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Buck-boost converter as power factor correction controller for plug-in electric vehicles and battery charging application

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Abstract. This paper discusses the working of buck-boost converter as power factor correction controller applicable for battery charging in electric vehicles application. The converter topology will operate in buck mode and boost mode of operation reliant on the rectified voltage at input side and battery voltage at load side. An informal and effective line frequency current shaping control for achieving power factor nearer to unity is implemented and presented. It also satisfies the harmonic compliance of source current in accordance to the IEEE519 recommendations. This objective is achieved by active power factor control circuit using continuous conduction mode (CCM) of buck-boost converter implementing adaptable duty cycle control scheme. The control is very simple and gives good performance. The performance of the control scheme is simulated for both open-loop and closed-loop control in Matlab/Simulink environment.

Keywords: Buck-Boost Converter, Proportional-Integral controller (PI), total harmonic distortion (THD), Power factor correction (PFC), Continuous conduction mode (CCM)

1 Introduction

Since, the energy conservation is the one of the important issue; also the fuel cost getting increased day by day due to depletion of fossil fuel on earth and also pollution ratio increasing on daily bases. So, researchers are providing alternative way to protect the environment by employing the battery fed electric vehicle[3].

In battery fed electric vehicle the battery should be charged and discharged precisely to improve the life as well as productivity of battery. To achieve this, conventional buck-boost converter is used in CCM to charge and discharge the battery[1, 6]. The input to the buck-boost converter is dc, supplied from ac supply through diode bridge rectifier. The conversion of ac to dc introduces distortion in the ac source current leading to the poor power factor[5].

In ac circuit, power factor quantifies the utility of available power and is defined as the ratio of real power delivered to load out of available power in the circuit referred as apparent power. Apparent power is the product of voltage and current of the circuit.

Now a day's power factor is one of the essential parameter that every distribution sectors has to look into it. Power factor at load side should be maintained near to unity to improve the efficiency of transmission line. In industries capacitor banks or any power factor correction panel were provided to maintain power factor near to unity. If the load power factor is poor, then it is the sign of increased system losses and the consumer will be penalized. Hence it is vital to provide power factor corrective measures by both equipment manufacturers and consumers.

To improve, the active power factor correction controller is being introduced so called line frequency current shaping control scheme. In that both constant voltage and constant current control scheme applied to

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improve the charging reliability of battery as well as power factor near to unity[4] that can sense the output voltage of buck-boost converter and rectified current of the buck-boost converter and given to PI controller togenerate PWM pulse with adjustable duty cycle and this pulses given to switch to make supply current sinusoidal to achieve unity power factor[2, 7–9].Main advantage of this topology is itssimple structure and it can be used for high power application.

2 Fundamental battery charging circuit

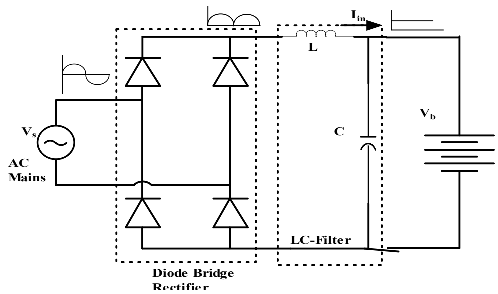

Fig. 1: Fundamental battery charging circuit diagram

The basic circuit diagram of the battery charger from AC supply is shown in Fig. 1. The ac voltage is rectified to dc voltage by means of a diode bridge rectifier circuit. The output of the bridge rectifier is pulsating dc i.e. dc voltage with ripples. The existence of ripples in dc voltage / current causes heating of batteries during charging. An L-C filter is connected at the output of diode bridge to filter the ripples and to smoother the dc voltage. The presence of capacitor at the rectifier output creates distortion in the source current and hence the associated problems. Power factor, source current / voltage distortion are the main factors that need attention. Poor power factor at the source side results in increased system losses and leads to poor performance.

The circuit in Fig. 1 is simulated in Matlab/Simulink environment to demonstrate the effect of output filter on the supply current and power factor. A 230V rms, 50Hz ac voltage is applied to diode bridge rectifier and L-C filter used for the purpose of reducing ripple from the output of rectifier.

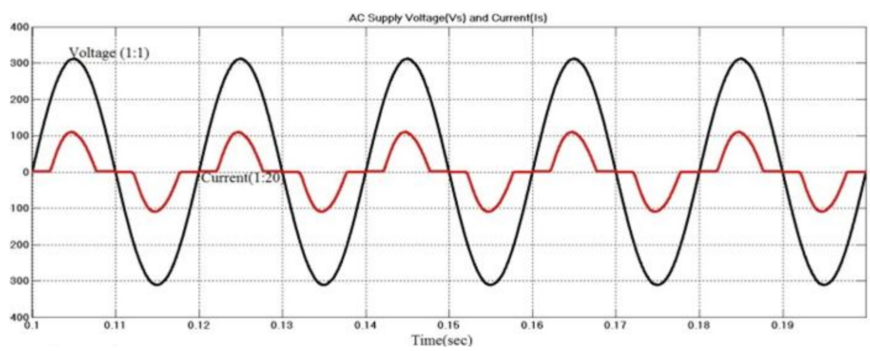

Fig. 2: Supply voltage and supply current

The plot of ac source voltage and current is shown in Fig. 2. The source voltage is a pure sinusoidal where as the source current is discontinuous and it is spiky in nature near the supply voltage peak. For better interpretation of the source current a current scale of 1:20 is taken.

The harmonic spectrum computed using Matlab/Simulink for the source current is shown in Fig. 3. The distorted source current has THD of 51.99% and a corresponding power factor of 0.8872. The power factor of the charging circuit is acceptable, but the presence of dominant third order harmonic in the source current needs to be limited. The provision of passive filter for lower order harmonics is not a feasible solution. Hence suitable active power control strategy has to be adopted for addressing the situation.

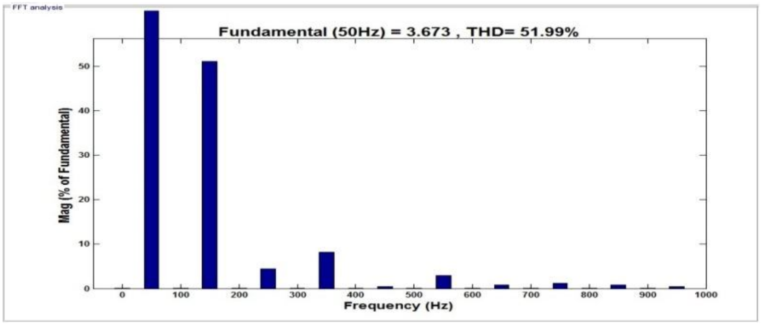

Fig. 3: THD spectrum of supply current

3 Battery charging circuit with buck-boost converter

The battery charger circuit with conventional buck-boost converter introduced in the dc-link between rectifier and battery load as shown in Fig. 4. The main purpose of introducing buck-boost converter is to make battery charging accurately as well as to reduce THD and losses at the source side. The reduction of THD, improves the power factor as stated in Eq. (1). The buck-boost converter acts as impedance matching circuit between the ac source and the dc load, so that the resulting network performs as purely resistive network without any distortions and at unity power factor.

$$\cos\emptyset = p.f. = \sqrt{\frac{1}{1+THD^2}}. \quad (1)$$

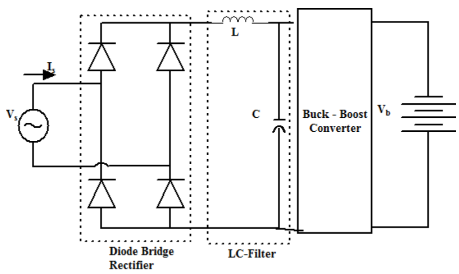

Fig. 4: Block diagram of battery charger with buck-boost converter in dc-link

3.1 Design parameter of converter

In this section, the circuit element values are computed and designed for the proposed buck-boost PFC converter considering all circuit parameter. The output voltage of the rectifier (V_{in})

$$V_{in} = 2 \times \sqrt{2} \times V_{rms}, \quad (2)$$

V_{rms} = AC supply voltage from mains.

The dc voltage conversion ratio of the buck-boost PFC converter can be represented as

$$\frac{V_b}{V_{in}} = -\frac{D}{1-D}, \quad (3)$$

V_b = Battery voltage; D= Duty cycle.

The critical of the inductor Lcric design is under the condition that buck-boost converter operates in continuous conduction mode (CCM), which can be expressed as

$$L_{\text{cric}} = \frac{(1-D)R}{2f_{sw}}, \tag{4}$$

$R =$ Output resistance; f_{sw} = Switching frequency.
The critical value of output capacitor is,

$$C_{\text{cric}} = \frac{D}{2f_{sw}R}. \tag{5}$$

Therefore, the critical inductor and capacitor of the proposed converter can be designed according to Eq. (4) and Eq. (5) where the inductance of inductor and output capacitance should be chosen higher than the critical value.

The design specifications of the system was given in Table 1.

Table 1: Design specifications

S. No.	Parameters	Values
1	Supply Voltage (V_s)	220 V
2	Supply Frequency	50 Hz
3	Switching Frequency (f_{sw})	20 kHz
4	Rated Power	300 W
5	Filter Inductor (L)	5mH,15 A
6	Filter Capacitor (C)	440μF, 220 V
7	Output Capacitor(C_b)	1500μF , 100 V
8	Converter Inductor (L_m)	5mH, 20 A
9	Nominal battery voltage (V_b)	48 V
10	Output Voltage	60 V

3.2 Battery charger with pfc controller circuit (open loop)

A typical battery charger circuit with buck-boost converter in its dc-link is shown in Fig. 5. The converter operation can be operated under two conditions, buck or boost switching mode. The buck mode is operated when the value of the rectified input voltage (V_{in})is higher than battery voltage V_b and the boost mode is operated when the value of the rectified input voltage (V_{in}) is lower than the battery voltage V_b. The buck-boost converter is operated in continuous conduction mode. The converter serves for two purposes namely output voltage regulation and input power factor correction. Both are vital controls in order to increase the reliable operation of the battery and the charging circuit.

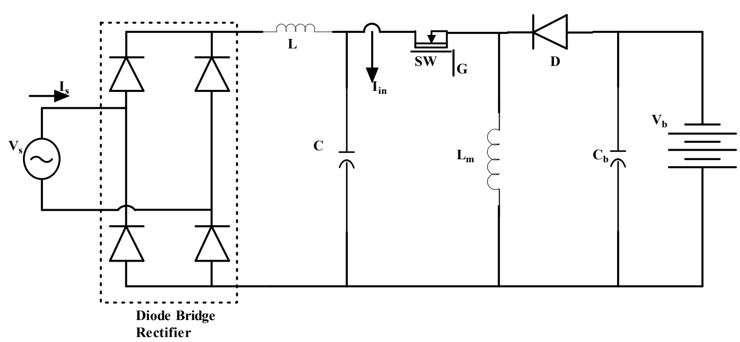

Fig. 5: Battery charging with buck-boost converter circuit in open-loop

Above cons of greater THD and lower power factor can be overcome by introducing buck-boost converter in between rectifier and load battery as represented in below Fig. 9.

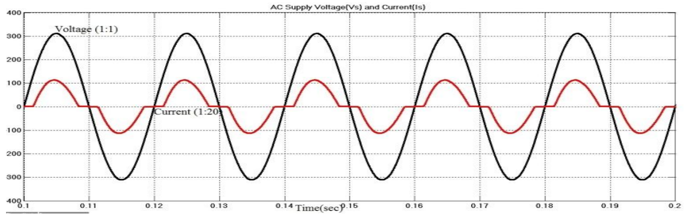

Fig. 6: Simulation results of source voltage and current

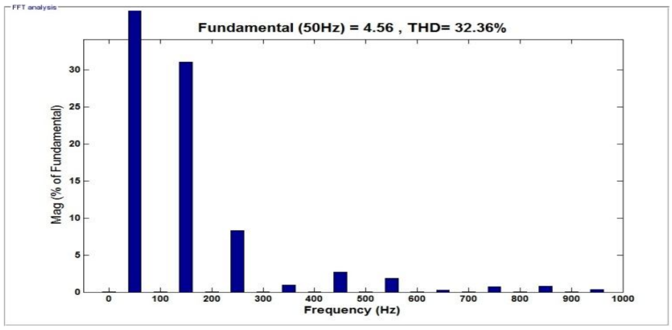

Fig. 7: THD spectrum of supply current

As shown in Fig. 6, the supply current (Ratio 1:20) shape is improved and is assumed to be sinusoid and nearly in phase with the supply voltage waveform.

The harmonic spectrum of supply current is shown in Fig. 7. The THD of the supply current accounts to 32.36% which is lesser compare to 51.99% of open loop without PFC converter. Hence power factor is improved to 0.9517.

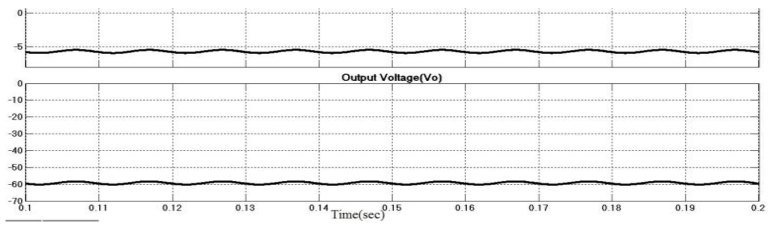

Fig. 8: Output current and voltage of buck-boost converter

The output voltage and current of the converter under open loop condition is shown in Fig. 8 and the polarity of the voltage and current is negative because it's depends on the modes of operation. Magnitude of average voltage is 60 volts and average current is 5 amps.

The status of battery charging is shown in Fig. 9. It demonstrates the state of charge of battery, charging current and voltage build up across its terminals at constant current. The charging current is constant $5A$ and the voltage across battery is building from $36V$.

3.3 Battery charger with pfc controller circuit (closed loop)

The circuit diagram for closed-loop implementation of buck-boost PFC converter employing a PFC converter is shown in Fig. 10. PI controller is employed for regulating the voltage and current and hence to improve the power factor and for THD minimization.

3.4 Power factor correction control scheme

The controller consists of two control loops wiz. The inner current control loop and the outer voltage control loop. The flow chart of line frequency current shaping control arrangement for power factor correction

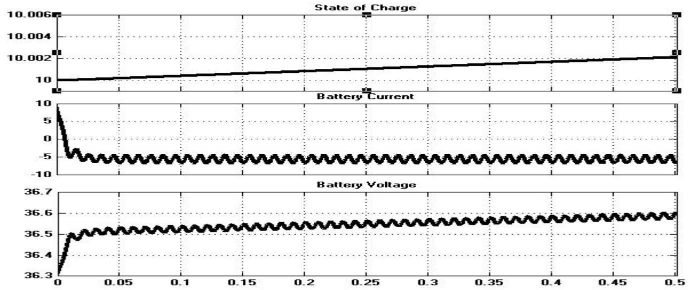

Fig. 9: Battery state of charge, current and voltage

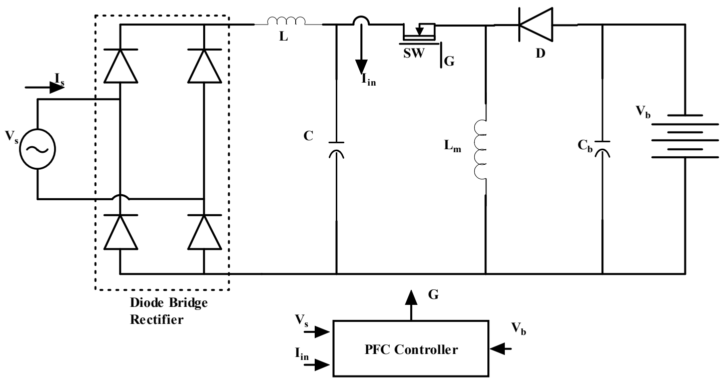

Fig. 10: Circuit of PFC charge controller in closed loop

is presented in Fig. 11. This controller consist of two modes of control are voltage control mode and current mode control mode to make the input power factor near to unity as well as to charge battery accurately for improving performance and life cycle of battery.

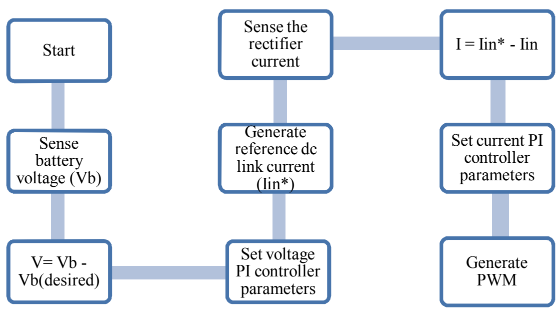

Fig. 11: Flow chart of buck-boost PFC converter control

3.4.1 Voltage controller

Voltage controller is operates as outer loop of PFC controller as shown in Fig. 11. The battery voltage (V_b) comparing with desire reference value of voltage (V_b*) and that produces error signal and that error signal is providing to PI controller where P accounts for present value of error and I accounts for past value of error and gives minimal value of the error signal current reference $(I_{in}*)$.

3.4.2 Current controller

In inner loop current control has the double the frequency $(100Hz)$ of supply and designed such a way that it can track the rectified supply voltage to make current in phase with voltage waveform. As shown in Fig.11

comparing the current reference signal ($I_{in}*$) generated by outer loop of voltage control with the rectified output current ($I_{in}*$) of rectifier the output signal given to current PI controller. This controller will minimize the error and produces a signal and applied to PWM generator. According to requirement of duty cycle PWM generator will generate pulses for the switch of proposed converter to make power factor unity.

By regulating voltage gain (K_{pv} and K_{iv}) and current gain (K_{pc} and K_{ic}) of PI controller results in source current shaping to nearly sinusoidal and in improving the power factor near to unity. The controller action is generated in such a way it provides control voltage for the PWM generator which will generate PWM pulses for the buck-boost converter with appropriate duty cycle. The resulting source current drawn from the supply is now nearly sinusoid and is in-phase relationship with the source voltage.

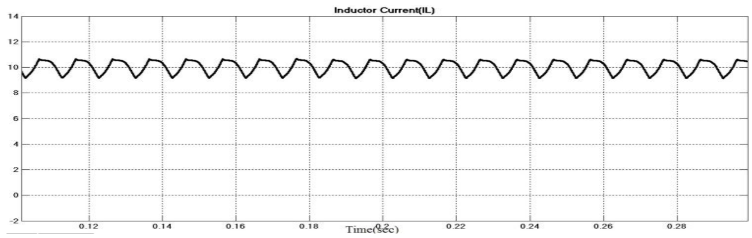

Fig. 12: Inductor current of buck-boost converter in closed-loop Operation

The CCM operation of buck-boost converter is ensured under closed operation and the inductor current waveform as shown in Fig. 12.

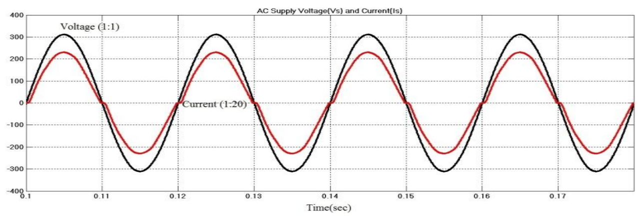

Fig. 13: Supply voltage and current waveforms in closed-loop operation

The plot of source voltage and source current (elevated scale of 1:20) in Fig. 13 shows the performance implemented control strategy for source current shaping. The distortion in the source current waveform is insignificant. Also the source current is in phase with the source voltage achieving nearly unity power factor at the ac side.

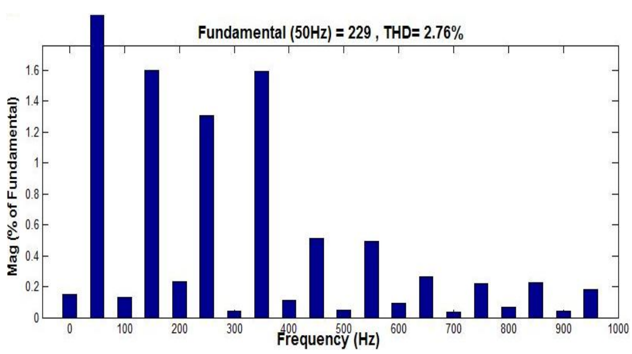

Fig. 14: THD spectrum of supply current in close loop control

The spectrum of source current in Fig. 14 shows the THD in source current is reduced to 2.76% satisfying IEEE519 recommendations for source current distortion in a distribution system. The power factor corresponding to the distortion level will be 0.9989 (lag).The effect of harmonic distortion is also reduced greatly which can further reduce the voltage distortion and losses in the system.

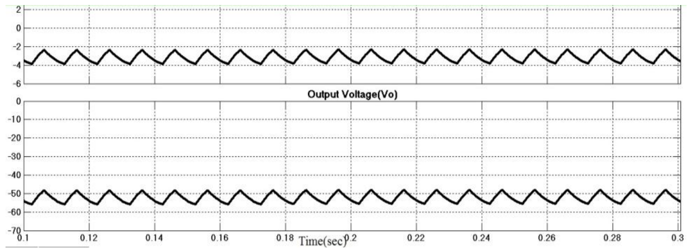

Fig. 15: Output current and voltage of buck-boost converter

The output current and output voltage waveforms are displayed in Fig. 15. The average output current is 4A and average output voltage is 55 volts.The state of battery charge condition is same and unaltered as presented in open-loop configuration as in Fig. 9.This proves the effectiveness of control on both input and output sides of the converter.

4 Conclusion

The performance of buck-boost converter as power factor correction converter for battery charging applications is demonstrated using Matlab/Simulink for the power rating of 300W.Line current wave shaping control strategy using PI controller is employed for shaping the source current to be pure sinusoidal achieving unity power factor operation at the ac mains. The effect of presence of filter capacitor at the output of diode bridge rectifier on source current is eliminated. Near unity power factor at the ac source side is attained by the implemented control strategy. The source current distortion and the THD is also reduced with higher degree of significance. The system studied is applicable for high voltage and high power application also gives more reliability to converter. The power factor calculations are carried out based on the phase angle relationship between the voltage and fundamental component of the source current.The results of simulations are satisfactory and it encouraged the author for prototyping of the system.

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