Discontinuous Conduction Mode Three Phase Buck-Boost Derived PFC Converter for More Electric Aircraft with Reduced Switching, Sensing and Control Requirements

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***Abstract*— In more electric aircraft (MEA), three phase power factor correction (PFC) rectifiers of several kilowatts are required. In this paper, a three phase buck-boost derived PFC converter with inductors connected in delta configuration for aircraft application is presented. The proposed converter is operated in discontinuous conduction mode (DCM) to achieve PFC at ac input. This avoids the inner current control loop which further eliminates the current sensors. It requires only one output voltage sensor unlike five sensors in conventional PFC converter and uses a simple voltage control loop to regulate the output voltage. This makes the system cost effective, more reliable and robust. The steady state operation, design calculations and simulation results are presented. The experimental results from a 2kW laboratory prototype are also presented to confirm the operation of the proposed converter.**

Keywords—PFC; more electric aircraft; buck-boost converter, DCM, AC to DC converter.

NOMENCALTURE

L_a, L_b, L_c	Input inductances
$v_{a,b,c}$	Input phase voltages
i_a, i_b, i_c	Input phase currents
i_{La}, i_{Lb}, i_{Lc}	Input inductor currents
$I_{Lap}, I_{Lbp}, I_{Lcp}$	Peak value of inductor currents at the end of mode-1
$I_{Las}, I_{Lbs}, I_{Lcs}$	Peak value of inductor currents at the end of mode-2
v_o	Output voltage
i_{do}	Output current before capacitor filter
i_o	Load current
i_c	Output filter capacitor current
t_{on}	On time period of the switch
t_s	Time duration of mode-2
t_r	Time duration of mode-3
t_d	Time duration of mode-4
T_s	Time period of one switching cycle
$D = {t_{on}}/{T_s}$	Duty cycle of the switch
V_m	Peak value of phase voltage
f	Line frequency
f_s	Switching frequency
$M = {V_o}/{V_m}$	Voltage conversion ratio
M_{cr}	Critical voltage conversion ratio
$i_{o,avg}$	Average output current

I. INTRODUCTION

The main goals of the MEA are aircraft empty weight reduction, engine emission reduction, engine noise reduction and low fuel consumption to make air travel more efficient and environmental friendly [1]. To achieve these goals one of the solution is to replace the hydraulic, mechanical and pneumatic subsystems with electrical systems. In recent commercial aircrafts Boeing 787 and Airbus A380, the mechanical gearbox called integrated drive generator (IDG) is eliminated and the generator is coupled directly to the engine which results in mains variable frequency 400 to 800Hz [2]. This variable frequency generation poses new challenges to power electronic converters to convert variable frequency ac to constant dc with high quality and reliability with less number of components and sensors.

Traditionally in commercial transport aircrafts, passive diode based transformer rectifiers were used to convert constant voltage constant frequency mains supply to constant DC voltage. In [3], a comparative evaluation was made between 12-pulse passive rectifiers and active three phase PWM converters. It is reported that the active systems show the potential for future use in terms of power density because of lacking progress in the development of magnetic materials. In the literature, numerous three phase rectifier topologies were reported for power factor correction and their detailed review is presented in [4]-[8]. The PFC converters are divided into four major categories; buck, boost, buck-boost and multilevel converters which have a high level of power quality at the input and output [6]. In literature, most of the PFC converters used five sensors to implement the control algorithm. By reducing the number of

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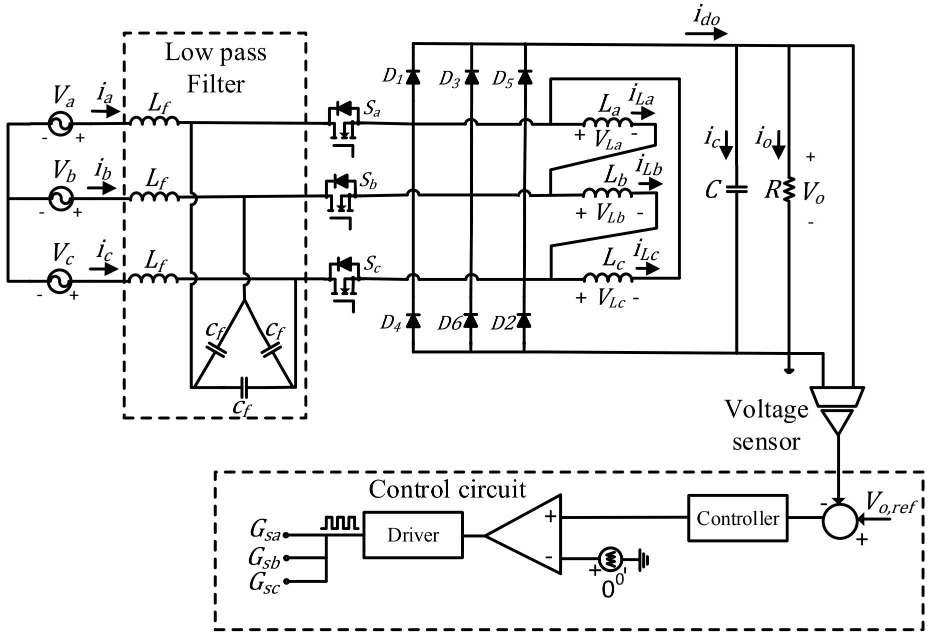

Fig.1. The proposed three phase buck-boost derived PFC converter

sensors, the system becomes more reliable, robust and cost effective. Further, it also reduces the system weight and increases the efficiency [9].

In this paper, a three phase buck-boost derived PFC converter with one output voltage sensor for aircraft application is proposed. It uses only three switches and all the switches are driven by the same gate signal. The proposed converter is operated in DCM to achieve PFC at ac input. The control is very simple and uses only one simple voltage control loop to regulate the output voltage. This paper is organized as follows, section II describes the proposed converter and control strategy. The steady state operation of the converter and detailed design calculations are presented in section III. Simulation and experimental results are presented in section IV and section V concludes the paper.

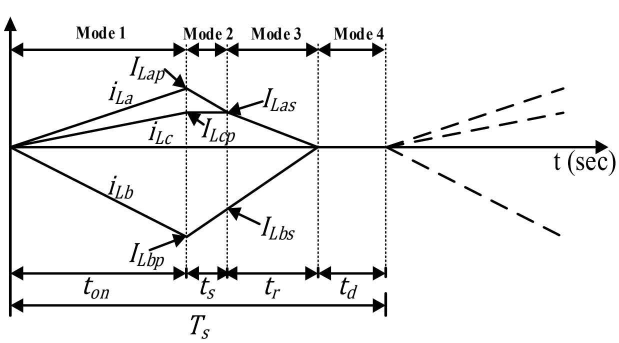

Fig. 2. The inductor current waveforms.

II. PROPOSED CONVERTER AND CONTROL STRATEGY

Fig. 1, shows the proposed three phase buck-boost derived PFC converter. It comprises of three power switches, one three phase full bridge converter and three inductors connected in delta configuration. It is considered that all three power switches are provided with the same gate signal. The objectives of a PFC converter are; 1) the sinusoidal input current in phase with the input voltage, 2) regulated output voltage. The proposed converter is operated in DCM to achieve the first objective. Because of discontinuous current in the inductor, in a given switching cycle, the energy stored in the input inductor is determined by the input voltage at that instant. It means that, the average inductor current naturally follows the input voltage in discontinuous conduction mode. The second objective is achieved by a simple voltage control loop as shown in Fig. 1. From the control loop, it is clear that the duty cycle of the switches depends only on the error between the reference voltage and the output voltage i.e. for a given output power and input voltage, the converter duty cycle is constant and it does not change with input voltage sinusoidal variation. However, the duty cycle changes only if there is change in output voltage reference or any disturbances viz. load change or variation in source voltage amplitude etc.

III. OPERATIONAL ANALYSIS AND DESIGN CALCULATIONS

To simplify the analysis, the following assumptions are made
1) All the switches, inductors and capacitors are ideal.

2) The output filter is large enough to maintain the output voltage constant.

3) As switching frequency is much higher than line frequency, the phase voltages and output voltage are assumed constant in one switching cycle.

4) As defined in (1), the input inductor values are same.

$$L_a = L_b = L_c = L \quad (1)$$

Because of symmetry, the converter is analyzed only for $wt = 0$ to $\pi/6$. The inductor current waveforms of the converter operating in DCM for $wt = 0$ to $\pi/6$ are shown in Fig. 2. The proposed converter has four operating modes and its equivalent circuits are shown in Fig. 3.

Mode 1: Prior to this mode, the input inductors are in fully discharged state. This mode starts when all the three power switches S_a, S_b, S_c are turned on. The equivalent circuit of this mode is shown in Fig. 3(a). In this mode, the input inductors stores the energy according to the voltages applied across the inductors and the output capacitor supplies the load. At the end of this mode the inductors are charged to their peak values as shown in Fig. 2.

Mode 2: This mode starts when the gating signals for the switches are withdrawn. The equivalent circuit of this mode is shown in Fig. 3(b). In this mode, the inductors L_a, L_b start to reset by giving the stored energy to the load through diodes D_2, D_3, D_4 at a rate of V_o/L and the inductor L_c retains its peak value. This mode ends when the inductor L_a current 'i_{La}' equals to the inductor L_c peak current 'I_{Lcp}' as shown in Fig. 2.

Mode 3: The equivalent circuit of this mode is shown in Fig. 3(c). In this mode, the inductors $L_a, L_b,\ L_c$ discharges to the load at a rate of $V_o/2L$, V_o/L, $V_o/2L$ respectively through diodes D_2, D_3. This mode ends when all the inductor currents reach zero as shown in Fig. 2.

Mode 4: The equivalent circuit of this mode is shown in Fig. 3(d). In this mode, none of the switches and diodes are in conduction. The output filter capacitor supplies the load.

According to the modes of operation, the inductor current equations are defined and tabulated in table-I.

A. Average output current

In a switching cycle, the average current of the output filter capacitor is zero. Therefore, the average output current of the converter is given by

$$i_{o,avg} = \langle i_o \rangle = \langle i_{do} \rangle \quad (2)$$

The equation of 'i_{do}' in mode-2 is given by

$$i_{do}(t) = i_{La}(t) - i_{Lb}(t) \quad (3)$$

$$i_{do}(t) = -\frac{3v_b}{L} DT_s - \frac{2V_o}{L} t \quad (4)$$

The equation of 'i_{do}' in mode-3 is given by

$$i_{do}(t) = \frac{3v_{ca}}{L} DT_s - \frac{3V_o}{2L} t \quad (5)$$

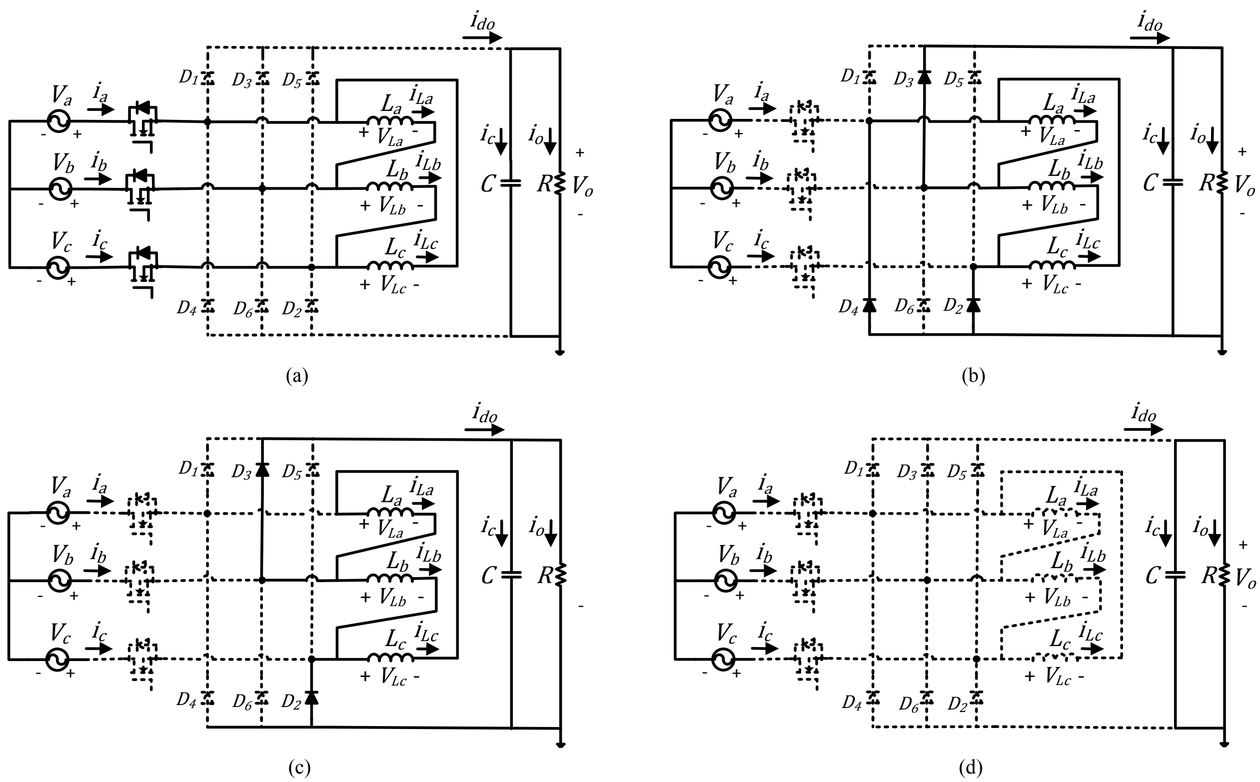

Fig. 3. The equivalent circuit of the proposed converter in different modes of operation (a) Mode 1; (b) Mode 2; (c) Mode 3; (d) Mode 4.

Table I: Mathematical representation of inductor currents for different modes of operation for $wt = 0$ to $^{\pi}/_{6}$

Description	Mode 1	Mode 2	Mode 3	Mode 4
$i_{La}(t)$	$i_{La}(t) = \frac{v_{ab}}{L} t$	$i_{La}(t) = I_{Lap} - \frac{V_o}{L} t$ $I_{Lap} = \frac{v_{ab}}{L} t_{on}$	$i_{La}(t) = I_{Las} - \frac{V_o}{2L} t$ $I_{Las} = \frac{v_{ca}}{L} t_{on}$	$i_{La}(t) = 0$
$i_{Lb}(t)$	$i_{Lb}(t) = \frac{v_{bc}}{L} t$	$i_{Lb}(t) = I_{Lbp} + \frac{V_o}{L} t$ $I_{Lbp} = \frac{v_{bc}}{L} t_{on}$	$i_{Lb}(t) = I_{Lbs} + \frac{V_o}{L} t$ $I_{Lbs} = -\frac{2v_{ca}}{L} t_{on}$	$i_{Lb}(t) = 0$
$i_{Lc}(t)$	$i_{Lc} = \frac{v_{ca}}{L} t$	$i_{Lc}(t) = I_{Lcp}$ $I_{Lcp} = \frac{v_{ca}}{L} t_{on}$	$i_{Lc}(t) = I_{Lcs} - \frac{V_o}{2L} t$ $I_{Lcs} = \frac{v_{ca}}{L} t_{on}$	$i_{Lc}(t) = 0$
Time period	$t_{on} = DT_s$	$t_s = \frac{3v_a}{V_o} DT_s$	$t_r = \frac{2v_{ca}}{V_o} DT_s$	$t_d = (T_s - t_{on} - t_s - t_r)$

where, D = duty cycle of the switch, T_s = switching period

From (4) and (5), the average value of output current can be calculated and it is given by

$$i_{o,avg} = \langle i_{do} \rangle = \frac{9D^2 T_s V_m^2}{4LV_o} \tag{6}$$

The average output current over a line period equals to

$$I_{o,avg} = \frac{6}{\pi} \int_0^{\pi/6} i_{o,avg}\ d(wt) = \frac{9D^2 T_s V_m^2}{4LV_o} \tag{7}$$

B. DCM condition

The condition to operate the converter in DCM is

$$t_{on} + t_s + t_r < T_S \tag{8}$$

On substituting t_{on}, t_s and t_r expressions from table-I in (8)

$$D < \frac{M}{M - \sqrt{3}\sin(wt - \frac{\pi}{2})} \tag{9}$$

The worst situation occurs when $\sin\left(wt - \frac{\pi}{2}\right) = -1$, which gives $wt = 0$. Therefore, to operate in DCM

$$D < \frac{M}{M + \sqrt{3}} \tag{10}$$

From (10), the critical value of conversion ratio which defines the boundary between continuous and discontinuous modes is expressed as,

$$M_{cr} = \frac{\sqrt{3}\, D}{1 - D} \tag{11}$$

For a given duty cycle D, the converter said to be operate in DCM when $M > M_{cr}$.

C. Input inductor design

For a given output power and output voltage, the average value of output current is given by

$$I_o = \frac{P_o}{V_o} = \frac{V_o}{R} \tag{12}$$

From (7), (10) and (12), the value of the inductor to operate the converter in DCM is given by

$$L < \frac{9}{4} \frac{RT_s}{\left(M + \sqrt{3}\right)^2} \tag{13}$$

IV. Results and Discussion

This section is divided into two parts. The first part presents the simulation results of the proposed converter performed in PSIM software. The second part presents the experimental results from the laboratory prototype.

A. Simulation results

The circuit under the simulation is the same one shown in Fig. 1. The design input specifications are; line to line voltage, $V_{L-L,rms}$ =110 V (V_m = 89.81), input frequency, f =400-800 Hz, output power, P_o =2 kW, output voltage, V_o =270 V. The converter is operated at a switching frequency of f_s =75 kHz (T_s = 13.33μs). From equation (13) and the input specifications, the input inductor 'L' shall be less than 48.83 μH to operate the converter in DCM. The circuit is simulated with input inductor value of L = 45 μH and output filter capacitor C = 450 μF. The filter parameters of L_f = 0.5 mH and C_f = 0.44 μF are selected and the results are presented for input frequency f = 400 Hz. A The simulated three phase input voltage and current waveforms are shown in Fig. 4(a) and Fig. 4(b) respectively. The currents are sinusoidal and are in phase with the phase voltages. The phase-A voltage and current waveforms are shown in Fig. 4(c). The input inductor current waveforms are shown in Fig. 4(d). The inductor currents are discontinuous and are in line with the analysis. The output voltage and input current of the converter when subjected to a load step change from 50% to 100% of the rated power are shown in Fig. 4(e). It is observed that the output voltage is well tracking the reference voltage and settled at 270V in 10msec.

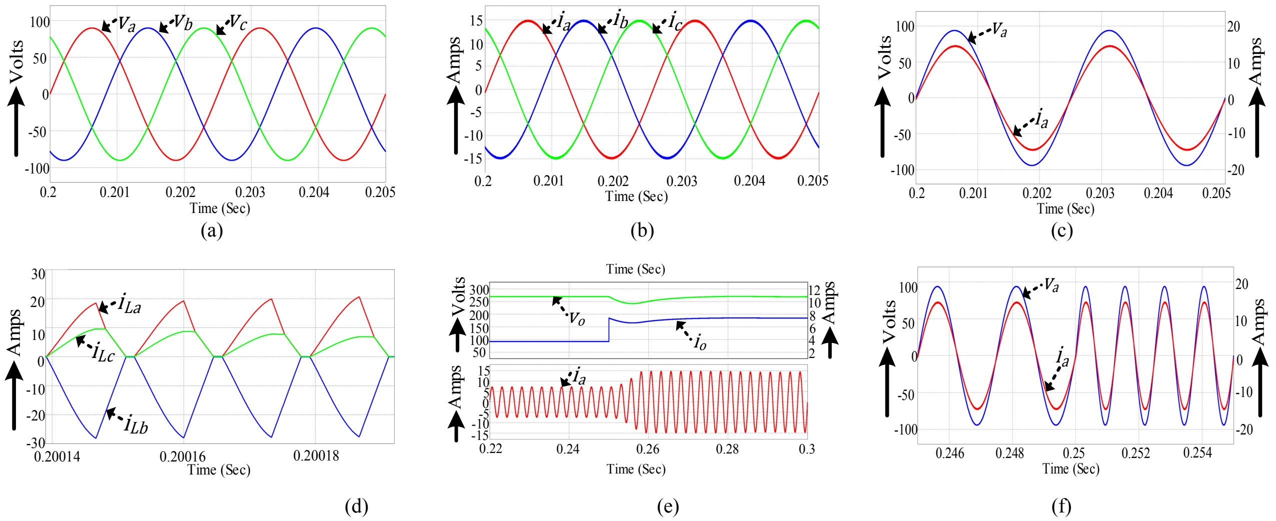

Fig. 4. Simulation results (a) input phase voltages; (b) input phase currents; (c) phase-A voltage and current; (d) input inductor currents; (e) output voltage and phase-A input current for load disturbance from 50% to 100% of rated power; (f) phase-A voltage and current for input frequency variation 400 Hz to 800 Hz.

B. Experimental Results

With the same parameters used in simulation, a 2 kW laboratory prototype is developed and is shown in Fig. 5(a). The components used to develop the prototype are listed in Table II. A PI controller ($k_p + \frac{k_i}{s}$) with the parameters k_p= 0.0498 and k_i= 3.1125 is used for controller. The output of the controller is compared with a saw-tooth waveform of frequency 75 kHz to generate the gate signal and it is fed to all the power switches.

TABLE II. EXPERIMENTAL SETUP COMPONENT SPECIFICATIONS

Component	Specifications
Power switches, S_a, S_b, S_c	C2M0080120D, Sic, 1200V, 80 mohm
Diodes, D_1 to D_6	RURG80100, 1000 V
Output capacitor, C	ESMQ451VSN471MR45S, 220 µF
Filter capacitors, C_f	PHE845VY6220MR06L2, 2 x 0.22 µF
Filter and input inductors	55 x 28 x 21, EE Ferrite cores

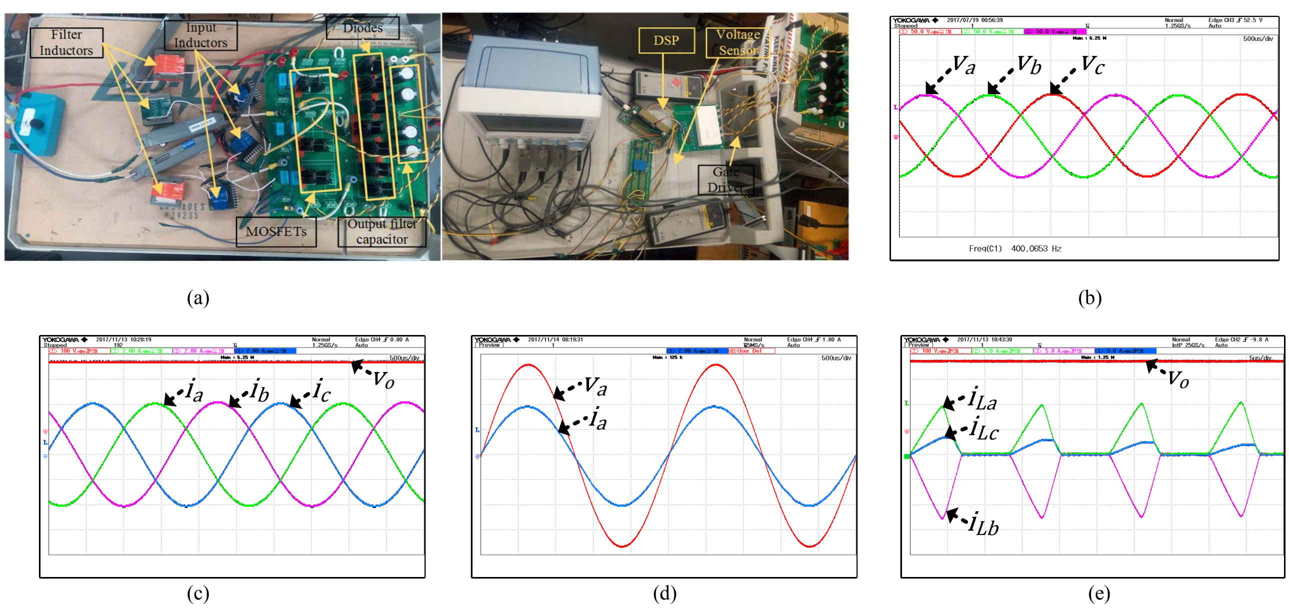

Fig. 5. (a) Experimental prototype setup; (b) phase voltages, 50 V/div, 400 Hz; (c) phase currents, 2 A/div and output voltage, 100 V/div; (d) phase-A voltage, 25 V/div, phase-A current, 2 A/div; (e) input inductor currents, 5A/div.

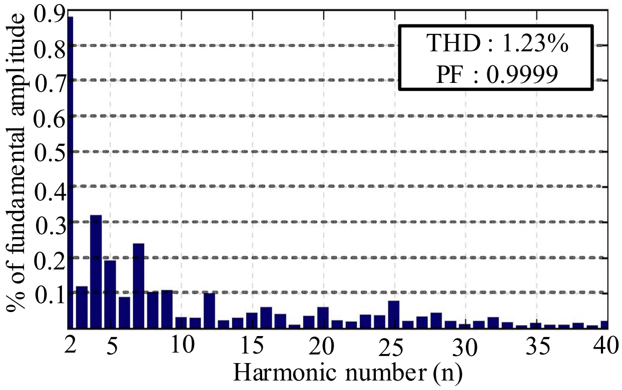

Fig. 6. Input current harmonic spectrum.

The measured input voltages are shown in Fig. 5(b). The measured three phase input currents and output voltage at 0.5 kW output power are shown in Fig. 5(c). The input currents are sinusoidal and the output voltage is settled at 270 V which is in line with the analysis. The input voltage and input current waveforms for one phase are shown in Fig. 5(d). The input current is sinusoidal and in phase with the input voltage. The input inductor current waveforms are shown in Fig. 5(e). The inductor currents are discontinuous and are in agreement with the analysis. Fig. 6, shows the input current harmonic spectrum. An input current THD of 1.23% and an efficiency of 95.1% are achieved at output power of 0.5 kW.

V. Conclusion

A new three phase buck-boost derived PFC converter with inductors connected in delta configuration for aircraft application is proposed. The proposed converter uses only three switches and all the switches are driven by the same gate signal. The converter is operated in DCM to achieve PFC at ac input. To operate the converter in DCM, the value of the input inductance required is quite small which reduces the system weight significantly. However, the converter requires high rated semiconductor power devices because the peak current through the device is significantly high due to DCM operation.

The converter control is quite simple and requires only one simple voltage control loop to regulate the output voltage and also it requires only one output voltage sensor unlike five sensors in conventional PFC converter. It makes the system cost effective, more reliable and robust. The steady state operation of the converter, design of the input inductor and the simulation results are presented in detail. Also, the results from a 2 kW laboratory prototype are presented to confirm the operation of the converter. The results demonstrate that the input currents are sinusoidal and the converter power factor is almost unity. The output voltage is constant and settled at 270 V. From the developed prototype, an input current THD of 1.23% and an efficiency of 95.1% are achieved at an output power of 0.5 kW.

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