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Analytical Approach of Designing Passive Filter for SMPS Load

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Abstract- **The use of switch mode power supply (SMPS) load such as computer, laptop, etc in residential as well as commercial areas give rise to harmonics pollution in the electrical power distribution system which causes the quality of power poor and the function of equipment connected to the electrical system is affected. Many electrical appliances have an SMPS design that characteristically draws a distorted current that flows back to the input supply and causes distortion in the voltage waveform. To ensure the safe functioning of various electrical devices, there is a need for the implementation of effective harmonics mitigating techniques. Passive filters have been used for mitigating voltage and current harmonics. This paper proposed an analytical approach to designing the passive filter instead of trial and error or a complex approach for harmonics mitigation. The Simulation Model of SMPS is developed in MATLAB/Simulink and used for validating the proposed approach. Simulation results show the attractive findings of the proposed approach for harmonic mitigation with the improvement of the power factor.**

Index Terms-- **Non-active power, Power quality, Passive Filter, SMPS load, Simulink Model.**

I. INTRODUCTION

Power Quality (PQ) is the capability of an electrical power system to be given the pure sinusoidal waveform from the point of deliverance [1]. The power supply is required under high-quality conditions in order to ensure the safe functioning of various electrical devices [2-3]. The basic reason for power quality disturbance (PQD) is the loads that are used in residential and commercial places, which can be categorized majorly into linear and non-linear loads. A linear load is that load for which a sinusoidal input voltage is applied and the load current also remains sinusoidal, while a non-linear load is that for which sinusoidal input voltage produces distorted or harmonic current [4].

Modern electronic devices use Switch Mode Power Supplies (SMPS) that are extremely susceptible to power quality (PQ) issues. Such switching actions generate harmonic distortion. Harmonic distortion causes the quality of the electrical system to be poor and the function of equipment connected to the electrical system to be affected.

When a non-linear SMPS load is connected to an AC electrical power distribution system, the current waveform is distorted, and distorted current flow back to the input supply distorts the voltage waveform [5]. It has been discovered that SMPS-based loads are less affected by varying voltage than distorted voltage [6]. Therefore, power quality (PQ) problems produce and cause enormous economic losses, overheating of equipment, overloading of the transformer, error in meter reading, protective relay malfunction, low power factor, electromagnetic interference in communication equipment, and fault occurrences in electrical power systems [7-8]. If harmonic sources are left unchecked, then increased temperature and interference can cause a greatly shortened life of SMPS-based load.

The integer multiples of the fundamental power frequency (f) are called current or voltage harmonics. In the case where (f= 50Hz) is the fundamental power frequency, then the fundamental frequency is itself called the 1st harmonic, while the 2nd harmonic is 100Hz, the 3rd harmonic is 150Hz, and so on. Harmonics can be further divided into even harmonics such as 2f, 4f, 6f, etc, and odd harmonics such as 3f, 5f, 7f, etc [9].

Less distortion and fewer harmonics lead to good power quality in the voltage and current sources [10].

The total effect of multiple harmonics in current and voltage waveforms is expressed as total harmonic distortion (THD) as in (1) and (2), called harmonic distortion indices.

$$\mathrm{THD_I} = \frac{\sqrt{\sum_{n=2}^{\infty} I_{rms,n}}}{I_1} \quad (1)$$

Similarly

$$\mathrm{THD_V} = \frac{\sqrt{\sum_{n=2}^{\infty} V_{rms,n}}}{V_1} \quad (2)$$

Where $I_{rms,n}$ and $V_{rms,n}$ are the root mean square values of current and voltage harmonics excluding fundamental value, and I_1 or V_1 are the fundamental components of current and voltage parameters as mentioned in (1) and (2) [11].

There are two types of filters basically used for mitigation of harmonics that are active filters and passive filters [12].

Passive filters compared to other mitigation techniques show the best characteristic concerning cost benefit. Passive filters are arrangements of R, L, and C elements connected in different combinations to gain the desired suppression of harmonics [13].

Passive filters can be classified into

(i) series filter

(ii) shunt filter

Series and shunt passive filters have been used for mitigating voltage and current harmonics, respectively.

Among shunt passive filters used for mitigation of current harmonics, the most general type is the single-tuned filter (STF).

Single-tuned filters are the preferred choice due to being the least expensive for implementation and easy to design.

A Single tuned passive filter prevents the flow of distorted current into the power system by providing a low resistance shunt connected path. It is a power factor improving capacitor connected with a series reactor.

The impedance of a single tuned passive filter is

$$Z = R + J\left(wL - \frac{1}{wC}\right) \quad (3)$$

In resonance conditions, $w_L = \frac{1}{w_C}$, so that Z=R, therefore due to low resistance, harmonics flow into the branch of the filter instead of going into the electrical system.

The procedural steps required for calculating the elements of the filter are stated in [14].

1. $X_C = \frac{V_S^2}{Q_C}$

2. $C = \frac{1}{2\pi f X_C}$

3. $X_L = \frac{X_C}{h^2}$

4. $L = \frac{X_L}{2\pi f}$

5. $R = \frac{X_L}{Q_L}$

Where the parameters required in these five steps can be described as

1.	Capacitive reactance	:	X_C in Ω
2.	Source voltage	:	V_s in V
3.	Capacitive Reactive Power	:	Q_C in Var
4.	Capacitive reactance	:	X_C in Ω
5.	Source voltage	:	V_s in V
6.	Capacitive Reactive Power	:	Q_C in Var
7.	Capacitance of filter	:	C in uF
8.	Supply frequency	:	f in Hz
9.	Inductive reactance	:	X_L in Ω
10.	Harmonic order	:	h in Number
11.	Inductance of filter	:	L in mH
12.	Resistance of filter	:	R in Ω
13.	Quality factor	:	Q_L in Number

The main criteria in designing the passive filter are by selecting an appropriate or suitable value of reactive power (Q_c), which further sets the size of the capacitor and inductor element that gives a reasonable reduction in harmonic distortion and improvement in power factor. The impedance-frequency of a filter depends on its reactive power capacity [15]. Therefore,the selection of reactive power for passive filters is one of the most important issues in designing procedures.

A brief review of different approaches is described below. Moura et al. used genetic algorithms for the design of passive filters and the objective function when projecting harmonic filters are to maximize fundamental frequency impedance in particular branches of the filter while simultaneously minimizing harmonic impedance at certain frequencies to reduce losses [16]. Chen suggested utilizing genetic algorithms to construct a passive LC filter for the full-bridge rectifier. The author also described that the performance of a passive LC filter for a constant load depends on the choice of inductor and capacitor. Finding the maximum power factor (PF) of the ac mains with the minimum inductor value is the goal of the fitness function in the suggested GA program [17]. Yousif and Wanik described how the selection of an appropriate size capacitor provides a tolerable power factor at the fundamental frequency and serves as the primary design criterion for filters [18]. Zubi et al. described the main performance factors in the filter design as typically the input PF, input current THD_i, filter energy efficiency, and the output voltage at no load and full load. The decision about the choice of filter type is greatly influenced by the cost and size criteria, which are present together with these performance criteria. The filter should be developed and tested after the filter settings satisfy the performance criteria. The design may be carried out using an analytical formula method or thorough computer simulations of the entire system [19]. Diwan et al. described that among the criteria used for performance evaluation may be the current and voltage ratings of each of the filter components and Chosen value of reactive power may be divided by assuming this ratio (1:1:1) i.e., equal reactive power distribution in all filter branches [20]. Chaudhari et al. designed passive harmonic filters based on reactive power supplied for increasing power factor , but the acquired THD_i is not under the acceptable limit and there is also Conflict b/w the result of reactive power before and after filter installation [21]. Zubair Ahmed et al. developed an experimental model with a three-phase six pulse converter for the mitigation of harmonic distortion [22]. Pyakuryal and Matin described that when used separately, each filter capacitor and filter inductor have a mathematical formula that can be used to determine their value for regulating the amount of ripple. However, when the capacitor and inductor are used together, there is no such formula. The Alternative Transients Program (ATP) model is mathematically validated in this study for the scenario where a filter comprises just a capacitor or an inductor. A methodology is described to construct a combination capacitor-inductor filter to regulate the ripple at a specified level following mathematical verification of the computer model [23]. Prasad et al. presented design methods for mitigation of source side harmonics for AC-DC–DC loads. There is no analytical method explained to select parameters of passive filters therefore THD_i , is also not obtained under the standard limit [24]. Anooja and Leena discussed the design and simulation of passive filters for diode rectifiers and SCR rectifiers supplied loads. The diode rectifier and SCR rectifier in six-pulse and twelve-pulse configurations are also contrasted. The usage of these filters reduces THD, and simulation studies show that the twelve-pulse configuration of these filters reduces harmonics in SCR and diode rectifiers relative to the six-pulse configuration. When the firing angle of an SCR rectifier is raised, the THD likewise rises [25]. Vijayakumar et al. investigated how PF and THD could change by just swapping out passive converter components, but they used only a trial and error method for the selection of filter elements [26]. Tawfeeq designed the three-phase Buck type rectifier fed D.C. motor drive (variable torque) with a speed control of a separately excited D.C motor utilizing a fuzzy model reference speed controller. The simulation findings demonstrate that the current controller performs well under variable load disturbance [27]. Rüstemli et al. used the following equation to determine reactive power for filters

$$Q=P(\tan\phi_1-\tan\phi_2) \quad (4)$$

Where P represents the system's total active power, Q represents the capacitor power that must be connected to the system to achieve the desired power factor, tan ϕ_1 and tan ϕ_2 represent tangents of the power angle before and after applying for compensation [28]. Soomro and Almelian calculated the optimal parameters of the passive filter by using the Lagrange interpolation method for a three-phase AC-DC converter [29]. Fahmi et al. used a single-tuned passive filter by reactive power compensation for the Plastic processing industry but this approach was not effective for input current value after compensation [30]. Ziad Ali et al. described eight approaches for reactive power division among Shunt multiple-arm passive filters for the petrochemical factory but doesn't mention how to select total reactive power compensation [31]. Mboving and Stéphane presented an analysis of the selected topologies for the LC passive harmonic filter's (PHF$_s$) effectiveness. The PHFs are studied in the time domain using an electrical system and the frequency domain using their impedance versus frequency characteristics [32].

So far, the existing research shows that most researchers have not performed an analytical study about the selection of reactive power compensation of passive filters, but use only empirical values or a trial and error approach and very complex methods for designing passive filters.
The goal of this paper is to present an analytical approach to determine the appropriate value of compensating reactive power for the design of parameters of passive filters.

The paper is organized as follows: Sections I described the effects of Switch Mode Power Supply (SMPS) based load, harmonics indices, and literature review of existing passive filters design and procedural steps of passive filter, section II presents the Simulink model of SMPS and obtained results, Section III proposed the design criteria steps of the passive filter using proposed approach and its implementation. Finally, section IV concludes the paper.

II. SIMULATION MODEL OF SMPS LOAD

Most modern electronic equipment uses SMPS, such as personal computers, fax machines, laser printers, battery chargers, photocopy machines, variable speed motor drives, and electronic lighting ballasts. Though SMPS have high efficiency over linear supply with placed on integrated circuit whose weight, size and cost are less but the quality of power get down due to presence of harmonics.

Here, harmonic quantification can be checked by developing an SMPS circuit model in the Simulink environment.
A circuit model of SMPS in MATLAB/Simulink is developed as shown in Fig.1 and parameters used for the Simulink model are shown in TABLE.I.

TABLE.I SIMULATION PARAMETERS

S.No.	Parameters	Magnitudes
1	V_s (V)	220
2	F (Hz)	50
3	R_{sys} (Ω)	2
4	L_{sys} (mH)	2
5	R_{SMPS} (Ω)	1
6	L_{SMPS} (mH)	1
7	V_f (v)	0.8
8	C_{dc} (uF)	10
9	R_L (Ω)	300

TABLE. II RESULTS OBTAINED

Index	Magnitudes
P_1 (w)	166.1
Q_1 (Var)	91.15
S_1 (VA)	189.5
DPF (CosØ)	0.8767
THD_V (%)	1.25
THD_I (%)	43.80

The obtained results of the simulation carried out are tabulated in the Table. II. The subscript 1 for P_1, Q_1, and S_1 shows the values related to the fundamental component of power frequency only, i.e. 50Hz.

Fig.8 and Fig.9 show the Fast Fourier Transform (FFT) results of the input voltage and input current signals of the simulation model. It is observed that THD_V is 1.25% and THD_I is 43.80%. According to international standards, the value of THD_v is within the acceptable limit of 5% while the value of THD_i is violated the standard limit. Therefore, it is necessary to install a filter for current harmonics mitigation.

III. PROPOSED DESIGN OF PASSIVE FILTER

Here, an analytical approach to calculating reactive power for passive filters is presented.

The required procedural steps are described below:

6. Fundamental apparent power :
$S_1 = V_1I_1$
7. Fundamental active power :
$P_1 = V_1I_1\cos\varphi$
8. Fundamental reactive power :
$Q1=V1I1\sin\varphi$

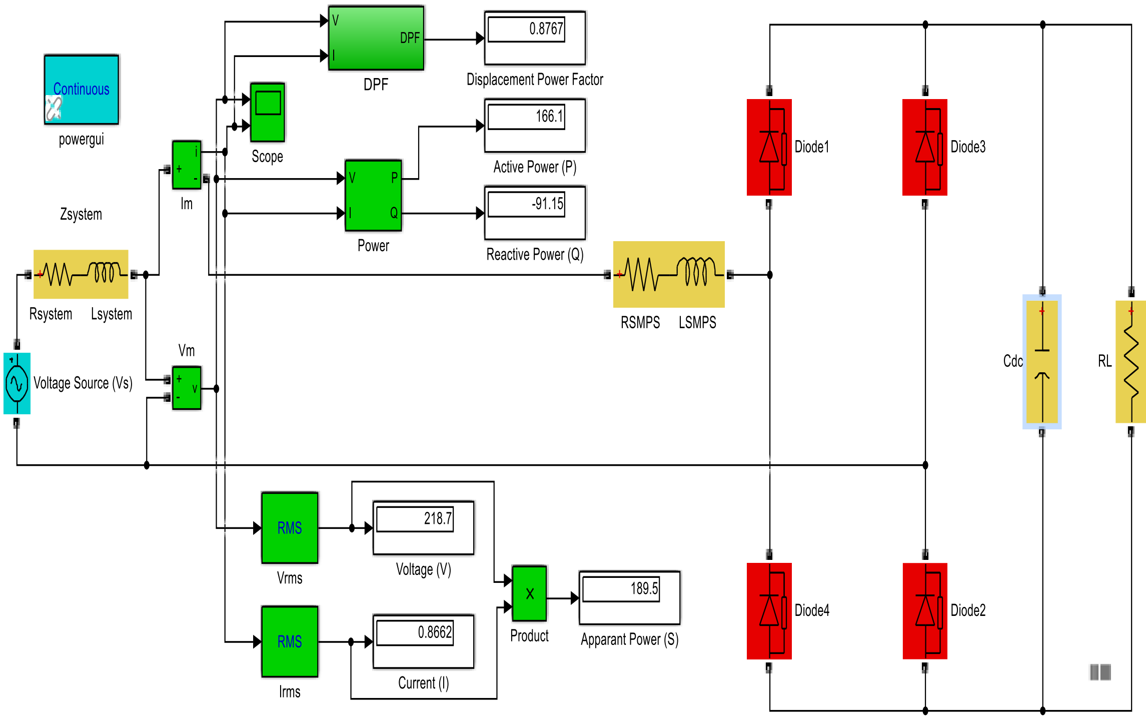

FIGURE.1 Simulink model of SMPS

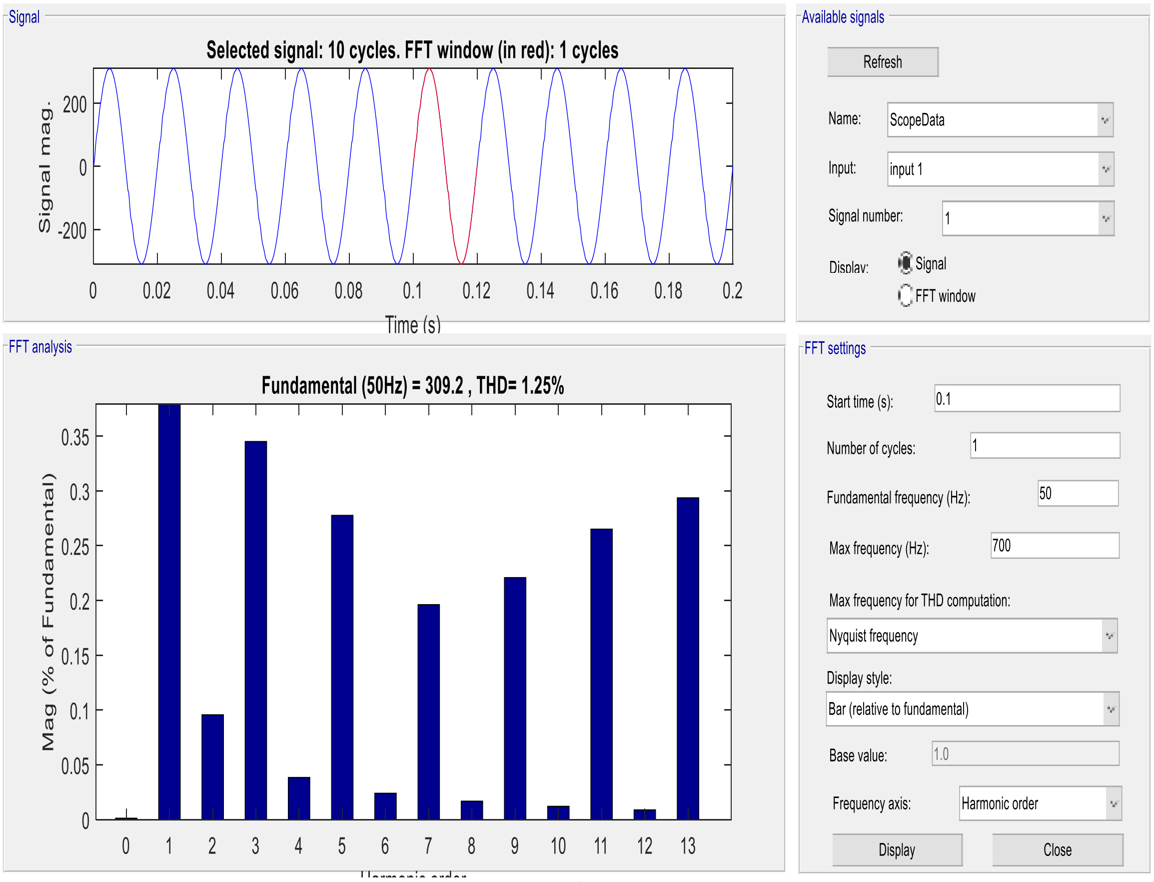

FIGURE.2 FFT of input supply voltage

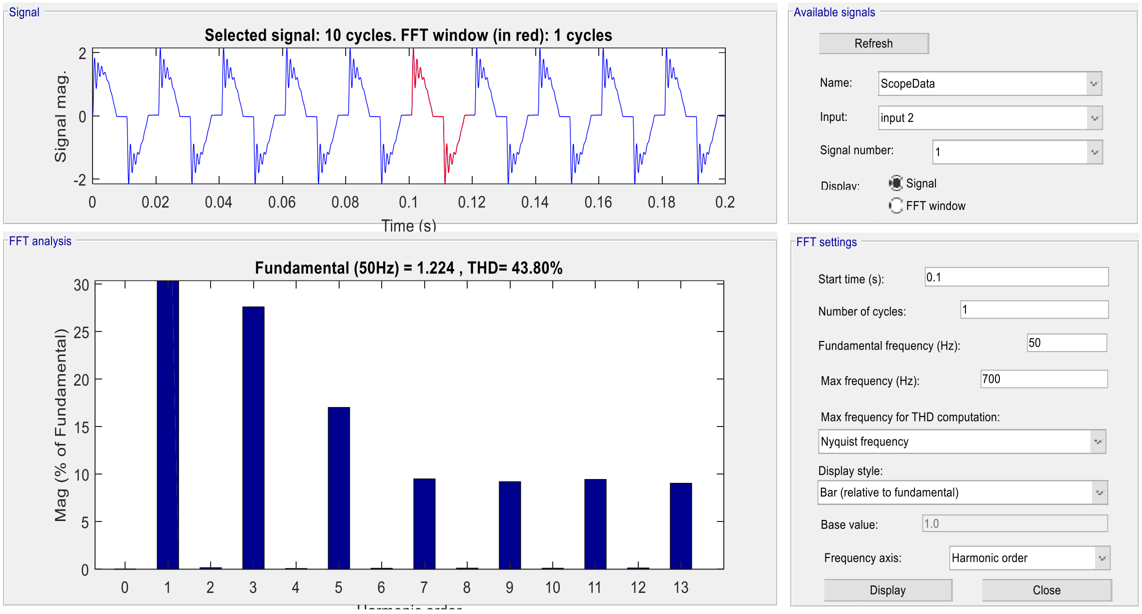

FIGURE.3 FFT of input supply voltage

9.Displacement power factor :

$DPF = Cos\emptyset = \frac{P_1}{S_1}$

10.Voltage distortion power :

$D_v = V_H I_1 = S_1(THD_v)$

11.Current distortion power :

$D_I = v_1 I_H = S_1(THD_I)$

12.Harmonic apparent power:

$S_H = V_H I_H = S_1(THD_I)\ (THD_v)$

13. Non fundamental apparent power :

$S_N = \sqrt{D_V^2 + D_I^2 + S_H^2}$

14. Non-active power :

$N = \sqrt{Q_1^2 + S_N^2}$

Here, non-active power (N) will be chosen as the value of Q_c for the passive filter to avoid using a trial-and-error approach for filter design,

For SMPS load more focus should be given on improvement in true power factor (TPF) rather than on displacement power factor. Therefore to check improvement in true power factor the following step can be used.

15. True power factor

$TPF = Cos\emptyset * \frac{1}{\sqrt{1+THD_V^2}} * \frac{1}{\sqrt{1+THD_I^2}}$

The value Q_c can be calculated analytically from procedural steps 6 to step 14.

After this, the values of C, L, and R for the filter can be determined from procedural steps 1 to step 5 and for step 5 value of quality factor (Q_L) is taken as 50.

Effective reduction in voltage and current harmonic distortion through this approach is validated using simulation studies in the environment of MATLAB/Simulink.

From simulation results, it is observed that 3rd, 5th, 7th, 9th and 11th order harmonics are high in magnitudes, so elements of five single tuned passive filters are calculated using the above steps and installed as shown in Fig.10.

TABLE.III DESIGNED 3rd,5th,7th,9th,11th ORDERS FILTERS

Harmonic Orders	**3rd**	**5th**	**7th**	**9th**	**11th**
C(uF)	8	8	8	8	8
L(mH)	138.8	49.3	25.1	15.2	10.1
R(Ω)	1.4	0.5	0.2	0.1	0.1

The obtained values of R, L, and C by the mentioned method are the lowest, most practical values and are also available easily.

After the installation of single-tuned passive filters, it is seen in Fig.5 that THD_I is 4.8%. Therefore total harmonic distortion is within an acceptable limit according to international standards.

To check the performance of the proposed method for reduction of distortion power and TPF improvement, repeat steps from step 6 to step 15. It can be observed that after the implementation of passive filters, the value of DPF increased from 0.8765 to 0.8817 and TPF increased from 0.7837 to 0.8826 as shown in Table. IV. Hence, the proposed method provides us not only an efficient reduction in harmonic distortion but also an improvement in TPF, which is a requirement in the case of non-linear SMPS load.

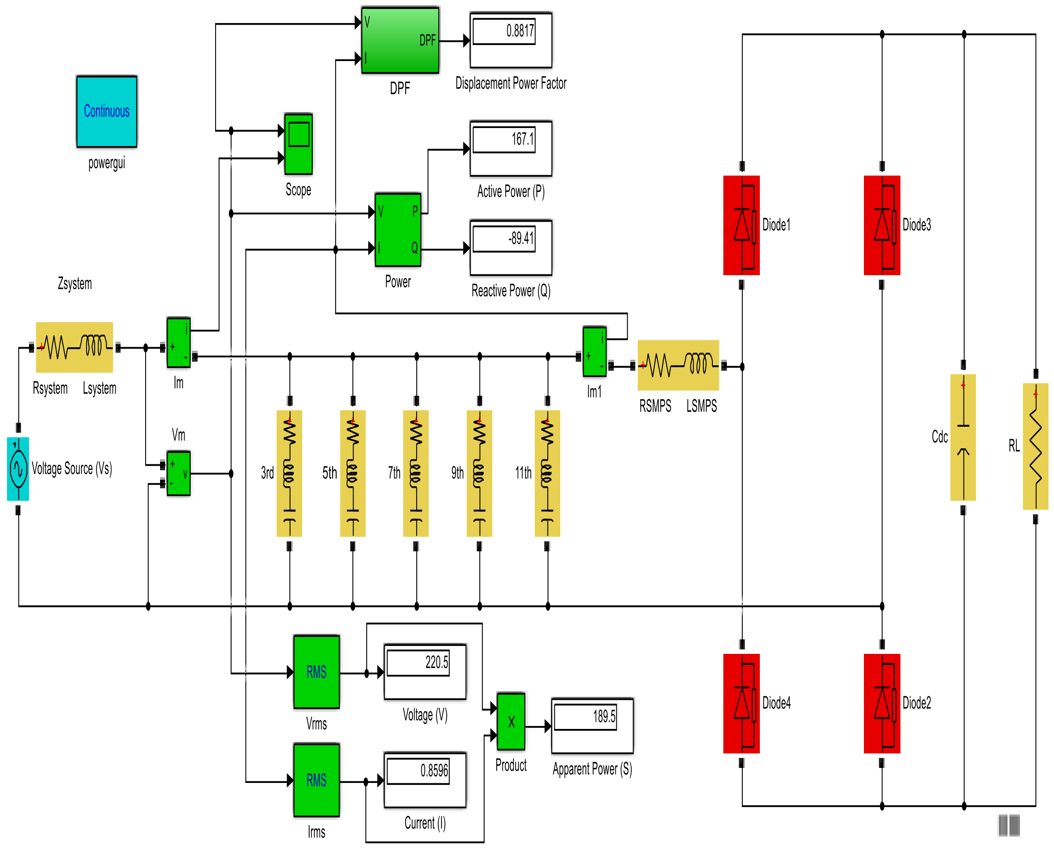

FIGURE 4. Simulink model of SMPS load after single tuned passive filter

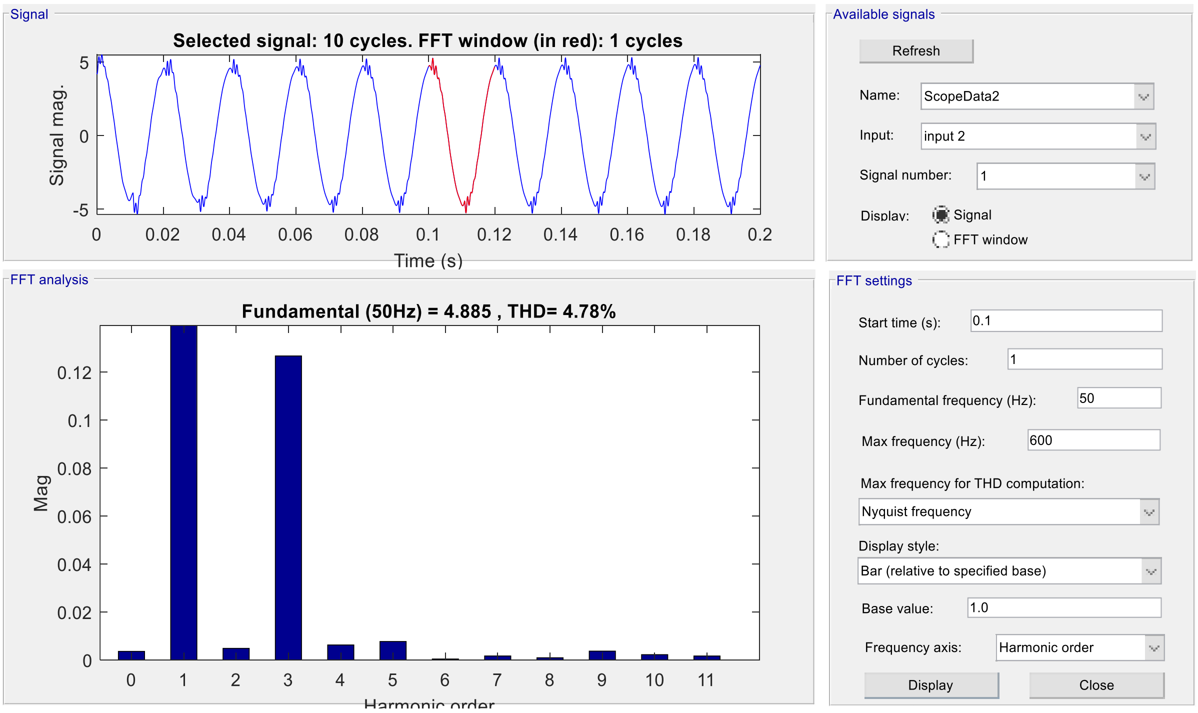

FIGURE.5 FFT of input supply current after single tuned passive filter

TABLE.IV OBTAINED RESULTS AFTER THE PROPOSED APPROACH

Index Terms	Before Passive filter	After proposed Passive filter
THD_I	43.80%	4.78%
Displacement Power factor	0.87	0.88
True Power factor	0.78	0.88

IV. CONCLUSION

Harmonic distortion is the major issue related to the power quality of an electrical power system. Nonlinear SMPS load connected in electrical power distribution system produced a significant amount of distortion power component that is not acceptable to limit specified by international standards. Filtering is one of the solutions to prevent the harmonics from entering the rest of the system. This paper considers an analytical approach for designing a passive filter for SMPS load.

From the above discussion, it can be concluded that the proposed analytical approach for designing passive filters used in this work has a good ability to reduce harmonic distortion and improve the true power factor effectively and has shown superior filtering performance. Hence, the proposed analytical approach is simple and cost-effective for power quality control and harmonic governance, which has good practicability.

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CONFLICTS OF INTEREST

The authors declare they have no conflicts of interest to report regarding the present study.

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