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Design Consideration for High Power Zero Voltage Zero Current Switching Full Bridge Converter with Transformer Isolation and Current Doubler Rectifier

Noor Ahmad[1], Awadhesh Kumar[2]
[1]PG Scholar Department of Electrical Engineering Madan Mohan Malaviya University of Technology Gorakhpur
[2]Assistant Professor Department of Electrical Engineering Madan Mohan Malaviya University of Technology Gorakhpur

Abstract: *This paper presents the design and analysis and of the proposed zero voltage zero current switching (ZVZCS) full bridge dc-dc converter with transformer isolation and current doubler rectifier for high power and high performance by introducing ZVS for lagging leg and ZCS for leading leg operation It has a simple and robust structure with asymmetrical shifted pulse width modulation technique. The ZVS operation is achieved with the help of transformer leakage inductance and output capacitance of the switches for passive leg and to obtain ZCS operation auxiliary transformer and two diodes are used for leading leg. Validation of the designed parameters are verified by simulation of the proposed converter with a load of 3kW and converter operating frequency is at 20kHz with a feature of current doubler rectifier*.

I. Introduction

The use of conventional dc-dc converter with hard switching condition gives considerable switching losses for various applications. With the use of soft switching technique in the conventional converters greatly reduce the switching losses as switching losses are proportional to the switching frequency used generally required wide range of frequency control. Quasi-Resonant converter and multi-resonant converter reduces the frequency range [1,2] but high component stress make them impractical for high power applications. The constant frequency converter are introduced [3,4] can provide ZVS and ZCS but component stress is large and also EMI for high switching frequency. This makes the considerable detrition in the the overall converter efficiency. There are many number of switching techniques are used to reduce the switching losses in the converter topology [5]-[6]. These topologies uses high frequency to reduce the system size and weight. The proposed ZVZCS full bridge dc-dc converter with transformer isolation and current doubler rectifier are used to reduce the switching losses considerably by using parasitic capacitances of the switches to achieve the ZVS operation of the lagging leg and ZCS operation of the leading leg with the use of the auxiliary transformer for the shifted phase PWM converter. The operation of the converter allows the MOSFET switch capacitances to make resonance with transformer leakage inductance to achieve the ZVS operation and auxiliary transformer with diodes to reset the input current to achieve the ZCS operation of leading leg in ZVZCS full bridge dc-dc converter with transformer isolation and current doubler rectifier.

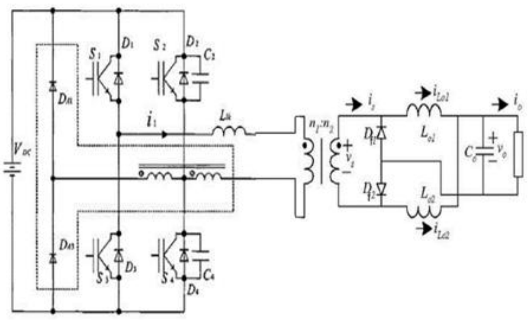

Figure1.The proposed ZVZCS Converter

II. Circuit Configuration And Principle Of Operation

The proposed ZVZCS full bridge dc-dc converter with transformer isolation and current doubler rectifier is shown in fig (1). In this converter the auxiliary circuit contain an auxiliary transformer and two diodes for achieving ZCS condition for the leading leg transition of the switch. The primary winding of the transformer is connected in series with the primary winding of the auxiliary transformer and the secondary winding of the auxiliary transformer is connected between the lagging leg and leading leg of the converter. To obtain the appropriate phase delay for ZVZCS operation shifted phase PWM is used to control the output of the controller. The ZVS condition is obtained on lagging leg with components C_{M2}, C_{M4}, L_{lk}, L_{f1} and L_{f2} of the circuit while the leading leg ZCS condition is operated by primary current. L_{lk} is the leakage inductance of the both main transformer and auxiliary transformer. The capacitances C_{M2}, C_{M4} of the switch M_2 and M_4 provides ZVS off of the switch M_2 and M_4 when turned off. L_{lk}, L_{f1} and L_{f2} provide ZVS on by changing the voltage of C_2 and C_4 in opposite and causing primary current flow through D_{M2} and D_{M4} prior to turn off the switch M_2 and M_4. The leading leg operates in ZCS condition with the help of auxiliary circuit by introducing resetting voltage and absorbs the trapped leakage inductor reactive energy and also provide resetting to the primary current prior to switch transition. The key waveforms and operating modes are shown in the fig (2) and fig (3).

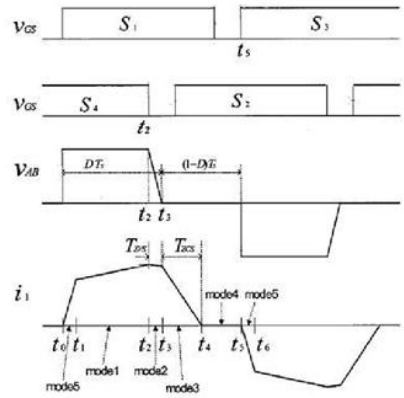

Figure2. Key waveforms of the converter

III. Modes Of Operation

The proposed converter operation is divided in five modes during complete cycle of the switching frequency. For simplicity and ease of calculation the magnetising inductance of the primary and secondary transformer is neglected.

MODE 1($t_1 - t_2$) : The switch S_1 and S_2 are in conduction and power to the output is delivered through main transformer, D_{f2}, L_{f1} and L_{f2}. The secondary winding of the auxiliary transformer is shorted by D_{A3} and S_4. The diode current at the output side is $i_{Df2}=0$ and the load current is given by $i_{Lo1} + i_{Lo2} = I_o$. The switch current of S_4 is the primary current of the circuit.

MODE 2($t_2 - t_3$) : This mode initiated with the turning off of the switch S_4. Resonance is created with the help of C_2, C_4, L_{lk}, L_{f1} and L_{f2} and the frequency of resonance is given by

$$\omega_o = \sqrt{1/(L_{lk} + n^2(L_{f1} + L_{f2}))C_{eq}} \quad (1)$$

And equivalent capacitance is given as

$$C_{eq} = 2C(n/n+1)^2 \quad (2)$$

The voltage across S_4 increases through zero results in ZVS turn off of the switch S_4.

MODE 3($t_3 - t_4$) : The switch S_4 voltage reaches to maximum value, primary current flows through D_2 diode of the switch S_2. The leakage inductor reactive energy is recovered to the dc side and the primary current decreases to zero by the auxiliary transformer as

$$V_{aux} = (V_{dc} / n) \quad (3)$$

The D_2 diode in conduction and switch S_2 can be turned on through ZVS.

MODE 4 ($t_4 - t_5$) : This mode shows the primary current becomes zero and the load current freewheels through D_{f1} and D_{f2} diodes of the secondary. The switch S_1 can be turned off with ZCS condition and the load current is given by

$$i_{Df1} + i_{Df2} = I_o \quad (4)$$

MODE 5 ($t_5 – t_6$) : The switch S_3 is turned on with ZCS condition and primary current flows through S_2 and S_3. The secondary auxiliary transformer is shorted by diode D_{A1} and S_2 switch. The load current is transferred from the secondary diode D_{f2} to D_{f1}.

This completes the one cycle of the converter operation in which ZVS and ZCS conditions are obtained for the switches. From this mode 1 is initiated with switch S_2 and S_3 are in conduction mode.

IV. Circuit Description

ZVS for lagging leg is achieved by the resonance criteria with the help of main transformer leakage reactance and ZCS is achieved with the help of auxiliary transformer by suppressing the primary current of the main transformer. For ZVS operation of the lagging switches the parasitic capacitance voltage must real to the positive maximum and the energy in the leakage inductor must be higher to make the resonance condition at the primary side of the main transformer. The energy is given as

$$E = (1/2)I_{lk}I_P^2 > (4/3)C_{MOS} + (1/2)C_{tr}V_{dc}^2 \quad (5)$$

The time for ZVS operation of the lagging switch is given as

$$T_{ZVS} = t_3 – t_2 = C_{eq}V_{dc} / I_1 \quad (6)$$

And the ZCS time can be calculated as

$$T_{ZCS} = t_4 – t_3 = L_{lk}I_1 / V_{aux} \quad (7)$$

The T_{ZCS} can be minimum and maximum according to the primary current as minimum and maximum. The condition for safe ZCS operation is given as

$$T_{ZCS\ max} < (1 - D_{max}) \quad (8)$$

Dead Time Between Pulses:

The lagging leg dead time is between t_2 and t_3 as shown in the figure (2), denoted by $T_{d2-4.}$ The left term defined as T_{ZVS} and the right term is as $T_{ZVS} + T_{ZCS}$ denoted below

$$T_{ZVSmax} < T_{d2-4} < T_{ZVSmax} + T_{ZCSmin} \quad (9)$$

For leading leg dead time is denoted by T_{dl-3} between t_4 and t_5 as the dead time for safe limit of the switching is given as

$$T_{dl-3} < (1 - D_{max})T_s - T_{ZCSmax} \quad (10)$$

Main Ttransformer:

The main transformer is used with a high frequency of 20 kHz and the leakage inductance is 1.5 μH. The converter is operated with low duty ratio of 0.45 as open circuit voltage is considerable for many applications.

Auxiliary Transformer:

ZCS operation is achieved by auxiliary transformer to reduce the losses due to switching but there is additional conduction loss due to flow of current in the auxiliary transformer and depend upon turn ratio and duty cycle of the auxiliary transformer. In welding purpose duty ratio is low as there is high open circuit is required therefore low conduction losses. The power delivered by auxiliary transformer to the source is given by

$$P_{aux} = 0.5\ L_{lk}I_1^2 2f_s \quad (11)$$

The power rating of the auxiliary transformer is low enough as 7% and the current rating of secondary side of main transformer is low due to current doubler rectifier giving not much conduction loss in the converter.

V. Design Description

The design of the proposed converter is described as the input voltage of the converter is V_{dc} = 600 volts; output voltage is taken as V_o = 70 volts with the output current as I_o = 29 ampere as a dc with a high switching frequency of 20 kHz, the other parameters of the simulation model with result are given as

Transformer main: $n = N_1/N_2 = 600/400$, $L_{lk} = 1.5\mu H$; Auxiliary Transformer: $n_1 = N_1/N_2 = 400/500$; Parasitic capacitance of switch: $C = 6$ nf;
Output inductor: $L_{o1} = 320\ \mu H$, $L_{o2} = 345\ \mu H$;
Output capacitor: $C_o = 150.5\ \mu f$;

The ripple current from the magnetising inductance of the main transformer is found to be

$$\Delta i_m = nV_oT_s / L_m \qquad (12)$$

Here we consider that the ripple current through each filter inductor is about 30% of the maximum load current, therefore $\alpha = 0.3$ and the output filter inductor is found as the formula

$$L_{o1} = 2V_oD_{max}T_s / \alpha D_{max} I_{o\ max} \qquad (13)$$
$$L_{o2} = 2V_oD_{max}T_s / \alpha(1 - D_{max}) I_{o\ max} \qquad (14)$$

The proposed converter having the value of $\Delta i_m = 4.6$ ampere and $L_{o1} = 320\ \mu H$ and $L_{o2} = 345\ \mu H$.

VI. Simulation Analysis

A 2kW model is developed and constructed on mat lab Simulink software. The input of 600 volt dc is applied and the output is taken as 70 volt with a high current of 29 ampere as a dc with a high switching frequency of 20 kHz Figure 4. signifies the ZVS-Off condition of the lagging leg switch S_4. Waveform of drain to source voltage of switch S_4 and gate signal is shown. Figure 5. signifies the ZVS-On condition of the lagging leg switch S_2. Waveforms of drain to source voltage of switch S_2 and gate pulse is shown. Figure 6. signifies the ZCS-Off condition of the leading leg switch S_1. Waveforms of the input primary current and gating signal is shown. Figure 7. signifies the ZCS-On condition of the leading leg switch S_3. Waveform of the input primary current and gating signal is shown.

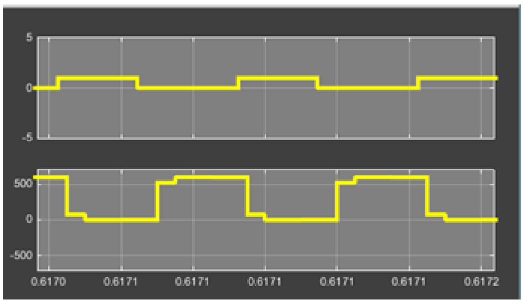

Figure4. PWM gate signal and V_{DS} (Volts) of switch S_4.

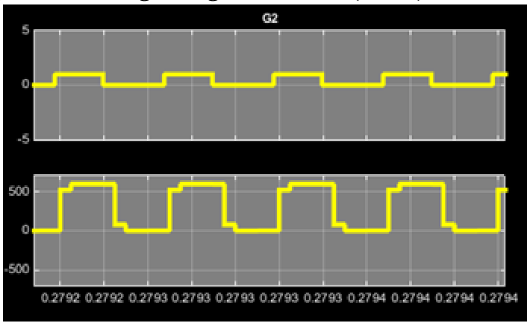

Figure5. PWM gate signal and V_{DS} (Volts) of switch S_3.

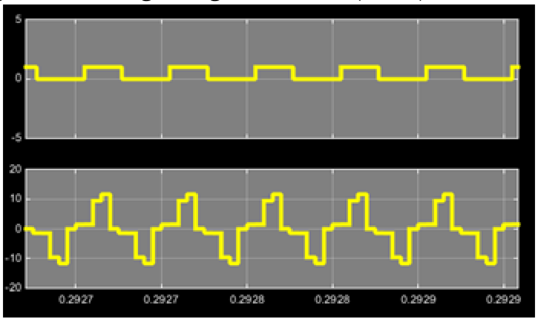

Figure 6. PWM gate signal and input primary current (Ampere) of S_1.

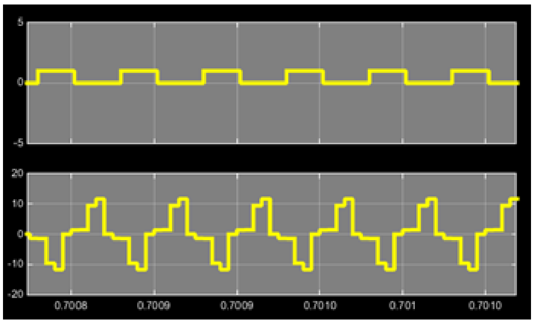

Figure 7. PWM gate signal and input primary current (Ampere) of S_2.

VII. Conclusion

A modified ZVZCS full bridge converter is proposed using auxiliary transformer and current doubler rectifier. The converter operates with ZVS for lagging leg and ZCS for leading leg switches. The current doubler rectifier is used at the secondary side to decrease the secondary winding current rating of the main transformer with the increase in the efficiency of the converter. Various simulation results are shown in support of the proposed converter.

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