International Journal of Recent Technology and Engineering (IJRTE)
ISSN: 2277-3878 (Online), Volume-8 Issue-2, July 2019

Cost Effective Power Quality Improvement Technique by Utilization of Solar Power for Non-Linear Loads

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Abstract*: *Nowadays usage of digital gadgets and other low power devices has increased exponentially, which has power converters to convert from utility AC voltage to required level of DC voltage. These power converters (Adopters), which are considered as Non-linear loads, in turn induces harmonics on the supply side. Due to these induced harmonics, power quality of the utility supply will be degraded affecting the performance of other linear loads connected to the same supply. This paper discusses the effects of non-linear loads and corrective actions available in the literature. An effort has been made to analyze the performance of some domestic non-linear loads using MATLAB/SIMULINK software and verify the same by experimental setup. The Total Harmonic Distortion is analysed using FFT window and simulation and experimental results were compared. Then, a solar powered DC supply is proposed which can power all digital gadgets and other low power devices. As DC supply is generated from the solar power, the connection of non-linear loads to utility supply is reduced, thereby improving the power quality of the distribution side. Adoption of the proposed DC supply for low power digital gadgets, both in rural and urban areas will definitely make the domestic power consumers to be independent of depleting conventional grid power supply at low cost.

***Index Terms*: *Non-linear loads, Total Harmonic Distortion, Power Quality,* SMPS**

I. INTRODUCTION

Recent days there are various types of household appliances such as laptop charger, personal computer, LED TV and bulbs, CFL lamps, water purifier, Refrigerators etc., which requires low voltage DC supply. The number of low power electrical appliances used in households has grown rapidly over the years [1]. All these types of non-linear loads introduce harmonics into the supply system. Earlier days, harmonics produced by grid connected domestic loads are ignored because of very low disturbances. But nowadays these loads are becoming advanced and increasing in number from the past few years. Remarkable number of such non-linear loads and large number of households will have a negative influence causing, dips, distortion and harmonics in electricity network [1]. Also, power electronic devices such as Laptop Charger, Cellphone charger, Adopter for water purifier, LED bulbs etc., have become abundant today because of their precise process control. Power quality has become a major concern to both electric utility and customers. The objective of electric utility is to supply its customers with a sinusoidal voltage with a fairly constant magnitude and frequency. But the rapid increase in the power electronic devices, such as diode, MOSFETS etc., made industrial loads non-linear. The non-linear loads connected to power system distribution side generate harmonic voltage and current. These non-sinusoidal current when it interacts with impedance of distribution system voltage distortion is created, that can affect both the equipment present on the distribution side and load connected to it. In the distribution side both the linear and non-linear load customers are connected at PCC (Point of Common Coupling). As the system impedance is connected to PCC, harmonic voltage distortion occurs due to the propagation of current harmonics. This also affects the linear load customers connected at PCC. The effects of non-linear loads ranging from adjustable speed drives to household appliances such as TV set on the utility voltage and current harmonics are analyzed in [2]. Some of the commonly used loads are modelled in PSCAD/EMTDC and analyzed for the total harmonic distortion. To overcome the effects of harmonics induced from the non-linear loads and to improve the power factor, the capacitor banks are used. Due to ever increasing residential loads, the effects caused by harmonics have become more significant. In [3], author explains about the simulation analysis of some of the nonlinear loads. The lower order harmonics due to current and voltage are analyzed for each of these non-linear loads. Also discussed the current type and voltage type harmonic producing source. For the mitigation of current harmonics, shunt passive filters are suggested. In [4], harmonic analysis of different non-linear loads present in the IT Park has been studied and they are simulated using MATLAB/Simulink. To mitigate the effects harmonics, a single tuned harmonic filter is used. In [5], some of the single phase and three phase non-linear loads are modeled using MATLAB /Simulink. The THD’s with and without UPQC for these non-linear loads are analyzed and compared.

Revised Manuscript Received on 30 July 2019.

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The analysis shows that, THD due to voltage and current are reduced by using UPQC. In [1] the harmonics and its adverse effects are explained. To overcome the effects of harmonics, filters such as active, passive filters are discussed.

This paper presents performance analysis of some of nonlinear loads used in domestic applications. The non-linear loads such as SMPS, which is used in almost all digital gadgets is modeled in MATLAB/Simulink to analyze the performance. %THD induced on input supply current due to SMPS is measured by FFT spectrum. The output voltage and current ripple are also measured on DC output side. The same SMPS model is then replaced by a DC supply fed with solar panel instead of AC supply and the output parameters are measured and compared. %THD obtained by Simulation results were verified by experimental setup of SMPS. To overcome the harmonic injection on AC supply side, an alternate solution is proposed, which uses solar power fed DC supply. This avoids the power conversion process from AC to DC and avoiding the non-linear load connection to AC supply. The choice of solar power converters is added advantage as renewable energy resource is used instead of depleting conventional energy resources. And also, the cost of proposed system is very nominal and affordable by both rural and urban people. In the following section, Section-II discusses about the effects of non-linear loads, Section-III about simulation analysis of Non-linear loads, Section-IV about Hardware implementation, section-V proposed method and section –VI conclusion.

II. EFFECTS OF NON-LINEAR LOADS

A. *Linear Load and Non-linear load*

For linear load applied voltage is directly proportional to current & its impedance is maintained constant along the whole alternating period. If load is considered as non-linear its impedance changes with the applied voltage [5]. The current drawn by the non-linear load will not be sinusoidal due to the changing impedance even when it is connected to a sinusoidal voltage as shown in Fig. 1.In previous years, non-linear loads were basically found in heavy industrial applications such as large variable frequency drives (VFD), arc furnaces, heavy rectifiers for electrolytic refining, etc. Nowadays utilization of domestic non-linear loads such as CFL, printers, laptop and mobile chargers have increased in large scale.

B. *Harmonics*

Day by day, harmonic distortion problems are common in both industrial applications and domestic applications as well. This is primarily due to new power conversion technologies, such as the Switch-mode Power Supply (SMPS). In most of the power electronic devices Switched Mode Power Supply (SMPS) are used and act as non-linear loads. Their increase in demand has made them a substantial portion of the total load in most of the commercial building. In the power electronic devices, the deviation of the voltage & current waveform from sinusoidal is described in the terms of waveform distortion, often expressed as harmonic distortion. Harmonic distortion is caused by nonlinear devices in power system where driven frequency is the power system fundamental component. Harmonics are electric voltage & current or electric power system that can cause power quality problems. Because equipment & machinery can be malfunctioning or fail in the pressure of high harmonics voltage and current level.

Harmonics are created by power electronic devices which are non-linear loads which draws the current abruptly of short

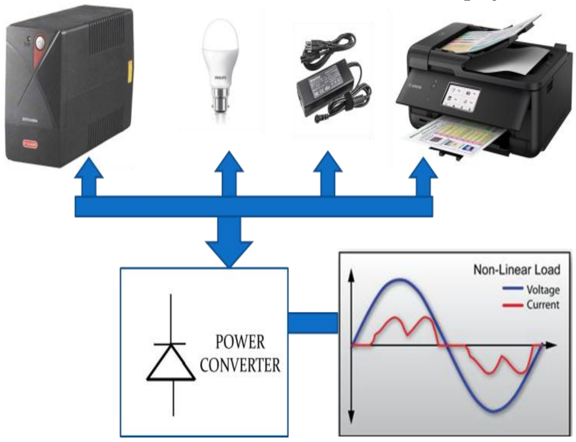

Fig. 1. Voltage and Current waveforms of Non-linear loads

pulses. The fundamental and harmonic component of non-linear load are shown in Fig. 2 [1]. The short pulses lead to distorted current waveforms, which results in harmonic currents to flow back into other parts of the power system. Harmonics are of higher percentage when there are many non-linear loads such as computer, laser printer, fax machine copies, florescent lighting, Uninterrupted Power Supply (UPS) etc., are connected to same utility supply. Due to these harmonics, the power quality level degrades which decreases the efficiency of all loads connected to same building. .

C. *Effects of Harmonics*

The ability of the power system to perform at optimal level is compromised when harmonics enters the system. Due to which the equipment operates inefficiently and increases the need for power consumption. This increases the overall current which results in increased cost and decreases the profitability. The following are the adverse effects caused due to harmonics [1].

1) Power factor

Harmonics increase the Distortion Power (D) i.e., it increases the apparent power (S) required by the system, while the “effective” real power at the fundamental frequency f1 (P1) does not benefit from that. This means higher current needs to be drawn from the point of common coupling, causing addition of wire section and higher protection rating.

2) Skin effect

It is the magnetic property of confining alternating current towards the outer area of conductor, and the frequency of that AC current is higher. This “effective” reduced area (compared to real cross-sectional area of the conductor), means higher resistive losses are directly proportional to frequency.

3) Conductor losses

The magnetic field generates eddy current that causes harmonic current to flow in the conductor.

This in turn modifies the current distribution displacing it towards the periphery.

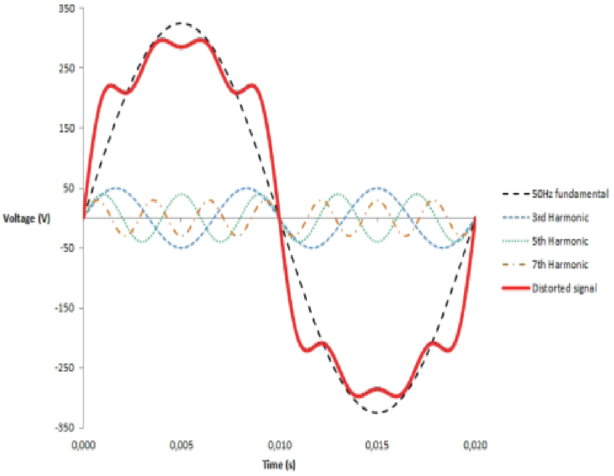

Fig. 2. Fundamental and Harmonic component of non-linear loads

4) Motors and Generators

Apart from being a possible cause of harmonics, generators can be affected by harmonic sources resulting in efficiency losses, overheat and derating. In case of generators the presence of high impedance, transfers the current harmonic distortion easily into voltage harmonic distortion. In other words, they affect the other loads supplied from that source. Generally, the effects of harmonics on both motors and generators are the same core losses increase with harmonics, copper losses are proportional to both I_{rms}^2R and frequency (skin effect), negative sequence harmonics (force against torque action) cause motor vibration, added heat etc.

5) Transformers

The effects of core losses and copper losses (windings) discussed for motors above are applicable for the case of transformers. Also, triplen harmonics in the neutral conductor of a Delta-Wye distribution transformer can dangerously over heat them. There is also a potential risk of resonance between transformer inductance and supplied capacitive loads, at the harmonic frequencies. Laminated transformer core also vibrate at certain harmonic frequencies causing audible noise and overheat the transformer winding this can also be affected by proximity effect like if two conductors carrying alternating current in same direction the magnetic flux is created in the area where both conductors are close to each other causing current distribution to the more distinct area of these two conductor due to which area between these two conductors are reduced. This is similar to skin effect.

6) Circuit breakers and fuses

Since thermal-magnetic tripping mechanism in circuit breakers responds proportionally to rms current, a highly distorted current signal can cause unwanted MCB's tripping, or need to oversize them. Similarly, for fuses, the higher the rms current, the higher the heating effect of that current in fuse, so the faster the fuse will act. In case of non-linear loads fuse may be derated.

D. *Corrective Actions*

The following are the corrective actions taken for reduction of harmonics [1]:

1) Transformers

Transformers by themselves, can have the ability to cancel certain load harmonics. Here, certain harmonics are made to circulate upstream in the installation instead of eliminating them.

2) Reactors (AC line, or DC link)

Harmonics distortion due to non-linear loads can be reduced by placing series inductors (reactor), either to the AC line, to the DC link circuit, or both, at non-linear load side the filtering action of harmonic current and decoupling of voltage distortion is taken care. Either of these added elements can also limit current peaks.

3) Passive Harmonic Filter

Passive Harmonic filter composed of inductor and capacitor sometimes damping resistors used to cancel or a certain trap a certain harmonic filter usually of lower order (5^{th}, 7^{th}, 11^{th}...). A Harmonic Passive Filter is added (inductors Ls, capacitors C_S), to minimize the current distortion at the point of common coupling. Such effect is obtained by tuning the resonance frequency of L_S-C_S at that 5^{th} harmonic. If other harmonic frequencies were needed to cancel in a same installation, additional passive filters (L-C) would need to be added.

7) Active Harmonic Filter

Active harmonic filters are power electronic equipment to cancel current harmonic pollution of an installation. The working principle consist of the current harmonics of the load and these active filters generate the same harmonics in the phase opposition so that addition of both current harmonics gets cancelled out and the only frequency left out is the fundamental frequency. This yields to THD reduction, at levels typically below 5%. They have the capacity to reduce the power factor nearly one. Due to its design and working principle, the distortion minimization is achieved for all load levels, and they are not affected by neither resonances nor line impedances.

Majority of the above discussed methods of reduction of %THD are applicable for high voltage transmission and distribution side. From the literature, least effort is observed on demand side, to overcome the effects of non-linear loads. In this paper, a solar power fed DC supply is proposed to overcome the effects of non-linear loads, which is totally concentrated on the demand side management.

III. SIMULATION ANALYSIS OF NON-LINEAR LOADS

The performance analysis is carried out for few non-linear loads to obtain the %THD, induced by these non-linear loads towards the supply side using MATLAB/Simulink. The %THD induced by non-linear loads is also evaluated by experimental set-up. The modeling of Switched-Mode Power Supply (SMPS) using MATLAB/Simulink and its experimental analysis are discussed below.

A. *Simulink Model of SMPS*

An SMPS are used in many digital appliances to convert unregulated DC input into a required level of controlled DC output voltage. The circuit comprises of switching devices such as MOSFETs or IGBTs and energy storage devices such as inductors and capacitors.

The Fig. 3 shows Simulink model of Switched Mode Power Supply (SMPS) where AC supply is been rectified and given to DC-DC buck converter, later the feedback path is given such that constant supply is maintained towards the output side [4]. The transformer is fed with 230 V, 50 Hz AC supply which is stepped down to 36V. The values of inductance and capacitance used here are 5.5mH and 56mF, 15µF. The resistive load of 50Ω is connected. The output of the BUCK converter in SMPS is set to 24V, which is controlled by closed loop PI controller. Hence, the output of the SMPS is maintained at constant DC voltage of 24V. The Fig. 4 shows the current waveform on the supply side of the SMPS. The total harmonic distortion due to current is analyzed using FFT spectrum of MATLAB/SIMULINK. The %THD is equal to 118.07% as shown in Fig. 5. Output waveforms of voltage and current respectively are as shown in Fig. 6 and Fig. 7. The ripple content in output voltage and current are in Fig. 8. The ripple voltage is 20mV and current ripple is 0.4 mA.

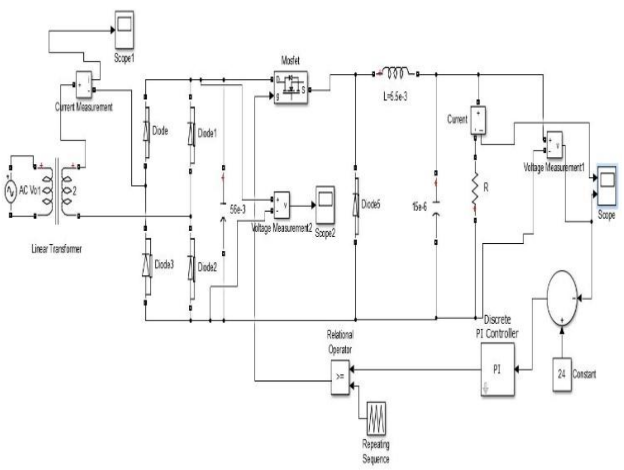

Fig. 3. Simulink model of SMPS

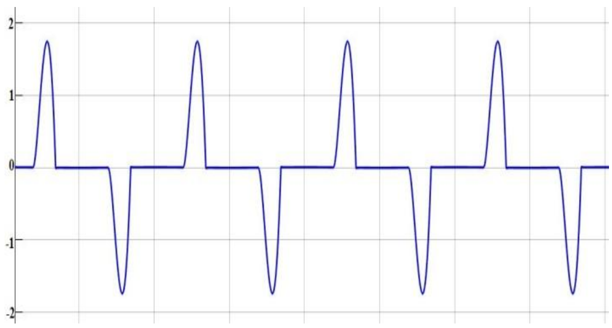

Fig. 4. Current waveform on supply side for SMPS

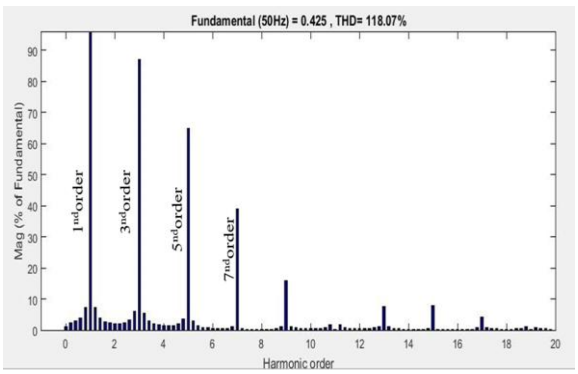

Fig. 5. FFT Spectrum of input current for SMPS

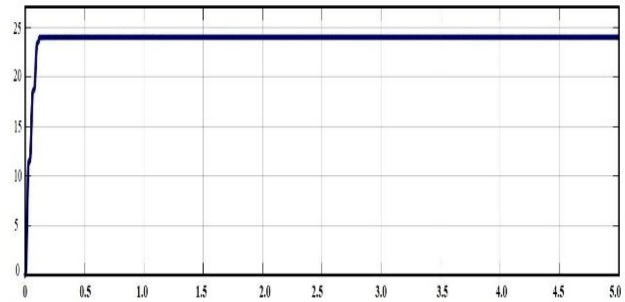

Fig. 6. Output waveform of voltage for SMPS

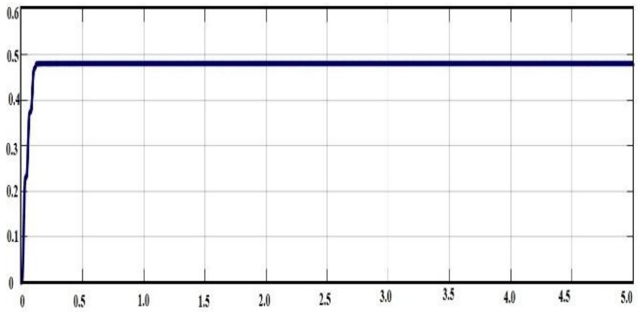

Fig. 7. Output waveform of current for SMPS

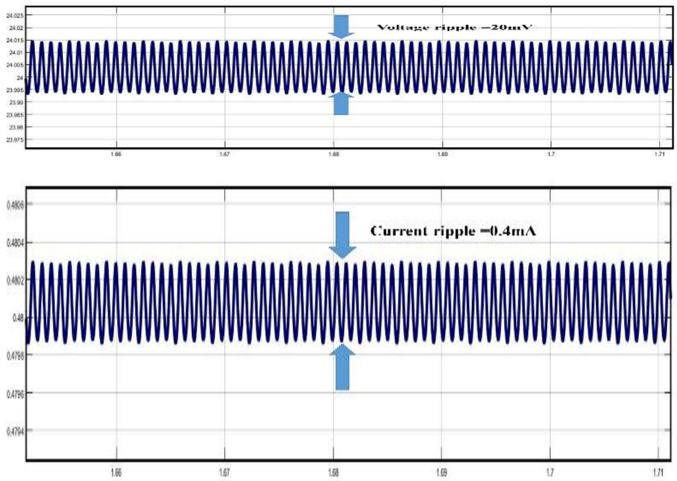

Fig. 8. Ripple content in the output voltage and current

B. *SMPS Fed With Solar Powered DC Supply*

The sinusoidal AC supply to the SMPS is replaced by DC supply using photovoltaic arrays. Fig. 9 shows the Simulink model of the SMPS fed with solar powered DC supply. The performance of the SMPS remains unchanged at the output side and the same is shown in Fig. 10 and Fig. 11. The output voltage and current waveforms are similar to Fig. 6 and Fig. 7. Even the output voltage and current magnitude and ripple values are maintained same as shown in Fig. 12. It can be noticed that, the frequency of the ripple voltage and current has reduced compared to SMPS fed with AC supply.

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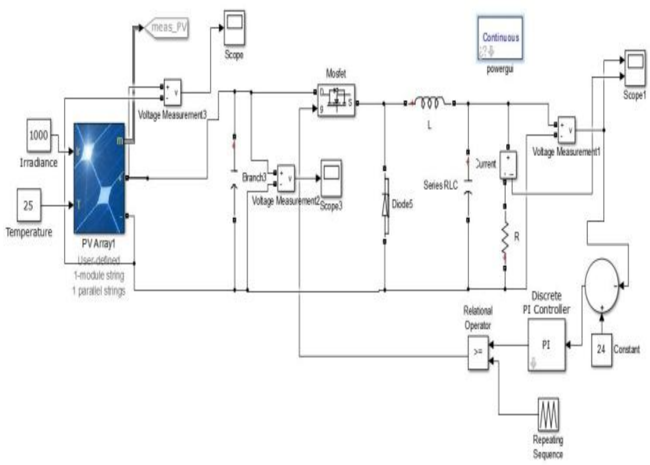

Fig. 9. Simulink model of SMPS fed with DC Supply

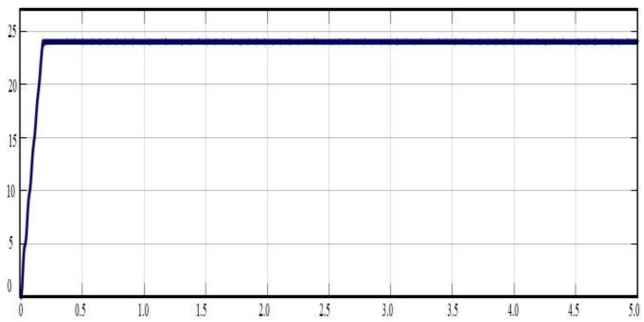

Fig. 10. Output waveform of voltage

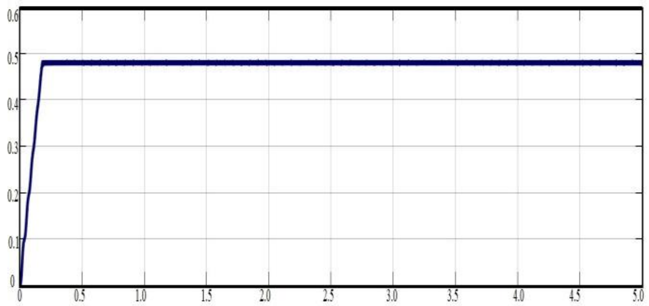

Fig. 11. Output waveform of current

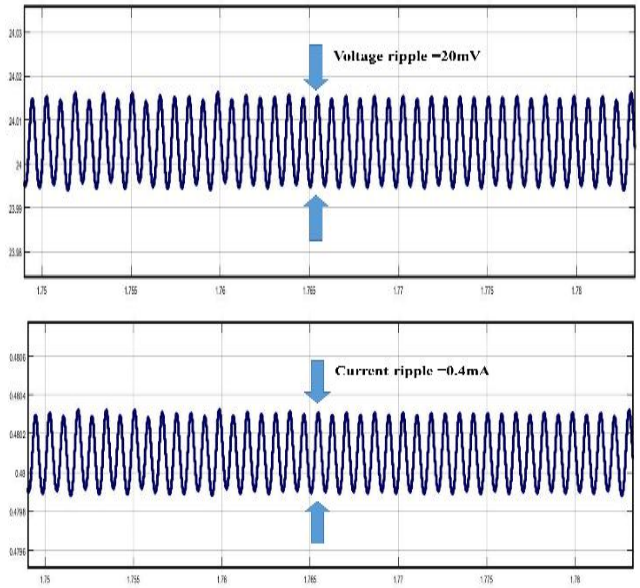

Fig. 12. Ripple content in output voltage and current

Table I shows the comparison of performance of SMPS with AC and DC supply. When an AC supply voltage of 230/36V is applied, the %THD of current induced on supply side is 118.56%. Output voltage and current required for the load is 24V, which is having ripple content of 20mV and 0.4mA. When AC supply is replaced with solar panel, it delivers same output voltage of 24V with 20mV voltage ripple and 0.4mA of current ripple. Hence, the performance of converter remains same even after replacing AC source by solar powered DC source. From the simulation it can be concluded that, the replacement of input supply for SMPS is not affecting the output voltage and current parameters. At the same time, injection of the harmonics to the grid AC supply is totally eliminated, as these non-linear load (SMPS) is not connected to the AC supply.

TABLE I
Comparison results of SMPS load with AC and DC supply

Parameters	With AC-DC	With DC-DC
Input Voltage	35 V	37 V
%THD	118.56	No harmonics
Output Voltage	24V	24V
Ripple Voltage	20mV	20mV
Output Current	0.48A	0.48A
Ripple Current	0.4mA	0.4mA

IV. HARMONIC ANALYSIS USING HARDWARE

The harmonic analysis was verified in laboratory of MOOG INDIA TECHNOLOGY CENTRE, Electronic city Phase-I, Bengaluru.

A. *Hardware Setup to Measure the THD from SMPS Load*

The input AC source is connected to the Switched Mode Power Supply (SMPS). The Fig. 13 shows the experimental setup of connecting non-linear load that is SMPS to the AC supply to measure % THD. A load of 50Ω is connected through the SMPS and the harmonics induced towards supply side is observed using digital storage oscilloscope (DSO). The Fig. 14 and Fig. 15 shows the waveform of current distortion towards the supply side and the FFT spectrum of input current. The current distortion waveform obtained from DSO is stored and analyzed using MATLAB/Simulink software. The %THD obtained from the hardware analysis is 118. 52%. The total harmonic current distortion obtained from simulation analysis is compared with the experimental results. The total harmonic distortion from the simulation analysis is 118.07% and is approximately equal to the experimental analysis. The results obtained from the harmonic analysis are tabulated in Table. II and it shows that, the total harmonic distortion from simulation and experimental evaluation are approximately the same. Hence, it is clear that whenever the power electronic devices are connected to AC supply, they induce harmonics on the supply side. These induced harmonics, in turn affects the performances of the other loads which are connected to PCC.

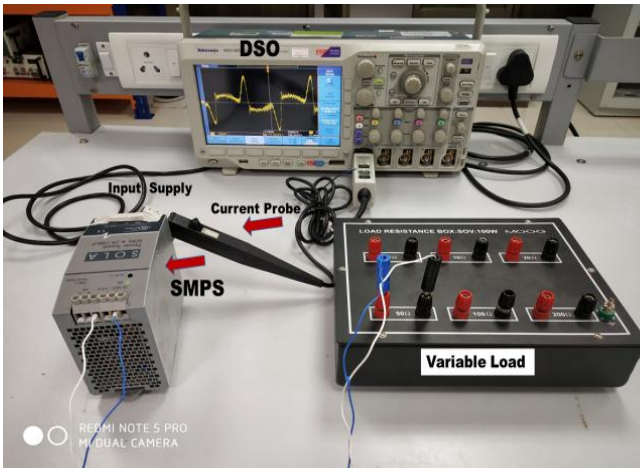

Fig. 13. Experimental setup to measure supply current of SMPS

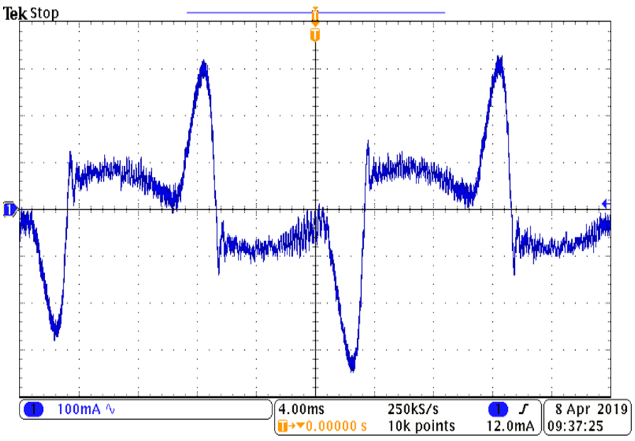

Fig 14. Current waveform on the supply side

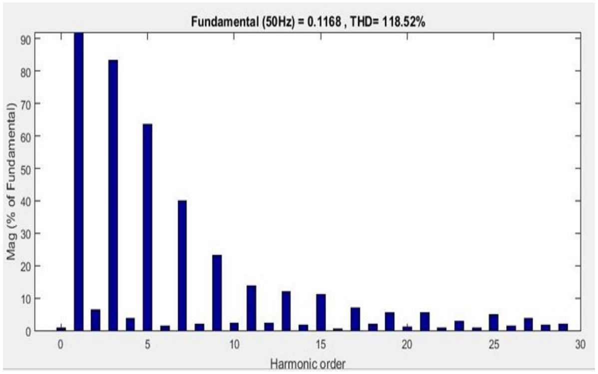

Fig. 15. FFT Spectrum of input current for SMPS load

Table II

Comparison of Simulation and Experimental Analysis

Parameters	Simulation Analysis	Experimental Analysis
Input Voltage	35V	35V
% THD	118.07	118.52
3rd order	87.26%	84.36%
5th order	65.26%	61.67%
7th order	39.96%	39.01%
9th order	16.56%	23.66%

V. PROPOSED METHOD FOR POWER QUALITY IMPROVEMENT

To overcome the problem discussed in the previous section, a solar powered DC supply is used to feed the nonlinear loads. A solar panel of suitable rating is selected which generates DC power. The generated DC power is connected to battery through a charge controller, which gives constant voltage to charge battery. The hardware description of solar panel, charge controller and battery rating details are tabulated in Table III. Various domestic non-linear loads, such as cell phone charger, laptop charger and LED bulb, which requires DC supply are connected as shown in Fig. 16. As DC supply is given to loads from solar panel through charge controller, adopter is removed from the respective chargers. Considering cell phone as example, the charging time taken for each source is tabulated and compared. From Table IV it is clear that, the charging time of the cell phone battery remains same for both AC and DC supply. Hence, this paper proposes the solar fed DC source to power for all the low voltage domestic appliances like cell phone chargers, laptop chargers, printers, water purifiers, LED and LCD lights and any other low power digital gadgets. The cost for the same depends on the wattage of devices and duration of usage of the devices. The sample calculation for selection of battery rating is shown below in equation (1) and (2). Hence, the proposed scheme is suitable for both urban and rural areas, by which the connection of non-linear loads to utility supply is completely avoided to overcome the problems of harmonics.

Table III

Hardware Details

Components	Hardware Description	
Solar Panel	Make	Souratech Solar Pvt Ltd
	Model	12V, 74W
	Type	Polycrystalline
Solar Charge Controller	Product Name	12/24V 10 A LCD USB Solar Regulator Charge Controller
	Product Model	CMT-A2410
	Current	10A, 20A, 30A
Lead Acid Battery	Manufacture	Renaissa Corp Limited
	Nominal Voltage	12 V

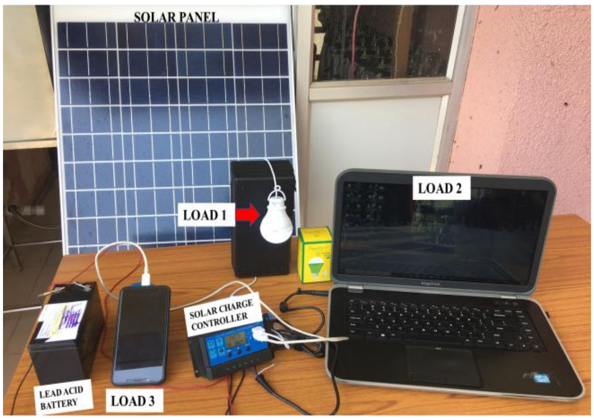

Fig. 16. Hardware setup of proposed scheme

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DOI: 10.35940/ijrte.B1816.078219
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TABLE IV
Comparison between charging time

Time Taken for Charging iPhone6S cell phone	
Using Adapter	Using Solar fed DC supply
1 hour	1 hour

A. *Calculation of Total Ampere Hours for BATTERY*

The following sample calculation shows the selection of battery rating for certain rated loads [7] – [8]. Considering two LED bulbs of 5W- glowing for 4 hours, two 10W mobile phone charger- charging for 2 hours and a laptop charger of 65W used for 3 hours.

Total appliances used = (2×5W×4hrs) + (1×5W×2hrs)
+ (65W×3hrs) = 245W hours (1)

For a Nominal Battery Voltage =24V,
Efficiency of Battery=0.85, Depth of discharge=0.6 and
Days of autonomy=1 Days,
Battery capacity can be calculated as follows:
Battery Capacity =
245WHrs×1days)/ (0.85×0.6×24) (2)
Total Ampere-hours required is = 20Ah

The method proposed in this paper is effective for the improvement of power quality. In other words, the harmonics is mitigated through the utilization of solar powered DC supply. In other words, the cost is reduced by avoiding the power converter circuits. Also, the method proposed in this paper employs hardware components that are cost affordable (Table V). If this scheme is adopted in each house in urban areas then, most of the problems from non-linear loads are mitigated. The power quality of the grid supply will also improve without any compensation. In rural areas, where getting continuous grid supply is nightmare, this scheme gives cost effective solution to overcome the power outage problems. Moreover, the depletion in the conventional energy is making everyone to opt renewable energy resources, among which solar power is the easiest and cheapest resource. Hence, proposed scheme is very well suited for power quality improvement of grid supply and also usage of low cost renewable energy resource.

Table V
Cost Analysis

Sl. No.	Component Used	Cost (Rs)	Total cost (Rs)
1.	Solar Panel (Polycrystalline)	3000/-	4,450/-~ 4,650/-
2.	Solar Charge Controller	600/- ~ 800/-	
3.	Lead Acid Battery	850/-	

VI. CONCLUSION

This paper discusses the effects of non-linear loads used in everyday life in domestic applications. Simulation and experimental results show that the %THD induced by non-linear loads on supply side will definitely damage the life of other linear loads connected to the same connection. To overcome the above problem, this paper proposes the replacement of adopters in domestic non-linear loads by direct feeding of DC voltage generated by solar power. The elimination of %THD from non-linear loads connection to the grid supply will definitely improve the power quality of distribution system at lower cost. If this proposal is implemented for every house in urban area, then power factor of the supply voltage will definitely boost.

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