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Soft Switching Operation Of Boost-Based Power Factor Correction Circuit By Using Auxiliary ZVT Circuit

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Abstract—A low loss auxiliary zero voltage transition (ZVT) circuit is proposed for boost based power factor correction circuit for on-Board Battery charger application in an Electric Vehicle and battery storage applications for home appliances. The ZVT circuit consists of an auxiliary MOSFET, a resonant inductor, and a diode. A resonant inductor resonates with capacitances of the main MOSFET and main diode during turn-on transition along with this, auxiliary MOSFET itself turns-off with zero current switching, and as a result of this power loss across the main MOSFET get reduces. The conduction time of the ZVT circuit is very small as compared with the main boost converter, due to this, auxiliary circuit consumes a small amount of output power which is negligible. A discharge mechanism consists of a capacitor and low-frequency diode which helps to transfer the energy from the auxiliary ZVT circuit to the output. The operating principles, waveforms, and the design of auxiliary ZVT circuit are discussed. The MATLAB simulation of the proposed topology also presented in detail.

Keywords—AC to DC power converter, a boost converter, soft switching, and Zero Voltage Transition (ZVT) circuit.

I. INTRODUCTION

Electric Vehicles have recently received many attentions from researchers due to their advantages over the conventional use of non-renewable sources. Electric Vehicle reduces the emissions that contribute to climate change and smog, improving public health and reducing ecological damage. To charge the electric vehicle battery, we require good quality ripple less DC voltage. To get the desired voltage, we supply the switching frequency. Due to an increase in the switching frequency, the switching losses and electromagnetic interference noises will have occurred. In order to improve the efficiency of the power factor correction (PFC) circuit, many efforts have been done on the soft-switching converter. The main goal of this project is to the reduction in switching losses, savings infiltration, and energy storage requirements, resulting in greatly improved power conversion densities without losing efficiency. The Zero-Voltage-Transition (ZVT) concept was first presented as a switch, a diode, and an inductor are implemented to achieve the lossless switching transition. The key drawback of this converter is that the auxiliary switch is turned OFF while it is conducting current. A single-stage isolated ac–dc approach has also been considered for low cost and good power density designs by eliminating the dc link [1], [2].

A review of unidirectional as well as bidirectional single-phase PFC rectifier topologies with improved power quality is presented in [3], where the most popular and widely used topology is a boost-type PFC which consists of a diode bridge followed by boost circuit. To achieve high power density and faster transient response, the boost PFC is pushed to operate at high switching frequencies. However, as switching frequency increases, the output diode operating at dc-link voltage produces significant reverse-recovery losses that appear as additional turn-on losses along with the increased switching loss in the circuit [4]. The auxiliary ZVT concept was first presented in [5], where a switch, a diode, and an inductor are implemented to achieve the lossless switching transition. The main drawback of this converter is that the auxiliary switch is turned OFF while it is conducting current. Due to hard-switching losses, we don't get the benefits gained with the auxiliary circuit. Converters in [6] and [7] use a dissipative snubber circuit to limit these losses but the auxiliary switch still operates in a hard-switched condition. A family of self-commutated auxiliary circuits is used to minimize these problems. These converters achieve zero current switching (ZCS) in the additional switch but experience higher voltage stresses in their passive components. A family of bridgeless PFC circuit having coupled inductors to ensure ZCT in the auxiliary switch was proposed in [8]. Also, a bridgeless PFC without additional voltage and current stresses in the auxiliary device was proposed in [9]. The auxiliary inductor and the auxiliary diode are in series with the boost diodes thereby carrying the full-load current and adding to the conduction losses.

In this paper, the application of low loss ZVT circuit is mentioned for PFC converter for which boost circuit is used. Section Ⅱ introduces the block diagram of proposed topology and explained in brief. Section Ⅲ gives information about the circuit diagram of proposed topology and small explanation about operating principle of circuit. After this, in section Ⅳ, boost circuit behavior is studied and waveforms of all voltages and currents are shown and along with this waveforms of losses at switch are presented. In section Ⅴ, boost circuit with low loss auxiliary ZVT circuit is presented. In this, all waveforms like voltages, currents and losses at main switch and auxiliary switch is given along with control strategy of circuit. Analysis and comparison table is given in section Ⅵ and conclusion is presented in section Ⅶ

II. BLOCK DIAGRAM OF TOPOLOGY

The block diagram of the proposed topology is shown in fig. 1. Single phase AC supply is given to the system. Simple diode bridge converter is used to convert AC into DC. With this, we get full wave conversion. After this DC-DC boost converter is connected along with zero-voltage-transition circuit.

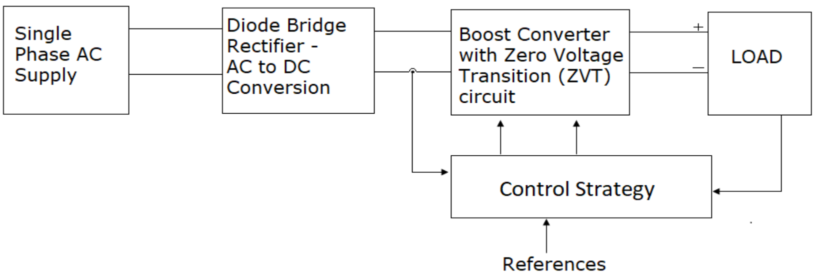

Figure 1. Block diagram of proposed topology

The output of this boost converter is connected to load. For close loop operation, output voltage and input current to boost converter circuit are used for feedback purpose. To maintain the output voltage, the reference value is given to the control strategy for comparison purpose with actual output voltage value.

III. PROPOSED CIRCUIT DIAGRAM AND OPERATION

The circuit diagram of the proposed ZVT circuit is shown in figure 2. The circuit comprises of single phase AC-DC diode bridge rectifier along with boost converter which used for power factor correction. The output current waveform of the diode bridge rectifier is distorted. Due to this whole system get affected. The shape of the current, as well as power factor, can get improve by using a boost converter. The boost converter allows a very low percentage of distortion, along with nearly unity power factor. In the circuit diagram, there are two MOSFETs are used in which one is the main switch for boost converter and another is for the auxiliary circuit.

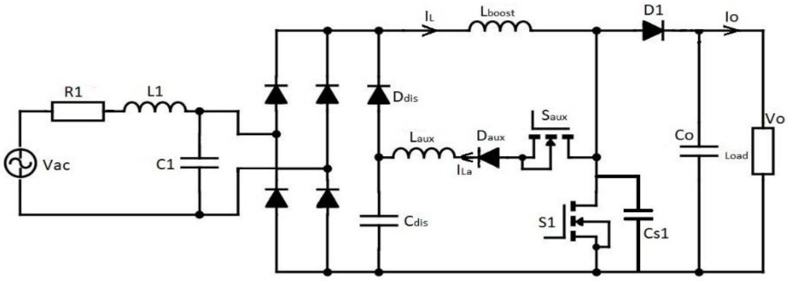

Figure 2. Circuit diagram of proposed topology

To achieve soft switching operation, the auxiliary MOSFET switch of ZVT circuit should turn-on first before main MOSFET switch of the boost converter. For soft switching operation of the main MOSFET switch, the ZVT circuit consists of MOSFET switch S_{aux}, diode D_{aux}, and a resonant inductor L_{aux} connected in series. After applying switching pulses to the switches, resonant inductor L_{aux} resonates with the capacitances across main switch S_1 and diode D_1 which is capacitors C_{S1} and C_{D1} respectively, just prior to the turn-on transition of S_1. A discharge mechanism helps in discharging the stored energy into the boost-based PFC circuit through the main inductor during turn-on. A discharge mechanism circuit consists of diode D_{dis} and capacitor C_{dis}. Capacitor C_{dis} is selected large enough so that voltage across it does not get change within a switching period.

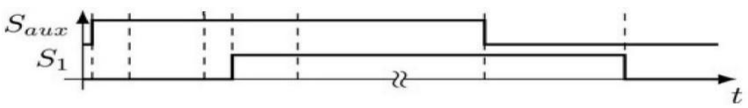

Figure 3. Required switching pulses for this topology

According to the operating principle of ZVT circuit, the auxiliary switch must be turned on first, because of this, the current through the main diode D_1 is slowly diverted to the auxiliary circuit and this rate of current depends on the value of L_{boost} and voltage across C_{dis}. When diode D_1 gets turned off, at that time L_{aux} is going to resonate withC_{S1} and C_{D1}, due to this action, the voltage across S_1 reduces (V_{S1}). After this diode D_1 is going to conduct and MOSFET switch S_1 is gated on with low power loss. Now, a current through the auxiliary circuit reduces and auxiliary switch S_{aux} gets turned off again with very low power loss. Switch S_{aux} gets to turn off before the switch S_1 getting turn off. After all this process, the power loss across the main switch is getting reduce and with this loss across the S_{aux}, a switch is very very low which is negligible.

IV. ANALYSIS OF BOOST CONVERTER

For the analysis of zero voltage transition (ZVT) circuit, first, we have to study the behavior of a simple boost converter. For that MATLAB software is used. We create a simple boost converter. Here AC supply is applied to diode bridge converter to convert into DC form and this DC value is given to boost converter for improving the power factor along with boosting the output voltage. MOSFET switch is used to operate the circuit. Pulse generator block is connected to give pulses to the switch. For filtering purpose, filter capacitor is connected across the circuit.

4.1. Simulation of Boost Converter

In this simulation work, 240V AC supply is given. After that, the output of the bridge converter is directly given to boost circuit. Here 10 kHz frequency is applied to the MOSFET switch. A load is connected next to the filter capacitor. A load may be consist of a resistor or resistor and inductor both. After running this simulation, we are getting around 400V DC voltage with around 4A load current. Due to the diode bridge rectifier circuit, the power factor gets deteriorate. Power factor improvement work is done by boost converter, along with increased voltage at the output side. Before using a boost converter, we got 0.3 to 0.5, but after the boost converter, we got 0.98 (unity).

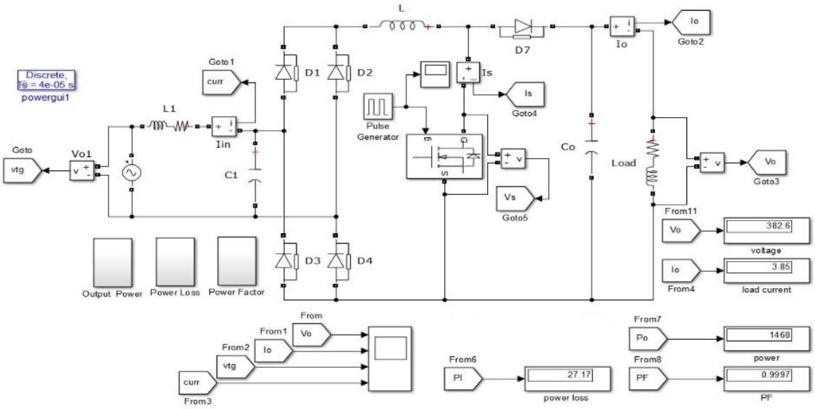

Figure 4. Boost converter simulation

The main problem is the switching power losses occurs across the MOSFET switch. If we calculate the losses across the switch, it comes to 30.41% of the output voltage. Due to this major loss, MOSFET switch performance, as well as circuit efficiency, get deteriorates. So minimization of losses across the switch is becoming mandatory. For that, Zero Voltage Transition (ZVT) circuit is proposed.

4.2. Waveforms, Analysis and Losses

After running the simulation, we got different waveforms of output and input voltages and currents. According to the waveform, we have to get 400V DC voltage and around 4A DC current. Along with this, we get 0.99 power factor and around 1500W output power. The waveforms are as follows:

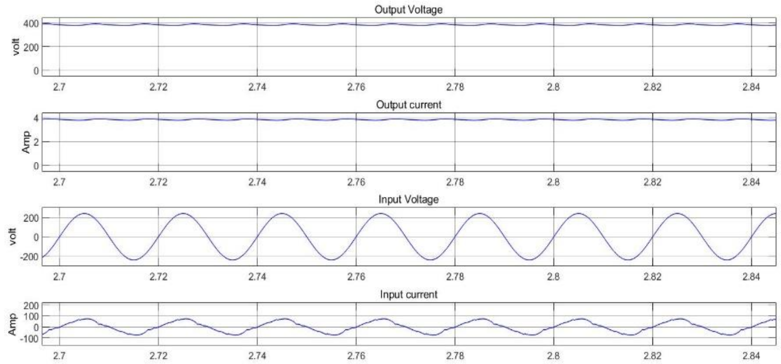

Figure 5. Waveforms of boost converter

But the major problem of this boost converter is the switching power losses across the main MOSFET switch. At the end of simulation we get around 27W power loss and if we calculate the average power loss of entire simulation, then we get loss around 441W. So this loss is approximately 30.4% of output power. The waveform of power loss is as below:

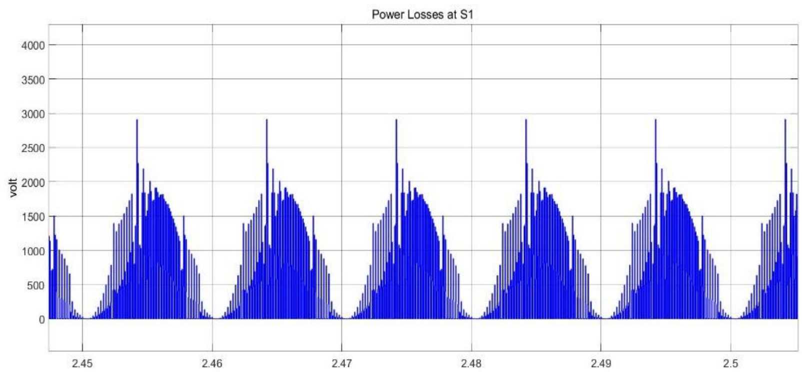

Figure 6. Power loss across switch S1

V. ANALYSIS OF BOOST CONVERTER WITH ZVT CIRCUIT

The proposed topology is about zero voltage transition (ZVT) circuit which reduces the power losses across the main switch. Along with this, the consumption of power loss across S_{aux} is very low which is negligible. The simulation of the proposed topology is presented below. Same as above boost circuit, all values came near to desired values i.e. output voltage 400V output current 6A. The output power rating is increased to 2300W. Here closed-loop simulation of proposed topology is given. The control strategy of this closed loop system is explained in brief.

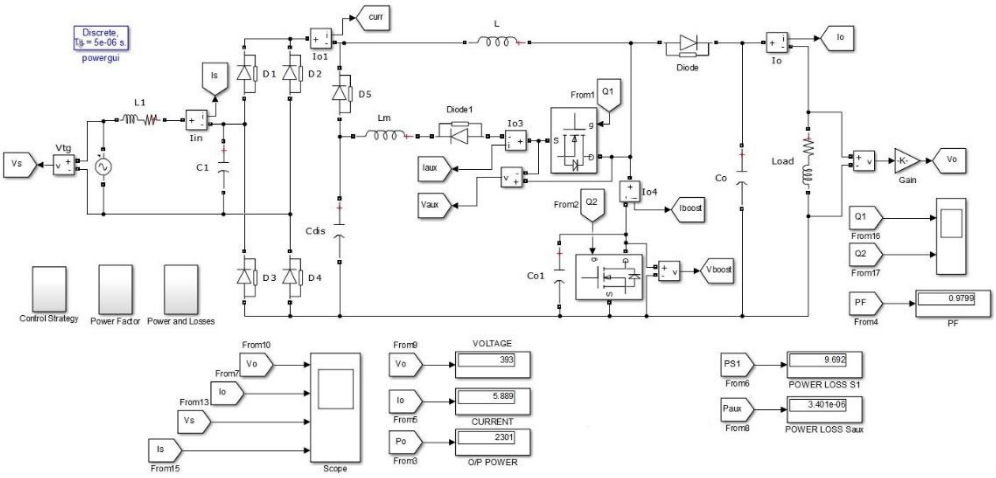

Figure 7. Closed loop simulation with ZVT circuit

5.1. Control Strategy and Switching Pulses

Two PI controllers are used to act as a voltage controller and current controller. At first actual output voltage is compared with the reference value. The reference value is our desired output voltage at which the whole control strategy should work on. Now first PI controller is voltage controller and output of that is given to next PI controller which is the current controller and that value is getting compared with a current value which is the actual value of input current to boost converter. After this, the output of the current controller is compared with the triangular wave with the help of a relational operator. Now generated pulses are given to auxiliary switch but for the main switch, there should be some delay, for that discrete variable time delay is used and 20 µsec delays are given.

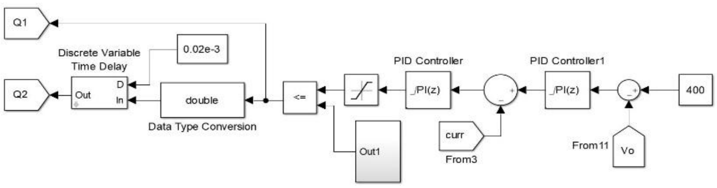

Figure 8. Control strategy

5.2. Waveforms and Analysis

The generated switching pulses are given below. These pulses are achieving our requirements that is S_{aux} signal is generated first and after that main S_1 switch pulse goes high and next is S_{aux} is going low before the main S_1 turns off.

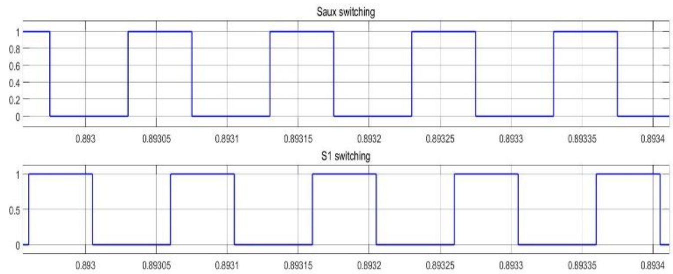

Figure 9. Desired switching pulses

The output waveforms of the closed loop of the proposed topology are shown below. Same like the previous (Boost circuit) output voltage is coming to 400V and output current of 6A. Input current wave shape is getting better (approximately sine wave) than without using the ZVT circuit. With this power factor always maintains constant to 0.97 (unity).

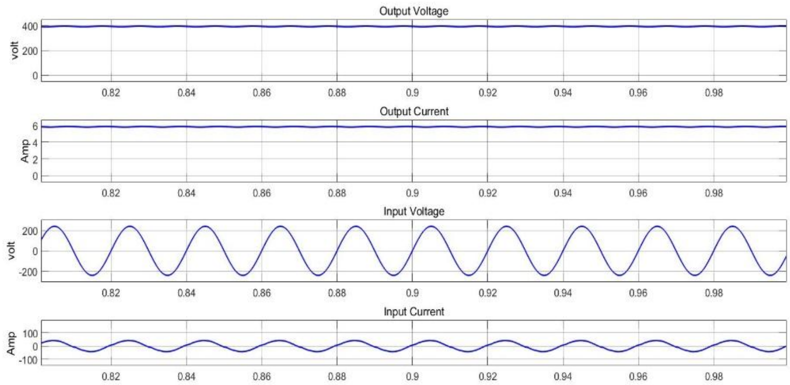

Figure 10. Waveforms of the closed loop system

5.3. Power losses and Comparison

The main objective of the proposed topology is to reduce the switching power losses across the main MOSFET of the Boost circuit. Now let's discuss the waveforms regarding the losses across the main switch. The waveform of power loss across the switch of the boost converter is given below. According to the waveform, the average power loss occurs at the main switch is around 140W. At the end of simulation time, nearly 9W power loss has occurred.

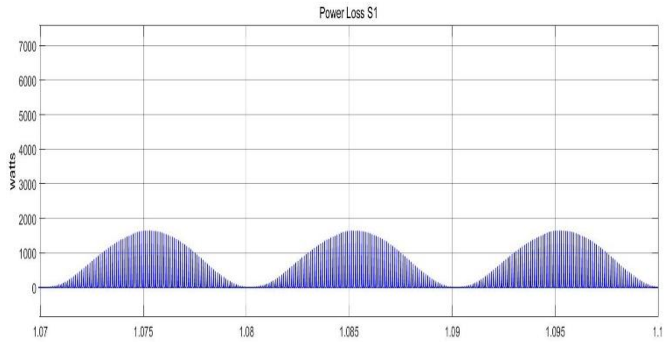

Figure 11. Switching Losses at switch S1

The power loss across the auxiliary switch S_{aux} is very low so we can neglect this. At the end of the simulation, the losses come to $3.4*10^{-06}$ W which is negligible. If we calculate the average power loss across the auxiliary switch, it comes to 5W.

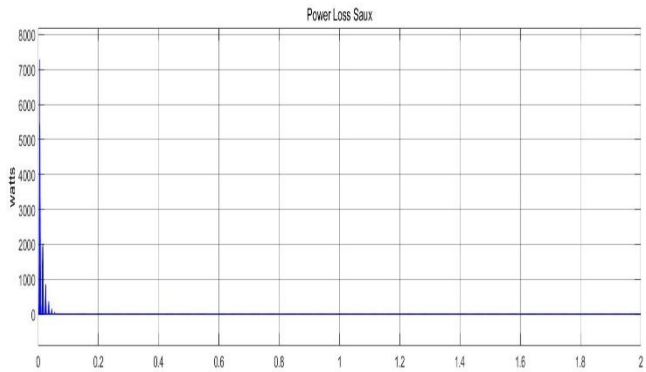

Figure 12. Switching Losses at S_{aux}

VI. ANALYSIS AND COMPARISON

No.	Analysis and Comparison		
	Boost Converter	***Without ZVT circuit***	***With ZVT Circuit***
1.	Power Loss at S1 -		
	a) Average Power Loss	441W (30.41%)	140W (6%)
	b) At the end of Simulation	27.17W	9.69W
2.	Output Power Rating	1500W	2300W
3.	Output Voltage	400V	400V
4.	Load Current	4A	6A
5.	Power Factor	0.98	0.97

At the end of the simulation of a closed loop system of proposed topology, we can compare this simulation result with the previous boost converter which is without ZVT circuit. We can analyze the power losses, output power, output voltage and load current as well as power factor. The comparison table is given below. Analysis of both the circuits is very simple and clear. The output voltage remains constant. Output power rating gets increases. A power factor of both the circuits remains the same that is 0.97. At last, the main purpose of proposed topology is to minimize the losses across the main MOSFET switch of the boost converter and this objective is got achieved by analyzing the results of the close-loop system of topology.

VII. CONCLUSION

In this paper, a simple auxiliary Zero-Voltage-Transition (ZVT) circuit is proposed for boost-based Power Factor Correction (PFC) converter which operates at 10 kHz frequency and it is suitable for on-board charger application for an electric vehicle as well as battery storage applications for home appliances. In this paper, the output voltage, load current, output power, and power factor is observed. By using auxiliary ZVT circuit, the power loss across the main switch is to get very much reduces than boost converter without using ZVT circuit. So that as switching losses reduces, the efficiency of circuit and performance of the system is going to increase. The losses at the main switch get reduce to 30.41% to around 6%. The brief information and operating principle of the ZVT circuit is explained. The simulation of a boost converter with and without ZVT circuit is shown. The output waveforms of both, with and without ZVT circuit is presented. The waveforms of switching losses of the main switch are observed and a comparison table is presented for analysis.

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