Simulation of Modular Fly-Back Current-Fed Push–Pull DC-DC Converter for High Voltage Low Current Applications

D. Beula, M. S. Indira, and N. Balaji

Abstract A DC-DC converter has been proposed using Fly-back Current-fed Push–Pull topology with multiple secondary windings for high voltage low current applications. The converter is modular at the output which gives the flexibility to cater to specific output voltage levels. The High Voltage Transformer (HVT) with multiple secondary windings and rectifier with voltage doublers result in a smaller turns ratio for higher voltage conversion. The rectifier components on the high voltage side are subjected to lower voltages that reduce the voltage stress on the rectifier component, compared to HVT with the single secondary winding. The converter is operated in complete energy transfer mode (Discontinuous conduction mode) for effective utilization of stored energy in the fly-back inductor as it is fed-back to the source. The discontinuous current-fed scheme provides an instantaneous current limiting facility for short circuits at the load side. Zero current turn-on of switches due to the discontinuous mode of operation reduces switching losses and the non-overlapping mode of power switches minimizes conduction loss. The operation of the converter is analyzed under steady-state conditions. A design procedure is established and the converter is designed for a typical load of 5 kV, 500 W at a switching frequency of 20 kHz. The performance of the converter is verified by simulation.

Keywords Current-fed · DC-DC converter · Modular · Energy feedback · High voltage application

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1 Introduction

High voltage converters find applications in medical X-ray units, Electrostatic Precipitator (ESP), traveling wave tubes, and many other areas [1–4]. Conventionally, these systems convert low voltage from a single/three phase source to high voltage DC typically of several kilovolts. In most of these applications, isolated DC-DC converters are used. For high voltage applications, voltage-fed isolated converters are not preferred due to the presence of an output filter inductor that experiences large voltage stress making them bulky and expensive [5–7]. In the case of multi-output applications inductor is necessary at each output circuit. Compared to voltage-fed converters, current-fed DC-DC converters are used in high voltage applications as the output inductor can be transferred to the primary side [8]. It has one single inductor on the input side that makes a good choice for multiple output power supplies. In case of flux imbalance, the inductor controls the peak current and protects against transformer saturation. In current-fed push–pull converters, the switches need to be operated in an overlapping mode to avoid sudden interruption of current when the switch is opened. The converter used in high voltage applications requires HVT of high voltage transformation ratio resulting in large parasitic capacitance and leakage inductance. Such converters use these stray components of HVT to achieve Zero Current Switching (ZCS) operation [9, 10]. Another current-fed topology is the fly-back current-fed push–pull DC-DC converter [11–13]. In this, the series inductor can be used as a fly-back transformer by providing a secondary winding to feed the energy to either input or output. In all these topologies, the rectifier used in the high voltage side of HVT with a single secondary winding has series-connected low voltage diodes in each rectifier branch, to achieve a high voltage output. This result in voltage imbalance among the diodes and compensation techniques are required to mitigate voltage imbalance [14].

In this paper, a high voltage power supply based on fly-back current-fed push–pull topology with multiple secondary winding and voltage doublers rectifier is proposed. It has a fly-back transformer at the input side in series with a push–pull primary and the fly-back secondary is connected back to the input. The fly-back inductance can be designed to limit the short circuit current. Operating the converter in discontinuous conduction mode makes effective utilization of the energy stored, by returning to the source. The power supply circuit is modular in nature, easy to realize required high voltage levels by connecting multiple secondary circuits in series. In this scheme, the rectifier components experience less voltage stress because each rectifier diode is directly supplied from the secondary of the transformer and it eliminates a series of connected diodes also the associated voltage mis-sharing. Zero current turn-on of power switches due to the discontinuous mode of operation reduces switching losses. Non-overlapping of power switches owing to buck mode of operation reduces conduction losses of switches. Operation of the converter at high-frequency results in reduced size of magnetic and filter components.

2 Operation of DC-DC Converter

The DC-DC converter circuit is shown in Fig. 1. Push–pull transformer (HVT) has a center tapped primary (L_{1p}) with multiple secondary windings (L_{s1}-L_{sn}). The series inductor L_{2p} is brought in the form of a fly-back transformer with its secondary winding (L_{2s}) returned to the input. The turns ratio of push–pull and fly-back are n_1 and n_2 respectively. The push–pull center tap voltage is denoted as V_{ct}. Each secondary of the push–pull transformer is connected to a rectifier and voltage doubler circuit. D1 and D2 are the rectifier diodes in the first secondary winding of a push–pull transformer. The total output voltage, V_o is obtained across load resistance R_L, by connecting secondary circuits in series. The fly-back transformer secondary winding, diode D3, capacitor C and D4 form an energy feedback circuit. This configuration can operate by overlapping "ON" times of switches S1 and S2 with a duty cycle greater than 0.5 and non-overlapping of these switches with a duty cycle less than 0.5. Analysis of the circuit is done in the non-overlapping mode of ON times of power switches. There are four operating modes in one switching cycle. The transformer is assumed to be ideal in this analysis.
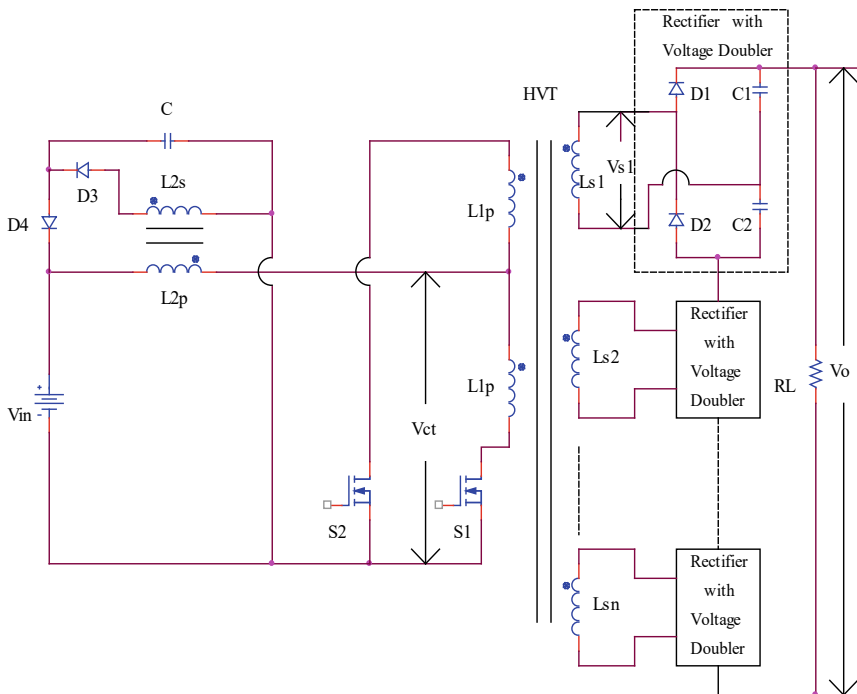

Fig. 1 Schematic of DC-DC converter

2.1   Mode 1: Switch S1 Closed and S2 Open

During the interval when S1 is "ON" current flows through L_{2p}, L_{1p}, and switch S1. This operation establishes the voltage across fly-back primary (L_{2p}) and push–pull primary winding (L_{1p}). The voltage across L_{1p} reflected on to the push–pull secondary windings (L_{s1} to L_{sn}) is $n_1 \times V_{ct}$, that forward biases rectifier diode D1 due to selected dot polarity and charges capacitor C1, to a voltage equal to V_{s1}. When the switch S1 is ON, energy is transferred from the source to the load. The diode D2 is reverse biased and the reverse voltage is equal to two times secondary induced voltage. During the same time, the dot end of fly-back secondary (L_{2p}) is negative with respect to non-dot end that reverses biases diode D3. Therefore no current flows through the secondary of the fly-back transformer.

2.2   Mode 2: Switch S1 Open and S2 Still Open

When the ON switch S1 turns OFF, the current forces a reversal of polarities in the winding, and dot end of L_{2p} goes positive. The dot end of L_{2s} also goes positive which makes diode D3 forward biased enabling the primary current transfer to the secondary fly-back transformer and also charges capacitor C in the feedback circuit. The circuit is designed to operate in discontinuous current mode. The energy stored in the fly-back inductance during the period when switch S1is ON, is transferred completely to the fly-back secondary and back to the source. The current in the secondary of fly-back decreases to zero before the next switch S2 goes ON. When both switches are OFF the polarity of push–pull secondary winding makes the diode D2 forward biased and makes a path through the capacitor C2. In this mode, no energy transfers from source to load.

2.3   Mode 3: Switch S2 Closed and S1 Open

During the interval when S2 is "ON" current flows through L_{2p}, L_{1p}, and switches S2. This operation is similar to the mode 1 operation. The voltage across L_{1p} is reflected across the push–pull secondary winding L_{s1}, which makes the diode D2 forward biased and charges capacitor C2 to a voltage equal to V_{s1}. The diode D3 in the feedback circuit is reverse biased and no current flows through the secondary of the fly-back transformer.

2.4 Mode 4: Switch S2 Open and S1 Still Open

When the ON switch S2 turns OFF, the dot end of L_{2s} goes positive and diode D3 gets forward biased. This operation is similar to mode 2. When both switches S1 and S2 are OFF the polarity of the push–pull secondary winding makes D1 forward biased and makes a path through C1. Energy stored in the fly-back inductor gets transferred to the source and there is no energy transfer from source to load.

3 Design Considerations

In developing a high voltage power supply system it is customary to make a preliminary design and verify through established simulation techniques. The design considerations are converter to be modular at the output end, short circuit limit capability, and energy feedback operation.

The first objective is to obtain high voltage by connecting multiple secondary circuits in series. This helps in achieving high voltages at the output making the unit modular with the reduction in the voltage stress across rectifier diodes.

The second objective is to limit the short circuit current at the load side. The drop across the primary of fly-back is assumed to be 25% of input DC voltage at rated load. When there is a short circuit at the load, the voltage across the primary fly-back increases and the short circuit current gets limited to four times the rated current.

The third objective is to make the system energy efficient. When power switches are conducting, energy is stored in the fly-back inductor. By operating it in discontinuous conduction mode, the stored energy is completely fed-back to the source when the switches are not conducting. Therefore the switches S1 and S2 are to be operated in non-overlapping mode with a duty cycle less than 0.5.

3.1 Design Specifications

To simulate the converter following design parameters are considered and the details are given in Table 1.

3.2 Design Steps

Determination of duty ratio: Maximum duty cycle occurs at a minimum value of input DC voltage (V_{in}) and minimum load resistance.

The relation between the output voltage at one of the secondary circuits and ON time for the non-overlapping mode of operation [15] is given by

Table 1 Design specifications

Output Power (P_o)	500 W
Output voltage (V_o)	5 kV
Output ripple	1% of V_o
Switching frequency	20 kHz, $T = 50\ \mu$s
DC input voltage	24 V nominal, $\pm15\%$
Discontinuous current mode and non-overlapping of power switches	

$$V_{o1} = \left[\frac{2V_{in}N_s}{N_P} \frac{T_{on}}{T} \right] \tag{1}$$

where V_{o1} is the voltage across one secondary circuit, V_{in} is the input voltage, N_P and N_S denote the number of turns in primary and secondary push–pull transformer, T_{on} is the on-time of the power switch, T is the switching period and D is the duty cycle. Let the turns ratio $N_S/N_P = n_1$ and duty ratio $T_{on}/T = D$. From Eq. (1)

$$D = \frac{V_{o1}}{2 \times n_1 V_{in}} \tag{2}$$

To calculate the maximum duty ratio, the minimum input voltage is taken as 15% less than the nominal voltage. The high voltage transformer has multiple secondary winding and each secondary winding has a rectifier with a voltage doubler circuit. In the present design, the number of secondary windings is assumed as four. Using Eq. (2) the maximum duty ratio obtained is 0.375 which is less than 0.5 indicating non-overlapping switches.

Calculation of primary and secondary inductance of push–pull transformer: The size of a transformer is designated by a parameter known as area product [15, 16]. Let A_p area product, P_o output Power in Watts, η transformer efficiency, B_m maximum flux density in Gauss, f_s switching frequency in Hz, J current density in A/cm^2, and k window utilization factor.

$$A_p = \frac{P_o\left(\sqrt{2} + \sqrt{2}/\eta\right) \times 10^8}{4B_m f_s k J}\ \text{cm}^4 \tag{3}$$

Using the value of output power and assumed value of η (0.9), B_m (2000), k (0.15), and J (200), the area product is calculated. Suitable core is selected from the core data book [17], which satisfies the area product requirement is E70/33/32. Let the primary number of turns required is N_p [17] and calculated using Eq. (4).

$$N_p = \frac{V_{ct}T_{on} \times 10^8}{A_c \times \Delta_B}\ \text{Turns} \tag{4}$$

Secondary number of turns N_s is obtained from the turns ratio n_1. The calculated value of turns ratio is 41, considering four secondary windings. This can be reduced by selecting more number of windings. Knowing the reluctance of core, values of primary and secondary inductance can be calculated and the corresponding values 35 µH and 64.7 mH, respectively.

Calculation of fly-back inductance: The fly-back inductance is designed, such that the drop across it is 25% of source voltage at rated current. The peak value of input current I_{pk} is calculated from the average input current at rated load. For discontinuous current mode of operation, peak-peak ramp amplitude ΔI is I_{pk}. When the switch is ON, the current starts from zero and ramps up linearly to a peak value I_{pk} in *2DT/2* interval. The frequency of the input current is twice that of the switching frequency. The average current is given as

$$i_{ave} = \frac{\frac{1}{2}2D\frac{T}{2}I_{pk}}{\frac{T}{2}} = DI_{pk} \tag{5}$$

Equation (5), gives the peak input current $I_{pk} = i_{ave}/D$.

Current through the secondary rectifying diodes is proportional to the input current and the load current is the average value of the rectifier current. The primary load current is the addition of all secondary windings currents reflected onto the primary side with their respective turns ratio. The peak input current,

$$I_{pk} = \frac{i_{ave}}{D}n_1 \times n \times 2 \tag{6}$$

Peak value of input current [15] at the end of ON time is

$$I_{pk} = \frac{(V_{in} - V_{ct})T_{on}}{L_{2p}} \tag{7}$$

L_{2p} is the fly-back inductance, n is the number of the secondary winding. The voltage drop across the inductance is assumed as 25% of the V_{in}. Fly-back inductance is calculated by using Eq. (7). The turns ratio n_2 of the fly-back transformer is selected such that the secondary current reduces to zero before the start of the next switch turn-on, for discontinuous mode. If the current ramp-down time is taken as t_f, then t_f is less than $(1 - 2D)T/2$. The secondary inductance (L_{2s}) is determined from the turns ratio (n_2) using, $\sqrt{L_{2s}/L_{2p}} = n_2$.

Calculation of output capacitance: The peak-peak voltage ripple is usually given as a percentage of the output voltage. The filter capacitor (C) is designed for an output ripple of 1% of V_o. The output ripple [18] is given by

$$\frac{\Delta V_0}{V_0} = \frac{1 - 2D}{32 \times L'_{2p} \times C \times f_s^2} \tag{8}$$

The value of the capacitor obtained from Eq. (8) is 1.09 µF.

4   Simulation Results and Discussion

The converter is simulated using Orcad PSPICE to validate the performance. The designed values of circuit parameters are $D = 0.375$, Turns ratio of high voltage transformer (Push–pull) $= 41$, Primary inductance and secondary inductance are $L_{1p} = 35\ \mu\text{H}$, $L_{s1} = 64.7$ mH, Fly-back inductance $L_{2p} = 1.12\ \mu\text{H}$, and filter capacitance $C = 1.09\ \mu\text{F}$. Ideal switches and diodes are used therefore ON-state voltage drops are neglected. Simulation of DC-DC converter is carried out with designed values of circuit parameters. The schematic diagram of the simulation used to perform the time domain analysis is given in Fig. 2.
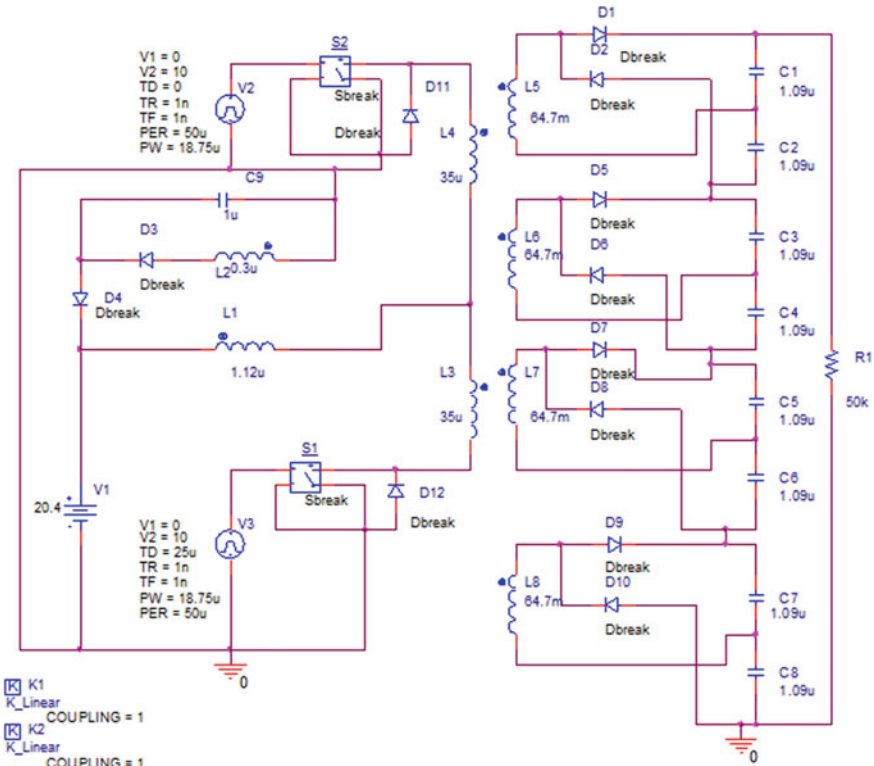

Fig. 2 Schematic diagram of the simulation

4.1 Modularity

High voltage transformer is designed to have a modular design in order to use it for different voltage levels. Being modular, failure of any one secondary circuit does not interrupt the output of the system, but can operate at reduced voltage making it a more reliable operation. As the high voltage transformer is designed to have four secondary windings each secondary circuit gives an output of 1.25 kV. The total output voltage obtained by connecting four secondary circuits in series is 5 kV. The simulated results of the output voltage of each secondary winding (V_{o1}-V_{o4}) and the total output (V_o) are shown in Fig. 3a.

The converter is more reliable compared single secondary circuit. In case of any one secondary circuit being open, output is available with the remaining secondary circuits, but at reduced voltage. Due to the reduction of one winding, the load current gets reduced and the reflected input current also reduces. This decreases the drop across the fly-back primary and higher voltage across push–pull primary winding. Figure 3b. shows the total output voltage (V_o) at maximum duty ratio with secondary circuit three being open is 4.239 kV. The voltage at the secondary circuit three (V_{o3}) is 770.756 mV.

Figure 4a shows the simulation results of the voltage, current, and power for 5 kV at 500 W output. Further the circuit is also designed and simulated for 50 kV at 1 kW from a 48 V input and the simulation results are shown in Fig. 4b. This ensures the design is robust and the converter is suitable for the generation of appropriate output voltage and power levels based on the application.
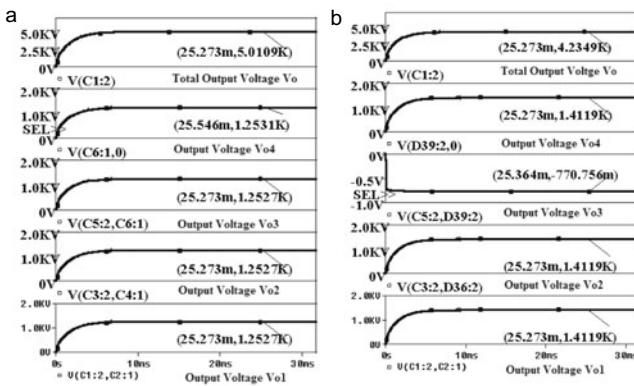

Fig. 3 **a** Output voltage of each secondary circuit and total output voltage, **b** output voltage of each secondary circuit when winding three is opened
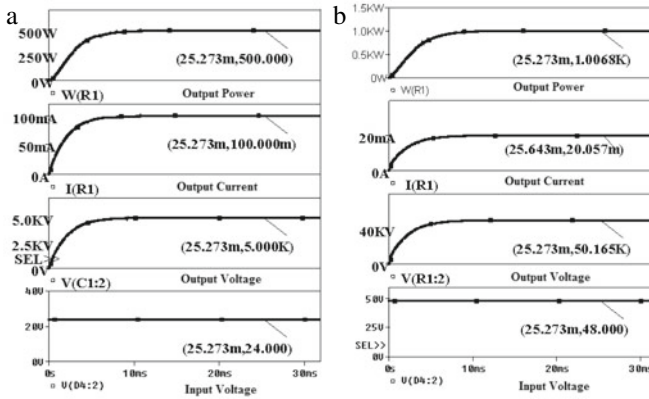
Fig. 4 **a** Simulation results for 5 kV, 500 W, **b** simulation results for 50 kV,1 kW

4.2 Voltage Stress on Rectifier Diodes

In the conventional high voltage power a supply, the transformer consists of a single secondary winding with high turns ratio to obtain high output voltages. In such conditions, a single commercially available diode cannot meet the required voltage rating and they need to be connected in series. Under such circumstances the series-connected diodes do not share reverse voltage equally though they are from a single manufacturer. To overcome this problem balancing resistors and capacitors are connected across each diode to take care of static and dynamic voltage mis-sharing.

The proposed converter use series-connected multiple secondary winding circuits to obtain the required high voltage. If there are "*n*" secondary winding with voltage doublers, then the turns ratio of each secondary winding gets reduced by a factor 1/2*n* as compared to the HVT with a single secondary winding. Each rectifier diode is directly supplied from a secondary high voltage transformer, therefore the rectifier devices have better reverse voltage sharing and reduction in voltage stress. Therefore commercially available diodes can be used, which reduces the overall cost of the circuit.

To verify this operation, the converter circuit with four secondary windings is simulated. Hence the voltage across anyone of the secondary winding is 625 V. When the rectifier diode is OFF, the maximum reverse voltage and hence the voltage stress across it is two times the voltage across the secondary winding. The maximum voltage stress on diode is 1.25 kV. Since each rectifier diode is directly supplied from the secondary of the transformer, string of series-connected diodes get eliminated, and the associated voltage mis-sharing. The voltage across the diode is 1.25 kV when it is OFF as shown in Fig. 5.
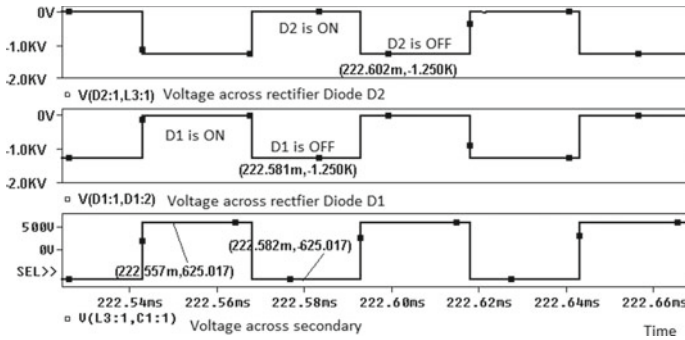
Fig. 5 From bottom to top: Trace 1. Voltage across one secondary of HVT, Trace 2 and 3. Voltage across rectifier diodes D1 and D2

4.3 Zero-Current Turn-On Operation and Short Circuit Limit

Zero-Current Turn-on Operation: When the converter is operating at higher switching frequencies switching losses and higher. Zero-voltage or zero-current switching reduces switching losses. As the converter is designed to operate in discontinuous conduction mode, the current starts building up linearly from zero. This ensures zero-current turn-on operation and minimizes the switching losses. This is achieved without any additional components. Zero current switch-off condition is not maintained in the circuit.

Zero current turn-on operation is verified through simulation and the results (waveforms) for rated load current of 100 mA are shown in Fig. 6a. At the instant when switch S1 is ON, the current through the switch starts increasing from zero linearly and reaches the peak value. There is a dead time where the current remains zero. Similar operation occurs with switch S2 also. Discontinuous operation is maintained in other load conditions also.

Short Circuit Limit: The fly-back transformer in the input side is an advantage in limiting the short circuit current at the load side. If there is a short circuit at load side, drop across the fly-back primary is increased. The drop across the fly-back primary is increased to 18.2 V, when the load current is 350 mA (3.5 times of rated current) as shown in Fig. 6b. This indicates the instantaneous current limiting capability under short circuit.

4.4 Recovery of Stored Energy by Feedback Operation

When the power switch is ON, considerable amount of energy is stored in the magnetic field of fly-back transformer. If the stored energy available is not properly handled, it gets lost and the efficiency of the converter also decreases. Therefore to recover the stored energy, it is transferred to the secondary side when switches
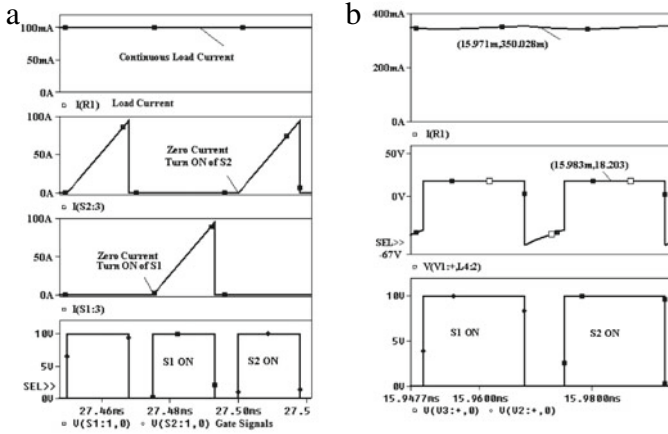
Fig. 6 **a** From bottom to top: Trace 1: gate signals S1 and S2, Trace 2: switch current S1, Trace 3: switch current S1, Trace 4: load current, **b** From bottom to top: Trace 1: gate signals S1 and S2, Trace 2: drop across fly-back inductance Trace 3: load current

are OFF. For the effective transfer of stored energy, the secondary inductance is designed such that discontinuous conduction mode (DCM) is ensured. This makes the effective transfer of stored energy and also resetting of flux in the magnetic core. When the switch S1 is closed, the fly-back primary winding current starts building up linearly from zero and the energy gets stored in the fly-back inductor. During the same time diode D3 is reverse biased due to the polarity of induced emf on the secondary winding of fly-back, and no current flows in the secondary winding L_{2s} of fly-back transformer. When switches S1 and S2 are OFF, reversal of polarity on the fly-back secondary winding makes the diode D3 forward biased. The fly-back secondary current decays to zero before next power switch S2 is ON, resulting in complete transfer of energy to the fly-back secondary and then back to the source.

The energy stored during ON time of switch is

$$E_{\text{Stored}} = \frac{L_{2P}\, I_{\text{pk}}^2}{2} \tag{9}$$

I_{pk} denotes the magnitude of fly-back primary peak current at the end of conduction period. By knowing the values of L_{2p} and I_{pk} from Eqs. (6) and (7), theoretical value of energy stored calculated at rated load condition using Eq. (9) is 4250 µJ. The value of energy stored obtained from the simulated waveform shown in the Trace 2 and 4 of Fig. 7.

$$E_{\text{Stored}} = 1.12\,\mu\text{H} \times 87.73^2/2 = 4257\,\mu\text{J}$$

Figure 7 Trace 3 shows that the secondary current reduces to zero before switch S2 is ON. This shows the circuit is operating in the discontinuous conduction mode and
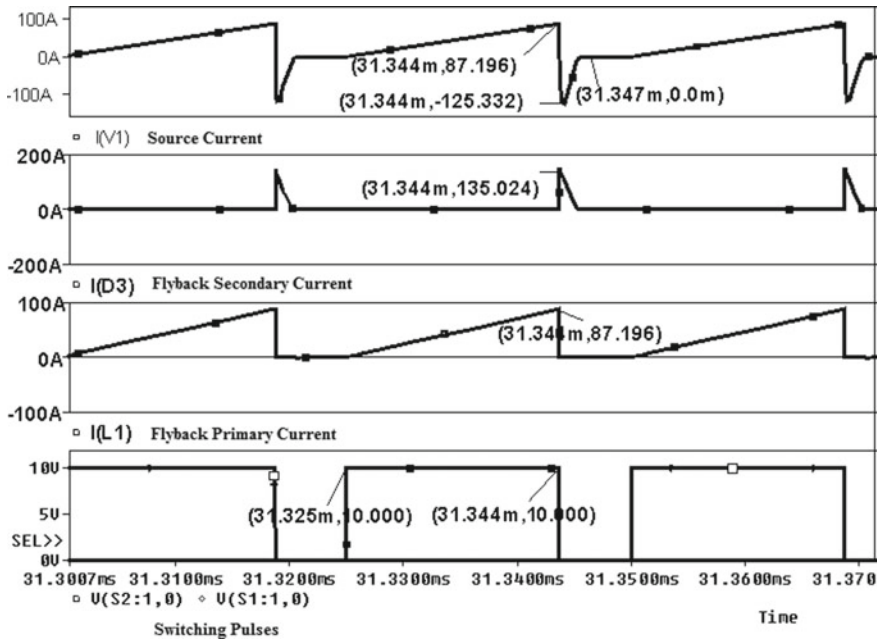
Fig. 7 From bottom to top: Trace 1: gate signals S1 and S2, Trace 2: fly-back primary current, Trace 3: fly-back secondary current, Trace 4: source current

energy is completely transferred to the source via fly-back secondary. The negative polarity on source current is shown in Trace 4, of Fig. 7 indicates current being fed-back to the source. Thus the energy fed-back to the source can be calculated as follows

$$E_{\text{Fed-back}} = V_{\text{in}} \times \left(I_{\text{pk}}/2\right) \times t_f$$
$$= 20.4 \times (125.33/2) \times 3\mu = 3835\,\mu\text{J} \tag{10}$$

Hence 90.09% of the total stored energy is fed-back to source while the remaining energy is stored in capacitor C of the feedback circuit. From the simulated waveforms and energy calculations, it is clear that the energy stored in the magnetic core of fly-back transformer during ON time of the switch is effectively transferred to the source during OFF time of the switch. The average current drawn from the source obtained using simulation is 31A. If the input source is the battery, then the energy feedback aids in charging the battery during OFF time of switches.

5 Conclusion

This paper presents a fly-back current-fed push–pull DC-DC converter suitable for high voltage low current applications. The four modes of operations of the converter over one switching cycle are analyzed. With an established design procedure the converter is designed for an output of 5 kV, 500 W from a 24 V source, operating at non-overlapping mode with four secondary windings simulated. The results obtained show that the converter with series-connected multiple secondary windings along with voltage doublers gives the flexibility in high voltage levels obtained at the output. Rectifier diodes are subjected to less voltage stress therefore commercially available diodes can be used which results in reduced cost. Zero current turn-on of switches ensures zero turn-on switching losses. Short circuit current at load side gets limited by dropping the voltage across the fly-back inductance. Energy feedback is effective due to Fly-back secondary connected back to the source. Simulation results show that at rated current, 90.09% of stored energy is fed-back to the source during OFF time, making the system energy efficient. The output of the converter for a voltage of 50 kV at 1 kW power level is also presented to validate the design procedure. The proposed converter is more suitable for small-scale ESP power supply applications.

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