

Impact Analysis of Damping Resistors in Damped Type Double Tuned Filter on Network Harmonic Impedance

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Abstract: - In recent years the usage of power electronics equipment and non-linear elements increased in various areas of power system. Power systems contain considerable levels of harmonics which cannot be ignored further because there is considerable effects on power system equipment due to the harmonics. The filters are useful to eliminate harmonics and provide reactive power compensation. Double tuned filter is the type of passive filters have been widely using in Industries and HVDC stations. This paper proposed the design procedure for the parameters of the damped type double tuned filter based in the tuned frequencies and parallel resonance frequency and reactive power demand and voltage of the network. This paper deals with the effect of damping resistors connected in different configurations on the network impedance .To find the parameters a program has been developed in MATLAB-2015b. The performance of the filter parameters are verified by using MiPower 9.1.

Keywords: Harmonics, Mitigation techniques, Harmonic distortion, Double tuned passive filters, Damped resistors.

I. INTROUDCTION

With the growing usage of nonlinear loads and power electronic equipment in the power system there is a great concern about power quality issues particularly harmonic distortion. The harmonic distortions in the voltage and current waveforms in the power system are increasing continuously due to these nonlinear equipment. These harmonics may produce undesirable effects on various type of equipment which are present in power system and communication systems[1]-[4]. So it is very important to reduce the harmonic content produce by nonlinear to avoid the damage of the utility equipment. To eliminate harmonics so many techniques are proposed. Filter design is the most old and popular mitigation technique used in industries. The In this paper passive filters design mainly damped type double tuned filter is design is presented. The estimation of double tuned filter parameters from the two parallel single tuned filter bank is proposed in [7].In this paper algorithm-2 is adopted from [8] and algorithm-1is adopted from [6].

II. BASIC DOUBLE TUNED FILTER

Passive filters are the circuits with R, L and C elements connected in different ways to eliminate desired harmonics by providing an alternative path to the harmonic currents. This passive filter technique is much popular, simple and easier than the advanced harmonic reduction techniques like PWM static VAR compensators and magnetic flux compensation, Active filters. Single tuned (ST) filters, Double tuned (DT) filters, and C-type filters are different type of passive filters. Double tuned filter is combination of one series resonant circuit and one parallel resonant circuit and it is used to eliminate two harmonic frequencies at a time. Generally To eliminate two harmonic frequencies at a time then two ST filters are required. The equivalent

impedances of two single-tuned filters near their resonance frequencies are practically the same as the basic double tuned filter configuration.

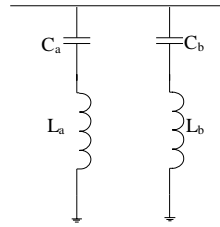


Figure.1. Two parallel single tuned filters

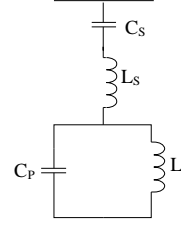


Figure.2. Double tuned filter

The basic double tuned filter is practically equal to the parallel branch of two single tuned filters. Hence the calculation of double tuned filter parameters has been done by equating the impedance of basic double tuned filter and parallel connection of two single tuned filters. The total impedance of the parallel connection of two single tuned filters has been written as

$$Z(\omega) = \left(j\omega L_a + \frac{1}{j\omega C_a} \right) \parallel \left(j\omega L_b + \frac{1}{j\omega C_b} \right) \quad (1)$$

The total impedance of the basic double tuned filter has been written as

$$Z(\omega) = j\omega L_s + \frac{1}{j\omega C_s} + \frac{j\omega L_p}{1 - \omega^2 L_p C_p} \quad (2)$$

By equating (1) and (2), the series branch parameters (L_s, C_s) and parallel branch parameters (L_p, C_p) of the double tuned filter can be expressed as

$$C_s = C_a + C_b \quad (3)$$

$$L_s = \frac{L_a L_b}{L_a + L_b} \quad (4)$$

$$C_p = \frac{C_a C_b (C_a + C_b) (L_a + L_b)^2}{(C_a L_a - C_b L_b)^2} \quad (5)$$

$$L_p = \frac{(C_a L_a - C_b L_b)^2}{(L_a + L_b) (C_a + C_b)^2} \quad (6)$$

Where L_a, L_b, C_a, C_b are the parameters of two individual single tuned filters. By using (3), (4), (5), (6) the parameters of the filters are tuned for the particular harmonic order with particular reactive power and bus voltage. From the above design it is not possible to choose the particular parallel resonant frequency, so a method is proposed in [8] to determine the parameters of the double tuned filter by choosing the desired parallel resonance.

III. ALTERNATIVE DESIGN OF DOUBLE TUNED FILTER BY CHOOSING THE PARALLEL RESONANCE FREQUENCY

In conventional design procedure of filter which is previously explained in section II there has been no choice to choose the intermediate frequency between interested tuned frequencies. If any harmonic frequency between the two selected tuned frequencies is causing severe harmonic injections into the system these harmonic contents can be minimized by reducing the filter impedance at that frequency. Because normally at parallel resonance frequency the impedance is very high. An alternative approach has been designed to shift the parallel resonance point to reduce the harmonic content. The procedure to determine the parameters using parallel resonance frequency has been explained in this paper. From the basic double tuned filter the impedance of the series and parallel circuits are $Z_s(\omega), Z_p(\omega)$ respectively

$$Z_s(\omega) = j\omega L_s + \frac{1}{j\omega C_s} \quad (7)$$

$$Z_p(\omega) = j\omega L_p \parallel \frac{1}{j\omega C_p} \quad (8)$$

$$Z_p(\omega) = \frac{j\omega L_p \frac{1}{j\omega C_p}}{j\omega L_p + \frac{1}{j\omega C_p}} = \frac{j\omega L_p}{1 - \omega^2 L_p C_p} \quad (9)$$

Where ω is the angular frequency and the series resonant frequencies of the series and parallel circuits respectively

$$\text{Series resonant frequency } \omega_s = \frac{1}{\sqrt{L_s C_s}} \quad (10)$$

$$\text{Parallel resonant frequency } \omega_p = \frac{1}{\sqrt{L_p C_p}} \quad (11)$$

When $\omega < \omega_s$ the series circuit impedance ($Z_s(\omega)$) is capacitive and when $\omega > \omega_s$ the series circuit impedance is inductive. When $\omega < \omega_p$ the parallel circuit impedance ($Z_p(\omega)$) is inductive and when $\omega > \omega_p$ the parallel circuit impedance ($Z_p(\omega)$) is capacitive

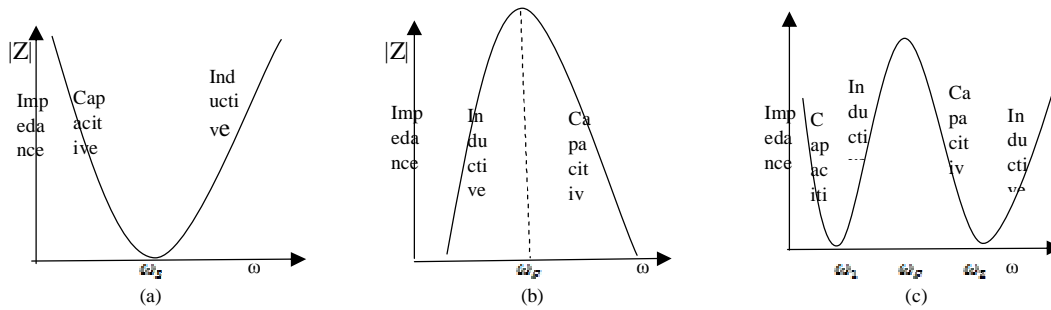


Figure.3. (a) Characteristics of the series branch of double tuned filter (b) Characteristics of the parallel branch of double tuned filter (c) Characteristics of the double tuned filter

The total impedance of the basic double tuned filter $Z(\omega)$ is

$$Z(\omega) = Z_s(\omega) + Z_p(\omega) \quad (12)$$

The total Thevinin impedance of double tuned filter at the tuned frequencies is zero

$$Z(\omega) = j\omega L_s + \frac{1}{j\omega C_s} + \frac{j\omega L_p}{1 - \omega^2 L_p C_p} = 0 \quad (13)$$

$$\Rightarrow \omega^4 L_s L_p C_s C_p - \omega^2 [L_s C_s - L_p C_p - L_p C_s] + 1 = 0 \quad (14)$$

Let ω_1^2, ω_2^2 are the roots of above equation, then

$$\omega_1^2 \omega_2^2 = \frac{1}{L_s L_p C_s C_p} \quad (15)$$

$$\omega_1 \omega_2 = \frac{1}{\sqrt{L_s C_s}} \frac{1}{\sqrt{L_p C_p}} = \omega_s \omega_p \quad (16)$$

$$\Rightarrow \omega_s = \frac{\omega_1 \omega_2}{\omega_p} \quad (17)$$

From (16), the obtained relations are

$$L_s = \left(\frac{\omega_p}{\omega_1 \omega_2} \right)^2 \frac{1}{C_s} \quad (18)$$

$$L_p = \frac{1}{\omega_p^2 C_p} \left(\frac{\omega_1^2 + \omega_2^2 - \omega_p^2}{\omega_s^2} - 1 \right) \quad (19)$$

Besides filtering the harmonic current, the double tuned filter has another performance of supplying the reactive compensation power. If the network fundamental rated voltage is V, and the fundamental reactive power supplied by the filter is Q, then the impedance of the filter at fundamental frequency is

$$Z(\omega_F) = \frac{-jV^2}{Q^2} \quad (20)$$

$$Z(\omega_F) = j\omega_F L_s + \frac{1}{j\omega_F C_s} + \frac{j\omega_F L_p}{1 - \omega_F^2 L_p C_p} \quad (21)$$

$$C_s = \frac{-2}{V^2} \left[\omega_F \left(\frac{\omega_p}{\omega_1 \omega_2} \right)^2 - \frac{1}{\omega_F} + \frac{\omega_F [(\omega_1^2 + \omega_2^2 - \omega_p^2) / \omega_s^2 - \omega_1^2 \omega_2^2]}{\omega_1^2 \omega_2^2 (\omega_s^2 - \omega_F^2)} \right] \quad (22)$$

By using the value C_s then simply, obtain the remaining parameters L_s, C_p, L_p . Finally the parameters of damped type double tuned filter are

$$L_s = \left(\frac{\omega_p}{\omega_1 \omega_2} \right)^2 \frac{1}{C_s} \quad (23)$$

$$L_p = \frac{1}{\omega_p^2 C_p} \left(\frac{\omega_1^2 + \omega_2^2 - \omega_p^2}{\omega_p^2} - 1 \right) \quad (24)$$

$$C_p = C_s \left(\frac{\omega_p^2}{\omega_1^2 + \omega_2^2 - \omega_p^2 - \omega_p^2} \right) \quad (25)$$

In order to design the filter C_s has been calculated initially from the known quantities like network voltage, reactive power required for the network and tuned frequencies. L_s , L_p , C_p are has to be calculated according to (22-25).

IV. DAMPED TYPE DOUBLE TUNED FILTER

The basic double tuned filter Thevenin impedance is almost pure inductive or capacitive in nature over the whole frequency range. If the system impedance is approximately equal in magnitude and conjugate to the impedance of the filter at some harmonic frequencies, as a result the network resonance will occur. Due to this resonance phenomenon the harmonic currents being severely amplified with the harmonic over voltage of the components in the filter and in power system. To prevent such a phenomenon, damping resistors are added to basic type of double tuned filter in different ways to obtain the different configurations of damped type double tuned filters. The characteristics and the performance of damped type double tuned filter will change with respect to the placing of damping resistor.

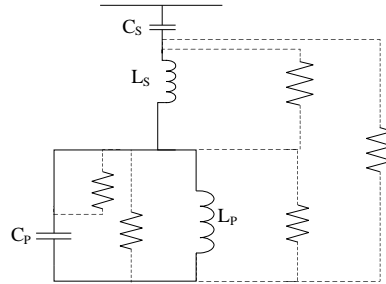


Figure .4. Damped type double tuned filter

Different configuration of damped type double tuned filter has been formed by inserting the damped resistor at different position in basic double tuned filter as showed in Figure.4.the various types of damped type double tuned filter configurations has been explained in section-V. The procedure to determine the parameters of damped type double tuned filter is explained in a step by step process as follows.

- | | |
|---------|--|
| Step 1 | START |
| Step 2 | Choose the type of filter and Read the Input Data $Q, V, \omega_1, \omega_2, \omega_p, R, \varepsilon$ |
| Step 3 | Select tuned frequencies Such that the magnitude of impedance should be minimum |
| Step 4 | Let $\omega_1^i = \omega_1$ and $\omega_2^i = \omega_2$ |
| Step 5 | Calculate $\omega_p, C_s, L_s, L_p, C_p$ using (22), (23), (24), and (25). |
| Step 6 | Find the tuned frequencies ω_{2_1} and ω_{2_2} from frequency scan plot |
| Step 7 | Find $\Delta\omega_1^i = \omega_1 - \omega_{2_1}^i$ and $\Delta\omega_2^i = \omega_2 - \omega_{2_2}^i$ |
| Step 8 | Find maximum value between $ \Delta\omega_1^i $ and $ \Delta\omega_2^i $ and take it as precession (ε) |
| Step 9 | Check the condition $\varepsilon_1 < \varepsilon$ |
| Step 10 | If "YES" Go to Step14 |
| Step 11 | If "No" Go to Step12 |
| Step 12 | Calculate $\omega_1^{i+1} = \omega_1^i + \Delta\omega_1^i$ and $\omega_2^{i+1} = \omega_2^i + \Delta\omega_2^i$ |
| Step 13 | Go to step 4 |
| Step 14 | Validate the performance of the filter |
| Step 15 | STOP |

From the above procedure a program has been developed in MATLAB software to calculate filter parameters accurately. The filter parameter values and performance and impact of the designed filters are explained in detail in section V.

V. CASE STUDY

To analyse the different double tuned filters a test case is taken from [5]. The test system showed in Figure.5 consisting of 220kV generator having short circuit capacity of 4000 MVA X/R ratio as 20 and 100 MVA, 220kV/33kV step down transformer having % impedance as 14 and X/R ratio is 10. This test system consisting linear load of 20MW and nonlinear load (adjustable speed motor drive) of 25MW installed at 33kV bus.100 MVA & 60Hz are considered as the base quantities. A Shunt capacitor having a rating of 8.4 MVAR is also installed at the 33kV bus. The harmonic source in this case study is a standard diode rectifier supplying 25 MW on the dc side. The harmonic content injected by the diode rectifier is tabulated in Table.1. The Harmonic analysis is carried out using MiPower software, with the load modelled as frequency dependent Reactance and constant Resistance (parallel combination) to find out impact of harmonic caused by diode rectifier. The performance of the designed damped type double tuned filters has been verified by using MiPower software. A frequency scan plots has been plotted for every configuration of filter.

Table.1. Harmonic currents injected by diode rectifier at 33kV bus

Harmonic order	5	7	11	13	17	19
Harmonic current(Amps)	87.68	62.22	39.59	33.23	25.45	23.33

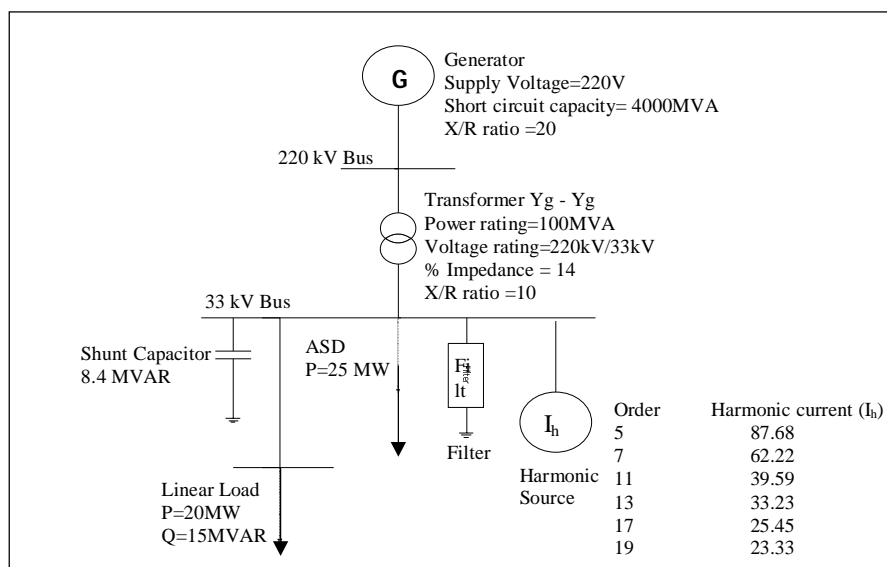


Figure .5. IEEE -319 Test system for harmonic analysis

The results obtained by performing the harmonic analysis on test system without filter and with the filters have been tabulated and also the variation of characteristics of different type of filters with respect to the variation in parallel resonance frequency also has been explained in this section. By performing the harmonic analysis using MiPower for the test system without any filter the results are tabulated in Table 2.

Table.2.Harmonic distortion at 33kV bus without filters

% Voltage harmonic distortions at 33kV bus without filter							
Harmonic order	Total	5	7	11	13	17	19
Harmonic distortion	12.1820	5.7409	8.8072	5.1726	2.8747	1.3365	1.0335

From the Table.2 the harmonic distortions injected by 5th, 7th, 11th order are deviating as per [1]. To eliminate these harmonic it is necessary to design the filter. This work is mainly focused on the different configurations of the damped type double tuned filter. Here the filters are designed for 5th and 11th order harmonics the reactive power has been taken as 8.4Mvar to design the harmonic filters which is previously supplied by capacitor. The filters are designed at 33kV bus voltage. The filter parameters for different configurations obtained through MATLAB programming using algorithm proposed in section-V is tabulated in Table 3. The damping resistor value should be very high if the resistor is connected in parallel to the filter components, and the value of the

resistor should low if the resistor is connected in series with filter elements. In order to satisfy these conditions in this paper the resistor values for different configuration of damped type double filters are tabulated in table.3.

Table.3.The Damped resistor values considered in different configurations of the damped type double tuned filter

Filter type	1	2	3	4	5	6
Damping Resistor value(Ohm)	500	500	500	0.2	$R_1=500, R_2=500$	$R_1=500, R_2=250$

The designed parameters of the damped type double filter by varying the parallel resonance frequency in between 5th and 11th harmonic order frequencies are tabulated in table.4.

Table.4.Filter parameters of different configuration of filters

Filter parameters	Double tuned filter (5 th , 11 th)	Damped type Double tuned filter(5 th , 11 th)			
		$N_p = 7$	$N_p = 8$	$N_p = 9$	$N_p = 10$
L_1 (Henry)	0.0047762	0.0057315	0.0075226	0.0095525	0.011821
C_1 (Farad)	1.9967e-05	1.9886e-05	1.9789e-05	1.9723e-05	1.9677e-05
L_2 (Henry)	0.0036369	0.0041249	0.0040827	0.0032613	0.0018618
C_2 (Farad)	4.7187e-05	3.4812e-05	2.6929e-05	2.6635e-05	3.7792e-05

The voltage harmonic distortions limits after installation basic double tuned filter is tabulated in Table.5.

Table.5. Impact of basic double tuned filter on 33kv bus

% Voltage harmonic distortions on 33 kV bus						
Total	5	7	11	13	17	19
5.3784	0.0001	4.799	0	0.9755	1.5043	1.6378

From the Table it is understand that the 5th and 11th order harmonics are eliminated after installation of basic type double tuned filter at 33kV bus.

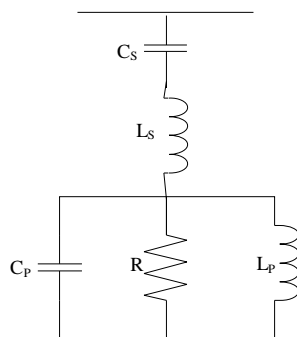


Figure.6. Filter (1)

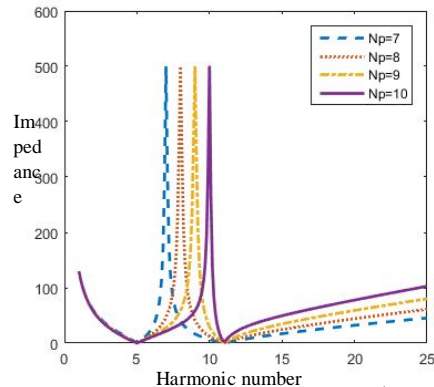


Figure.7.Characterstics of Filter (1)

The filter-1 has been formed by inserting the damped resistance in parallel with the parallel branch of simple double tuned filter. The characteristics of Filter (1) damped type double tuned filter will depend upon the resistor R value

1. if $R=0$ then the resistance branch is short circuited and the damped type double tuned filter will act as single tuned filter at some resonant frequency, this resonant frequency will depend up on the modelled series filter elements of damped type double tuned filter.
2. If R is finite value then then the impedance of the damped type double tuned filter will be in the order of that R value. The value of R must be chosen like it should be more.
3. If R is infinite then the resistance branch is open circuit then it will act as a simple double tuned filter.

From figure.7. It is clear that impedance of filter (1) is in order of $R=500$ ohms at every order of parallel resonance frequency 7th, 8th, 9th and 10th. So it is concluded that impedance of filter (1) is on the order of R at ω_p . The voltage harmonic distortions after installation of filter (1) by selecting the interested parallel resonance frequency are tabulated in Table.6.

Table.6. Impact of filter (1) on 33kV bus

% voltage harmonic distortions by changing the parallel resonance							
Parallel resonance frequency order	Total	5 th order	7 th order	11 th order	13 th order	17 th order	19 th order
7	4.7037	0.23	3.8137	0.056	1.1619	1.692	1.8199
8	4.4836	0.1455	3.076	0.1473	1.5074	1.9848	2.0944
9	4.6367	0.0725	2.7176	0.2991	1.8848	2.2452	2.3292
10	4.9306	0.0201	2.5097	0.519	2.2893	2.4726	2.5274

Filter (2) is formed by inserting the damping resistor in double tuned filter as shown in figure.8.

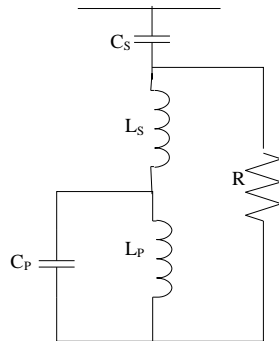


Figure.8. Filter (2)

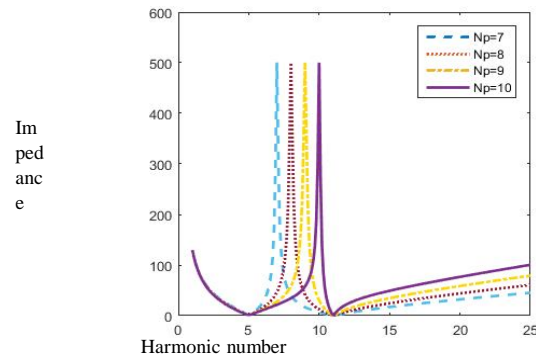


Figure.9.Characteristics of Filter (2)

For filter (2) the resistance (R) value has been chosen 500 ohms to satisfy the relation $R > \sqrt{L_1/C_1}$. the impedance the impedance takes 500 ohms as asymptotic line when ω is more than 11th order frequency.it has been concluded that In filter (2) the impedance takes R as asymptotic line when ω is more than ω_r .The voltage harmonic distortions after installation of filter (2) is tabulated in Table.7.

Table.7. Impact of filter (2) on 33kV bus

% voltage harmonic distortions by changing the parallel resonance							
Parallel resonance frequency order	Total	5 th order	7 th order	11 th order	13 th order	17 th order	19 th order
7	4.7237	0.6291	3.8163	0.0609	1.1545	1.6723	1.7946
8	4.4857	0.6324	3.0665	0.0613	1.4964	1.9575	2.0599
9	4.6154	0.6365	2.7021	0.0617	1.8681	2.2093	2.2851
10	4.8737	0.6393	2.491	0.062	2.263	2.4277	2.4739

Filter (3) is formed by inserting the damping resistor in double tuned filter as shown in figure.10.

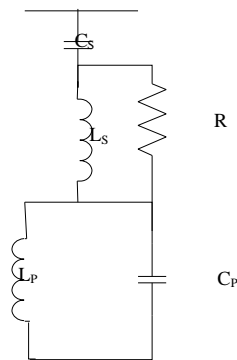


Figure.10. Filter (3)

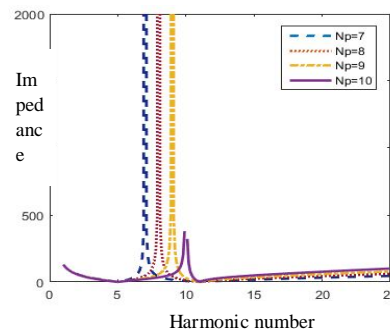


Figure.11.Characteristics of Filter (3)

The impedance of the filter(c) reaches the infinite value at each and every order of parallel resonance frequency 7th, 8th, 9th and 10th. The impedance of filter (c) at ω_p is very large but the impedance above ω_p is in the order of R. The voltage harmonic distortions after installation of filter (3) is tabulated in Table.8.

Table.8. Impact of filter (3) on 33kV bus

% voltage harmonic distortions by changing the parallel resonance							
Parallel resonance frequency order	Total	5 th order	7 th order	11 th order	13 th order	17 th order	19 th order
7	4.7024	0.108	3.8405	0.2292	1.1507	1.666	1.7886
8	4.4647	0.183	3.0872	0.387	1.4879	1.9484	2.0516
9	4.6142	0.2929	2.7156	0.6071	1.8549	2.1996	2.2767
10	4.9237	0.4437	2.4967	0.8925	2.2501	2.4209	2.4682

Filter (4) is formed by inserting the damping resistor in double tuned filter as shown in figure.12.

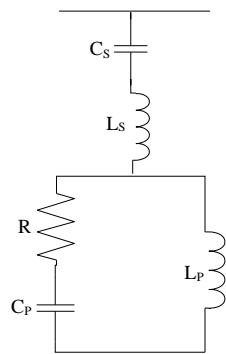


Figure.12. Filter (4)

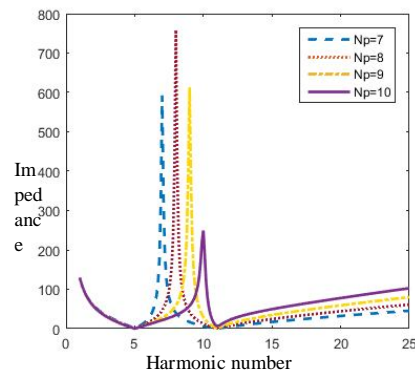


Figure.13.Characteristics of Filter (4)

The damping resistor value in Filter (D) is very less because the resistor is connected in series with the reactive element. Filter (D) behaves as a high pass filter. The voltage harmonic distortions after installation of filter (3) is tabulated in Table.9.

Table.9.Impact of filter (4) on 33kV bus

% voltage harmonic distortions by changing the parallel resonance							
Parallel resonance frequency order	Total	5 th order	7 th order	11 th order	13 th order	17 th order	19 th order
7	4.6774	0.2478	3.7758	0.2824	1.1596	1.6863	1.8145
8	4.4851	0.0377	3.0826	0.1831	1.5053	1.9831	2.0928
9	4.64	0.0183	2.7207	0.362	1.8824	2.2436	2.3278
10	5.0222	0.0102	2.5096	1.1025	2.2852	2.4709	2.5261

Filter (5) is formed by inserting the damping resistor in double tuned filter as shown in figure.14.

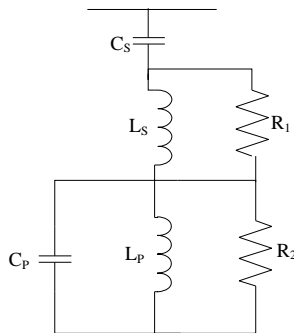


Figure.14. Filter (5)

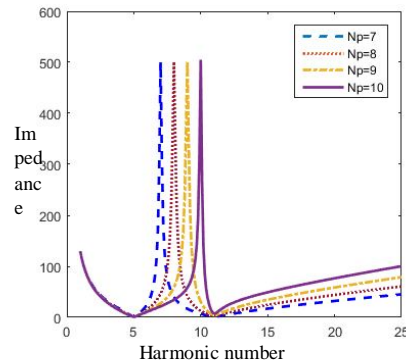


Figure.15.Characteristics of Filter (5)

The resistance (r_1) value for filter(5) has been taken as 500ohm in order to satisfy the relation of $R_1 > \sqrt{L_1/C_1}$, the impedance of the filter(5) is limited to the resistance values at 11th order and above 11th order .it is concluded that Filter (5) has limited impedance at ω_p and also above ω_2 . The voltage harmonic distortions after installation of filter (5) is tabulated in Table.10.

Table.10.Impact of filter (5) on 33kV bus

%voltage harmonic distortions by changing the parallel resonance							
Parallel resonance frequency order	Total	5 th order	7 th order	11 th order	13 th order	17 th order	19 th order
7	4.6942	0.3335	3.8137	0.282	1.1518	1.6658	1.7884
8	4.4781	0.3248	3.0749	0.5195	1.4899	1.9481	2.0514
9	4.6564	0.3624	2.7116	0.8548	1.8569	2.1994	2.2765
10	5.0076	0.4624	2.4963	1.2703	2.2506	2.4209	2.4681

Filter (6) is formed by inserting the damping resistor in double tuned filter as shown in figure.16.

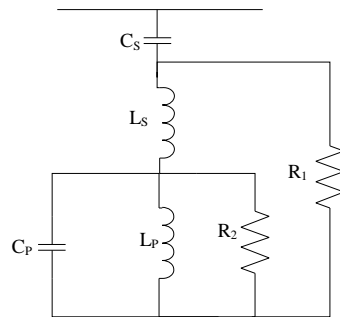


Figure.16. Filter (6)

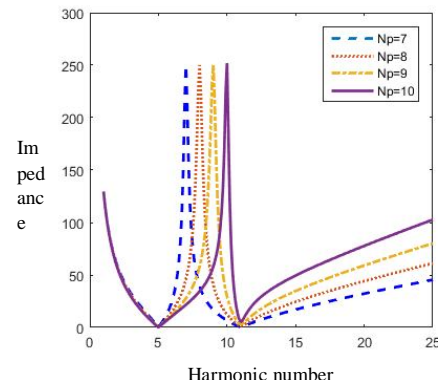


Figure.17.Characteristics of Filter (6)

Impedance of filter (F) is limited to 250 ohms which is the lower value of R_1 and R_2 both at frequency order 7th, 8th, 9th and 10th and above 11th order. Hence it is concluded that the Impedance filter (6) is limited to the lower value of R_1 and R_2 both at ω_p and above ω_2 . The voltage harmonic distortions after installation of filter (6) is tabulated in Table.11.

Table.11. Impact of filter (6) on 33kV bus

%voltage harmonic distortions by changing the parallel resonance							
Parallel resonance frequency order	Total	5 th order	7 th order	11 th order	13 th order	17 th order	19 th order
7	4.7619	1.0377	3.7723	0.1703	1.153	1.6712	1.7938
8	4.5262	0.8936	3.0457	0.3446	1.493	1.9558	2.0587
9	4.6679	0.7674	2.6936	0.6189	1.8631	2.2077	2.2841
10	4.9725	0.6758	2.489	0.9803	2.2593	2.427	2.4735

As per [1] the voltage individual harmonic distortion limits for 33kV bus should be 3%. The voltage individual harmonic distortion limits caused by the 5th and 11th harmonics has been eliminated with the usage of basic double tuned filter. By adding a damped resistor to the double tuned filter the total voltage harmonic distortion is further reduced as compared to basic double tuned filter. It is concluded that with the variation of the parallel resonance frequency order in between the 5th and 11th the harmonic content produced by the intermediate harmonics i.e., 7th harmonic is also reduced and as a result the total harmonic content in the test system is also reduced. The individual voltage harmonic distortions due 7th order harmonic also significantly reduced by increasing the parallel resonance frequency order from 7th to 10th.

VI. CONCLUSION

An algorithm to determine the parameters of different configurations of double tuned filters is proposed in this paper. With the proposed algorithm the intermediate harmonic between the tuned frequencies also reduced by changing the parallel resonance frequencies. The variation in the characteristics of damped type double tuned filter by varying the damping resistance is also explained briefly in this paper.

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