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Selection of Isolated DC-DC Converter for Low Power Applications with Current Double Rectifier

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ABSTRACT

A high frequency, low voltage, high current DC-DC converter is most suitable for high speed electronic circuits like microprocessors, telecommunication networks etc. This paper presents the details regarding the selection of Isolated DC-DC converter for high current applications using Current Double Rectifier (CDR) among four isolated DC-DC Converters such as flyback, forward, push-pull and two switch forward converter. To increase the efficiency of the transformer, CDR is used at the output which has the property of one diode conduction drop, provides much higher conversion ratio without using high turns ratio, thereby reducing stress on the secondary side. All the above isolated converters like flyback, forward, push pull and two switch forward converters were designed and simulated and results were validated for 5V/10A at 100kHz switching frequency. For the same output power level Forward converter is found to be the most suitable among other isolated converters having minimum turns ratio and low leakage inductance.

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INTRODUCTION

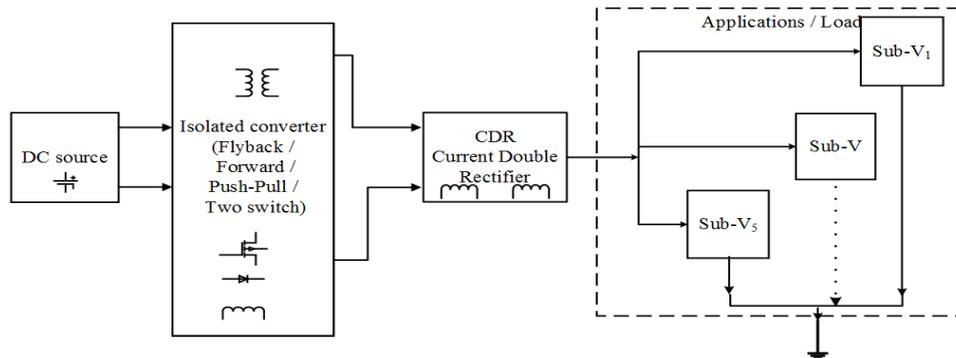


Fig. 1: Block diagram of isolated converter topology with CDR.

The DC voltage from standalone source or uncontrolled rectifier circuit is fed to isolated converter topology and the output of converter is given as input to CDR (Laszlo, 1999) circuit which reduces the transformer secondary burden. Any one of the Isolated Converter topologies like flyback, forward, or Push-pull can be used in block2 of fig.1. For comparative analysis, parameters like output voltage V_o , duty cycle (D) and switching frequency f_s , the same values have been taken throughout. Fig.1 is the Block diagram representation of isolated converter topologies and CDR with multiple output voltage levels. By single step power conversion a high efficiency greater than 90% and high power density can be achieved. Basic nonisolated converters like Buck, Boost and Buck-Boost converters are used for low power applications. For industrial power supply like SMPS (Bor-Ren and Shih-Jung, 2005) in a hazardous environment (explosive, radiation, etc.,) where DC isolation required between the supply and load, isolated converters are used. Further for high power density applications,

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different voltages that are connected together can cause ground loop current due to slight difference in ground potential. Power supplies are subjected to transient noise in switching circuits. Ground loop and common noise interferences are interrupted by DC isolation. Considerable reduction in size of transformer can be achieved when incorporated in DC-DC structure operated at high frequencies. Leakage inductances and resistances influence conduction losses of the converter. The leakage inductance causes not only voltage stress across the switch but also undesirable oscillation with parasitic capacitance. Hence transformers with minimum leakage inductance are preferred. In soft switching, leakage inductance can be used as a part of resonant snubber circuit to reduce losses. L_m plays a vital role in converter operation. The impedance of magnetizing inductance L_m is large over a wide range of frequency such that magnetizing current i_m is small compared to the primary current. Magnetizing current is proportional to magnetic field. If i_m increases magnetic field also increase causing core saturation. Magnetic inductance decays towards zero and ultimately shorting transformer. Magnetizing inductance like inductor obeys Volt-Sec balance rule, the average voltage across it in steady state switching cycle being zero.

Basic isolated converters like flyback and forward converters are used for low power level from 50W to 200W. For medium power level, Push-pull and Half Bridge converter from 500W to 1kW are used. For high power levels Full Bridge converter from 1kW to 5kw are used. For very high power levels (1kW) three level or multilevel converters can be used. Medium frequency IGBTs for On-board medium power applications (20-500 kW e.g., air conditioners) and high frequency MOSFETs for On-board low voltage applications (1-100 kW e.g., battery chargers, control units, emergency apparatus, LED lightings) are used.

Flyback converter is a buck-boost converter with an isolation element. To realize input to output DC isolation control circuit also needs isolation circuits such as optocouplers or transformers. This is one of the oldest converters used not only in 19th century by Hertz but also in 20th century it was used in ignition system of Ford T model car. Flyback converter is most widely used in low power, high input voltage applications designed to work with rectified universal AC lines, typically from 20 to 200 W from battery-operated digital cameras, DVD players adapter television sets, computer monitors, printers, lasers, spark-ignition engines, etc. Since its efficiency is low, it prevents it from medium to high power applications. From all isolated SMPS flyback converter has smallest part count.

Push-pull converter is a combination of two forward converters operated in antiparallel. It is a buck derived medium power converter.

Forward converter is a single-ended (uses one half of B-H curve) isolated buck derived converter. Its air gap core is bulky and requires core reset. Transformer magnetizing inductance is not used to store magnetic energy. The switch has to withstand high voltage stress. This converter is better suited for low to medium power applications. Negative output can be obtained by reversing secondary and two diodes. Single or multiple outputs are possible. The origin of the forward converter was as early as 1956 of Paynter, who uses a primary-side circuit containing two transistors, one for transferring the power and one labeled "reset".

Various researches on isolated buck derived converters with interleaving like Push-pull (Hong et al, 2004) & (Hong et al, 2005), FB (Rene et al, 2008) have been done. Interleaving (CDR) enables the converter topologies to operate at increased power levels. Further soft switching (ZVS) techniques to turn on the main switch have been analyzed in FB (Lin et al, 2006), two switch forward converter (Lin et al, 2007), forward-flyback converter (Laszlo and Milan, 1999). In biomedical implant using Transcutaneous energy transfer (TET) on Push-pull converter (Bob et al, 2010) is under development. For battery charger and power factor correction Hybrid Phase Modulated Converter (HPMC) (Rinkle et al, 2006) uncontrolled FB and Controlled PM are used. To enhance CDR performance Coupled inductor with soft switch on FB have been implemented. CDR is the most preferred rectifier technique (Laszlo, 2000), (Alou et al., 2006) for high current application (Lin et al, 2006). With increased output current both in isolated and nonisolated Point of Load (POL) converters, number of phases in a converter and number of paralleled channels are highly demanding. Current sharing (Tsai-Fu et al, 2008) in CDR is a critical issue since uneven current sharing can cause inductor saturation, thermal stress and decreased performance of converters. CDR finds its use in Fuel Cells (Jung-Min and Bong-Hwan, 2009). This paper presents selection of isolated DC-DC converter for 50W low power applications based on comprehensive comparative analysis of buck; boost and buck-boost derived isolated converters. All the simulations are done on Matlab-simulink environment for CCM.

This paper is organized as follows. The CDR and its modes of operation are reviewed. Three isolated converters and its mathematical model of flyback, forward, and Push-pull are done. Comparison of isolated converter with CDR is illustrated. Finally concluded with Simulation results and discussions.

Current Double Rectifier

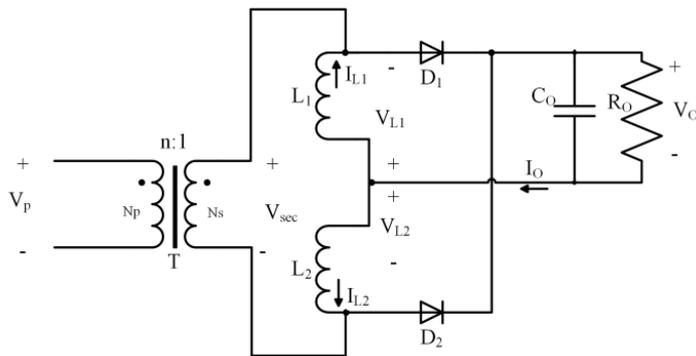


Fig. 2: Circuit diagram of CDR.

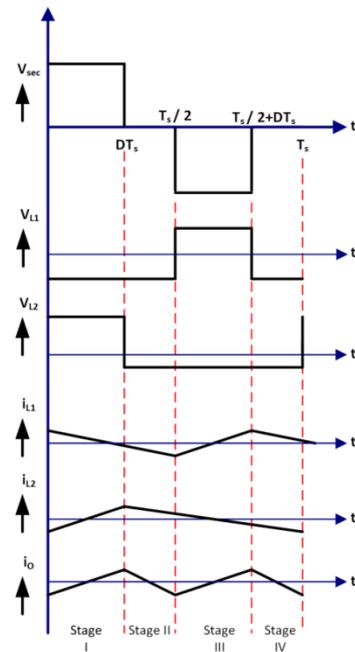


Fig. 3: Waveforms of CDR.

CDR is an alternate rectification circuit as shown in fig.2 and their waveforms for all four modes of operation are shown in fig.3. Power supplies which handle large load currents, CDR can be used. With Its simple structure and better utilization of isolation transformer in Push-pull, Half Bridge (HB), bridge power circuits lower and better power distribution with smaller magnetic components can be achieved. A Push-pull, HB and bridge circuit utilizes bipolar voltage across the secondary winding where Full Wave Rectifier is normally used.

The current double rectifier contains a secondary winding in a single-ended configuration, with two output Inductors and an output capacitor. The voltages across the primary and secondary windings, and across the two inductors, as well as the inductor currents, i_{L1} and i_{L2} , are defined as shown in the fig.3.

For the push-pull, half-bridge and full-bridge converters, a current double rectifier can be used. It can be used in a zero-voltage-switching (ZVS) forward converter (called a forward/flyback converter due to its typical operation). The common property of these converters is that they present a bipolar voltage across the secondary winding of their transformer.

A current-mode control, like peak-current type, has to be used to keep the average values of the two output inductors currents to be equal.

Particularly in power supplies used for delivering a very low output voltage (for example those supplying integrated circuits), the load current can take very large values, causing large power dissipation. In full-wave rectifier with center-tapped transformer secondary, in each of the freewheeling stages the output current was evenly distributed between the two halves of the secondary winding. However, in practice, the leakage inductance of the transformer causes a different behavior. After an energy-transfer stage, the half part of the rectifier circuit, which was carrying the load current during the active stage, will continue to carry most of it, while the current in the other half of the rectifier circuit builds up slowly depending on the energy stored in the leakage inductance. Eventually, after some time, both rectifier diodes and halves of the secondary winding will carry equal half-load current. This uneven current distribution causes large root-mean-square (rms) values of the currents in each half of the secondary circuit, implying larger conduction losses in the secondary winding and rectifier diodes. The same discussion is valid for full-wave diode bridge rectifiers.

Some important properties of CDR compared to Full Wave Rectifier (FWR its counterpart) are like it doesn't require center tapping with fine turns ratio. It has simple transformer structure. Further transformer secondary as well as each filter inductor carries approximately half of the average DC output current. To have equal currents in the filter inductor current-mode control can be used. Ripple current cancels at the output capacitor.

Isolated Converters:

Flyback Converter:

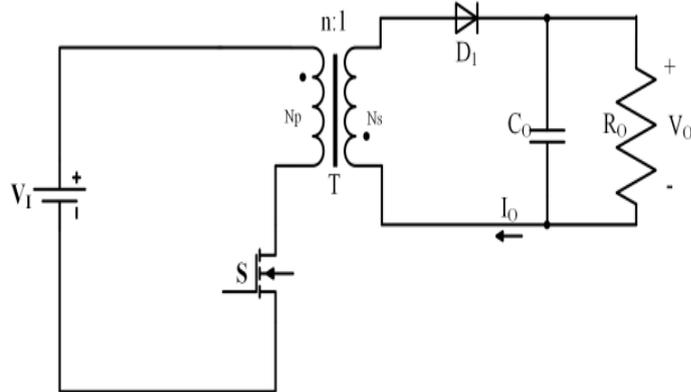


Fig. 4: Circuit Diagram of Flyback converter.

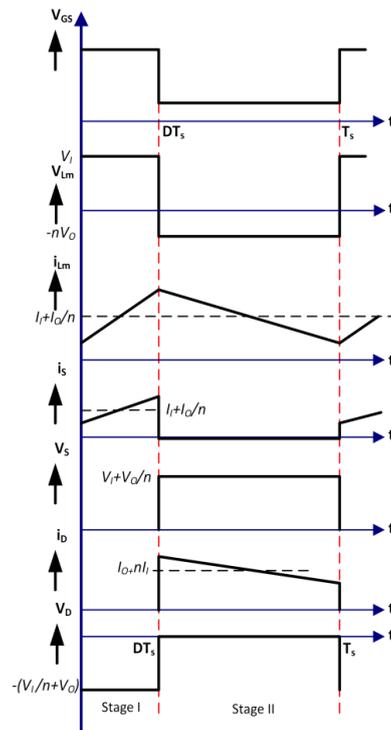


Fig. 5: Waveforms of Flyback converter.

Flyback converter is shown in fig.4. And its waveforms are shown in fig.5. Transformer performs several functions like DC isolation, Magnetizing inductance of transformer stores magnetic energy hence inductor is not required. It changes output voltage levels; it could be positive or negative. Additional secondary windings and rectifiers could be added to have multiple output of any polarity.

In the first switching freewheeling stage, the magnetizing inductance stores input energy. No energy is transferred to load. The voltage across the diode is $-(V_1/n + V_o)$ which maintains the diode in OFF state. The voltage across magnetizing Inductance L_m is V_1 , and the inductor current increase linearly with the slope (V_1/L_m) .

In the active powering stage, when the switch is OFF, diode is ON, that is when the input voltage is disconnected, and energy is transferred to load. Isolation element is coupled inductor, acts like inductor in case of buck-boost converter. There is no need for magnetic reset mechanism. Thus ends up in simple structure. The voltage across magnetizing inductance L_m is $(-nV_o)$ which decreases the magnetizing inductance current by $(-nV_o/L_m)$. The voltage across the switch is $(V_1 + nV_o)$.

The principle of operation of flyback converter as shown in fig.5 is by idealized current and voltage. The transformer is modelled by ideal transformer and its magnetizing inductance L_m .

Design Equations:

The output voltage and currents are V_o and I_o . f_s is the Switching frequency.

The minimum and maximum RMS AC input voltages are V_{imin} and V_{imax} .

$$P_{Omax} = V_o I_{Omax}, P_{Omin} = V_o I_{Omin} \tag{1}$$

$$M_{VDCmin} = \frac{V_o}{V_{imax}}, M_{VDCmax} = \frac{V_o}{V_{imin}} \tag{2}$$

$$R_{Lmin} = \frac{V_o}{I_{Omax}}, R_{Lmax} = \frac{V_o}{I_{Omin}} \tag{3}$$

$$V_{dc_min} = \sqrt{2}V_{imin}, V_{dc_max} = \sqrt{2}V_{imax} \tag{4}$$

$$n = \frac{N_p}{N_s} = \frac{\eta D_{max}}{(1 - D_{max})M_{VDCmax}} \tag{5}$$

$$D_{min} = \frac{nM_{VDCmin}}{nM_{VDCmin} + \eta}, D_{max} = \frac{nM_{VDCmax}}{nM_{VDCmax} + \eta} \tag{6}$$

$$L_{m_min} = \frac{n^2 R_{Lmax} (1 - D_{min})^2}{2f_s} \tag{7}$$

$$C_{min} = \frac{D_{max} V_O}{f_s R_{Lmax} V_{C_{pp}}} \quad (8)$$

Forward Converter:

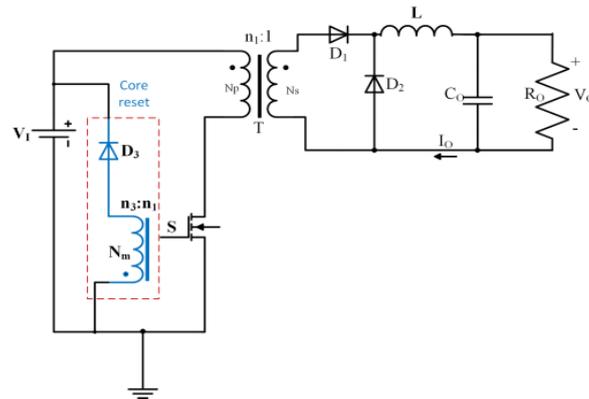


Fig. 6: Circuit of Forward converter.

Forward converter is shown in fig.8 and its waveforms are shown in fig.9 and fig.10.

Forward converter is buck derived converter by adding transformer and diode D_1 between switch and freewheeling diode D_2 . Magnetizing inductance L_m cannot be connected parallel to with diode D_2 because average steady state voltage across inductor is zero and average voltage across diode is negative. To overcome this contradiction D_1 is connected between inductor L_m and diode D_2 . The average voltage across $V_{D1}=V_{D2}$. The switch and the diode D_1 are either ON or OFF during the same time intervals whereas the diode D_2 is in opposite state to both switch and diode D_1 . When the switch is ON, voltage across inductor is equal to V_1 and inductor current increases linearly. When the switch is turned OFF, the diode D_1 is also turned OFF and the inductor is open circuited. The current and energy stored in inductor are nonzero. To demagnetize the inductor L_m and extra winding with reversed polarity coupled to inductor N_m and D_3 are added. This extra winding called core reset tertiary winding (clamp winding) cause negative voltage across it and the inductor current decreases. It has same number of winding as primary winding and bifilar wound. It clamps the voltage across the switch at twice the line voltage V_1 . Reset branch creates a path for discharging L_m after the switch is turns OFF. The duty cycle is limited to 50%. In addition switch is held off long enough for inductor current to decrease to zero. A negative output voltage can be obtained by reversing secondary and diodes D_1 and D_2 . Multiple output converter voltage can be obtained by adding extra secondary winding, D_1 , D_2 , filter inductor L and filter capacitor C . The disadvantage of buck converter (switch neither gate nor source connected to ground) is overcome by moving the switch and connected to ground as in boost converter.

Design Equations:

$$P_{Omax} = V_O I_{Omax}, P_{Omin} = V_O I_{Omin} \quad (9)$$

$$M_{VDCmin} = \frac{V_O}{V_{Imax}}, M_{VDCmax} = \frac{V_O}{V_{Imin}} \quad (10)$$

$$R_{Lmin} = \frac{V_O}{I_{Omax}}, R_{Lmax} = \frac{V_O}{I_{Omin}} \quad (11)$$

$$V_{dc min} = \sqrt{2} V_{Imin}, V_{dc max} = \sqrt{2} V_{Imax} \quad (12)$$

$$n_1 = n_3 = \frac{N_p}{N_s} = \frac{\eta D_{max}}{M_{VDCmax}} \quad (13)$$

$$D_{min} = \frac{n M_{VDCmin}}{\eta}, D_{max} = \frac{n M_{VDCmax}}{\eta} \quad (14)$$

$$L_{m_min} = \frac{R_{Lmax} (1 - D_{min})}{2 f_s} \quad (15)$$

$$\Delta i_{Lmax} = \frac{V_O (1 - D_{min})}{f_s L} \quad (16)$$

$$V_r = 1\% V_O, r_{cmax} = \frac{V_r}{\Delta i_{Lmax}} \quad (17)$$

$$C_{min} = \left\{ \frac{D_{max}}{2 f_s r_c}, \frac{1 - D_{min}}{2 f_s r_c} \right\} \quad (18)$$

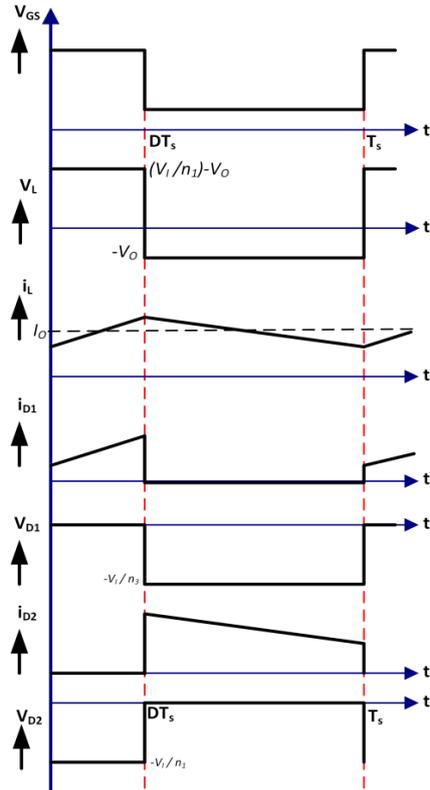


Fig. 7: Waveform of Forward converter.

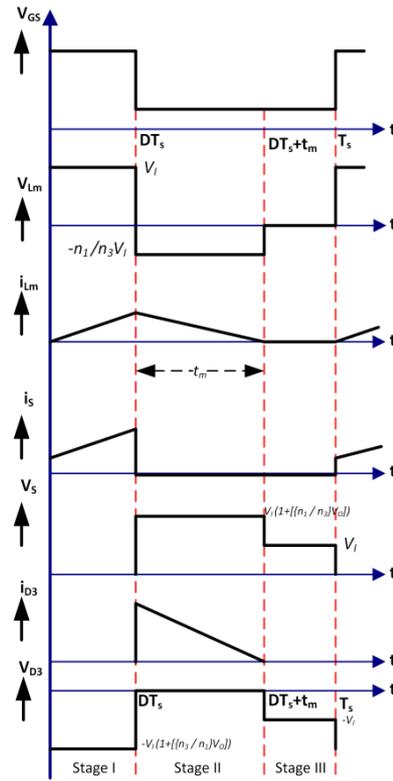


Fig. 8: Waveform of Forward converter.

Push-pull converter:

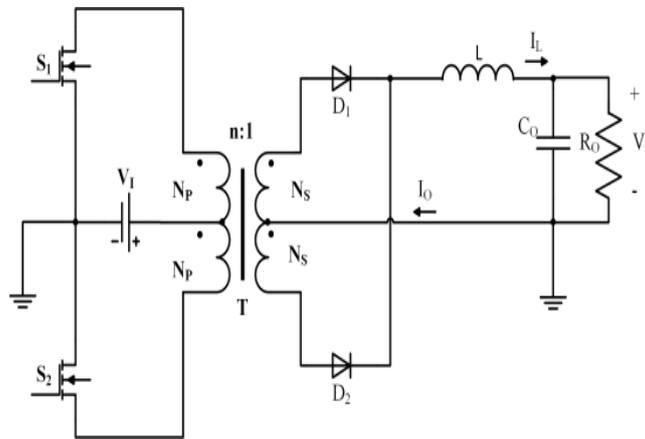


Fig. 9: Circuit of Push-pull converter.

Push-pull converter is shown in fig.14. And its waveforms are shown in fig.15 and fig.16. The primary side contains two switches driven in antiphase (180°) by nonoverlapping signals i.e., when S_1 is ON, D_1 is ON and D_2 is OFF and When S_2 is ON, D_2 is ON and D_1 is OFF are shown in fig.17 to fig.20. The voltage across the switch is high. Flux imbalance due to DC current in transformer primary cause core saturation. Each switch operates with a duty cycle equal to 0.5 (practically ≤ 0.5). To avoid "shoot through" current spikes the dead time has to be at least equal to the turn-off duration of the switch. Both the switches are connected with the gate referenced to ground. A small high frequency double center tapped excited at both ends is used to have better utilization of transformer core. The two windings of primary are wound in the same direction on the same core and two halves of a center tapped windings can be treated as two separate windings. The two primary and two secondary windings are identical each one with N_p , N_s turns. Transformer does not store energy. It has high magnetizing inductance to reduce magnetizing current.

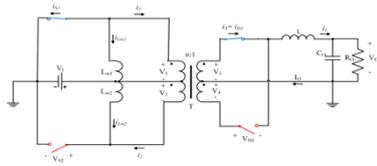


Fig. 10: Circuit of Push-pull for $(0 \leq t < DT_s)$.

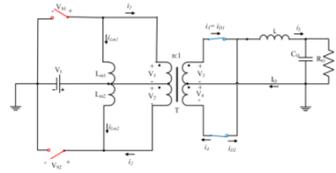


Fig. 11: Circuit of Push-pull for $(DT_s \leq t < \frac{T_s}{2})$.

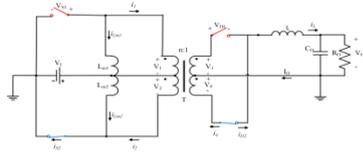


Fig. 12: Circuit of Push-pull for $(\frac{T_s}{2} \leq t < \frac{T_s}{2} + DT_s)$.

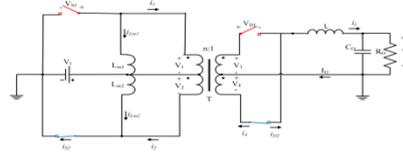


Fig. 13: Circuit of Push-pull for $(\frac{T_s}{2} + DT_s \leq t < T_s)$.

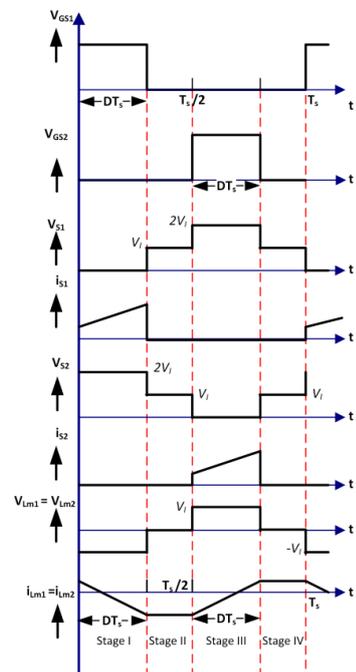


Fig. 14: Waveforms of Push-pull converter.

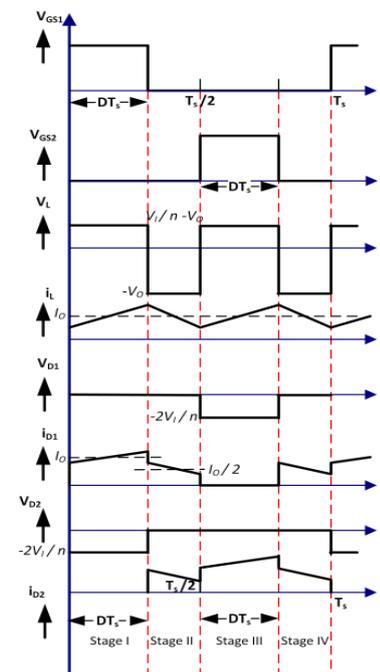


Fig. 15: Waveforms of Push-pull converter.

Design Equations:

$$P_{Omax} = V_O I_{Omax}, P_{Omin} = V_O I_{Omin} \tag{19}$$

$$M_{VDCmin} = \frac{V_O}{V_{Imax}}, M_{VDCmax} = \frac{V_O}{V_{Imin}} \tag{20}$$

$$R_{Lmin} = \frac{V_O}{I_{Omax}}, R_{Lmax} = \frac{V_O}{I_{Omin}} \tag{21}$$

$$V_{dc\ min} = \sqrt{2}V_{Imin}, V_{dc\ max} = \sqrt{2}V_{Imax} \tag{22}$$

$$n = \frac{N_p}{N_s} = \frac{M_{VDCmax}}{nM_{VDCmin}} \tag{23}$$

$$D_{min} = \frac{2\eta}{nM_{VDCmin}}, D_{max} = \frac{nM_{VDCmax}}{2\eta} \tag{24}$$

$$L_{m_min} = \frac{R_{Lmax} (\frac{1}{2} - D_{min})}{2f_s} \tag{25}$$

$$\Delta i_{Lmax} = \frac{V_O (\frac{1}{2} - D_{min})}{f_s L} \tag{26}$$

$$V_r = 1\% V_O, r_{cmax} = \frac{V_r}{\Delta i_{Lmax}} \tag{27}$$

$$C_{min} = \left\{ \frac{D_{max}}{2f_s r_c}, \frac{\frac{1}{2} - D_{min}}{2f_s r_c} \right\} \quad (28)$$

Simulation Results:

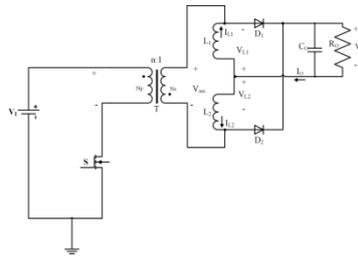


Fig. 16: Circuit of Flyback with CDR.

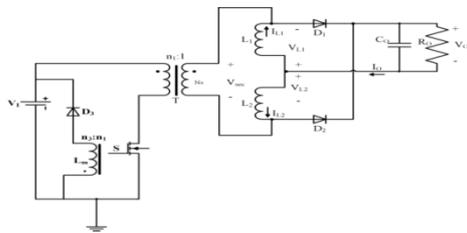


Fig. 17: Circuit of Forward with CDR.

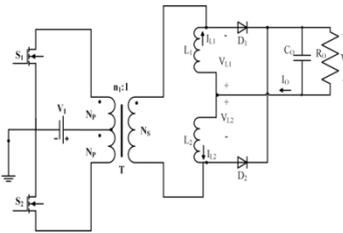


Fig. 18: Circuit of Push-pull with CDR.

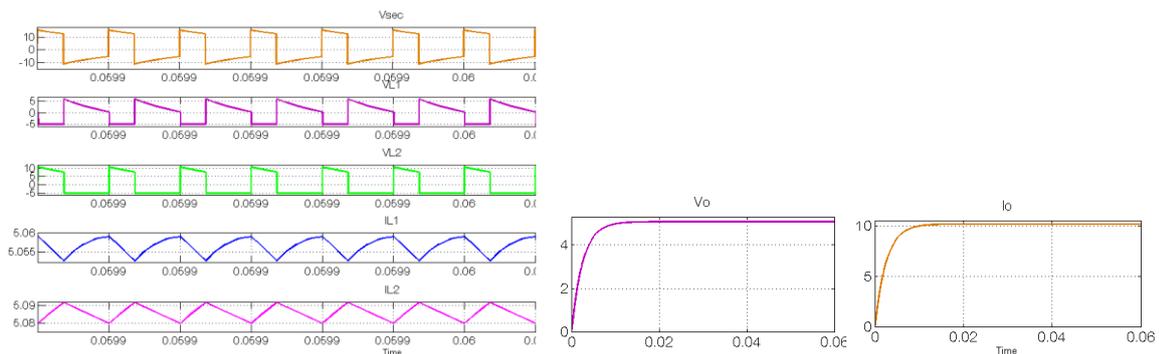


Fig. 19: Flyback - CDR Waveforms, Output voltage and Output current.

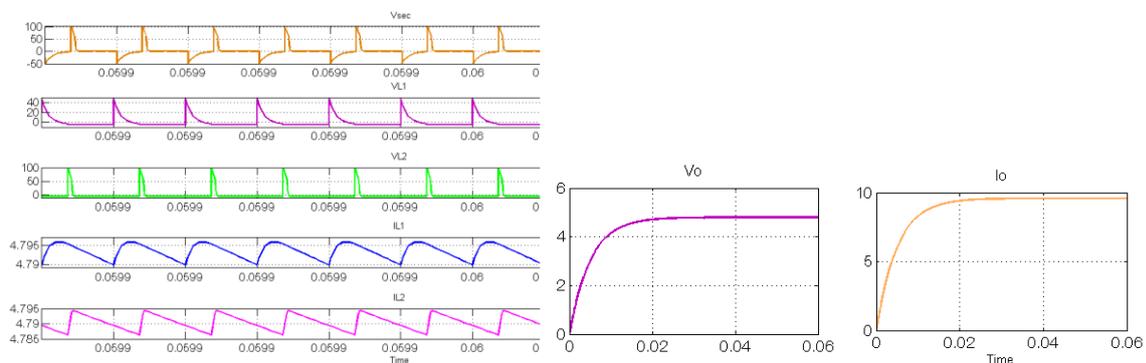


Fig. 20: Forward - CDR Waveforms, Output voltage and Output current.

The three isolated converter with CDR are shown in fig. 17 to fig.19. And their simulated key waveforms are shown in fig. 20 to fig. 22. Secondary voltage V_{sec} and CDR voltages V_{L1} and V_{L2} , currents I_{L1} and I_{L2} , Output voltage V_o and output current I_o is shown in figures.

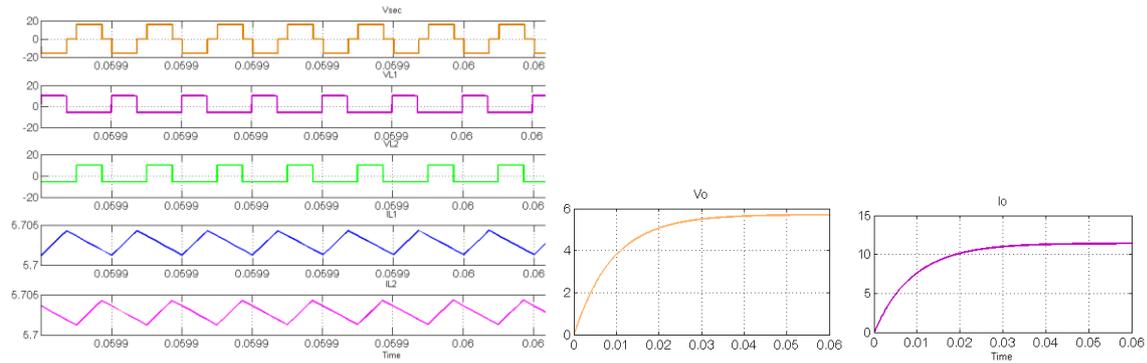


Fig. 21: Push-pull - CDR Waveforms, Output voltage and Output current.

RESULTS AND DISCUSSIONS

A comprehensive design and comparison is being made on all the above mentioned converters in Matlab Simulink and the following inferences are drawn.

Design specifications of isolated converters for CCM:

All the isolated converters were designed for

- Output voltage (V_o) ----- 5V
- Output current (I_o) ----- 1A to 10A
- Maximum output power (P_o)----- 50W
- Output ripple voltage (V_{ripple})----- $\leq 1\% V_o$
- Targeted overall efficiency (η)----- 80%
- Maximum duty cycle (D)----- 0.36
- Universal input voltage range (V_{rms})-- 85 to 264
- Maximum load resistance----- 5 Ω

Parameter of isolated converters:

Table I: Comparison of Isolated Converters.

PARAMETERS	FLYBACK	FORWARD	PUSH-PULL
Derived type	Buck-Boost	Buck	2 forward converter-antiparallel
Power range	20-200W	30-500W	150-500W
No. of switches	1	1	2
Core reset	No	Yes	No
Magnetic storage	Yes	No	No
B-H curve	Single ended	Single ended	Double ended
Voltage stress on switch	$V_1 \max + nV_o$	$2V_1 \max$	$2V_1 \max$
Magnetizing inductance (L_{m_min})	$\frac{n^2 R_{L_max} (1 - D_{min})^2}{2f_s}$	$\frac{R_{L_max} (1 - D_{min})}{2f_s}$	$\frac{R_{L_max} (\frac{1}{2} - D_{min})}{2f_s}$
Magnetizing current (Δi_{Lm_max})	$\frac{nV_o (1 - D_{min})}{f_s L_{m_min}}$	$\frac{V_o (1 - D_{min})}{f_s L_{m_min}}$	$\frac{V_o (\frac{1}{2} - D_{min})}{f_s L_{m_min}}$
Voltage ripple ($V_{c_{pp}}$)	$\frac{V_o D_{max}}{f_s R_{L_min} C_{min}}$	$\frac{\Delta i_{Lm_max}}{8f_s C_{min}}$	$\frac{\Delta i_{Lm_max}}{16f_s C_{min}}$
Filter Capacitor (C_{min})	$\frac{D_{max} V_o}{f_s R_{L_max} V_{c_{pp}}}$	$\frac{\Delta i_{Lm_max}}{8f_s V_{c_{pp}}}$	$\frac{\Delta i_{Lm_max}}{16f_s V_{c_{pp}}}$
Output voltage (V_o)	$\frac{DV_1}{n(1 - D)}$	$\frac{DV_1}{n_1}$	$\frac{2DV_1}{n}$
Sensitivity of output voltage ($S \equiv \frac{d}{dD} V_o$)	$\frac{V_1}{n(1 - D)^2}$	$\frac{V_1}{n_1}$	$\frac{2V_1}{n}$
Duty cycle (D)	$0 \leq D \leq 1$	$0 \leq D \leq 0.5$	$0 \leq D \leq 0.5$
DC voltage transfer function (M_{V_DC})	$\frac{D}{n(1 - D)}$	$\frac{D}{n_1}$	$\frac{2D}{n}$
Efficiency ($\% \eta$)	$V_o / (V_1)$	$V_o / (V_1)$	$V_o / (V_1)$

Table II: CCM/DCM Boundary as a Function of Duty Cycle (D).

NORMALIZED LOAD CURRENT AND LOAD RESISTANCE, B-Boundary conditions		
CONVERTER	LOAD CURRENT	LOAD RESISTANCE
FLYBACK	$\frac{I_{OB}}{nV_O/2f_s L_{m_min}} = (1 - D_{min})^2$	$\frac{R_{LB}}{2f_s L_{m_min}/n} = \frac{1}{(1 - D_{min})^2}$
FORWARD	$\frac{I_{OB}}{V_O/2f_s L_{m_min}} = (1 - D_{min})$	$\frac{R_{LB}}{2f_s L_{m_min}} = \frac{1}{(1 - D_{min})}$
PUSH-PULL	$\frac{I_{OB}}{V_O/2f_s L_{m_min}} = \left(\frac{1}{2} - D_{min}\right)$	$\frac{R_{LB}}{2f_s L_{m_min} n} = \frac{1}{\left(\frac{1}{2} - D_{min}\right)}$

Table III: Components of Isolated Converters.

PARAMETERS	FLYBACK	FORWARD	PUSH-PULL
Turns ratio (n)	11	7	14
Filter Capacitance C _O (μF)	200	200	70
Magnetizing inductance L _m (mH)	0.22	0.022	250
Leakage resistance of transformer R _m (Ω)	25	250	550
CDR inductance L ₁ and L ₂ (mH, each)	2.75	5.5	12

Table I gives the comparison of four isolated converter parameters and its design equations whereas Table II is for inductor selection which limits its value between CCM and DCM boundary conditions. Table III gives the numerical values for all four converter parameters based on design equation mentioned in Table I.

From Table III, it is found that forward converter is the most suitable one for low power applications. It has very low leakage inductance 0.022mH and low output filter inductor each of 5.5mH compared to other converters. Further it has very low turns ratio of 7.

From Table. I, Some cons of one switch converter like smaller power capability than a full or HB topology, disadvantage of buck derived converters can be overcome by moving the position of switch to ground, limited duty cycle excursion because of core reset, the drain voltage swings to twice the input voltage or more.

With more than one switch transformer B-H curve can be fully utilized. In spite of push-pull being two switch converter, it has high turns ratio.

To maintain constant output voltage, input voltage V_I and duty cycle D can be varied.

By resetting core, energy stored in magnetizing inductor is fed back to input power supply. Without core reset the current builds up at each switching cycle and saturates core.

Some standard techniques are

- Tertiary winding, as in forward converter to increase duty ratio $> 50\%$. Switch stress is very high $> 2V_I$.
- RCD clamp, to increase duty ratio greater than 50%. Costs less than tertiary winding. Design and simulation complicated.
- 2-switch forward, easy to implement and limits the switch stress to V_I . Additional switch and diodes and complicated driving circuit.

Conclusions:

For the same power output forward converter has a good power density with minimum turns ratio and low transformer leakage inductance. This enables to have compact transformer. Though the size of CDR inductor is double that of the other converters the use of single switch with reduced stress makes forward converter as a better choice compared to others in addition to the reduction in transformer size. If the rectifier diodes were replaced by self-driven synchronous rectifiers (SDSR), switching losses can be further minimized. Thus overall size reduction of converter with reduced switching loss can be achieved by single switch forward converter with CDR. In this connection an Active Clamp Forward converter with SDSR can be investigated.

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