MOHF Forward Buck DC-DC Converter Based SMPS

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Abstract–An improved power quality, cross regulated, multiple output high frequency (MOHF) isolated forward buck DC-DC converter based switched mode power supply (SMPS) is designed in the continuous conduction mode (CCM) using an average current control (ACC) for personal computer applications. The proposed SMPS is formed by using a single phase diode bridge which is connected to a MOHF isolated forward buck DC-DC converter. The output of MOHF isolated forward buck DC-DC converter is connected to multi-winding high frequency (HF) transformer. Multiple secondary windings of a HF transformer are used to provide different DC voltages and currents. The closed loop control of proposed MOHF isolated forward buck DC-DC converter based SMPS provides power factor improvement by shaping the input current to sinusoidal and in phase with input voltage. Simulated results of the proposed power supply are presented to validate its design and to demonstrate its improved performance.

Keywords–Forward buck DC-DC converter, multiple outputs, ACC, power factor correction.

I. Introduction

In recent years, the use of personal computers (PCs) in most of the fields is increasing massively for high and efficient work productivity. PC power supply is very sensitive and requires good power quality at the input AC mains. The reduction in size, cost and weight the modern computer power supply now calls for high frequency (HF) switching, use of minimum number of components and magnetic elements. Therefore, switched mode power supplies (SMPS) with these meritorious features are used in PCs extensively [1]. SMPS for PCs normally requires AC-DC converter, input filter, multiple output high frequency (MOHF) DC-DC converter, HF transformer for isolation and multiple outputs, output filter and power factor correction (PFC) circuit. A diode bridge is commonly used for AC-DC conversion that draws non-sinusoidal current from the AC supply which is highly undesirable resulting in deterioration of the power quality. Therefore, PFC is used at the front end in the power supplies to satisfy the power quality standards set by various international organizations such as IEC (International Electrotechnical Commission) and IEEE. These standards specify power factor and harmonic limits at the point of utility interface.

The power supply for computers normally requires various DC voltages at different current ratings. These multiple voltages are obtained by adding a number of secondary windings to the HF transformer. An ACC (Average Current Control) is used such that the input current is shaped to sinusoidal and remains in phase with input voltage to achieve improved power quality and less used to control the multiple DC output voltages of computer power supply which is complex. In weighted harmonic distortion. Normally weighted error approach is error approach, the weigh stages of all DC output voltages and output currents are taken into account for power quality improvement [2]. These drawbacks are overcome by using the cross regulation technique which offers very simple, cost effective control with improved power quality. Only one DC output voltage which is most sensitive to disturbances is sensed and compared with the required constant DC voltage. All the other DC outputs are regulated by the duty cycle of the MOHF isolated forward buck DC-DC converter, determined by the control loop of the sensed output. Only one stage conversion further enhances the reliability and reduces the complexity.

In a multi-output forward converter, for improving cross regulation, an objective function is arrived at for each dc output to maintain the error within limits [3]. Single switch DC-DC converters consisting of isolated multiple outputs with cross regulation have been reported in the literature [4]. These converter topologies require HF transformer for isolation consisting of multiple secondary windings and a PFC circuit for achieving unity power factor (UPF) and reducing harmonics at the input. Extensive research has been carried out on single switch converter with MOHF isolated outputs and their improvements are presented in the literature [5-6]. Single switch PFC using a forward converter is widely used in industry for a variety of purposes such as computer power supplies, automotive and telecom applications. A simple isolated single output forward converter and its extension to multioutput are discussed in [7-8]. Further advancement in forward converter is proposed by adding two diodes and a capacitor at the input of the HF transformer to recycle its magnetizing energy for preventing core saturation in [9]. The magnetizing energy is absorbed by the clamping capacitance and the diode when the HF switch is turned off. The analysis and implementation of an active clamp forward converter is presented and the results are compared with the conventional forward converter in [10]. At the output of HF transformer, a synchronous rectifier is used to reduce the conduction losses. A forward converter with independently and precisely regulated multiple outputs is presented in [11-12] where each output has its own control. An improved efficiency for all load conditions with master and slave control is reported in the literature using a forward converter [13]. Xiaodong et al [14] have proposed a double forward multiple output converter with weighted time-sharing control and switch-linear hybrid technique. A control scheme for multi-output forward converter with wide variations in load provides independent and precise voltage regulation irrespective of operation mode which has been discussed in [15]. The winding power loss for a HF forward buck DC-DC converter in CCM is estimated based of Fourier series of

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the winding current waveforms in [16]. A forward converter is proposed in [17] with zero current switching where the transformer core is reset through resonance. Here, the auxiliary circuit consists of an auxiliary switch and a capacitor for obtaining zero current switching of the HF switch and to reset the transformer core**.**

In this paper, a MOHF isolated forward buck DC-DC converter based SMPS is designed with improved power quality within the constraints of IEC and IEEE-519 standards at the utility end [18-19]. It consists of single phase AC supply, a diode bridge, connected to an MOHF isolated forward buck DC-DC converter, controlled using ACC technique. The analysis of MOHF isolated forward buck DC-DC converter is carried out and necessary design equations are derived for estimating the different components values. Only one DC output voltage is sensed, controlled and regulated. All the other DC output voltages are inherently regulated by the MOHF transformer. The analysis and design of the MOHF isolated forward buck DC-DC converter is carried out in CCM (Continuous Current Mode) and the optimum parameters are estimated to attain UPF with reduced harmonic distortion. Simulation results are presented to demonstrate that the proposed SMPS has sinusoidal UPF input current with less harmonic distortion at the utility interface over a wide range of operating conditions.

II. Configuration, Analysis And Design of Forward Buck DC-DC Converter Based SMPS

The configuration and detailed design of the MOHF isolated forward buck DC-DC converter based power supply is presented in this section for the power quality improvement at the utility. The closed loop control is used to regulate only one DC output voltage and all other DC output voltages are regulated inherently through HF transformer of MOHF forward buck DC-DC converter based SMPS. The configuration and design equations for the forward buck DC-DC converter based SMPS is described in following subsections.

A. MOHF Power Supply Configuration

Fig. 1 shows a circuit configuration of the power supply consisting of a single phase AC supply, bridge rectifier and MOHF isolated forward buck DC-DC converter. This multi-output configuration offers the benefits of buck topology with a high level of power quality. V_{in} and I_{in} are the AC supply input voltage and current respectively drawn by the single phase diode bridge rectifier. The rectified uncontrolled DC voltage V_d is given to MOHF isolated buck forward DC-DC converter. It consists of a magnetizing inductor L_m and HF switch S_w at the input side. A tertiary winding N_r with freewheeling diode D_{11} is connected for resetting the magnetizing flux. It should reduce to zero before the start of next switching cycle. Multiple output voltages, voltage scaling and isolation are provided by the HF transformer which consists of one primary winding N_p and five secondary windings N_{s1}, N_{s2}, N_{s3}, N_{s4}, N_{s5} respectively. The voltage across the primary winding is V_{p1} and the secondary windings voltages are V_{s1}, V_{s2}, V_{s3}, V_{s4} and V_{s5} respectively. At the secondary side, the high frequency diodes, D_1, D_2, D_3, D_4, D_5, D_6, D_7, D_8, D_9 and D_{10} are connected to rectify the voltage with the output filter inductors L_1, L_2, L_3, L_4, L_5 respectively.

When HF switch S_w turns ON, the uncontrolled DC output voltage of the diode bridge V_d is applied to the primary winding of the HF transformer. It makes high frequency diodes D_2, D_4, D_6, D_8 and D_{10} to be reversed biased. When the switch S_W turns OFF, the primary winding and all the secondary windings currents are suddenly brought down to zero thus high frequency diodes; D_2, D_4, D_6, D_8 and D_{10} provide the freewheeling path for the output currents. Output capacitors C_{o1}, C_{o2}, C_{o3}, C_{o4} and C_{o5} are discharged across the loads. A feedback control is incorporated to regulate the DC output voltages by means of PWM (Pulse Width Modulation) control that supplies the gating signal for the HF switch. An ACC is used to control the DC voltages, shaping the AC input current and to achieve UPF. In ACC, two loops are used to regulate the DC output voltages and to improve the power quality. External voltage loop regulates the output DC voltages while internal loop shapes the input AC mains current. One of the most affected DC output voltage (V_{o1}) is sensed and compared with reference voltage V_{re} for error voltage generation. This error voltage is given to the voltage controller and output of the voltage controller I_b is multiplied with the unit amplitude sine wave template $|V_d|$ sampled from the input voltage to obtain reference current I_d*. This reference current is compared with the sensed current. The current error is fed to a current controller. The output of the current controller is compared with a HF saw-tooth ramp (V_c) to control the duty cycle of the switch S_w. Thus, the control provides regulated DC output voltages with input current shaping. Only one DC output voltage is controlled by the closed loop control, all the other DC output voltages are controlled by the duty cycle of the forward buck DC-DC converter.

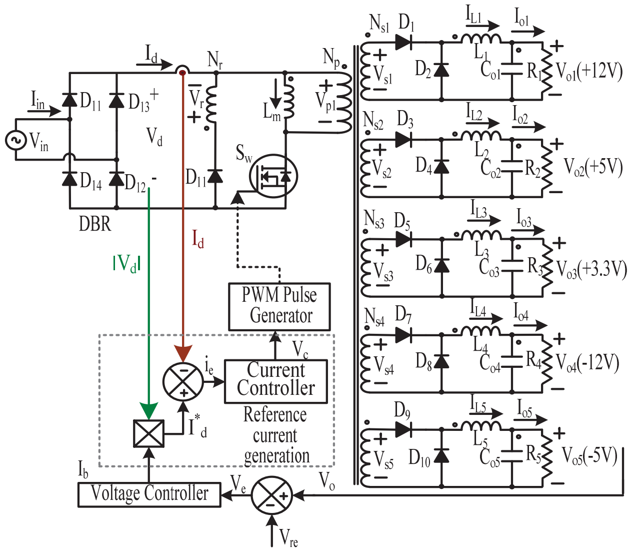

Fig. 1: Circuit configuration of the power supply consisting bridge rectifier and MOHF isolated forward buck DC-DC converter

B. Analysis and Design

An improved power quality MOHF isolated forward buck DC-DC converter is analyzed to obtain the required design equations for estimating the component values. The input output voltages relationship and component values are obtained by considering only one controlled DC output voltage although the same analysis can be extended for the other DC outputs as well. The HF switch and diodes are considered ideal in nature. The output filter capacitor C_o is considered large enough to keep the output DC voltage constant. The operation of a forward buck DC-DC converter is explained in two stages in every PWM cycle. In stage 1, a switch (S_w) is turned ON over a period and in the next stage it is turned OFF. Stage 1 is called as ON period and the second stage is called as OFF period.

I. Stage 1: ON Period

When HF switch S_w is ON, the inductor currents i_{L1} and i_{Lm} increase. The change in inductor current i_{L1} is,

$$\Delta i_{L1ON} = \{V_d (N_{s1}/N_p) - V_{o1}\} DT/L_1 \quad (1)$$

The change in current of the magnetizing inductance L_m is expressed as

$$\Delta i_{LmON} = (V_d DT)/L_m \quad (2)$$

II. Stage 2: OFF Period

HF Switch S_w turns OFF but the currents in inductor L_1 and L_m cannot change instantaneously. Diode D_{11} performs the freewheeling action so that the stored magnetic energy in L_m is feedback to input.

When diode D_{11} is conducting, the voltage across tertiary winding N_r is

$$V_r = -V_d \quad (3)$$

During OFF period of HF switch S_w, the change in current of inductor L_1 is written as

$$\Delta i_{L1OFF} = -\{V_{o1}(1-D)T\}/L_1 \quad (4)$$

Under steady state condition, the change in the inductor current is zero over one PWM period. Therefore, it is as

$$\Delta i_{L1ON} + \Delta i_{L1OFF} = 0 \quad (5)$$

Substituting a value of change in the inductor current during ON and OFF periods, (5) is rewritten as

$$\{nV_d - V_{o1}\}(DT/L_1) - \{V_{o1}(1-D)T\}/L_1 = 0 \quad (6)$$

$$V_{o1} = nV_d D \quad (7)$$

The DC output voltage of MOHF isolated forward buck DC-DC converter based SMPS depends on the duty cycle, turns ratio and the diode bridge output voltage. A value of inductance L_1 for a given current ripple is estimated from (4) as

$$L_1 = \{V_{o1}(1-D)T\}/\Delta_{iL1} \quad (8)$$

The output filter capacitor is designed for maintaining DC voltage constant at any desired load current. The DC output power at an instant (n) is equal to input power and is expressed as

$$\begin{aligned} P_o(n) &= V_o I_o \\ &= V_{o1}I_{o1} + V_{o2}I_{o2} + V_{o3}I_{o3} + V_{o4}I_{o4} + V_{o5}I_{o5} \end{aligned} \quad (9)$$

Similarly, the input power $P_{in}(n)$ from the single phase ac source is expressed as

$$P_{in}(n) = V_{in}\sin\omega t I_{in}\sin\omega t = V_{in}I_{in}(1-\cos\omega 2t) \quad (10)$$

For output voltages regulation approach, a common core is used for the multi-winding HF transformer and the input output power balance is maintained. Since individual outputs have different voltage ratios, it can be denoted as,

$$\begin{aligned} I_{in} &= I_{o1}(N_{s1}/N_p) + I_{o2}(N_{s2}/N_p) + I_{o3}(N_{s3}/N_p) \\ &+ I_{o4}(N_{s4}/N_p) + I_{o5}(N_{s5}/N_p) \end{aligned} \quad (11)$$

$$I_o = (V_{in}I_{in} - V_{in}I_{in}\cos 2\omega t)/V_o \quad (12)$$

The average value of DC output current I_o from (12) is written as,

$$I_{oavg} = V_{in}I_{in}/V_o \quad (13)$$

The output filter capacitor for reducing the second order harmonic and low voltage ripple is designed by using the relationship,

$$C_o = I_o/(2\omega\Delta V_o) \quad (14)$$

where, ΔV_o is the ripple in output voltage.

III. Design Example Using Forward Buck DC-DC Converter Based SMPS

The components of MOHF isolated forward buck DC-DC converter based SMPS is designed through an example. The MOHF isolated forward buck DC-DC converter based SMPS using following specifications to exemplify the design procedure: Supply rms voltage of 220 V at 50Hz is given to a diode bridge. The average output voltage V_d of the diode bridge is 198V. The output voltages of MOHF forward buck DC-DC converter are V_{o1}=12V, V_{o2}=5V, V_{o3}=3.3V, V_{o4}=-12V and V_{o5}=-5V and the switching frequency is 50 kHz. The ripple in output voltage is considered 3% and current ripples are also considered 2%. The nominal duty ratio of the switch D=0.4. The values of inductors are calculated from (8). These are L_1=0.45mH, L_2=0.125mH, L_3=0.0825mH, L_4=9mH and L_5=10mH. The output capacitor values from (14) are C_{o1}=70 mF, C_{o2}=254 mF, C_{o3}=386 mF, C_{o4}=3.5 mF and C_{o5}=3.18 mF.

These designed component values are considered in the modeling of the MOHF isolated forward converter based power supply for power quality improvement.

IV. Average Current Control (ACC) of Proposed SMPS

ACC is used to regulate the multiple output dc voltages against the load disturbances. It consists of a voltage controller, reference current generator and a PWM generator. In this technique, voltage error V_e, i.e. the difference between the reference voltage V_{re} and the sensed DC output voltage V_{o1}, is fed to a PI voltage controller. The outer voltage loop provides the proper current reference signal by multiplying a scaled replica of rectified voltage by the output of voltage controller. This is further multiplied with an uncontrolled DC voltage unit template to generate the reference current. The error between reference current and input sensed current is fed to another PI controller to shape the input current. The output of current controller (V_c) is compared with a HF saw-tooth ramp to control the duty cycle of the HF switch S_w.

A) Voltage Controller

The output of PI voltage controller is written as,

$$I_b(n) = I_b(n-1) + K_{pb}\{V_e(n) - V_e(n-1)\} + K_{ib}V_e(n) \quad (15)$$

where K_{pb} and K_{ib} are the gains of the voltage controller and $V_e(n)$= $V_{re}(n)$-$V_{o1}(n)$ at n^{th} instant.

B) Reference Current Generator

It generates the reference current (I^*_d) by multiplying the output of PI voltage controller and unit template input voltage which is compared with the sensed current (I_d) to generate the current error Δi_e=(I^*_d-I_d). This current error is fed to a current controller. The output of current controller V_c at n^{th} instant of time is,

$$V_c(n) = V_c(n-1) + K_{pi}\{i_e(n) - i_e(n-1)\} + K_{ii}i_e(n) \quad (16)$$

C) PWM Pulse Generator

The output of PI current controller is compared with HF saw-tooth ramp to get the PWM gating signals for the switch. When the saw-tooth ramp is less than the output of the current controller, the HF switch remains ON, otherwise it remains OFF.

The gain parameters of the voltage controller and reference current generator are to be selected properly to ensure the constant dc voltages during dynamic conditions. The Ziegler Nichols method [20] is used for the tuning of gain parameters. A mathematical formula for tuning of gains is given where proportional and integral gains are described.

$$K_{pb}=0.45K_u \qquad (17)$$
$$K_{Ib}=1.2K_{pb}/P_u \qquad (18)$$

where, K_u is the ultimate gain at which the output of the control loop starts to oscillate and P_u is the oscillation period. K_{pb} and K_{Ib} are calculated as 0.06 and 0.24 and K_{pi} and K_{ii} are 0.005 and 0.6 for the voltage loop control and reference current generator. These values are further tuned to improve the performance of the system (K_{pb} =0.08, K_{ib} 0.21, K_{pi}=0.008, K_{ii}=0.56).

V. Simulation of MOHF Isolated Forward Buck Converter Based SMPS

To validate the design of the proposed power supply based on MOHF isolated forward DC-DC converter, its model is developed in MATLAB/simulink environment and extensive simulations are made to demonstrate the improved performance. Fig. 2 shows the developed MATLAB model of the single-phase MOHF isolated forward buck DC-DC converter based SMPS configuration. The single phase forward buck DC-DC converter is operated in CCM in such a way to obtain nearly UPF and low harmonic content of the input current. Table I shows the design specifications of proposed MOHF isolated forward buck DC-DC converter based SMPS. The performance of the proposed SMPS is studied at full load and light load conditions.

Table I
MOHF Isolated Forward Buck DC-DC Converter Based SMPS Specifications

Specification	Values
Supply rms voltage	220 V, 50 Hz
Output Voltages/ Output Currents	12V/16A
	5V/24A
	3.3V/24A
	-12V/0.8A
	-5V/0.3A
Switching frequency	50kHz

VI. Results And Discussion

In this section, simulation results of the proposed MOHF isolated forward converter based SMPS are presented and discussed in detail. The simulated waveforms of the MOHF isolated forward buck DC-DC converter based SMPS are shown in Figs. 3-6. Fig. 3 shows the input voltage/current, DC output voltages V_{o1}, V_{o2},

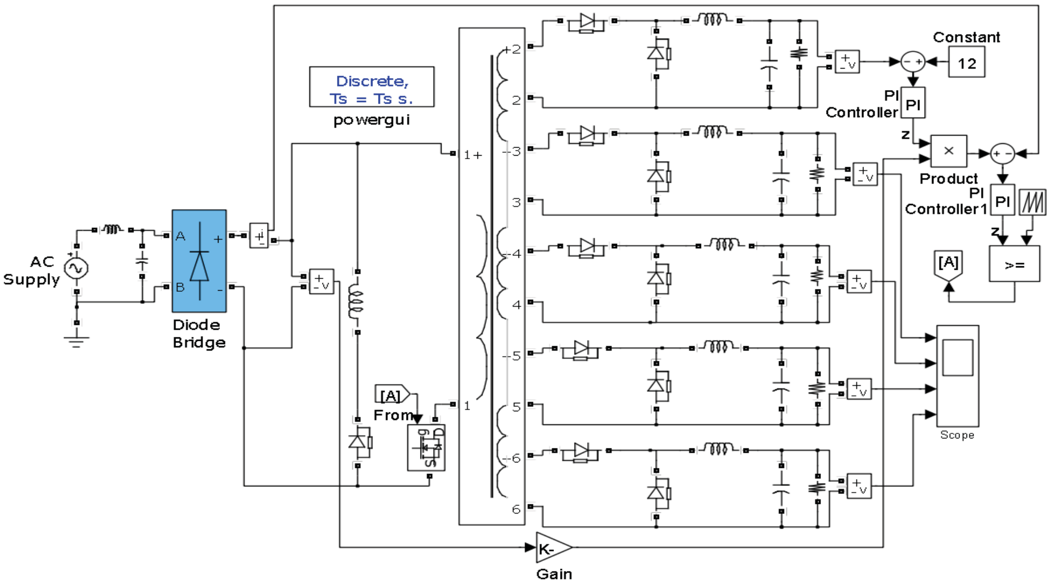

Fig. 2: MATLAB model of the single-phase MOHF buck forward dc-dc converter based SMPS

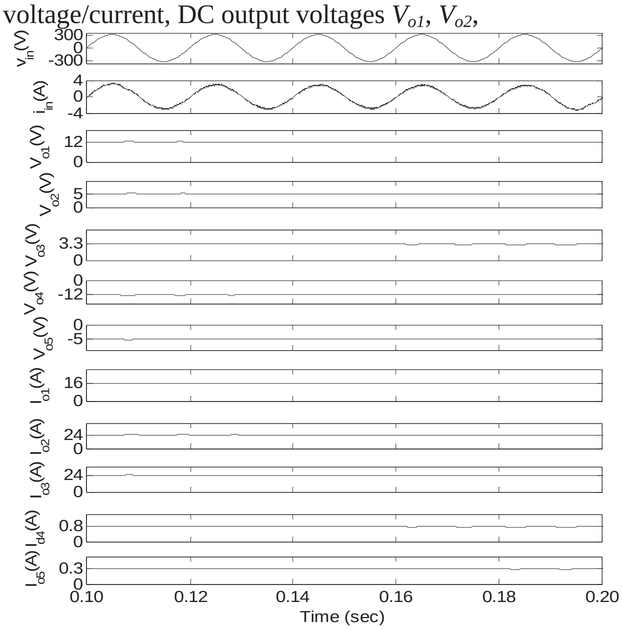

Fig. 3: Input voltage/current and output voltages/currents of forward buck DC-DC converter based SMPS

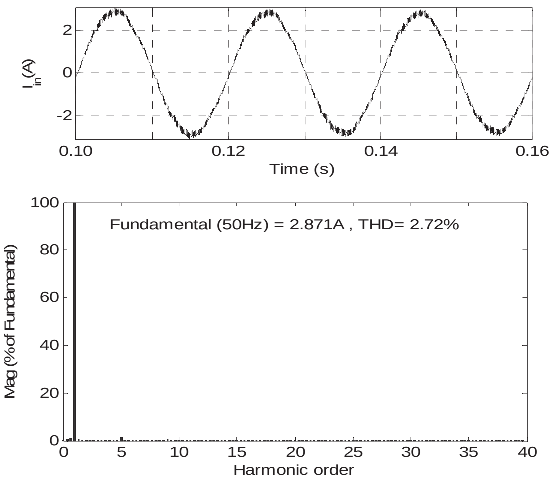

Fig. 4: Harmonic spectrum of input current of forward buck DC-DC converter based SMPS at full load

V_{o3}, V_{o4} and V_{o5} and DC output current waveform I_{o1}, I_{o2}, I_{o3}, I_{o4} and I_{o5} of the MOHF isolated forward buck DC-DC converter based 403 W SMPS at full load. All the DC output voltages are constant due to closed loop control. The input current waveform is sinusoidal and in phase with the input voltage which results in nearly UPF. Fig. 4 shows the waveform and harmonic spectrum of the input AC mains current at full load. The harmonic distortion of the input current at full load is 2.72% which is very low.

To study and demonstrate the dynamic behavior of the MOHF isolated forward converter based SMPS, the load on the SMPS is varied (on +12V) and its effect on various power quality indices are depicted in Table II. Fig. 5 shows the response of proposed SMPS at varying load in the highest current rated winding. The load current corresponding to +12V suddenly decreases from 16A to 8A (50%) at 0.17 S. All the other load currents remain constant. A +12V DC output voltage takes about 0.08s to settle down to its nominal value. The input current remains sinusoidal but the harmonic distortion is increased. The power factor at light load is 0.9989 which is very close to unity. The harmonic spectrum of input current at light load is shown in Fig. 6. At light load, the harmonic distortion of input current in 4.66% which is well within the IEEE standard limit. Table II shows a comparison in terms of harmonics distortion, power factor, displacement power factor (DPF) and output voltage ripple of the SMPS. The ripples of DC output voltages have reduced, for the same allowable DC output voltage ripple. It can be observed clearly from Table II that it results in nearly UPF at full and light load.

TABLE II
FORWARD CONVERTER SIMULATED PARAMETERS

Output voltage	Harmonic distortion		DPF		DF		PF		Ripple (ΔV_o%)	
	100%	50%	100%	50%	100%	50%	100%	50%	100%	50%
V_{o1}									1.9	1.8
V_{o2}	2.72	4.66	1	1	0.9996	0.9989	0.9996	0.9989	1.9	1.8
V_{o3}									1.8	1.8
V_{o4}									1.8	1.8
V_{o5}									1.7	1.7

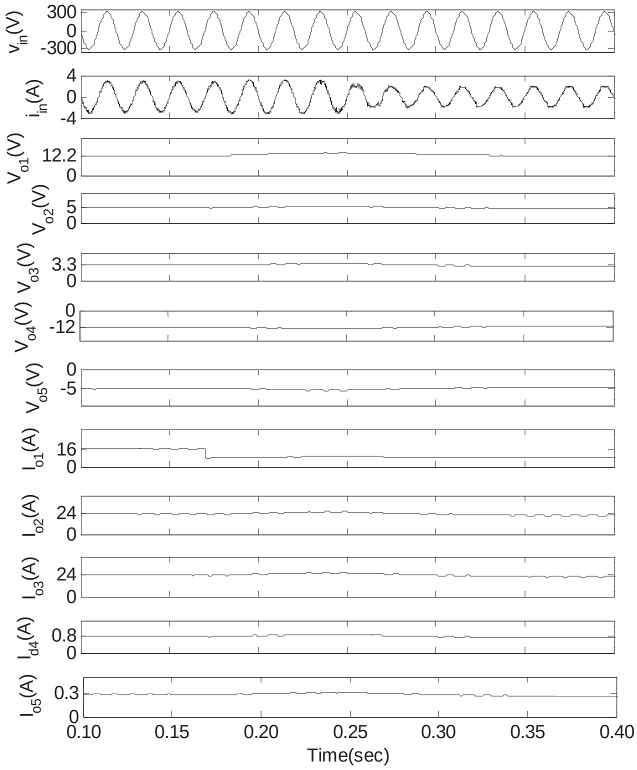

Fig.5: Input voltage/current and output voltages/currents of forward buck DC-DC converter based SMPS at step change in load (+12V)

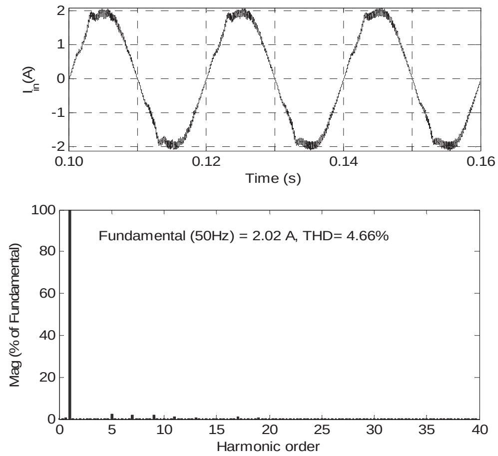

Fig. 6: Harmonic spectrum of the input current of forward buck DC-DC converter based SMPS at 50% load in +12V DC output

VII. CONCLUSION

An improved power quality MOHF isolated forward buck DC-DC converter based SMPS has been designed. The design of proposed power supply has been validated for improved power quality at the utility interface in terms of reduced harmonic distortion of input current and high power factor. Average current control has been applied to the MOHF isolated forward buck DC-DC converter to provide good DC output voltage regulation with input current shaping. Only single DC output is controlled and all the other DC outputs are regulated by the same duty cycle. The harmonic distortion of the power supply is found within the limits set by standards for full load as well as for varying load conditions with nearly unity power factor operation. The observed performance of MOHF forward buck DC-DC converter has been found to be a promising candidate for power supplies for PCs.

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