Current Driven Full-Bridge Converter With Series And Parallel Inductors

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Abstract-*A novel Series-Parallel Current- Driven (SPCD) full-bridge DC/DC converter is able to process and deliver power efficiently over a wide range of load variations. In order to guarantee reliable operation, the converter should able to sustain soft-switching for a wide range of operating conditions. The SPCD full-bridge converter, proposed in this paper, is able to offer soft-switching for the input power semiconductors and smooth commutations. Also, the proposed converter structure eliminates the need for extra auxiliary circuits to provide reactive current for soft-switching at light loads. The proposed topology can fully eliminate voltage spikes across the output diodes by providing smooth and lossless commutations for the output diodes. Thus, the proposed converter can be an efficient and reliable solution for variety of applications with a high switching frequency and a high output voltage.*

Keywords*-*DC-DC converter, Zero voltage switching (ZVS), Current Driven Converter, Full- Bridge Converter.

I. INTRODUCTION

Isolated DC/DC converter have widely been used in several applications such as renewable energy power conditioning systems, Electric Vehicles (EVs), Telecom, etc. The well-known full-bridge inverter (including two legs with high-side and low-side power semiconductors) has extensively been utilized for DC/DC converters in industrial applications. Since the switch ratings are optimized for the full-bridge topology as an integral part of different power converters. For applications in the range of a few kilowatts, MOSFETs are mostly used to implement the full- bridge inverter. In order to have robust and reliable operation, MOSFETs should be switched under zero voltage. Operation with Zero Voltage Switching (ZVS) has numerous advantages including elimination of switching losses, a noise free environment for the control circuit,superior

EMI performance, and reliable operation of the power converter. ZVS is achieved by discharging the output capacitor of the MOSFET prior to the rising edge of the gate signal [5]. In isolated full- bridge converters the energy stored in the leakage inductance of the transformer is used to realize ZVS. However, in most cases, this energy is adequate only for heavy loads and the converter loses ZVS for light load conditions. For high frequency power converters, loss of ZVS implies that there will be extremely high switching losses and very high EMI due to the high di/dt of the snubber discharge current. Loss of ZVS can also cause a noisy control circuit, which leads to shoot- through and loss of power semiconductor switches. The ZVS range can be extended by increasing the series inductance. However, having a large series inductance limits the power transfer capability of the converter and reduces the effective duty ratio of the converter.

Another fundamental problem related to the conventional full-bridge phase-shift DC/DC converter is the voltage spikes across the output diodes. The voltage spikes are caused by the interaction between the leakage inductance of the transformer and the output inductor. The power losses caused by the voltage spikes are intensified by increasing the switching frequency and the load of the converter. Thus, the diodes are usually designed to be overrated so that they are able to withstand the voltage spikes (in many design exercises the diodes are designed to be able to withstand twice the nominal output voltage). In addition, the voltage spikes significantly contribute to the EMI noise produced by the converter. The aforementioned difficulties greatly confine the application of the full-bridge topology for high frequency, high voltage applications with a wide range of loadvariations.

Resonant converters are widely used to mitigate the aforementioned difficulties of the full-bridge converters [1]-[2]. The performance of the current- driven resonant converters (e.g. series

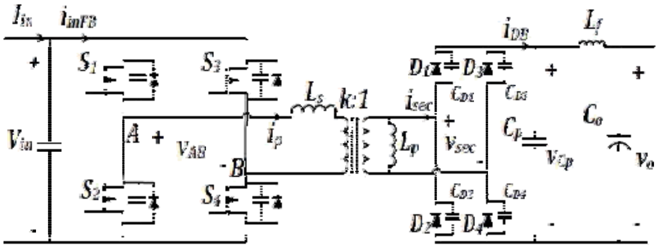


Fig 1. Circuit diagram of proposed series-parallel current-driven full-bridge DC/DC converter.

Resonant converters and LLC resonant converters) has proven to be superior compared to the voltage-driven resonant converters (e.g. LCC resonant converters). Resonant converters require extra passive components, which usually carry a significant amount of high frequency current. Therefore, achieving high power density and high efficiency is very challenging with resonant topologies. Also, the resonant topologies may lose soft-switching for light loads depending on the resonant circuit design and control system [3]-[9]. Asymmetric auxiliary circuits are used to significantly extend the soft-switching range of the full-bridge converter.

The auxiliary circuits provide inductive current to realize ZVS. Even though this topology is able to provide load independent ZVS, it is not able to eliminate voltage spikes across the output diodes. Also, the auxiliary circuits increase the current burden of the power semiconductors. In some references, the voltage spikes are reduced by decreasing the leakage inductance as much as possible though the transformer winding structure. However, reducing the leakage inductance decreases the ZVS operating range of the full-bridge converter, which results in a narrow range of ZVS operation. Snubber circuits are commonly used to mitigate the voltage spikes across the diodes. The main problem with the snubber circuits is the amount of losses in the snubber resistor, which considerably degrades the efficiency of the converter especially at higher power and it can only reduce the peak value of the voltage spikes. In [10], an active clamp circuit has been added to the converter to clamp the voltage across the output diodes. This method can effectively clamp the voltage spikes of the output diodes. However, the active clampcircuitincreases the complexity of the converter as well as small losses in the clamp circuit. Several Energy Recovery Clamp Circuits (ERCCs) have been proposed in [11]-[14]. Although the ERCC techniques are able to reduce the voltage stress across the output diodes, the amount of the voltage stress depends on the duty ratio and input voltage of the converter in most of the ERCC techniques.

In addition, using extra semiconductors is inevitable in all of these aforementioned methods. The problem of voltage spikes is essentially related to the voltage driven output rectifiers. In [30], a current driven full- bridge DC/DC converter has been proposed, which is able to completely eliminate the voltage spikes across the output diodes. The current- driven structure of this topology guarantees the smooth performance of the outputdiodes. Therefore, the reverse-recovery losses of the output diodes are eliminated and there is no need for expensive Silicon-Carbide (SC) diodes. The topology proposed in [15] is a good candidate for high-frequency high voltage DC/DC converters. The issue related to this topology is the need for an extra auxiliary circuit to guarantee ZVS for very light load conditions. The auxiliary circuit increases the current ratings of the power semiconductor and also decreases the power density of the DC/DC converter.

In this paper, a series-parallel current-driven full-bridge converter is proposed, which is able to provide soft-switching from light loads to full-load conditions without using any auxiliary circuit. Also, it is able to eliminate the voltage spikes across the output diodes and provide smooth commutations for the output diodes. This topology is intended for high-frequency high-voltage applications with high power density.

II. SERIES-PARALLEL CURRENT- DRIVENFULL-BRIDGECONVERTER

The arrangement in Fig.1 shows the proposed series-parallel current-driven full-bridge DC/DC Converter. The series-parallel current-driven full- bridge topology consists of a series branch including Ls and a parallel branch including Lp and Cp. According to Fig.1, the series inductor, Ls, is used to convert voltage pulses to current pulses and the parallel branch, Lp and Cp, is used to produce the reactive current for ZVS and realize the current-driven structure of the converter.

The series inductance, Ls, and the parallel inductance, Lp, can easily be embedded in the high frequency transformer. Also, the parallel inductance eliminates the need for the auxiliary circuit used to achieve ZVS. Thus, the series-parallel current-driven full-bridge topology can result in an efficient converter with a high power density. This is due to the fact that this topology is able to absorb the parasitic components of the transformer and use them to transfer power efficiently.

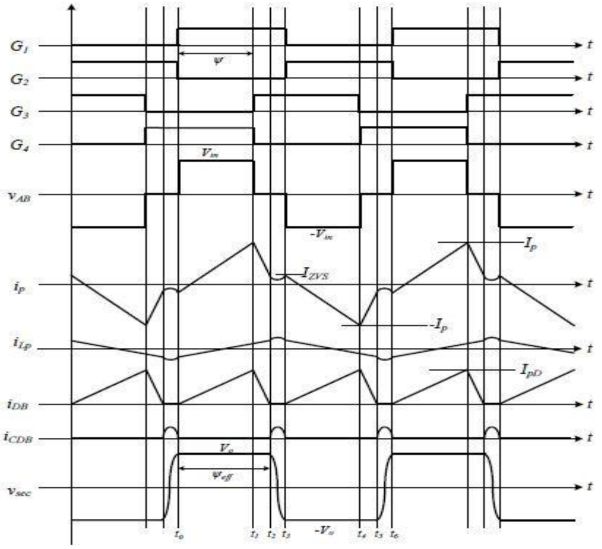


Fig 2. Key waveforms of the series-parallel current driven DC/D converter

According to Fig.1, when the parallel inductance current reaches the series inductance current the output diodes turn off. Therefore, the energy stored in the series inductance as well as the energy stored in the parallel inductance at that instant is used to discharge the effective output capacitance of the power semiconductors of the leading-leg (the effective output capacitance is the equivalent capacitor at the output of the power MOSFETs, including their parasitic capacitance and external snubber capacitors inserted to eliminate the turnoff losses of the MOSFETs). Since the energy of the two inductances are used to discharge the output capacitor of the power semiconductor, a small current is required to guarantee ZVS. Whereas, in the conventional full- bridge converter, only the energy of the leakage inductance is used to provide ZVS.

Fig. 2 shows the key waveforms of the proposed topology. According to this figure, the operation of the converter is divided into 10 different operating modes. Due to the symmetry, only five modes are presented as follows.

Mode 1: During mode1, the energy stored in series inductance is the difference between input voltage and parallel capacitance voltage. Now, switches S1 and S4 are conducting at the primary side and rectifier diodes D1 and D4 are forward biased. Across the primary of transformer +VDC voltage will appear and the current through series and parallel inductance starts to increase linearly. Fig 3 shows the equivalent circuit of an SPCD converter topology during Mode 1.

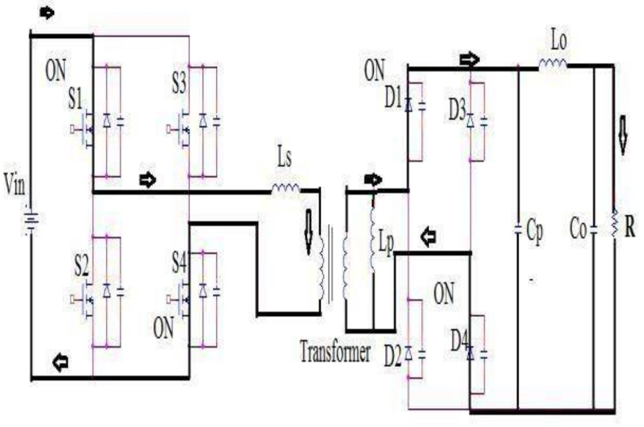


Fig 3. Equivalent circuit during Mode1

Mode 2: In this mode switch S1 continues to conduct where as primary S4 switch will turn off, such that the primary current starts to flow through output capacitance of MOSFET C3 and C4 by charging and discharging respectively. Now, there is a shift in voltage across primary of the transformer from +VDC to zero. Fig 4 shows the equivalent circuit of an SPCD converter topology during Mode2.

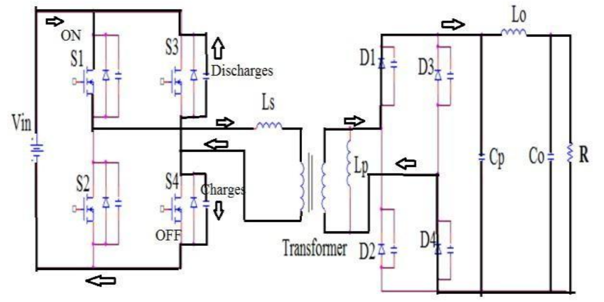


Fig 4. Equivalent circuit during Mode 2

Mode 3: During this mode since the voltage across S3 switch is zero, the primary current starts to flow through S3 diode by making it forward bias. This diode conducts for very short interval until the gating signal is applied to S3 switch and at the same time primary current will start to decrease slowly. Fig 5 shows the equivalent circuit of an SPCD converter topology during Mode3.

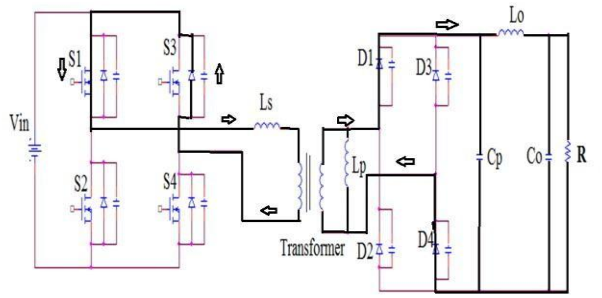


Fig 5. Equivalent circuit during Mode 3

Mode 4: During this mode S1 and S3 switches are completely ON and primary current continue to decrease to non-zero value. Now, the voltage across primary of the transformer is zero. Fig 6 shows the equivalent circuit of an SPCD converter topology during Mode4.

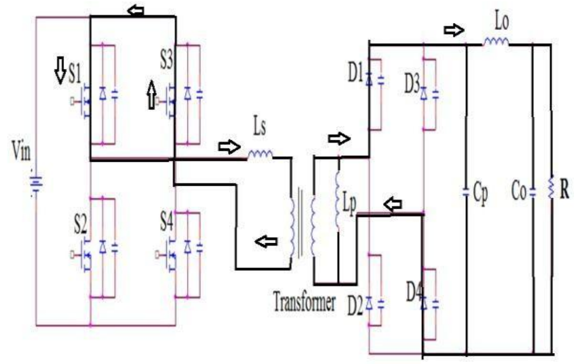


Fig 6. Equivalent circuit during Mode 4

Mode 5: In this mode rectifier diode D1 and D4 turns off ,when series inductor current reaches parallel inductor current. It means when the inductor current is at max level then there is no voltage across rectifier diode, which leads to turning OFF of diodes. Fig 7 shows the equivalent circuit of SPCD converter topology during Mode 5.

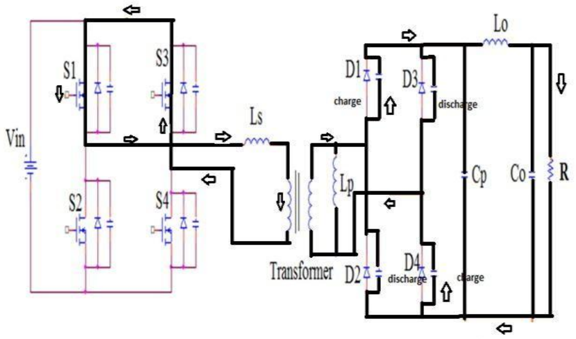


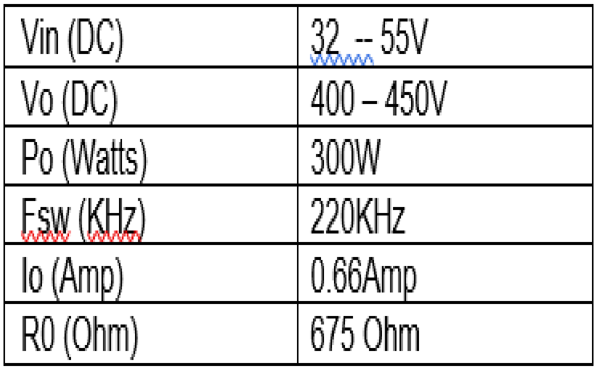
Fig 7. Equivalent circuit during Mode 5

Now the energy stored in parallel inductor plus the charge in rectifier diode D2 capacitance is used to charge the rectifier diode D1 capacitance. Similarly, charge in rectifier diode D3 is used to charge rectifier diode D4capacitance.

The series inductor, the parallel inductor, the parallel capacitor and the output capacitances of the output diodes form a resonant circuit. The resonant circuit is effectively determined by the series inductor, Ls, and the output capacitance of the output diodes, CD, since the parallel inductor is placed in parallel with the series inductor and the parallel capacitor is placed in series with the output capacitances of the diodes in the resonant circuit. Due to the fact that the parallel inductor is usually much larger than the series inductor and the parallel capacitor is much larger than the output capacitances of the diodes, the effective resonant frequency is determined by the series inductor and the output capacitance of the diodes.

III. PERFORMANCE ANALYSIS THROUGH SIMULATION

Specification:



Vin (DC)	32 -- 55V
Vo (DC)	400 – 450V
Po (Watts)	300W
Fsw (KHz)	220KHz
Io (Amp)	0.66Amp
R0 (Ohm)	675 Ohm

Open loop simulation

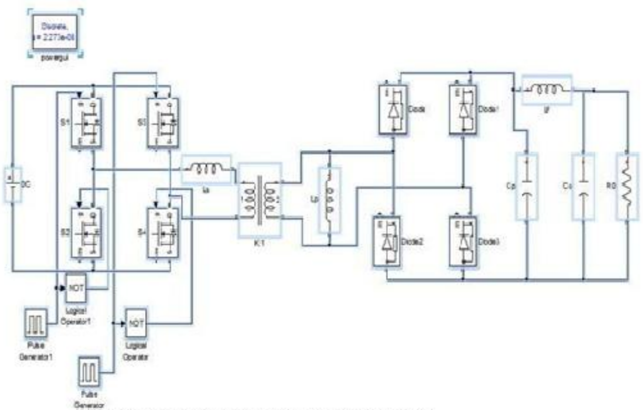


Fig8. Simulation circuit of open loop SPCD converter topology

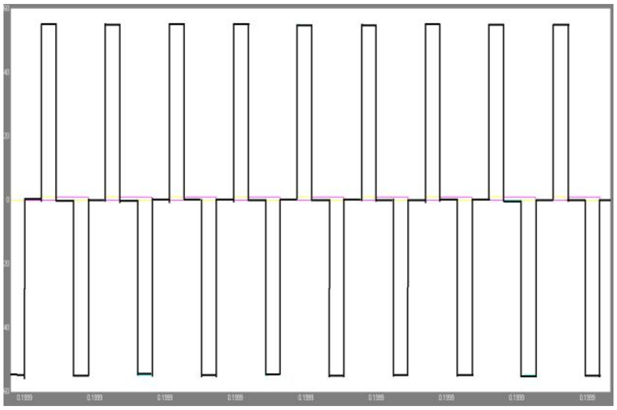


Fig 9. Primary voltage waveform

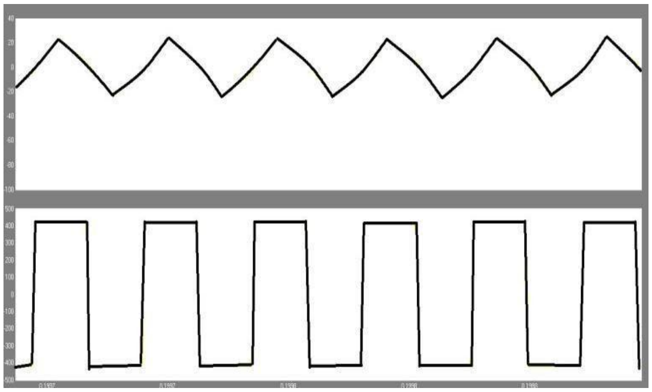


Fig 10. Primary current and secondary voltage waveform

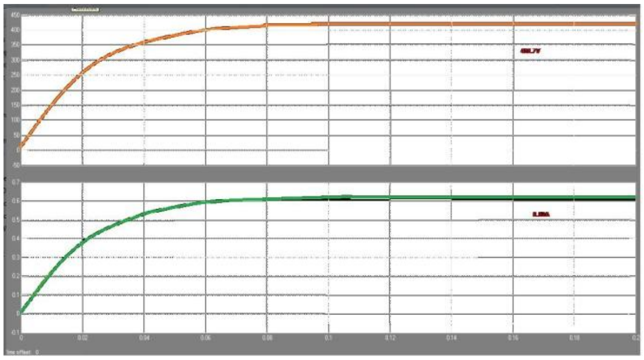


Fig 11. Output voltage and current waveform

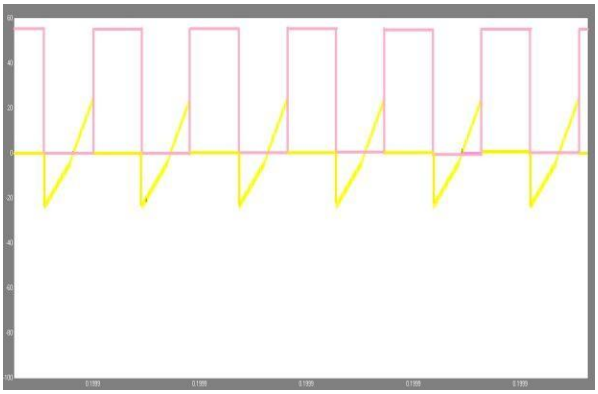


Fig 12. Drain to source voltage and drain current waveform

Measured output voltage and current after simulation

Vo (V) 418.7V
Io(Amp) 0.62Amp
Po (Watts)260W

Closed loop simulation:

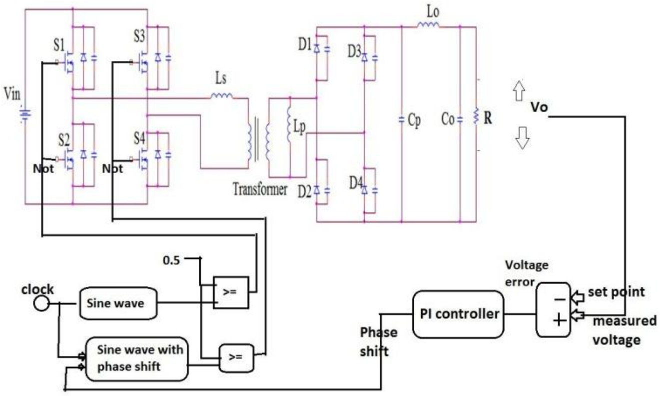


Fig 8: circuit diagram of closed loop SPCD converter

Closed loop Simulated Results

(Before)

Vo(V)	Io(Amp)	Po (Watts)	Ro (Ohms)
450	0.66	300	675
450	0.55	250	810
450	0.44	200	1.0125k
450	0.33	150	1.35k
450	0.22	100	2.025k

(After)

Vo (V)	Io(Amp)	Po (Watts)
430	0.63	271
430	0.53	228
430	0.43	185
430	0.33	142
430	0.21	90.3

IV. CONCLUSION

A SPCD full-bridge DC/DC converter topology has been presented in this paper. The proposed converter is able to provide soft-switching for the primary-side MOSFETs as well as lossless and smooth commutations for the output diodes. The particular structure of the converter makes it a good candidate for applications with a high switching frequency and a high output voltage. Also, this topology is able to offer high power density due to the use of anintegrated transformer in the converter and due to minimal extra components in the converter. Simulation and experimental results demonstrate the superior performance of the proposed SPCD full-bridge DC/DC converter.

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