International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 3 Issue 1, January - 2014

A Harmonic Based Phase Shifted Control LLC Resonant Converter For Inductively Coupled Power Transfer System

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ABSRACT

The quality of sinusoidal waveform becomes a major concern. The power electronics inverters have drawn a non sinusoidal waveform due to causes of harmonic distortion and limit the utilization of the available electrical supply. In this work, LLC series-parallel resonant converter (SPRC) is presented. A harmonic based phase shifted control (HPSC) on inverter is done in this paper. The switching frequency is set as equal to resonant frequency for first - order harmonic. The switching frequency is set as less than resonant frequency for third – order harmonic and fifth – order harmonic. The proposed method simulation is done in MATLAB SIMLINK.

1. INTRODCTION

Inductively Coupled Power Transfer (ICPT) is different from other power transfer method using wires. The power transfer using wires which can generates sparks causes accidents. Generally ICPT is under the principle of mutual induction like transformer. The energy is inductively transferred from primary coil to the secondary coil. The magnetic flux in the Primary coil is transferred to the secondary coil. By means of magnetic flux an voltage is induced in the secondary coil.

A harmonic-based series resonant converter of phase shifted control method is proposed in [1]. The series resonant inverter output voltage is presented for third-order and fifth- order harmonic component other than first-order harmonic component to transferred power. In [2] proposed developed state space model for multivariable frame work and frequency domain is mapped to compute the transfer function of eight order bidirectional IPT system. In [3] the three phase contactless power transfer system model is proposed. A three phase contactless power transformer has the magnetic coupling for the phase winding. The magnetic coupling depends on the displacement of the secondary armature with respect to the primary armature. The three phase resonant capacitance value for the simplified model.

In [4] proposed as impedance matching method. The position of secondary coil is not dependent only primary coil can share with other device for wide area power feeding. In [5] based on circular coils for contactless power transfer (CPT) is proposed for electric vehicle (EV) charging. The system dimension plays an important role of the effect of mutual inductance for the system performance and the analytical model of the system is derived. In [6] proposed a new multiphase pickup. The continuously powered automatic guided power vehicle is considered for improved tolerance of the power receiver. In [8] proposed a recent multiphase (quadrature) pickup of a practical prototype suited for contactless power transfer system (CPT) .The automated guided vehicle system is designed for commercial pickup based on investigation.

In [11] proposed online electric vehicle for a new inductive power transfer system with a narrow rail width, large air gap .The system drive freely for roads. In [12] proposed LCL resonant topology of full isolation and protection. The new three phase IPT system is developed for a power supply of a standard six switch inverter.

In [15] a inductive power transfer application, a new type series ac processing is proposed. The zero current switching condition uses an ac switch operating for the proposed pickup in series with a resonant network to produce a controllable ac voltage source suitable for driving incandescent lights.

In this paper proposed LLC series- parallel resonant converter (SPRC). Due to harmonic distortion in single phase full bridge inverter a square wave or modified square wave pulse are produced. The proposed LLC series-parallel resonant converter changed into sine wave pulse. And further a harmonic based phase shifted control done on inverter. The output voltage of inverter is regulated and the THD values are improved. The first – order harmonic, third – harmonic, fifth – order harmonic are reduced in this paper.

The organization of this paper is as follow section II discuss as Load resonant converter, section III discuss as proposed model, section IV discuss as harmonic based phase shifted control on full bridge inverter, section V discuss as simulation and results, section VI discuss as conclusion.

2. LOAD RESONANT CONVERTER

The resonant converter is the combination of the inductance and capacitance that the part is load is load resonant converter. The combination of inductance and capacitance provides a soft switching and can able change the soft switching compare to hard switching. The load resonant converter consists of series resonant converter, parallel resonant converter, series-parallel resonant converter. The series-parallel resonant converter is further classified into LLC resonant converter, and LCC resonant converter.

Series resonant converter: The resonant inductance L_r , and resonant capacitance C_r , are connected in series is called series resonant converter.

Parallel resonant converter: The resonant inductance L_r , and resonant capacitance C_r , are connected in parallel is called parallel resonant converter.

Series – parallel resonant converter: The combination of series and parallel resonant converter is called series – parallel resonant converter.

LLC series – parallel resonant converter: The resonant inductanceL_r , and resonant capacitance C_r , are connected in series and magnetizing inductance L_m , are connected in parallel is called LLC series – parallel resonant converter.

LCC series – parallel resonant converter: The resonant inductanceL_r , and resonant capacitance C_{r1} , are connected in series and resonant capacitance C_{r2} , are connected in parallel is called LCC series – parallel resonant converter.

3. PROPOSED MODEL

The LLC series – parallel resonant converter is proposed in this paper. The LLC resonant converter has two resonant frequencies.

$$f_{r1} = \frac{1}{2\pi\sqrt{L_r\, C_r}} \qquad (1)$$

And

$f_{r2} = \frac{1}{2\pi\sqrt{(L_r+L_m)C_r}}$ (2)

Where f_{r1} = resonant frequency 1; f_{r2} = resonant frequency 2 L_r= resonant capacitance; C_r = resonant capacitance; L_m = magnetizing inductance;

$\omega_r = 1/\sqrt{((L_r + L_m)C_r)}$ (3)

Where ω_r = resonant angular frequency;

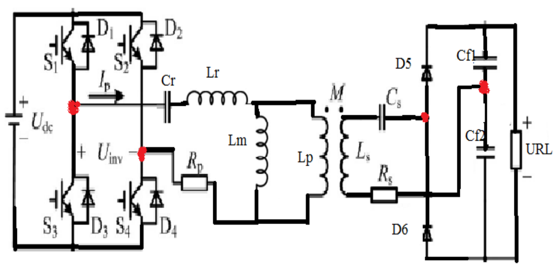


Fig-1: ICPT with LLC series – parallel resonant converter

The circuit diagram of ICPT with LLC series – parallel resonant converter is shown in Fig.1.

U_{dc}= Input DC voltage source

S_1 - S_2 = Switching components of full bridge inverters;

D_1 - D_4 = Freewheeling diodes

U_{inv} = Full bridge inverter output voltage

I_p = Full bridge inverter output current

M =Mutual inductance

R_p= Total resistance of primary winding

R_s = Total resistance of secondary winding

L_p = Total inductance of primary winding

L_s = Total inductance of secondary winding;

D_5 - D_6 = voltage doubler of diodes

C_{f1} = Voltage doubler Capacitance 1

C_{f2} = Voltage doubler capacitance 2

U_{RL} = Voltage of load resistance

The input dc voltage is given to full bridge inverter. The inverter can change dc voltage in to ac voltage. It produces a modified square wave pulse.

$U_{pk} = \frac{2\sqrt{2}}{k\pi} U_{dc} \cos k\,\alpha/2$ (k = 1, 3, 5, 7....) (4)

Where U_{pk} = Root mean square value of kth – order harmonic component of U_{inv}. α = Phase – shifted angle. K= Harmonic order. Then the square wave pulse is given to LLC series – parallel resonant converter. It converts modified square wave pulse into sine wave .Then it is given to inductively coupled power transfer (ICPT). The magnetic flux in the primary coil is transferred to the secondary coil. By means of magnetic flux a voltage is induced in the secondary coil. Then induced voltage in the secondary coil is given to voltage doubler. It has two actions. First, it convert ac voltage in to dc voltage as rectifier and second, it twice the dc voltage. And then given to output resistance.

TABLE I

LLC RESONANT CONVERTER PARAMETER

Parameter	Designator	Value
Input Voltage	V_{in}	90 V
Resonant Inductor	L_r	100 μH
Resonant Capacitor	C_r	0.36 μF
Magnetizing Inductor	L_m	0.05 μH
Resonant Frequency	f_r	21.65 KHZ
Switching Frequency	f_s	21.65 KHZ

The table I shows the parameter of LLC resonant converter.

4. HARMONIC BASED PHASE SHIFTED CONTROL

The inverter output voltage is regulated by changing the switching frequency of inverter is phase –shifted control. To reduce the harmonic component of kth order, switching frequency of inverter to be change.

$\omega_s = 2\pi f_s$ (5)

$\omega_s = \frac{\omega_r}{k}$ (6)

Where ω_s = angular switching frequency; f_s = switching frequency;

The path of HPSC of full bridge inverter is divided into six stages as shown in Fig.2.

Stage 1: At $[t_0, t_1]$: S_3 turns OFF at t_0 . From t_0 to t_1 , the power is oscillating freely through S_2, L_p, R, C_r, L_r, L_m and D_1 . U_{inv} is equal to 0 during this stage.

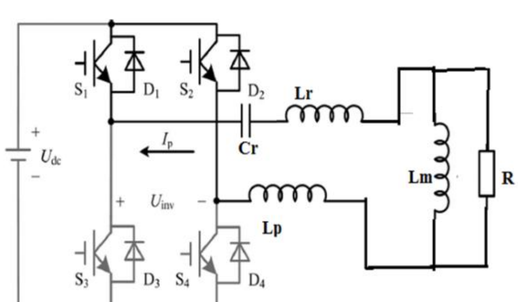
Stage 2: At $[t_1, t_2]$: At t_1, S_1 turns ON at zero voltage switching (ZVS) when D_1 conducts. The power is oscillating freely through S_1 , L_r, L_m, R, L_p , and D_2.

Stage 3:At t_2, S_2 turns OFF at ZVS when D_2 conducts.

Stage 4: At $[t_3, t_4]$: S_4 turns ON at t_3 , and D_2 turns OFF at the same time. The conduction current through S_4 is same with the turning OFF current of D_2 . The power is transferred from input dc source to load through S_1, C_r, L_r, L_m, L_p , and S_4 . U_{inv} is equal to U_{dc} during this stage.

Stage 5: At $[t_4, t_5]$: Inverter output current I_p crosses zero and changes its direction at t_4 . The power is circulated from load to input dc source through $D_4, L_r, C_r\ R, L_m, C_p$ and D_1 . This stage finishes when I_p reaches zero.

Stage 6: At $[t_5, t_6]$: After the current I_p crosses zero and changes its direction at t_5 , the power is transferred from input dc source to load through S_1, L_r, C_r, L_m, R, L_p , and S_4 during this stage. This stage ends when S_1 turns OFF at t_6 .



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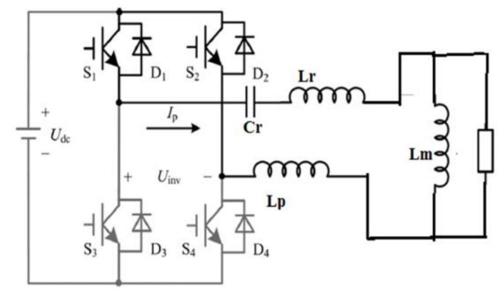

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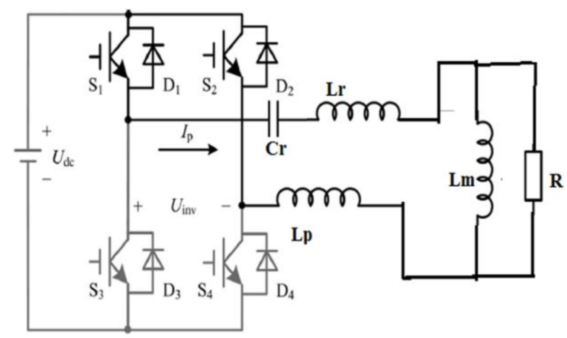

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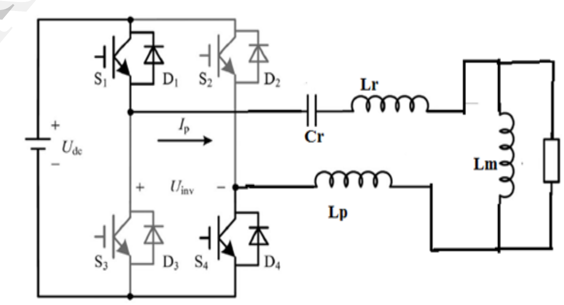

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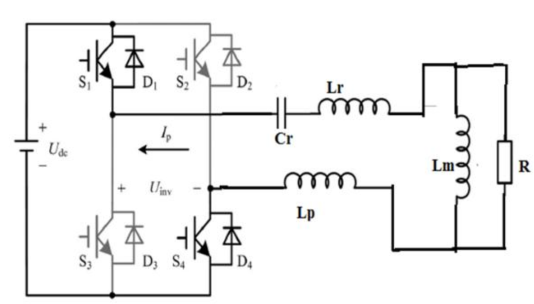

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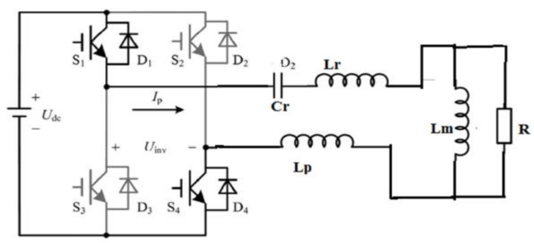


(f)

Fig-2: Path of HPSC for full bridge inverter

TABLE II
SWITCHING FREQUENCY FOR HPSC

Method	Switching Frequency
First- order harmonic in HPSC	f_s = 21.65 KHZ
Third –order harmonic in HPSC	f_s = 7.61 KHZ
Fifth – order harmonic in HPSC	f_s= 4.33 KHZ

The table II shows the switching frequency for HPSC.

5. SIMULATION AND RESULTS

The simulation circuit of LLC resonant converter is shown in Fig.3.

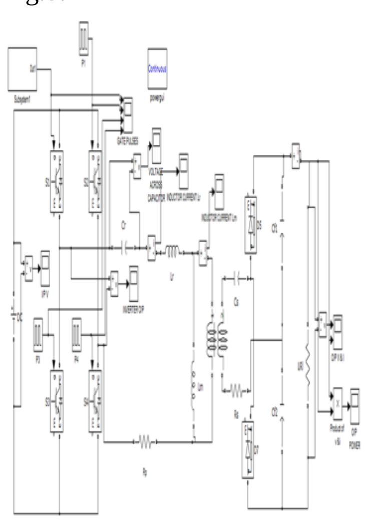


Fig-3: Simulation circuit of LLC resonant converter

The simulation circuit of full bridge inverter for HPSC is shown in Fig.4.

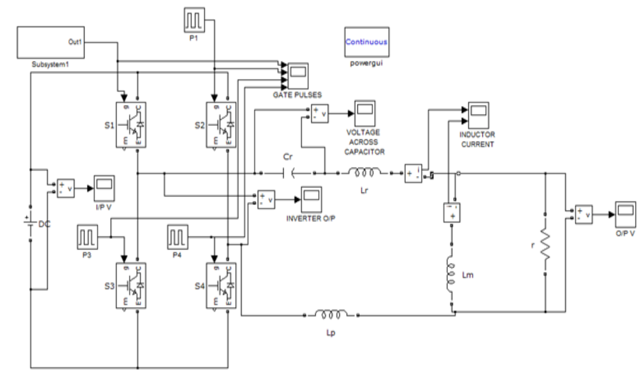


Fig-4:Simulation circuit of full bridge inverter for HPSC

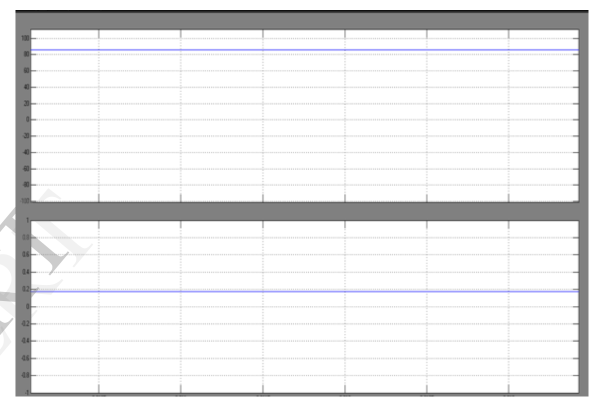
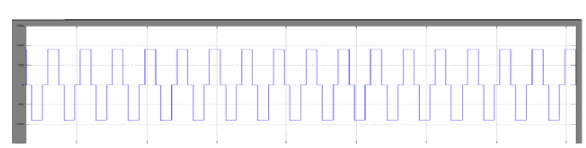


Fig-5: Waveform of DC output voltage and current.

The DC output voltage and current is shown Fig.5. The DC output voltage is 86 V and DC output current is 0.19 A of f_s = 21.65 KHZ for first- order harmonic in HPSC.



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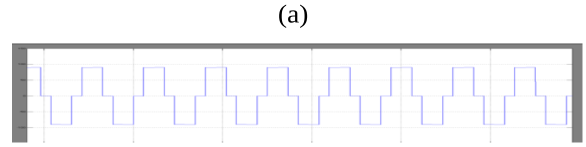

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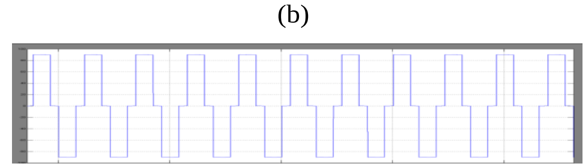
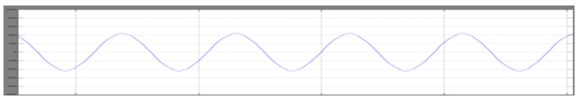


(c)

Fig-6: Waveform of inverter output voltage (a) f_s =21.65 KHZ first – order harmonic in HPSC (b) f_s =7.61 KHZ third – order harmonic in HPSC (c) f_s=4.33 KHZ fifth – order harmonic in HPSC. U_{inv}=90 V



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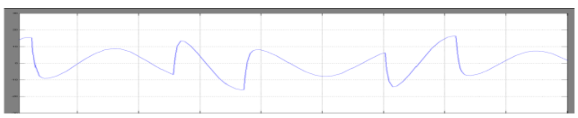

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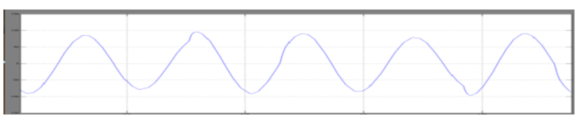

(c)

Fig-7: Waveform for LLC resonant converter output voltage (a) f_s = =21.65 KHZ first – order harmonic in HPSC (b) f_s =7.61 KHZ third – order harmonic in HPSC (c) f_s=4.33 KHZ fifth – order harmonic in HPSC

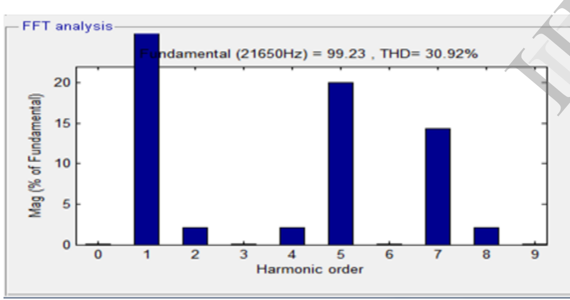

Fig-8: FFT analysis of f_s = =21.65 KHZ first – order harmonic in HPSC.

Fig.8. shown FFT analysis the THD value of first -order harmonic is 30.92%

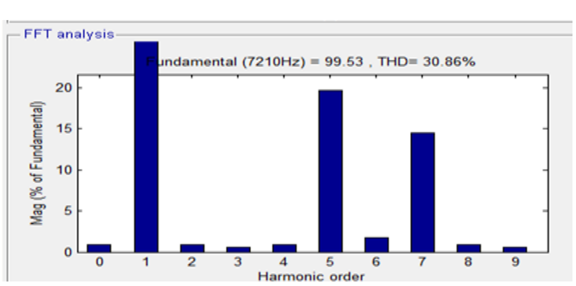

Fig-9: FFT analysis of f_s =7.61 KHZ third – order harmonic in HPSC.

Fig.9. shows FFT analysis the THD value of third – order harmonic is 30.86%

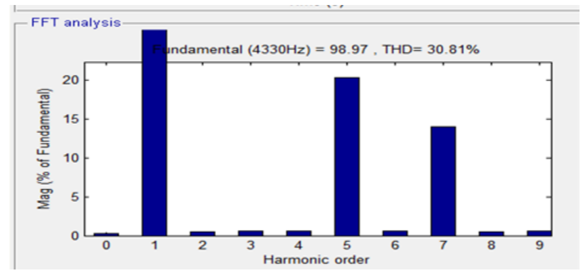

Fig-10: FFT analysis of f_s=4.33 KHZ fifth – order harmonic in HPSC.

Fig.10. shows FFT analysis the THD value of fifth – order harmonic is 30.81%

6. CONCLUSION

A novel inverter output voltage are regulated called HPSC for full bridge LLC series - parallel resonant converter is proposed in this paper. In this method, switching frequency is set as equal to first - order harmonic and switching frequency is set as less than resonant frequency for third – order harmonic and fifth – order harmonic. The THD value is improved compare to conventional method. The sine wave output is obtained for LLC resonant converter. Furthermore, the equal and reduced switching frequency can be achieved by regulating inverter output voltage.

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