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A DC-DC Converter for Low Power Loads in Electric Vehicles

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Abstract

Dual-voltage power system is required in electric vehicles to supply power to low power low voltage and high power and high voltage loads. Power to high power loads can be directly obtained from the battery bank where as a DC-DC converter is required to supply conventional low-power, low-voltage loads. Several DC-DC converters such as isolated, non-isolated, half-bridge, full-bridge, and unidirectional and bidirectional topologies, for electric vehicles are available. The purpose of this paper to identify the best circuitry topology to design an advanced step-down DC/DC converters with the smallest mass, volume, highest efficiency and power.

Keywords; *DC-DC Converters, buck converter, Electric Vehicle*

I. INTRODUCTION

Introduction of higher dc system voltage distribution networks, such as the 48-V in future Hybrid electric vehicles and PHE'V appears to be an unavoidable consequence of meeting the increasing future electrical power demand. This is a response to meet the increasing electrical power demand of future vehicles due to usage of several electrical loads such as electric power steering, antilock brakes, electric compressors, electric brakes, electric water pump, heated seats etc., for improving passenger comfort and safety [1]– [3]. In other words, these high-power loads stand to gain much from higher operating voltages, and there are a large number of low power electric loads such as head and tail lights, heating fans, audio systems and so on, that are penalized by higher voltage and hence dual-voltage power system is required in electric vehicles. DC-DC converter supplies conventional low-power, low-voltage loads. Several DC-DC converters such as isolated, non-isolated, half-bridge, full-bridge, and unidirectional and bidirectional topologies are available.

The purpose of this paper is to design an isolated DC/DC converter for EV application, a DC/DC converter that will link the main battery (48 V) with the electrical equipment (12V) in the vehicle with the smallest mass, volume, highest efficiency and power

II. DC/DC CONVERTERS FOR ELECTRIC VEHICLES

The most common type of DC-DC converters can be divided into two categories depending on how they transfer the power. The energy can go from the input through the magnetics to the load simultaneously or the energy can be stored in the magnetics to be released later to the load Many different types of DC/DC power converters are proposed in literature [4]- [5]. The most common DC/DC converters can be grouped as follows:

A. Non-isolated converters

The non-isolated converters type is generally used where the voltage needs to be stepped up or down by a relatively small ratio (less than 4:1). And when there is no problem with the output and input having no dielectric isolation. There are five main types of converter in this non-isolated group, usually called the buck, boost, buck-boost, Cuk and charge-pump converters. The buck converter is used for voltage step-down, while the boost converter is used for voltage step-up. The buck-boost and Cuk converters can be used for either step- down or step-up. The charge-pump converter is used for either voltage step-up or voltage inversion, but only in relatively low power applications.

B. Isolated converters

Usually, in this type of converters a high frequency transformer is used. In the applications where the output needs to be completely isolated from the input, an isolated converter is necessary. There are many types of converters in this group such as Half-Bridge, Full- Bridge, Fly-back, Forward and Push-Pull DC/DC converters [5]- [6]. These converters can be used as bi-directional converters and the ratio of stepping down or stepping up the voltage is high.

III. FULL BRIDGE PWM DC-DC CONVERTER

The full-bridge PWM converter [8–13] contains two switching legs. Therefore, it draws two current pulses from the input voltage source per cycle of the transistor switching frequency and can deliver more output power than the half-bridge converter. The voltage stresses of the switches are low and equal to the dc input voltage V_I . For this reason, the full-bridge converter is used in off-line high-power supplies.

A. OPERATION PRINCIPLES AND ANALYSIS

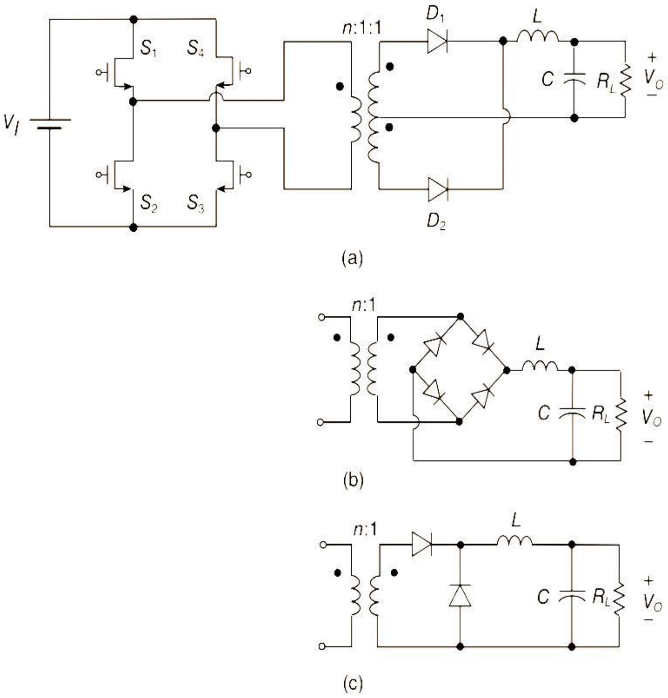


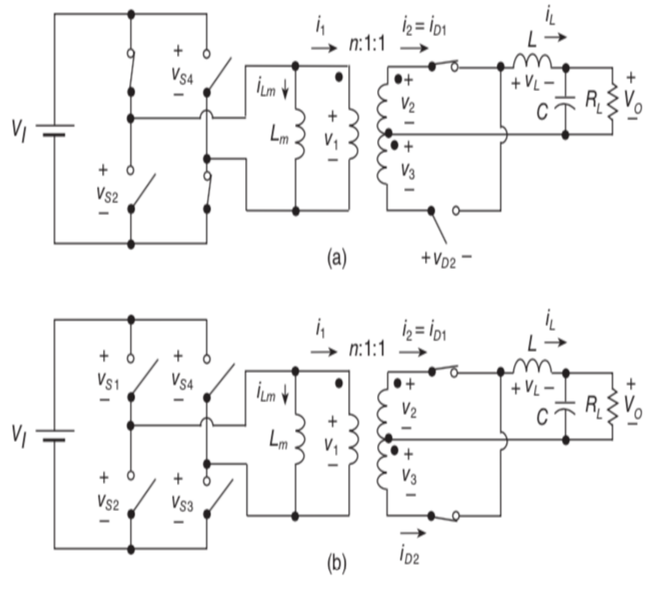
Figure 1. Full-bridge converter.

(a) With a transformer center-tapped rectifier.

(b) With a full-bridge rectifier.

(c) With a half-wave rectifier

A circuit of the PWM full-bridge DC–DC converter is depicted in Figure 1 (a). It is composed of a PWM inverter and a PWM rectifier. The inverter consists of a transformer and four power MOSFET's used as controllable switches S_1, S_2, S_3, and S_4. The transistors in each switching leg are driven by non-overlapping voltages that are out of phase by 180°. The maximum duty cycle of the gate-to-source voltages is slightly less than 50%. Pulse transformers can be used to drive the upper transistors. The bottom transistors can also be driven by pulse transformers. Pulse transformers driving transistors S_1 and S_3 may be connected to one output of a control circuit. Similarly, pulse transformers driving transistors S_2 and S_4 may be connected to the second output of a control circuit. The two outputs of a control circuit provide non-overlapping voltages, which are out of phase by 180°. The isolation transformer is not required to store energy. Its magnetizing inductance L_m should be large enough to reduce the current through this inductance. On the other hand, if the magnetizing inductance is too large, it requires many turns and is physically large. Ideally, the dc component of the current through the magnetizing inductance is zero. A coupling capacitor may be added in series with the primary winding to achieve zero dc component of the current through the magnetizing inductance and thereby removing an imbalance of the magnetic core. The transformer center-tapped rectifier consists of two diodes D_1 and D_2, an inductor L, a filter capacitor C, and a load resistor R_L. This rectifier is most suitable for low output voltage applications because only one diode conducts, when two switches are on. The voltage stress of the diodes is $2V_I/n$, which is higher than that in the bridge rectifier. Therefore, the transformer center-tapped rectifier is not suitable for high-voltage applications. The bridge rectifier is suitable for high output voltage applications because the voltage stress of the diodes is V_I/n, which is half of the transformer center-tapped rectifier. This rectifier is not suitable for low-voltage applications because the two diodes conduct when the two switches are on, and the total forward voltage across the two diodes may become comparable with the output voltage, resulting in low efficiency.



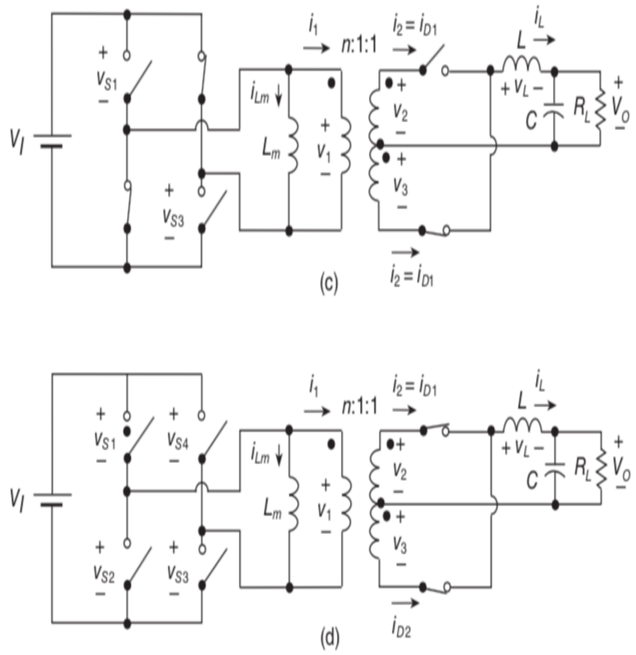


Figure 2 Equivalent circuits of the full-bridge converter with a transformer center-tapped rectifier for CCM.

(a) $0 < t \leq DT$. (b) For $DT < t \leq T/2$.

(c) For $T/2 < t \leq T/2 + DT$. (d) For $T/2 + DT < t \leq T$.

(i) Time Interval: 0 $< t \leq DT$

During the time interval $0 < t \leq DT$, the switches S_1 and S_3 as well as the diode D_1 are on, whereas the switches S_2 and S_4 as well as the diode D_2 are off. An ideal equivalent circuit for this time interval is shown in Figure 2 (a). The voltages across the switches S_2 and S_4 are

$$v_{S2} = v_{S4} = V_I$$

The voltage across the primary winding and the magnetizing inductance L_m is

$$v_1 = v_{Lm} = V_1 = L_m \frac{di_{Lm}}{dt}$$

Hence, the current through the magnetizing inductance L_m is

$$i_{Lm} = \frac{1}{L_m}\int_0^t v_{Lm}\,dt + i_{Lm}(0)$$
$$= \frac{1}{L_m}\int_0^t V_1\,dt + i_{Lm}(0)$$
$$= \frac{V_1}{L_m}t + i_{Lm}(0)$$

where i_{Lm} (0) is the initial current through the magnetizing inductance L_m at t = 0. This current is negative. The peak-to-peak ripple current of the magnetizing inductance is

$$\Delta i_{Lm} = i_{Lm}(DT) - i_{Lm}(0) = \frac{V_1 DT}{L_m} = \frac{V_1 D}{f_s L_m}$$

the current through the magnetizing inductance at t = 0 is

$$\Delta i_{Lm}(0) = -\frac{\Delta i_{Lm}}{2} = -\frac{V_1 D}{2 f_s L_m}$$

and the current through the magnetizing inductance at t = DT is

$$\Delta i_{Lm}(DT) = \frac{\Delta i_{Lm}}{2} = \frac{V_1 D}{2 f_s L_m}$$

The maximum value of the peak-to-peak ripple current of the magnetizing inductance is

$$\Delta i_{Lm(max)} = \frac{D_{min} V_{Imax}}{f_s L_{m(min)}}$$

which gives the minimum magnetizing inductance

$$L_{m(min)} = \frac{D_{min} V_{Imax}}{f_s \Delta i_{Lm(max)}}$$

The voltages across the transformer secondary windings are

$$v_2 = v_3 = \frac{v_1}{n} = \frac{V_1}{n}$$

The voltage across the diode D_2 is

$$v_{D2} = -v_2 - v_3 = -\frac{V_1}{n} - \frac{V_1}{n} = -\frac{2V_1}{n}$$

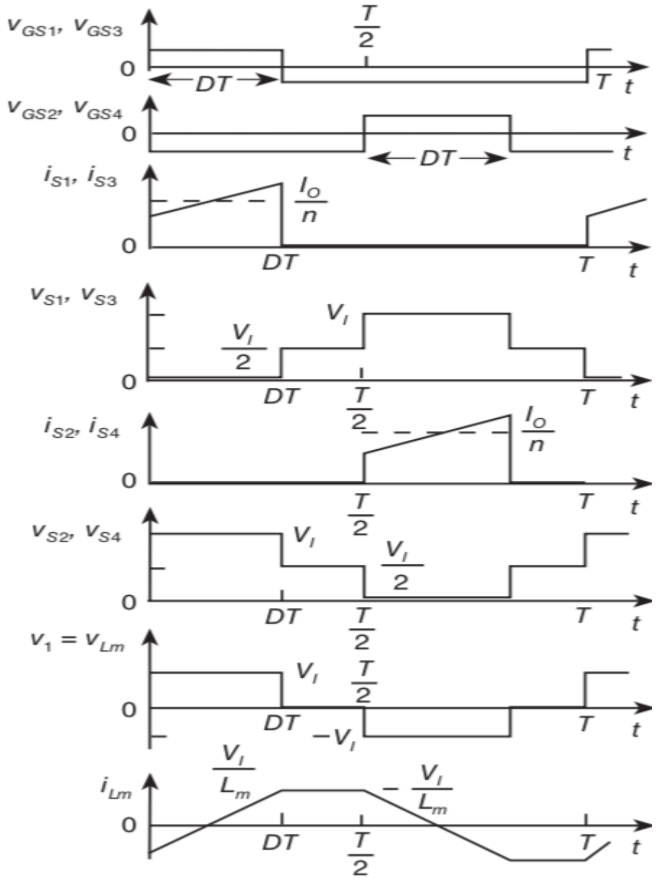


Figure 3 Waveforms of the full-bridge converter with a transformer center-tapped rectifier for CCM

since $v_{D2} < 0$, the diode D_2 is off. The voltage across the inductor L is given by

$$v_L = \frac{V_1}{n} - V_0 = L\frac{di_L}{dt}$$

resulting in the current through the inductor L

$$i_2 = i_{D1} = i_L = \frac{1}{L}\int_0^t v_L\,dt + i_L(0)$$
$$= \frac{1}{L}\int_0^t \left(\frac{V_1}{n} - V_0\right)dt + i_L(0)$$
$$= \frac{\frac{V_1}{n} - V_0}{L}t + i_L(0)$$

where i_L (0) is the initial current in the inductor L at time t = 0. The peak inductor current becomes

$$i_L(DT) = \frac{\left(\frac{V_1}{n} - V_0\right) DT}{L} + i_L(0)$$

and the peak-to-peak value of the ripple current through the inductor L is

$$\Delta i_L = i_L(DT) - i_L(0) = \frac{\left(\frac{V_1}{n} - V_0\right)DT}{L} = \frac{V_0(0.5-D)}{f_s L}$$

where $V_1 = \frac{nV_0}{(2D)}$ as will be shown shortly. The maximum value of the peak-to-peak ripple current through the inductor L is

$$\Delta i_{L(max)} = \frac{V_0(0.5 - D)}{f_s L}$$

The current through the primary winding of the ideal transformer is

$$i_1 = \frac{i_2}{n} = \frac{i_L}{n} = \frac{\frac{V_1}{n} - V_0}{nL} t + \frac{i_L(0)}{n}$$

and the current through the switch is

$$i_{S1} = i_{S3} = i_1 = i_{Lm}$$
$$= \frac{\frac{V_1}{n} - V_0}{nL} t + \frac{i_L(0)}{n} + \frac{V_1}{L_m} t + i_{Lm}(0)$$

Figure 3 shows current and voltage waveforms in the full-bridge converter with a transformer center-tapped rectifier for CCM.

(iii) Time Interval: $DT < t \leq T/2$ Figure 2 (b) shows an equivalent circuit of the converter for the time interval $DT < t \leq T/2$, during which all four switches are off and both diodes are on. If the off-resistances of the switches are same, the voltages across all the switches are

$$v_{S1} = v_{S2} = v_{S3} = v_{S4} = \frac{V_I}{2}$$

Therefore, the voltage across the primary winding and the magnetizing inductance L_m is

$$v_1 = v_{Lm} = L_m \frac{di_{Lm}}{dt} = 0$$

which gives the current through the magnetizing inductance

$$i_{Lm} = i_{Lm}(DT) = \frac{V_1 D}{2 f_s L_m}$$

and the current through the primary winding of the ideal transformer

$$i_1 - i_{Lm} = -i_{Lm}(DT) = -\frac{V_1 D}{2 f_s L_m}$$

The voltages at the transformer outputs are

$$v_2 = v_3 = 0$$

The voltage across the inductor L is

$$v_L = -V_0 = L \frac{di_L}{dt}$$

and the inductor current is

$$i_L = \frac{1}{L} \int_{DT}^{t} v_L \, dt + i_L(DT)$$
$$= -\frac{V_0}{L}(t - DT) + i_L(DT)$$

If the rectifier circuit is symmetrical, the inductor current is divided equally between the diodes

$$i_{D1} = i_{D2} = \frac{i_L}{2} = -\frac{V_0}{L}(t - DT) + \frac{i_L(DT)}{2}$$

(ii) Time Interval: $T/2 < t \leq T/2 + DT$

Figure2 (c) shows an equivalent circuit of the converter for the time interval $T/2 < t \leq T/2 + DT$, during which the switches S_1 and S_3 as well as the diode D_1 are off, and the switches S_2 and S_4 as well as diode D_2 are on. The voltages across the switches S_1 and S_3 are

$$v_{S1} = v_{S2} = V_1$$

and the voltage across the primary winding and the magnetizing inductance L_m is

$$v_1 = v_{Lm} = -V_1 = L_m \frac{di_{Lm}}{dt}$$

The current through the magnetizing inductance is

$$\begin{aligned} i_{Lm} &= \frac{1}{L_m}\int_{T/2}^{t} v_{Lm}\,dt + i_{Lm}\left(\frac{T}{2}\right) \\ &= -\frac{V_1}{L_m}\left(t-\frac{T}{2}\right) + i_{Lm}\left(\frac{T}{2}\right) \\ &= -\frac{V_1}{L_m}\left(t-\frac{T}{2}\right) + \frac{V_1 D}{2 f_s L_m} \end{aligned}$$

and the voltages at the output of the transformer are

$$v_2 = v_3 = \frac{v_1}{n} = -\frac{v_1}{n}$$

The voltage across the diode D_1 is

$$v_{D1} = v_2 + v_3 = -\frac{2v_1}{n}$$

The voltage across the inductor is expressed by

$$v_L = \frac{V_1}{n} - V_0 = L\frac{di_L}{dt}$$

Hence, the current through the bottom transformer winding, the diode D_2, and the inductor L is

$$\begin{aligned} i_3 = -i_{D2} = i_L &= \frac{1}{L}\int_{T/2}^{t} v_L\,dt + i_L\left(\frac{T}{2}\right) \\ &= \frac{\frac{V_1}{n} - V_0}{L}\left(t-\frac{T}{2}\right) + i_L\left(\frac{T}{2}\right) \end{aligned}$$

Hence, the current through the primary winding is

$$i_1 = \frac{i_3}{n} = \frac{-i_{D2}}{n} = -\frac{\frac{V_1}{n} - V_0}{nL}\left(t-\frac{T}{2}\right) + \frac{i_L\left(\frac{T}{2}\right)}{n}$$

The current through the switches S_2 and S_4 is

$$\begin{aligned} i_{S2} = i_{S4} = -i_1 = -i_{Lm} & \\ &= \frac{\frac{V_1}{n} - V_0}{nL}\left(t-\frac{T}{2}\right) + \frac{i_L\left(\frac{T}{2}\right)}{n} \\ &+ \frac{V_1}{L_m}\left(t-\frac{T}{2}\right) - i_{Lm}\left(\frac{T}{2}\right) \\ &= -\frac{\frac{V_1}{n} - V_0}{nL}\left(t-\frac{T}{2}\right) + \frac{i_L\left(\frac{T}{2}\right)}{n} \\ &+ \frac{V_1}{L_m}\left(t-\frac{T}{2}\right) - \frac{V_1 D}{2 f_s L_m} \end{aligned}$$

(iv)Time Interval: $T/2 + DT < t \le T$

An equivalent circuit of the converter for the time interval $T/2 + DT < t \le T$ is shown in Figure 2(d). All switches are off and both diodes are on during this time interval. The equivalent circuit of Figure 2(d) is the same as that of Figure 2 (b).

IV. DESIGN OF 1KW DC-DC FULL BRIDGE CONVERTER

$V_{Inom} = \sqrt{2} \times 4 = 68V$; $V_{Imax} = \sqrt{2} \times 54 = 76V$

$V_{Imin} = \sqrt{2} \times 42 = 60V$

$V_0 = 12\ V$; $I_{0min} = 8.3\ A$; $I_{0max} = 83\ A$

$P_{0max} = 12 \times 83 = 996w \approx 1000W$ and $P_{0min} = 12 \times 8.3 \approx 100W$

The minimum and maximum values of the load resistance are

$R_{Lmin} = \frac{V_0}{I_{0max}} = 0.1445$ ohms;

$R_{Lmax} = \frac{V_0}{I_{0min}} = 1.445$ ohms

The minimum, nominal, and maximum values of the dc voltage transfer function are

$M_{VDCmin} = \frac{V_o}{V_{Imax}} = 0.1578$;

$M_{VDCnom} = \frac{V_o}{V_{Imax}} == 0.1764$

$M_{VDCmax} = \frac{V_o}{V_{Imin}} = 0.2$

Let us assume the converter efficiency $\eta = 85\%$ and the maximum duty cycle $D_{max} \approx 0.4 < 0.5$. Hence, the transformer turns ratio is

$n = \frac{2\eta D_{max}}{M_{VDCmax}} = \frac{2\times 0.85\times 0.4}{0.2} = 3.4$ Let n = 3.4. The minimum, nominal, and maximum values of the duty cycle are

$$D_{min} = \frac{M_{VDCmin}\,n}{2\eta} = 0.3156\ ;$$

$D_{nom} = \frac{M_{VDCnom}n}{2\eta} = 0.3528$ and

$$D_{max} = \frac{M_{VDCmax}n}{2\eta} = 0.4$$

Assume the switching frequency f_S = 50 kHz. The minimum inductance required to maintain the converter operation in CCM is $L_{min} = \frac{R_{Lmax}\left(\frac{1}{2}-D_{min}\right)}{2f_s} = 2.66\mu H$; Taking $L = 3\mu H$

The maximum ripple of the inductor current is

$$\Delta_{iLmax} = \frac{V_o\left(\frac{1}{2}-D_{min}\right)}{f_s L} = 14.75A$$

The ripple Voltage is

$$V_r = \frac{V_o}{100} = 120mV$$

If the filter capacitance is large enough,

$V_r = r_{Cmax}\Delta i_{Lmax}$.

Hence, the maximum ESR of the filter capacitor is

$$r_{Cmax} = \frac{V_r}{\Delta_{iLmax}} == 8.13mOhms$$

Pick a capacitor with r_C = 10 mΩ. The minimum value of the filter capacitance at which the ripple voltage is determined by the ripple voltage across the ESR is

$$C_{max} = \max\left\{\frac{D_{max}}{2f_s r_C}, \frac{\frac{1}{2}-D_{min}}{2f_s r_C}\right\}$$
$$= \max\left\{\frac{0.4}{2f_s r_C}, \frac{\frac{1}{2}-0.3156}{2f_s r_C}\right\} = \frac{D_{max}}{2f_s r_C}$$
$$= \frac{0.4}{2\times 50\times 10^3\times 0.01} = 400\mu F$$

Pick C = 500 μF/100 V/10 mΩ.

The corner frequency is

$$f_o = \frac{1}{2\pi\sqrt{LC}} = 4.11kHz$$

Since $i_1 = i_{D1}/n$, the maximum peak current through the ideal transformer primary winding is

$$I_{1max} = \frac{I_{Omax}}{n} + \frac{\Delta i_{Lmax}}{2n} = 26.57A$$

Let us assume that the maximum peak-to-peak value of the magnetizing current is less than 10% of I_{1max}. Thus,

the maximum peak of the magnetizing inductance current is

$$\Delta i_{Lmmax} = 0.1I_{1max} = 2.657\ A$$

Hence, the minimum magnetizing inductance is

$$L_{m(min)} = \frac{D_{min}V_{1max}}{f_s\Delta_{iLmax}} = 0.1805mH$$

Pick $L_m = 2mH$

$$V_{sMmax} = V_{1max} = 76\ V$$

$$I_{SMmax} = \frac{I_{Omax}}{n} + \frac{\Delta i_{Lmax}}{2n} + \frac{\Delta i_{Lm(max)}}{n} = 27.90A$$

The voltage stress of the diodes in the transformer center-tapped rectifier is

$$V_{DMmax} = \frac{2V_{Imax}}{n} = 200V$$

and the current stress of the diodes is

$$I_{DMmax} = I_{Omax} + \frac{\Delta i_{Lmax}}{2} = 90.375$$

The power losses and the efficiency will be calculated at the maximum load current I_{Omax} = 83 A and the minimum dc input voltage V_{Imin} = 60 V. The conduction power loss in each switch is

$$P_{rDSI} = \frac{D_{max}r_{DS}I_{Omax}^2}{n^2} = 6.1\ W$$

The switching power loss per transistor is

$$P_{sw} = f_s C_o V_{Imin}^2 = 0.018W$$

Hence, the total power loss in each transistor is

$$P_{switch} = P_{rDSI} + \frac{P_{sw}}{2} = 6.1081W$$

Assume that the winding resistance of the primary winding is r_{T1} = 0.05Ω and the winding resistances of the transformer on the secondary side are r_{T2} = r_{T3} = 0.004 mΩ, the conduction power losses in these resistances are

$$P_{rC_c} = \frac{2D_{max} r_{c_c} I^2_{Omax}}{n^2} = 2.383W$$

$$P_{rT_1} = \frac{2D_{max} r_{T1} I^2_{Omax}}{n^2} = 2.383W$$

$$P_{rT_2} = P_{rT_3} = \frac{(2D_{max} + 1) r_{T2} I^2_{Omax}}{4} = 1.34W$$

The diode loss due to R_F is

$$P_{RF1} = \frac{(2D_{max} + 1) R_F I^2_{Omax}}{4} = 38.75W$$

The diode power loss due to V_F is

$$P_{VF1} = \frac{V_F I_{Omax}}{2} = 29.05W$$

and the conduction power loss in each diode is

$$P_{D1} = P_{RF1} + P_{VF1} = 67.8W$$

If the dc inductor ESR is $r_{L(dc)}$ = 10 mΩ, the conduction power loss in the inductor ESR is

$$P_{rL} = r_L I^2_{Omax} = 6.889W$$

and the power loss in the capacitor ESR is

$$P_{rc} = \frac{r_C (\Delta i_{Lmax})^2}{12} = 0.1813W$$

$$\text{Total Loss} = 4P_{rDSI} + 4P_{switch} + P_{rT_1} + 2P_{rT_2} + 2P_{D1} + P_{rL} + P_{rc} = 36.2083\ W$$

$$\eta = \frac{1000}{1000 + 36.20} = 96.5\%$$

Figure 4 Show the simulation result of Forwarded DC –DC Converter with 48 Volts Input and 12 V output voltage

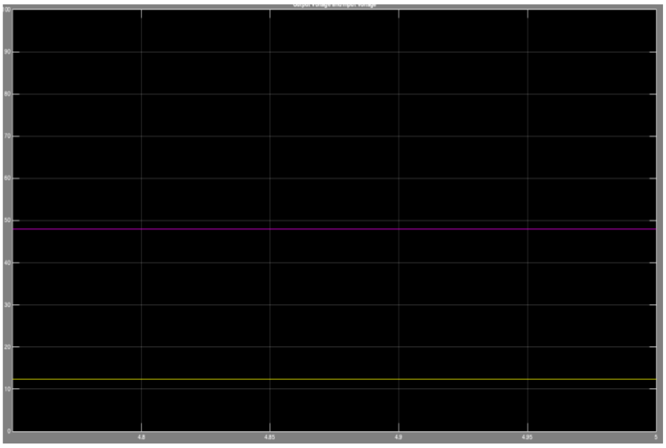


Figure 4. Input Voltage and Output Voltages

V. CONCLUSIONS

In this paper, a comprehensive analysis of isolated forwarded DC –DC converter in EV applications is presented and developed in MATLAB Simulink environment. Design considerations for 1kW are done. Converter step down the high voltage 48 battery pack to 12-14V to power auxiliary loads

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