Analysis Of Asymmetrical Duty-Cycle-Controlled LCL T Resonant Converter with Capacitive Output Filter

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***Abstract*: In many pulse width modulated DC-DC converter topologies, the controllable switches are operated in switch mode where they are required to turn the entire load current on and off during each switching cycle. Under such conditions, the switches are subjected to high switching stresses and power losses. Recently there is an increased interest in the use of resonant type DC-DC converters due to the advantages of high frequency of operation, high efficiency, small size, light weight, reduced Electro Magnetic Interference (EMI) and low component stresses. Resonant converters find applications especially in distributed energy systems like solar systems, vertical axis aero-generator and fuel cell power systems. Resonant converters are also employed in a variety of applications including power supplies for personal computers, space-craft power systems, lap-top computers, telecommunication equipments as well as DC motor drives.A series parallel resonant converter with LCL T resonant converter has been simulated and studied in this paper with open loop and closed loop operation. The proposed concept is analysed through simulation studies using MATLAB/Simulink.The simulated and experimental results shows that the output of converter is free from ripples and the converter can be used for aerospace applications.**

Keyword: Resonant Converter, MATLAB, Electro Magnetic Interference,LCL T Resonant Converter.

I.INTRODUCTION

The developments of the DC-DC Resonant Converters are increasing now a day due to its performance.A DC- DC Resonant Converter (RC) are used in telecommunication and aerospace application, at high frequency these converters experience high switching losses, reduced reliability, electromagnetic interference (EMI) and acoustic noise. To overcome these drawbacks, the SPRC is found to be suitable, due to various inherent advantages. The Series and parallel Resonant Converter (SRC and PRC respectively) circuits are the basic resonant converter topologies with two reactive elements. The merits of SRC include better load efficiency and inherent dc blocking of the isolation transformer due to the series capacitor in the resonant network.LCL –T Resonant converter has advantages like reduced transformer size, reduced filter size and current source characteristics.LCL-T Voltage can be done by using a PWM rectifier at the output. While the resonant converters (RCs) have been popularly used in various other applications, such as high-frequency ac distribution system[1], fluorescent lamps[2], power factor correction[3], charging applications[4], etc., they are also shown to be a potential candidate for an application as a CC power supply due to zero-voltage switching (ZVS), zero-current switching (ZCS), high-frequency operation, high efficiency, small size, and low electromagnetic interference (EMI).

The merits of LCL-T RC are:
1) It is essentially output short-circuit proof. With clamp diodes, in addition, it is protected from overload operation[9].
2) The bridge output voltage and current are in phase. The current reduces proportionally with the load power thus maximizing full-load and part-load efficiency[5],[7],[8].
.3) The converter lends itself for easy paralleling without any complex control for equal current sharing. Phase-shifted operation of paralleled modules reduces input and output filtering requirement[8].
4) The transformer leakage inductance is absorbed into the resonant network and the winding capacitance can also be gainfully utilized without losing the current-source property[11].

LCL-T RC has also been successfully applied to constant voltage power supplies[12],induction heating[13],and inductive power transfer applications[14].Although the output current of LCL-T RC is constant irrespective of changes in the load resistance, for practical application as a current-source power supply, it should be possible to regulate the output current against input voltage variations.Some applications also demand that it should be possible to set and regulate the output current from near-zero to the maximum rated value. Since LCL-T RC behaves as a current source only when it is operated at the resonant frequency, the method using variation of switching frequency cannot be applied to control the output.Therefore,fixed frequency control methods need to be used.Clamped mode[15]-[18] or Phase

Shift Pulse Width Modulation(PSPWM) and Asymmetrical Duty Cycle PWM(ADC PWM) are the common fixed PWM control strategies.

II.ASYMMETRICAL DUTY CYCLE(ADC) PULSE WIDTH MODULATION

The CM control can be applied only with the full-bridge converter whereas ADC control can be used with half-bridge as well as full-bridge converters. While ADC control leads to asymmetric operation of the high-side and the low-side switches and leads to unequal voltages across the leg capacitors, it has been widely applied to power converters (resonant as well as non resonant) due to simpler implementation and soft switching.

III.LCL T RESONANT CONVERTER

Resonant converters use a resonant circuit for switching the transistors when they are at the zero current or zero voltage point, this reduces the stress on the switching transistors and the radio interference. To control the output voltage, resonant converters are driven with a constant pulse duration at a variable frequency. The pulse duration is required to be equal to half of the resonant period time for switching at the zero-crossing points of current or voltage. A Constant-frequency, phase-shifted operation of the primary side switches provides a convenient method for achieving zero-voltage turn-on of the switches, significantly reducing switching losses. Traditional methods utilized to achieve zero-voltage switching in full-bridge, constant-frequency PWM converters typically rely upon either the energy stored in the isolation transformer leakage inductance and/or the inclusion of a resonant inductor in series with the transformer to act as a supplemental energy storage element. This stored energy is used to charge and discharge bridge switch capacitance during a freewheeling stage created by phase shifting the "on" times of opposite pairs of transistors in the bridge configuration. Assuming sufficient energy storage, the body diode of the switch is forced into conduction before that particular device is turned on, enabling loss-less switching.

A.Circuit Description and Operation:

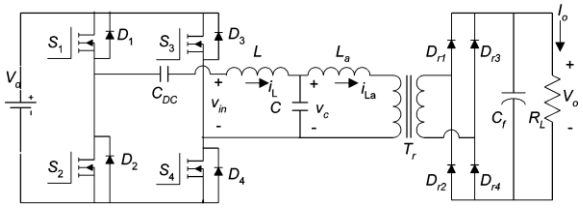

Fig 1.Circuit diagram

The circuit diagram of the full-bridge LCL-T RC is shown in Fig.1, Wherein MOSFET switches S_1–S_4 and their body-drain diodes D_1–D_4, respectively, constitute the full-bridge square-wave inverter. A diode rectifier (D_{r1}– D_{r4}) and filter capacitor (C_f) convert high-frequency ac to output dc. A dc blocking capacitor C_{dc} is required in the full-bridge circuit to block the dc component in voltage v_{AB} at the bridge output. At the output port of the resonant network, an isolation transformer matches the required output voltage V_o and current I_o to the input dc voltage.

Assuming the turns ratio (N_1/N_2) of isolation transformer T_r to be unity, the current gain (H) and voltage gain (M) are given by,

$$H = Io/(Vd/Zn)$$

$$\mathrm{H} = \frac{1}{1/\mathrm{Q}(\omega\mathrm{n}^2)+\mathrm{j}\pi^2/8[(1+\gamma)\omega_\mathrm{n}-\omega_\mathrm{n}^3]} \quad (1)$$

$$\mathrm{M} = V_o/V_d$$

$$\mathrm{M} = \frac{1}{(1-\omega_n^2)+j\pi^2/8Q[(1+\gamma)\omega_n-\gamma\omega_n^3]} \quad (2)$$

Where $\omega o = 1/(\sqrt{LC})$, $\omega n = \omega/\omega o$, $Zn = \sqrt{(L/C)}$, $Q = \omega oL/R_L = Z_n/R_L$, and $\gamma = L_a/L$

We see from (1) that the load current is independent of load if operated at $\omega_n = 1$ and

$$\mathrm{H}|(\omega_n = 1) = \frac{8}{\pi^2}$$

Thus, the LCL-T RC behaves as a constant-current source when operated at $\omega_n = 1$, if the input voltage is constant.

B.Modes Of Operation:

Mode I:

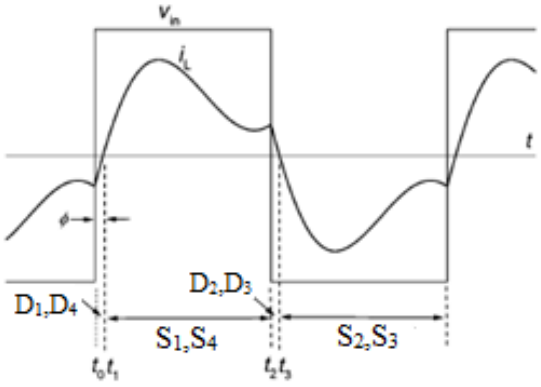

Fig 2. Mode 1

This mode of operation mainly occurs when D ≈ 0.5. Before t = to , switches S_2,S_3 were conducting. At t = to , S_2,S_3 are turned off and a gate pulse is applied to S_1,S_4. Since i_L is negative at this instant, it flows through D_1,D_4. At t = t1 , D_1,D_4 turns off naturally at zero current and i_L now flows through S_1,S_4.Similarly in the next half cycle, S_1,S_4 are turned off at t = t2 and a gate pulse is applied to S_2,S_3. Since i_L is positive at this instant, it flows through D_2,D_3. At t = t3 , D_2,D_3 turns off naturally at zero current and i_L flows through S_2,S_3. At t = t4 , S_2,S_3 are turned off and S_1,S_4 are turned on once again marking the beginning of the next cycle. Thus, in this mode, the device conduction sequence is such that the antiparallel diodes conduct prior to the switch conduction resulting in ZVS turn-on for both the switches.

Mode II:

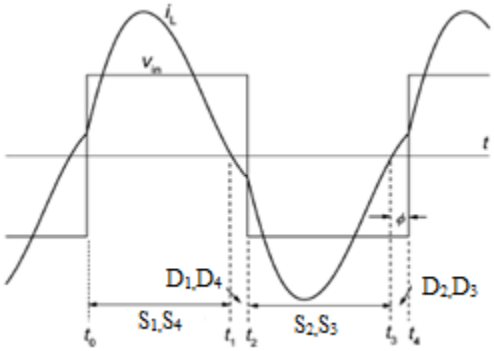

Fig 3. Mode 2

This mode of operation can also occur when D ≈ 0.5. Before t = to , diode D_2,D_3 were conducting. At t = to , a gate pulse is applied to S_1,S_4. Diode D_2,D_3 turns off and i_L flows through S_1,S_4. At t = t1 , i_L reverses its direction and becomes negative. S_1,S_4 turns off at zero current and i_L is transferred to D_1,D_4 until t = t2 when gate pulse is applied to S_2,S_3. At this instant, diode D_1,D_4 turns off and i_L is carried by S_2,S_3. At t = t3, S_2,S_3 is turned off naturally with zero current as iL reverses its direction and starts flowing through D_2,D_3. At t = t4, S_1,S_4 is turned on once again marking the beginning of the next cycle. Thus, in this mode, the device conduction sequence is such that the antiparallel diodes conduct after the switch conduction resulting in ZCS turn-off for both the switches.

Mode III:

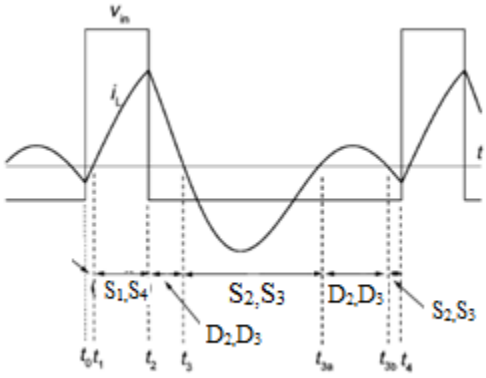

Fig 4. Mode 3

Similar to Mode I, the device conduction sequence in Mode III results in ZVS turn-on of all the switches. The difference is that i_L oscillates across zero twice during the time interval between t = t2 and t = t4 causing S_2,S_3 and D_2,D_3 to conduct twice during this interval. At t = t2 , S_1,S_4 are turned off and a gate pulse is applied to S_2,S_3. Since i_L is positive at this instant, it flows through D_2,D_3 until t = t3 when it reverses and starts flowing through S_2,S_3 . Current i_L reverses its direction at t = t3a causing D_2,D_3 to conduct and once again at t = t3b causing S_2,S_3 to conduct. The additional commutations of S_2,S_3 and D_2,D_3 in this mode of operation are ideally lossless since they occur under zero-current and zero-voltage condition. At t = t4 , S_1,S_4 are turned on once again marking the beginning of the next cycle.

Mode IV:

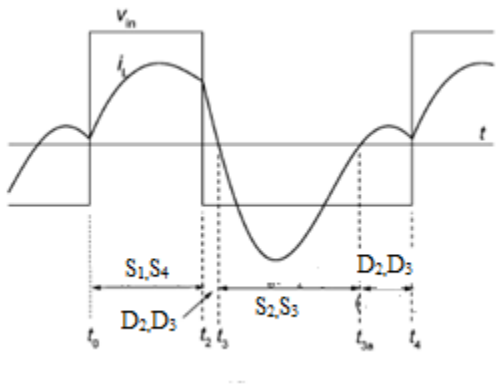

Fig 5. Mode 4

Before t = to , diode D_2,D_3 was conducting. At t = to , switch S_1,S_4 are turned on, which turns D_2,D_3 off. The current i_L flows through S_1,S_4 until t = t2 when it is turned off and a gate pulse is applied to S_2,S_3. Since i_L is positive at this instant, it flows through D_2,D_3. At t = t2 , D_2,D_3 turns off naturally at zero current and i_L now flows through S_2,S_3. At t = t3a, i_L reverses direction once again causing D_2,D_3 to conduct until t = t4 when S_1,S_4 are turned on marking the beginning of the next cycle. As compared to Mode II, in Mode IV, i_L does not reverse its direction while a gate pulse is applied to S_1,S_4. This causes D_2,D_3 to conduct twice during the time interval t = t2 to t = t4. Also, diode D_1,D_4 never conducts in this mode. Observe that D_2,D_3 conducts prior to the conduction of S_2,S_3, resulting in ZVS turn-on condition for S_2,S_3. However, S_1,S_4 operates under hard-switching condition.

C.State space modeling of LCL T resonant converter

The equivalent circuit of LCL-T SPRC is shown in Fig.6.The mathematical modeling using state space technique can be obtained assuming all the components to be ideal

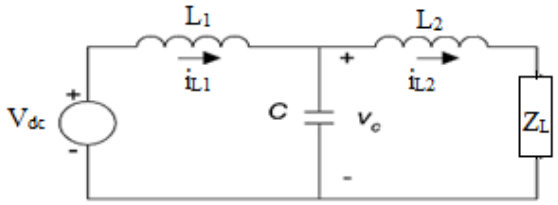

Fig.6.Equivalent Circuit Model of LCL T SPRC.

The Transfer Function for the LCL-T SPRC is given below from fig.6

$$\frac{V_0(S)}{V_i(S)} = \frac{Z_L}{L_1\,L_2Cs^3+L_1Z_LCs^2+(L_1+L_2)s+Z_L} \quad (1)$$

The State Space model for LCL-T SPRC find from the equation (1)

$$\frac{Y_0(s)}{u_i(s)} = \frac{Z_L}{L_1\,L_2Cs^3+L_1Z_LCs^2+(L_1+L_2)s+Z_L} \quad (2)$$

Taking inverse laplace transform and the state space equations are

$$\dot{X}_1 = x_1$$
$$\dot{X}_2 = x_3$$
$$\dot{X}_3 = \frac{-Z_L}{CL_1L_2}x_1 - \left(\frac{L_1}{CL_1L_2}+\frac{L_2}{CL_1L_2}\right)x_2 - \frac{L_1Z_L}{L_1L_2}x_2 + \frac{Z_L}{CL_1L_2}u_i(s)$$

The State Space model for LCL-T SPRC is

$$\begin{bmatrix}\dot{X}_1\\ \dot{X}_2\\ \dot{X}_3\end{bmatrix} = \begin{bmatrix}0 & 1 & 0\\ 0 & 0 & 1\\ -\frac{Z_L}{CL_1L_2} & \frac{-1}{CL_2}-\frac{1}{CL_1} & \frac{-Z_L}{L_2}\end{bmatrix}\begin{bmatrix}x_1\\ x_2\\ x_3\end{bmatrix} + \begin{bmatrix}0\\ 0\\ \frac{Z_L}{CL_1L_2}\end{bmatrix}[u_i(s)] \quad (3)$$

The output equation is,

$$Y_0 = \begin{bmatrix}1 & 0 & 0\\ 0 & 0 & 0\\ 0 & 0 & 0\end{bmatrix}\begin{bmatrix}x_1\\ x_2\\ x_3\end{bmatrix} \quad (4)$$

IV.SIMULATION STUDY

The validation of the system performance is done for various regions viz. load variations, steady state region and also components variations. Simulations has been performed on the LCL T Resonant circuit with open loop and closed loop.The performance of the LCL T RC Matlab/Simulink simulation model is depicted in Fig. 7.Asymmetrical Duty Cycle PWM is

implemented in LCL T RC.During device switching,all switches operated as ZVS and ZCS condition are evaluated in Matlab/Simulink Thus the switching losses reduced.

SIMULATION MODEL OF LCL T RC WITH OPEN LOOP

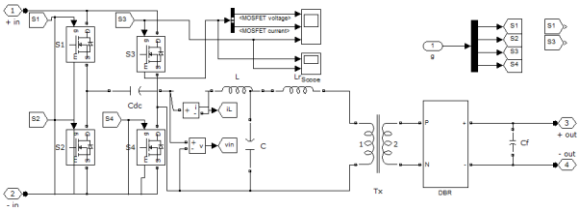

Fig 7.Simulation Diagram For LCL T RC

SUBSYSTEM OF LCL T RC WITH OPEN LOOP

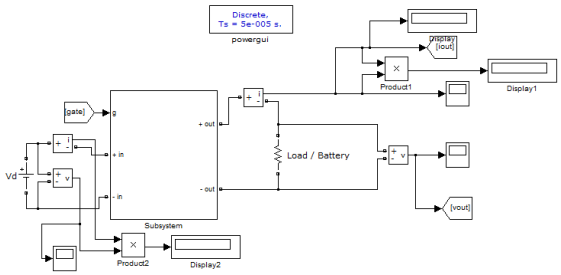

Fig 8.Subsystem Diagram

SIMULATION MODEL FOR ADC PWM GENERATION

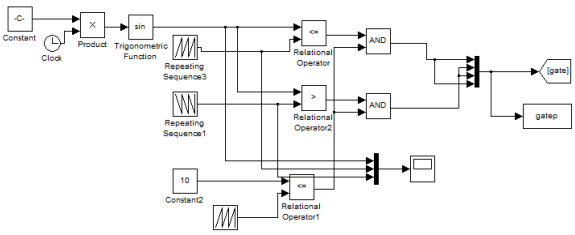

Fig 9.ADC PWM Generation

ADC PWM SIGNAL GENERATION

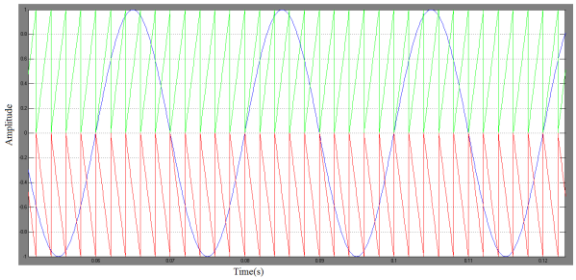

Fig 10.ADC PWM

ZERO VOLTAGE SWITCHNG & ZERO CURRENT SWITCHING

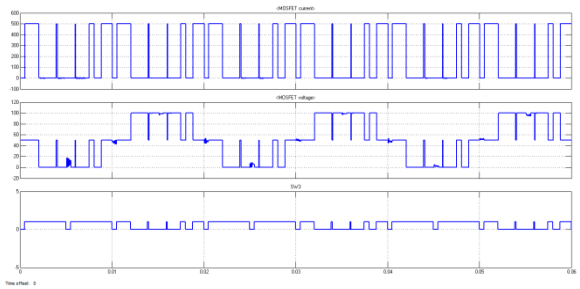

Fig 11.Simulated Output Response of ZVS, ZCS waveform of LCL-T Resonant Converter

OUTPUT VOLTAGE & CURRENT OF LCL T RESONANT CONVERTER

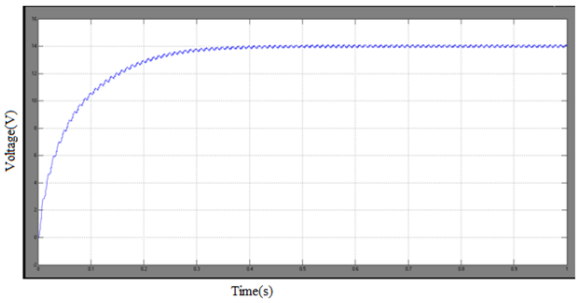

Fig 12.Output Voltage response of LCL-T Resonant Converter

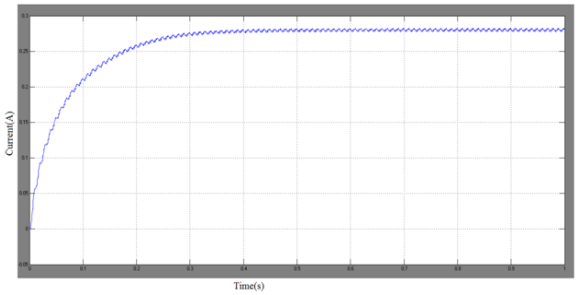

Fig 13.Output current response of LCL-T Resonant Converter

SIMULATION MODEL FOR LCL T RC USING PI CONTROLLER

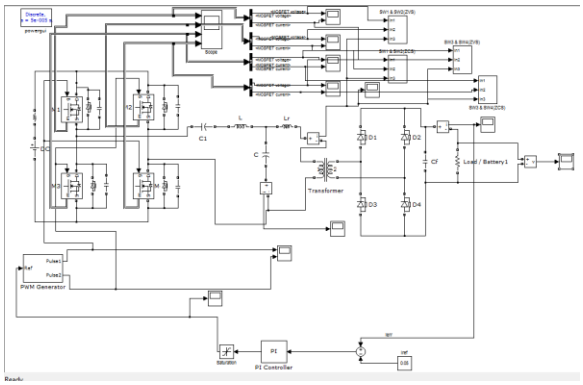

Fig 14. Simulation Diagram For LCL T RC PI Controller

OUTPUT VOLTAGE & CURRENT OF CLOSED LOOP LCL T RC WITH LOAD VARIATIONS

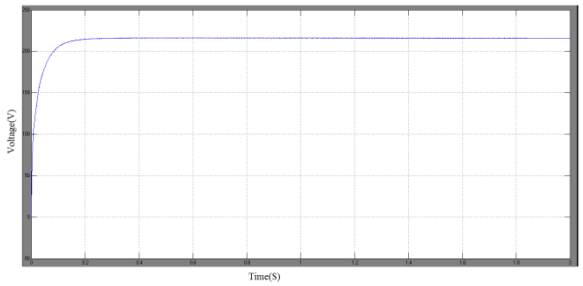

Fig 15.Output voltage response of LCL-T Resonant Converter with PI Controller

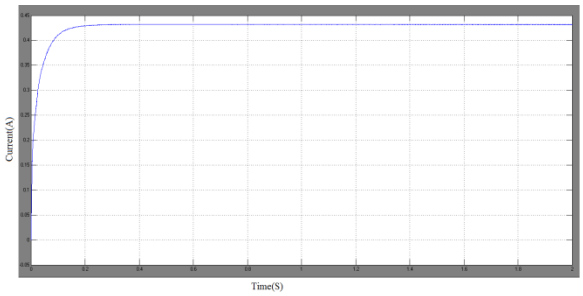

Fig 16.Output current response of LCL-T Resonant Converter with PI Controller

CAPACITOR OUTPUT CURRENT

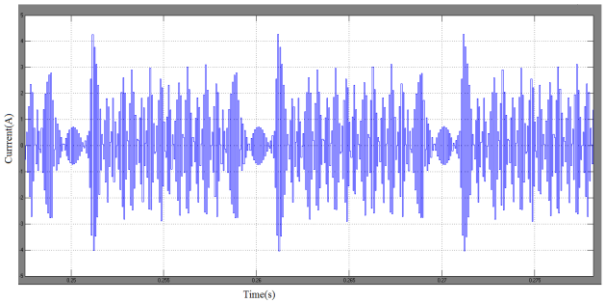

Fig 17.Capacitor output current of LCL-T Resonant Converter with PI Controller

IV.CONCLUSION

The LCL-T RC has studied by solving the state-space model of the converter. Four distinct operating modes are identified having different circuit waveforms representing different device conduction sequences, thereby creating different conditions during device switching. Then all switches operated as ZVS and ZCS condition and thereby reducing the switching losses. This paper has successfully demonstrated the analysis, and suitability of asymmetrical duty cycle controlled (ADC) PWM of LCL T Resonant converter. The simulation based performance analysis of LCL T Resonant converter circuit has been presented along with its state space averaged model and the comparative study of LCL T RC(open loop and closed loop) with and without PI controller is presented. It is observed that ADC PWM control allows ZVS and ZCS operation over a wider range than CM control.

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