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A COMPARATIVE STUDY OF ACTIVE POWER FACTOR CORRECTION AC-DC CONVERTERS FOR ELECTRIC VEHICLE APPLICATIONS

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ABSTRACT

The rising growth in the usage of electronic equipment's internally works on DC voltage. The conversion from AC to DC will cause high current peaks which lead to harmonic distortion of the supply current and low power factor. This results in voltage distortion, low efficiency, and poor power factor. Active Power Factor Correction (APFC) is implemented in circuits to shape the input phase currents, so that they are sinusoidal in nature and are in phase with the input phase voltages. A suitable DC-DC converter is proposed and Interleaved Boost Converter (IBC) topology is discussed in this paper. The performance of two-phase uncoupled and directly coupled Interleaved Boost Converter (IBC) have been analyzed and compared with classical boost converter. Advantages of Interleaved Boost Converter compared to the classical Boost Converter are low total harmonic distortion, low input current ripple, high efficiency, faster transient response, and improved reliability. The waveforms were obtained using MATLAB/SIMULINK. Using the simulation results, the best topology is concluded.

Keywords: interleaved boost converter (IBC), active power factor correction (APFC), harmonic distortion.

INTRODUCTION

To meet the demand of drastic increase of energy in the 20th Century, fossil fuels become the main source of energy due to convenience and cost. Recently the price of oil and problems caused by pollution, have increased significantly which leads to spend on other solutions to replace fossil fuels. Consequently, interest in other means of transportation, such as Hybrid Electric Vehicles (HEV) and Electric Vehicles (EV) has increased.

Hybrid Electric Vehicles (HEV) and Electric Vehicles (EV) technology has existed since 19th Century. However, the higher cost and low energy density of available energy storage systems, primarily batteries, had limited the interest in EV and HEV. Recent innovations in lithium-ion batteries, the higher price of gas and the air pollution associated with fossil fuels have significantly crushed the alternative transportation industry.

The front-end AC-DC converter is a fundamental component of the charger system mainly for EV applications. The purpose of this paper is to illustrate the solution for AC-DC power factor corrected converters for EV application [1-2]. A variety of circuit topologies have been developed for the PFC application [3]. An EV can be recharged by connecting a plug to an external electric power source. The charging AC outlet without doubt needs an on-board AC/DC charger with a power factor correction circuit.

The boost converter is widely used in single phase power factor correction (PFC) converters because its input current is continuous and the topology is simple. The high-step-up DC-DC converters can be non-isolated but they should operate at high efficiency while taking high currents from low-voltage DC sources at their inputs. In a conventional boost converter, the duty ratio increases as the output to input voltage ratio increases. Therefore, they will require extreme duty ratios to meet the high voltage step-up requirements [4-6].

It is a main task to operate the boost converters at high efficiency [7]. This is because, with the high output voltage, the boost switch has to block a large voltage and hence the ON-state resistance, $R_{DS\text{-ON}}$, which varies almost proportionally with the square of blocking voltage, will be very high. Moreover, the low-level input voltages cause large input currents to flow through the switches. The extreme duty cycle operation drives short-pulsed currents with high amplitude to flow through the output diodes and the capacitors; which cause severe diode reverse recovery problem and increase in the conduction losses. The high *RDS*-ON of the switches, the increased conduction losses, and the severe reverse recovery problem will degrade the efficiency and limit the power level of the conventional boost converters [8]. To minimize the ripples, an IBC has been proposed [9]. Two-phase boost converter operates at a very large duty cycle due to a high output voltage and a low input voltage. Interleaved method is used to improve converter performance in terms of efficiency, size, conducted electromagnetic emission and transient response [10].

However IBC improves converter performance at the cost of additional inductors, switching devices and output rectifiers. Simulation study has been performed to understand the efficiency of the IBC and the results have been validated. IBC's main advantage is that sharing the input current among the parallel converters and also has an added advantage that the switching and conduction losses are less in interleaved boost converter than the conventional boost converter [11]. The frequency of the current ripple is twice for two phase IBC than the conventional boost converter. Due to a phase shift of 180 degrees ripple cancellation takes place.

POWER FACTOR CORRECTION

Power factor correction (PFC) is necessary for AC-to-DC converters in order to comply with the requirements of international standards. PFC can reduce the harmonics in the line current, increase the efficiency of power systems. Power Factor Correction (PFC) allows power distribution to operate at its maximum efficiency [12-13]. Many methods have been proposed to solve the problem of a poor power factor, unless some correction circuit is used, the input rectifier with a capacitive filter circuit will draw pulsating current, resulting in poor power quality and high harmonic contents. As a result, there is a need for a reduction in line harmonics current for power factor correction (PFC) and harmonic reduction circuits. There are two types of PFC, Active PFC and Passive PFC. All of our power supplies are either Active PFC Power Supplies or Passive PFC Power Supplies. Active PFC techniques result in significant improvement in power factor and harmonic performance compared to the conventional ac-dc. Active PFC offers better THD and is significantly smaller and lighter than a passive PFC circuit [14].

HOW DOES PFC CIRCUITS WORKS?

The ideal requirement of power factor correction is to make nature of input current waveform same as that of the input voltage. Major two power factor correction techniques are Active PFC and Passive PFC. A passive PFC uses a filter at the AC input to correct poor power factor. The passive PFC circuitry uses only passive components-an inductor and capacitors. A passive PFC rarely achieves low Total Harmonic Distortion (THD). Also, because the circuit operates at the low line power frequency of 50Hz or 60Hz, the passive elements are normally bulky and heavy. The active methods of PFC, which involve the shaping of the line current, using switching devices such as MOSFETs and IGBTs, is a result of advances in power semiconductor devices.

OPERATION OF CONVENTIONAL BOOST CONVERTER

The conventional boost topology is the most popular topology for PFC applications. It uses a dedicated diode bridge to rectify the AC input voltage to DC, which is then followed by the boost section, as shown in Figure-1. In practical applications as the power level increases, the diode bridge losses become significant, so dealing with heat dissipation in a limited surface area is important, particularly from an efficiency point of view. Therefore, the conventional PFC boost is limited to a low to a medium power range.

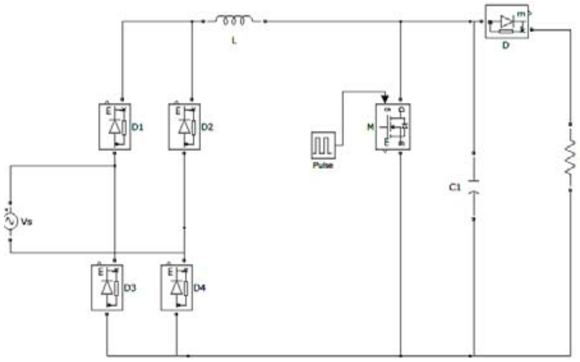

Figure-1. Conventional boost converter.

OPERATION OF INTERLEAVED BOOST CONVERTER

A two-phase interleaved boost converter is usually employed in high input-current and high input-to-output voltage conversion applications. Interleaving brings additional benefits such as reducing ripple currents in both the input and output circuits [15-17]. Higher efficiency is realized by splitting the output current into ‘n’ paths, substantially reducing power losses and inductor losses. The advantages of interleaved boost converter are minimizing current ripple, increasing efficiency, making faster transient response, reducing electromagnetic emission and improving reliability. The gating pulses of the switches of the two phases are shifted by 360/n, i.e., 360/2 for n = 2, which is 180. Figure-2 shows a two-phase interleaved boost converter.

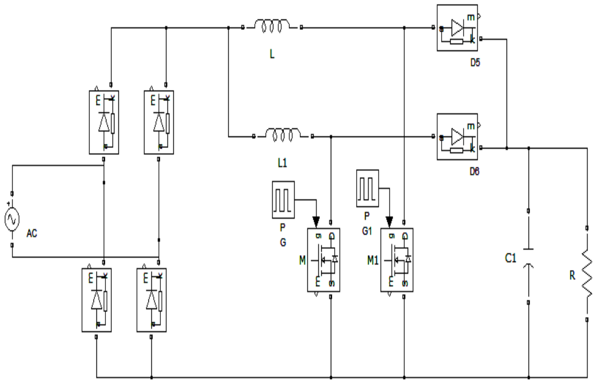

Figure-2. Interleaved uncoupled boost converter.

The interleaved PFC boost converter is simply two boost converters in parallel operating 180° out of phase. The input current is the sum of the two inductor currents. Because the inductor’s ripple currents are out of phase, they tend to cancel each other and reduce the input ripple current caused by the boost inductors [18-22]. By switching 180° out of phase, it doubles the effective switching frequency and introduces smaller input current ripples, so the input EMI filters will be smaller. The maximum input inductor ripple current cancellation occurs at 50% duty cycle. The output capacitor current is the sum of the two boost diode currents. In order to design the interleaved PFC converter, it should be treated as two conventional boost PFC converters with half of power rating. Therefore, all equations for the inductor, transistor, and diode in conventional PFC are valid here, since the stresses are unchanged except the ripple current through output capacitors. The input bridge diode has the same power rating as the conventional PFC boost converter. But the capacitor will get the most benefit of interleaving through reduced current ripple. As it can be noted, the input rectifier current is exactly the same as input rectifier current in a conventional boost PFC converter, but the inductor current is exactly half, and the switches has less stress, due to the fact that they have to deliver half of the power as in a conventional boost PFC converter. In addition, the interleaved boost converter takes advantage of paralleling semiconductors, and by having them switched out of phase, it doubles the effective switching frequency and introduces smaller input current ripples, so the input filters will be smaller compared to conventional. Two-phase IBC's with (i) uncoupled inductors and (ii) directly coupled inductors (iii) boost converters performance have been analyzed.

The choice of the duty cycle is based on the number of phases. This is because depending upon the number of phases; the ripple is minimum at a certain duty ratio. For two phase interleaved boost converter, the ripple is minimum at duty ratio, D = 0.5. Hence, the design value of the duty ratio is chosen as 0.5. For a specific input and output voltages and power rating of the converter, the duty ratio is calculated as:

$$D = \frac{Vo - Vin}{Vo}$$

The inductor and capacitor values can be calculated as follows:

$$C = \frac{VoDF}{R\Delta Vo}$$

Where Vo represents the output voltage (V), D represents the duty ratio, F represents frequency (Hz), R represents resistance (Ω) and ΔVo represents the change in the output voltage (V).

$$\mathrm{L} = \frac{VsD}{\Delta iLF}$$

Where Vs represents the source voltage and ΔiL represents the inductor current ripple

Selection of coupled inductors for directly coupled IBC can be done by using the following equation.

$$L_{eq} = \frac{V_{in}DT}{\Delta I_{phase}}$$

Where

V_{in} = Input voltage, D = Duty ratio, ΔI_{phase} = Phase ripple current

$$\Delta I_{phase} = \frac{V_{in}DT}{L} . \frac{1 + \alpha + 2\alpha\frac{D}{1-D}}{1 + \alpha - 2\alpha^2}$$

The self-inductance of coupled inductor can be found as follows:

$$L = \frac{1 + \alpha\frac{D}{1-D}}{1 + \alpha - 2\alpha^2} L_{eq}$$

The mutual inductance L_m can be found by the following equation:

$$L_m = \alpha . L$$

The leakage inductance L_k can be calculated as:

$$L_k = (1 - \alpha) . L$$

Figure-3 shows the schematic diagram of the two phase interleaved boost converter with directly coupled inductors. A capacitor filter is needed at the output to limit the peak to peak ripple of the output voltage. The capacitance of the output filter is the function of the duty cycle, frequency, and minimum load resistance during maximum load. The input ripple current for directly coupled inductor circuit is reduced as compared to that of uncoupled inductor circuit. Therefore the harmonic distortion is reduced to 10.27% and hence the power factor can be improved to 0.98.

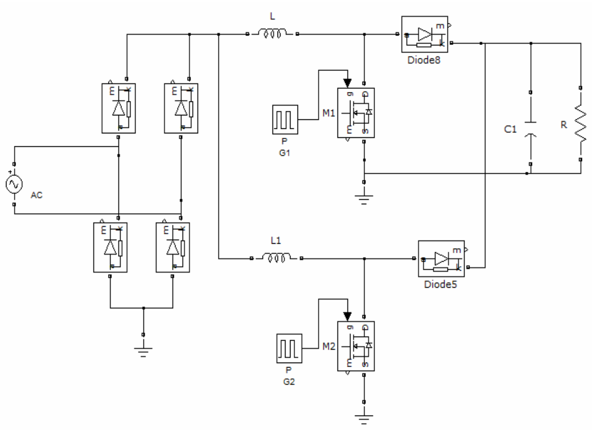

Figure-3. Interleaved directly coupled boost converter.

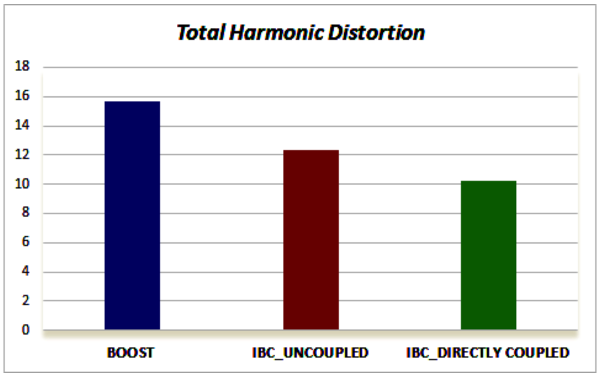

Figure-4. Comparison chart for total harmonic distortion (THD) of supply current.

Figure-4 shows the comparison chart of total harmonic distortion (THD) between different topologies namely boost converter, uncoupled converter and directly coupled converter for the supply current.

SIMULATION RESULTS

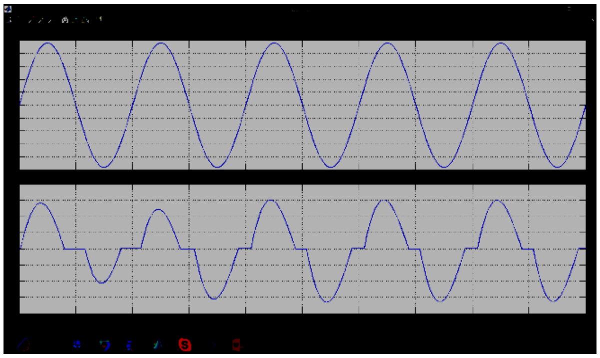

Figure-5. Supply side voltage and current (Boost).

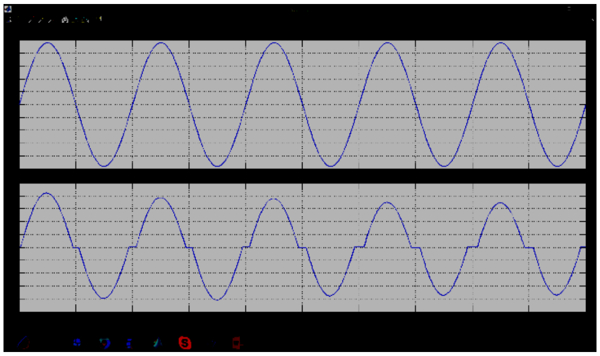

Figure-6. Supply side voltage and current (Uncoupled).

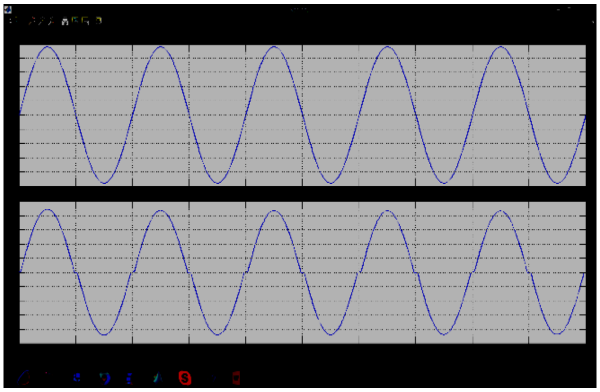

Figure-7. Supply side voltage and current (Directly coupled).

Figures 5, 6, 7 show the supply side voltage and current waveforms.

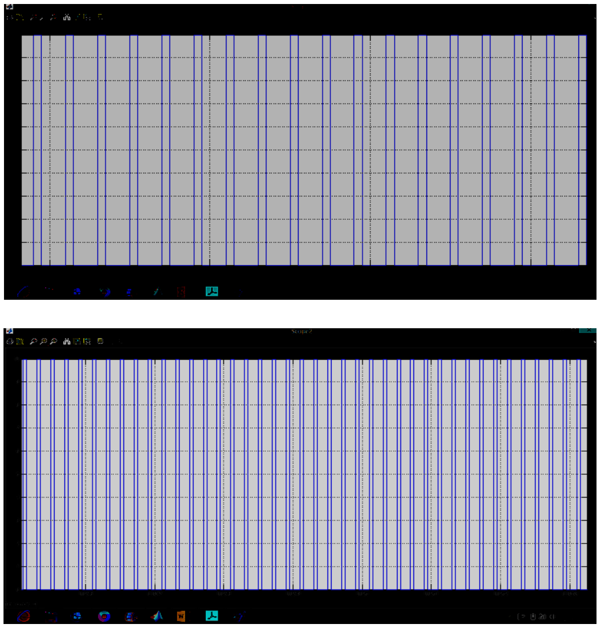

Figure-8. Switching pattern for IBC.

Figure-8 shows the switching pattern for interleaved boost converter (IBC).

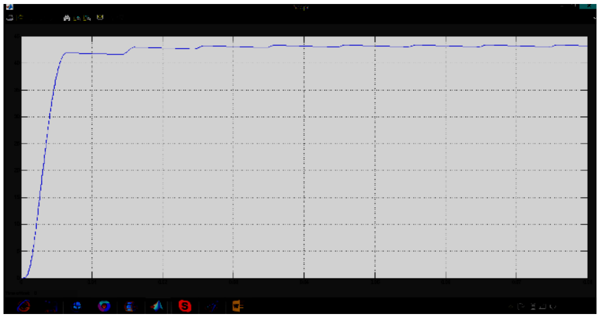

Figure-9. Output voltage (Uncoupled).

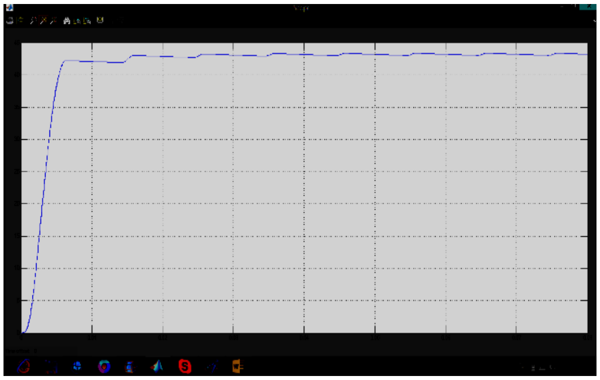

Figure-10. Output voltage (Directly coupled).

Figures 9, 10 show the output voltage waveforms of uncoupled and directly coupled converter.

PERFORMANCE PARAMETERS

For an ideal sinusoidal input voltage, the power factor can be expressed as the product of the distortion factor and the displacement factor.

$$PF = \frac{V_{rms}\ I_{1rms}}{V_{rms}\quad I_{rms}} \cos Ø = \frac{I_{1rms}}{I_{rms}} \cos Ø$$

$$= Kd\ cc$$

$$PF = Kd.K\theta$$

Where $K\theta$ = cos φ and $K\theta$ is the displacement factor and the distortion factor *Kd* is given by the following equation:

$$Kd = \frac{I_{1rms}}{I_{rms}}$$

The distortion factor *Kd,* is the ratio of the fundamental root mean-square current *(Irms (1)*) to the total root mean square current *(Irms*). The displacement factor *k*θ is the cosine of the displacement angle (φ) between the fundamental input current and the input voltage.

The following equations link total harmonic distortion to power factor.

$$PF = \frac{\cos Ø}{\sqrt{1 + \text{THD}^2}}$$

Where Φ is the angle between voltage and current. PF is the power factor; *THD is the* total harmonic distortion.

The calculated values of THD, PF and Phase Angle for different topologies are tabulated below in Table-1. From the calculated values it is clear that the THD is reduced to 10.27% for directly coupled converter circuit. Hence the PF is improved to 0.98, which is very close to unity.

Table-1. Summary of parameters for different topologies.

PARAMETER	BOOST	IBC_UNCOUPLED	IBC_DIRECTLY COUPLED
Total harmonic distortion	15.65%	12.31%	10.27%
Power factor	0.92	0.96	0.98
Phase angle	20	15	10

CONCLUSIONS

The conventional AC rectification is an ineffective process, effects in current waveform distortion. The harmonic distortion can be reduced and the supply can be made effective by active power factor correction technique (APFC). Active PFC offers better THD and is significantly smaller and lighter than a passive PFC circuit.

This paper has investigated the performance of two-phase IBC and conventional boost converter. The relationship between total harmonic distortions, current ripple and power factor is analyzed. From the simulation results it is clear that the directly coupled converter reduces the total harmonic distortion and improves the power factor up to 0.98. Hence active power factor correction results in low total harmonic distortion and significant improvement in power factor compared to conventional methods.

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