Electric Vehicle Charger Based on DC/DC Converter Topology

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Abstract:
Since electric vehicles have gained more and more popularities in the current research area, there is need to design a circuit and converter for charging these electric vehicles by means of the excess amount of electricity produced by the grid. Since they should compete in the market with their traditional counterparts, their efficiency is the winning point in their competence with respect to the traditional ones. Thus, there is a need to design using DC/DC converter to increase the efficiency. In this paper, Forward converter followed by a boost converter is designed and their elements are selected in order to meet the design criteria. Eventually, the converter is simulated in PLECS to get a validation of the calculations.

Keywords- Boost Converter, DC/DC converter, Electric Vehicle, Efficiency, Forward Converter

I. INTRODUCTION

Environmental concerns and increase in oil and gas prices motivate development and deployment of the Plug-in hybrid electric vehicles (EVs). Although EVs increase the power system based on the load electrical consumption, an aggregating of a large fleet of EVs can form virtual power plants (VPPs) and can supply the power system with ancillary services [1]. Main challenges to develop EVs were limited storage capability, inefficiency in conventional energy conversion (fossil fuel to AC, AC to DC), and high cost. Recently, all these difficulties are fading away by presenting some methods for new technologies [2, 3].

Some efforts are directed toward developing an improved propulsion system for electric vehicle, and the capability of different electrical machines including permanent magnet synchronous machine, induction machine, switch reluctance machine [4], brushless DC machine [5], dual mechanical port machine [6-8], and etc. in EV application. Recent advancement in the power electronics and novel switching techniques [9] lead to significant improvements in performance and efficiency of power electronics applications including EVs. The problem of their huge costs has also been solved by introducing chargers that can use excess energy produced by grid utilities [10].

In the last decade, the energy efficiency of power converters used for converting electrical energy from AC to DC type and vice versa is a very challenging issue specially in industrial use and for electric vehicles, due to the fact that by increasing their efficiency, their costs can decrease in a large number. Hence, power supplies and sources are required for high efficiency [11, 12].

The conventional sources are more in AC types. They are installed in the system having AC loads. Thus, electrical vehicles which need DC voltage should be accompanied by AC/DC converters to use the AC energy produced by the sources. The voltage sourced inverters are usually used to connect electrical vehicles to the grid [13, 14]. Although adding a converter increases the total costs, but distributed generations in AC type can be optimally sized and located in the system to reduce costs and energy losses [15, 16]. Moreover, small size distributed generations can be used in smaller systems having an electric vehicle as their loads. These sources can also be optimally placed for decreasing the energy losses in loads or electrical vehicle [17].

Since most of such electric vehicles are in DC type, DC/DC converters are needed for connecting them to the grid. There are different kinds of converters used in industrial applications. They are in the type of Buck converter, Boost converter, Flyback converter, etc. Two switch forward converters are mainly used in converting DC to DC voltages and make them applicable to using for electric vehicles. The main reason for using this converter is that it improves the efficiency of the system and makes it more affordable for industrial and commercial use. Moreover, similar to isolated DC/DC converters [18-20], in order to achieve high efficiency in the system, the switching frequency we should be increased to reduce the size of capacitors, inductors, and transformers [21].

In order to obtain a power supply in an isolated form, two-switch Forward converters are mainly employed. The reason of employing two switch converter instead of single switch converter is that the power switches can block only the input voltage instead of two times of the input voltage as the same as the applications in Flyback or single switch Forward converters [22].

Since the resistance of switches especially MOSFETs is dependent on the blocking voltage, by means of double switch Forward converter, MOSFETs can be much cheaper to use in the converters. Therefore, the two-transistor forward converter is cheaper, more efficient, and more interesting in power electronic area [23].

This paper consists of a boost converter followed by forward two-switch converter. The performance of the boost converter and its controller are discussed in [24], and the forward two-switch converter is completely explained in [21, 22].

The first part of the paper is steady state analysis in order to find the maximum and minimum duty cycles and turn ratio between primary and secondary turns of the transformer used in the converter to make the input isolated from the output.

As for the second step, power devices are selected in order to meet the design specifications. To select the power devices and switches, a safety margin of 1.5 is considered. In order to calculate the efficiency and make the converter more efficient, power losses are allocated to the transformer and other passive elements of the system. In the end, the designed Forward converter was simulated in software PLECS to check the circuit calculations.

Before discussing the methodology of this paper, some other discussions in this approach help power system to be worthwhile. It should be noted that massive integration on EVs can have an impact on the power systems and other smart appliances inside the house. In the future, the solution can be defined as development of Internet of Things (IoT) in conjunction with EVs charge/discharge schedules for a demand of the environment response [25, 26].

II. CIRCUIT SPECIFICATION

In Fig. 1, a typical schematic of a forward converter is shown. Transistors Q1 and Q2 are controlled by the same gate drive signal, so they both conduct during subinterval 1, and are off during subintervals 2 and 3.

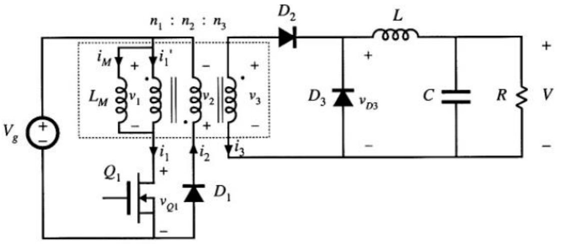

FIGURE 1
FORWARD CONVERTER [25]

The secondary side of the converter is identical to the single-transistor forward converter; diode D_3 conducts during subinterval 1, while diode D_4 conducts during subintervals 2 and 3. During subinterval 2, the magnetizing current $i_M(t)$ forward-biases diodes D_1 and D_2. The transformer primary winding is then connected to V_g with a polarity opposite that of subinterval 1. When the magnetizing current reaches zero, diodes D_1 and D_2 become reverse-biased. The magnetizing current then remains at zero for the balance of the switching period. So the operation of the two-transistor forward converter is similar to the single-transistor forward converter, in which $n_1 = n_2$. The duty cycle is limited to D<0.5. This converter has the advantage that the transistor peak blocking voltage is limited to V_g.

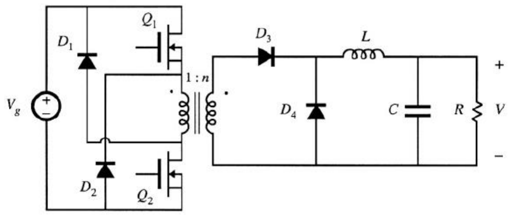

FIGURE 2
TWO SWITCH FORWARD CONVERTER [27]

Thus, one switch transformer can be considered as the forward converter and also, $n_1=n_2$ for the turns ratio.

TABLE I
DESIGN SPECIFICATION

Parameters	Value
V_{in}(v)	120-150
V_{out} & P_{out} (kW)	400v – 3.3 kW
Efficiency (%)	90%-92%
V_{out} (ripple) (%) (Peak-Peak)	3%
I_L (ripple) (%) (Peak-Peak)	5%
Switching frequency	50 kHz or higher

III. DESIGNING THE CONVERTER

The Forward converter is a transformer-isolated converter, operates based upon the buck converter. Its non-pulsating output current, shared with other buck-derived converters, makes the forward converter well suited for applications involving high output currents. The maximum transistor duty cycle is limited in value. In the Forward converter (Fig. 1) the primary of the transformer is inserted in series with the MOSFET. The secondary is connected to the output LC filter, where the diode D_2 is the free-wheeling diode. A second diode D_1 is inserted in order to prevent a negative current in the secondary of the transformer. The energy is transferred directly between the primary and secondary sides.

For this project, in which the forward converter is following a boost converter, the value of input voltage should be chosen for the forward converter and design the converters separately.

Thus, the first step is considering a separate forward converter with the input voltage of 250 V. This amount is chosen based on the fact that the boost converter causes increasing the voltage level, hence for the forward converter this value is a desirable value because it is not too high, so the turn ratio become acceptable.

IV. SELECTION OF POWER SWITCHES AND DIODES

1. Selection of Power MOSFET

The maximum voltage on Power MOSFET is $V_t = V_g\left(\frac{N_1}{N_2}+1\right)$

Since N_2=N_1 and V_g (max) = 250 V, V_t = 250 (1+1) = 500 V. Although there are two switches series in one winding, the blocking voltage would be half time, that is 250V. As mentioned in the specifications, safety margin should be taken into account of at least 1.5. Therefore, V_t = 250×1.5 = 375 V. For the current carrying, MOSFET current waveform shows that the following peak current would be carried by switches:

$$I_{peak} = \frac{N_3}{N_1}\left(I_0 + \frac{\Delta I_L\left(peak - peak\right)}{2}\right)$$

The load current is 8.25A. Current ripple can be considered 5% of the output current, but because of two cascaded converters, only a current ripple can be considered 2% and it lets the boost converter has some ripple. Thus, the peak current would be:

$$I_{peak} = \frac{N_3}{N_1}\left(I_0 + \frac{\Delta I_L\left(peak - peak\right)}{2}\right) = 3.6\times\left(8.25+\left(0.01\times 8.25\right)\right) = 30 \text{ (A)}$$

A safety margin of 1.5 and I_{peak}=45 A should be considered. This number of current is very much as the carrying current of MOSFET so n_3 and n_1 are chosen with the different amount as shown in the following:

$$V_{in} = 500,\ D_1 = 0.45,\ \frac{n_3}{n_1} = 1.78$$

$$V_t = V_g\left(\frac{n_1}{n_2}+1\right) = 2\times 500 = 1000$$

$$V_q = 500\times 1.5 = 750 \text{ V}$$

$$I_{peak} = \frac{N_3}{N_1}\left(I_0 + \frac{\Delta I_L\left(peak-peak\right)}{2}\right) =$$

$$\rightarrow 1.78\times\left(8.25+\left(0.01\times 8.25\right)\right) = 14.83 \text{ (A)}$$

Therefore, a safety margin of 1.5 and I_{peak}=22.245 A should be considered.

It has been seen from the calculation that there is a trade-off between voltage and current. In order to obtain the desired value between two extreme options, I_d can be determined 30 A with the safety margin of 1.5. In addition, with turn ration of 2.4 and V_g = 400 V, then V_t is obtained and to reduce the total losses, a MOSFET with small RDS is selected.

$$V_t = 1.5\times 400 = 600 \text{ V}$$

2. Magnetizing Diode (D_m)

The maximum voltage on the magnetizing diode is $V_g \frac{\left(\frac{N_1}{N_2}+1\right)}{2}$ = 400V. Peak voltage for D_m is 600V using a safety margin of 1.5. Carrying current i_c is the turn ratio multiplied by I_m. Since N_1 is equal to N_2, the current is equal to the magnetizing current. Magnetizing current I_m cannot be calculated in this step. It is defined as an arbitrary and its amount is greater than the real one. In reality, it is much less than 1 A, So the suitable amount is 1 A.

3. Selection of Output Capacitor (C)

For calculating the amount of capacitor, the voltage is defined as a ripple of 1% which is 4 V. Then, the capacitor can be obtained from the following equation:

$$C = \frac{\Delta I_L\left(p-p\right)}{8\times\Delta V_{p-p}\times f_{sw}} = \frac{0.02\times 8.25}{8\times 4\times 100000} = 51.5\ nF$$

By considering 1.5 safety margin, it would be 77nF.

4. Selection of Output Inductor (L)

For this part, frequency is very important to be specified. So, for this project, 100 kHz is compatible because it has to be greater than 50 kHz. As mentioned before, the current of the load is 8.25 A and current is assumed to have ripple of 2%. So, the output inductor can be selected from the following equation:

$$L = \frac{D\times\left(\frac{V_g N_3}{N_1} - V\right)}{f_{sw}\Delta I_l} \rightarrow$$

$$\rightarrow \frac{0.45\times\left(\left(2.4\times 400\right)-400\right)}{\left(100000\times 0.02\times 8.25\right)} = 15.3\ mH$$

5. Efficiency calculation and power loss distribution

Different elements of the system lose power in the conduction mode and so they creat power loss in the system. Thus, the losses should be allocated to the elements for the efficiency to meet the criteria.

- ✓ MOSFET: Power MOSFET has conduction and switching loss. There are two MOSFET as series connection, so their amounts of power loss should be multiplied by two.
- ✓ Diode: One of the diode is for conducting current and another one is magnetizing diode. For calculation of their power loss, output current is needed. Io is about 0.1 A.
- ✓ Inductor: as parallel or series connection with the switching elements.
- ✓ Capacitors: Since the capacitors are too small, their ESR are neglected.

The calculated losses are tabulated in the following table.

TABLE II
POWER LOSSES

	Devices	Power Loss (w)	Percentage (%)
	Transformer	100	30
Forward Converter	MOSFET(conduction)	74	22
	MOSFET(switching)	50	15
	Magnetizing Diode	0.19	0.05
	Diodes (D_1, D_2)	20.95	6
	Inductor	5.455	1.6
	Capacitor	0	0
Boost Converter	MOSFET(conduction)	29.2	8.6
	MOSFET(switching)	31.2	9.2
	Diode	6.9	0.2
	Inductor	20.4	6
	Capacitor	0	0
	Total	338.3	100

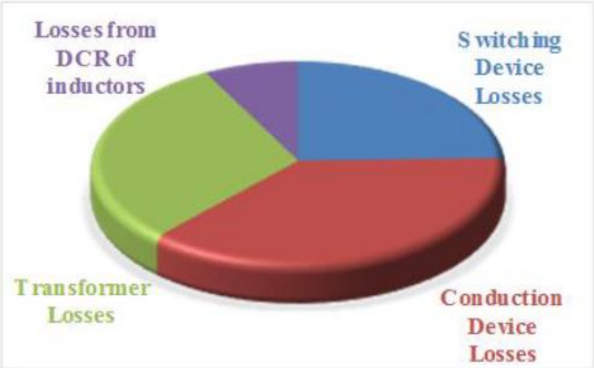

FIGURE 3
THE PIE CHART RELATED TO ABOVE AMOUNTS OF LOSSES

6. Simulation of forward converter

The circuit is modeled and simulated in PLECS. Load is considered at the rated load as 48.48 Ω. V_{in} is 150 V and corresponded diode voltage is 0.625. The voltage and current across the MOSFET of Forward converter is as following:

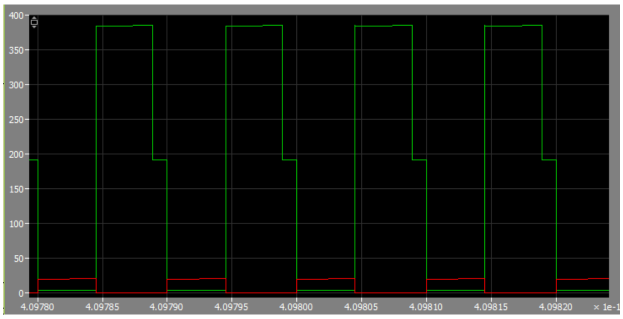

FIGURE 4
FORWARD CONVERTER MOSFET VOLTAGE (GREEN) AND CURRENT (RED)

In order to validate the performance of the magnetizing inductance, its voltage and current are shown in the following figures, respectively.

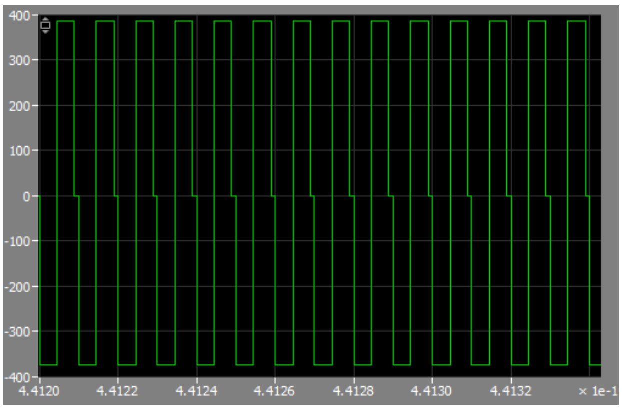

FIGURE 5
VOLTAGE OF L_M

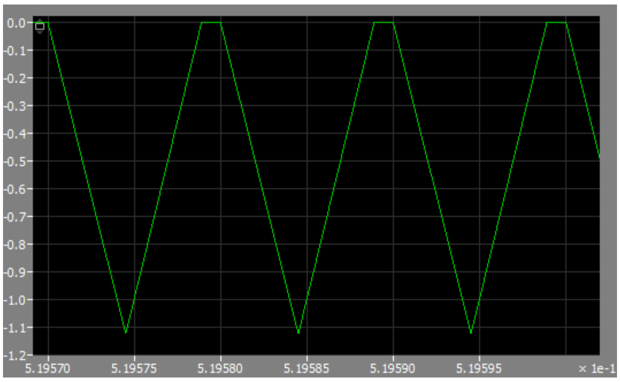

FIGURE 6
CURRENT OF LM

As it can be seen in the figures, the volt-sec balance is completely achieved for the magnetizing inductance and there is saturation across the transformer. Also, it can be seen that the converter works at DCM mode which is completely acceptable to the Forward converter which works at isolated mode from input.

The final validation is that the output power should be constant around 3340 W. The following figure shows this validation.

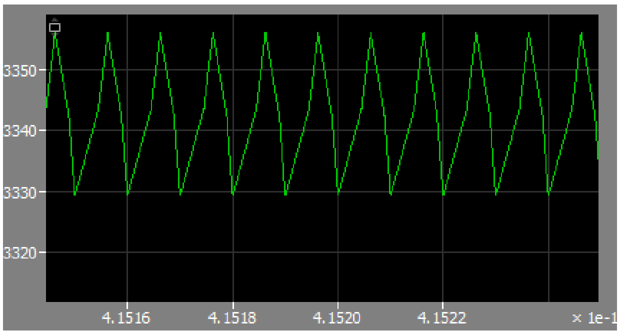

FIGURE 7
OUTPUT POWER

if the design meets the criteria about efficiency and if the system has highest efficiency among variation of loads, the converter is simulated for different amounts of load and the efficiency for all of these cases are calculated. The following curve shows the efficiency of the whole system over load changes. As shown in this figure, the system is perfectly designed for performing around 3.4 kW.

V. CONCLUSION

The paper has an effect on understanding the operation of forward converter plus boost converter. Since electric vehicles are gaining more and more popularities, there is need to design a converter for charging them. Thus, there is need to design a circuit using DC/DC converter to increase the efficiency. In this paper, Forward converter followed by a boost converter is designed and their elements are selected in order to meet the design criteria. Finally, the converter is simulated in PLECS in order to validate the calculations. The results show that the converter is perfectly designed around operating point which is defined for that.

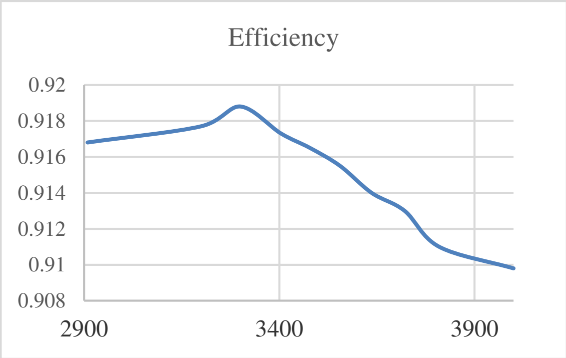

FIGURE 8
EFFICIENCY VERSUS LOAD

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