Indian Journal of Engineering & Materials Sciences
Vol. 22, June 2015, pp. 256-260

Development of rapid large batteries charging system with on-line LCD monitoring

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Received 24 September 2014; accepted 11 March 2015

With increasing demand of electric driving power applications, the design of large batteries charger integrated with a well appropriate power supply is essential. However, normally commercial products are not suitable for such a requirement due to large size, complex system, high cost, etc. Therefore, this study proposes a rapid large batteries charging system based on optimal multi-stage mechanism and integrated with a simple high switching power supply and real-time charging curves tracking. It can provide a large constant charging current before reaching an overcharge point. The charging status can be displayed on LCD dynamically. The high-frequency switching converter using the PWM controlling scheme for the charger can provide a stable DC 60 V up to 15 A. The experimental results confirm that the proposed charging system is superior in term of simple structure, high efficiency, and robustness.

Keywords: Power supply, Battery charger, High-frequency transformer

Traditionally, battery charging strategies can be classified into: (1) constant voltage (CV), (2) constant current (CC), (3) constant voltage-constant current (CV-CC), (4) pulse and (5) positive and negative pulse[1]. The CV mode is well-known as the simplest way to charge the battery using a constant voltage[2]. Its charging current is dependent on the charged voltage although it normally does not cause the battery temperature rising considerably. Also, it needs a long charging time, and it may be at a risk of overrated current at the initial charging stage. The CC mode has a benefit in the rated charging current set so that the charging time can be shorter[3]. However, it may suffer from over-charge and result in battery overheated problem. The CV-CC mode combines the superiority of both CV and CC charging methods[4]. Accordingly, the charging time can be reduced dramatically at the initial process. However, more complex circuit design is required to achieve a satisfactory performance. For pulse charge method, each charging cycle includes “charge” and “rest” stage[5]. Therefore, the battery voltage can get more stable to prolong its working life. Positive and negative pulse charge applies a short discharge pulse during the charging cycle, sometimes referred as "reflex charging" or "burp charging"[6].

The charger needs to be provided a stable and suitable DC power supply. Some representative power supply designs are reviewed briefly. A 1000 W soft-switching single-phase DC power supply system was proposed by Wang *et al.*[7] However, the efficiency of the proposed system is lower than that of the conventional hard-switched DC power supply system when output in lighter than 200 W. Another method is that a soft-switching full-bridge topology was proposed to perform the DC-DC conversion[8]. Although the interleaved boost converter is quite efficient as a pre-regulator stage, the efficiency is significantly low in a lower output power. In Ref.[9], a combination of two design techniques revealed that the time-domain peaks as well as the spectral power of the supply current can be reduced. However, this paper was only focused on noise reduction. A topology of full-bridge DC-DC converter was proposed by featuring zero-voltage-switching (ZVS) of active switches by *Borage* et al.[10] Though the ZVS operation over the entire conversion range is achieved, the performance of the proposed converter is only verified with experimental results on a 500-W prototype.

Fundamental Concept of Multi-Stage Charge Mechanism

The four-state charge mechanism can be used to describe an optimal battery charge performance as shown in Fig. 1. The charge states start from trickle charge, bulk charge, over charge, and float charge, respectively.

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State 1 - A pre-charge current (I_T) is loaded to a completely discharged battery until the predefined V_T is reached. Usually, State 2 - This state allows a maximum bulk current.

I_{MAX} to charge the battery, and the voltage will continue to rise toward V_{12} rapidly. State 3 – After passing through V_{12} point, it enters the over-voltage state applied by a constant V_{OC}. The initial current value equals the bulk charge current. When the battery approaches about its full capacity, the charging current will taper off until I_{OCT} point is reached. State 4 – This state is to maintain a maximum battery capacity level V_F. If the battery is loaded and its voltage falls below V_{31}, the charger will go back to State 2 and reapply I_{MAX} to charge.

Design of rapid large batteries charging system

The proposed rapid large batteries charging system shown in Fig. 2 consists of four parts: (i) High switching DC power supply: AC voltage 110 V, 60 Hz is as an input, and the output is DC voltage 60 V, and maximum output current is $i_{L(max)}$=15 A;

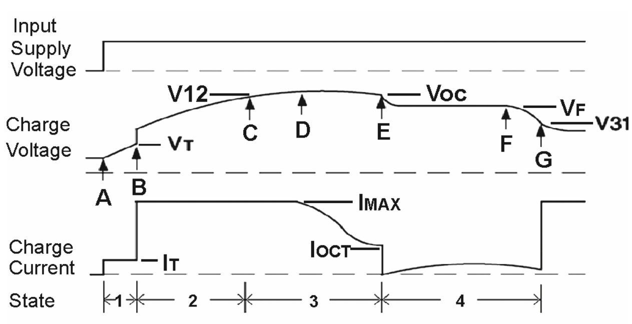


Fig. 1 – Depict of multi-stage charge mechanism

(ii) Quick large batteries charger: It can provide a buck constant charging current up to 11 A before reaching an overcharge point. Once the battery is fully charged 80%, the current will soon switch to a small holding current below 1 A; (iii) Batteries equilibrium circuit: It drives every battery to be about the same voltage level via a discharging circuit before the charging process commences; and (iv) On-line LCD display: The real-time charging status is displayed on LCD for easy tracking.

High-frequency switching converter

In Fig. 3, the proposed high-frequency switching DC/DC converter is based on the full-bridge method. Using four switches ($Q_1 \sim Q_4$), the V_i, i.e., 156 V, can be stepped down to the desired voltage (V_o = 60 V).

(i) Switches Q_1, Q_4 closed

Closing Q_1, Q_4 establishes the voltage across the primary winding at

$$V_p = V_i \qquad \dots (1)$$

where V_p denotes the voltage transferred from V_i (rectified voltage).

The V_p then results in the voltage from the secondary winding at

$$V_x = V_p\left(\frac{N_s}{N_p}\right) \qquad \dots (2)$$

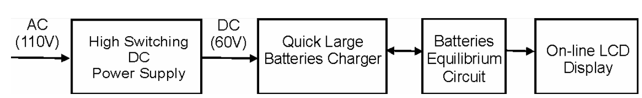


Fig. 2 – Block of rapid large batteries charging system

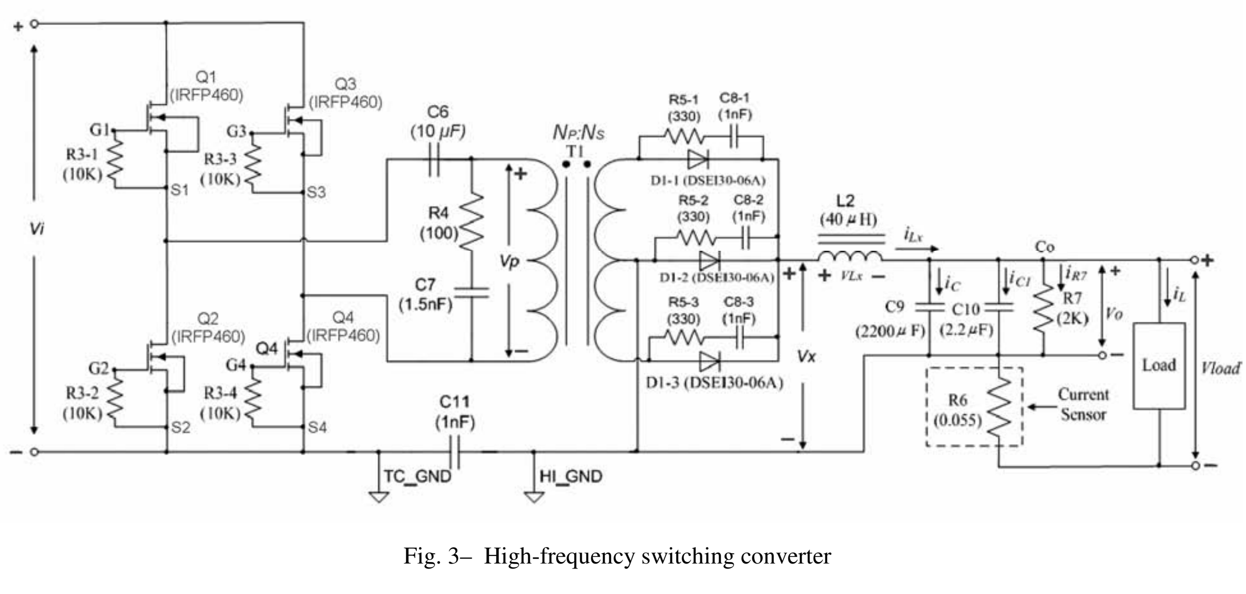


Fig. 3– High-frequency switching converter

where the diode $D_{1\text{-}1}$ is forward biased, and both $D_{1\text{-}2}$ and $D_{1\text{-}3}$ are reverse biased.

$$V_{Lx} = V_x - V_o = V_p(\frac{N_s}{N_p}) - V_o \qquad \dots (3)$$

$$\frac{\Delta i_{Lx}}{\Delta t} = \frac{\Delta i_{Lx}}{DT} = \frac{V_{Lx}}{L_2} = \frac{V_p(\frac{N_s}{N_p}) - V_o}{L_2}$$

$$(\Delta i_{Lx})_{\text{closed}} = \frac{V_p(\frac{N_s}{N_p}) - V_o}{L_2} \cdot DT \qquad \dots (4)$$

(ii) Switches Q_2, Q_3 closed

Closing Q_1, Q_4 obtains the same results as switches Q_1, Q_4 closed, i.e., Eqs (1)-(4).

(iii) Switches Q_1, Q_2, Q_3, Q_4 open

When either switches (Q_1, Q_4) or (Q_2, Q_3) are open, the current flowing in the primary winding is zero. The current in the filter inductor L_2 must maintain continuity so that both $D_{1\text{-}1}$ and $D_{1\text{-}3}$ will become forward biased, and the inductor current (i_{Lx}) divides evenly between the transformer secondary windings. The voltage across each secondary winding is zero, and

$$V_x = 0 \qquad \dots (5)$$

$$V_{Lx} = V_x - V_o = -V_o \qquad \dots (6)$$

$$\frac{\Delta i_{Lx}}{\Delta t} = \frac{\Delta i_{Lx}}{\frac{T}{2} - DT} = -\frac{V_o}{L_2} \qquad \dots (7)$$

Solving for Δi_{Lx},

$$(\Delta i_{Lx})_{open} = -(\frac{V_o}{L_2})(\frac{1}{2} - D)T \qquad \dots (8)$$

Since the net change in the inductor current over one period must be zero for steady-state operation,

$$(\Delta i_{Lx})_{\text{closed}} + (\Delta i_{Lx})_{open} = 0 \qquad \dots (9)$$

Accordingly,

$$\frac{V_p(\frac{N_s}{N_p}) - V_o}{L_2} \cdot DT + (-\frac{V_o}{L_2})(\frac{1}{2} - D)T = 0 \qquad \dots (10)$$

Solving for V_o,

$$V_o = 2V_i(\frac{N_s}{N_p})D \qquad \dots (11)$$

Quick large batteries charger

The proposed quick large batteries charger shown in Fig. 4 is designed to achieve an optimal charging performance based on multi-state principle[1]. It can provide a large constant charging current up to 11 A when the dominant path controlled by Q_1 and Q_2 are turned on. Once the four series-connected lead-acid batteries (110 AH) arrives at the over-charge point, the charging current will be soon down to the holding current (below 1 A) passing through only R_E, R_{SH}, and diode (D), where both Q_1 and Q_2 are turned off at this stage.

The allowable maximum current (I_{MAX}) is decided by the Darlington circuit (Q_1, Q_2). R_{SM} is determined as

$$R_{SM} = \frac{0.25}{I_{MAX}} \qquad \dots (12)$$

where 0.25 V is generated by UC3906.

R_{DD} can be calculated as

$$R_{DD} = \frac{V_{IN} - 0.7}{I_{MAX}} \cdot \beta_1 \cdot \beta_2 \qquad \dots (13)$$

where $V_{IN} \approx 15V$, and β_1 and β_2 are the current gain of Q_1 and Q_2, respectively.

Once the holding current I_H is chosen, then R_{SH} can be obtained as

$$R_{SH} = \frac{0.025}{I_H} \qquad \dots (14)$$

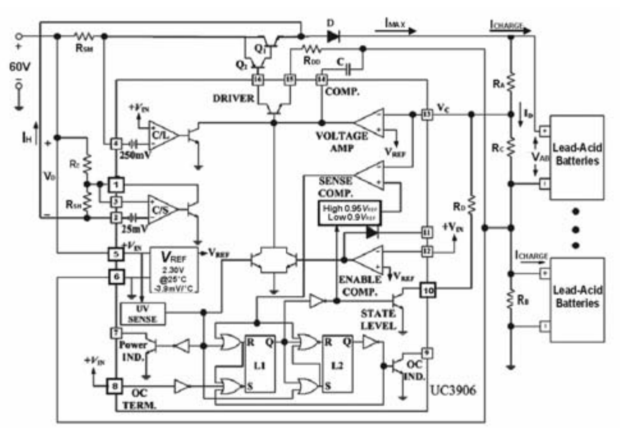


Fig. 4 – Depict of quick battery charger

where 25 mV is generated by UC3906.

The voltage drop (V_D) between the input supply (V_{IN}) and series batteries voltage is about 3 V. Therefore, R_E can be calculated as

$$R_E = \frac{V_D - 0.025}{I_H} \quad \ldots (15)$$

where $V_D \approx 3V$.

Based on the voltage divider rule, the following equation can be formed as

$$0.95V_{REF} = \frac{R_C // R_D}{R_A + R_C // R_D} \cdot V_{OC} \quad \ldots (16)$$

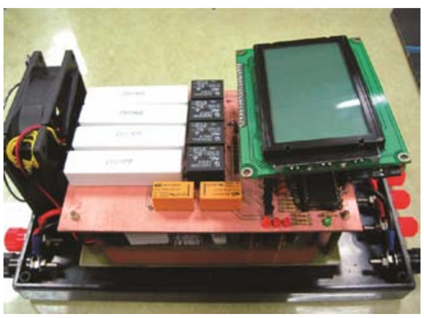


Fig. 5 – Profile of the proposed system

where $V_{REF} = 2.3V$ is generated by UC3906, and R_D is connected to ground.

$$V_{OC} = 0.95V_{REF}\left(1 + \frac{R_A}{R_C} + \frac{R_A}{R_D}\right) \quad \ldots (17)$$

$$V_F = V_{REF}\left(1 + \frac{R_A}{R_C}\right) \quad \ldots (18)$$

$$R_D = \frac{0.95V_{REF}R_A R_C}{V_{OC}R_C - 0.95V_{REF}R_A - 0.95V_{REF}R_C} \quad \ldots (19)$$

Experimental Results

The parameters values of high switching DC power supply are set as f=55 kHz, L_2 = 40 μH, D=0.5, N_s/N_p=15/39. The parameters values of quick large batteries charger are chosen as R_{SM} = 0.02 Ω, R_{DD} = 10 kΩ, R_E = 5 Ω, R_A = 116.5 kΩ, R_B =23.7kΩ, R_C =140.2 kΩ, R_D = 267.2 kΩ and R_{SH} = 0.025 Ω. The physical profile of entire system is shown in Fig. 5.

From the high switching DC power supply, the PWM signals for Q5 - 1, Q6 - 1 and Q5 - 2, Q6 - 2 are shown in Fig. 6(a). Four trigger signals (V_{G1S1}, V_{G2S2}, V_{G3S3}, V_{G4S4}) to drive MOSFETs Q1,

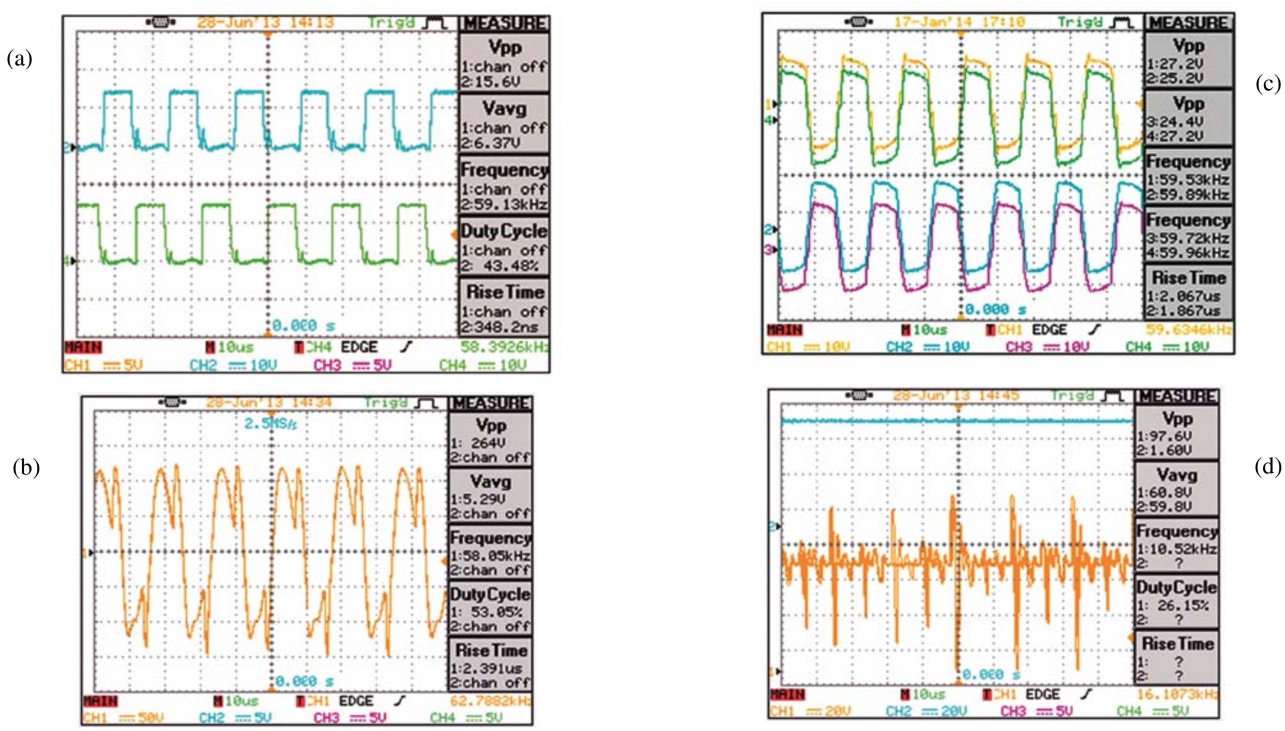
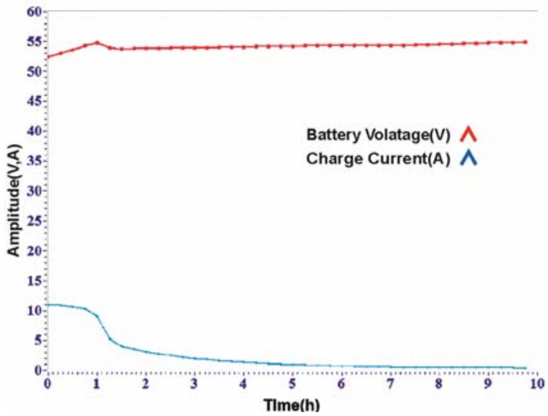
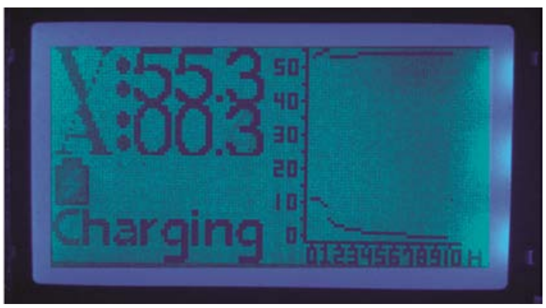


Fig. 6 – Waveforms from different locations (a) CH2: PWM signal(Q5 -1, Q6-1), CH4: PWM signal(Q5 -2, Q6 – 2); (b) CH2 - CH3: V_{G2S2}, V_{G3S3}, CH1 - CH4: V_{G1S1}, V_{G4S4}; (c) Waveforms of V_p and (d) CH1: V_x, CH2: V_o



(a)



(b)

Fig. 7 – Charging curves using (a) Lab View and (b) LCD

Q2, Q3 and Q4, respectively are shown in Fig. 6(b). In Fig. 6(c), the waveform V_p is regarded as an alternative signal, and its peak amplitude is over 100 V. The waveform V_x is shown in CH1 signal of Fig. 6(d). The output voltage (V_o) shown in CH2 signal of Fig. 6(d) is generated DC 60 V.

Four lead-acid batteries (48 V) are connected in series for charging. Each battery capacity is 110 AH, and the maximum charging current is limited as 11 A (1/10C) for better charge efficiency. From the experimental results, the outcome using LabVIEW shown in Fig. 7(a) reveals that the charging current keeps a near constant value (11 A) for about one hour until the over-charged point (55 V). Since then, the current is going down quickly toward a holding value (below 1 A). In Fig. 7(b), the charging curves from LCD confirm that its charging curves are synchronous and same as Fig. 7(a).

Conclusions

This paper has successfully designed the rapid large batteries charging system that is supported by a simple high switching power supply and quick large batteries charger. The PWM duty cycle of high switching power supply is selected as 0.5, resulting in no frustration appearing in the output voltage. The switching frequency is up to 59 kHz, and therefore the transformer size can be reduced considerably. Also, the proposed charger can provide a bulk constant current (11 A) to charge the battery so that the charging time can be reduced dramatically. The on-line LCD monitoring function provides user more friendly interface.

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