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RESEARCH ARTICLE

Comparison of Level 2 Charging Topologies for Electric Vehicles

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ABSTRACT

This article presents the charging status of electric vehicles by implementing two different charging topologies and demonstrates the comparison of power factor corrector (PFC) and Boost Cascaded by Buck-Boost (BoCBB) topologies. The former topology charger operates in boost mode, while the latter topology charger can operate in both modes (buck and boost) with a wide range of output voltage ranging from 30 V to 500 V. Moreover, using the harmonic modulation technique, former topology charger operation results in reduced total harmonic distortion, more efficiency, and high input power quality than the latter one. They are also evaluated on the basis of charging time, and by using PFC topology, the battery is charged to 5% in 10 min, while by using BoCBB the battery is charged to 3% in 10 min. The model's performance is verified by using MATLAB-Simulink.

Index Terms—Boost Cascaded by Buck-Boost, finite impulse response, pulse width modulation, proportional integral and derivative, synchronized pulse-width modulation

I. INTRODUCTION

Due to the combustion of oil and carbon dioxide emissions, environmental pollution is getting severe day by day, and alternative energy sources need to be utilized. Therefore, electric vehicles (EVs) or plug-in hybrid electric vehicles (PHEVs) are becoming more popular nowadays and are the best option over conventional vehicles due to their high fuel price. IEEE, the Society of Automotive Engineers (SAE), and the Infrastructure Working Council (IWC) are preparing standards and codes for utility/customer interfaces [1].

Instead of charging EVs in public places, the level 2 chargers are the prime method of charging at home. These chargers are plugged into a 220 V outlet and are semi-fast chargers. The advantage of the level 2 charger is that it can be used as a bidirectional charger; i.e., it provides power from the EV to the grid when there are peak hours and from the grid to the EV for charging the battery. The preference for level 2 at private and public places is that it draws less power compared to the level 3 charger, which provides us fast charging at the cost of high load at grid network, sometimes causing overloading of a network [2].

Typically, these chargers have a power level of 3–7 kW [3–5]. The comparison of basic converter topologies based on self-power factor corrector (PFC) capabilities in the discontinuous mode of operation is discussed in [6]. Topologies based on bridgeless converters [7] and multilevel converters [8] are also reviewed. The limitation of the former converter is the significant degradation at low voltages, while the latter has a great number of passive components. Interleaved converters [9] and cascade converters [10] are also reviewed which not only have the advantage of high power factor and power quality but also have the disadvantage of cost and more stress on electrical components. Many controlled techniques like proportional integrator and proportional derivative in BoCBB have also been studied in [11] and [12]. Moreover, the Cuk converter [13] or Flyback converter [14] can also be used instead of buck-boost, but they have the disadvantage of high component sizes as they have inverting output voltages and cause minimum direct energy transfer which increases the stress on the components too. For high-voltage applications, single-switch buck-boost topology cannot be used and hence two-switch boost and buck topology are reviewed in [15] and [16]. This article aims to implement and compare the performance of level 2 chargers with improved power factor and efficiency by implementing two topologies. These topologies are compared on the basis of their charging time. The block diagram for these topologies is shown in Fig. 1.

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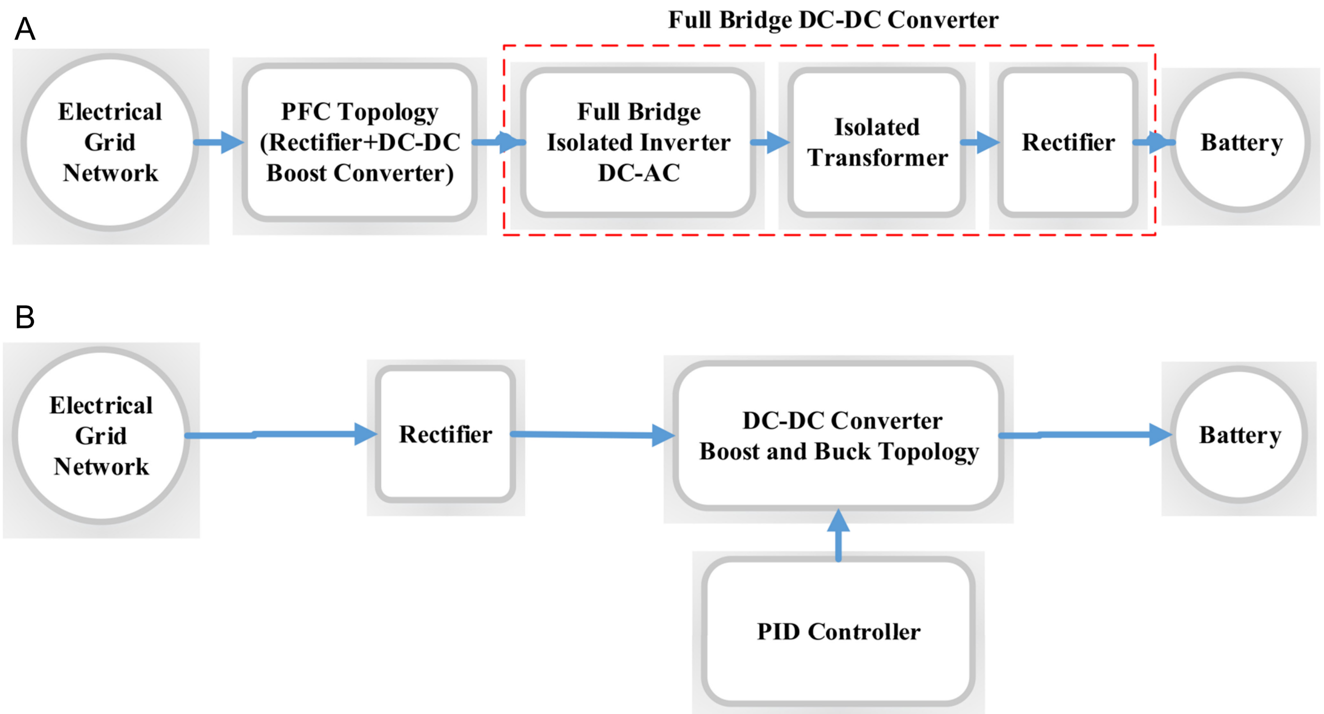

Fig. 1. Block diagram of smart electric vehicle charger: (a) power factor corrector topology (b) Boost Cascaded by Buck-Boost topology.

Fig. 1(a) shows an EV charger with PFC topology which consists of a two-stage converter one is the PFC stage that is followed by an isolated DC–DC converter. The PFC topology used has several advantages low cost, less stress on components, high efficiency, and a high power factor [3]. Fig. 1(b) demonstrates an EV charger with Boost Cascaded by Buck topology which consists of the rectifier and two-switch buck-boost converter. An improvement in the power quality of the converter is made by a smooth transition provided by the alterable DC link between the two modes of operation: buck and boost.

Section II contains the description of topologies. Section III presents the methodology and simulation results of PFC study. Similarly, methodology and simulation results of BoCBB study are presented in Section IV and Section V presents conclusions.

Main Points

- After comparison, the power factor corrector (PFC) topology resulted in more power factor and reduced harmonic distortion, making it more efficient.
- The PFC topology takes 3–4 h for complete charging of battery, while the Boost Cascaded by Buck-Boost (BoCBB) takes 8–9 h in boost mode and 2–3 h in buck mode.
- Construction of PFC topology is less expensive and less complicated than BoCBB.
- PFC topology has fewer design calculations making it more reliable.

II. REVIEW OF TOPOLOGIES

A. Power Factor Corrector Topology

Electric vehicle supply equipment (EVSE) with PFC topology is composed of two stages, i.e., PFC and a DC–DC converter stage. The purpose of PFC is to improve power factor and reduce total harmonic distortion such that the rectifier takes the input of 220 V from the supply and rectifies it to 220 V DC and then the boost converter with diode D_5 and switch S_5 increases the voltage up to 400–450 V. The full bridge inverter converts the signal into AC controlled by uni-polar SPWM with a 20 kHz switching frequency. Four IGBTs are used with signals S_1, S_2, S_3 and S_4. These signals are obtained by comparing the saw-tooth with a 20 kHz normalized input signal and its phase-reversed counterpart [17]. The output of the inverter is connected to a 1:1 galvanic isolation transformer. This transformer prevents unwanted current from flowing between these two isolated units. After that, the full bridge rectifier rectifies the signal which is filtered via a capacitor C_2 and will supply the desired value of current and voltage to the battery for charging [3]. The simulation circuit using PFC topology is shown in Fig. 2.

B. Boost Cascaded by Buck-Boost Topology

Boost Cascaded by Buck-Boost (BoCBB) topology is composed of two stages, i.e., DC–DC Boost Converter and DC–DC Buck Converter. This universal charger can address battery voltages of range 36–48 V, 72–150 V, and 200–450 V. The circuit consists of two switches, S_1 and S_2. Single-switch circuit (Cuk or buck-boost) results in low efficiencies and high voltage and current stresses [13–16]. The circuit diagram of BoCBB is shown in Fig. 3.

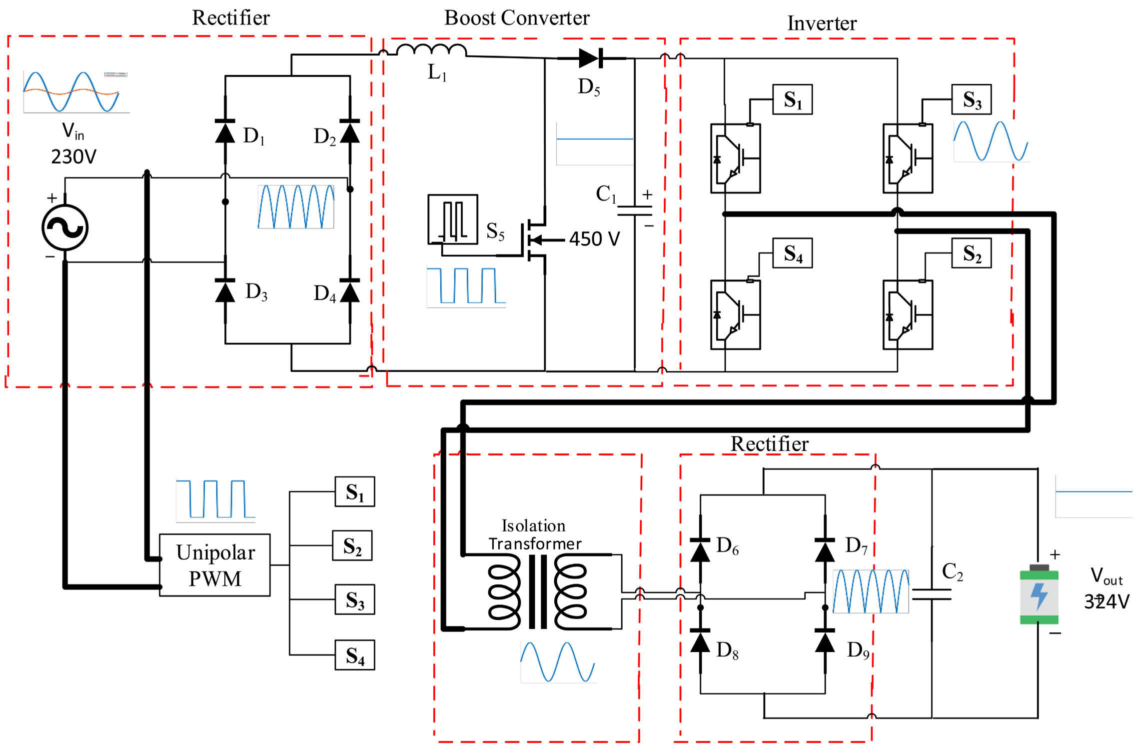

Fig. 2. Circuit diagram of power factor corrector topology.

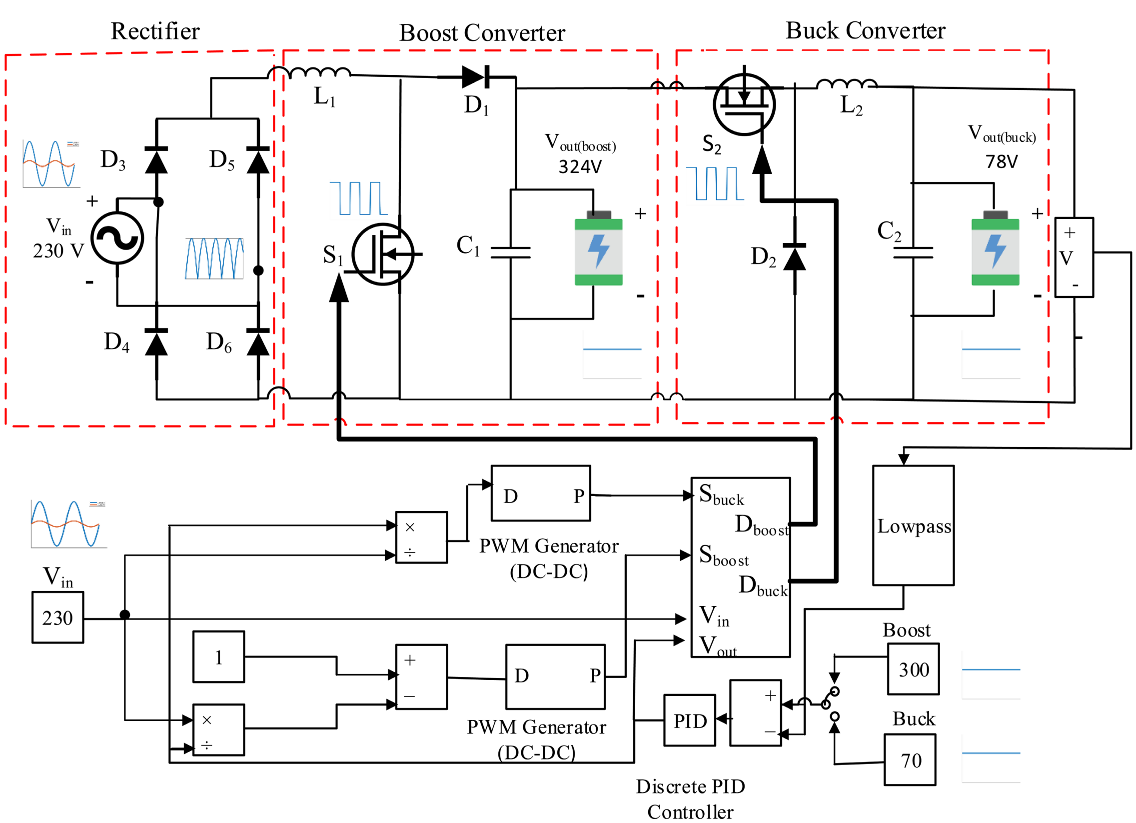

Fig. 3. Circuit diagram of Boost Cascaded by Buck-Boost topology.

An AC supply of 230 V is applied to the full bridge rectifier which is converted into a DC of 230 V. Rectifier is connected with a boost converter with switches S_1 and D_1, and it is followed by a buck converter with switch S_2 and diode D_2. When the required output voltage (V_{out}) needs to be greater than the input voltage (V_{in}), the circuit must be operated in boost mode and in buck mode otherwise. For boost mode, a battery of 300 V and 500 Ah is connected across C_1, and for buck mode, a battery of 70 V and 20 Ah is connected across C_2.

For control implementation, FIR low-pass filter is connected at the output which is taken as feedback to block high-frequency voltage. After that PID controller is connected which is eliminating steady-state error. This error voltage is obtained by comparing the low-pass output voltage with the reference voltage which is fed to the PID controller [18]. In the buck mode duty cycle, S_{buck} will adjust the width of the pulse signal and S_{boost} will be zero at that time. Similarly, for boost mode S_{boost} is nonzero and S_{buck} is zero. A MATLAB Function (Fig. 4) is implemented which is comparing reference input voltage V_{in} with PID output voltage V_{out} (shown in Fig. 3) and provides a switching signal to S_1 and S_2 accordingly.

III. POWER FACTOR CORRECTOR STUDY

A. Methodology

Sub-operation modes are such that during positive half diodes D_2 and D_3 are on, while in negative half D_1 and D_4 are on, so that an output DC signal of 230 V is obtained. The boost PFC converter's main purpose is to rapidly flip the switch S_5 in Fig. 2 on and off, i.e., when S_5 is closed, the first state occurs L_1 is energized by the rectifier causing the inductor current to increase. At the same time, diode D_5 is reverse-biased (since its anode is connected to the ground via S_5), and capacitor C_1 powers the inverter circuit.

When S_5 is open, the second state happens. In this stage, the inductor L_1 de-energizes as it transfers energy to the load and recharges the capacitor C_1. Cycling between the two states occurs at a high frequency in a way that keeps the output voltage constant while also controlling the average inductor current [19–20].

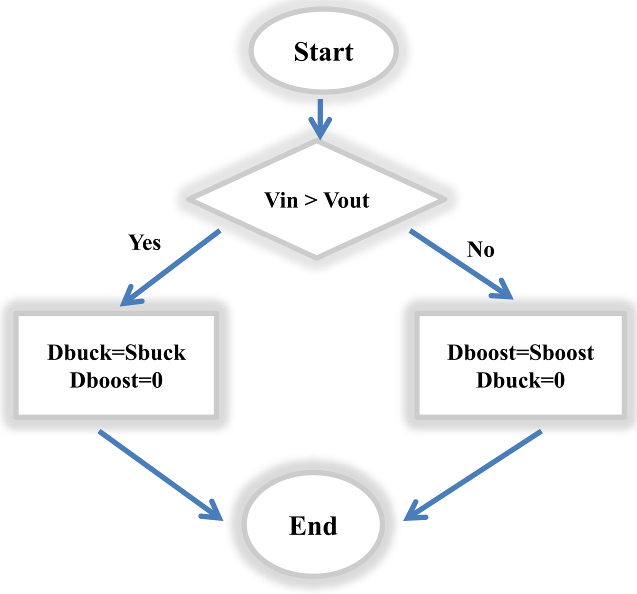

Fig. 4. Implementation of MATLAB code.

TABLE I.
PARAMETERS OF POWER FACTOR CORRECTOR TOPOLOGY

Parameters	Boost Mode
V_{in}	230 V
f_s	20 kHz
L_1	1.25 mH
C_1	2.17 uF
C_2	2.17 uF
Power rating	3.45 kW
V_{out}	320–400 V

This PFC circuit gives an output range of 450V which serves as the input for the inverter circuit. When S_1 and S_2 are on the positive half of magnitude 380 V and S_3 and S_4 are on the negative half of magnitude 380V is obtained. The output of inverter circuit is given to the input of galvanic transformer (1:1) and the output of transformer which is 380V is connected with input of full bridge rectifier with diodes D_1, D_2, D_3, and D4 to produce output signal of 324V. Table I.

B. Simulation Results

It is pertinent to mention here that, in Fig. 2, 300 V, 500Ah battery is used.

After simulation, the voltage at the terminal of the boost converter in the PFC block is a DC signal boost up to 400–450 V. In Fig. 5, charging of the battery can be observed at the initial point as 1% whereas after 10 min it goes up to 6% approximately. It is also observed as the charging state of the battery gets higher the rate of charging gets slow as it is described in Table II.

Moreover, power quality is greatly affected by nonlinear load, i.e., the EV charger. This is because when charger is connected to the grid for charging purpose, harmonics and current-voltage fluctuations are produced. Electric vehicles with low SOC (state of charging) will have a great chance to produce harmonics. As a result, PFC topology has THD less than BoCBB topology. It can be measured by THD of voltage and current.

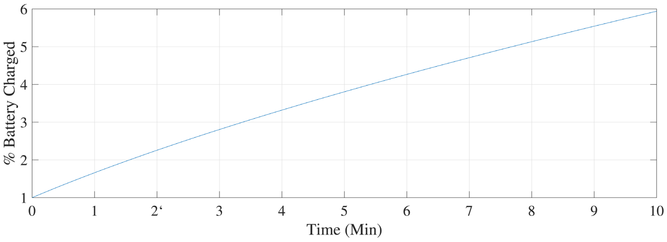

Fig. 5. Charging of battery using power factor corrector topology.

TABLE II.
COMPARISON OF PARAMATERS FOR BOTH TOPOLOGIES

		BoCBB	BoCBB
Parameters	**PFC**	**Boost**	**Buck**
V_{out}	324 V	324 V	78 V
Charging time	3–4 h	8–9 h	1–2 h (20 AH)
Efficiency	96%	94.43%	96.1%
Battery charged in 10 Min			
Initial state 1%	6%	1.7%	7%
Initial state 60%	61.6%	60.7%	61.4%

$$THD_i = \frac{\sqrt{\sum_{n=2}^{N} I_n^2}}{I_1} \times 100\% \quad (1)$$

$$THD_v = \frac{\sqrt{\sum_{n=2}^{N} V_n^2}}{V_1} \times 100\% \quad (2)$$

IV. BOOST CASCADED BY BUCK-BOOST STUDY

A. Methodology

The switches S_1 and S_2 are controlled by duty cycles that are given by

$$D_{boost} = \frac{(V_{out} - V_{in})}{V_{out}} \quad (3)$$

$$D_{buck} = \frac{V_{out}}{V_{in}} \quad (4)$$

These switches alternate between the two states such that when S_1 is on, and S_2 is off, the charger operates in Boost mode while in the opposite case, the charger will operate in Buck mode. Output voltage after low-pass filtering is passed through PID after comparison with a reference voltage. Proportional integral and derivative signal and V_{in} are the parameters considered for the duty cycle. Pulse width modulation signal is generated on the basis of the duty cycle and the charger will operate in Buck or Boost mode after the comparison in MATLAB function. The calculated parameters of BoCBB are shown in Table III and their equations are as follows.

$$L_{Boost} = \frac{V_{in}}{2\Delta i_L} DT_s \quad (5)$$

$$C_{Boost} = \frac{I}{2\Delta V} DT_s \quad (6)$$

$$L_{Buck} = \frac{V_{in} D'}{2\Delta i_L} DT_s \quad (7)$$

$$C_{Buck} = \frac{V_{in} D'}{16\Delta V L f_s} DT_s \quad (8)$$

TABLE III.
PARAMETERS OF BOOST CASCADED BY BUCK-BOOST TOPOLOGY

Parameters	**Buck and Boost Mode**
V_{in}	230 V
f_s	20 kHz
L_1	5.6 mH
L_2	7.4 mH
C_1	100 uF
C_2	50 uF
Power rating	3 kW
$V_{out\ (buck)}$	70–78 V
$V_{out\ (boost)}$	320–400 V

Where D is the duty cycle, Δi_L is the average inductor current, $D' = (1 - D)$ and $T_s = \frac{1}{f_s}$.

Sub-operation modes are as, during positive half diodes D_3 and D_6 are on, while in negative half D_4 and D_5 are on, so that an output DC signal of 230 V is obtained. When S_1 is closed, L_1 is energized by the rectifier causing the inductor current to increase. At the same time, diode D_1 is reverse-biased and capacitor C_1 powers the battery to 324 V. When S_1 is open, S_2 is closed. In this stage, the inductor L_1 de-energizes and recharges the capacitor C_1, while inductor L_2 energizes as D_1 becomes forward biased, and D_2 becomes reverse biased, hence charging the battery to 78V.

B. Simulation Results

Following are the simulation results of the circuit shown in Fig. 3. The battery used for boost mode is 300 V and 500 Ah with an initial state of charge of 1% and charged for 10 min as shown in Fig. 6. The battery used for buck mode is 70 V and 20 Ah with the initial state of charge of 1%, i.e., shown in Fig. 7. This circuit is simulated for 10 min. The output voltage across the battery can be visualized as 324 V and 78 V in the case of Boost and Buck mode, respectively.

In Table II, a charging time comparison is presented at different initial states of the battery using different topologies. It is observed that when initially the battery is at 1% PFC topology requires 1 min 34 s,

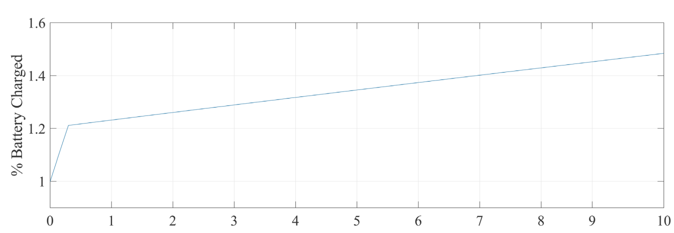

Fig. 6. Charging of battery using Boost Cascaded by Buck-Boost topology in boost mode.

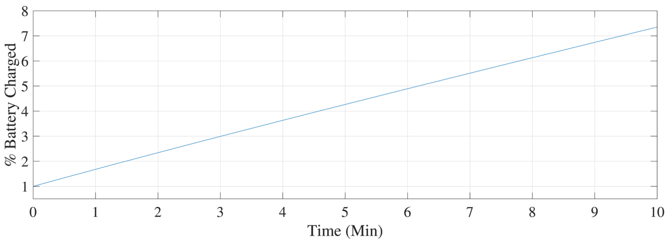

Fig. 7. Charging of battery using Boost Cascaded by Buck-Boost topology in buck mode.

Buck Mode requires 1 min 30 sec, and Boost mode requires more than 15 min to charge a further 1% of the battery. Moreover, a comparison can only be made between the 500 Ah battery's charging with each other, whereas 70 V and 20 Ah battery has less capacity so they will get charged to a higher percentage in an interval compare to other batteries used in the simulation.

Power loss analysis greatly affects the efficiency of a charger. Total power dissipated will be the sum of power losses at each component, i.e., MOSFET, inductor, and diodes. Moreover, conduction losses are higher than switching losses. Efficiency decreases 3–5% as switching frequency increases. Efficiency is given by the equations:

$$Efficiency = \frac{P_{out}}{P_{in}}\% \quad (9)$$

V. CONCLUSION

In this article, level 2 EV Charger is implemented via PFC topology as well as BoCBB topology. Power factor corrector topology improves the power factor, reduces harmonics, and increases efficiency. By using PFC topology, the battery is charged up to 6% in 10 min while by using BoCBB battery is charged up to 1.7% and 7%, respectively, in boost and buck mode during 10 min with the initial state of battery at 1%. Power factor corrector topology is more efficient than that of BoCBB topology as the former takes 3–4 h for complete charging of the battery while the latter takes 8–9 h for a complete charge of battery charge mode, while for buck modes it takes 2–3 h for a charge.

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