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A Closed Loop Phase Shift Control of Isolated Buck Boost Converters for High Voltage Applications

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Abstract:
A novel isolated buck-boost converter with high gain output voltage controlled by a closed loop phase shift control is proposed here. The phase shift control dynamically changes the converter output voltage with reduced ripple content. Here, a family of semi active rectifiers (SARs) is introduced to act as a secondary rectification circuit, to reduce the voltage stresses on the devices and improves the voltage gain thereby achieving the high conversion efficiency. A transformer with smaller turn's ratio, MOSFETs and diodes with better switching and conduction performances is employed to achieve the high conversion efficiency. As an example, an isolated full bridge converter is analyzed here. To achieve the IBB conversion phase shift modulation technique to this converter is applied. With this converter the soft switching operation of switches and diodes over a wide voltage range can be achieved. The converter design and modeling is done in MATLAB software. The experimental results and graphs of the proposed converter are represented.

Keywords:
DC-DC Converter, IBB Converters, Semi Active Rectifiers (SAR's), Soft switching Technique

1. INTRODUCTION

Isolated DC-DC converters are most commonly used converters in renewable energy and battery discharging applications for a wide range of input and output voltages and galvanic isolation requirements. The classification of these isolated converters is done into three: Buck converters [2]-[4], Boost converters [5] and Buck Boost converters [1], [6]. Isolated Buck converters are used for voltage step down conversion where the converter efficiency decreases due to decrease in voltage conversion ratio whereas Isolated Boost converters are the converters used for voltage step up conversion. Hence high conversion efficiency for wide input/output voltage ranges [6] cannot be achieved using these isolated Buck converters and Boost converters. But in practical, for power systems high–efficiency power conversion is important. For example, due to variation in the radiation of solar energy and ambient temperature the voltage at the output of the PV cell may vary, due to change in the state of charge the voltage at the terminals of battery fluctuates. Achieving high-efficiency power conversion using Isolated Buck Boost converters is a promising approach. Because of high voltage or current stresses and hard switching of the devices the other converters are not preferable. A two-switch buck-boost converter consisting of a buck cell, boost cell and a dc-link inductor is as shown in the below Fig 1.

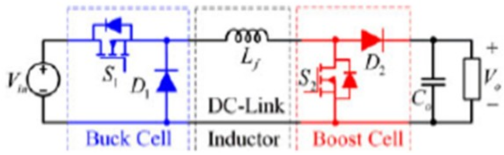

Fig. 1: Non Isolated Buck Boost Converter

The non-isolated converters can be used for voltage step up and step down conversion with high conversion efficiency over a wide voltage range but it cannot satisfy the galvanic isolation requirement. The secondary side active switches and rectifying diodes of these converters are subjected to hard switching which in turn decreases the conversion efficiency. By replacing buck cell in two switch non-isolated buck boost converters with isolated buck cell, a family of IBB converters was developed. With these converters the flexible control for a wide range of voltage gain can be achieved. IBB conversion with single stage and soft switching operation to get high conversion efficiency is potentially an interesting topic.

The significant challenge of the IBB conversion is to convert the low output voltages of PV cells and the batteries to higher voltages. As the output voltages of the PV arrays, batteries, Fuel cells used in the renewable power systems is very less compared to that of dc input of grid connected

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inverter. To increase the converter efficiency whose output is used for high voltage applications it is necessary to decrease the voltage stresses on the power devices especially on MOSFET's.

A new concept based on semi active rectifier (SAR) as ac boost cells is introduced here to reduce the stresses on the devices and achieve the high conversion efficiency. By this family of converters, one can achieve soft switching operation, single stage power conversion, low voltage and current stresses. The high frequency current ripples at the input can be eliminated with high switching frequency.

2. ISOLATED BUCK BOOST CONVERTER AND ITS DERIVATION

A non-isolated two-switch converter is constructed by using a dc buck cell, dc boost cell and a dc link inductor whereas an IBB is constructed by replacing dc buck cell and dc boost cell in non IBB by ac buck cell and ac boost cell, high frequency transformer for providing galvanic isolation and an ac link inductor . The general structure of an isolated buck boost converter is as shown in the above Fig 2.

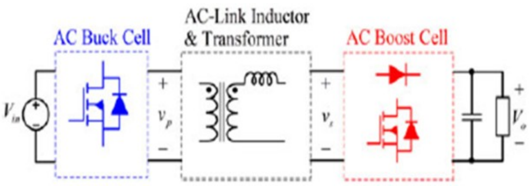

Fig. 2: IBB Converter General Structure

The ac buck cell on the primary side of the transformer generates high frequency ac voltage. The primary circuit of the IBB i.e., ac buck cell can be realized by the circuits as shown in the below fig. 3.

A high frequency ac voltage Vs should be generated by the ac boost cell of the IBB converter. A family of SAR's which can reduce the voltage stresses on the devices is introduced in the secondary side of the converter. Merging a symmetrical half bridge circuit and a boost switched capacitor with active switches develops an SAR. In the proposed converter, SAR is comprised of active switches S1 and S2; diodes D1 and D2; capacitors C1, C2, C3, C4 where C1 and C2 are series capacitors, C3 and C4 are the output capacitors. Complimentarily turning ON/OFF the switches S1 and S2 generates high frequency ac voltage Vs. The output voltage (Vout) is four times the peak value of Vs and voltage stresses on the switches and diodes in the SAR is half of the Vout.

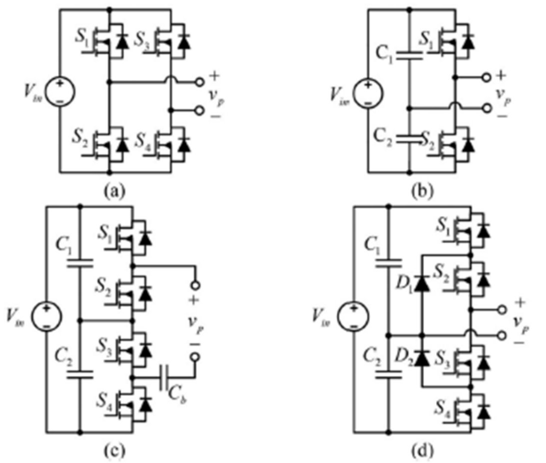

Fig. 3: AC Buck-cell Implementation (a) Full-bridge (b) Half-bridge(c) and (d) Three-level

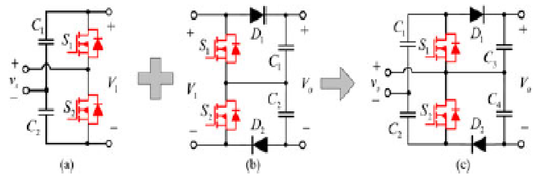

Fig. 4: Derivation of the SAR (a) Symmetrical half-bridge circuit. (b) Boost switched-capacitor circuit. (c) SAR

3. FULL BRIDGE IBB CONVERTER FOR HIGH VOLTAGE APPLICATIONS

A full bridge isolated buck boost converter is a novel approach for buck boost conversion. The operation of this converter is based on the gain of the converter. The proposed topology of the converter is as shown in the below Fig 2.

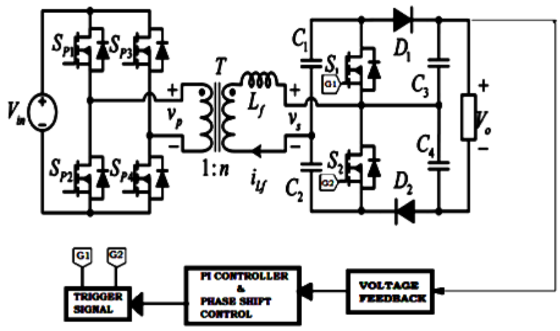

Fig. 5: Proposed topology of Full Bridge IBB Converter

For high voltage applications the converter is made to operate in boost mode. Therefore the gain of the converter is maintained at one or greater than one i.e., $G \geq 1$.

The voltage gain of the converter is given by

$$G = \frac{Vout}{4nVin}$$

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Where n is the transformers turns ratio and n = N1/N2 Vout is output voltage and Vin is the source voltage at the input.

If the gain of the converter is greater than 1 i.e., G ≥ 1, then the converter operates in boost mode and when G < 1 then the converter operates in buck mode. For flexible control of the converter the various control methods that can be employed are PWM control or phase-shift control or PWM plus Phase-shift control.

The primary and secondary sides of the converter are active full bridge and Hybrid Bridge respectively. The primary side consists of input voltage source (Vin) and four active switches Sp1, Sp2, Sp3, Sp4.The secondary side of the converter is an ac boost cell with SARs. SAR is a hybrid bridge composed of two active switches S1, S2 and two diodes D1, D2 and four capacitors C1, C2, C3, and C4. Here C1 and C2 act as the series capacitors whereas C3 and C4 are output capacitors.

The primary side active switches Sp1, Sp2, Sp3 and Sp4, and secondary side active switches S1 and S2 are operated alternatively. The phase difference between the Sp1 and Sp3 gate signals is defined as the primary phase shift angle ɸp. The phase difference between the Sp2 and Sp4 gate signals is defined as the secondary phase shift angle ɸs.

4. CONTROL AND MODES OF OPERATION

The converter can be operated in boost mode by maintaining the gain value G ≥ 1. For flexible control of the converter the various control methods that can be employed are PWM control or phase-shift control or PWM plus Phase-shift control. Phase shift control using PI Controller is the suitable method to control the output voltage of the converter.

The one switching period of the converter in boost mode is analyzed by ten states starting from T0 to T10. Only five states of the converter are analyzed here, due to symmetry of the circuit. Before T0, the active switches Sp2, Sp3 and S2 and diode D1 are in on state.

The energy stored in the inductor Lf and energy from Vin is delivered to the load at the output. Capacitors C1 and C2 are charged while the capacitors C3 and C4 will be discharging the energy stored in them.

State 1 [T0, T1]:

The active switches S2 and Sp3 and turned Off at T0 and the body diodes of the active switches Sp1 and Sp4 starts conducting due to the stored energy in inductor Lf. The inductor current iLf in this state 1 is given by

$$iLf(T) = \frac{nVin + \left(\frac{Vout}{4}\right)}{Lf}(T - \mathrm{T0}) + \mathrm{iLf(T0)}$$

Where,

$$iLf(To) = \frac{nVin + 2Ds - 1\left(\frac{Vout}{4}\right)}{4fsLf}$$

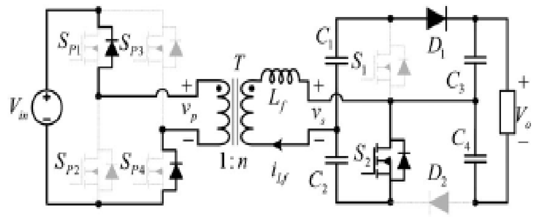

Fig. 6: Equivalent circuit of switching state in State 1 [T0, T1]

State2 [T1, T2]:

With zero voltage switching the active switches Sp1 and Sp2 are turned on at T1. At the end of this state iLf recovers to zero, with zero current diode D1 is naturally turned off.

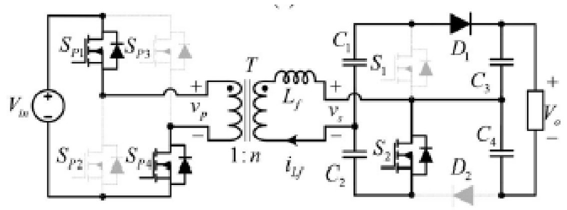

Fig. 7: Equivalent circuit of switching state in State 2 [T1, T2]

State3 [T2, T3]:

Due to the input voltage and the voltage of capacitor C2, the inductor Lf is charged in this state.

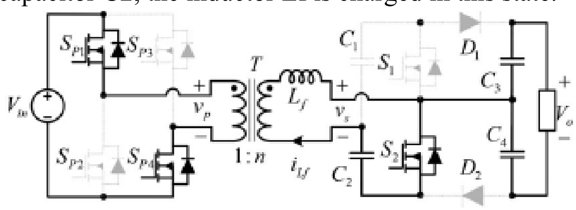

Fig. 8: Equivalent circuit of switching state in State 3 [T2, T3]

State4 [T3, T4]:

At T3, the active switch S2 present in the secondary side of the converter is turned off. The body diode of the switch S1 and diode D1 begin to conduct due to positive iLf current. Hence, the energy to the load is delivered from Vin and Lf. The capacitors C1 and C4 will be charging while C2 and

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C3 will be discharging the stored energy. The inductor current iLf is this state 4 is given by

$$iLf(T) = \frac{nVin + \left(\frac{Vout}{4}\right)}{Lf}(T - \mathrm{T3}) + \mathrm{iLf(T3)}$$

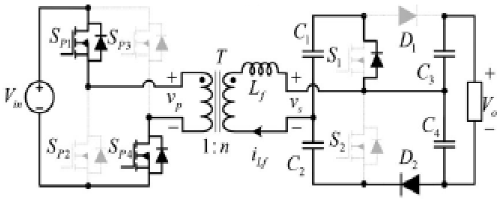

Fig. 9: Equivalent circuit of switching state in State 4 [T3, T4]

State5 [T4, T5]:

With zero voltage switching (ZVS) the switch S1 turns on. The source transfers the power continuously to the load.

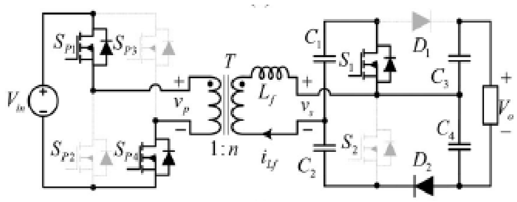

Fig. 10: Equivalent circuit of switching state in State 5 [T4, T5]

The output power of the converter in boost mode is given by the equation

$$Pout = \frac{Ds(1 - Ds)Vout^2}{32fsLfG}$$

5. SIMULATION RESULTS

The Simulation studies have been performed on proposed Family of Isolated Buck Boost converter based on Semi Active Rectifiers under variable input voltages with phase shift control method.

The converter parameters that are chosen for the simulation studies are input voltage Vin is40-56 V, desired output voltage 380 V, inductance L=15μH, capacitance C=100μF, load resistance R=100Ω, the switching frequency fs is set to 100 kHz. A simple PI controller is considered here for the closed loop control of output. The simulations are done using MATLAB/SIMULINK.

A PI controller is used in the closed loop circuit in order to maintain the output voltage at 380 V. Faster response of the converter can be achieved by this method. Using this PI controller the phase shift of the switches on the secondary side of the converter is controlled. For various input voltages the output voltage and power of the converter are maintained at a constant magnitude.

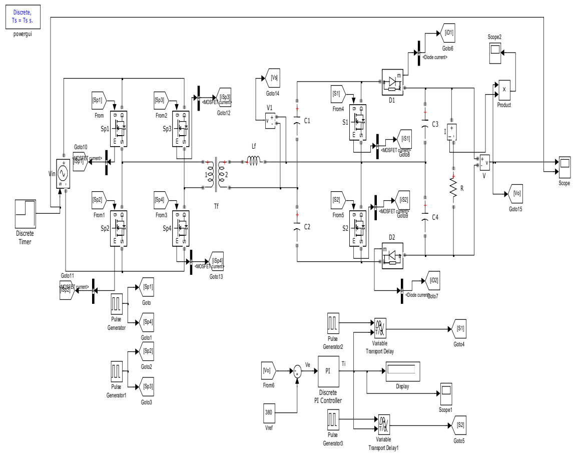

Fig. 11: Simulink Model of Proposed Full Bridge IBB Converter with Closed Loop Control

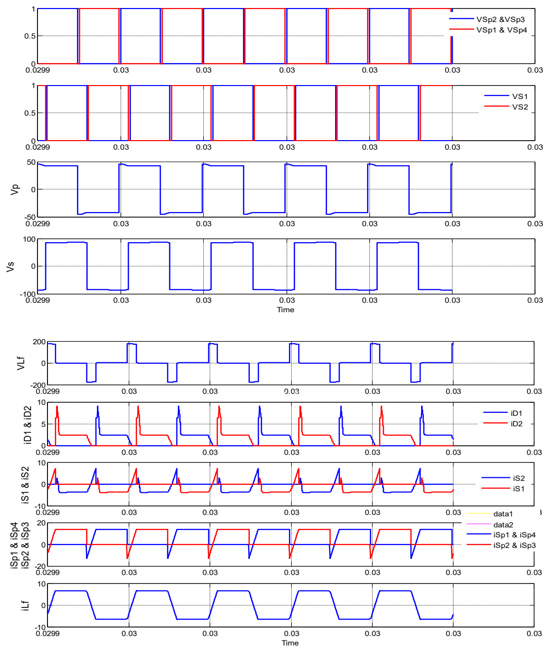

Fig. 12: Switching waveforms of the FB IBB Converter

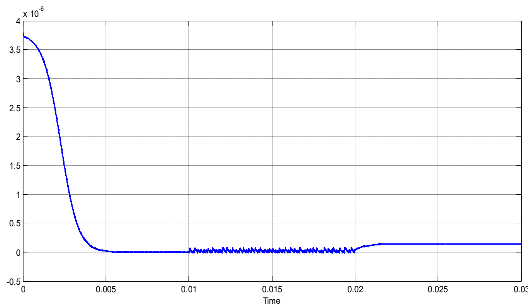

Fig. 13: Phase shift of the PI Controller

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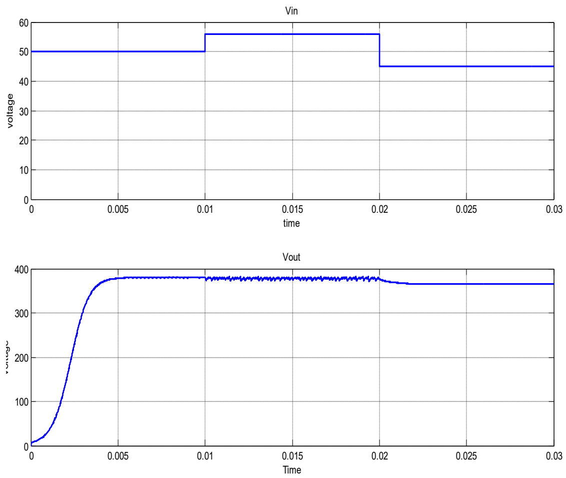

Fig. 14: Input and Output Voltage Waveforms

For variable input voltages the output voltage of the converter is maintained at 380 V. And the Output power is about 500 W for the above mentioned closed loop IBB converter.

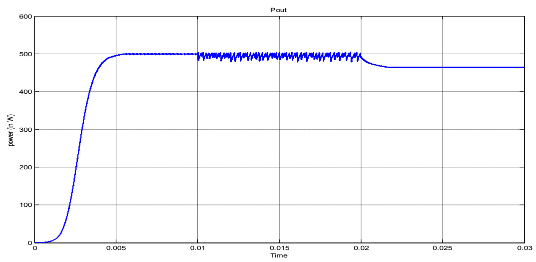

Fig. 15: Output Power of Closed loop FB IBB Converter

6. CONCLUSION

An Isolated Buck Boost Converter for high voltage applications with a closed loop phase shift control is proposed here. Isolated Buck Boost Converters are obtained by replacing DC buck cell and the DC boost cell with AC buck cell and AC boost cell. Semi Active Rectifiers (SAR's) are introduced in the secondary side of the converter. These SAR's reduces the voltage stresses of the devices used in the converter circuit. Soft switching technique has been achieved for all the diodes and the active switches by phase shift control. Therefore, the efficiency of the converter is improved. The closed loop control of the converter maintains the output voltage and power at a constant magnitude. Soft switching technique, Operation of the converter, Output characteristics of Full Bridge Isolated Buck Boost Converters for high voltage applications in detail is represented here. A 500 W, 380 V output voltage, 40-56 V input prototype is analyzed. For high output voltage applications with improved efficiency IBB converter is a novel approach.

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