A Sepic Type Switched Mode Power Supply System For Battery Charging In An Electric Tricycle (Auto-Rickshaw)

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Abstract: This paper analyzes the plug-in electric tricycle (Auto rickshaw) battery charging system using a non-isolated DC-DC SEPIC converter which operates as a switched mode power supply (SMPS). The control of dc voltage output is by varying the gating pulses duty cycle of the switch in the dc-dc converter using PID controller based PWM technique. The 60 V, 30 A DC-DC SEPIC converter is designed to provide non-inverting voltage buck from the rectified AC mains for charging deep cycle battery bank in an electric auto rickshaw. The charger system is implemented using MATLAB/Simulink.

Index Terms: SMPS, AC mains, Electric tricycle (Auto rickshaw), PID Controller, PWM, SEPIC converter, MATLAB/Simulink

1 INTRODUCTION

Switched mode power supplies (SMPS) are extensively used in charging batteries [2]. Designing high performance battery chargers using DC-DC non-isolated power converters with low cost, small size, and high efficiency makes it a challenge due to the electro-magnetic interference (EMI) [3]. The design becomes more difficult for applications that demand high voltage gains with low input and output current ripple [2]. The single-ended primary inductor converter (SEPIC) is a DC-DC voltage converter that is able to boost or buck a dc input voltage. One of the merits of a SEPIC converter is its non invertion of the output voltage unlike the buck-boost converter; it also offers easy implementation of magnetic coupling [5-7]. But they usually suffer from higher switch voltage stresses and their control can be complex, due to the two pairs of un-damped complex poles in its duty cycle to output voltage gain [4-6]. Lithium-ion battery use in plug-in electric vehicle battery technologies has been high due to its high power density and good depth of discharge but its high cost has made it a reason why Electric Vehicles (Evs) are expensive and not affordable. The Lead acid battery is cheap, affordable and easily available for use especially in developing countries where cost is a major factor in making purchase decisions [8-10]. A wide voltage range of the on-board charger is mapped to a wide voltage range of Lead acid cell [9]. The charging profile of a lead acid battery is as shown in Figure 1.

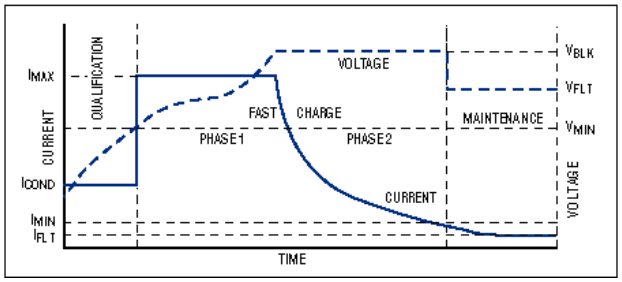

Figure 1: *Lead acid battery charging profile*

The battery charging stages of any typical lead acid value regulated lead acid (VRLA) battery include [3-6]; i. Trickle charge ii. Bulk charge iii. Absorption charge iv. Float charge. This paper implements a 60 V, 30 A SMPS system using a non-isolated SEPIC converter which is used to charge the 48 V battery bank of an electric tricycle (electric auto rickshaw) using MATLAB/Simulink software.

2. RESEARCH METHOD

One of the methods for improving low power factor is to install a SEPIC converter as a power factor corrector. The SEPIC converter is connected to a AC-DC rectifier as presented in Figure 2.

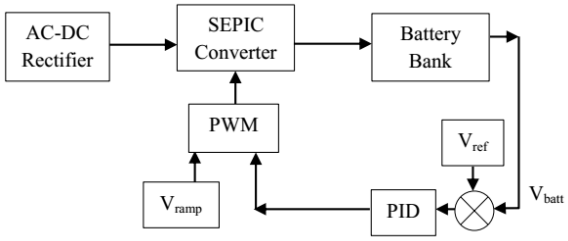

Figure 2: *Block diagram of the system*

From Figure 2, the reference voltage V_{ref} is compared with the output voltage of the SEPIC converter, the error is fed into a tuned PID controller circuit which is then compared with a ramp voltage to produce the gating pulses needed to switch the power MOSFET. A SEPIC DC-DC converter consist of two inductors (L_1 and L_2), two capacitors (C_1 and

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C_o), a diode (D_1) and switch (Q) which is typically a transistor such as MOSFET.

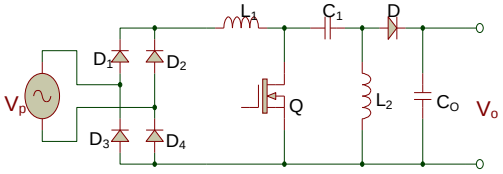

Figure 3: *The circuit diagram of the SMPS.*

The SEPIC converter in Figure 3 is in Continuous Conduction Mode (CCM) therefore, current in the inductor L_1 is always greater than zero.

3. DESIGN ANALYSIS

3.1 DC analysis

During switch ON: From Figure 3, when the switch (Q) is ON, the voltage across both inductors is equal to V_p and capacitor C_1 and inductor L_2 are connected in parallel. The Diode D_1 is reverse bias, and the load current is supplied by capacitor C_o.

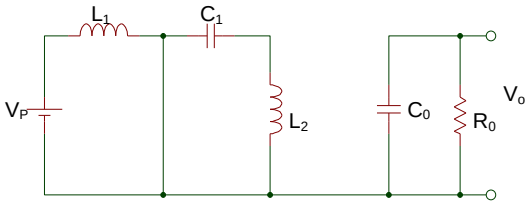

Figure 4: *Equivalent circuit of the SEPIC when Q is ON.*

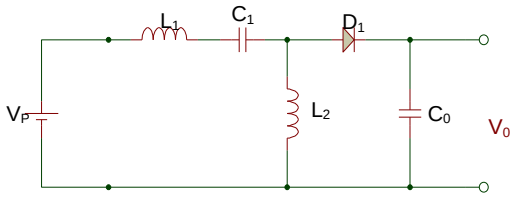

Figure 5: *Equivalent circuit of the SEPIC when Q is OFF*

When the power switch Q is OFF, capacitor C_1 is charged via the inductor L_1 and inductor L_2 supplies the output current to the load as shown in Figure 5. Summing the average currents using KCL in Figure 5.

$$I_{D1} = I_{L1} - I_{L2} \qquad (1)$$

When Q turned ON, let T = Switching Period,
f_{sw} = Switching Frequency, t_{on} = Switch ON time, t_{off} = Switch OFF time, D = Duty cycle,
Applying KVL with reference to L_1,
Since, $V_o = V_{C2}$

$$I_{L1} = \frac{V_p - V_{c1} - V_o}{L_2} \times t_{off} \qquad (2)$$

$$I_{L2} = \frac{-V_o}{L_2} \times t_{off} \qquad (3)$$

Average Voltage across L_1 & L_2 is zero, therefore,

$$V_p - V_{L1} - V_{C1} - V_{L2} = 0 \qquad (4)$$

Voltage across the coupling capacitor (C_1) is equal to V_p, as the capacitance of C_o is adequate to supply output current when the switch is ON.

$$V_p = V_{C1} \qquad (5)$$

Substituting equation (5) into equation (2) we have

$$I_{L1} = \frac{-V_o}{L_1} \times t_{off} \qquad (6)$$

Averaging the equations (2) & (3) to zero,

$$\frac{V_p}{L_1} \times t_{on} - \frac{V_o}{L_1} \times t_{off} = 0$$
$$V_p \times t_{on} = V_o \times t_{off}$$

But $t_{on} = DT, and\ t_{off} = (1-D)T$

Substituting in t_{on} and t_{off}, we shall have the expression as:

$$V_p \times DT = V_o \times (1-D)T, \qquad (7)$$

V_o/V_p is the transfer function of the SEPIC converter in continuous mode as: $\frac{V_o}{V_p} = \frac{D}{1-D}$

Duty cycle consideration: The duty cycle D in terms of voltage, of a SEPIC converter operated in CCM is given as:

$$D = \frac{V_o}{V_p + V_o} \qquad (8)$$

Duty cycle D maximum and minimum values are:

$$D_{max} = \frac{60}{50+60} = 0.55 \text{ and } D_{min} = \frac{60}{340+60} = 0.15$$

3.2 Selection of SEPIC Power Components

The components for the SEPIC converter are:

Inductor Selection:
The inductors are wound on the same core, thus the inductance is given by:

$$L_1 = L_2 \geq \frac{V_{p(min)} \times D_{max}}{2 \times \Delta I_L \times f_{sw}} \geq \frac{50 \times 0.55}{2 \times 5.24 \times 200 \times 10^3} \geq 26.24\ \mu H$$

For inductor ripple current for L_1 is:

$$\Delta I_L = \frac{I_o \times (V_o + V_{D1})}{V_{p(min)} \times \eta} \times 30\ \% = \frac{30 \times (60 + 0.5)}{50 \times 0.9} \times 30\ \% = 12.1\ A$$

Peak inductor current for L_1 is:

$$I_{L1(peak)} = \frac{I_o \times (V_o + V_{D1})}{V_{p(min)} \times \eta} \times \left\{1 + \frac{30\ \%}{2}\right\} = \frac{30 \times (60 + 0.5)}{50 \times 0.9} \times \left\{1 + \frac{30\ \%}{2}\right\} = 46.38\ A$$

Peak inductor current for L_2 is:

$$I_{L2(peak)} = I_o + \frac{\Delta I_L}{2} = 30 + \frac{12.1}{2} = 36.05\ A$$

Capacitor selection:
The input coupling capacitor of the SEPIC converter is chosen as 10 *μF*.

Output capacitor selection:
Assuming the peak-to-peak ripple is 2-5% of the output voltage, then:

$$C_o \geq \frac{I_o}{0.5 \times \Delta V_{ripple}} \times \frac{D_{max}}{f_{sw}} \geq \frac{30}{0.02 \times 60 \times 0.5} \times \frac{0.55}{200 \times 10^3} \geq 137.5 \times 10^{-6} \geq 137.5\ \mu F$$

Power Mosfet Selection
Mosfet peak current is:

$$I_{Q1(peak)} = I_{L1(peak)} + I_{L2(peak)} = 46.38 + 36.05 = 82.43\ A$$

And R.M.S current value is:

$$I_{Q1(rms)} = I_o \times \sqrt{\frac{V_o + V_D}{V_{in(min)}}} = 30 \times \sqrt{\frac{60+0.5}{50}} = 33\ A$$

The open loop transfer function of the SEPIC converter can be expressed as:

D = 0.55, $L_1 = L_2$ = 26.24 μH, C_1 = 10 μF, C_o = 220 μF, R = 1.2 Ω, V_p = 340 V

$$\frac{V_o(s)}{d(s)} = 1679.0 \times \frac{-s^3 + 6.635 \times 10^9 s^2 - 30.33\, s + 1.475 \times 10^{13}}{s^4 + 3788000\, s^3 + 3.055 \times 10^8 s^2 + 5.209 \times 10^{11} s + 3.072 \times 10^{16}}$$

3.3 Simulation Study
The simulation of the PID controlled SMPS used for charging a battery bank is done in MATLAB/Simulink. The simulation parameters are as presented in Table

Table 6: *SEPIC DC-DC Converter design specifications:*

Description	Value
Minimum Input voltage	50 V
Maximum Input voltage	340 V
Switching frequency	200 kHz
Output current	30 A
Output voltage	60 V
Efficiency (η)	90 %

The simulation is done in the Simulink environment of MATLAB software and the circuit is as presented in Figure 6

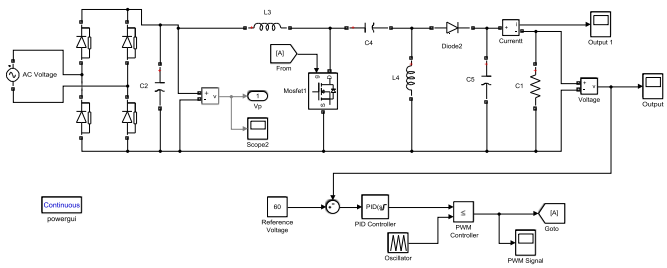

Figure 6: *Simulink model of the SEPIC Converter with PID controller feedback control.*

4.0 RESULTS
This chapter presents output obtained from the simulations of analysis done in chapter three.

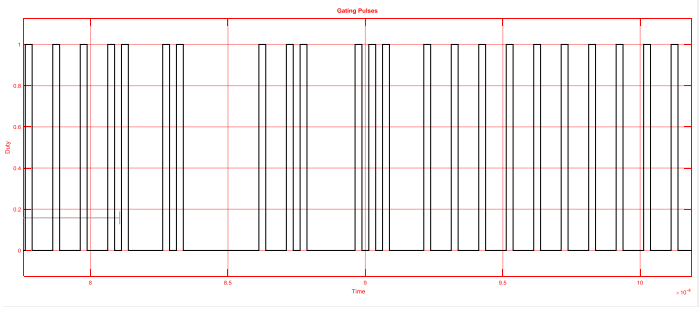

Figure 7: *PWM Gating pulses*

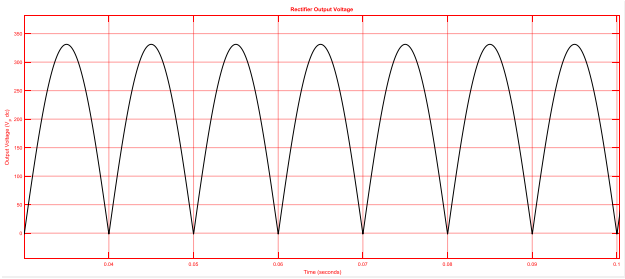

Figure 8: *240 Vrms to 339 Vdc AC-DC rectified Voltage on load*

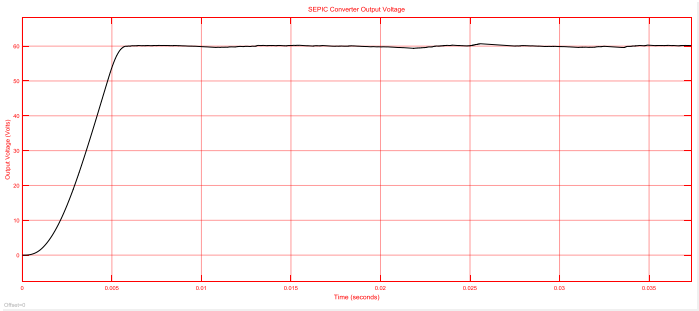

Figure 9: *Output Voltage of SEPIC converter with PID control*

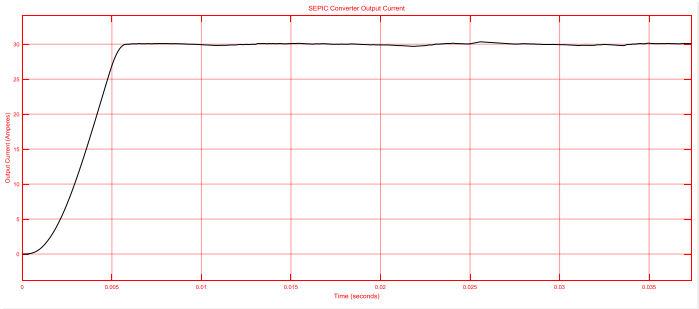

Figure 10: *Output current of the SEPIC converter with PID control*

Figure 7 depicts the PWM gating pulses used to switching the power Mosfet on and off. Figure 8 represents the output voltage of the rectifier on no-load of a 240 Vrms AC main indicates 339 V dc rectified voltage with ripples without filtering. Figure 9 represents the output voltage of 60 V for the SEPIC converter with PID controller feedback control from AC mains. Figure 10 represents the current output from the SMPS PID controlled SEPIC converter.

5.0 CONCLUSION

This paper presents a battery charging circuit using SEPIC converter which can be used for charging lead acid battery bank in an electric tricycle. From the results presented in Figures 6-10, the PWM pulses are determined by the PID controller via the error from the difference of the set voltage and output voltage. Also the output dc voltage of the SEPIC converter is 60 V and the output current is 30 A.

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