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Design of Robust & Efficient SMPS for Charging of Lithium Ion Battery used in Electric Vehicle

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ABSTRACT: The popularity of electric vehicles (EVs) is increasing rapidly in India & so is the demand for reliable, efficient battery chargers. The conceptual development of an SMPS based battery charger for charging of Lithium- Ion batteries used in Electric vehicles is explained here. The various protections provided in the circuit are also mentioned.

In order to charge the batteries efficiently, and to ensure their long life, we need a correct battery charging system. This charging system can support both Lithium Ion and Lead acid battery.

Several topologies such as LLC resonant converter, fly back and forward converter are possible. A Forward converter topology is adopted. It has several features like Input surge protection through MOV, current inrush protection through fuse and NTC. It works for a wide band of input voltage by use of Window comparator, soft start using TOTEM pole comparator & uses a current controlled PWM. It uses a single switch (MOSFET) and has relay drive logic at the output with protection from reverse charging of batteries. It regulates the output voltage through feedback. Simulation and experimental results reveal that the proposed SMPS based charger offers better Power quality and reliability. A prototype has been built to validate the feasibility and benefits of the system.

KEYWORDS: EV, Electric vehicle, SMPS, Lithium Ion battery, MOSFET, MOV, Current controlled PWM, Forward topology, Soft start, Reverse battery charging protection

I. INTRODUCTION

SMPS based battery charger plays important role in charging of Lithium Ion battery used in electric vehicles.

A. EV Charger:

An EV charger, also called Electric Vehicle Supply Equipment (EVSE) is an element in EV infrastructure that supplies electric energy for recharging the electric vehicles.

B. Charger Type:

B.1 Private Charger

The home private chargers are generally used with 230V/15A single phase plug which can deliver a maximum of up to about 2.5KW of power. Thus, the vehicles can be charged only up to this rate.

B.2 Public charger:

For charging outside the home premises: the electric power needs to be billed and payment needs to be collected. Further, the charges may depend on state of grid (whether it is power-surplus or is in power-deficit state).

B.3 AC Chargers:

Batteries are DC and needs DC power for charging it. If the public chargers (also known as off board chargers) are DC chargers, the batteries / vehicles could be charged directly. For public outlets feeding AC supply to the EV, the chargers are on-board and these on-board chargers are supplied by vehicle manufacturer.

The electric 2-wheeler, 3-wheeler and 4-Wheeler vehicles in India do not have an on-board charger beyond 2.5kW or 3kW. This is to save or minimize costs in vehicle. For such chargers, the charging point needs to be only 230V single phase. These AC 2.5KW or 3KW Chargers could fast charge a 2-wheeler and are mostly SMPS.

II. LITERATURE REVIEW

Switched mode power supply (SMPS):

The SMPS is selected for i) higher efficiency, ii) regulated output voltage through feedback circuitry that adjusts the duty cycle, iii) size is compact, iv) lower manufacturing cost and less heat. But its circuit is complex and it produces electromagnetic interference. Nevertheless, it is quite suitable for Battery charging application.

SMPS topologies:

SMPS is the Switched Mode Power Supply circuit which is designed for obtaining the regulated DC output voltage from an unregulated DC or AC voltage. There are four main types of SMPS such as

- DC to DC Converter
- AC to DC Converter
- Fly back Converter
- Forward Converter

The AC to DC conversion part in the input section makes the difference between AC to DC converter and DC to DC converter. The Fly back converter is used for Low power applications. Also there are Buck Converter and Boost converter in the SMPS types which decrease or increase the output voltage depending upon the requirements. The other type of SMPS include Self-oscillating fly-back converter, Buck-boost converter, Cuk, Sepic, etc.

Selection of Forward Topology:

In FORWARD topology, most of the energy is stored in the output inductor rather than the primary winding of the transformer; as done in FLYBACK topology. When the switch is OFF, the diode D1 is reverse biased and D2 is forward biased. The current through the inductor cannot change instantaneously and continues to flow through the output. As the current flows through the energy storage element in both the halves of the switching cycle, there is much less output ripple than FLYBACK converter.

The first step in the design is to decide on the operating frequency of the switching regulator. No concrete rules can be given for this decision.

High frequency operation is distinctly advantageous in that the cost, weight and volume of both Land C filter elements are reduced. However, above the frequency where the capacitor ESR exceeds its capacitive reactance, no further reduction in capacitor size or cost will occur. This frequency, in the range of 1-50 kHz, depends upon the "quality" of the capacitor in terms of ESR. Above this frequency, the inductor will continue to diminish in size and cost, although when the inductor reaches a very small size, cost will level off. Operation above 20 kHz is desirable to eliminate the possibility of audio noise.

The main factor limiting high frequency operation is the drop in efficiency caused by switching losses in the power switching transistor and "catch" diode. The higher cost of these fast switching semiconductors required to operate efficiently at high frequencies must be weighed against the reduced cost, size and weight of the Land C components to arrive at the optimum frequency for any specific application. It may be desirable to work the design through at several frequencies in order to make a decision. [Citation: Unitrode handbook 1987]

PWM CONTROL:

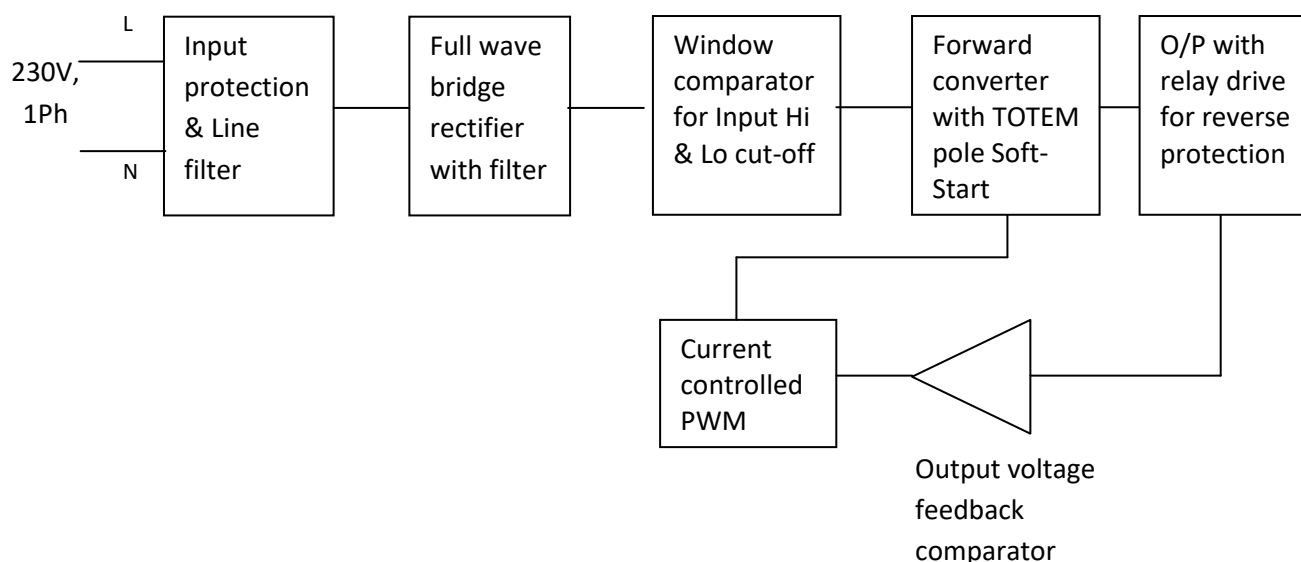
As the load increases, the output voltage tends to decrease. This decrease is sensed by the PWM control, and it increases the turn-on time so as to increase the Power delivering capability. This way it restores the output voltage. The

other method is by controlling the off time, instead of ON time. Thus the reduced OFF-time raises the drive frequency and hence the power delivering capability.

SOFT Start: Like the inrush control, the soft start action also checks the heavy inrush of the current to the supply during the initial switch-on. While the inrush limiting circuitry limits the current in to the input capacitors, soft start acts on the converters control circuitry in such a manner that the ON –time pulse width applied to the Switching transistor is very narrow during switch-ON period. The pulse width is then gradually increased to the normal value. This gradual increase in the pulse width greatly reduces the stress on the output capacitors and other components of the converter like switching transistor, fast recovery rectifiers etc. It is also desirable to delay the operation of the Power converter at its full pulse width and rated load so that it does not draw current from the input capacitors which must be allowed to fully charge after initial switch-on.

III. CIRCUIT EXPLANATION

Fig. 1: Block diagram of SMPS based charger for Li Ion battery



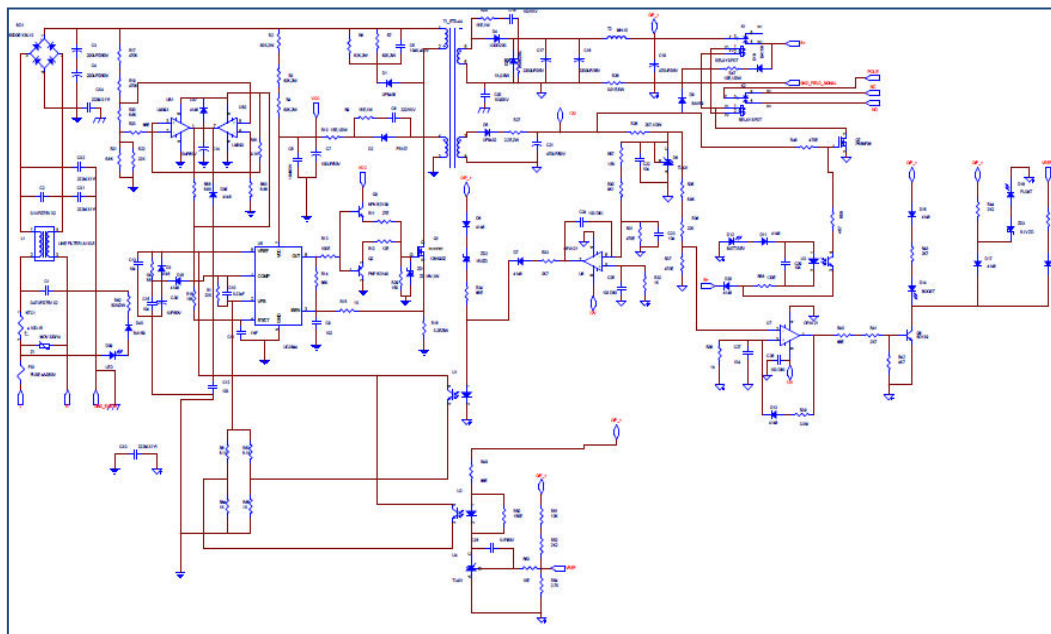


Fig. 2: Schematic of SMPS based charger

IV. DESIGN OF COMPONENTS

The above design and topology is implemented to make Battery charger for charging of Lithium Ion battery used in Electric vehicles.

Inductor volt-second balance during each switching cycle "T":

$$V_{in} \times t_{on} = (V_o - V_{in}) \times t_{off} \quad (1)$$

Note that since the average current is continuously changing according to the input voltage, strictly speaking, volt-seconds across "L" are not exactly balanced. However, because normally, the switching frequency F_{sw} is at least three orders of magnitude higher than mains frequency, we can neglect net current change over one switching cycle.

If D - duty cycle, then $t_{on} = DT$ and $t_{off} = (1-D)T$. Substituting this into (1) we find:

$$D = 1 - V_{in}/V_o \quad (2)$$

From (2) we can derive current ripple:

$$\Delta i_L = V_{in} \times t_{on} / L = V_{in}(V_o - V_{in}) / L \times F_{sw} \times V_o \quad (3),$$

where $F_{sw} = 1/T$ - switching frequency.

Where P_o - output power, η - efficiency in decimal. Therefore for CCM at certain V_{in} rms the inductance should satisfy

$$L > \frac{V_{rms}^2 \cdot \eta \cdot (V_o - \sqrt{2} \cdot V_{rms})}{2 \cdot F_{SW} \cdot P_o \cdot V_o} \quad (5)$$

the following equation:

In practice, often select "L" value such that at low line $\Delta i_L < 20 \dots 60\%$ of I_{pk} , so practically "L" is selected several times larger than the result from (5). With such selection, at higher input voltages the current ripple ratio will be higher and the converter may even become discontinuous. Let's now calculate the currents in this circuit. These numbers can be used for components selection and for thermal design. For simplicity we will assume that L is sufficiently large so we can neglect Δi_L . Since the switch (which is usually a FET) conducts only during the DT portion of the period T, its RMS current during one switching period is $I_{Qrms}(\Phi) = I_L(\Phi) \times \sqrt{D(\Phi)}$. All quantities here vary with the phase angle Φ of input voltage. Substituting (2) and (4) into the above expression yields:

$$I_{Qrms}(\Phi) = \frac{\sqrt{2} \cdot P_o \cdot |\sin \Phi|}{V_{rms} \cdot \eta} \cdot \sqrt{1 - \frac{\sqrt{2} \cdot V_{rms} \cdot |\sin \Phi|}{V_o}} \quad (6)$$

Then I_{Qrms} averaged over entire period of input AC is:

$$I_{Qrms} = \sqrt{\frac{2}{\pi} \cdot \int_0^{\frac{\pi}{2}} [I_{Qrms}(\Phi)]^2 d\Phi} \quad (7)$$

Note that although technically we should've integrated from 0 to 2π , the result would be the same- RMS value of I_{Qrms} over first quarter of input sine wave is the same as over entire AC cycle. Substituting (6) into (7) and calculating the integral (7) we get:

$$I_{Qrms} = \frac{P_o}{V_{rms} \cdot \eta} \cdot \sqrt{1 - \frac{8 \cdot \sqrt{2} \cdot V_{rms}}{3 \cdot \pi \cdot V_o}}$$

The above value determines conduction losses in the FET. The boost diode conducts during $(1-D)T$ time. Therefore during each switching cycle $I_{diode_rms}(\Phi) = I_L(\Phi) \times \sqrt{(1-D(\Phi))}$. By considering the integral of $I_{diode_rms}(\Phi)$ squared similar to (7), the RMS diode current can be calculated as follows:

$$i_{drms} = \frac{P_o}{V_{rms} \cdot \eta} \cdot \sqrt{\frac{8 \cdot \sqrt{2} \cdot V_{rms}}{3 \cdot \pi \cdot V_o}}$$

The rectifier should be selected based on the V_o and i_{drms} . It is important to note that when it turns off, its reverse recovery current causes significant switching losses and generate noise in the range 30 to 50 MHz Therefore the diode should be selected with ultra fast soft switching characteristic. The best performance for this application is achieved by silicon carbide (SiC) diodes. Output capacitor is charging when the diode conducts and is discharging to the load when "Q" is ON. Assuming the load consumes fixed DC current P_o/V_o , we can find the total capacitor current:

$$I_{crms} = \frac{P_o}{V_o} \cdot \sqrt{\frac{8 \cdot \sqrt{2} \cdot V_o}{3 \cdot \pi \cdot V_{rms}} - 1}$$

The capacitor current contains two components: twice line frequency and switching frequency:

$$I_{c_{2F_rms}} = P_o / (V_o \sqrt{2}) \quad (11)$$

$$I_{c_{sw_rms}} = \frac{P_o}{V_o} \cdot \sqrt{\frac{8 \cdot \sqrt{2} \cdot V_o}{3 \cdot \pi \cdot V_{rms}}} - 1.5$$

The capacitor should be selected to handle $I_{c_{2F_rms}}$ and $I_{c_{sw_rms}}$. Its capacitance should be enough to provide during power interruptions the required hold up time at a given load P_o .

V. RESULTS AND TESTING PHOTOS

Table: 1, Test results

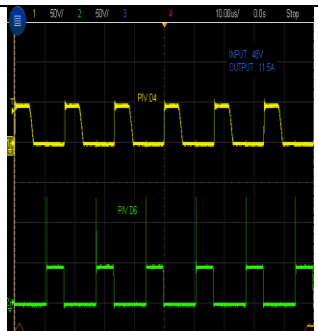
Sr.	Input parameters (AC)	Output parameters (DC)	Results
Routine test at no load & full load			
1	Voltage (High)-310V	24	Pass
2	Voltage(Low)-150V	24	Pass
3	Voltage Nominal-230V	24	Pass
4	Output full load-20A	24	Pass
Type test			
Sr.	Test	Result	
1	Output short circuit NA	Internal components are OK after the test. SMPS works OK.	
2	Output connections reversed NA	Does not charge the battery and reverse LED glows.	
3	High Voltage (Both input short circuit connected to positive probe and output terminals short circuited and connected to negative probe-apply 1.5 kV for 1 minute	Pass -Leakage current <10 mA	
4	Megger , 500V DC for 1 minute, connections same as above	>200 M Ohm, Pass	
5	Switching frequency, 75 kHz	75.kHz	
6	Switching waveform between Drain and Source		
7	Output ripple	<0.5 V, Pass	

Table 2: Functional parameters

Sr.	Description	Rating
1	Input voltage	230V ac +/-10%
2	Output nominal voltage	24 VDC
3	Power output	500 W

4	Efficiency	>90%
5	Power factor	>0.95
6	Regulation	<1%
7	Topology	Single ended forward
8	Switching frequency	75kHz
9	Cooling	Air cooled for prototype
10	Battery requirement	Li-Ion Phosphate
11	Rate of discharge	C2*

*‘C’ is the Charge storage capacity of the battery. While C10 means that a 100 AH battery can be discharged at a rate of 10A for 10 hrs. C2 has discharge duration of 2 hrs. with 31.65A discharge current.

VI. CONCLUSION

This work presented is a prototype assembled PCB (Board) suitable to rapidly charge Lithium- Ion battery used in Electric vehicles. This charger is suitable for charging two- wheeler battery.

Various features like the Input Protection, Soft start, Wide band, Output reverse connection protection, Output voltage control, Output short circuit protection makes it suitable for domestic use.

As the battery charges, the voltage increases, and if it approaches the full-charge state, the PWM controller starts the operation to disconnect. Through this operation, the stress on the battery is reduced. So the battery life is enhanced and at the same time the battery can be maintained continuously in a full-charge state. This board assures the fast, safe and complete battery charging process.

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