Improvement of Harmonics Using Passive Harmonics Filter

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***Abstract*—Power quality problems are continuously increased and received a great attention due to the impacts on both utilities and consumers. The most frequently reported power quality problem is the harmonics. The aim of this project is to enhance the system performance under the load variation effect through desirable filter placement. In this project, two types of passive filter called single tuned and 3rd order C-type are studied. Load flow analysis is performed to calculate the load bus voltage and total harmonic distortion (THD) that determine the effectiveness of filter application. The work was simulated using Electrical Transient Analyzer Program (ETAP) and tested on two test systems namely the 4-bus and IEEE 14-bus. The results of this work show that single tuned filter is more effective in filtering the harmonic compared to the 3rd order C-type. Furthermore, installing the single tuned filter near to the source of harmonics produces a better result.**

***Index Terms*—C-Type Filter; ETAP; Harmonics; Passive Filters; Single Tuned Filter.**

I. INTRODUCTION

Power quality is the ability of the electrical equipment to interact with the electrical power supply. In recent years, power quality issues are becoming a major concern in power system [1]. The electrical engineers consider power quality issue as anything that affects the voltage, current and frequency of power being supplied to the end user [2]. There are many types of power quality problem such as voltage sag, interruptions, voltage swell, voltage unbalanced and the most frequently reported is harmonics.

The harmonics of power frequency have been around for a long time. As early as 1890's, they have been observed on the transmission systems, however, at that time it had no detrimental effects. The widespread of electronic devices that are sensitive to waveform distortion caused many undesirable effects on power system operation. For controlling the harmonic levels in power system, the IEEE Standard 519-1992 is a recommended guideline that specifies distortion limits at the point of common coupling (PCC) between utility and end users [3].

Besides the need for complying with the standard, another mitigating measure commonly practiced by the electric utility is by the installation of passive filters. Passive filters are considered as one of the cheapest ways of mitigating harmonics [4]. The effectiveness of filter in the system depends on the filter position to the harmonic source at load bus. The purpose of this study is to investigate the effect of load variation on the location of filter buses for different types of passive filter in the modern power system.

II. HARMONICS AND ITS EFFECT

Harmonics is a way of describing distortion of voltage and current waveforms. The term harmonics refers to a sinusoidal component of a periodic waveform that has integer multiple of the fundamental frequency [5]. The harmonics problem is caused by non-linear loads such as electric arc furnaces, inverters, DC converters, switch mode power supplies and DC or AC motor drives. A load is considered as non-linear if its impedance changed with the voltage applied. The changing of impedance means that the load current waveform is not sinusoidal even though is supplied by a sinusoidal voltage. Further, the non-sinusoidal current that interacts with the impedance of power system creates voltage distortion. The distorted voltage may affect both utility system equipment and also consumer loads.

The presence of harmonics in the electrical system creates several significant effects and symptoms. The major impact of voltage and current harmonics is the increase in the machine and transformer heating caused by increased iron losses and copper losses. A large number of harmonics sometimes can lead to malfunctioning of the system which eventually results in downtime and increased operational cost. Other problems relate to harmonics are misoperation of electronic equipment, disruption of variable speed drives, resonance and also flickering of lights which can be perceptible by human eye [6].

III. PASSIVE HARMONIC FILTER

Among several harmonics solutions, a passive filter is a very common and effective mitigation method [7]. Passive filters are designed to provide low impedance shunt path for harmonic currents [8]. In this way, the harmonic currents are deflected to the ground. Another function of passive filters is to suppress the flow of harmonic currents between parts of the system by tuning the passive elements to create resonance at a single frequency or a band of frequencies.

Passive harmonic filters generally consist of capacitors, inductors, and resistors. An array of these elements is arranged in one or more shunt arms to form different topologies. Among popular topologies of passive filters are single tuned, second order, third order and C-type filters [9]. The schematic configuration of these filters is shown in Figure 1.

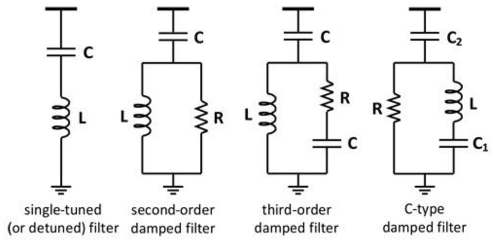

Figure 1: Types of passive filter

In this study, two types of passive harmonic filter are used. The single tuned filter is the most economical type and extensively installed for suppressing the harmonic problem in the industry. This type of filter consists of a series resistor, inductor and capacitor. From its name, a single-tuned filter is tuned to a single harmonic frequency that makes its inductive and capacitive reactance to be equal, thus filter has purely resistive impedance [10].

$$Z_h = R_h + j\left(\omega L_h - {}^{1}\!/_{\omega C_h}\right) \qquad (1)$$

where: h = harmonic order at the resonant frequency

$$\omega L_h = {}^{1}\!/_{\omega C_h}$$

$$Z_h = R_h$$

Another harmonic filter is the third order or C-type filter. A C-type filter consists a set of capacitors in series with a reactor and in parallel combination with a resistor. This type of filter provides a low impedance for a wide range of frequencies [11]. Referring to Fig. 1, The C-type filter has different behaviours with various categories of frequencies. In other words, it acts as various types of passive filters. At fundamental frequency, the resistor is bypassed due to the tuned arm (series $L - C_1$) where arm circuit exhibits much lower losses. As the frequency increases, the filter acts as a single-tuned filter with a damping resistor where the inductor starts to resonate with C_1 and C_2 [12].

The impedance Z_{Ch} of the C-type passive filter varies with the harmonic order h. At the tuned harmonic frequency, the total reactance of the filter should be zero. The magnitude of the impedance can be calculated as follows [13]:

$$Z_{Ch} = R_{Fh} + jX_{Fh} \qquad (2)$$

where resistance at the fundamental frequency, R_{Fh}

$$R_{Fh} = \frac{RX_{LCh}^2}{R^2 + X_{LCh}^2} \qquad (3)$$

reactance at the fundamental frequency, X_F

$$X_{Fh} = \frac{RX_{LCh}^2}{R^2 + X_{LCh}^2} - \frac{X_{C1}}{h} \qquad (4)$$

And

$$X_{LCh} = hX_L - \frac{X_{C2}}{h} \qquad (5)$$

Apparently, filter tuning is also important to meet the required filtering performance. Passive filters should be customarily designed according to specific system impedance. Without proper tuning, the overall filter design will result in poor system performance prior to filter installation [14].

IV. RESULTS AND DISCUSSION

This section presents the harmonic analysis for voltage waveform which is considered as a vital electrical parameter. The result for voltage distortion is represented by an index known as THDv. The goals are to minimize harmonic problems using a harmonic filter and to investigate the effect of load variation on THD level. Two test systems namely 4-bus [15] and IEEE 14-bus are simulated using Electrical Transient Analyzer Program (ETAP). The 4-bus system consists two non-linear loads at bus 2 and 3; one linear at bus 4 and one motor load at bus 1. Meanwhile, the IEEE 14-bus system is a standard test system that represents a portion of the American Electric Power System as of February 1962 [16]. The system consists of 5 generators, 14 buses and 11 loads. The non-linear loads are placed at bus 6 and bus 13. Figures 2 and 3 show the single line diagram of both systems respectively.

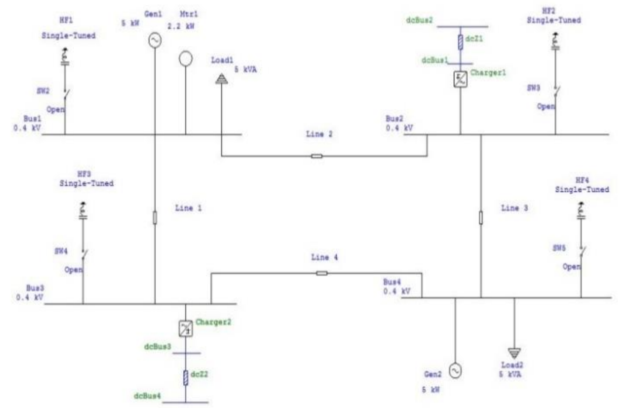

Figure 2: 4-bus with non-linear load [15]

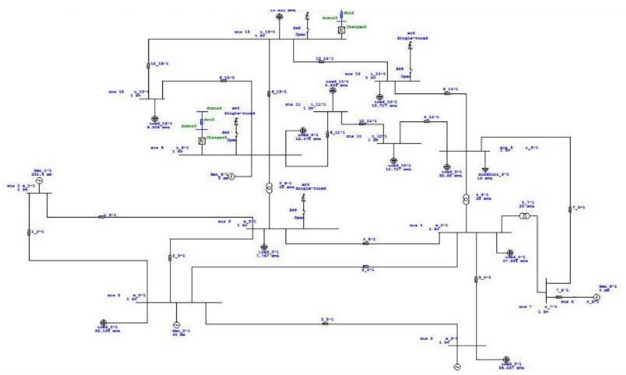

Figure 3: IEEE 14-bus with non-linear load [16]

Initially, the load flow analysis is executed to get the power factor and apparent power (MVA) on each bus. These values will be used to determine the suitable size of the filter. Next, harmonic analysis is run in order to get THD value at all buses of the system before the harmonic filter is used. Table 1 and 2 show the THDv value at each bus in the 4-bus and 14-bus test systems respectively without any filter. Noticeably, the THDv value is higher at bus 2 and bus 3 for the 4-bus system, while bus 6 and bus 13 indicate high voltage distortions in the 14-bus system.

The condition of both systems without any filtering devices illustrate that non-linear load is the source of harmonic distortion.

Table 1
THDv with Non-Linear Load for 4-bus

	THDv (%) at monitoring bus			
Non-linear load without filter	Bus 1 21.32	Bus 2 27.80	Bus 3 27.80	Bus 4 23.53

Table 2
THDv with Non-Linear Load for IEEE 14-bus

	THDv (%) at monitoring bus			
Non-linear load without filter	Bus 5 1.17	Bus 6 6.61	Bus 13 9.15	Bus 14 4.21

Table 3
THDv for Two Types of Filter in 4-bus

	Filter location	THDv (%) at monitoring bus			
		Bus 1	Bus 2	Bus 3	Bus 4
Single tuned filter	Bus 1	16.48	23.86	23.86	19.91
	Bus 2	15.31	18.56	22.04	16.75
	Bus 3	15.31	22.04	18.56	16.75
	Bus 4	18.13	23.87	23.87	18.37
	Bus 2 & 3	12.63	16.71	16.71	13.73
3rd order C-type	Bus 1	24.41	25.06	25.06	21.67
	Bus 2	24.31	35.33	27.75	26.73
	Bus 3	24.31	27.75	35.33	26.73
	Bus 4	19.67	25.07	25.07	26.58
	Bus 2 & 3	26.86	33.43	33.43	29.35

Table 3 shows the compensated results with single and combined filter location for the 4-bus system. Comparison of the simulated results in Table 1 and 3 shows the installation of the single tuned filter provides an improvement of THDv value. Averagely the THDv satisfactorily reduced to 40% when the harmonic filter is placed on bus 2 and 3. However, applying the C type filter has an adverse interaction with the power system impedance. When the reactance of capacitors equal to the reactance of inductor, a wide range of frequencies is allowed to flow in the system thus some of the frequencies potentially create power system resonance. Resonance will cause amplification of voltage and its harmonics.

Similarly, Table 4 shows the compensated results with single and combined filter location for the 14-bus system. Comparison of the simulated results in Table 2 and 4 shows the installation of the single tuned filter provides an improvement of THDv except for bus 6. The best result is obtained when the harmonic filter is placed on bus 6 and 13 where THDv averagely reduced to 31%. Meanwhile, the results before and after applying the C type filter shows not much different. This result shows that the effectiveness of filter size depends on the size of the power system.

In real practice, the size of the non-linear load is not fixed all the time. Thus, it is necessary to examine the performance of the passive filter when the load size varies. Tables 5 and 6 give the condition of the system with the single tuned filter when the load is varied +/- 5% from its initial value.

The results show that the small changes in load level do not affect the THDv value so much. This is because the filter compensation characteristic is nearly similar with a small amount of load variation. A possible reason is that most passive components have standard tolerance values of 5% to 10%, therefore the filtering performance within this tolerance can be expected of the same effect.

Table 4
THDv for Two Types of Filter in IEEE-14 bus

Detail	Filter location	THDv (%) at monitoring bus			
		Bus 5	Bus 6	Bus 13	Bus 14
Single tuned filter	Bus 5	0.65	6.75	9.30	4.46
	Bus 6	1.03	6.62	9.11	4.38
	Bus 13	0.60	5.45	7.44	2.57
	Bus 14	0.90	6.48	9.00	3.23
	Bus 6 & 13	0.59	5.39	7.35	2.54
3rd order C-type	Bus 5	1.17	6.58	9.12	4.18
	Bus 6	1.16	6.53	9.03	4.15
	Bus 13	1.20	6.45	10.24	4.61
	Bus 14	1.17	6.58	9.11	4.33
	Bus 6 & 13	1.18	6.37	10.12	4.55

Table 5
THDv with 5% Load Variation in 4-bus

	Filter location	THDv (%) at monitoring bus			
		Bus 1	Bus 2	Bus 3	Bus 4
Linear load increased 5%	Bus 1	16.00	23.31	23.31	19.37
	Bus 2	14.87	18.14	21.56	16.30
	Bus 3	14.87	21.56	18.14	16.30
	Bus 4	17.61	23.31	23.31	17.85
	Bus 2 & 3	12.29	16.37	16.37	13.37
Linear load decreased 5%	Bus 1	17.00	24.44	24.44	20.48
	Bus 2	16.77	19.02	22.55	17.24
	Bus 3	15.77	22.55	19.02	17.24
	Bus 4	18.69	24.46	24.46	18.92
	Bus 2 & 3	12.99	17.06	17.06	14.10

Table 6
THDv with 5% Load Variation in IEEE 14-bus

Detail	Filter location	THDv (%) at monitoring bus			
		Bus 5	Bus 6	Bus 13	Bus 14
Linear load increased 5%	Bus 5	0.65	6.77	9.33	4.48
	Bus 6	1.03	6.63	9.12	4.38
	Bus 13	0.59	5.45	7.45	2.57
	Bus 14	0.90	6.50	9.03	3.24
	Bus 6 & 13	0.59	5.40	7.36	2.54
Linear load decreased 5%	Bus 5	0.66	6.74	9.28	4.46
	Bus 6	1.04	6.61	9.09	4.37
	Bus 13	0.60	5.44	7.42	2.56
	Bus 14	0.92	6.47	8.97	3.22
	Bus 6 & 13	0.60	5.38	7.33	2.53

Interestingly, when the size of the load is varied larger by 20%, the results show significant differences in the THDv value. For the 4-bus system, Table 7 shows lower THDv value is achieved when the load is increased 20%, however, the THDv value grows higher when the load is decreased by the same amount. In general, the system shows mixed results. This suggests that under higher loading condition the single tuned filter need to be detuned separately to estimate the parameters of the filter. The effectiveness of the single tuned filter decreases with large loading variation.

Table 7
THDv with 20% Load Variation in 4-bus

	Filter location	THDv (%) at monitoring bus			
		Bus 1	Bus 2	Bus 3	Bus 4
Linear load increased 20%	Bus 1	14.70	21.86	21.86	17.92
	Bus 2	13.71	17.02	20.31	15.08
	Bus 3	13.71	20.31	17.02	15.08
	Bus 4	16.22	21.85	21.85	16.45
	Bus 2 & 3	11.38	15.48	15.48	12.43
Linear load decreased 20%	Bus 1	18.78	26.48	26.48	22.46
	Bus 2	17.35	20.59	24.31	18.89
	Bus 3	17.35	24.31	20.59	18.89
	Bus 4	20.60	26.52	26.52	20.83
	Bus 2 & 3	14.20	18.28	18.28	15.35

However, for the 14-bus system, results in Table 8 nearly similar to results in Table 6 except bus 6 shows significant improvement when loading is increased 20%. This shows that with the larger power it is more difficult to control and suppress the harmonic flow. The operation of non-linear loads creates harmonic current that flow throughout the power system, thus, creates larger crossover point between the inductive and capacitive reactance which affects the overall performance of the filter. In such situation, more units of the filter could be considered to be placed in other locations in the system. This work could also be extended to include the effect of resonance between inductive and capacitive components in the system.

Table 8
THDv with 20% Load Variation in IEEE 14-bus

Detail	Filter location	THDv (%) at monitoring bus			
		Bus 5	Bus 6	Bus 13	Bus 14
Linear load increased 20%	Bus 5	0.64	6.96	9.64	4.63
	Bus 6	0.62	5.80	8.55	3.00
	Bus 13	0.59	5.55	7.60	2.62
	Bus 14	0.89	6.70	9.34	3.35
	Bus 6 & 13	0.54	5.18	7.31	2.51
Linear load decreased 20%	Bus 5	0.68	6.71	9.25	4.44
	Bus 6	0.91	6.61	9.09	4.37
	Bus 13	0.63	5.42	7.40	2.55
	Bus 14	0.96	6.45	8.94	3.21
	Bus 6 & 13	0.61	5.37	7.31	2.52

V. CONCLUSION

Harmonics are largely produced in power system due to the increased operation of non-linear loads. Out of many existing harmonic mitigation methods available, this paper presented the application of passive harmonic filter as a solution to the harmonic problem. Two types of passive harmonic filter that is the single tuned filter and 3rd order C-type filter is studied. From the result analysis, the single tuned filter shown to be more effective for filtering the harmonic compared to the 3rd order C-type. With regards to filter placement, installing the single tuned filter near to the source of harmonics produces better results. This is because the single tuned is better to filter the harmonic near the power frequency. For the effect of load level parameter to THD, increasing the load level give a slightly lower THD value compared to decreasing the load. Finally, harmonic analysis using ETAP software is easier and save a lot of time.

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