Study of Interleaved LLC Resonant Converter Operating at Constant Switching Frequency Using SCC

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Abstract - The LLC resonant converter operating at constant switching frequency by interleaving technique has been analysed using MATLAB/Simulink. The LLC resonant converter has the advantages of high efficiency, high power density, and low cost. They can be operated at no load condition and at resonance for nominal input voltage. The load sharing problem of LLC resonant converter has been overcome by SCC (Switch Controlled Capacitor). In interleaving technique, all the stages of LLC operate at same switching frequency for the purpose of current ripple cancellation. It has been proposed to reduce the switching losses and voltage ripple by using a PI Filter.

Keywords: Switch-controlled capacitor (SCC), LLC resonant converter, MATLAB/SIMULINK.

I. INTRODUCTION

The converter which eliminates much of the switching losses associated with fixed frequency by enabling switching at either near - zero voltage or near - zero current is known as resonant converter. The resonant converters can be classified into two types namely, series and parallel resonant converters. The drawback of series resonant converter is that it cannot regulate output at no load condition and output current is high. The disadvantage of parallel resonant converter is circulating current is high and has lower efficiency at reduced loads.

To overcome these drawbacks LLC resonant converter is preferred. The LLC resonant converter can operate at nominal input voltage and at no load conditions. Here we use SCC modulated LLC to overcome the load sharing. Interleaved method is used here is defined as the parallel combination of DC – DC converters with an interleaving difference of 360/N between the adjacent phases. The purpose of using interleaving method is to reduce the ripple currents at both input and output terminals.

In this paper, the Switch Controlled Capacitor (SCC) is used to control the output voltage by controlling the equivalent capacitance of LLC resonant converter at each stage, thus modulating resonant frequency. As a result of constant switching frequency, the voltage regulation is achieved in individual phases of LLC. In the proposed SCC-LLC topology, a SCC is connected in series with the resonant tank to modulate the equivalent capacitance C_r thereby controlling resonant frequency. The resonant frequency in turn controls the voltage gain.

II. LITERATURE REVIEW

The system proposed in [1] a simple and accurate design methodology for LLC resonant converters, based on a semi empirical approach to model steady-state operation in the "below-resonance" region. This has led to simple yet accurate design-oriented model and to a simple step-by-step design procedure that ensures stable operation at no load, ZVS under all operating conditions. The methodologies based on first harmonic approximation (FHA) analysis are much simpler but due to lack of accuracy especially in below-resonance region it is not used. The system in [2] proposes an approximate analysis of LLC resonant converter with capacitive filter operating above and below resonance. An equivalent AC resistance model of the rectifier valid for discontinuous as well as continuous conduction modes is proposed. The DC voltage conversion ratio is then obtained using the fundamental harmonic approximation analysis method. Here Fundamental Harmonic Analysis method has been used. Here LLC can operate with wide load range and can achieve step-up as well as step-down voltage conversion. Since it is applicable to off-line converters it has relatively large DC holdup and output capacitor need to provide output voltage support in case of line fault of light load to full load transients. This reduces the power density and has drawback of alleviating fast voltage control. The project in [3] proposed Simulation and Implementation of High Gain Interleaved Boost Converter for Fuel cell applications. For designing high efficiency fuel cell power systems, a suitable DC-DC converter is required. Among the various topologies,

interleaved converters using switched capacitor are considered as a better solution for fuel cell systems due to high conversion efficiency. In the proposed interleaved converter, the front end inductors are magnetically cross-coupled to improve the electrical performance and reduce the weight and size. Also, switched capacitors are used to improve the voltage gain of the converter.

III. PROPOSED SYSTEM

The system proposed in this paper uses the LLC resonant converter for analysis as in [1], [2] and uses Switch controlled capacitor based on interleaving technology for achieving high voltage gain.

The features of the proposed system are:
- Interleaved LLC resonant DC-DC converter with modulated SCC is used.
- This techniques deals with voltage ripple reduction by using PI filter in the output.
- The load used is a PMDC motor load.

The simple block diagram of interleaved DC-DC converter is shown in Fig 1. Since this paper deals with interleaved technique we use a parallel – parallel combination of LLC resonant converter as shown in the block diagram.
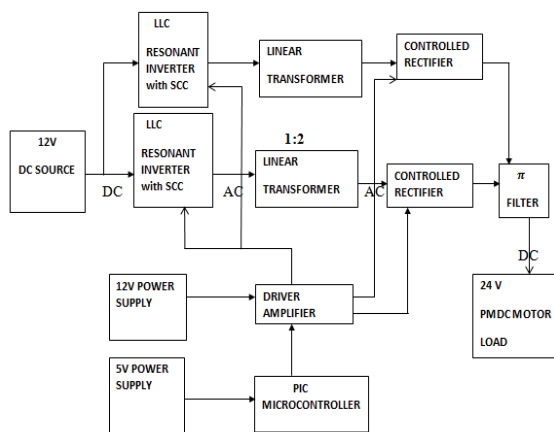

Fig. 1: Block Diagram of proposed system

The Entire system Block Diagram is shown in Fig.1 The Block diagram consists of LLC resonant converter with SCC, Linear Transformer, Controlled Rectifier, PIC controller, PI filter and Driver Amplifier. The input source is a 12 V DC source. The DC output from DC source is given to the resonant inverter which converts DC to AC and gives the AC output to the transformer which steps up the voltage. Now the AC output from the transformer is given to a rectifier where it is converted to DC and fed to the PMDC motor.

IV. INTERLEAVED LLC RESONANT CONVERTER

The LLC resonant converter with interleaving technique is mainly used to achieve high power level. The Fig.2 shows the topology of LLC resonant converter with PI filter feeding R load. The modes of operation of below circuit are explained as follows.
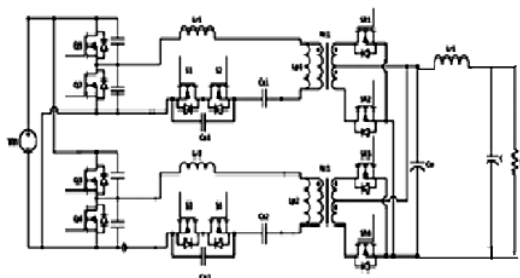

Fig.2: Topology of LLC resonant converter

In mode 1, the Q_1, $S_1$are in ON state. The current flows in the direction Q_1-L_1-$L_{r1}C_1$-D_2-S_1. The voltage with positive polarity is given to the primary. Similarly voltage is induced in upper half of secondary. When SR_1 is closed current flows through the load. The Q_3, S_3 are ON and the current flows from Q_3-L_2-L_{r2}-C_2-D_4-S_3. Now S_{r3} is closed and current flows through the load.
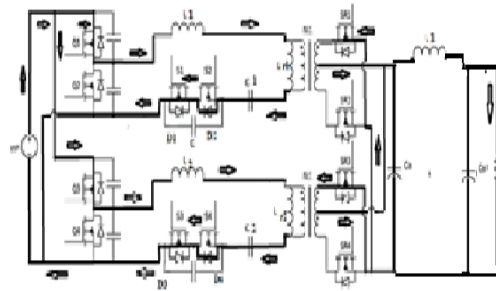

Fig.3: Mode 1 operation of LLC resonant converter

During negative half cycle when Q_2 and S_2 are in ON state in mode 2. The current flows in the direction Q_2-D_1-S_2-C_1-L_{r1}-L_1. The voltage across the capacitor is applied to the primary with negative polarity. Similarly voltage is induced in the secondary with negative polarity. Current flows through SR_2 and load. The Q_4 and S_4 are in ON state. The current flows through Q_4-D_2-S_4-L_{r2}-L_2. The S_{r4} is closed and current flows through the load.
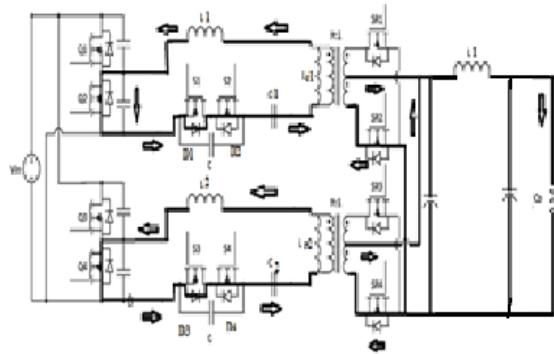

Fig .4: Mode 2 operation of LLC resonant converter

V. THEORETICAL ANALYSIS

The output voltage of the proposed LLC resonant converter can be increased by interleaving technique. The resonant frequency is given by

$$f_r = \frac{1}{2\pi\sqrt{L_r C_r}} \quad ....1$$

The equivalent capacitance of SCC is given by

$$C_r = \frac{C_s C_{sc}}{C_s + C_{sc}} \quad ....2$$

The Capacitor which is controlled by switches S_1 and S_2

$$r = \frac{1}{4\pi f_r C_{sc}R} \quad ....3$$

The inductance value is calculated using

$$L_s = \frac{(1-D)V_o}{8f f r} \quad ....4$$

The torque equation for PMDC motor is

$$T = K\phi I_a \quad ...5$$

f_r is the resonant frequency, r is the ripple factor, C_{sc} is the value of equivalent capacitance which is calculated Series capacitor C_s and Resonant capacitor C_r. The value of Capacitor which is controlled by switches S_1 and S_2 is calculated from ripple factor. The value of series inductance of resonant converter is

calculated using equation 4. The torque of PMDC motor is calculated using equation 5 and the speed is obtained from the torque value calculated.

VI. VOLTAGE RIPPLE REDUCTION

12V is given as input and the ouput voltage obtained is 24 V. The interleaved topology is frequently used to achieve low ripple current and to achieve high efficiency compared to other existing topologies. Here the LLC resonant converter is connected in parallel with another LLC resonant converter to achieve interleaved topology.
      The proposed system of LLC resonant converter with PI filter is shown in Fig 4.1. The input DC supply is given to the LLC resonant inverter where the resonant operation is carried out and the input DC is converted to AC and is given to the transformer. The transformer will step up the voltage and gives it to the rectifier. The rectifier converts AC to DC and supplies to the load connected. C filter is used in the existing system to reduce the ripples in the output voltage and current. But PI filter reduces more ripples than C filter and hence we go for the proposed system as shown in Fig 5.
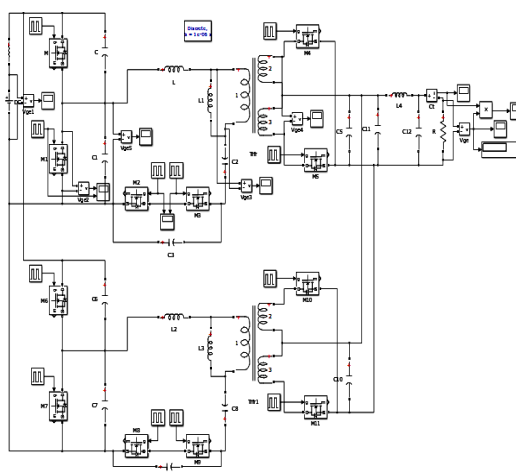

Fig.5: Simulation circuit of LLC resonant converter with R Load

The DC input voltage is boosted up and is supplied to the load. The ripples reduced by C filter are less compared to PI filter. So, C filter is replaced by PI filter in the proposed system.
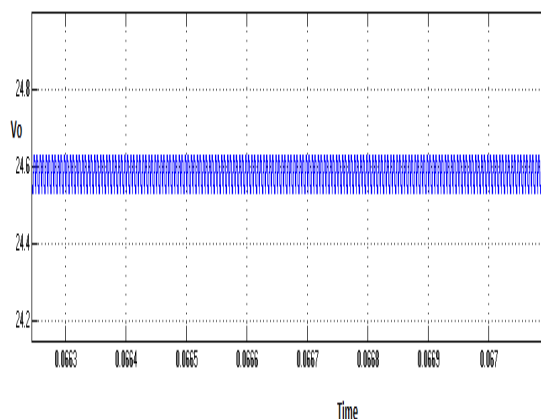

Fig.6: Voltage Ripples with C filter with R load

      The simulation results of LLC resonant converter with PI filter connected to an R load are given. The voltage ripples with R load connected to C filter and PI filter is shown in Fig 6 and Fig 7.
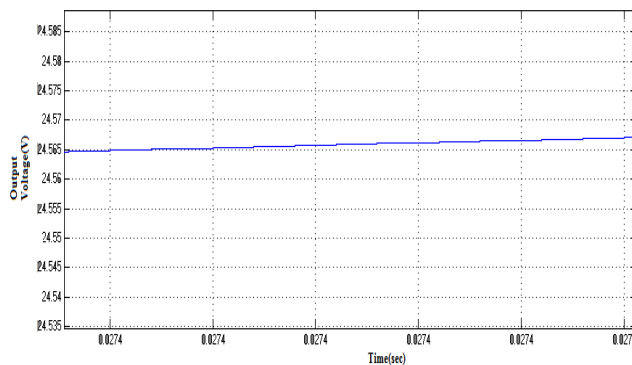
Fig.7: Output voltage of PI filter with R Load

The interleaving technique requires all the stages of LLC resonant converter to operate at constant switching frequency for the cancellation of ripple current. An SCC is connected in series with the resonant tank in order to modulate the equivalent resonant capacitance(C_r) and thus controlling resonant frequency. The centre tapped full wave rectifier mainly replaces four diodes by two diodes. The resonant frequency in turn controls the voltage gain. About 99% of ripples get reduced by PI filter and the output will be obtained as shown in the waveform. The advantage of using PMDC motor is that, there is no need for field excitation and is cost effective compared to other motors.
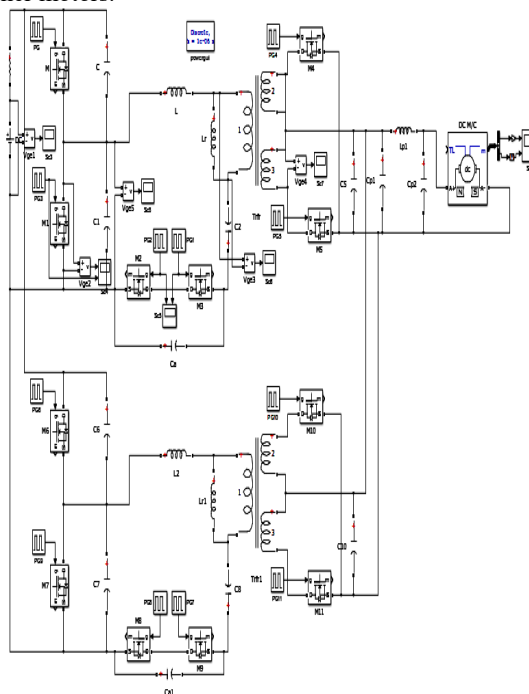

Fig.8: Open loop simulation of LLC resonant converter feeding PMDC Motor

The speed and torque characteristics of LLC resonant converter with motor load for open loop circuit are shown in the Fig 9. The value of speed obtained for open loop LLC resonant Converter is 209 rpm and the torque value obtained is 1.32 Nm.
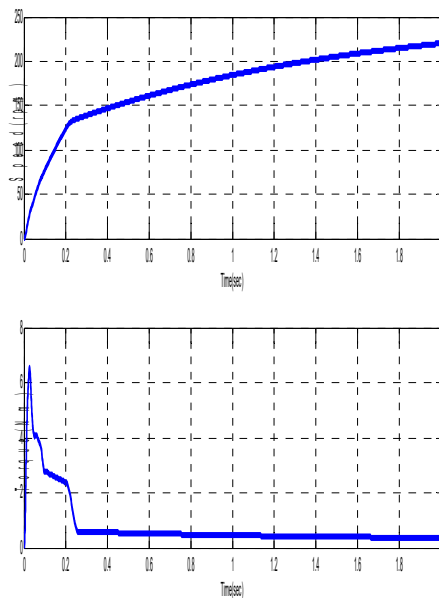
Fig9 Speed and Torque characteristics of PMDC motor

The comparison of LLC resonant converter with C filter and PI filter is given in the table below.

PARAMETERS	EXISTING C FILTER	PROPOSED PI FILTER
Input voltage	12V	12V
Output voltage	24V	24V
Output current	1.2A	1.2A
Output power	30W	30W
Ripple	9%	0.1%

TABLE.1: System comparisons of C Filter and PI Filter for Proposed LLC Resonant converter with Motor Load

VII. CONCLUSION

The simulation of LLC resonant converter with PI filter fed to PMDC motor was successfully carried out using MATLAB/Simulink software and output waveforms were observed. The voltage ripples are reduced by using PI filter. The voltage regulation will be achieved as the result of individual LLC phases which will have same switching frequency at all the phases. The comparison has been carried out between existing system and proposed system. From the analysis it is clear that proposed system is advantageous over the existing system, and it is used to drive a PMDC motor.

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