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A Three Level Single Stage PFC Converter for Variable Power Applications

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Abstract: **AC/DC power converters are required to operate with high power factor (PF) and low total harmonic distortion (THD) for improved grid quality and full capacity utilization of the transmission lines. Passive PF correction (PFC) circuits consist of inductive and capacitive filters followed by a diode bridge. They provide the simplest way of achieving high PF with high efficiency; however, they require low line frequency filters which are bulky and heavy. This work presents a new single stage three level isolated AC/DC PFC converter for high DC link voltage low-power applications achieved through an effective integration of AC/DC and DC/DC stages where all of the switches are shared between two operations. With the converter and switching scheme, input current shaping and output voltage regulation can be achieved simultaneously without introducing additional switches or switching actions. Due to the flexible DC link voltage structure, high power factor can be achieved at high line voltage. The performance of the single stage PFC converter is simulated in MATLAB/SIMULINK environment.**

Keywords: **Power Factor (PF), DC Link Voltage, Power Factor Correction Circuits (PFC).**

I. INTRODUCTION

AC/DC power converters are required to operate with high power factor (PF) and low total harmonic distortion (THD) for improved grid quality and full capacity utilization of the transmission lines. Passive PF correction (PFC) circuits consist of inductive and capacitive filters followed by a diode bridge provide the simplest way of achieving high PF with high efficiency; however, they require low line frequency filters which are bulky and heavy. In order to operate at high frequency and reduce the size of the circuit, high frequency two stage active PFC converters have been used [1]. In this architecture, a front-end AC/DC PFC converter is operated with a switching frequency in the order of tenths to several hundred kHz for converters with Si semiconductor devices, and from several hundreds of kHz to tenths of MHz with wide-band gap devices, to shape the input current close to sinusoidal waveform in phase with the grid voltage . The second stage DC/DC converter provides the galvanic isolation and output voltage regulation. The controllers of the two stages are completely independent. The flexibility in control allows optimizing power stages, fast output voltage regulation and operating with high PF and low THD. However, this method comes with the expense of more components and larger size. Moreover, the constant switching losses such as parasitic capacitance losses associated with power switches reduce the efficiency of the converter at light load condition. For medium to high power applications, the research efforts have focused on AC/DC single-stage full-bridge (SSFB) converters. Current-fed SSFB converters deploy a current shaping inductor connected to the input of the diode-bridge achieving high PF [2]; however, due to the lack of DC bus capacitor on the primary side of the transformer, the DC bus voltage is subjected to excessive overshoots and ringing. Voltage-fed SSFB converters do not exhibit the drawbacks of current-fed SSFB converters, where a large capacitor is located on the primary side DC bus. However, the DC bus voltage remains unregulated [3] and it can be excessive at light load condition, as both input current shaping and output regulation are achieved with a single controller.

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II. THREE LEVEL SINGLE STAGE PFC CONVERTER

The PFC converter is essentially an integrated version of a boost PFC circuit and three level isolated DC/DC converter. Basically, a diode bridge and an inductor are added to the three level isolated DC/DC converter topology as shown in Fig.1. Here, the inductor is charged when S_2 and S_3 are turned on simultaneously. Body diodes of S_1 and S_4 serve as the boost diode of the PFC boost converter. At the same time, S_1 to S_4 are switched to apply $V_{dc}/2$,-$V_{dc}/2$, and zero voltage

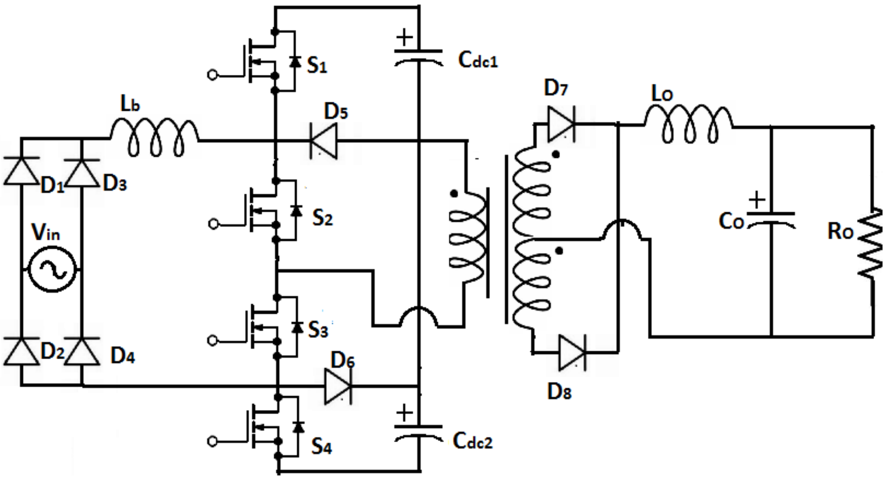

Fig. 1: Circuit diagram

across the primary side of the transformer. Thus, all of the switches are shared between the two stages, which makes it fully integrated single-stage converter without any additional auxiliary switches. When a boost inductor and a diode bridge is added to the nodes the overlap of gate signals of S_2 and S_3 enables applying input voltage across the boost inductor. The steady state wave form of the converter is given in Fig. 3. The switches S_2-S_3, and S_1-S_4 have 180 degree phase shift with respect to each other. The duty ratios of S_2-S_3 should be greater than 0.5 such that two signals overlap[6]. Here, the circuit is explained considering that input inductor current is discontinuous and the switching scheme is as follows; S_1 is turned on right after S_3 is turned OFF, and similarly, S_4 is turned on when S_2 is turned OFF. A dead-time should be inserted in between the turning ON instant of S_1 and turning OFF instant of S_3, and likewise between switching of S_2 and S_4 to avoid short-circuit.

A. *Modes of Operation:*

(a). Mode 1$[t_0 - t_1]$

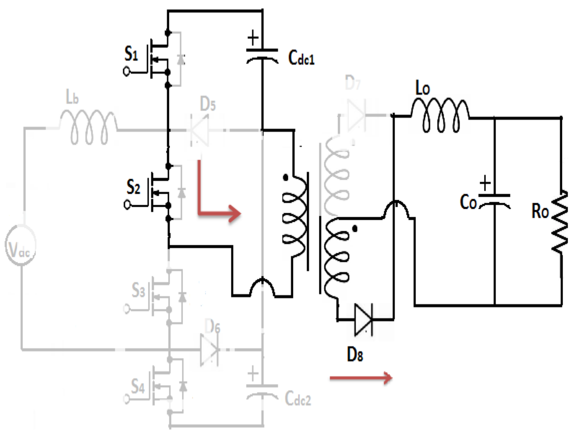

Fig. 2: Equivalent circuit of mode 1

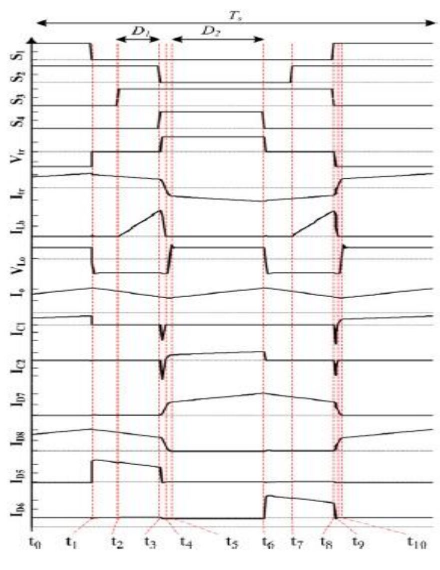

Fig. 3: Steady State Wave form

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In this mode, both S_1 and S_2 are on. The upper capacitor C_{dc1}, discharges to the load by applying $-(V_{dc}/2)$ to the primary side of the transformer. The primary side current increases linearly under constant voltage. D_8 conducts at the secondary side of the transformer. In this mode, the boost inductor, L_b does not interfere to the operation of the circuit.

(b). Mode 2[$t_1 - t_2$] , Mode 3[$t_2 - t_3$]

At t = t_1, S_1 is turned OFF and S_2 is kept on. The current in the leakage inductance conducts D_5 and the primary side current freewheels; hence, zero voltage is applied across the primary side of the transformer. The output inductor voltage is equal to $-V_o$ The output inductor current decreases linearly.

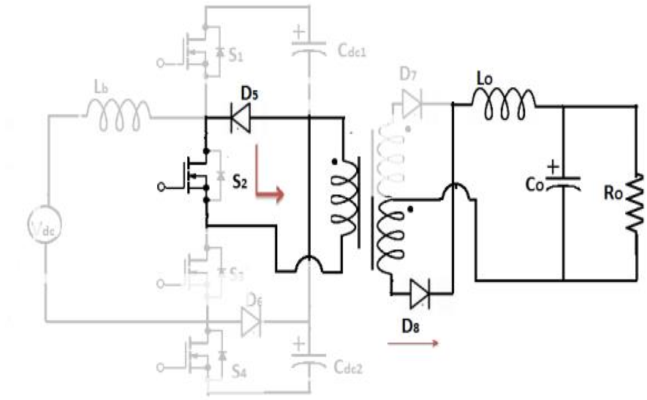

Fig. 4: Equivalent circuit of mode 2

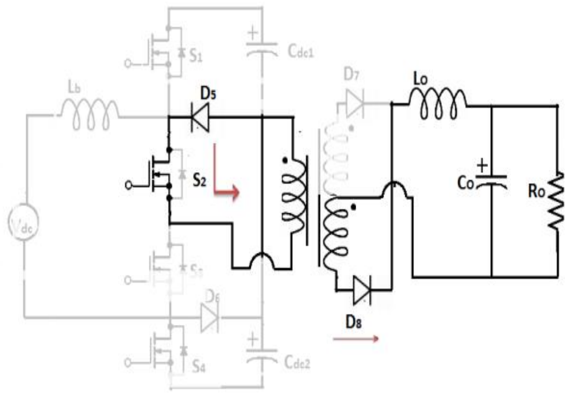

Fig. 5: Equivalent circuit of mode 3

At t = t_2, S_3 is turned on, while S_2 still remains on. The primary current continuous to freewheel and zero voltage is applied across the primary side; hence, the output inductor current continuous to decrease under output voltage. Meantime, V_{in} is applied across L_b , and input current increases linearly storing energy in the inductor.

(c). Mode 4[$t_3 - t_5$], Mode 5[$t_4 - t_6$]

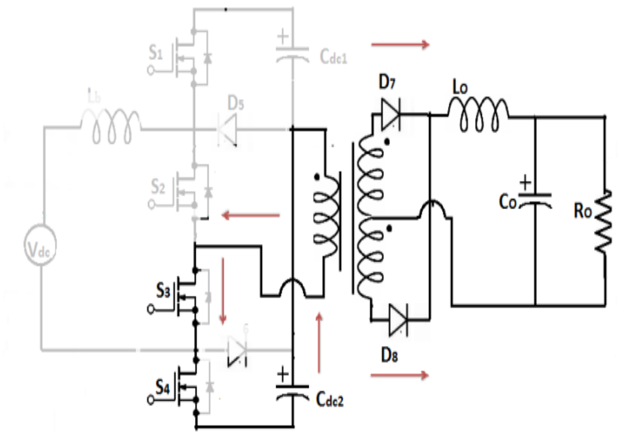

Fig. 6: Equivalent circuit of mode 4

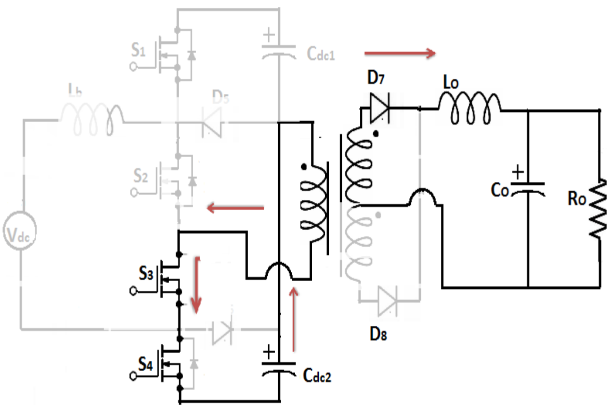

Fig.7: Equivalent circuit of mode 5

In the beginning of this mode, S_2 is turned OFF, S_4 is turned ON, while S_3 is kept on. Within this time interval, the following two operations are completed. The energy stored in the input inductor is transferred to the DC-link capacitors. The inductor current decreases linearly under V_{in} - V_{dc}. Meantime, $V_{dc}/2$ is applied across the primary side of the transformer. The current in the leakage inductance is transferred to C_{dc2}. This causes the output current to commute from D_8 to D_7. At the end of this time interval, the energy in the input inductor is completely transferred to the DC link capacitors and the commutation of the output diodes is completed. Depending on the DC bus voltage, and input current, one of these operations ends earlier than the other one. In this case, the energy stored in L_b is transferred to the DC link at t = t_5. C_{dc2} discharges over to the load and $V_{dc}/2$ is applied across the primary side of the transformer. The input current remains at zero in DCM mode.

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(d). Mode 6[$t_6 – t_7$], Mode 7[$t_7– t_8$]

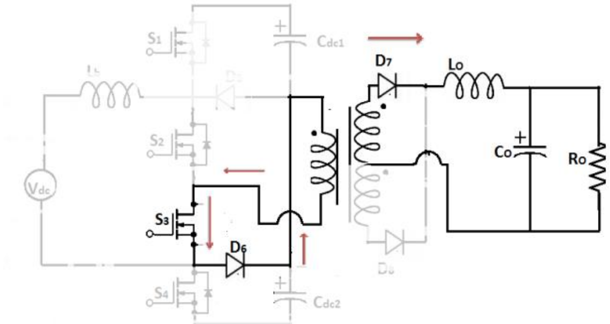

Fig. 8: Equivalent circuit of mode 6

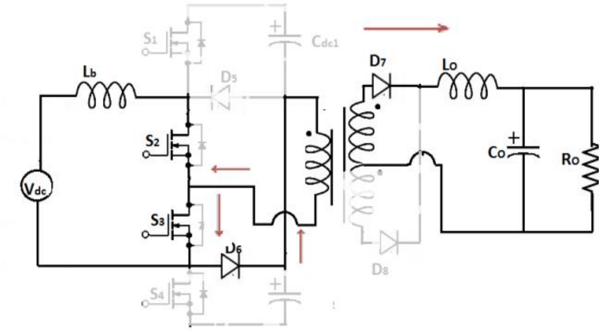

Fig. 9: Equivalent circuit of mode 7

At t = t_6, S_4 is turned OFF, and only S_3 is on. This allows leakage current to freewheel through D_6 , and zero voltage is applied to the primary side. The output current decreases linearly under $–V_0$. At t = t_7, S_2 is turned ON. The energy from the input is stored in the inductor. This is similar to Mode 3, except that this time the primary side current is opposite to that in Mode 3 and freewheels through D_6.

(e). Mode 8[$t_8– t_{10}$]

At the beginning of this interval, S_3 is turned OFF, S_1 is turned ON, and S_2 remains ON. This mode is similar to Mode 4, where the stored energy in the inductor is transferred to the dc bus capacitors, and $V_{dc}/2$ is applied to the primary windings. In the meantime, the output inductor current commutates from D_7 to D_8.

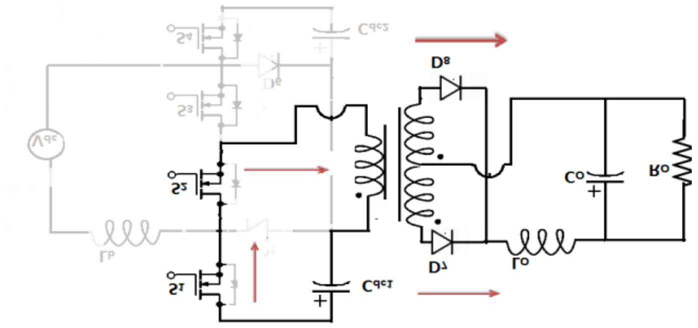

Fig. 10: Equivalent circuit of mode 8

III. SIMULATION MODEL AND RESULTS

In order to verify the operation principle and the theoretical analysis, a converter is simulated with MATLAB/SIMULINK simulation software and the simulation parameters are listed in Table.1. All switches using in simulation are ideal switches.

Table I: Simulation parameters

Parameters	Specification
Input Voltage V_{in}	230 V
Resistor	4.6 Ω
Capacitor C_{dc1}, C_{dc2}	470 µF
Inductor L_o, L_b	27 µH
Switching frequency	125 kHz

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A. Control Strategy:

Control pulses for switch are generated by PWM method. Usually it is done by comparing a saw tooth carrier and a reference value. A repeating sequence of required frequency is compared with constants 0.6 and 0.4, the duty ratio to generate pulses with 60% ON and 40% ON time. Whenever repeating sequence is less than the constant, it will output a high value and if constant is smaller, it will output a low value. By varying the value of constant, duty ratio of MOSFET can be controlled.

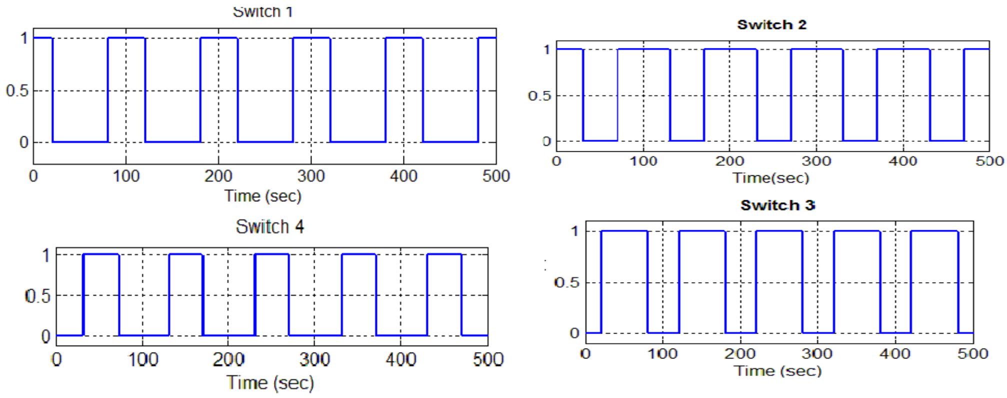

Fig. 11: Switching pulses

A. Simulink Model:

Simulink model of single stage PFC converter is shown in fig.12. MOSFET's are used as switches. Output voltage and stresses across switches are analyzed from the simulation results.

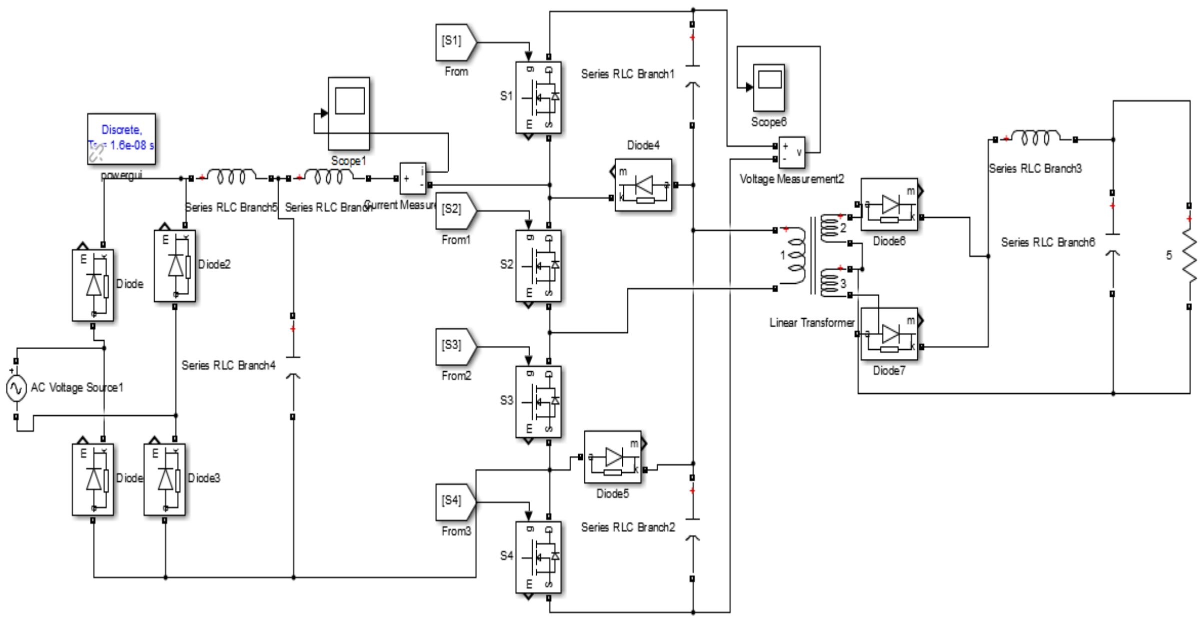

Fig. 12: Simulink model of single stage PFC converter

B. Simulation Results:

Fig.13 shows the output voltage (50 V) at input voltage of 230V. The converter exhibits high PF 0.9173 with less number of switches/diodes, operated at constant duty ratio. Fig. 15(a,b) shows the input voltage and input current. Transformer primary voltage is about +300 V, 0 and -300 V, as shown in fig. 16. The DC link voltage is obtained as 625 V. The total harmonic distortion of input current is about 0.04 %. Fig. 19 shows the input inductor current and fig.20 describe efficiency of system at various output power with DC link voltage of 400 V.

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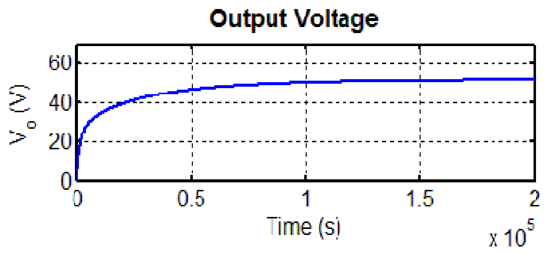


Fig. 13: Output voltage (50 V)

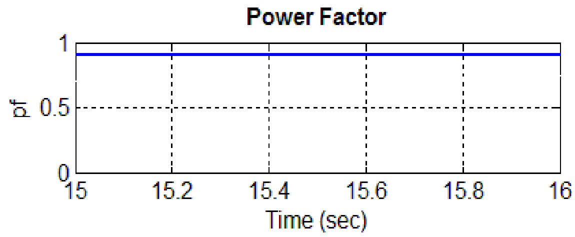
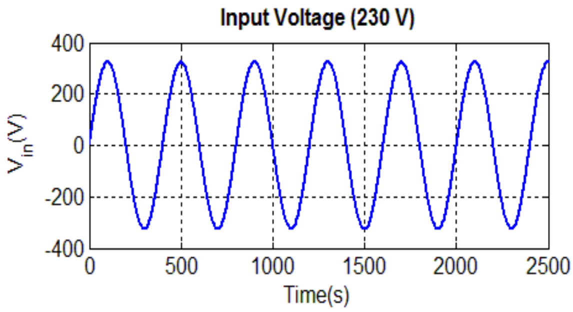


Fig. 14: Power Factor

From the input voltage and input current waveform we can conclude that the converter exibit high power factor without using additional switches.



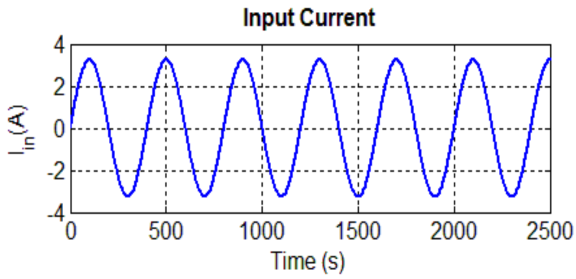


Fig. 15(a,b): Input voltage and Input current

Transformer primary voltage is about +300 V, 0 and -300 V, as shown in fig. 17. The DC link voltage is obtained as 625 V.

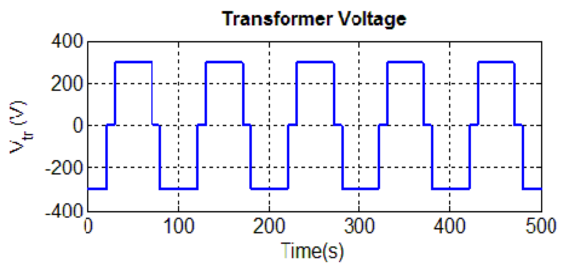


Fig. 16: Transformer primary voltage

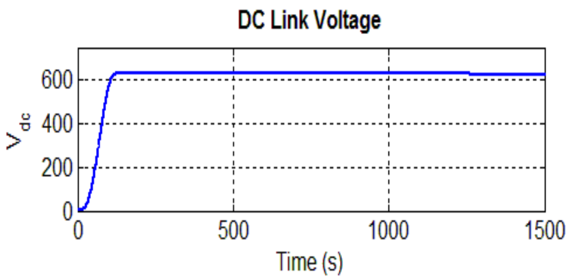


Fig. 17: DC Link voltage

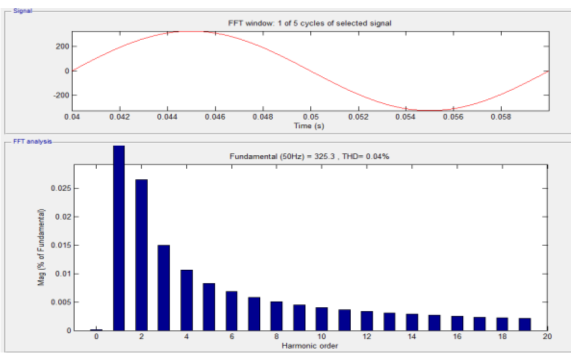


Fig. 18: THD of input current

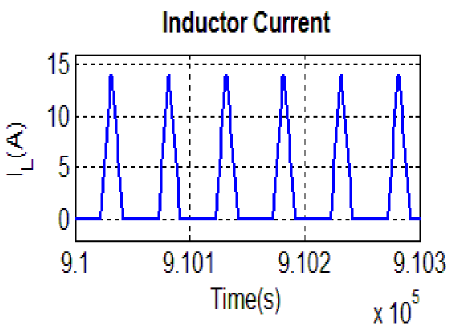


Fig. 19: Inductor current

Fig.20 describe efficiency of system at various output power with DC link voltage of 400 V. The efficiency for corresponding output power is plotted by varying the resistive load.

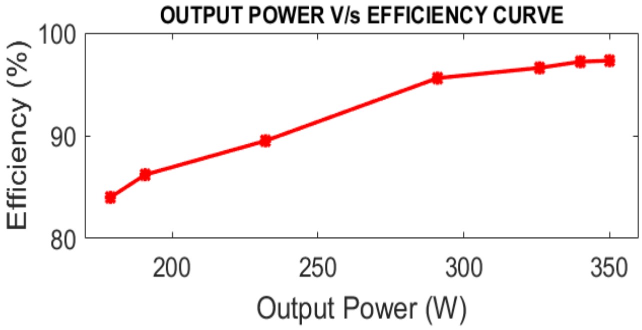


Fig. 20: Efficiency curve

IV. CONCLUSIONS

The converter exhibits high PF with less number of switches/diodes, operated at constant duty ratio. A PFC inductor and a diode bridge are added to the conventional three-level isolated DC/DC converter, while the switching scheme is modified to be compatible with single stage operation. The input current ripple frequency is twice of the switching frequency contributing to using smaller PFC inductor. Two independent controllers, in favour of shaping the input current and regulating the output voltage, are adopted which simplifies the control of the circuit. The inductor is charged when S_2 and S_3 are turned on simultaneously. Body diodes of S_1 and S_4 serve as the boost diode of the PFC boost converter. At the same time, S_1 to S_4 are switched to apply $V_{dc}/2$,- $V_{dc}/2$ and zero voltage across the primary side of the transformer. Thus, all of the switches are shared between the two stages, which makes single stage converter without any additional auxiliary switches. The total harmonic distortion of input current is about 0.04 % and power factor is 0.9173.

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