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OPTIMAL DESIGN OF A SINGLE TUNED PASSIVE FILTER TO MITIGATE HARMONICS IN POWER FREQUENCY

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ABSTRACT

Electricity has been one of the most important necessities for industrialization, increasing living standard of people around the world. Power electronic devices are applied in industry as well as in domestic appliances. The excessive use of these devices causes power quality (PQ) problems in the power system (PS), due to generation of harmonics. The consequences of harmonics include; increased probability in occurrence of resonance, neutral overload in 3-phase systems, overheating of all cables and equipment, loss of efficiency in electric machines, electromagnetic interference with communication systems, and errors in measurements when using average reading meters, nuisance tripping of thermal protections. Many researches are being done to find out the best solution against the cause. For this, various tools and techniques are being improved and applied to mitigate such cause and enhance the PQ of the PS. One of the methods to mitigate harmonics is by designing and using passive filter. Moreover, it reduces the need of capacitor for supplying extra needed kVAr. Due to these two attracting features of Passive filter, its design and application can be found in many researches. The main aspect of filter design has been challenging issue. This paper presents the optimal design of single tuned passive filter that its application is to mitigate harmonics in power frequency. The optimal parameters of this filter were calculated by using Lagrange interpolation method. The results were obtained by MATLAB/simulation which shows the effectiveness of this filter.

Keywords: power quality, passive filter, total harmonic distortion, MATLAB/simulink.

INTRODUCTION

Harmonic signal can be described as a signal whose frequency is the integer multiple of the fundamental/reference frequency. Mathematically, it is described as the ratio of the frequency of such a signal to the frequency of the reference signal (Grady, W. M, 2001).

Power distribution system is designed to operate with sinusoidal voltage and current waveform at constant frequency. However, when nonlinear load like thyristor drives, converters and arc furnace are connected to the system, excessive harmonic currents are generated and this causes both current and voltage distortions. These harmonics pollute the PS and produce many adverse effects like malfunction of sensitive equipment, reduced power factor, overloading of capacitor, flickering lights, overheating of equipments, reduced system capacity, etc.

Few of the other reported harmonic effects include; excessive current in neutral wire, overheating of the motor, microprocessor problem and unexplained computer crash. Its more effect can be found at distribution grid stations as well as industrial sectors where it causes higher transformer losses, line losses, reactive power and resonance problems, untoward protection system activations, harmonic interactions between customers or between the utility and the load.

Basically, the common source of harmonic signal is nonlinear load. It is due to the fact that current does not vary smoothly with voltage. Nonlinear load such as fluorescent lamp, electric welding machine and three-phase rectifier generates primarily 5^{th} and 7^{th} current harmonic and some of higher order harmonics.

The harmonic signal cannot be totally mitigated, but it can be reduced by several ways, such as by using active filters, passive filters and hybrid filters. The common practice for harmonic mitigation is the installation of passive harmonic filters due to many advantages. Passive filters are the simplest, no power supply required and exhibit the best relationship cost-benefit among all other mitigation techniques when dealing with low and medium voltage rectifier system (Fujita *et al.* 2000).

SINGLE TUNED PASSIVE FILTER DESIGN

The concept of passive filter is followed by the use of passive components such as capacitors, inductors and resistors which conceal the harmonic components from the nonlinear loads (Dugan *et al.* 1996).

Basic configuration of passive filter

The basic structure of passive filter is as shown in Figure-1 (Srivastava, K *et al.* 2013). It consists of the voltage source, non-linear load and passive filter. The three phase voltage source supplies sinusoidal waveform to the non-linear load. This load affects the sinusoidal waveform causing waveform, distorted. The distorted waveform or harmonic contented current is to be compensated by a passive filter in the system. Passive filter is shunt connected.

Optimal passive filter design

Use of passive harmonic filter is the simplest, cheapest, and the most effective way to reduce harmonics of the voltage and current waveforms. Any passive filter

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consists of the combination of an inductor, resistor and capacitor elements. Optimal design means minimizing the cost of the filters and reduces the total harmonic distortion of currents and voltages. This requires calculating the lowest values of capacitor, inductor, and resistor to obtain the standard total harmonic distortion (THD) of current (Dastfan *et al.*, 2014).

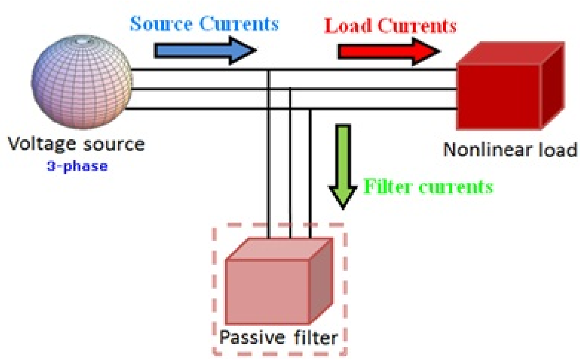

Figure-1. Basic configuration of passive filter.

There are several types of passive filters. The most common filter types are as shown in Figure-2 (Das, J. C, 2011).

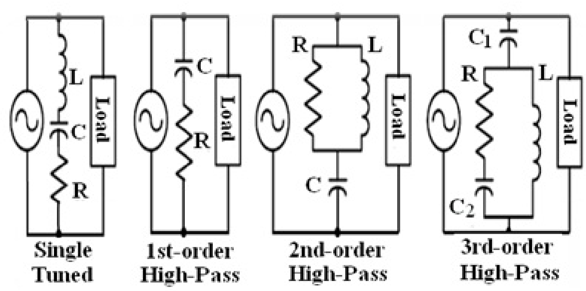

Figure-2. Different type of passive filters.

Single tuned passive filter design

The single tuned filter is the most common type of filter which is used in industry for mitigating the harmonic. This filter is inexpensive and simplest compared with other filters for mitigating the harmonic problems (Cho, Y. S *et al.* 2011), (Buła, D *et al.* 2010).

This filter is connected in shunt with the distribution system and it will offer low impedance to current through which harmonic current will tend to divert in the system. A very simple arrangement of the single tuned passive filter is shown in the Figure-3 (Singh, B *et al.* 1999). For designing the single tuned passive filter, it is important to calculate an appropriate resistor, capacitor and inductor values that enable to mitigate harmonics in power frequency. The equation of resonant frequency for single tuned frequency is given by following equation.

$$f_r = \frac{1}{2\pi\sqrt{LC}} \quad (1)$$

f_r = Frequency resonant in Hertz
L = Inductance of Filter in Henry
C = Capacitance of Filter in Farad

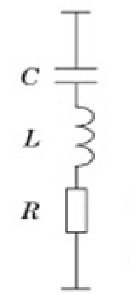

Figure-3. Simple arrangement of single tuned passive filter.

Following are the steps, to designing the single tuned passive series filter:

Step 1: Determine the three-phase capacitive reactive power (Q_c) in VArs. Specify it with a positive value. For this, a range of Q_c i.e. 500 to 9500 at the step of 1000 was used. To get THD ≤ 5%, an optimal value of (Q_c) was obtained by using Langrange interpolation method. This method is discussed later on.

Step 2: Evaluate the capacitive reactance (X_c), at the fundamental frequency (f).

$$X_C = \frac{V^2}{Q_c} \quad (2)$$

$$C = \frac{1}{2\pi f X_C} \quad (3)$$

V = The (rms) nominal line to line voltage (in kV)

Step 3: Calculate the inductive reactance (X_L) and inductance (L) at the fundamental frequency.

$$X_L = \frac{X_C}{{h_n}^2} \quad (4)$$

$$L = \frac{X_L}{2\pi f} \quad (5)$$

h_n = The harmonic order

Step 4: Calculate the resistance (R) for a specified quality factor (Q). The range value of Q lies between 30 and 50.

$$R = \frac{X_n}{Q} \quad (6)$$

$$X_n = \sqrt{X_L X_C} \tag{7}$$

X_n = The characteristic reactance

Lagrange interpolation method

Mostly data is given in discrete points such as (x_0, y_0), (x_1, y_1), …., (x_n, y_n). Therefore to represent (n+1) with a continuous function $f(x)$ passing through the (n+1) points is as shown in Figure-4.

Through interpolation one can find the value of (y) at any other value of (x).

If $f(x)$ falls outside the range of (x) for which the data is given, it is no longer interpolation but instead it is called extrapolation.

A polynomial is a common choice for an interpolating function because polynomials are easy to evaluate, differentiate and integrate, relative to other choices such as a trigonometric and exponential series.

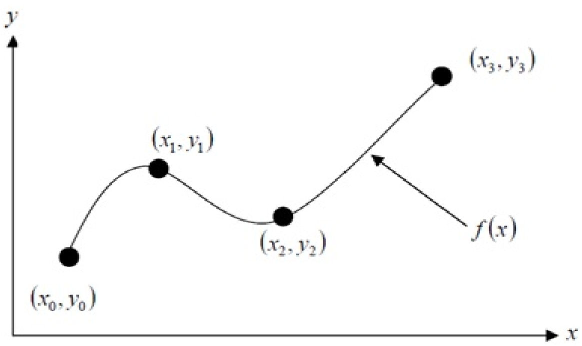

Figure-4. Interpolation of discrete data.

Polynomial interpolation involves finding a polynomial of the order (n) that passes through the (n+1) data points. One of the methods used to find this polynomial is called the Lagrangian method of interpolation. Other methods include Newton's divided difference polynomial method and the Direct method. The Lagrangian interpolating polynomial is given by:

$$f_n(x) = \sum_{i=0}^{n} L_i(x) f(x_i) \tag{8}$$

Where (n) in $f(x)$ stands for the (n^{th}) order polynomial that approximates the function $y = f(x)$ given at (n+1) data points as (x_0, y_0), (x_1, y_1),…., (x_n, y_n), and

$$L_i(x) = \prod_{\substack{j=0 \\ j \neq i}}^{n} \frac{x - x_j}{x_i - x_j} \tag{9}$$

Where $L_i(x)$ is a weighting function that includes a product of (n-1) terms with terms of $j=i$ omitted.

Parameters of single tuned passive filter design

The values of C, L and R were calculated based on the equations from equation (2) to equation (9). The Table-1 that shows the circuit parameters of Figure-5.

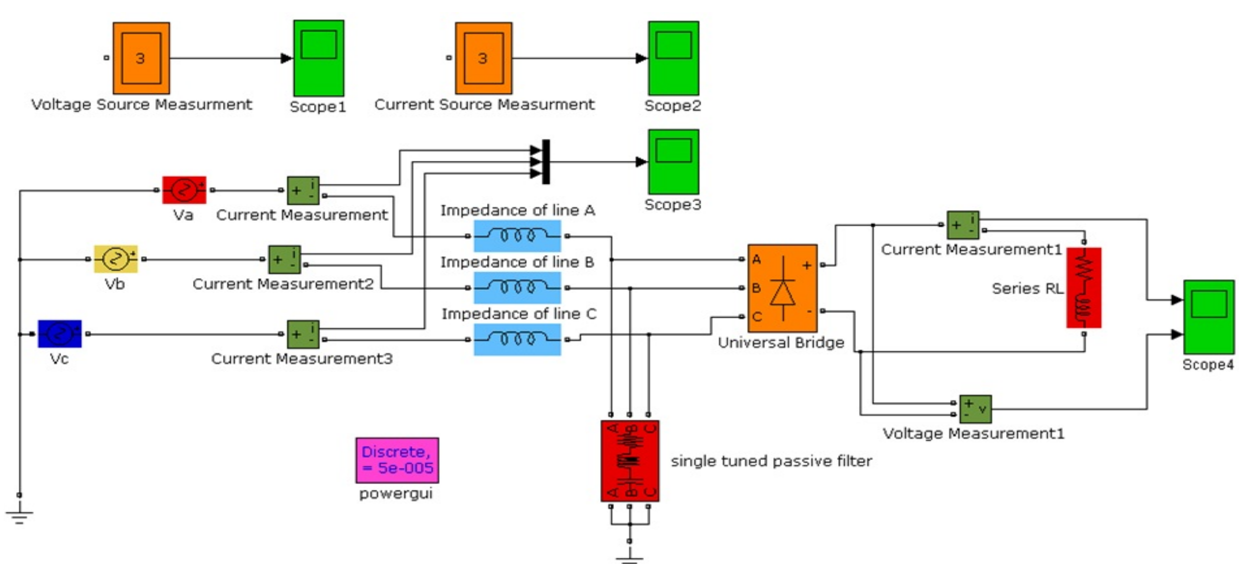

Figure-5. Power system model with single tuned passive filter.

Table-1. Circuit parameters (Das, J. C, 2011).

Components	Parameter Values
Source Voltage	$V_{LL} = 220\ V_{rms}$
Source Frequency	$f = 50$ Hz
Line inductance	$L_{abc} = 1.7$ mH
Rectifier load inductance	$L_L = 1$ mH
Rectifier load resistance	$R_L = 100\ \Omega$

Table-2 shows the optimal values of the single tuned filter where the optimal parameters of the single tuned passive filter are computed at Q=50 and 5% THD based on IEEE Standard 519 (F II, 1993). The filter is tuned to the 5th harmonic because it is found the highest value of the fundamental harmonic component as shown in Table-3.

Table-2. Values of designed filter.

C (F)	*L (H)*	*R* (Ω)
0.3995e-3	1.0145e-3	0.0319

RESULTS ANALYSIS AND DISCUSSION

The performance of the single tuned filter parameters has been verified by using MATLAB/Simulink software.

In this paper, non-linear load (three-phase AC-DC converter) has been simulated with and without single tuned filter. The simulated circuit is shown in Figure-5.

Figure-6 and Figure-7 show the supply voltage and current waveform respectively, without a single tuned passive filter. From Figure-7, it is clear that the current waveform contains some non-linear relationship. Therefore to obtain its frequency spectrum and know the THD, fast fourrier transform analysis was used as shown in Figure 8. It shows the THD of the order of 28.28%.

Table-3 presents the harmonic value in % with respect to the fundamental component, while developed single tuned filter is not connected.

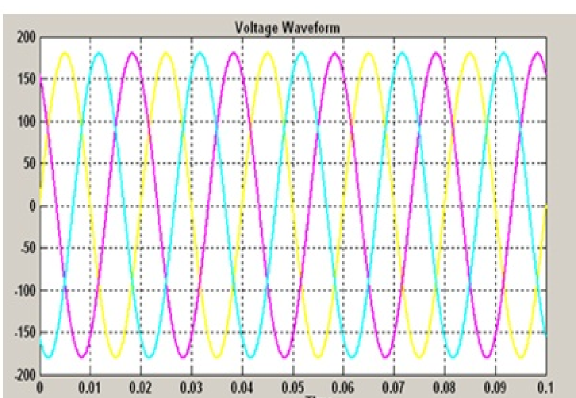

Figure-6. Supply voltage without single tuned passive filter.

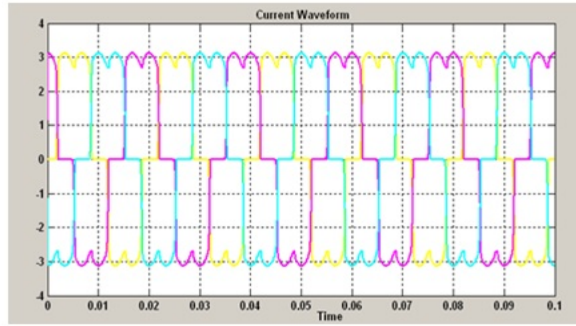

Figure-7. Supply current without single tuned passive filter.

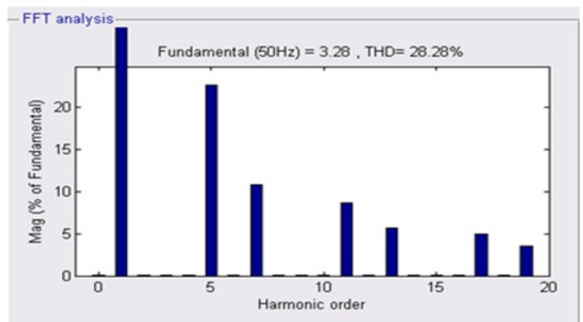

Figure-8. Frequency spectrum of Supply current without single tuned passive filter.

Table-3. Harmonic values in the supply current with respect to the fundamental component (without single tuned passive filter).

Fundamental (50Hz) = 3.28 % THD = 28.28%			
Harmonic order	% of fundamental harmonic	Harmonic order	% of fundamental harmonic
1	100	11	8.64
2	0.03	12	0.03
3	0.05	13	5.69
4	0.03	14	0.03
5	22.59	15	0.05
6	0.03	16	0.02
7	10.83	17	4.94
8	0.03	18	0.02
9	0.05	19	3.52
10	0.03	20	0.00

Figure-9 shows the supply current waveforms when single tuned passive filter is connected. The 5th harmonic is eliminated of the source current, as can be seen in its frequency spectrum, which is shown in Figure-10 and in Table-4 (harmonic value in % with respect to the fundamental component). We can see how the harmonic values decrease, improving the THD from 28.28% to 4.87% by using one type of passive filter namely single tuned filter.

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(Memon, Z *et al.* 2012) have used two types of passive filters, namely single tuned filter and second order high pass filter and found that THD have decreased from 20.77% to 4.32%. Otherwise, the source current amplitude increased from 3.28 A to 25.38 A due to the impedance of the single tuned filter where (Anooja, C. L. et al) have used four single tuned filters and found that the source current increased from 6.35 A to 13.06 A. However the source current amplitude increased from 3.28 A to 25.38 A, which is due to the impedance of the single tuned filter.

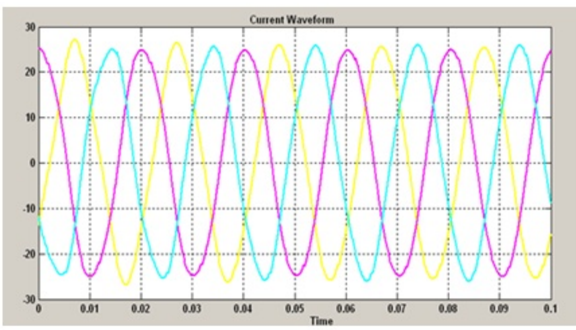

Figure-9. Supply current when single tuned passive filter is connected.

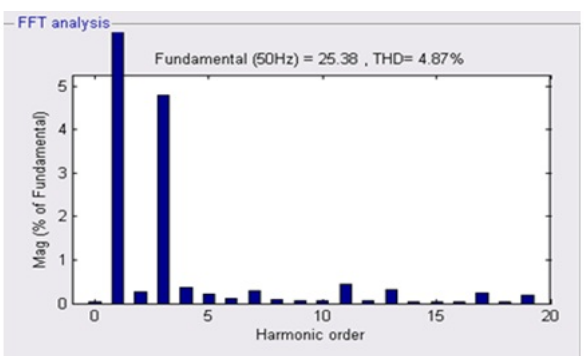

Figure-10. Frequency spectrum of Supply current with single tuned passive filter.

Table-4. Harmonic values of the supply current when single tuned passive filter is connected.

Fundamental (50 Hz) = 25.38%		THD = 4.87%	
Harmonic order	**% of fundamental harmonic**	**Harmonic order**	**% of fundamental harmonic**
1	100	11	0.44
2	0.26	12	0.05
3	4.79	13	0.32
4	0.36	14	0.04
5	0.21	15	0.04
6	0.13	16	0.03
7	0.28	17	0.25
8	0.08	18	0.03
9	0.07	19	0.19
10	0.06	20	0.00

CONCLUSIONS

This paper presented the design of single tuned passive filter to mitigate harmonic distortion caused by nonlinear loads in a power system by using MATLAB/Simulink. From the simulation results, it can be concluded that the efficiency results of the designed filter was successfully achieved by mitigating the harmonics at the value of filter Q as 50. Generally, the THD of line current has been successfully decreased from 28.28% to 4.87% for the used non-linear load system, which fulfills the recommended harmonic standard (IEEE 519) i.e. THD less than 5%. Otherwise, the source current amplitude increased from 3.28 A to 25.38 A due to the impedance of the single tuned filter. Comparing the harmonics before and after the developed filter installation cases, the 5th harmonic was decreased from 22.59% to 0.21%, the 7th harmonic was decreased from 10.83% to 0.28% and 11th harmonic decreased from 8.64% to 0.44%. As a conclusion, the performance of single passive filter is depending on the parameter values such as*C*, *L*, and *R* to mitigate the harmonics.

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