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ORIGINAL PAPER

Design and Testing of SMPS in Accordance with IEC 61000-4-11 Standard with Measurement Uncertainty

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Abstract: This paper presents design and testing of an efficient switched-mode power supply (SMPS) with load in accordance with IEC 61000-4-11 standard. This paper aims to design and present a SMPS that works efficiently under different electrical conditions. In this work, the designed SMPS provides multiple constant DC voltages of 5 V, 12 V and 15 V with overload protection for a wide range of AC input (80–300 VAC). Investigation of various voltage dips ranging from 0 to 80% in accordance with IEC 61000-4-11 standard is also presented. To confirm the validity of proposed design, various experimental results are obtained using programmable AC source, digital multimeter, digital storage oscilloscope (DSO) and digital power meter. The results show an efficiency of more than 90% and high-power factor of 0.9. The maximum expanded uncertainty is found to be ± 0.02 V at coverage factor k = 2.07 for approx. 95% confidence level.

Keywords: SMPS; Flyback converter; IEC 61000-4-11; Voltage dip; Voltage surge

1. Introduction

An electronic equipment is required to operate reliably under various harsh electrical environments like high voltage, high frequency, electrical fast transients, surges and electrostatic discharge. It is required that the equipment must be immune against these disturbances and continues to function normally. The aim of this paper is to design and present a switched-mode power supply (SMPS) that works efficiently under varying electrical conditions. Voltage sag is one of the major factors that impacts electrical equipment adversely. It is a sudden and temporary dip in fundamental voltage frequency in one or more phases [1]. Multiple reasons have been identified for this phenomenon by researchers. 80% of all the power-related issues can be traced to voltage sag. In terms of magnitude, voltage sag is measured as the percentage of residual RMS magnitude, i.e., 80% sag is taken as 176 V for a 220 V normal RMS supply. Line voltage sags can even shut down or damage SMPSs. Earlier researchers have presented the voltage tolerance AC coil contactors usually employed as AC switches, for voltage sag variations of 10–90% and wave values ranging from 15° to 90° [2]. It was seen that sensitivity of AC coils changes with different makes. Analysis of sensitivity of voltage ride vulnerability for five PCs of varying specifications on SEMI F47 standard specifications has also been conducted [3]. Authors claim to satisfy the design goals for all the PCs under test. However, it was seen that there is high inrush current due to the presence of DC capacitors. In the literature, the sensitivity of gas discharge lamps along with contactors has also been tested [4]. It was observed that contactors could survive an outage of several milliseconds but trips even if there is a 50% sag lasting one cycle. Further, it was shown by authors that line voltage sags can be improved by using a large DC capacitor and reducing the minimum voltage for DC–DC converter [5]. However, these tests were performed in a PSPICE simulation set-up. The studies performed on effect of voltage sag is very limited in the literature. The performance of SMPS under voltage lag has been analyzed and discussed in detail in the presented work.

Apart from the issue of voltage lag, there are other concerns like performance of the device under varying input voltage conditions, no load conditions, etc. that needs to be looked into. An interleaved AC to DC converter had also been implemented in the literature. The converter developed by them resulted in better EMI performance. This was on account of the passive component used in the structure that reduced the current spikes. However, the

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impact and reduction of voltage lag were not analyzed in the circuit [6]. The concept of segmentation in the power stage of a SMPS to improve the power efficiency had also been implemented by researchers [7, 8]. In the literature, different other converters have also been proposed to improve the power quality. Buck converter has a limited output voltage range [9, 10] and boost converter also typically suffers from the same problem. A buck–boost converter although sustains variations in input voltage and has low induction losses but shows higher number of ripples in output voltage [11, 12]. Further, a converter proposed in the literature shows a large output voltage range but causes the polarity of the output current to be reversed [13]. Further, a bridgeless converter-based SMPS was also proposed [14]. Here, the bridge rectifier was replaced by a single-ended primary inductance converter. Due to the availability of two switches and the absence of diode bridge, power quality improves. However, the proposed circuit has not been extended and tested for various voltage lags as well as varying input voltages. A super junction MOSFET SMPS was also proposed in the literature. In this, the reduced operating temperature increased the reliability of the circuit and also the presence of the super junction MOSFET leads to better reverse recovery rate as compared to the conventional SMPS [15]. However, in this paper, the authors had tested the circuit for zero voltage switching. Also, authors had presented a SMPS under a high-level current pulse injected in differential mode [16]. The authors had considered a flyback converter topology and to get a better output extraction of the transformer model, and saturation phenomena were used. The testing and results were analyzed for high-level current pulse as well as varying input voltage. However, other associated parameters were not considered and analyzed. Performance and reliability of high power conversion systems are presented and analyzed in the literature for obtaining a compact, high power density and high switching frequency flyback SMPS[17]. A technique to check the product using simulation technique before actually developing the final SMPS is also suggested in the literature. In the literature, successfully testing a model of SMPS using SIMPLIS simulation engine was also presented [18]. Through this method, it was shown that system was found to be working successfully under simulation test for the given parameters. Though, this system needs to be implemented practically using hardware system set-up under varying conditions and then further tested.

The need of the time is to develop a robust and efficient SMPS that provides constant DC voltage with varying input conditions. Also, the developed SMPS should successfully handle various voltage dips as well as present a high-power factor. In this paper, authors have developed and successfully tested such a SMPS for air conditioners. All the measurements are done in laboratory using equipment's like programmable AC source, DSO, digital power meter, Fluke 3–1/2 digit multimeter and PCB. An actual air conditioner unit is used as load.

The proposed SMPS is based on flyback converter topology. The flybackmode converter operates differently in ON and OFF periods [19]. During its power switch on time, these converters store energy in the primary of the transformer, while load current is supplied from an output filter capacitor (Fig. 1). When the power transistor turns off, the energy stored in the power transformer is transferred to the output as load current and to the filter capacitor to replenish the charge it lost when it alone was delivering load current. Switching off the power supply results in the voltage trying to rise or shoot up or as the name suggests fly-up suddenly in voltage. The exceeding voltage is clamped by snubber diode, stored in snubber capacitor and that stored energy is dissipated through snubber resistor. The inductor is then de-energized by charging the output capacitor. This leads to the necessity to protect power switch for prevention from getting damaged by voltage spikes.

Primary peak current, I_{ppk}, of flyback converter is given by the equation:

$$I_{ppk} = I_{spk} * \frac{N_s}{N_p} \quad (1)$$

Here, I_{spk} is secondary side peak current, N_s stands for secondary winding, and N_p stands for primary winding. The designed SMPS is robust, as compared to the other flyback supplies. Excessive tests according to IEC 61000-4-11 standard have been done on this design, which are presented in the paper. The design passed all the tests. Unlike the other flyback supplies, it is having a very wide operating range of (80–300 V AC). This is used in the air conditioner that requires the uninterrupted operation in the harsh operating condition like high voltage sag, sudden surge, etc. The design has smallest size with minimum component count as required in air conditioner to accommodate inside it.

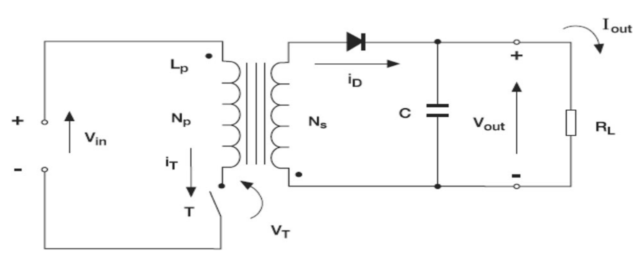

Fig. 1 Flyback converter basic circuit

2. Proposed SMPS Circuit

The proposed SMPS circuit configuration is shown in Fig. 2. This SMPS comprises of a fault protection circuit, EMI line filter, full-wave bridge rectifier, bulk capacitor, transformer, snubber circuit, PWM control IC (with power switch), output LC filter, voltage regulator, feedback optocoupler.

Although standard AC voltage supply in India is 220–230 V @50 Hz but a significant variation in input voltage, ranging from as low as 80 V to as high as 300 V, is generally recorded. This SMPS design is made immune to operate normally in the wide input voltage range of 80–300 V AC. The main function of SMPS is not only to convert AC to DC supply but also to protect the device from any sudden rise in supply voltage or current. In the proposed SMPS, a fuse is used for overload or short-circuit protection. A NTC (Negative Temperature Coefficient) is used for inrush current protection. A metal oxide varistor (MOV) is connected to protect the device from input voltage surge. As soon as the MOV is short, input fuse is blown out to cut off the main supply of the device. A PI filter is integrated in the circuit to protect the device from electromagnetic interference (EMI). EMI filter consists of common mode choke, X-cap and Y-cap. Common mode choke is used to filter the high frequency common mode noise. X-caps are connected between line to neutral to protect against differential mode interference and absorb the high frequency surge element. Y-caps are connected between line to earth and neutral to earth to filter out the common mode noise and provide a path for leakage current from line to earth and neutral to earth. Four IN4007 diodes are used as bridge rectifier for AC to DC conversion. A step-down transformer is used to get a low voltage AC output that will be rectified by the output rectifier diode. Turns ratio is calculated according to the duty ratio allowed and the output voltage requirement. A resistor–capacitor–diode (RCD) snubber circuit is used for protection of MOSFET switch from high voltage spikes generated by leakage inductance of transformer. Diode DA1 clamps the voltage to a safe limit and stores the rest of the leakage energy in clamping capacitor C16 and dissipates this energy into snubber resistor R38.

A PWM control IC BM2P092F of ROHM semiconductor is used for switching. This IC contains a 650 V MOSFET inbuilt with open-circuit protection, short-circuit

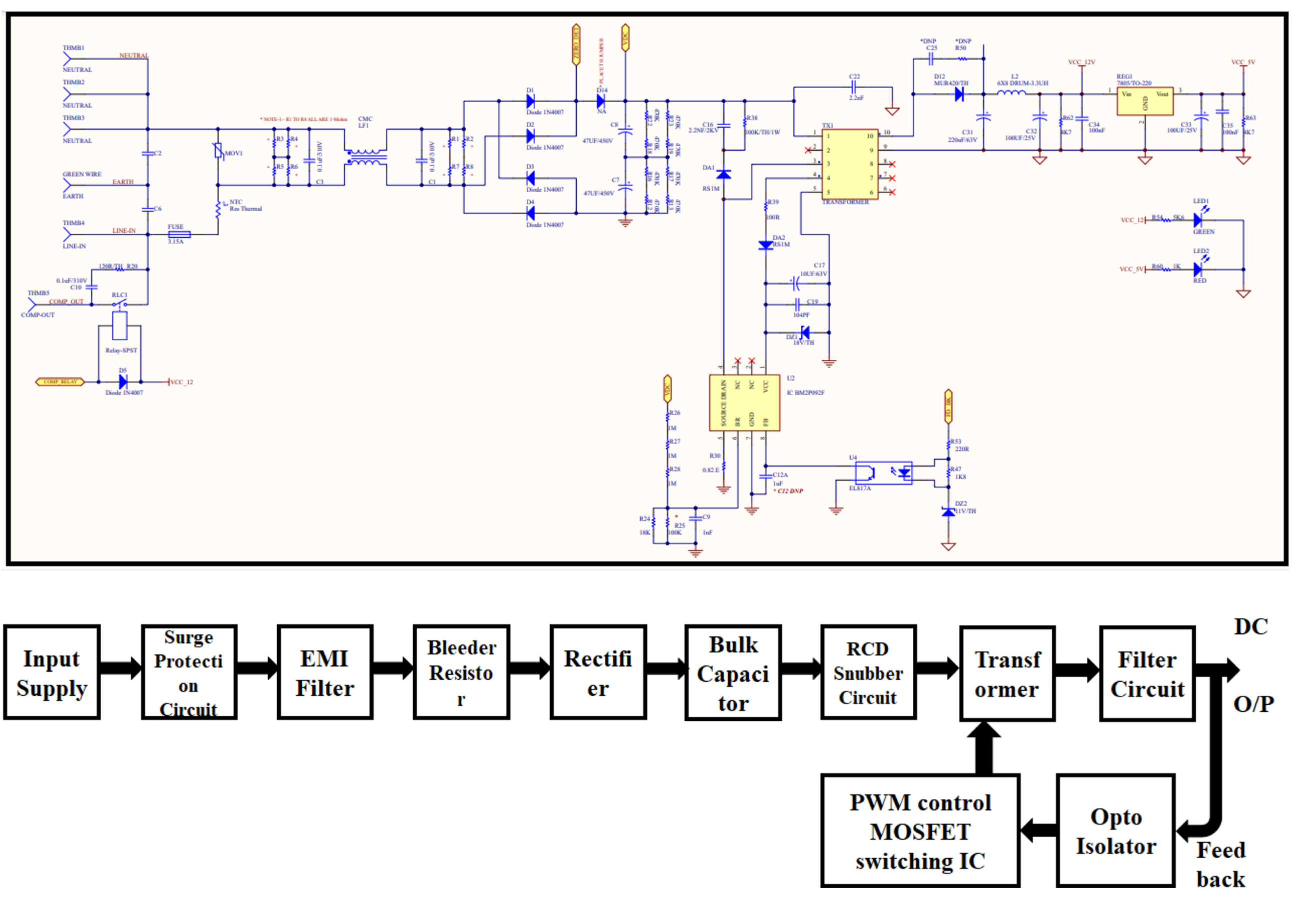

Fig. 2 Proposed SMPS circuit

protection, overload protection, etc. This IC works in current mode PWM control and PWM frequency is 65 kHz. The circuit also has a LC filter in output comprising of 220 µF, 63 V and 100 µF, 25 V capacitors and an inductor L2 to filter the output voltage ripple and current ripple to provide a stable power supply. This LC filter will supply the load when the power switch is on and will charge and support the load when power switch is off. A fixed voltage regulator is connected to give a 5 V fixed DC output voltage. The input range for 7805-voltage regulator is between 7 and 35 V. The regulator gets a 12 V at its input and provides a fixed 5 V DC output voltage. An isolator is required to separate the high voltage AC from the DC output. EL817 is used in the SMPS to isolate the secondary feedback portion with the primary side. The primary side of the transformer relates to the optocoupler IC. However, there is no electrical connection from the output end as the communication is achieved optically. This also further helps in the isolation process.

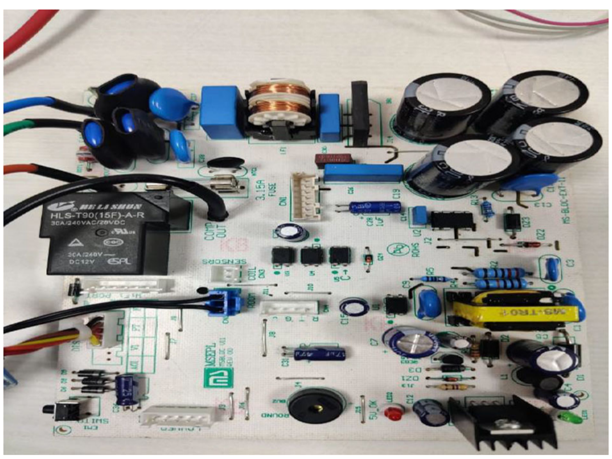

Fig. 3 Photograph of the designed PCB

3. Experimental Results

Testing of the SMPS is done in accordance with the referred standard IEC61000-4-11 [20] in which the device under test (DUT) should be tolerant to voltage dip variation of 0–80% of normal input supply voltage. The designed SMPS PCB as shown in Fig. 3 is subjected to voltage dips of 0%, 40%, 70% and 80% for various time durations generated from programmable AC source, at 28 °C temperature and 60% humidity. Table 1 summarizes the respective performance status of the PCB under test:

Figure 4 illustrates the input voltage graphs for 40%, 70% and 80% voltage dips in supply voltage, as observed on Tektronix DSO (model no. TBS1102B) for various time durations. SMPS under test continued to give a constant uninterrupted output supply thereby validating the absence of any visible effect on its performance when subjected to continuous input voltage changes.

After the successful testing of SMPS under no load condition, it is further examined for full load condition. An air conditioner unit comprising of transmitter, compressor, relay, fan motor and stepper motor is selected. Figure 5 shows the testing set-up along with block diagram of set-up.

Further, the working of on-board transmitter, fan motor, compressor, relay, stepper motor, display panel and constant DC supply of + 5 V, + 12 V, + 15 V of SMPS is observed for 300 cycles in three different phases; each phase carrying 100 varying input AC cycles as illustrated in Fig. 6.

For phase 1, equipment under test was subjected to input variations of 220 V AC for 5 min, then 0 V AC for, the next 5 min, followed by 220 V, 176 V, 220 V and 160 V for 30 s, 5 s, 30 s and 0.2 s, respectively, for a total of 18 h and 28 min duration. Phase 2 lasted for 50 min and 51 s. It started with 220 V AC for first 30 s and tested further for reduced voltage conditions by dropping the input voltage level to 140 V for 0.02 s and swiftly returned to 220 V AC from 154 V AC in 0.5 s. In Phase 3, the equipment's

Table 1 Test results for different variations in input voltage depth

Test instrument		CHROMA programmable AC source (Model 6560)		Ambient temperature		28 °C	Humidity 60%
				Input		230 V AC/50 Hz	
Input voltage dip (%)	Working status (OK/Not OK) duration						Observations
	10 ms	20 ms	50 ms	500 ms	1 s	5 s	
0	OK	OK	OK	OK	OK	OK	PCB restarts
40	OK	OK	OK	OK	OK	OK	PCB working
70	OK	OK	OK	OK	OK	OK	PCB working
80	OK	OK	OK	OK	OK	OK	PCB working

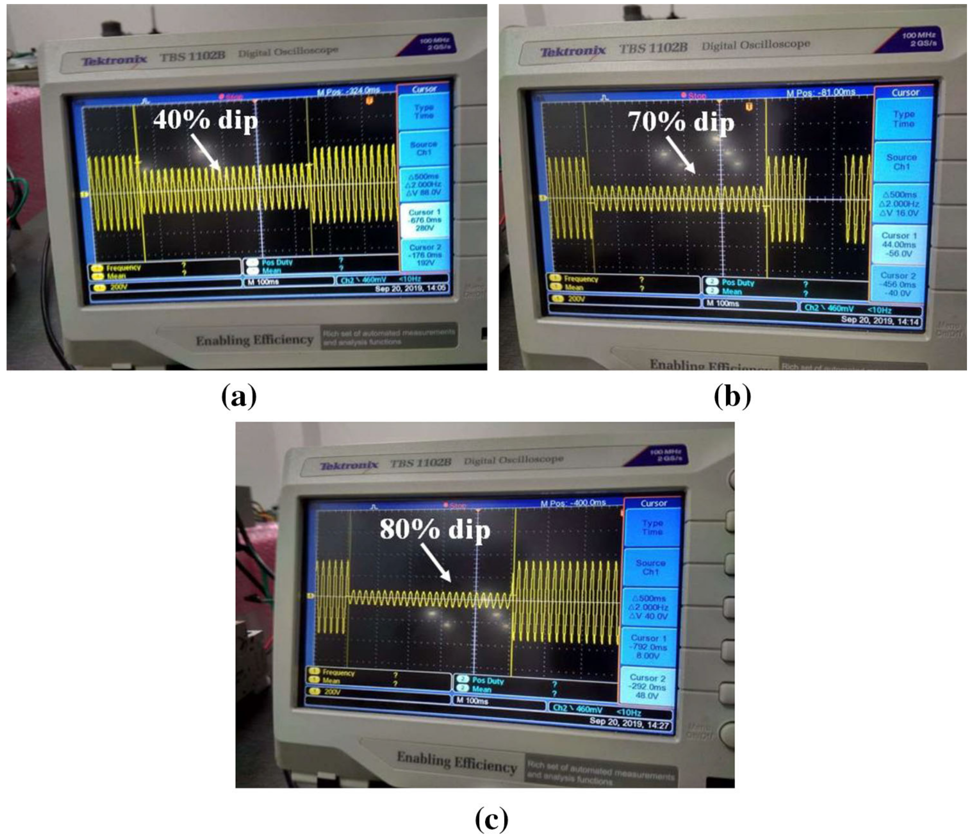

Fig. 4 Input voltage with **a** 40% dip, **b** 70% dip, **c** 80% dip

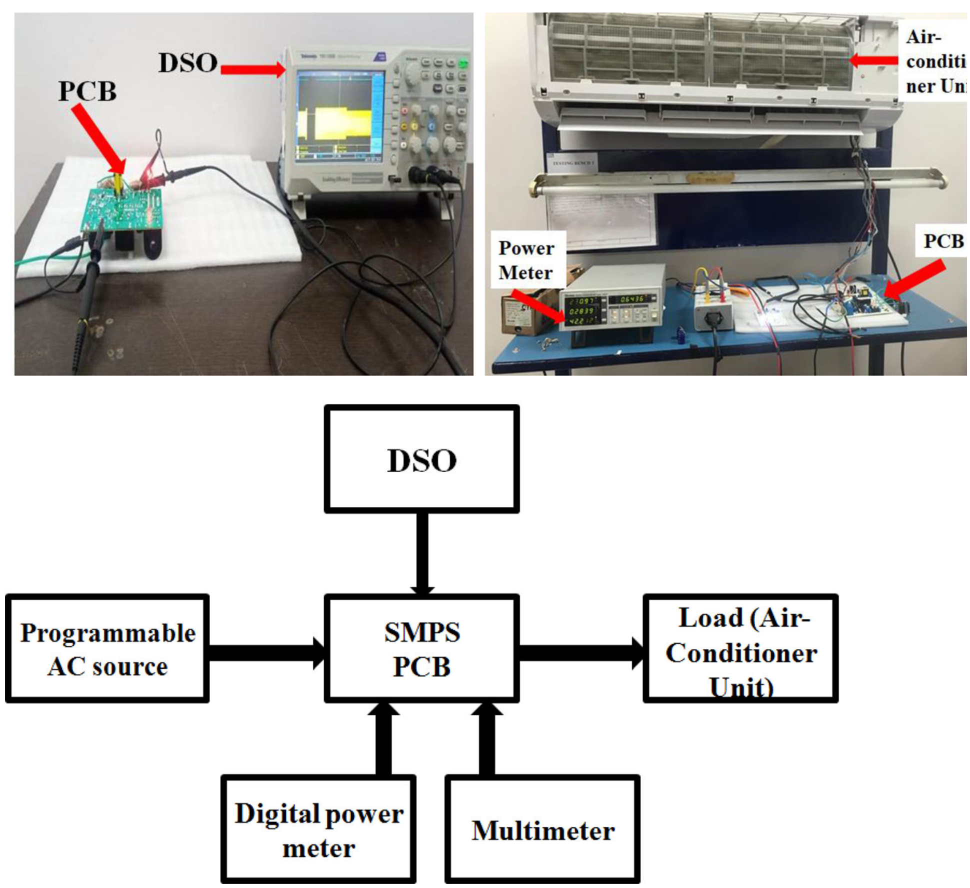

Fig. 5 Test set-up

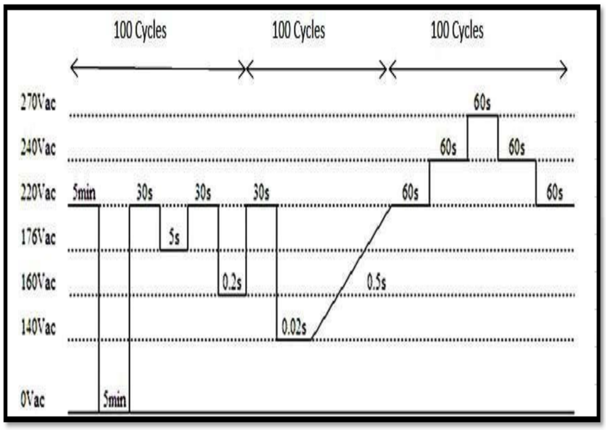

Fig. 6 Input voltage variations curve

performance is tested for various input voltage surges. Initially, 220 V AC is supplied for 60 s followed by 240 V in next 60 s and then at an increased voltage of 270 V for the next 60 s. Finally, the voltage drops to 240 V and 220 V AC in subsequent 60 s intervals. The readings are taken at an interval of 6 h each, and observations of phase 1 are tabulated in Table 2. In ideal condition, transmitter section and stepper motor should work properly irrespective of input voltage variations. The fan motor should continue to run at a constant speed without jerks. The + 5 V, + 12 V and + 15 V output DC voltage should not exceed the tolerance limit of 0.1 V, 0.5 V and 0.1 V, respectively. As evident from the results, all the components continued to operate normally for all the input

Table 2 Summary of observations in Phase 1

Input voltage variation test (Phase 1)					
Input supply	220 V AC for 5 min-0 V AC for 5 min-220 V AC for 30 s-176 V AC for 5 s-220 V for 30 s-160 V AC for 0.2 s				
SMPS output voltage	Readings				
	9:30 am	3:30 am	9:30 pm	3:40 am	Measured average value along with uncertainty at approx. 95% confidence level
+ 5 V DC	5.08 V	5.09 V	5.09 V	5.08 V	5.08 V ± 0.02 V
+ 12 V DC	12.04 V	12.04 V	12.05 V	12.04 V	12.04 V ± 0.02 V
+ 15 V DC	15.06 V	15.06 V	15.07 V	15.06 V	15.06 V ± 0.02 V

Table 3 Summary of observations in Phase 2

Input voltage variation test (Phase 2)					
Input supply	220 V AC for 30 s-0 V AC for 5 min-140 V AC for 0.02 s-154 V AC to 220 V in 0.5 s				
SMPS output voltage	Readings				
	4:00 pm	4:20 pm	4:40 pm	5:00 pm	Measured average value along with uncertainty at approx. 95% confidence level
+ 5 V DC	5.08 V	5.10 V	5.09 V	5.09 V	5.09 V ± 0.02 V
+ 12 V DC	12.04 V	12.03 V	12.05 V	12.05 V	12.04 V ± 0.02 V
+ 15 V DC	15.06 V	15.06 V	15.08 V	15.07 V	15.06 V ± 0.02 V

Table 4 Summary of observations in Phase 3

Input voltage variation test (Phase 3)					
Input supply	220VAC for 60 s then 240VAC for 60 s, then 270VAC for 60 s. Total cycles = 100				
SMPS output voltage	Readings				
	12:00 pm	2.30 pm	5.30 pm	8:00 pm	Measured average value along with uncertainty at approx. 95% confidence level
+ 5 V DC	5.08 V	5.09 V	5.09 V	5.08 V	5.08 V ± 0.02 V
+ 12 V DC	12.04 V	12.04 V	12.05 V	12.04 V	12.04 V ± 0.02
+ 15 V DC	15.06 V	15.06 V	15.07 V	15.06 V	15.06 V ± 0.02

Table 5 Type A uncertainty (repeatability) evaluation for SMPS output voltages of 5 V, 12 V and 15 V

No. of readings of SMPS output voltage	SMPS output voltage 5 V reading measured through DMM (V)	SMPS output voltage 12 V reading measured through DMM (V)	SMPS output voltage 15 V reading measured through DMM (V)	Remarks
(a) Input voltage variation to Phase-1				Maximum type A uncertainty in SMPS output voltages of 5 V, 12 V and 15 V in input voltage variations for all the three phases is 0.0048 V
R1	5.08	12.04	15.06	
R2	5.09	12.04	15.06	
R3	5.09	12.05	15.07	
R4	5.08	12.04	15.06	
Average value	5.085	12.043	15.063	
Standard deviation	0.005774	0.005	0.005	
Type A uncertainty	0.0029	0.0025	0.0025	
(b) Input voltage variation to Phase-2				
R1	5.08	12.04	15.06	
R2	5.10	12.03	15.06	
R3	5.09	12.05	15.08	
R4	5.09	12.05	15.07	
Average value	5.090	12.043	15.068	
Standard deviation	0.008165	0.009574	0.009574	
Type A uncertainty	0.0041	0.0048	0.0048	
(c) Input voltage variation to Phase-3				
R1	5.08	12.04	15.06	
R2	5.09	12.04	15.06	
R3	5.09	12.05	15.07	
R4	5.08	12.04	15.06	
Average value	5.085	12.043	15.063	
Standard deviation	0.005774	0.005	0.005	
Type A uncertainty (repeatability)	0.0029	0.0025	0.0025	

voltage variations. Maximum DC voltage of + 5.09 V, + 12.05 V and + 15.07 V is measured which falls within the permissible tolerance range.

In any experimental work, uncertainty budget plays a very important role as various sources of uncertainties are involved in the measurement. The uncertainty budget estimates the quality of work and level of confidence with which the results are taken. Type A and Type B method of uncertainty evaluation is used in uncertainty analysis [21, 22].

For phase 2, the readings are taken at an interval of 20 min each, and observations are tabulated in Table 3. All the components continued to operate normally for all the input voltage variations for phase 2 also. Maximum DC voltage continues to remain in tolerance limits reaching maximum up to + 5.10 V, + 12.05 V and + 15.08 V, respectively. In phase 3, reliable working of the components for high input voltage is tested and verified. Results are summarized in Table 4. The repeatability in measurement (Type A uncertainty) evaluation and uncertainty budget for SMPS output voltage of 5 V, 12 V and 15 V is given in Tables 5 and 6, respectively. The multimeter used is Fluke model 101, 3½ digit digital multimeter.

From Table 6, we conclude that maximum expanded uncertainty is ± 0.02 V for approx. 95% confidence level. The uncertainty budget is applicable to all 3-phases.

Effect due to temperature and humidity, etc., is ignored as the uncertainty contribution is negligible.

Table 6 Uncertainty budget in SMPS output voltages of 5 V, 12 V and 15 V

Source of uncertainty X_i	Estimates x_i	Limits $\pm \Delta x$	Probability Distribution (Type A or B)	Standard uncertainty $u(x_i)$ ($\pm$)	Sensitivity Coefficient c_i	Standard Uncertainty $u_i(y) = c_i\ u(x_i)$ ($\pm$)	Degree of Freedom ν_i
Digital multimeter (calibration certificate)	5 V, 12 V and 15 V	0.008 V	Normal Type B	0.008 V	1	0.004 V	∞
Digital multimeter (maximum error)	5 V, 12 V and 15 V	0.01 V	Rectangular Type B	0.0058 V	1	0.0058 V	∞
Digital multimeter(resolution)	0.01 V	0.005 V	Rectangular Type B	0.0029 V	1	0.0029 V	∞
Repeatability maximum value	5 V, 12 V and 15 V	0.0048 V	Normal Type A	0.0048 V	1	0.0048 V	3
Combined uncertainty u_c						0.0091 V	37
Expanded uncertainty U (at $k = 2.07$ for $\nu_{\text{eff}} = 37$, approx. 95% confidence level)						0.02 V	37

Table 7 Comparison of this SMPS with other similar devices

Refs	Device under test (DUT)	Standard used	Working status of DUT			
			Voltage dip			
			0%	40%	70%	80%
[4]	PC	ITI Curves	Working till 100 ms	Working till 100 ms	Not working	Not working
[23]	Calorimeter	EN-61000-4-11/IEC-1000-4-11	Working OK	Gain reduced	Data not available	Data not available
[2]	SMPS of PC	IEC 61000-4-11	Working till 40 ms	Working till 40 ms	Working till 40 ms	Working till 40 ms
[24]	CIAA (industrial controller)	IEC 61000-4-11	Working till 10 ms	Working till 10 ms	Working till 10 ms	Working till 10 ms
[25]	PC	ITIC and SEMI F47	Working till 200 ms	Working till 200 ms	Working till 200 ms	Working till 200 ms
Proposed	SMPS of air conditioner	IEC 61000-4-11	Working OK	Working OK	Working OK	Working OK

Table 7 gives the comparative summary of this work with other similar works.

The measured power factor (using digital power meter), efficiency of the proposed flyback converters SMPS and effect of input frequency variation on output voltage are presented in Fig. 7a–c. SMPS is tested for different load conditions ranging from 1 to 8 W. As evident from Fig. 7d, a negligible variation in SMPS output voltage is recorded for various loads. An excellent power factor of more than 0.9 is achieved with high efficiency of more than 90% for wide range supply voltage variation.

4. Conclusion

In this paper, the designing as well as testing of a flyback converter-based SMPS is demonstrated. Functional verification of the PCB of designed circuit is conducted in accordance with IEC 61000-4-11 standard on an air conditioner unit. The desired output voltage of 5 V, 12 V and 15 V is measured for various input voltage dips and surges. All the used instruments are well calibrated before use. The efficiency of the proposed circuit is high (more than 90%) with a very good power factor of 0.9. The output voltage of the SMPS is within permissible limits as described in IEC 61000-4-11 standard. The maximum expanded uncertainty

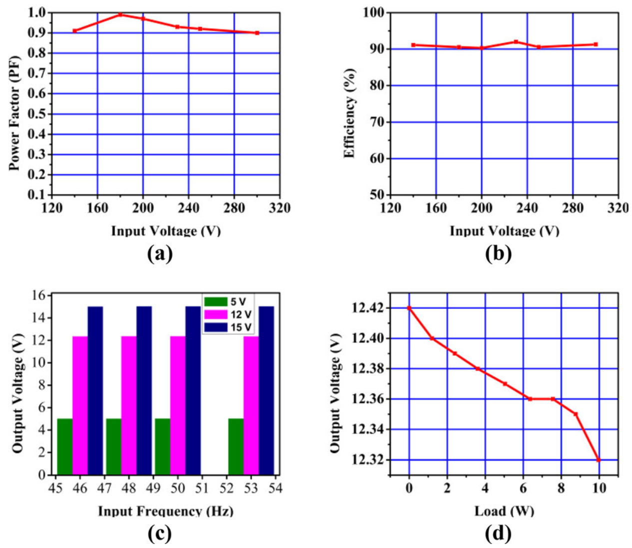

Fig. 7 **a** Power factor versus input voltage **b** efficiency versus input voltage, **c** input frequency versus output voltage, **d** output voltage versus load

in SMPS output voltage is found to be ± 0.02 V at $k = 2.07$ for approx. 95% confidence level. The performance of the circuit can be further evaluated for other topologies like single-ended primary inductor converter (SEPIC), Cuk, Zeta converters.

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