shift from the CC controlling to CV controlling, an external logic will need to change the given voltage reference value in regular controller [5]. Another side, an impedance transformation is needed to convert the current reference to voltage reference when perform CC controlling. It is not flexible to the EV charging system for the impedance relationship of the battery are varies frequently.

A dual PI loop parallel connected controller is used in paper [6], its structure is shown in Fig. 1. In such controller, the CC controlling and CV controlling is implemented separately, the output of each controller is compared each other to choose the minimum one to perform the controlling. It is more flexible than the regular double close loop controller for the shift progress from CC controlling to CV controlling can be performed automatically. However, the design of the dual controller may need more carefully consideration, because of the structure of the controller is changed among the CC to CV controlling shift progress, and the change may introduce the instability or impulse into the controlling output.

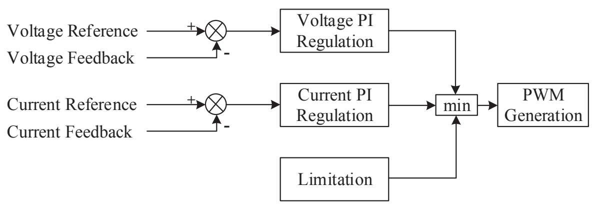


Fig. 1. The block diagram of dual PI loop parallel control

Another side, some surge will occurred when the controlling switched from CC mode to CV mode, for the structure of the controller is changed suddenly. This surge will also influent the performance of the input source, and some EMC problem will be introduced to the grid which the charger connected. And this affection will be more serious when thousands of such EV charger is connected into the grid. So that an intelligent and kindly controlling method for the EV charger is urgent needed to the future smart grid.

This paper presents an improved double close loop controller, in which a minimum comparator is hired to perform the seamless handover from the CC controlling to CV controlling. The controller can perform the CC charging and CV charging controlling separately with the given current and voltage reference value, without the external logic participated in. And the structure of the controller will maintain stable and fix during the shift progress.

II. CONTROL STRATEGY OF EV CHARGER

Fig. 2 shows a full bridge based AC/DC converter which are regular used in high-power EV charging system. The phase shift modulation method is used to control the output voltage and current. L_o and C_o compose the battery-side filter, and the hall sensor will sample the current through the inductor L_o and the voltage on the capacitor C_o, then send it to the controller as the feedback value.

The block diagram of the intelligent double close loop controlling system is shown in Fig. 3. The inner inductive current (i_L) loop is using in CC charging progress, while the outer capacitive voltage (v_C) loop is used to process the CV charging. Different to the regular double close loop controller, a minimum comparing segment is inserted between the inner current loop and the outer voltage loop. Which became the key point to perform the intelligent shift during the CC to CV switching.

The voltage loop regulator $G_{VR}(s) = K_{vp} + K_{vi}/s$ and the current loop regulator $G_{CR}(s) = K_{ip} + K_{ii}/s$ are all the stationary frame PI regulators, while the $G_{pwm}(s)$ is the gain of the converter.

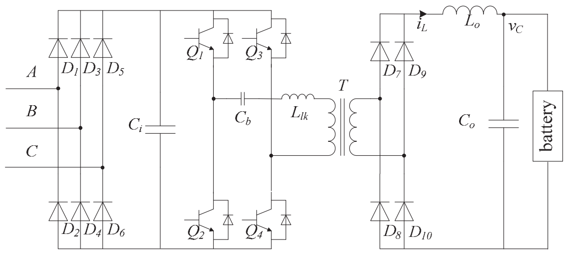


Fig. 2. Full bridge AC/DC converter for EV charger

A. CC Charging Progress

Generally, the common current charging is always performed firstly during the EV charging progress, for the impedance of the battery is very small when it is almost empty. Consequently, the voltage on the battery will keep low level during the CC charging progress. Notice to the error of the outer loop $e_v = v_{ref} - v_{fb}$, where the feedback voltage is v_C which is equal to the battery's voltage when the loss on the wire is ignored.

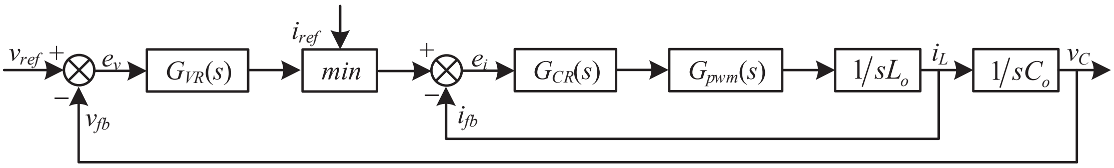


Fig. 3. Block diagram of the intelligent double close loop controller

Obviously, the voltage reference value v_{ref} is always bigger than the battery voltage when the battery is not fully charged. So that the error e_v is always keep to be greater than zero. By the effect of the integration segment, the output of the regulator G_{VR} will be saturated, and its value will be much higher than the current reference value i_{ref}. As the result, the outer loop controller is peeled off and only the inner current loop take effect.

B. CV Charging Progress

When the charging progress entering to the CV charging progress, the voltage on the battery will reach to a high level, and the impedance of the battery is much greater, while the charging current will decrease to a lower value. For the voltage on battery is very close to the voltage reference value, the outer voltage loop will take part in the function. Another side, due to the rising impedance, and the stable voltage, the corresponding current will keep lower than the current reference value i_{ref}. Thus, the current reference cannot make an impact to the output, and the whole controller will transfer into a regular double close loop controller.

C. CC to CV Switching

As described in the previous sections, the close loop transfer function of the controller can be presented in segmental expression as the following.

$$\begin{cases} v_C = \dfrac{1}{sC_o} i_L = \dfrac{G_{CR} \cdot G_{pwm}}{s^2 L_o C_o + sG_{CR} \cdot G_{pwm} C_o} i_{ref} & (G_{VR} e_v \geq i_{ref}) \\ v_C = \dfrac{G_{VR} \cdot G_{CR} \cdot G_{pwm}}{s^2 L_o C_o + sG_{CR} G_{pwm} L_o + G_{VR} \cdot G_{CR} \cdot G_{pwm}} v_{ref} & (G_{VR} e_v < i_{ref}) \end{cases} \tag{1}$$

If the output of the minimum segment is treated as an expression like $i'_{ref} = i_{ref} - \Delta$, then the upper expression can be rewritten as following.

$$\begin{gathered} v_C = \frac{G_{CR} \cdot G_{pwm}}{s^2 L_o C_o + sG_{CR} \cdot G_{pwm} C_o} i'_{ref} = \frac{G_{CR} \cdot G_{pwm}}{s^2 L_o C_o + sG_{CR} \cdot G_{pwm} C_o} \left(i_{ref} - \Delta \right) \\ \begin{cases} \Delta = 0 & (G_{VR} e_v \geq i_{ref}) \\ \Delta = i_{ref} - e_v G_{VR} & (G_{VR} e_v < i_{ref}) \end{cases} \end{gathered} \tag{2}$$

As mentioned before, the output of the outer voltage loop is saturated during the CC charging progress, and the value of

$G_{VR}e_v$ is always greater than i_{ref}. While the voltage on the battery is increased, and the error of the voltage close loop is dropped down, the value of $G_{VR}e_v$ will get close to i_{ref}. By the accumulation effect of the integration parts, the value of $G_{VR}e_v$ will keep saturated until the voltage on the capacitor reach or over the reference voltage. And as the error of the outer voltage loop drops below the zero, then the value $G_{VR}e_v$ decreased and bellows to i_{ref}, the charging progress is shifted to CV charging seamlessly.

Another side, the block diagram of the inner current loop can be redraw as Fig. 4. by (2). Obviously, the variable Δ can be considered as a disturbance signal, and its amplitude will be very small for the inertia of the battery. And the influence of this disturbance can be easily eliminated by the inner current controlling loop. So that, even though there's some possibility of oscillating between i_{ref} and $G_{VR}e_v$ during the changeover progress, the output of the charging system will always keep stable.

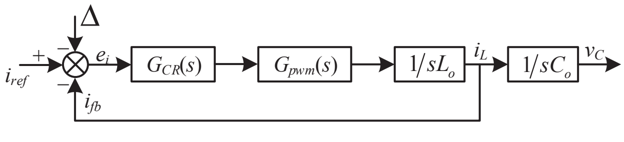


Fig. 4. Block diagram of the inner current loop

III. Regulator Design

A. Small Signal Model

According to [7], the small signal model of phase-shifted full bridge DC/DC converter is based on the small signal model of the BUCK regulator. And different from the BUCK regulator, mainly on the loss of duty cycle d_{eff} which related to the leakage inductance of the primary side of transformer L_r, load, input voltage V_{in}, and the switching cycle T.

Fig.5 shows the small signal model of phase-shifted full bridge DC/DC converter, and the relationship between the variables are showing as (3).

$$\begin{cases} D_{eff} = D - D_{loss} \\ D = 2\left(t_6 - t_2\right)/T \\ D_{loss} = 2\left(t_5 - t_2\right)/T = 2nL_r\left(2I_{L_o} - V_o\left(1-D\right)T/2L_o\right)/V_{in}T \end{cases} \tag{3}$$

The t_2, t_5, t_6 represent several marks points in the waveform of phase-shifted full bridge DC/DC converter showing in Fig.6, In this circumstance, $\hat{v}_i$ can be set to 0, thus the transfer function of input voltage can be derived as (4) , and in which R represents the load.

$$\begin{cases} G_{vd}(s) = nV_i/\left(s^2L_oC_o + s\left(L_o/R + R_pC_o\right) + \left(R_p/R + 1\right)\right) \\ G_{id}(s) = G_{vd}(s)/Z_\infty \\ G_{pwm}(s) = sL_oG_{id}(s) \end{cases} \tag{4}$$

Where the parameter R_p, Z_∞ can be calculated by the relations as $R_p = 4n^2L_rf$ and $Z_\infty = 1/(1/R + sC_o)$.

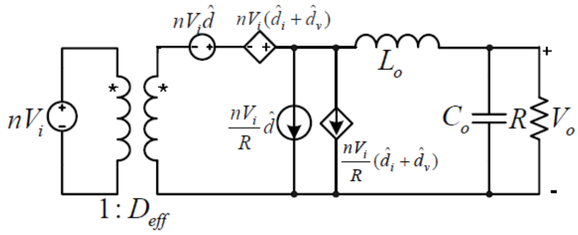


Fig. 5. The small signal equivalent circuit of phase-shifted full bridge DC/DC converter

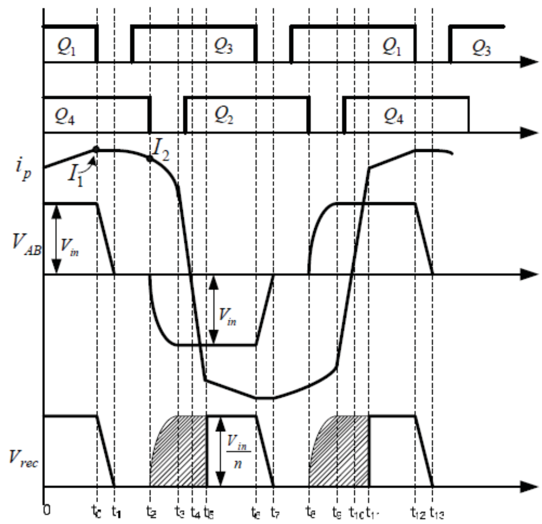


Fig. 6. The waveform of phase-shifted full bridge DC/DC converter

B. Current Regulator Design

From the (1), the close loop transfer function of the inner current loop can be drawn out easily. To the certain EV charging system, as the parameter of the components are fixed, then the inner current loop can be treated as a simple PI controller. The small signal model can be used to get the gain of the converter, and the traditional tools as bode plot can be used to analyze its response performance.

For an ideal system, its frequency response should contain those features: enough phase margin, high gain and wide bandwidth. Considering the load could be constantly changing and it could be the worst circumstances as with empty load $R = \infty$, thus when setting up the inner current regulators' the $G_{id}(s)$ can be written as $G^*_{id}(s) = snVC_0/(s^2L_0C_0 + sR_pC_0 + 1)$. $G_{CR}(s)$ could be converted to $G_{CR}(s) = K_{ip}(1 + 1/\tau s)$ in which τ represents the integral time constant. The value of K_{ip} has little effect on the phase-frequency characteristic of the system, but significant effect on the amplitude-frequency characteristic. On the contrary, τ has great influence on phase frequency characteristic. Therefore, while designing the regulator, the values of τ can be fixed first, such as $G_{CR}(s) = K_{ip}(1 + 1/\sqrt{L_0C_0}s)$. Then the value of K_{ip} could be adjusted to an appropriate value to obtain proper shearing frequency and low frequency gain. Once the K_{ip} has been set properly, the τ can be adjusted to obtain an appropriate phase margin.

C. Voltage Regulator Design

To the outer voltage close loop, it can be treated as a regular double close loop, the parameter of the PI controller can be drawn out by taking into account the inner current loop in terms of a sample delay.

Owing to the voltage regulator contains an integral term, which leads to insert a time delay process between the shifts from CC process to CV process. Considering the persistent CC charging will engender an excess voltage that may out of battery's endurance which leads a bad cause of the system robustness. Therefore, a voltage regulator with a limiter, which in this case it represented as a minimum comparator between the current regulator and voltage regulator.

And the method of setting the voltage regulator parameters can be analogous to the parameters setting in current regulator.

D. Robustness Analysis

To obtain a robust system, several conditions should be considered when designing regulator:

1) The frequency response of curve begin to decline rapidly around $f_{sw}/10$.

2) The decline point of the frequency response curve of voltage is ahead of the one of current's.

When backtracking the procedure, those main problem that lead a bad cause of system robustness can be found: The interior features would vary with different capacity of battery, thus when designing regulators, amplitude-frequency response should be tested in the worst circumstances as with empty load.

Comparing to the control strategies introduced in[2][7], facing to the noise in the grid, the shift progress in[2][7]would operate in advance or delay, which will lead to an impact on the charging progress. However, due to the proposed control method's improved structure, the current regulator is continuing impact while shifting from CC to CV, which help prevent the charging progress from over current, and the interaction between those regulators can provide a protection from pulse in grid.

IV. Simulation and Experimental Result

A. System Index

An experimental platform of 10kW AC/DC converter has been established to verify the intelligent charging controlling method. The topology of the experimental platform is similar to the Fig. 2. While 2 Lithium battery is used as the load of the converter, which is represented as the EV. The parameters of the experimental platform is provided in Table I and Table II.

TABLE I. PARAMETERS OF THE EXPERIMENTAL PLATFORM

Parameters	Value	Parameters	Value
L_o	2mH	L_{lk}	30uH
C_o	3000uF	C_b	10uF
C_i	2500uF	f_{sw}	20kHz
v_{bat}	320V	Battery volume	20Ah

TABLE II. PARAMETERS OF THE EXPERIMENTAL BATTERY

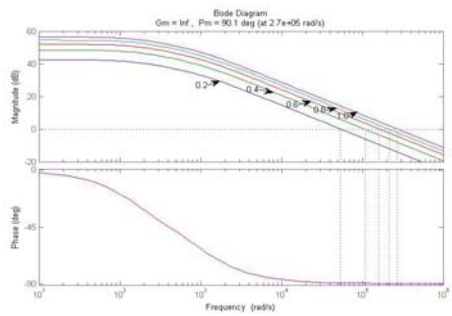
Parameters	Value	Parameters	Value
Nominal Voltage	320V	Nominal Capacity	20Ah
Voltage Range	275V~355V	Charging Current	10A

B. Simulation of Control System

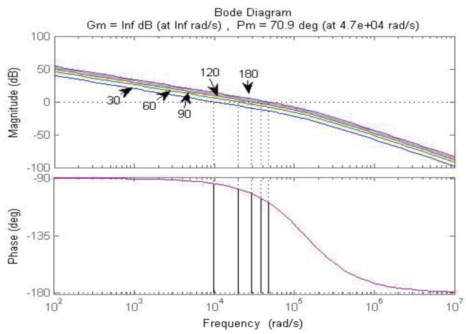
According to the parameters of system index, the regulators has been set up by the method mentioned in section III. Fig.7 illustrating several representative amplitude-frequency (A-F) response diagram while designing inner current close loop while applying the regulator design scheme. For ease of reference, the results of parameters of regulators are written in the figure.

Paper [8] presents a battery dynamic model for EV Applications, which help set up a complete model for parameter setting, simulation and robust analysis. Fig.8 expands the block diagram of the intelligent double close loop controller with application of the small signal model and the battery dynamic model proposed in [8]. With the parameters showing in the Table I and Table II, a simulation of control system has been set up in SIMULINK/Matlab. The frequency response of curve begins to decline rapidly around $f_{sw}/10$ and the decline point of the frequency response curve of voltage is ahead of the one of currents. All of those features assure the performance more robust.

To ensure the switch between CC and CV as smoothly as possible, the reference voltage should be set around the inflection point of the curve of voltage of CC charging, thus in this case, refer to the performance index of the lithium battery, the reference voltage is set to 330V.



(a) A-F response diagram of $G_{CR}(s)$ $G_{id}(s)$ with different K_{ip}



(b) A-F response diagram of $G_{CR}(s)$ $G_{id}(s)$ with different K_{vp}

Fig. 7. Representative amplitude-frequency response diagram

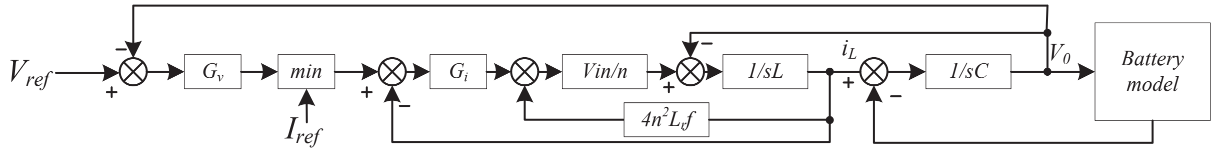
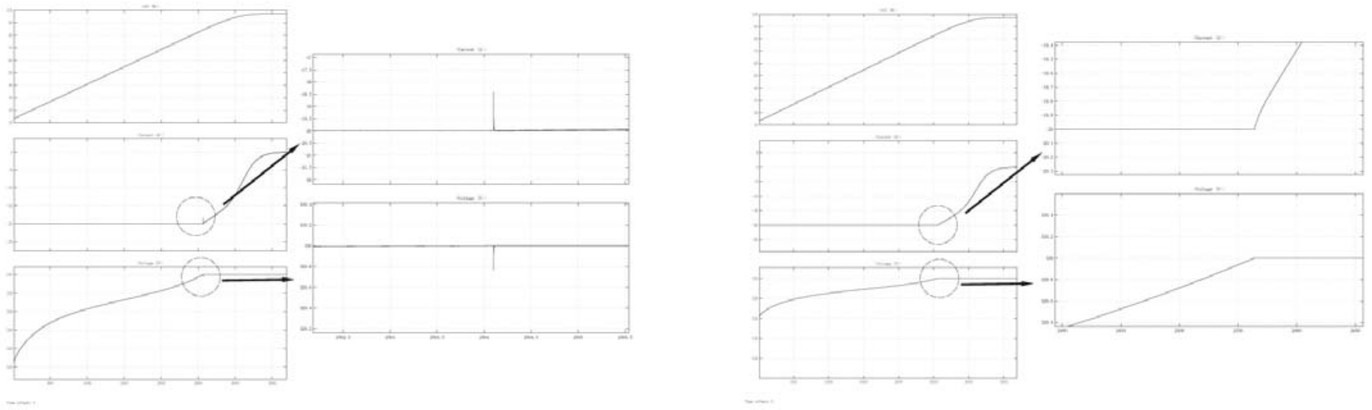


Fig. 8. The simulation of experimental control system

C. Simulation Result Analysis

Fig.9 shows the simulation result of the method proposed and the comparison with the former CC-CV control method which is depicted in the Fig.9 (a), several different can be found in those drawings of partial enlargement such as a time delay between the voltage and current reflect, a pulse in the shifting progress. The improved double close loop control method can avoid those problems which can help charger facing complex or instable environment of gird, which will help the charging system to fit the demand of the smart grid.



(a) The performance of former CC-CV charging method

(b) The performance of proposed charging method

Fig. 9. The curve of charging simulation with proposed method

D. Experiment Result

To verify the intelligent controlling method, an experiment platform has been established. A 10kW AC/DC converter circuit is running as an EV charger, in which a phase-shift full bridge DC/DC converter topology is used. And the structure of the circuit is almost same as which shown in Fig.2. A DSP TMS320F28335 is used as the main controller to perform the digital controlling, and the proposed intelligent controlling method is programmed into the DSP. The controlling parameters such as the P value and I value of the controller can be configured through communication.

Two lithium battery modules, one is 128V and another 192V, is connected serially to form a 320V, 20Ah battery module. The picture shown in Fig.10 (a) is the experiment platform which is running in charging mode. And the connected lithium battery module is shown in Fig.10 (b).

The AC/DC converter is powered by 3-phase, 380V input power system from the grid. After the regulation, the voltage of the DC bus is reach to around 540V. While the turn ratio of the high frequency transformer T is 22:24, and then the duty cycle of the phase shift full bridge will be controlled to 50%~60% to achieve the 340V output voltage.

Fig.11 shows the voltage waveform (CH1) of the primary wing of the transformer, and the output current (CH2) which flow through the output filter inductor L_o. It can be found that the duty ratio of the voltage waveform is controlled to be 59.6%, and the RMS value of the output current is controlled to be 10A. Another side, the waveform of the output current is very flat and fluctuated less, which means that the current is well controlled.

(a) The experiment platform

(b) The lithium battery module

Fig. 10. The picture of the experiment platform

Calculated by the method presented in section III, and optimized during the experiment progress, the parameter of the voltage controlling loop and current controlling loop has been drawn out and shown in Table III, while the CC value and the CV value are also presented in Table III. From the information get from the BMS system, 340V is the highest voltage when the battery is charging to 100% SOC, that's why the CV value is set to be 340V.

TABLE III. PARAMETERS OF THE EXPERIMENTAL BATTERY

Parameters	Value	Parameters	Value
CV reference	340V	CC reference	10A
P value of the current loop	0.484	I value of the current loop	0.005
P value of the voltage loop	8.2	I value of the voltage loop	0.0045

During a long time charging progress, the SOC of the lithium battery is charged from the 60%~95%. The output voltage and the current of the AC/DC converter is sampled and send to the monitor PC. And then the charging curve is drawn out from the data collected, which is shown in Fig.12.

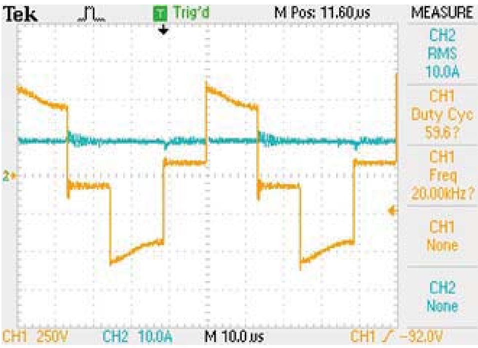


Fig. 11. The waveform of the voltage of transformer and the output current

It can be drawn out that the CC charging progress is last from the beginning to the time almost equal to 1000 second, and then the voltage of the output is closed to the voltage reference value of 340V. So the intelligent controlling method will make the progress entering the CC to CV switching stage, and the output voltage will increase while the current begin to drop down. When the time is reaching to almost 1460 second, the output voltage is reaching to the CV reference value, and the charging progress is controlled to be CV mode, and the voltage curve shown in Fig.12 is almost kept to be 340V after this time. The fluctuates which on the voltage curve cannot be avoid because of the accuracy of the voltage sensor is limited to ±1%, which makes that the sample error will covers almost ±3V.

From the charging curve shown in Fig.12, it can be easily found that the switching progress from CC to CV is very smooth, and there's no any assault or glitch happened during the switching progress. It is proved that the intelligent charging method can achieve an excellent performance.

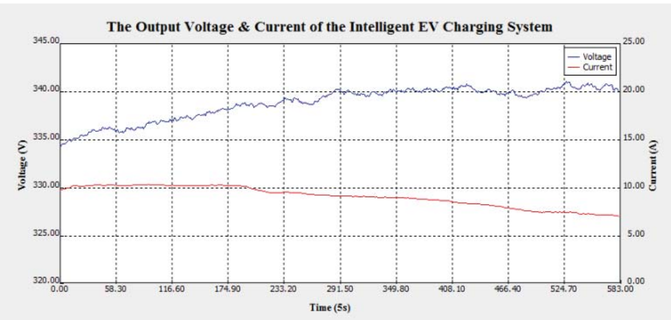


Fig. 12. The charging curve of the intelligent EV charging system

V. CONCLUSION

The presented intelligent charging control method using a minimum comparing segment to decoupled the CC and CV charging progress. The switching from the CC to CV charging progress can be performed automatically and seamlessly. As the parameters of the converter being fixed, the controller of the inner current loop and the outer voltage loop can be easily designed as the regular double close loop controller.

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