CLOSED LOOP CONTROL OF THE Z SOURCE RESONANT CONVERTER FOR THE ELECTRIC VEHICLE WIRELESS CHARGER

Shwetha K B[1], Shubha Kulkarni[2]
[1]P.G. Student, Power Electronics, Dayananda Sagar College of Engg., Bangalore, India
[2]Asst prof, Electrical & Electronics Engineering, Dayananda Sagar College of Engg., Bangalore, India

Abstract
Wireless charger for Electric Vehicles (EVs) is an off-line application and it needs power factor correction (PFC) function, which usually consists of a front-end boost PFC and a cascaded DC/DC converter. Recently, Z-source resonant converter (ZSRC), a single-stage solution with low cost and high efficiency, was proposed for EV wireless charger. Combining with the Z-source network, the control scheme is more challenged and sophisticated. Traditional phase-shift control and pulse notch control have been applied to ZSRC performing PFC function and load regulation successfully. To make the system output stable with variable input voltage, here, the closed loop control of ZSRC by using the PI controller is used to control the output voltage. MATLAB simulation is done with a variable input voltage and a constant voltage of 88v and 200W prototype with a closed loop Z Source Resonant Converter for the application of wireless charging of the electric vehicle..
Keywords: Closed loop control, Electric vehicle, PI controller, wireless power transfer(WPT), Z source resonant converter(ZSRC).

I. INTRODUCTION

Recent attention to transportation electrification and the rise in electric vehicle deployment have led researchers to investigate several aspects of electric vehicle and charging technologies including advanced battery technologies, electric drives, on-board charging systems, and off-board level 3/ fast-charge systems[1]. On-board chargers are burdened by the need for a cable and plug charger, galvanic isolation of the on-board electronics, the size and weight of the charger, and safety and issues with operating in rain and snow. Wireless power transfer (WPT) is an approach that provides a means to address these problems and offers the consumers a seamless and convenient alternative to charging conductively. In addition, it provides an inherent electrical isolation and reduces on-board charging cost, weight and volume[2].

A conventional on-board battery charger (OBC) is usually a two-stage structure; a power factor correction (PFC) front-end part and a dc–dc converter part with high-frequency transformer, as shown in Fig. 2.

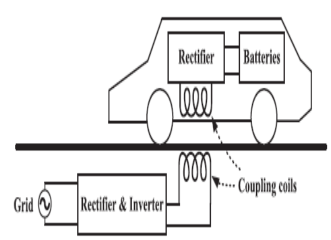

Fig 1.Configuration of a WPT system for on line power transfer(OLPT)

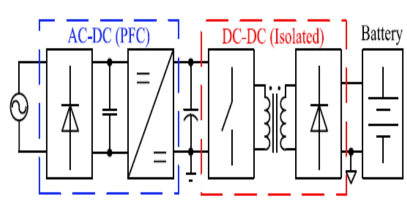

Fig. 2. Block diagram of a conventional OBC

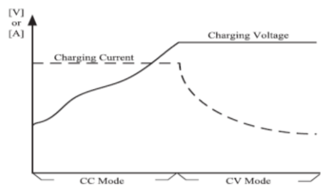

Fig.3. OBC charging mode

Load regulation function is required for the dc–dc converter as the battery charger has constant current (CC) mode and constant voltage (CV) mode, as shown in Fig. 3. The dc–dc converter would always try to output maximum current in CC mode without regulation that the low-medium load range in CV mode consumes 40% of the total charge time [3].In other words, load regulation in CV mode is essential in terms of the overall performance of the OBC.

The series resonant converter is widely adopted in wireless power transfer because of its high efficiency and simplicity. However, owing to the large ratio between the leakage inductance and magnetizing inductance (greater than 10:1) in WPT application, an SRC has a high quality factor. A Z-source inverter,well known for its boost feature and being immune to shoot-through problem, can be applied to any kind of power conversion between dc and ac. A combination of Z-source network (ZSN) and SRC has been studied. It can improve the efficiency over a wide input voltage and load variation[4]. Furthermore, a Z-source resonant converter (ZSRC) was proposed in and proved its advantage over conventional boost PFC with a cascaded dc–dc[5].

1.1 CLOSED LOOP CONTROL SYSTEM:

A control system with feedback loop is called "closed loop control system". In other words, the control system which uses its feedback signal to generate output is called " closed loop control system". In these control systems, the input is controlled by the feedback signal from input so that it can correct the errors occurred. Feedback means , some part of output is taken and connected it to the input of the system to maintain the stability of the control system. By providing a feedback loop, we can convert any open loop control system into closed loop system. The feedback loop provides the automatic correction of the input signal based on the output requirement. By comparing the generated output with the actual condition, the closed loop system maintains and achieves the desired output. If the produced output is deviated from decided (actual) output, the closed loop control system generates an error signal and the error signal is fed to the input of the signal.So by adding the error signal to the input, the generated output of the next loop will be corrected. So these are also called as automatic control systems. Closed loop systems are less prone to external disturbances.

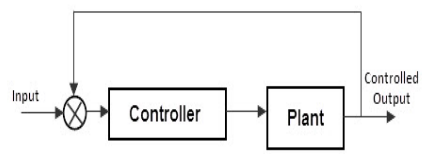

Fig 4 **Block diagram** of the closed loop system

II. OPERATION OF THE Z SOURCE RESONANT CONVERTER

Different from dc/ac application, the ZSRC has more states in one switching cycle. It is important to clarify all these states to understand the ZSRC. The boost ratio of ZSN is still related to the total shoot-through state duty cycle among these states. In this section, the operation principle of the ZSRC is described based on an example of the phase-shift control method. Assuming that the ZSN is symmetrical (C1 = C2 = C, and L1 = L2 = L) in Fig. 4, therefore, $VC1 = VC2 = VC$, and $vL1 = vL2 = vL$. Also, the resonant frequency of L and C in ZSN is at least ten times smaller than the switching frequency. Hence, the ZSN inductor current and the ZSN capacitor voltage are considered constant in one switching cycle. Fig. 5 shows the conducting devices in different states—active state, shoot through state, and zero state.The time domain waveforms of these states are illustrated in Fig.7(6).

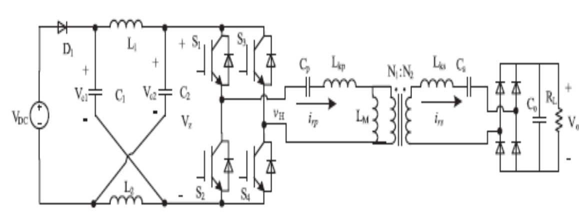

Fig.5 Circuit schematic of the z source resonant converter

1) Active State: During the two active states time interval [see Fig. 6(c) and (g)], the diagonal switches are on, and the input side diode *D*1 is conducting. The resonant network draws current from both the ZSN inductor and capacitor. The difference between load current and ZSN inductor current is provided by a series connection of the two ZSN capacitor and dc source[7]. The current going through the switches are only load current The ZSN inductor voltage for this time interval is given as

$$V_L = V_{DC} - V_C \text{………(1)}$$

2) Shoot-Through State: Four shoot-through state's time intervals are demonstrated in Fig. 6(b), (d), (f), and (h). Three of the switches are ON. The two horizontal switches are carrying the load current and the switches in one-phase leg are carrying the ZSN inductor current. Hence, there is one switch carrying the sum of the two currents. Since the flow of ZSN inductor current is always in one direction and the load current would be bipolar, these two currents either subtract from each other or add together, contributing to the sum with their absolute value. Fortunately, phase-shift control only allows different polarity currents going through the same switch in shoot-through state. Here, the ZSN capacitors will charge ZSN inductors (this is how the ZSRC can boost the voltage). The ZSN inductor voltage for this time interval is given as

$$V_L = V_C \text{……………..(2)}$$

3) Zero State: During the zero state's time interval [see Fig. 6(a) and (e)], two horizontal switches are ON. The ZSN is isolated from the load. The load current is freewheeling and the ZSN inductors charge the ZSN capacitors. The ZSN inductors voltage for this time interval is given as

$$V_L = V_{DC} - V_C \text{…..….(3)}$$

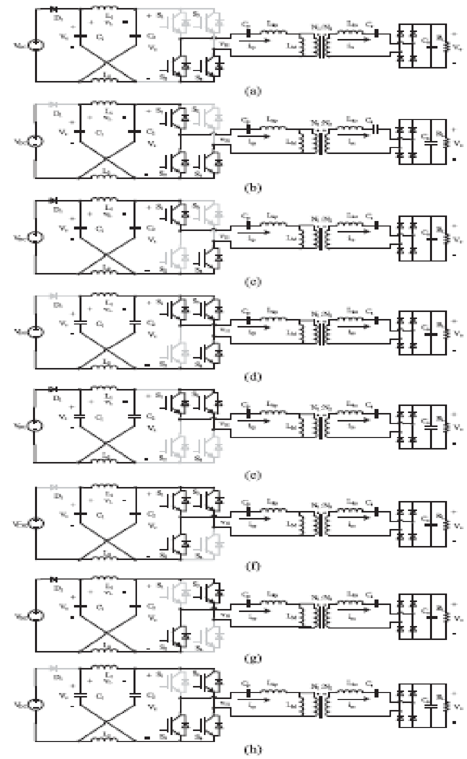

Fig.6 ZSRC circuit diagram in different states: (a) zero state, t0 to t1 and t8 to t9 ; (b) shoot-through state, t1 to t2 ; (c) active state, t2 to t3 ; (d) shoot-through state, t3 to t4 ; (e) zero state,t4 to t5 ; (f) shoot-through state, t5 to t6 ; (g) active state, t6 to t7 ; and (h) shoot-through state, t7 ot t8.

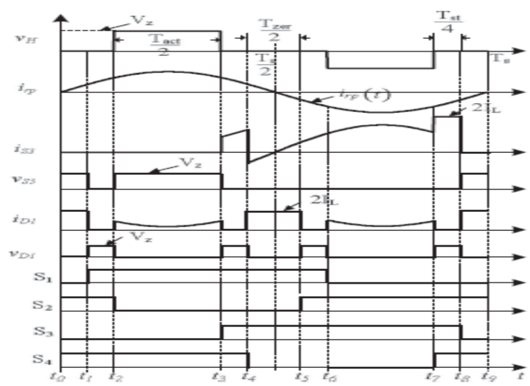

Fig.7 Time domain waveforms for phase-shift control in the ZSRC.

III. Z SOURCE RESONANT CONVERTER WITH CLOSED LOOP OPERATION

The closed loop z source resonant converter for the wireless power transfer in which the output has an effect on the input quantity in such a manner that the input quantity will adjust itself based on the output generated[8]. Open loop control system can be converted in to closed loop control system by providing a feedback. This feedback automatically makes the suitable changes in the output due to external disturbance. In this way closed loop control system is called automatic control system. Figure below shows the block diagram of closed loop control system in which feedback is taken from output and fed in to input[9].

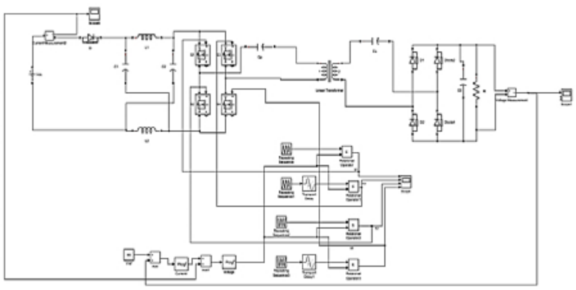

Fig.8 closed loop ZSRC for the wireless power transfer

Fig.8 shows a closed loop system for a dc-dc converter. The circuit consists of a high frequency (HF) z source resonant converter. High frequency switching is implemented using MOSFET switches. This is the high frequency link. A HF transformer provides voltage transformation and isolation between the DC source and the load. At the output side, a full bridge rectifier is connected to load. For analytical study, a resistive load is selected. The closed loop is controlled for constant output.

IV. DESIGNING OF THE Z SOURCE RESONANT CONVERTER

The input voltage of the ZSRC is Vs=33V and the output voltage and current is Vo=88v and Io=2.28A with the resonant frequency of 20kHZ. Assuming that the ZSN is symmetrical (C1 = C2 = C, and L1 = L2 = L) therefore, $VC1 = VC2 = VC$, and $VL1 = VL2 = VL$. Also, the resonant frequency of L and C in ZSN is at least ten times smaller than the switching frequency. Hence, the ZSN inductor current and the ZSN capacitor voltage are considered constant in one switching cycle.

Hence,

C1 = C2 = C = 4.7mF

L1 = L2 = L = 1Mh…………..(4)

Assuming purely resistive loading for the converter, then the load resistor can be found as,

$$R_0 = \frac{V_0^2}{P_0} = \frac{88^2}{200} = 38.59\Omega \ldots\ldots(5)$$

The significant part of the design is choosing the inductor and capacitor values and operating frequency. On the contrary, use of the low frequency leads to increases both on the size and also the cost of inductors and capacitors. Thus, there is a trade-off between the size and efficiency in determining the operating frequency of the converter. The frequency is selected as 20*kHz* . Hence, the period of the circuit is,

$$T_s = \frac{1}{f} = \frac{1}{20k} = 50\mu s \ldots..(6)$$

The size of the inductors and the average currents through them cannot be determined unless the duty-factor is determined. Inserting the input voltage and output voltage values gives the numerical value of duty-factor for the specific case in the simulation as

$$D = \frac{V_0 - V_s}{2V_0 - V_s} = \frac{88-33}{2*88-33} = 0.38\ldots\ldots(7)$$

The output voltage of the z source resonant converter is given by

$$V_0 = \frac{(1-D)V_s}{1-2D} = \frac{(1-0.38)33}{1-2*0.38} = 85.25V\ldots.(8)$$

The output current of the z source resonant converter is given by

P = V*I =85.25*2.28=194.37W………(9)

The main requirements of the Z-source dc/dc converter are listed at Table 1.

Input voltage(Vdc)	33V
Output	88 V/2.28A
Resonant frequency	18.2kHz
Transformer turns ratio	15:20
ZSN capacitors(C1,C2)	4.7mF
ZSN inductors(L1,L2)	1mH
Primary-side compensating capacitor(Cp)	180Nf
Primary side leakage inductance(Lkp)	0.415Mh
Magnetising inductance(Lm)	61.87uH
Secondary side leakage inductance(Lks)	1.07Mh
Secondary-side compensating capacitor(Cs)	65.8nF
Output filter capacitor(Co)	1mF

Table 1. Parameters and values

V. SIMULATION RESULTS

Simulations of the proposed system have been performed at full-load conditions. Table I shows the parameters and components values used for the simulations. The switching frequency for these systems range between 10 and 50 kHz. In this 18.2 kHz was selected. The simulation of closed loop system is done using MATLAB software and the results are presented.

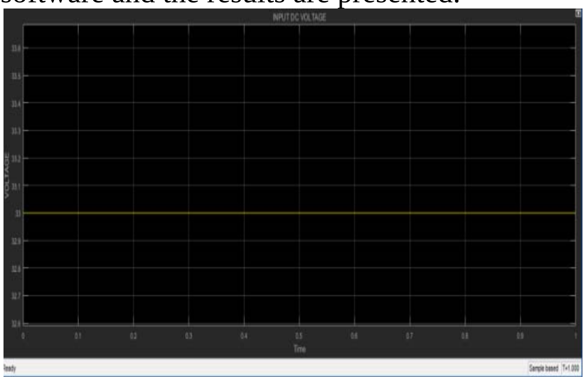

Fig 9 Waveform of Input voltage: Input voltage Vin=33V a DC constnt voltage of the z source resonant converter.

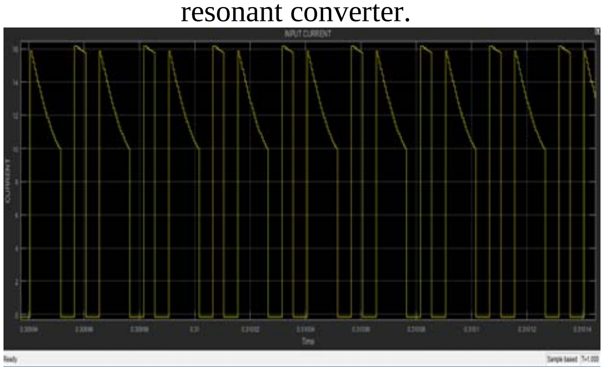

Fig.10 Waveform of input current: This shows the input current with a magnitude of Iin=16

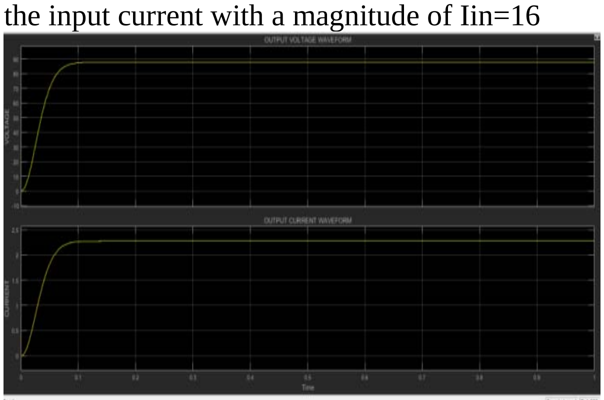

Fig.11 Waveform of output voltage and output current of the ZSRC: The output voltage and current of magnitude Vo=88V and Vin=2.28A where the output voltage remains constant when the input and the output current is varied

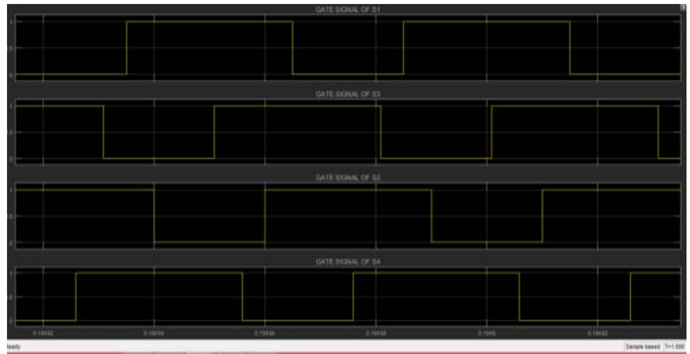

Fig.12 Waveform of Gating signal for MOSFETS: This figure shows the gate signal of the inverter at the primary side with the different states of operation i.e active state, shoot through state, and zero state.

Fig.13 Waveform of Voltage across z source network:The magnitude of the voltage is of 150V.

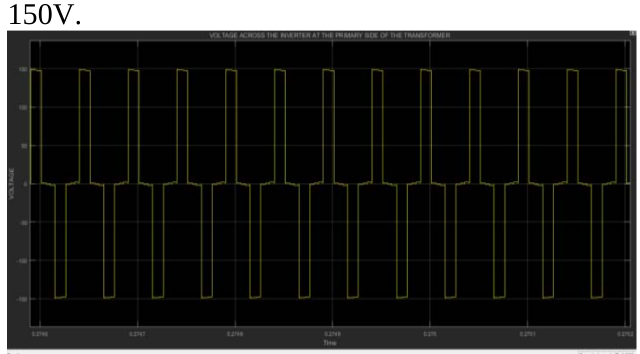

Fig.14 Voltage across the H bridge at the primary side:This shows the output of the inverter at primary side of magnitude 150V where the higher power factor correction is achieved .

The below table gives the comparison of the output voltage and input voltage, when the input voltage is varied the output remains constant which performs the closed loop operation. The PI controller with the trial and error method has the Kp and Ki values as follows: For the voltage controller Kp=5 and Ki=10 and for the current controller Kp=0.2 and Ki=0.9 respectively

Input voltage(Vs) in volts	Output voltage(V0) in volts
33	88
40	88
45	88
50	88
53	88
55	88

Table 2 Comparison of input and output voltage.

VI. CONCLUSION

Z-source resonant converter (ZSRC), a single-stage solution with low cost and high efficiency, was proposed for EV wireless charger. To make the system output stable with variable input voltage, here, the closed loop control of ZSRC by using the PI controller is used to control the output voltage. MATLAB simulation is done with a variable input voltage and a constant voltage of 88v and 200W prototype with a closed loop Z Source Resonant Converter for the application of wireless charging of the electric vehicle. This can be applied to the renewable energy sources like PV, Fuelcells where the output voltage remains constant.

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