Harmonic Analysis of Non-Linear Loads in Distribution System and Mitigation Using Passive Filters.

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Abstract - *Linear and nonlinear loads are the two types of loads in a power system. As the use of nonlinear loads such as power electronic devices, bridge rectifiers, arc furnaces, air conditioners, computers, UPS (uninterruptible Power Supply), fluorescent lamps, and other nonlinear loads increases, the injection of harmonics into the source increases. To improve power quality, a variety of harmonic mitigation strategies are available. Different types of passive filters were built with the input parameters in this work. MATLAB SIMULINK software is employed to simulate the results.*

Key Words: Linear & Non-linear loads, Bridge Rectifier, Total Harmonic Distortion (THD), Passive Filters, STF, DTF and C-Type Filter.

1. INTRODUCTION

Many loads are now nonlinear due to the exponential adoption of power electronic components. Harmonics are introduced into the system by this nonlinear load, prohibiting utilities from providing high-quality power to their customers. According to IEEE Recommended Practice for Monitoring Power Quality, power quality is defined as "the concept of powering and grounding sensitive equipment in a manner that is suitable for operation of that equipment" (IEEE Std 1159- 1995). When harmonics are introduced into a system, the sinusoidal voltage and current are disturbed or deviated from the fundamental frequency, and the loads may be affected as a result of the harmonic impacts. Harmonics produce copper loss, iron loss, dielectric loss, and thermal stress in cables, transformers, and rotating machines; THD can be decreased using filters to improve power quality.

Active and passive harmonic filters are the two primary types of harmonic filters. Low pass and high pass filters are two types of passive filters. Because it is connected in shunt with the load and provides a low impedance path at resonance ($X_L = X_C$), low pass filters (LPF) are employed to minimize current harmonics. Because it is connected in series with the load and provides a high impedance path during resonance, high pass filters (HPF) are employed to minimize voltage harmonics. Passive filters reduce harmonics and enhance power factor while compensating for reactive power.

Passive filters provide the following advantages; low cost, simple design and implementation, and great reliability. It is incapable of resolving random fluctuations in load current waveforms. Passive filters, on the other hand, are best suited for consistent loads since they eliminate or bypass predetermined harmonics of current (3rd, 5th, 7th, etc.) by adjusting the passive filters at resonance frequency. Because a power system typically contains several frequency harmonics, a set of parallel tuned filters is required to filter harmonics. For mitigating Harmonics, the double tuned filters optimal solution compare to two parallel single tuned passive Filters for mitigating 5th and 7th Harmonic filters, as well as a special sort of C-Type High Pass Filter for reducing 3rd Harmonic. Lower order harmonics are more harmful to power quality compare to the High order harmonics.

In This Proposed work, the Design & performance of STF, DTF & Special type of C- Type High pass filter was studied and simulated using MATLAB software.DTF provides the optimal solution when compared to two separate parallel connected single tuned passive filters is evident from this work.

2. LINEAR AND NON-LINEAR LOADS

2.1 Linear Loads

Linear loads are defined as any load that draws a sinusoidal current (with the same frequency) when a sinusoidal voltage is applied. They only have resistors (R), inductors (L), and capacitors as active components (C). Power Factor Improvement Capacitors, Incandescent Lamps, and Heaters are examples of linear loads.

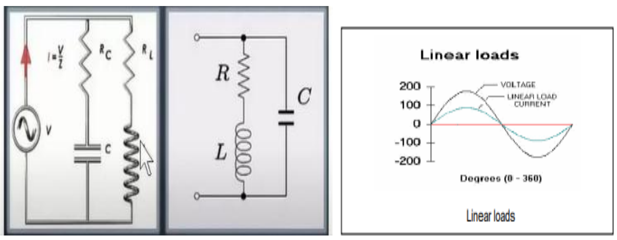

Fig -1: Linear Load.

2.2 Non-Linear Loads

Any load that draws a non-sinusoidal current when a sinusoidal voltage is given to it is classified as a non-linear load. Rectifiers, IGBTs, Diodes, MOSFETs, SCRs, and other Power Electronic Devices are included. Personal computers, television sets (TVs), compact fluorescent lamps (CFLs), printers, battery chargers, uninterruptible power supplies (UPS), fluorescent tubes with electronic ballasts, and other equipment supplied by switched-mode power supplies (SMPS) units are examples of non-linear loads [2].

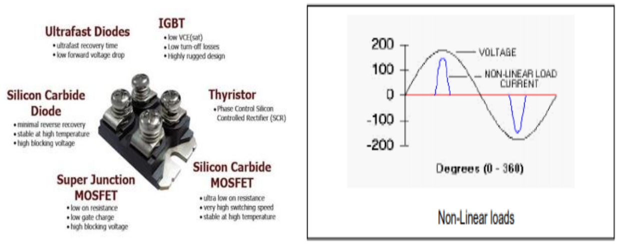

Fig -2: Non-Linear Load.

Harmonic deformation, which is induced by load non-linearity, is becoming an increasing source of power quality concern. This is because most home gadgets use the rectification phenomenon, which causes harmonic distortion. Total Harmonic Deformation (THD) is defined as the percentage measurement of the deformation caused in voltage or current waveforms due to harmonic distortion [1].

$$THD_i = \frac{\sqrt{\sum_{h=2}^{n} I_h^2}}{I_1} \qquad (1)$$

A series of sine and cosine functions, often known as the Fourier series, can be used to describe any periodic signal (waveform) mathematically.

$$u(t) = U_{dc} + \int_{n=1}^{\infty} (U_{max} Sin(nwt)) + (U_{max}\, Cos(nwt)) \qquad (2)$$

As a result, when a signal goes through a non-ideal, non-linear device, harmonics of the original frequencies are added, and these harmonics are multiples of the fundamental frequency nf, thus destroying the signal.

$$THD_i = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 \;\ldots\ldots\ldots + I_\infty^2}}{I_1} \qquad (3)$$

Hence, THD refers to the ratio of all signal components of numerous frequencies, to the fundamental frequency of signal component. Total Harmonic Distortion in Voltage or Current (THD) for the system should not exceed 5%, according to the IEEE standard [1].

3. PROBLEM STATEMENT

The exponential use of power electronic components, many loads are now nonlinear in nature. This nonlinear load introduces *Harmonics* into the system, preventing utilities from providing high-quality power to their customers.

4. METHODOLOGY

This Proposed work chooses the methodology of designing passive filter to suppress the harmonic level (THD) within standard limit and providing the high quality power to their customer and also compare the design and performances of different combination of passive filter to reduce THD (Total Harmonic Distortion). In This Proposed work MATLAB SIMULINK software is used to model Non-Linear Loads connected at PCC of distribution system and observed the Voltage & Current waveforms of non-linear loads with & without filter. THD is measured using FFT Analysis tool from MATLAB SIMULINK software.

5. DESIGN OF PASSIVE FILTERS

A passive filter, as contrast to an active filter, is an electronic filter made completely of passive materials, such as paper. A passive filter consists of capacitors, inductors, and resistors tuned to resonate at a certain frequency or a range of frequencies. In power systems, passive filters are used to suppress harmonic currents and reduce distortion. Current harmonics can also be eliminated using a three phase shunt active filter with appropriate control techniques, but the cost is much higher than with a passive filter.

A filter can be set up in a series or shunt configuration. In the Series Configuration Filter, the harmonic frequency to be blocked should have a high impedance. Shunt filters divert harmonic currents to ground while also supplying reactive power, which can be used to correct Power Factor.

5.1 Different Types of Passive Filters:

- **Band-pass filters [Low Pass Filters]:** These are used to filter the lowest order harmonics, such as the 5th, 7th, 11th, and 13th. Filters can be set to a single frequency (single-tuned filter) or two frequencies (double-tuned filter).

- **High-pass filters:** These filters are used to filter high-order harmonics and cover a wide frequency range. To provide reactive power & eliminate parallel resonances, a specific sort of high-pass filter called a C-type high-pass filter is used. Filtering low-order harmonics (i.e., 3rd) while maintaining zero losses at the fundamental frequency is possible [6].

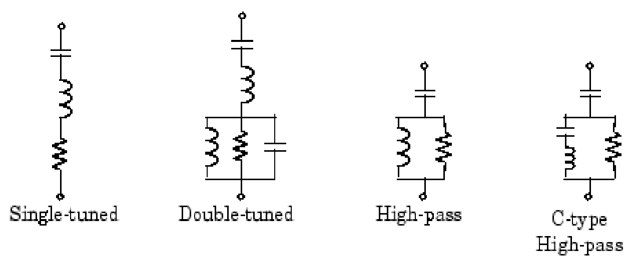

Fig.3: Different types of Passive Filters.

The following quantities should be stated first when designing any passive filter:

- V is the voltage at which the filters will be fitted (V_{L-L})
- Q is the reactive power that the filter will generate at fundamental frequency (assumed)
- f = Fundamental Frequency
- f_h = Tuning Frequency
- Q_f = Quality Factor

The ratio of resistance to reactance of the parallel R-L circuit at the tuned frequency is defined as the quality factor (Q_f) of filter.

(The bandwidth that defines that sharpness of the tuning frequency is determined by the quality factor.)

5.2 Modeling of Single Tuned Shunt Passive Filter

As illustrated in fig.4, single tuned shunt passive filters are essentially composed of series coupled resistance, inductance, and capacitance that are in parallel with the nonlinear load. At resonance, it can be adjusted to lower order harmonics (5th, 7th, 11th, and 13th, for example). This type of filter isn't suitable for higher order harmonics because tuning gets difficult at that point. At resonance, the inductive reactance equals the capacitive reactance (XL = XC), resulting in a lower total impedance and a low impedance path to the resonant frequency (fh), effectively removing harmonics caused by nonlinear loads. It also contributes to an increase in the power factor. The circuit is capacitive if the frequency is less than the resonance frequency, and inductive if the frequency is more than the resonance frequency.

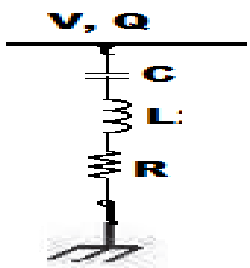

Fig.4: Single Tuned Passive Filter Configuration.

The Single Tuned Filter (STF) parameters [3] are derived using the equations below, using the input parameter listed in the Table-1 below.

- The inductive reactance X_L is,

$$X_L = 2\pi * f_h * L_h \tag{4}$$

Where,

f_h is the h^{th} harmonic frequency.

- The capacitive reactance X_C is,

$$X_C = \frac{1}{2\pi * f_h * C_h} \tag{5}$$

- At Resonance,

$$X_L = X_C \tag{6}$$

$$X_C = \frac{V^2}{Q} \tag{7}$$

- The capacitance value for tuning

$$C_h = \frac{1}{2\pi * f_h * X_C} \tag{8}$$

- The inductance value for tuning

$$L_h = \frac{1}{(2\pi * f_h)^2 * C_h} \tag{9}$$

- The resistance value for tuning

$$R_h = \frac{(2\pi * f_h) * L_h}{Q_f} \tag{10}$$

Where,

The resonant frequency f_h is

$$f_h = \frac{1}{2\pi * \sqrt{L_h C_h}} \tag{11}$$

Quality factor determines the filtering sharpness & it ranges from 5 to 100.

Table-1: Input & Calculated Parameters of STF.

Single Tuned Filter, h=5th harmonic [f_5 = 250 Hz]			
Input Parameters	V_{L-L} = 400V	Calculated Parameters	
	F_5 = 250Hz		C_5=59.6µF
	Q = 150Var		L_5 =6.80 mH
	Q_f =30		R_5 = 356Ω
Single Tuned Filter, h=7th harmonic [f_7 = 350 Hz]			
Input Parameters	V_{L-L} = 400V	Calculated Parameters	
	F_7 = 350Hz		C_7=42.63µF
	Q = 150Var		L_7 =4.85mH
	Q_f =30		R_7 =355Ω

5.3 Modeling of Double Tuned Shunt Passive Filter

A double tuned filter is made up of passive elements connected in series and parallel as shown in fig.5. It can filter lower order harmonics (5th, 7th, 11th, 13th, etc.) with a single circuit, whereas, single tuned requires two parallel circuits. One resonant frequency (W_S) is produced by a series circuit, while another is produced by a parallel circuit (W_P).

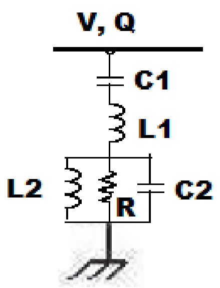

Fig.5: Double Tuned Passive Filter Configuration.

In Designing a Double Tuned Filter with Known tuned frequencies W_1 & W_2 and Input Parameters, the parameters of a Double Tuned Filter (DTF) are computed using the equations below with the input parameter given in Table-2 below. The Filter's Parallel Resonance Frequency W_P is chosen to be somewhere between W_1 and W_2.

- The Filter Series Resonance is,

$$W_S = \frac{W_1 W_2}{W_p} \qquad (12)$$

Neglecting the resistance in reactors and dielectric losses in Capacitors

- The Capacitor C_1 is given by,

$$C_1 = \left[W_f \left(\frac{W_p}{W_1 W_2}\right)^2 - \frac{1}{W_f} + \left[\frac{W_f\left(W_1^2 + W_2^2 - W_p^2\right)W_p - W_1^2 W_2^2}{\left(W_1^1 W_2^2\left(W_p^2 W_s^2\right)\right)}\right]\right] \frac{V}{Q} \qquad (13)$$

- The Inductance value of L_1 is,

$$L_1 = \left(\frac{W_p}{W_1 W_2}\right)^2 * \frac{1}{C_1} \qquad (14)$$

- The Capacitance value of C_2 is,

$$C_2 = C_1 * [\left(\frac{\left(W_1^2 + W_2^2 - W_p^2\right)}{W_S^2}\right)^2 - 1 \qquad (15)$$

- The Inductance value of L_2 is,

$$L_2 = \frac{1}{W_P^2 C_2} = \frac{1}{W_P^2 C_1} \frac{\left(W_1^2 + W_2^2 - W_p^2\right)}{W_S^2} \qquad (16)$$

- The resistance value for tuning

$$R = \left(2\pi * f_m * L_2\right) * Q_f \qquad (17)$$

Where,

$$f_m = \sqrt{f_s * f_p} \qquad (18)$$

Table-2: Input & Calculated Parameters of DTF.

Double Tuned Filter, h_1=5th & h_2=7th harmonic [f_5 = 250 Hz & f_7 =350 Hz]			
Input Parameters	V_{L-L} = 400 V	Calculated Parameter	C_1= 51.11 µF
	F_5 = 250 Hz		L_1 = 5.82 mH
	F_7 =350 Hz		C_2 =5.969 µF
	Q = 1000Var		L_2 = 6.150mH
	Q_f =50		R = 571.51 Ω

5.4 Modeling of C-Type High Pass Filter

The capacitor and inductor are parallel with the resistor; the C-type high-pass filter has smaller losses at the fundamental frequency. The resonance frequencies of L2 and C2 are set to the fundamental frequency to prevent fundamental currents from passing through the resistor.[6]. Usually High pass filter used to reduce high order harmonics but this is Special type of C-Type High Pass Filter it is used to reduce lower order harmonic i.e., 3rd Order Harmonic.

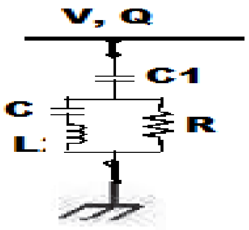

Fig.6: Special types of High pass Filter(C-Type High Pass Filter) Configuration.

The Parameters of C-type High Pass Filter are derived using the equations below and using the input parameter listed in the Table-3 below.

$$C_1 = \frac{Q_1}{WV^2} \quad (19)$$

$$C = \frac{(h^2-1)Q_1}{WV^2} \quad (20)$$

$$L = \frac{V^2}{(h^2-1)WQ_1} \quad (21)$$

$$R = Q_f * W_h * L \quad (22)$$

Table-3: Input & Calculated Parameters of C-Type Filter.

C-Type Filter			
Input Parameters	V_{L-L} = 400V	Calculated Parameters	C_1=19.8µF
	f_h = 150Hz		C= 159µF
	Q = 1000Var		L = 63.6 mH
	Q_f =5		R =300 Ω

6. SIMULATION RESULTS AND DISCUSSION

The simulation model for various nonlinear loads, such as a personal computer, fluorescent lamp, and uninterruptible power supply, load connected at PCC of Distribution System is modelled with & without Filter using SIMULINK, and the influence of harmonics from Home Appliances is observed without filter and mitigates harmonics with different combination of passive filter and Results are listed in the Table -4.

6.1 Simulation of Non-Linear Loads without Filter

At PCC of Distribution System Linear Load is connected. For the period 0.1 to 0.2 sec Non-Linear Load is connected to the system through three phase breaker. This Non-Linear Load draws distorted current from source supply shown in waveform below and FFT Analysis of Source current is carried out to measure THD using MATLAB Simulink & results are tabulated in Table -4.

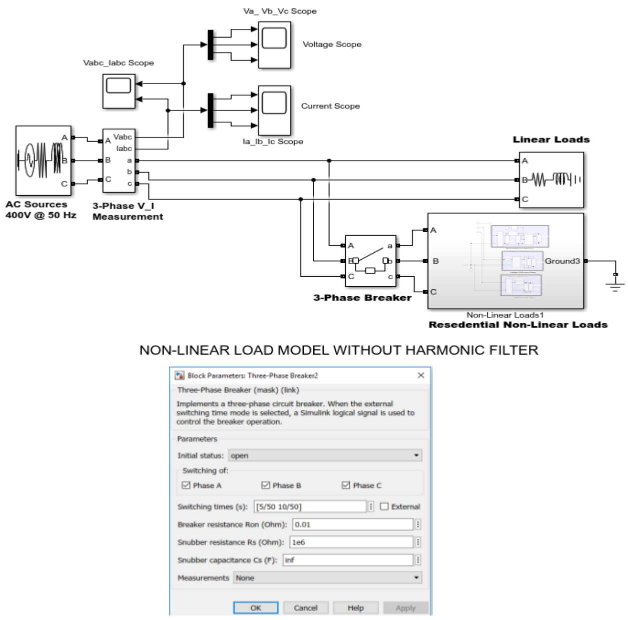

Fig.7: Non-Linear Load Model without Filter.

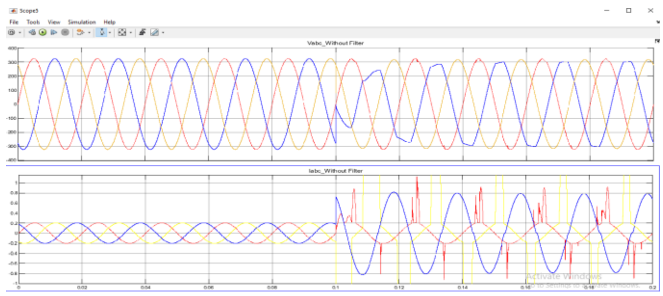

Fig.8: Voltage & Current waveforms of Non-Linear Load without Filter.

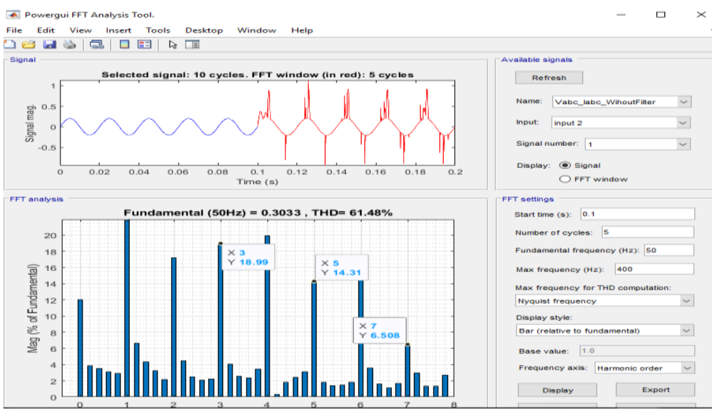

Fig.9: FFT analysis of Current of Non-Linear Load without Filter.

6.2 Simulation of Non-Linear Loads with Filter

Simulation of Non-Linear Load with filter (different combination of passive filter) is simulated using MATLAB Simulink and Results are tabulated in table.4 from the table it's clear that measured THD is within IEEE standard Limit.

Case.1: Passive Filter with Double Tuned Filter (DTF) and C-Type High pass Filter.

3rd order Harmonic is eliminated by C-Type High pass Filter and Double Tuned Filter eliminate 5th & 7th order Harmonics. Simulation of Non-Linear Load model with Passive filter with double tuned filter and C-Type High pass filter combination shown in fig.10 below.

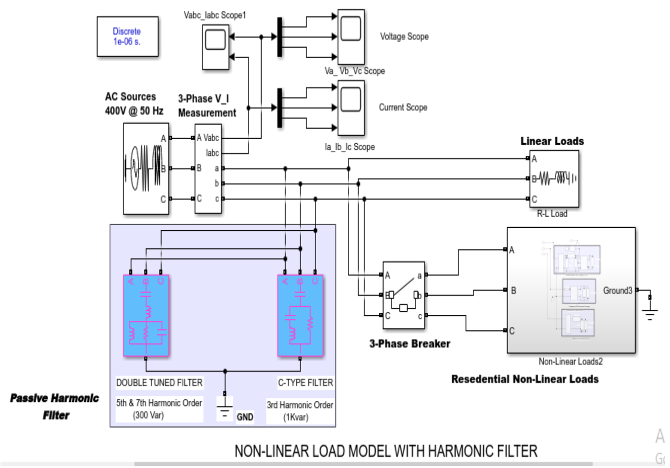

Fig.10: Non-Linear Load Model with Filter (C-type and DTF).

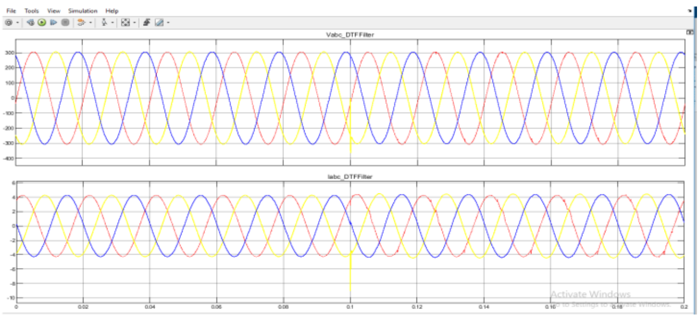

Fig.11: Voltage & Current waveforms of Non-Linear Load with Filter (C-type and DTF).

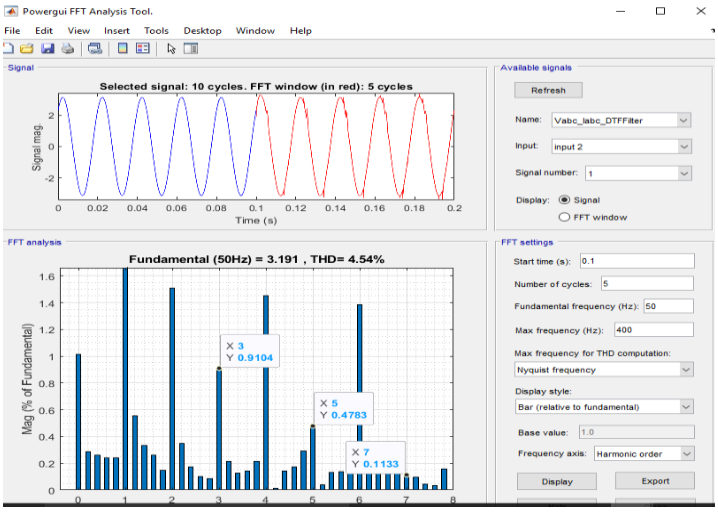

Fig.12: FFT analysis of Current of Non-Linear Load with Filter (C-type and DTF).

Case.2: Passive Filter with Two Single Tuned Filter (STF) and C-Type High pass Filter.

3rd order Harmonic is eliminated by C-Type High pass Filter and Two Single Tuned Filter eliminate 5th & 7th order Harmonic simulation of Non-Linear Load model with Passive filter with two single tuned filter connected in parallel and C-Type High pass filter combination shown in fig.13 below.

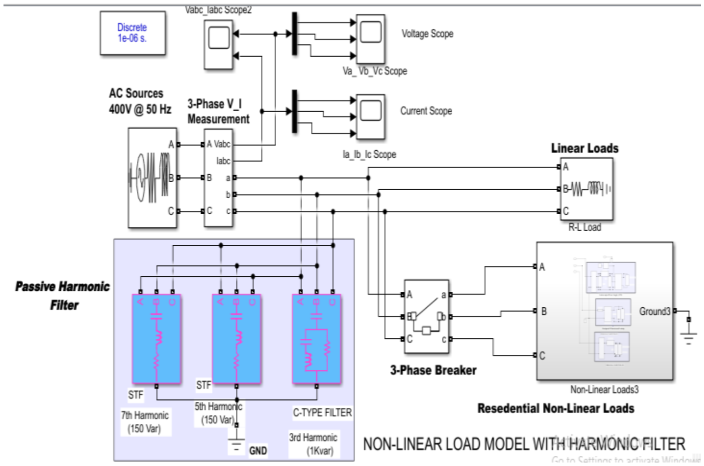

Fig.13: Non-Linear Load Model with Filter (C-type and Two STF).

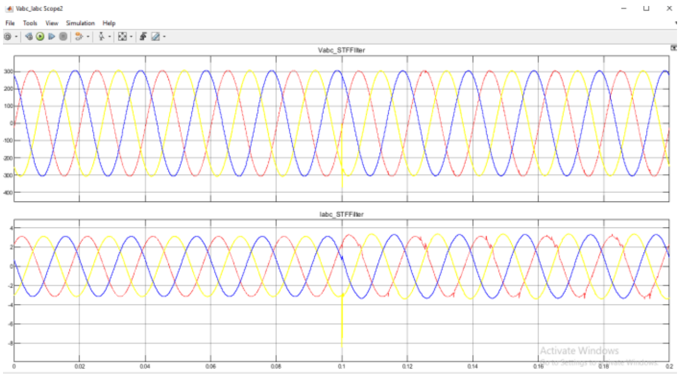

Fig.14: Voltage & Current waveforms of Non-Linear Load with Filter (C-type and Two STF).

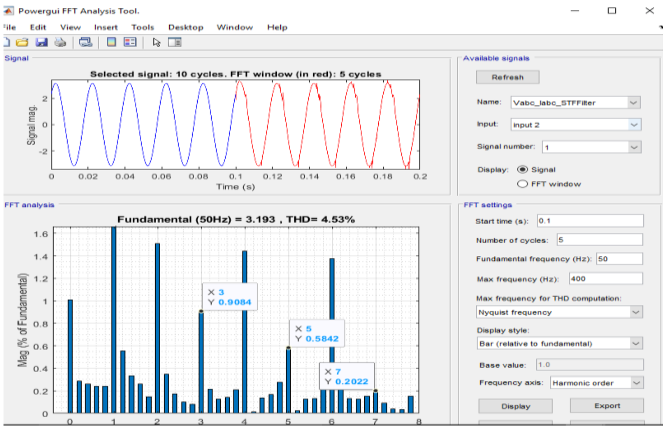

Fig.15: FFT analysis of Current of Non-Linear Load with Filter (C-type and Two STF).

RESULTS:

Non-Linear Load connected in the system through three phase breaker for the period 0.1 to 0.2 sec and observed the waveform Source current is distorted in case of without fiter & THD is measured through FFT analysis of source current using MATLAB FFT Analysis tool i.e., 61.48% and 3rd & 5th order harmonic are predominated shown in Table-4.

Table -4: THD Results of Non-Linear Load Model with and without Filter.

SI. NO.	Filter Combination	THD (%)	Magnitudes of Harmonic Order		
			3rd	5th	7th
1.	Without Filter	61.48%	18.9%	14.3%	6.50%
2.	With Filter	4.54%	0.91%	0.47%	0.11%
Different Passive Filter Combination					
3.	C-Type High Pass Filter & STF	4.54%	0.91%	0.47%	0.11%
4.	C-Type High Pass Filter & DTF	4.53%	0.90%	0.58%	0.20%

From the Results it's clear the Performance of both single tuned and double tuned filter with combination of C-Type High pass filter is same but DTF is required less Size & Cost Compared to STF.

7. CONCLUSION

The simulation revealed that most residential appliances produce a highly distorted current waveform when connected to a distribution system, resulting in a significant amount of harmonic distortion. The issue becomes much more problematic when the distribution system's high level load is considered, which causes the THDi at PCC, as well as several other individual harmonic components, to exceed the Standard limit (as per IEEE-519 Std.). As a result, operating the distribution system at near-maximum efficiency may not be as useful as expected due to increasing losses incurred by increased harmonic Pollution.

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REFERENCES

[1] Suad Ibrahim Shahl "Simulation and Analysis Effects of Non-Linear Loads in the Distribution Systems" International Journal of Scientific & Engineering Research Volume 10, Issue 7, July-2019 ISSN 2229-5518.

[2] H.Farooq, Md. Emad Farrag and Glasgow "Analyzing the Harmonic Distortion in a Distribution System Caused by the Non-Linear Residential Loads" International Journal of Smart Grid and Clean Energy · January 2013.

[3] Young-Sik Cho & Hanju Cha "Single-tuned Passive Harmonic Filter Design Considering Variances of Tuning and Quality Factor" Journal of International Council on Electrical Engineering. ISSN: PP2234-8972. https://www.tandfonline.com/loi/tjee20.

[4] A Shah1, R K Ali, N Khan "Design of a C-type Passive Filter for Reducing Harmonic Distortion and Reactive Power Compensation" International Journal of Software & Hardware Research in Engineering ISSN-2347-4890Volume 4 Issue 12 December, 2016.

[5] Kumar Reddy Cheepati, Sardar Ali and Surya Kalavathi M. "Performance Analysis of Double Tuned Passive Filter for Power Quality" I J C T A, 9(7), 2016, pp. 3295-3305 © International Science Press ISSN: 0974-5572.

[6] https://www.mathworks.com.

[7] Power Quality Lab Manual G.N.I.T.S.

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