A Three-Level Half-Bridge Flying Capacitor Topology for Single-Stage AC-DC LLC Resonant Converter

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***Abstract*— LLC resonant converters are one of the best choices in AC-DC converters. But, low power factor is a serious problem in AC-DC LLC resonant converters. Adding a boost circuit in front of the converter improves the power factor albeit the increase in circuit complexity. To reduce the size and cost, both the boost and LLC stage can be controlled by the same switches. However, these single stage topologies are less efficient in regulating DC bus capacitor voltage pertaining to transients in the line voltage and load conditions. The paper proposes a new single stage topology for AC-DC LLC resonant converters. The circuit consists of three-level half-bridge flying capacitor topology. Discontinuous conduction mode ensures inherent unity power factor operation. Switching frequency control and PWM duty ratio control are used to regulate the output voltage and bus capacitor voltages of the converter respectively. This dual control scheme makes the converter DC bus voltage nearly constant over a wide range of load and line voltage variations. Furthermore, the three level topology guarantees reduced switching stress and losses. The operation of the topology has been validated using MATLAB simulation.**

Index Terms—AC-DC power converter, LLC Resonant converter.

I. Introduction

Soft switching, short circuit and open circuit protection, and high efficiency are some of the novel benefits of LLC resonant converters [1] [11]. They work on very high switching frequency which reduces the weight of the converter [2] and particularly suited for electric vehicle battery charging applications.

Low power factor is the main drawback in LLC converters. To avoid this issue, a power factor correction (PFC) stage is usually inserted in front of the converter. The PFC stage usually consists of a boost converter operating in discontinuous conduction mode. The recent trend is to use a single switch for controlling both power factor and LLC stage [3] [4]. However, DC bus voltage regulation is a significant issue in single stage LLC converter. Variations in the input line voltage and load conditions change the DC Bus voltage, which can lead to unstable operation of the converter or even to the destruction of bus capacitor.

The work mentioned in [3], discuss on power balance between input boost and output stages. The design condition for stable operation of the converter is determined. Even though it increases the stable region of the converter, the work does not give a permanent solution for the problem. Topology cited in [4] proposes a bridgeless topology and use a minimum number of switching devices. The converter can return additional energy stored in the DC bus capacitor back to the supply and thereby regulating the DC bus voltage. During normal operation, the converter operates with unity power factor. However, returning power to the grid distorts the current waveform and increases the total harmonic distortion (THD). The circuit in [6] uses a three-level half-bridge topology for power factor correction. The work gives better voltage regulation compared to the topologies discussed earlier.

The proposed work discusses a three-level half-bridge flying capacitor topology. Compared to [6], topology requires lesser number of diodes which reduces the power loss. Switching frequency and its duty ratio are the two control parameters used. The output voltage of the converter is regulated by controlling the switching frequency. Pulse width modulation (PWM) technique regulates the DC bus voltage by duty ratio control. The dual control loop accurately fixes the DC bus voltage at the desired level and makes the converter stable even at light loads. Simulation results verify the predicted performance.

The article is categorised in the following order. Section II gives a brief description of the topology. Section III describes its different modes of operation. Part IV discusses the control logic for generating switching pulses. Section V analyses the design features. Segment VI examines the simulation results and explains the effectiveness of the topology. Section VII concludes the work.

II. Proposed Topology

The power circuit of suggested topology consists of 3 parts (1) Rectification part (2) Boost stage (3) LLC operation and AC-DC conversion stage. Figure 1 presents the power circuit. A diode bridge rectifier forms the rectification part. A three-level half bridge flying capacitor topology is modified to produce the Boost stage. Four switches used in the boost stage control both the boost operation and LLC operation of the third stage. The voltage applied to the LLC stage contains three discrete levels. This voltage pattern makes the controller adjust the duty ratio without disturbing the symmetry between the positive and negative half cycles. For symmetry, the voltage across Capacitors C1, C2 and C3 should be at the same voltage level (Here Vbus/2). Figure 7 presents the LLC stage input voltage waveform. The switch pairs Q1, Q2 and $\overline{Q1}$, $\overline{Q2}$ operates in complementary fashion. The circuit

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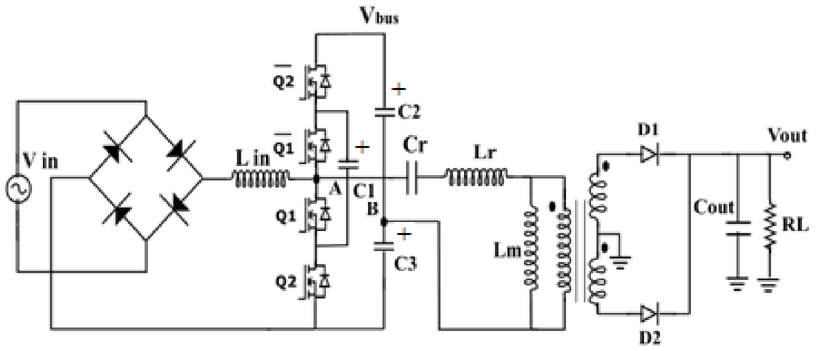


Fig.1 Proposed topology

guarantees zero voltage switching (ZVS) for all the switches. To achieve natural power factor correction the converter is operated in discontinuous conduction mode.

III. Modes of Operation

In this section, different modes of action for the boost stage of the converter is analysed in detail. LLC stage operation and working are not explained in the paper since it is similar to [4] [10] [11]. It can be noted that the voltage across the LLC (V_{AB}) is a three level voltage.

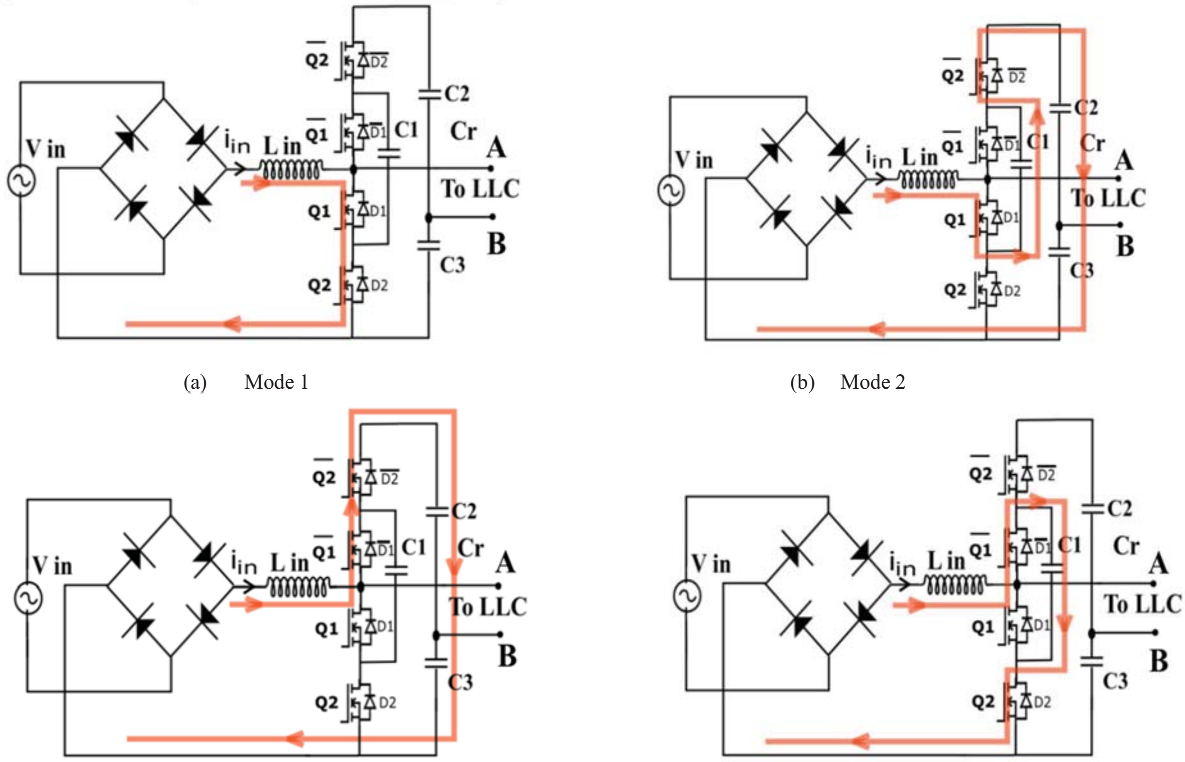
Mode 1: Switch Q1 and Q2 are turned ON. Input inductor L_{in} charges through the switches Q1 & Q2. Figure 2a describes the mode. The voltage across capacitor C3 is applied across the LLC terminals (V_{AB}= -Vbus/2).

Mode 2: Switch Q2 is turned OFF. The inductor current flows through C1 and $\overline{D2}$. $\overline{Q2}$ is then turned ON (ZVS). In this mode, the input inductor current discharges C1 and charges C2 and C3. In this mode, the voltage across LLC is zero (V_{AB}=0). Figure 2b represents this mode.

Mode 3: Switch Q1 is turned OFF. Current completes its path through $\overline{D1}$. $\overline{Q1}$ is now turned ON (ZVS). Input inductor charges C2 & C3. The voltage across LLC is equal to the voltage across capacitor C2 (V_{AB}= +Vbus/2). Figure 2c shows the mode.

Mode 4: In this mode, the switches $\overline{Q1}$ and Q2 are turned ON and C1 gets charged up (V_{AB}= 0). Figure 2d depicts the mode.

Operation in the negative half cycle will be similar and hence not explained. Timing diagram based on the different modes is shown in figure 3.



(a) Mode 1
(b) Mode 2
(c) Mode 3
(d) Mode 4

Fig.2 Modes of operation.

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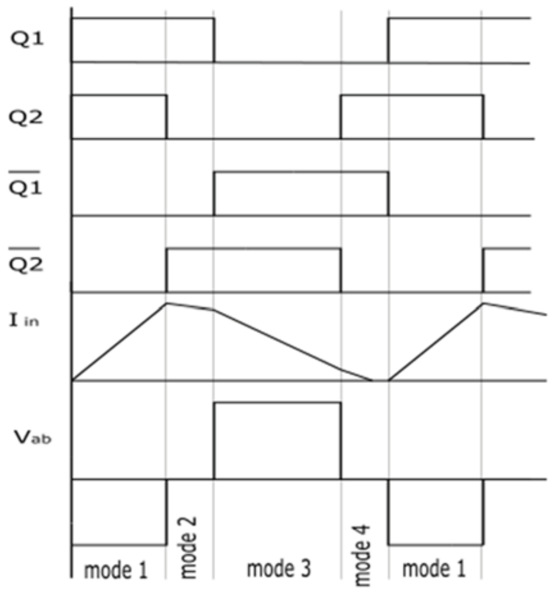

Fig.3 Timing diagram based on the modes of operation

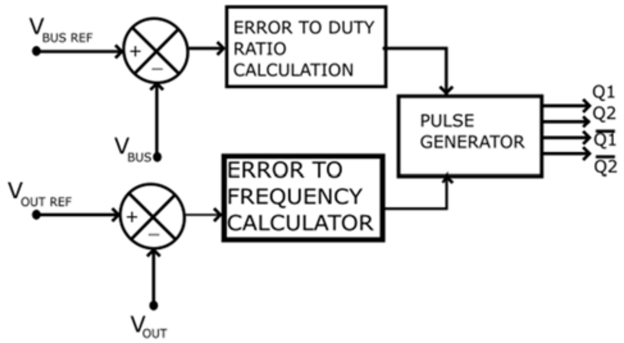

Fig.4 Control Strategy

IV. Control Strategy

The converter is designed to operate in discontinuous conduction mode which automatically shapes the input current without any closed loop control [3] (See figure 5). The Switching frequency and duty ratio are the two control parameters used by the controller. Figure 4 shows the control strategy.

The controller compares the actual output voltage with the reference voltage to generate an error signal. It is given to a PI controller. The output of the PI is given to a switching frequency calculator block. Similarly, DC bus capacitor voltage is also compared with a reference bus voltage to make the second control loop. The PI controller of the second loop outputs to the duty ratio calculator block. The reference frequency and duty ratio are assigned to the pulse generator to generate the switching pulses. Pulse generator selects different operating modes so as to balance the capacitor voltages. Charging and discharging action of the capacitors are shown in Table 1. The capacitor C1 is charge controlled using switching state redundancy in mode 2 and mode 4 (VAB=0).

The transient load changes can vary the DC bus capacitor voltage. If the DC bus capacitor voltage rises beyond a limit, controller fails to fix the output voltage at the desired level. The overvoltage will finally lead to the unstable operation or destruction of the bus capacitor. So, for the stable operation of the converter, DC bus capacitor voltage should be regulated. To reduce the DC bus capacitor voltage, here the controller reduces the charging time of input inductor by duty ratio control. The action decreases the energy transferred to the bus capacitor by the input inductor. Hence the DC bus capacitor voltage can be controlled to the desired level.

If the converter is designed for battery charging purpose, then load current can be taken as the feedback signal. It is then compared with the reference current to generate the error signal.

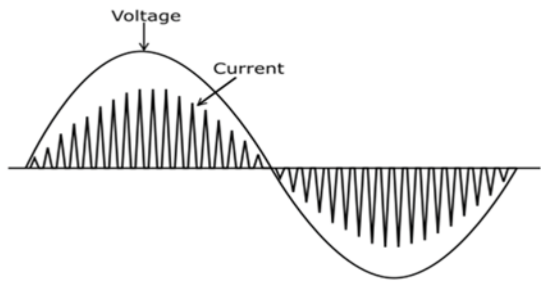

Fig.5. Input current and voltage in discontinuous conduction mode

TABLE I

Charging discharging operation of capacitors

	C1	C2	C3
Mode 1	0	0	0,-2
Mode 2	-1	1	1
Mode 3	0	1,-2	1
Mode 4	1	0	0
1 = Charging Through input inductor			
0 = Not Affected			
-1 = Discharging through input inductor			
-2 = Discharging to load			

V. Converter Design

The section outlines the estimation of the bus voltage and the design of input inductor. Operation and design of LLC stage are explained in [10][11].

A. Bus voltage estimation

DC Bus capacitor voltage variation is mainly due to the power imbalance between boost stage and output stage of the LLC converter [3]. In this topology, a major advantage is that the boost power can be controlled by adjusting the duty ratio. For discontinuous conduction mode of operation, DC bus voltage should be at least two times greater than the input voltage.

B. Input inductor design

Average current through the input inductor can be found out by equating the average output and input powers of the

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converter. Then the maximum value of fundamental component of input current is given by [4]

$$I_{Lm} = \frac{I_{in\,avg}\,\pi}{2} \tag{1}$$

To design Input inductor, boundary conditions are applied. The duty ratio is assumed to be at 0.5. That means input inductor charges for half the time in a switching cycle. So inductor should be able to discharge within the next half cycle. The slope of discharging current through inductor Lin should be higher than its charging slope.

$$\frac{V_{bus} - V_{in}}{L_{in}} > \frac{V_{in}}{L_{in}} \tag{2}$$

$$V_{bus} > 2V_m \tag{3}$$

T_{sw} is the switching period. Figure 6 can be used to derive expression for I_{Lm} as

$$I_{Lm} = \frac{V_{bus} D(1-D)T_{sw}}{2L_{in}} \tag{4}$$

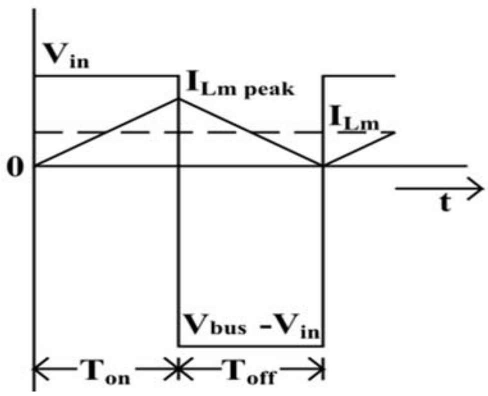

Fig.6 Boost stage converter at the boundary of continues – discontinues mode

To confirm discontinuous conduction mode, select a value less than what obtained from the equation.

VI. Result and Discussion

A 100W, 18V AC-DC converter is designed and simulated using MATLAB Simulink. The circuit was designed with following parameters. Quality factor Q= 6, Peak input voltage V_{in} = 200V, Bus capacitor is voltage, V_{bus} = 560V and minimum switching frequency, f_{sw} = 50KHz. Table 1 shows the component values.

TABLE I
COMPONENT VALUES

L_{in}	0.35mH
C_{Bus}	330 µF
L_r	2mH
C_r	4.8nF
L_m	10mH
$\frac{N_p}{N_s}$	$\frac{25}{1}$
C_{out}	1000µF

Figure 6 depicts the unity power factor operation of the converter. The fundamental component of the inductor current is sinusoidal without any phase difference between them. The duty ratio of the switches is controlled to generate a three level voltage waveform across AB. The voltage waveform exhibits half-wave symmetry. Voltage across AB and current through LLC are shown in figure 7. In conventional single stage LLC resonant converters [3], decreasing load makes the bus capacitor voltage to rise beyond the estimated value leading to unstable operation of the converter. However, in proposed converter by duty ratio control DC bus voltage is fixed to the reference value making the stable operation possible even at light loads.

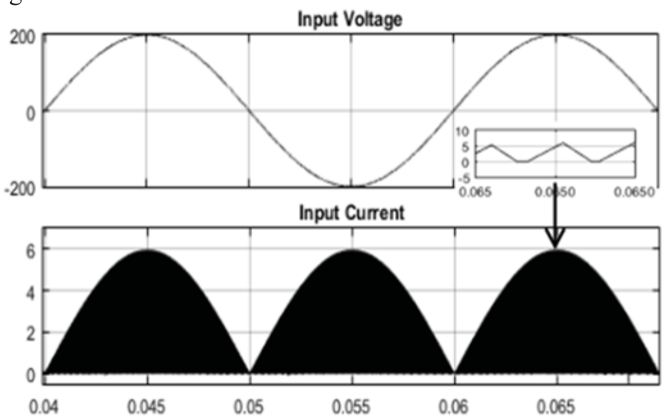

Fig.6 Input voltage and inductor current

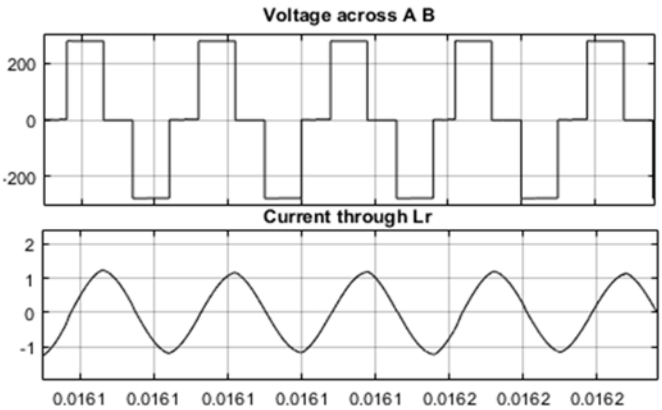

Fig.7 Voltage across AB and current through LLC

Figure 8 shows the ZVS operation of switch $\overline{Q1}$. The OFF state voltage across the switch $\overline{Q1}$ is 280V, which is half of the DC bus capacitor voltage. Similarly, voltage stress across each switch gets reduced to half of the DC bus voltage. Figure 9 presents the transient voltage response of the DC bus capacitor when load current gets reduced by 25% at 1.5 sec. At the instant of load removal, DC bus voltage varies by about 6V. But within .25 seconds it returns to the reference value by proper control action. Transient change in load does not make any noticeable voltage change in capacitor C1. To illustrate this, mode 4 of the circuit is disabled from time 0.6 to 0.8 sec (See fig. 10). It can be noted that the voltage is controlled back to the original value within 0.1 seconds.

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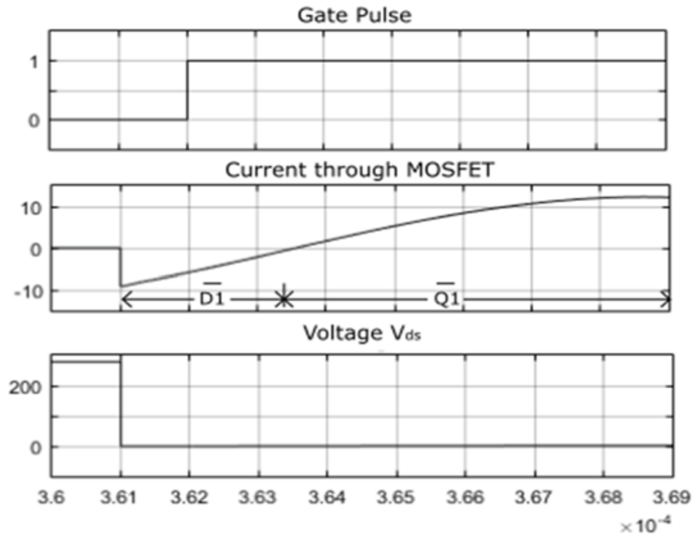


Fig.8. ZVS Turn ON of switch $\overline{Q1}$.

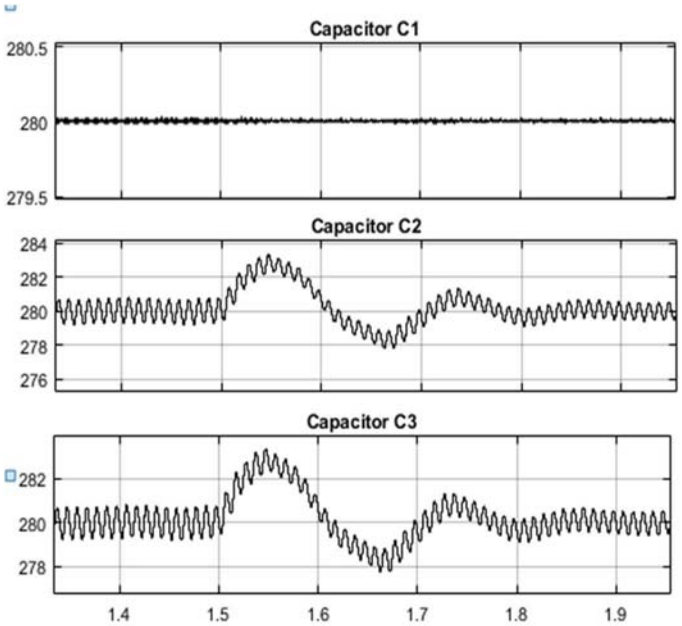
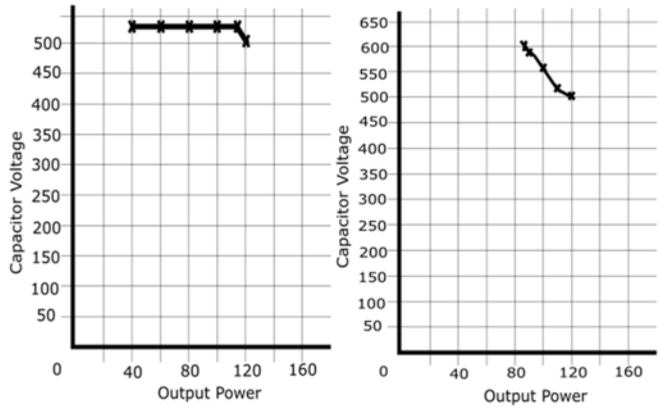


Fig.9. Transient response of DC bus capacitor voltage when the load is reduced to 25% at t = 1.5 sec

Fig. 10 Transient voltage response of capacitor C1 when mode 4 is disabled from time .6 to .8 seconds to show the effectiveness of the control scheme



(a) (b)

Fig.11. Capacitor Voltage -Output power. (a) Proposed converter. (b) Conventional converter [3]

Figure 11 presents the DC bus voltage regulation in the proposed and conventional converters as load power is changed. In the proposed converter (Fig.11 a), it can be seen that the DC bus voltage is well regulated for wider variation in power. The line voltage regulation was also good. The converter showed very good performance even for 20% changes in line voltage.

VII. Conclusion

In this paper, a new three-level half-bridge flying capacitor topology for single stage AC-DC LLC resonant converters has been proposed. The controller uses two control parameters - switching frequency and duty ratio. The output voltage gets controlled by adjusting the switching frequency, and the DC bus capacitor voltage is regulated by controlling the duty ratio. In conventional single-stage topologies, transient changes in load vary the DC bus capacitor voltage. The problem above is rectified in the suggested topology by duty ratio control. The converter operates in discontinuous conduction mode to achieve natural power factor correction. Using LLC resonant property, zero voltage turn ON is possible which reduces the switching losses. The voltage stress of switches are also gets reduced due to three level operation.

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