Overview of Double Tuned Harmonic Filters in Improving Power Quality under Non Linear Load Conditions

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Abstract

Improving power quality play a vital role in distribution systems since, these are majorly connected to nonlinear loads. Nonlinear loads generate harmonics, which in turn disturb the source of supply. The double tuned filters are designed by either equivalent method or parametric method but the parametric method is most preferable because of consideration of reactive power demand of the nonlinear load. In this proposed research paper, various types of damped double tuned filters are designed for different nonlinear loads and a comparison between aforementioned two methods when connected to different nonlinear loads has been discussed. A flowchart has developed to optimize the damped double tuned filter parameters by measuring impedance with frequency and tested by using MATLAB programming.

Keywords: *Damped Double Tuned Filters, Harmonics, Non-Linear Loads, Power Quality, Reactive Power Demand, Triple Tuned Filters.*

1. Introduction

Now a days many power quality issues arising in day to day life, which are creating much inconvenience to the customers and utilities. After the power electronic revolution, many consumers are connected to power electronic controlled loads as it gives so much of flexibility, smooth control and many advantages. By means of adjustable speed drives a smooth control is possible which gives lot of benefits to the consumers in saving energy and cost but, on the other side it generates harmonics into the power system. Harmonics may be even, odd, triplen and sub harmonics. Harmonics create unbalance in the power system, malfunctioning of circuit breaker, damaging the sensitive equipment, heating of neutral conductor and so on. It is very much essential to eliminate harmonics in the power system to improve the power quality. Power Quality means improving both voltage and current waveform into purely sinusoidal at the source. Many current harmonic filters are mentioned in the literature, but the recent trend is to go for double tuned and triple tuned filters to eliminate current harmonics when connected to nonlinear loads. Earlier days single tuned filters were used but it eliminates only one harmonic for each filter, it requires separate circuit breaker for each harmonic elimination, it creates resonance problem with the source impedance, the circuit size becomes bulky to eliminate multiple harmonics. Later on active filters have been evolved it gives lot of advantages as compared to single tuned filters, it eliminates harmonics up to the 20th order, very suitable for dynamic nonlinear loads, very less resonance problems with the source impedance. The drawback of active filter is the more cost due to the usage of power electronic converters and the controlling technique is very difficult as it has to generate harmonics which are equal and opposite of the source harmonics. The recent trend is double tuned

filters which gives the performance almost equal to the active filter. The advantage of double tuned filter is that it requires only one circuit breaker in each phase, the space requirement is less, design is easy, less maintenance and finally the cost is very less as compared to active filter [1]. Double tuned filters are classified into two types one is conventional double tuned filter and the other one is damped double tuned filter. The double tuned filters can be solved either by means of equivalent method or parametric method. In equivalent method, the parameters of double tuned filter can be solved by using the parameters of single tuned filters but it is not an accurate method to calculate because it does not consider the actual reactive power demand of the nonlinear loads like bridge converters, arc furnace, induction motor, Switched Mode Power supply (SMPS), saturable transformers and so on [2]. In parametric method, the double tuned filter parameters can be calculated by using a known data such as reactive power demand (Q) of the nonlinear load, tuned frequencies (ω_1, ω_2) and parallel resonance frequency (ω_p) [2].

In conventional double tuned filter the harmonics gets amplified when the filter impedance is equal to the system impedance, so the harmonic distortion will be more during this condition [2]. In order to suppress harmonic amplification during resonance condition, a suitable resistor is added to the conventional double tuned filter that becomes a damped double tuned filter [2]. Many topologies of damped double tuned filters are available in the literature.

This research paper sectioned into six sections, Section 2 deals with the design of conventional double tuned filter, the design of various damped double tuned filters are elaborated in Section 3, Optimization of damped double tuned filters was explained in Section 4, Section 5 explains the results and discussion, conclusions and future scope is detailed in Section 6.

2. Design of Conventional Double Tuned Filter

Figure 1. a) Double Tuned Filter b) Equivalent Single Tuned Parallel Filter

The conventional double tuned filter is as shown in Figure 1 consists of series resonant circuit and parallel resonant circuit connected together in series. The series resonant circuit offers low impedance at series resonance frequency (ω_s) whereas parallel resonant circuit offers high impedance at parallel resonance frequency (ω_p). The combination of series and parallel resonance circuit offers low impedance path for the two resonant frequencies as shown in Figure 2. The double tuned filter can be designed either by equivalent method or parametric method.

2.1 Equivalent Method of Designing Double Tuned Filter

In this method, the double tuned filter parameters are calculated by using two single tuned filters connected in parallel. The impedances of both double-tuned filter and two single tuned parallel filters are same [3].

Figure 2. Characteristics of Double Tuned Filter

The series circuit impedance is

$$Z_s = j\omega L_1 + \frac{1}{j\omega C_1} \quad (1)$$

The parallel circuit impedance is

$$Z_p = \left(j\omega C_2 + \frac{1}{j\omega L_2} \right) \quad (2)$$

The total impedance is

$$Z = j\omega L_1 + \frac{1}{j\omega C_1} + \left(j\omega C_2 + \frac{1}{j\omega L_2} \right)^{-1} \quad (3)$$

$$Z = \frac{\left(1 - \frac{\omega^2}{\omega_s^2} \right) \left(1 - \frac{\omega^2}{\omega_p^2} \right) - \omega^2 L_2 C_2}{j\omega C_2 \left(1 - \frac{\omega^2}{\omega_p^2} \right)} \quad (4)$$

The series resonance frequency (ω_s), parallel resonance frequency (ω_p) in radians/sec can be expressed as

$$\omega_s = \frac{1}{\sqrt{L_1 C_1}}; \omega_p = \frac{1}{\sqrt{L_2 C_2}} \quad (5)$$

Let, ω_a, ω_b are the resonant frequencies of two single tuned passive filters.

$$\omega_a = \frac{1}{\sqrt{L_a C_a}}; \omega_b = \frac{1}{\sqrt{L_b C_b}} \quad (6)$$

The impedance of two parallel single tuned filters can be expressed as

$$Z_{ab} = \frac{\left(1 - \frac{\omega^2}{\omega_a^2} \right) \left(1 - \frac{\omega^2}{\omega_b^2} \right)}{j\omega C_a \left(1 - \frac{\omega^2}{\omega_b^2} \right) + j\omega C_b \left(1 - \frac{\omega^2}{\omega_a^2} \right)} \quad (7)$$

The cumulative impedance of double tuned filter is same as cumulative impedance of two single tuned passive filters [4].

$$Z = Z_{ab} \quad (8)$$

Comparing coefficient of ω^4

$$\omega_a \omega_b = \omega_s \omega_p \quad (9)$$

Comparing coefficient of ω

$$C_1 = C_a + C_b \quad (10)$$

Comparing coefficient of w^3

$$C_b \frac{1}{w_a^2} + C_a \frac{1}{w_b^2} = C_1 \frac{1}{w_p^2} \quad (11)$$

The parameter L_1 is given by

$$L_1 = \frac{1}{C_a w_a^2 + C_b w_b^2} \quad (12)$$

The series resonance frequency w_s and parallel resonance frequency w_p of double tuned filter can be obtained by

$$w_s = \frac{1}{\sqrt{L_1 C_1}} \quad (13)$$

$$w_p = \frac{w_a w_b}{w_s} \quad (14)$$

Since, w_a is the zero of double tuned filter impedance, so $Z(w_a) = 0$. The equation to solve L_2 is

$$\left(1 - \frac{w_a^2}{w_s^2}\right) \left(1 - \frac{w_a^2}{w_p^2}\right) - w^2 L_2 C_1 = 0 \quad (15)$$

The above equation can be simplified to get L_2

$$L_2 = \frac{\left(1 - \frac{w_a^2}{w_s^2}\right) \left(1 - \frac{w_a^2}{w_p^2}\right)}{C_1 w_a^2} \quad (16)$$

The value of C_2 can be obtained by

$$C_2 = \frac{1}{L_2 w_p^2} \quad (17)$$

Hence, all the parameters needed for double tuned filter (L_1, C_1, L_2, C_2) can be calculated from the parameters of two parallel-connected single tuned filters (L_a, C_a, L_b, C_b).

This double tuned passive power filter can provide better performance in eliminating lower order current harmonics than two single tuned passive filters. The size and the reactive power requirement of double tuned passive filter is less as compared to single tuned passive filter. Hence, double tuned passive filter is the best choice for eliminating two lower order current harmonics.

2.2 Parametric Method of Designing Double Tuned Filter

The drawback of equivalent method is that, it does not consider the actual reactive power demand of the nonlinear loads and it is not an accurate method. In parametric method, the parameters of double tuned filter can be calculated by using the known data

such as tuned frequencies (w_1, w_2) , parallel resonant frequency (w_p) and reactive power demand (Q) of the nonlinear loads.

At tuned frequencies, the total impedance of double tuned filter is zero

$$Z = j\omega L_1 + \frac{1}{j\omega C_1 + \left(j\omega C_2 + \frac{1}{j\omega L_2} \right)^{-1}} = 0 \quad (18)$$

Eq. (18) gives the following relation

$$w^4 L_1 L_2 C_1 C_2 - w^2 (L_2 C_1 + L_1 C_1 + L_2 C_2) + 1 = 0 \quad (19)$$

The roots of the Eq. (19) are solved by using vida's theory. According to Vida's theory, the relationship between the roots and the coefficients of the Eq. (19) is given by

$$w_1^2 w_2^2 = (L_1 C_1 L_2 C_2)^{-1} \quad (20)$$

i.e

$$w_1 w_2 = \frac{1}{\sqrt{L_1 C_1}} \frac{1}{\sqrt{L_2 C_2}} = w_s w_p \quad (21)$$

In Eq. (21) w_1 & w_2 are the tuned frequencies and w_s & w_p are the series and parallel resonant frequencies.

The harmonic currents at tuned frequencies $(w_1 \text{ \& } w_2)$ will be bypassed by the double tuned filter [5]. The tuned frequencies $(w_1 \text{ \& } w_2)$ are defined first, and then the parameters L_1, C_1 & L_2, C_2 will be derived. The filter impedance is infinite at the parallel resonant frequency (w_p) and zero at series resonant frequency (w_s) . To prevent some harmonic currents near w_p from being severely amplified, engineers should take account of the network harmonic impedance and select a parallel resonant frequency w_p properly in the designing process. If w_1, w_2 and w_p is determined, w_s is certainly defined by Eq. (21). Substituting Eq. (5) into Eq. (19) yields

$$\frac{w^4}{w_s^2 w_p^2} - \left(\frac{C_1}{C_2} \frac{1}{w_p^2} + \frac{1}{w_s^2} + \frac{1}{w_p^2} \right) w^2 + 1 = 0 \quad (22)$$

Since, w_1, w_2 are the solutions of Eq. (22), substituting w by w_1 & w_2 , the relationship between C_1 & C_2 can be obtained as

$$\frac{C_1}{C_2} = \frac{w_1^2 + w_2^2 - w_p^2}{w_s^2} - 1 \quad (23)$$

From Eq. (20), L_1 can be calculated as

$$L_1 = \left(\frac{w_p}{w_1 w_2} \right)^2 \cdot \frac{1}{C_1} \quad (24)$$

From Eq. (5) L_2 can be calculated as

$$L_2 = \frac{1}{w_p^2} \cdot \frac{1}{C_2} = \frac{1}{w_p^2 C_1} \left(\frac{w_1^2 + w_2^2 - w_p^2}{w_s^2} - 1 \right) \quad (25)$$

Apart from bypassing the harmonic currents, the double tuned filter also compensates reactive power, which demands by the nonlinear load. Suppose the fundamental system voltage is U , and the fundamental reactive power supplied by the filter is Q , the impedance of the filter at the fundamental frequency (ω_F) is

$$Z(\omega_F) = \frac{-jU^2}{Q} \quad (26)$$

The impedance of the filter at the fundamental frequency is

$$Z(\omega_F) = j\omega_F L_1 + \frac{1}{j\omega_F C_1 + \left(j\omega_F C_2 + \frac{1}{j\omega_F L_2} \right)^{-1}} \quad (27)$$

Equating Eq. (26) and (27) gives the value of capacitor C_1

$$C_1 = \left\{ \frac{1}{\omega_F} - \omega_F \left(\frac{\omega_p}{\omega_1 \omega_2} \right)^2 + \frac{\omega_F \left[(\omega_1^2 + \omega_2^2 - \omega_p^2) \omega_p^2 - \omega_1^2 \omega_2^2 \right]}{\omega_1^2 \omega_2^2 (\omega_p^2 - \omega_F^2)} \right\} \frac{U^2}{Q} \quad (28)$$

Since, ω_1, ω_2 & Q are known, and ω_p is determined at first, then the parameters of the basic double tuned filter can be obtained.

In case, when $\omega_s = \omega_p = \omega_0 = \sqrt{\omega_1 \omega_2}$, the equations can be simplified as

$$\frac{C_1}{C_2} = \frac{(h_2 - h_1)^2}{(h_1 h_2)} \quad (29)$$

$$C_1 = \frac{h_1^2 + h_2^2 - (h_1 h_2)^2 - 1}{(h_1 h_2 - 1) h_1 h_2} \cdot \frac{Q}{\omega_F U^2} \quad (30)$$

$$L_1 = \frac{1}{\omega_0^2 C_1} \quad (31)$$

$$L_2 = \frac{(\omega_1 - \omega_2)^2}{\omega_0^4 C_1} \quad (32)$$

$$\text{Where } h_1 = \frac{\omega_1}{\omega_F}, \quad h_2 = \frac{\omega_2}{\omega_F}$$

3. Design of Damped Double Tuned Filters

Figure 3. Various Types of Damped Double Tuned Filters

The drawback of conventional double tuned filter is that, at situations where the filter impedance is equal to the system impedance, the harmonics are heavily amplified due to the resonance condition. To avoid the harmonics excessively amplified during the resonance condition, a resistor is used with suitable configuration in conventional double tuned filter is known as damped double tuned filter as shown in Figure 3.

Many configurations of damped double tuned filters are available as shown in Figure 3. Whatever may be the type of damped double tuned filter, the final objective is to suppress the excessive over voltage harmonics during the resonance condition.

The resistance R_1 in Figure 3 (a) must be an asymptotic line when ω is above ω_2 . Figure 3 (b) acts like a high pass filter when ω is above ω_2 , the resistance R_1 is adjusted in such a way that the inductive and capacitive reactance must cancel each other to provide high impedance path during resonance condition. The impedance of the filter in Figure 3 (c) at ω_p is of the order of R_1 . The impedance of the filter in Figure 3 (d)

should meet the relationship of $R_1 > \sqrt{L_1/C_1}$. Filter of Figure 3 (e) has limited impedance both at ω_p and above ω with its parameters should meet the relationship of $R_1 > \sqrt{L_1/C_1}$ & $R_2 > \sqrt{L_2/C_2}$. Finally, the filter of Figure 3(f) with its impedances both at ω_p and above ω_2 are limited to the lower value of R_1 and R_2 .

4. Optimization of Damped Double Tuned Filter

By scanning the impedance of the damped double tuned filter in frequency domain, there are three pairs of tuned frequencies.

1. The frequencies ω_{z1}, ω_{z2} , at which the impedances of the filter are minimum;
  2. The frequencies ω_{x1}, ω_{x2} , at which the total reactances of the filter equal zero.
  3. Others are the solutions of ω_1 and ω_2 at which the impedance of filter is zero.
- The algorithm for the optimization of double tuned filter is shown in Figure 4.

4.1 Flowchart for the Optimization:

Figure 4. Flow Chart for the Optimization of Double Tuned Filters

5. Results and Discussions

5.1 Three Phase System Connected to Different Nonlinear Loads without Filter

In this research paper, a full bridge rectifier has been chosen to generate harmonics. From the analysis it has been observed that harmonic generation is different for controlled

and uncontrolled rectifier, so the harmonic elimination by the proposed filter was done separately for controlled and uncontrolled bridge rectifiers.

5.1.1 Three Phase System Connected to Uncontrolled Bridge Rectifier

The waveform and THD of the source current when it is connected to uncontrolled bridge rectifier with R-L load is shown in Figure 5 & 6

Figure 5. Source Current

Figure 6. THD of Source Current

5.1.2 Three Phase System Connected to Controlled Bridge Rectifier

The waveform and THD of the source current when it is connected to controlled bridge rectifier (30° firing angle) with R-L load is shown in Figure 7 & 8

Figure 7. Source Current

Figure 8. THD of Source Current

5.2 Comparison of Double Tuned Filter with Equivalent and Parametric Method

5.2.1 Double Tuned Filter with Equivalent Method using Uncontrolled Bridge Rectifier as Nonlinear Load

The waveform and THD of the source current with equivalent method of double tuned filter, when it is connected to uncontrolled bridge rectifier with R-L load is shown in Figure 9& 10.

Figure 9. Source Current

Figure 10. THD of Source Current

5.2.2 Double Tuned Filter with Parametric Method using Uncontrolled Bridge Rectifier as Nonlinear Load

The waveform and THD of the source current with parametric method of double tuned filter, when it is connected to uncontrolled bridge rectifier with R-L load is shown in Figure 11& 12.

Figure 11. Source Current

Figure 12. THD of Source Current

5.2.3 Double Tuned Filter with Equivalent Method using Controlled Bridge Rectifier as Nonlinear Load

The waveform and THD of the source current with Equivalent method of double tuned filter, when it is connected to controlled bridge rectifier (30° firing angle) with R-L load is shown in Figure 13& 14.

Figure 13. Source Current

Figure 14. THD of Source Current

5.2.4 Double Tuned Filter with Parametric Method using Controlled Bridge Rectifier as Nonlinear Load

The waveform and THD of the source current with parametric method of double tuned filter, when it is connected to controlled bridge rectifier (30° firing angle) with R-L load is shown in Figure 15& 16.

Figure 15. Source Current

Figure 16. THD of Source Current

5.3 Implementation of Damped Double Tuned Filter

Damped double tuned filter can realized by means of only parametric method of designing. In this research paper two configurations i.e Figure 3(d) & 3(e) have been selected for the implementation.

The waveform and THD of the source current with parametric method of damped double tuned filter of Figure 3(c), when it is connected to controlled bridge rectifier (30° firing angle) with R-L load is shown in Figure 17& 18.

Figure 17. Source Current

Figure 18. THD of Source Current

The waveform and THD of the source current with parametric method of damped double tuned filter of Figure 3(d), when it is connected to controlled bridge rectifier (30° firing angle) with R-L load is shown in Figure 19& 20

Figure 19. Source Current

Figure 20. THD of Source Current

6. Conclusions and Future Scope

Form the MATLAB results, it can be concluded that elimination of current harmonics is essential to improve the power quality at HVDC converter stations. HVDC converter stations mainly uses SCR or IGBT based converters.

Conventional double tuned filter can be designed by two methods, but the parametric method is more efficient because of consideration of reactive power demand of the load. The double tuned filter eliminates current harmonics, compensates reactive power demand and also it improves true power factor.

Damped double tuned filter is very much suitable during resonance conditions. During resonance, the filter impedance is equal to the source impedance, so higher order harmonics will amplify severely due to that more harmonic distortion present at the source.

From the analysis, it has been observed that the thyristor controlled bridge rectifier having more non linearity than IGBT controlled bridge rectifier, but the most of the High Voltage HVDC converters uses thyristor controlled converters due to their high withstand capability. Research is going on to implement IGBT controlled converters at High Voltage HVDC converters due to their less non linearity.

A three phase shunt active filter with suitable control technique can also be used to eliminate current harmonics, but the cost is very high as compared to the double tuned filter.

A triple tuned filter can also be implemented by the proposed two methods, but the design is difficult. Research is going to evaluate the parameters of triple tuned filter.

The parameters selected for the double tuned and damped double tuned filter are tabulated in Table 1

Table 1. Parameters of Double Tuned and Damped Double Tuned Filter

Parameters	Value
Three phase power supply (V_{sPh-Ph} , f , R_s , L_s)	415 V, 50 Hz, 0.8929 Ω , 16.58 mH
Load Resistance(R_L)& Inductance(L_L)	40 Ω , 180Mh
Equivalent method of Double tuned passive filter	4.56mH, 5.56×10^{-4} H 60 μ F, 5.5×10^{-4} F
Parametric method of Double tuned passive filter (L_1 , L_2 , C_1 , C_2)	0.5372mH, 0.063149mH 509.721 μ F, 4846.64 μ F
Damped double tuned method of Figure 3(c) (L_1 , L_2 , C_1 , C_2 , R_1)	0.5372mH, 0.063149mH 509.721 μ F, 4846.64 μ F, 2740 Ω
Damped double tuned method of Figure 3(d) (L_1 , L_2 , C_1 , C_2 , R_1 , R_2)	0.5372mH, 0.063149mH, 509.721 μ F, 4846.64 μ F, 476 Ω , 2744 Ω

The THD levels of different harmonic filters with uncontrolled bridge rectifier is tabulated in Table 2

Table 2. THD Levels of Different Harmonic Filters with Uncontrolled Bridge Rectifier

Type of Filter	THD of Source Current
Without filter	16.51
Equivalent method of Double tuned passive power filter	1.56
Parametric method of Double tuned passive power filter	0.10
Damped double tuned method of Figure 3(d)	0.10
Damped double tuned method of Figure 3(e)	0.09

The THD levels of different harmonic filters with controlled bridge rectifier are tabulated in Table 3.

Table 3. THD Levels of Different Harmonic Filters with Controlled Bridge Rectifier

Type of Filter	THD of Source Current
Without filter	24.56
Equivalent method of Double tuned passive power filter	1.56
Parametric method of Double tuned passive power filter	0.10
Damped double tuned method of Figure 3(d)	0.10
Damped double tuned method of Figure 3(e)	0.09

Acknowledgments

The authors are highly acknowledged J.N.T.U, Kakinada, S.V.E.C, Tirupathi and JNTU, Hyderabad for giving research support and encouragement during the Ph. D programme.

Note: The authors declare that there is no conflict of interest regarding the publication of this paper.

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