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Modeling and Simulation of Battery Charging System

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Abstract: This paper attempts to develop a simulator of charging system including valve regulated lead-acid (VRLA) battery pack and high frequency switching mode charger (HFSMC) to analyze charging process and optimize the design of charger. A new battery-charging circuit model is initially presented to describe battery transient dynamics including inductance characteristic at high frequency. Next, in order to model HFSMC, IGBT circuit model, high frequency pulsed transformer coupling model and silicon fast recovery diode model are set up. Finally comparisons between simulation and laboratory measurement of charging system are presented to verify battery model and system model. Some applications of the battery-charging simulator such as design optimization of HFSMC are given, too.

Key words: simulation; charging system; charger; battery; design optimization;

1. Introduction

To better understand battery performances is of great help to improve charging algorithm, increase charging efficiency. To know the working states of charger is helpful to optimize the design of charger. This paper studies on modeling and simulation of charging system including high frequency switching mode charger (HFSMC) and rechargeable battery and intends to develop a battery-charging simulator to understand the working states of charger and battery and the impacts of each other.

2. Battery-Charging Model

2.1 Battery-Charging Model

While HFSMC inverter switches on high frequency and charging current is DC current of high frequency ripple, experiments show that batteries exhibit inductance characteristic. By revising Thevenin model [1,2], this paper presents a new battery-charging model, shown in Fig. 1, mainly to describe AC transient dynamics of battery at high frequency.

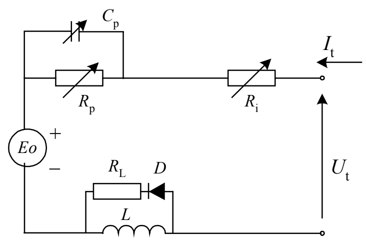

Fig. 1 battery-charging model

It should be noted in this fundamental study that:

(a) all of the elements have dependencies on environmental temperature and age/shelf life that will be neglected;

(b) state of charge SOC=Q/Ca, where $Q=\int I_t dt$, Ca is the available charge/discharge capacity which is a function of rate of charge/discharge.

The elements of Fig. 1 are explained below.

U_t & I_t: battery pack terminal voltage and current.

R_i: electrolyte resistance is primarily a function of SOC.

R_p: overvoltage resistance, is a function of charging current and SOC.

C_p: overvoltage capacitance, results in currents temporarily by-passing the charge transfer stage. It has less impact on the phase changes of U_t & I_t.

E_o: open circuit voltage, or "rest" potential, is a function of SOC.

L: battery inductance, is added to the battery model in series to describe battery inductance characteristic at high frequency. It is constant and determined by the internal structure of battery.

D: diode

R_L: parasitical resistance of L. Current of R_L is almost 0A during charging and R_L can be neglected in this study.

2.2 Determination of Battery Model Elements

Charging current of high frequency ripple and battery terminal voltage can be expressed with the approximation of the following forms (1) and (2):

$$I_t = I_0 + A\sin(\omega t) = I_0 + i_t \quad (1)$$

I_0 is average charging current

A is charging current ripple

ω=2πf, f is inverter switching frequency

t is the time

i_t is AC component of charging current.

$$U_t = U_0 + B\sin(\omega t + \varphi) = U_0 + u_t \quad (2)$$

B is terminal voltage ripple

φ is the phase difference of voltage and current.

u_t is AC component of terminal voltage.

R_{ch} is defined as R_p+R_i, named charging internal resistance. Then, approximately,

$$R_{ch} = (U_0 - E_o)/I_0 \quad (3)$$

$$E_o = SOC(U_{soc1} - U_{soc0}) + U_{soc0} \quad (4)$$

(5) describes E_o as a linear function of SOC, which is often acceptable for lead-acid battery. When U_{soc1} =51.6V, SOC≈100%. When U_{soc0}=46.8V, SOC≈0%.

As to AC component of U_t and I_t, we can obtain the following formulas approximately.

$$u_t = L\,{di_t}/{dt} + i_{R_p}R_p + i_t R_i \quad (5)$$

$$1/C_p \int i_{C_p}\,dt = i_{R_p}R_p \quad (6)$$

$$i_t = i_{C_p} + i_{R_p} \quad (7)$$

From formulas (1), (2), (5), (6) and (7), the following formulas can be derived approximately.

$$L = \omega B / A \quad (8)$$

$$\tan(\varphi) = \frac{\omega(L - C_p R_p^2 + C_p^2 R_p^2 \omega^2 L)}{R_p + R_i + R_p^2 R_i C_p^2 \omega^2} \quad (9)$$

U_0 can be obtained by constant current charging experiments of a battery and R_{ch} can be obtained by formula (3). L can be obtained by formula (8). R_i is less than R_p and assumed typical constant 0.12 Ω (5 mΩ/cell). Although C_p can be derived from (9), it makes little sense to solve this equation and C_p can be set an experiential value 1uF since the C_p value variation has less impact on the phase changes of U_t & I_t.

3. Modeling HFSMC

Diagram of the charging system is shown in Fig. 2. HFSMC includes some main components such as IGBT, high frequency pulsed transformer and fast recovery diode. In system simulation, it is important to model them correctly.

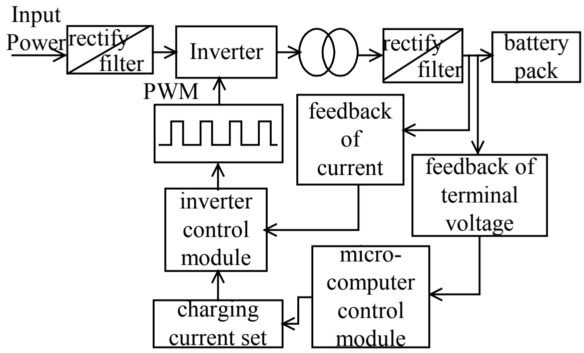

Fig. 2 block diagram of charging system

3.1 IGBT Circuit Model

It is necessary to set up an IGBT model suitable for charging system despite many IGBT models existed in the simulation software PSPICE. IGBT mixed coupling model is shown in Fig. 3. Simulation results and manual data are compared and IGBT model is verified. The details are omitted in this paper.

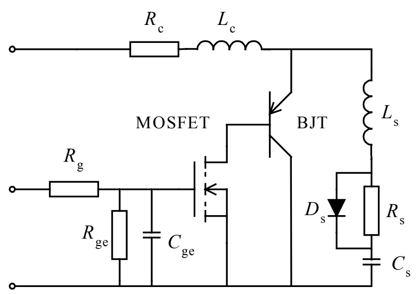

Fig. 3. IGBT mixed coupling model

R_c: IGBT collector down-lead resistance

L_c: IGBT collector down-lead inductance

R_g: IGBT gate resistance

R_{ge}: IGBT gate-emitter resistance

C_{ge}: IGBT gate-emitter capacitance

L_s: snubber circuit down-lead inductance

R_s: snubber circuit resistance

C_s: snubber circuit capacitance

D_s: silicon fast recovery diode.

3.2 Transformer Coupling Model

High frequency pulsed transformer coupling model is set up according to Jiles-Atherton model [3] provided by PSPICE. Transformer coupling model parameters are shown in Table 1.

Table 1 transformer model parameters

Description	Parameter	value
Mean magnetic cross-section area	Area(cm^2)	2.80
Mean magnetic path length	Path(cm)	25.1
Effective air-gap length	Gap(cm)	0
Magnetization saturation	Ms(A/m)	954.6k
Thermal energy parameter	A(A/m)	6.75
Domain flexing parameter	C	10.01E-3
Domain anisotropy parameter	K	1.625
Pack (stacking) factor	Pack	1
Model index	LEVEL	2

3.3 Silicon Fast Recovery Diode Model

Equivalent circuit model of silicon fast recovery diode provided by PSPICE is shown in Fig. 4.

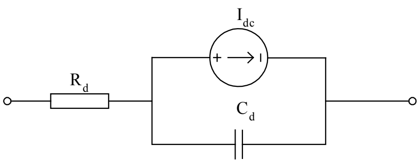

Fig. 4. silicon fast recovery diode circuit model

4. Simulation of Charging Transient Process

Power transforming main circuit of charger is shown in Fig. 5. Although single-end positive-exited inverter is simple, it is reliable and easy to realize. Therefore it is still applied in charging experiment. What's more, the method of modeling and simulation of charging system presented in this paper is practicable to other types of inverters.

The results obtained by simulation will be compared with measurement results to verify the battery-charging model and system model. Take about 50% SOC as an example. Battery terminal voltage and charging current waveforms at about 50% SOC during charging VRLA battery pack (48V/65Ah) are shown in Fig. 6. The curves of simulation by PSPICE are shown in Fig. 7. When SOC at that time is 47.68%, E_o=49.09V, R_{ch}=0.4066Ω, R_i=0.12Ω, R_p=0.2866Ω, C_p=1uF, L=0.0096mH.

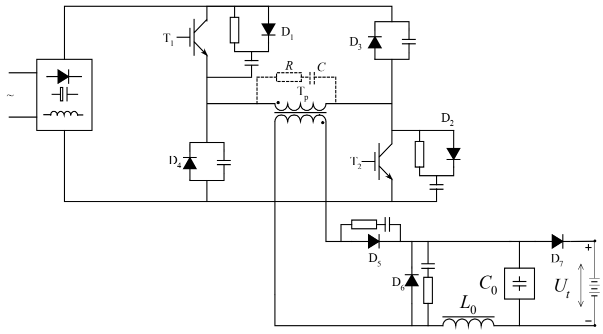

Fig. 5 diagram of IGBT double single-end positive-exited power transforming main circuit of charger

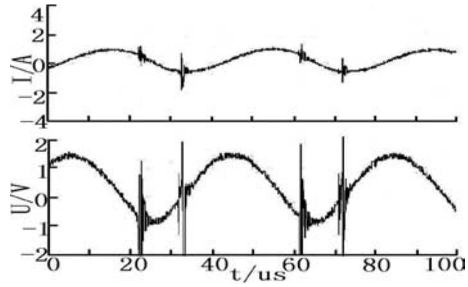

Fig. 6 laboratory measurements of AC component of charging current and battery terminal voltage at SOC=47.68%

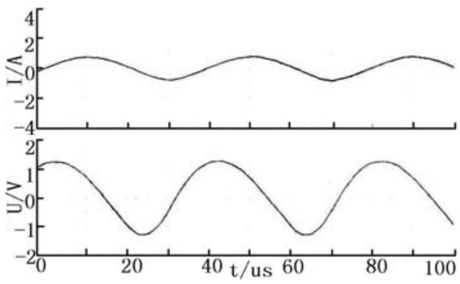

Fig. 7 AC component of battery terminal voltage and charging current obtained by simulation

5. Application Examples of Battery-Charging Simulator

To develop such a simulator is beneficial. We can understand battery charging performances, especially transient dynamics of battery by computer instead of real charging experiment. We can know how HFSMC works and optimize its design. We can also know the working states of a particular component of HFSMC. Two application examples of the simulator are given below.

5.1 Magnetic Core Working State Simulation

Traditional design commonly insists that main transformer of single-end positive-exited inverter only works in the area from remnant magnetic induction density

Br to saturation magnetic induction density Bs in quadrant Ⅰ of B-H coordinate. Therefore magnetic core is not made full use of.

Two simulation studies are carried out for comparison, the first case (a): no RC network added and air *Gap*=0cm; and the second (b): RC network added (*R*=30Ω, *C*=3000PF, shown in Fig. 5) and air gap adjusted (*Gap*=0.16cm). Magnetic core works from -3721.54 GS to 4314.39 GS in (a) and that magnetic core works from -4274.81 GS to 3809.50 GS in (b). Although they all work in quadrant Ⅰ and Ⅲ of B-H coordinate, the main working points of (b) approach to quadrant Ⅲ more.

Experimental formula of transformer design is shown:

$$N_1 = \frac{U_1 \times 10^2}{\Delta B.AREA.f} \quad (10)$$

where

N_1: first winding turns of transformer,

$\triangle B$: working magnetic induction density,

AREA: Mean magnetic cross-section area,

f: switching frequency,

U_1: first winding voltage.

According to formula (10), we can optimize designs of *AREA*, N_1 and *f* theoretically by increasing △B.

5.2 Optimum Selection Of Component Values

Simulation results of battery terminal voltage and charging current based on battery model (shown in Fig. 1) under different combination of filter inductance L_0 and filter capacity C_0 values are shown in Table 2.

Table 2 simulation results of battery voltage and charging current under different L_0 and C_0 values

L_0 (mH)	2	0.685	0.685
C_0 (uF)	8	8	18
*I*max(A)	10.526	10.877	10.403
*I*min(V)	10.008	9.357	9.901
*V*max(V)	55.698	56.384	55.585
*V*min(V)	54.820	53.807	54.735
current ripple (%)	5.05	15.02	4.94
voltage ripple(%)	1.59	4.68	1.54

The results of Table 2 show that previous design that L_0=0.685mH and C_0=8uF does not satisfy the requirements since ripple factor of battery terminal voltage is 4.68% greater than the desired 1.5%. In order to achieve desired voltage ripple or current ripple, a optimum selection of L_0, C_0 values may be gained by simulation analysis.

6. Conclusion

In this paper, a new battery-charging model is presented. And modeling and simulation of battery charging system are carried out. Simulation results verify battery model and system model. Two application examples are given, too.

Our effort of developing the battery-charging simulator has proven to be successful, Charging performances, especially transient dynamics of battery, working states of HFSMC and the impacts of each other can be observed by the simulator. The simulator will provide a convenient tool for further research on battery charging and design consideration of charger.

Acknowledgments

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