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Optimal Harmonic Filter Placement for Power Quality Improvement in Industrial Distribution Network

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Abstract

The harmonics have existed in the power system for many years. It has become a major concern for electric utility company and consumers. It is produced by many factors, the important ones being the increase in non-linear loads, the increasing penetration of DG and other sources, the non-linearity of transformers and other equipment etc. The non-linear loads draw non-sinusoidal current from the system. Therefore, for a system with large number of non-linear loads, the impact of harmonic pollution is severe. One suitable scheme for controlling the harmonic pollution is the use of filter. The use of filters is a costly solution, and should be optimized. The optimum use of the filters and the effectiveness of their use is to be validated by simulations.

Keywords

harmonics – harmonic filters – optimization

1. Introduction

An Industrial feeder is a typical example of a system with large number of non-linear loads. The industrial components, mainly the VFDs (Variable Frequency Drives), UPS (Uninterruptible Power Supplies) and AC/DC Converters inject various harmonic components in the distribution system. With the application of capacitor, which may be for the purpose of loss reduction, power factor improvement, voltage profile improvement etc., there is an increasing chance of harmonic indices exceeding their recommended values and the probability of resonance with the system inductance resulting in high voltage stress and high current damage. Thus, it becomes necessary to perform a harmonic impact study of such system and analyze the performance of the recommended solutions. It would be cost effective and time saving if the harmonics and their effects could be reduced. In order to work efficiently, the distribution system needs to be upgraded. Low pass filters can solve this problem to some level if they are optimized by using an effective optimization technique. Harmonic filters like low pass filters are commonly used elements in distribution system to improve the power quality. Nowadays, even active filters are being used commonly to provide a better power quality improvement. Active filters are superior in performance but costlier than their passive counterparts. [1]

One of the solution to the problem of harmonic distortion and system resonance severity is to filter out and suppress the harmonic by using filters. But the filters being expensive components of the power system, their siting and mix of active and passive needs to be optimized. Thus an optimization technique is utilized in the site selection and active filters are applied for dynamic response of the harmonic filters.

2. Sensitivity Analysis based Placement procedure for Passive filter

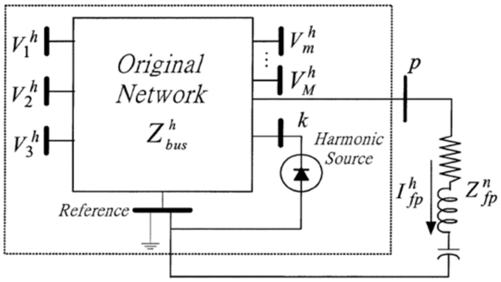

Figure 1: M bus Power network for harmonic filter placement

The sensitivity Analysis based placement procedure is based on the theoretical background of [2]. As shown in fig. 1 An M-bus power network with an h^{th} order of harmonic current source I^h_k at bus k and a single tuned passive filter for h^{th} harmonic at bus p is considered.

Before the passive filter is installed, the h^{th} order of harmonic voltage at any bus m is given by

$$V^h_{m,o} = Z^h_{mk,o} \quad I^h_k \tag{1}$$

Where $m = 1, 2, \ldots, M$

and, $Z^h_{mk,o} = Z^r_{mk,o} + jZ^i_{mk,o}$ is the harmonic transfer impedance between buses m and k, which includes both the real and imaginary parts. The harmonic transfer impedance is determined according to the system harmonic impedance matrix without the filter, as given in (2)

$$Z^h_{bus} = \begin{bmatrix} Z^h_{11,o} & Z^h_{12,o} & \cdots & Z^h_{1M,o} \\ Z^h_{21,o} & Z^h_{22,o} & \cdots & Z^h_{2M,o} \\ \vdots & \vdots & \ddots & \vdots \\ Z^h_{M1,o} & Z^h_{M2,o} & \cdots & Z^h_{MM,o} \end{bmatrix} \tag{2}$$

If there is more than one harmonic current source of the h^{th} order existing in the network, the corresponding harmonic voltage at any bus m becomes

$$V^h_{m,o} = \sum_{k=k_1}^{k_n} Z^h_{mk,o} \quad I^h_k = \sum_{k=k_1}^{k_n} V^h_{mk,o} \tag{3}$$

Where $k_i, i = 1, 2, \ldots, n$ are bus numbers of harmonic sources. In fig 1, the single tuned passive filter connected to bus p is composed of a capacitor in series with an inductor. Assuming that the internal resistance of the inductor is R and the quality factor is Q , the filter impedance at any harmonic order h can be expressed as

$$Z^h_{fp} = R + j\left(h\, X_{p,L} - \frac{X_{p,c}}{h}\right) \tag{4}$$

Where, $Q = X_{p,L}/R$ and $X_{P,L}$ and $X_{p,C}$ are the inductor and capacitor impedances at fundamental frequency, respectively. At the tuned harmonic order n, (4) becomes $Z^n_{fp} = X_{p,C}/Q_n$

The total system harmonic voltage distortion after placement of the passive filter for the hth harmonic at bus p can be expressed as

$$\varphi = \sum_{m=1}^{M} \left|(V^h_{m,o} - \Delta V^h_{fp}\right| \tag{5}$$

as defined previously, and

$$\begin{aligned} \Delta V^h_{fp} = Z^h_{mp,o}\, I^h_{fp} &= \frac{Z^h_{mp,o}\, V^h_{p,o}}{Z^h_{pp,o} + Z^h_{fp}} \\ &= \frac{Z^h_{mp,o} \sum_{k=k_1}^{k_n} V^h_{pk,o}}{Z^h_{pp,o} + Z^h_{fp}} \end{aligned} \tag{6}$$

According to equation (3), the following relation holds:

$$\frac{V^h_{mk,o}}{V^h_{pk,o}} = \frac{Z^h_{mk,o}\, I^h_k}{Z^h_{pk,o}\, I^h_k} = \frac{Z^h_{mk,o}}{Z^h_{pk,o}} \tag{7}$$

Therefore,

$$V^h_{pk,o} = \frac{Z^h_{pk,o}}{Z^h_{mk,o}}\, V^h_{mk,o} \tag{8}$$

By substituting (8) into (6), we have

$$\varphi = \sum_{m=1}^{M} \sum_{k=k_1}^{k_n} \left| \left[1 - \frac{Z^h_{mp,o}\, Z^h_{pk,o}}{Z^h_{mk,o}\left(Z^h_{pp,o} + Z^h_{fp}\right)} \right] V^h_{mk,o} \right| \tag{9}$$

Where the second term in the parenthesis of (9) represents the h^{th} order of harmonic voltage variation at bus m after the placement of filter at bus p. Based on the sensitivity analysis, the siting index for placement of the filter for the h^{th} harmonic order becomes

$$\begin{aligned} S^{h,p}_V &= \sum_{m=1}^{M} \sum_{k=k_1}^{k_n} \frac{\delta\varphi}{\delta|V^h_{mk,o}|} \\ &= \sum_{m=1}^{M} \sum_{k=k_1}^{k_n} \left| \left[1 - \frac{Z^h_{mp,o}\, Z^h_{pk,o}}{Z^h_{mk,o}\left(Z^h_{pp,o} + Z^h_{fp}\right)} \right] \right| \end{aligned} \tag{10}$$

Therefore, the filter candidate bus that gives the least value of (10) is the most effective bus on controlling the h^{th}e order of harmonic voltage of the system.

3. System under study

The system under study is the 33 kV, 22 km long industrial feeder, old Bhairahawa, supplying power to industrial customers through nineteen nodes. The major sources of non-linearity are the AC/DC converters and the AC/AC converters, mainly the ABB drives DCS5006P converter, the DCS80012P converters, the furnace load and the ACS100012P converters located in major seven locations as shown in fig. (2)

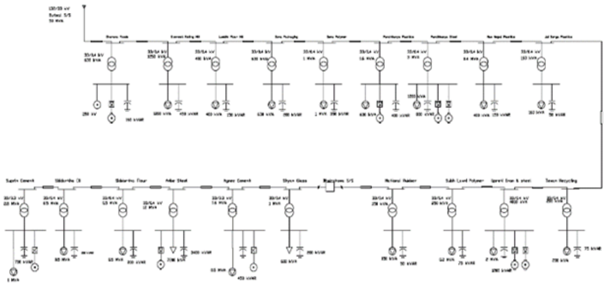

Figure 2: 19 bus system under study

4. Software and Tools

The important software tools used for analyzing the harmonic performance are OpenDSS, ETAP and MATLAB. OpenDSS is the main software for harmonic simulation, frequency scan analysis etc. ETAP is mostly used for preliminary simulation and verification. MATLAB integrates effectively with OpenDSS to perform optimization studies, analysis etc.

5. Methodology

The methodology followed for this study is summarized in flowcharts in figs 3 and 4.

The general simulation process starts with harmonic analysis in ETAP followed by the optimal capacitor placement, which are then used to create OpenDSS models, and then integrating OpenDSS with MATLAB, the harmonic load flow study is carried out for all harmonics concerned.

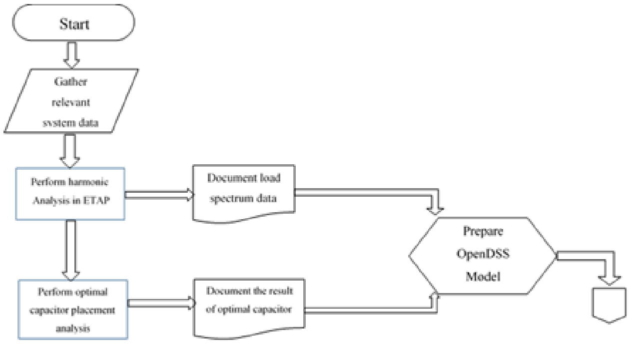

Figure 3: General Metholology flow chart 1

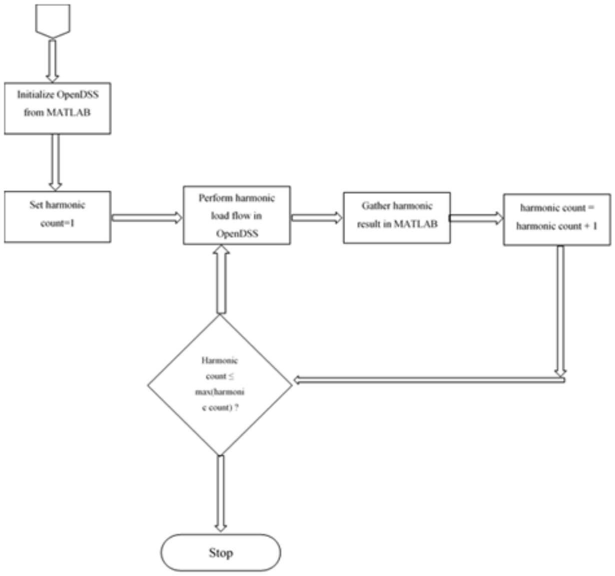

Figure 4: General Metholology flow chart 2

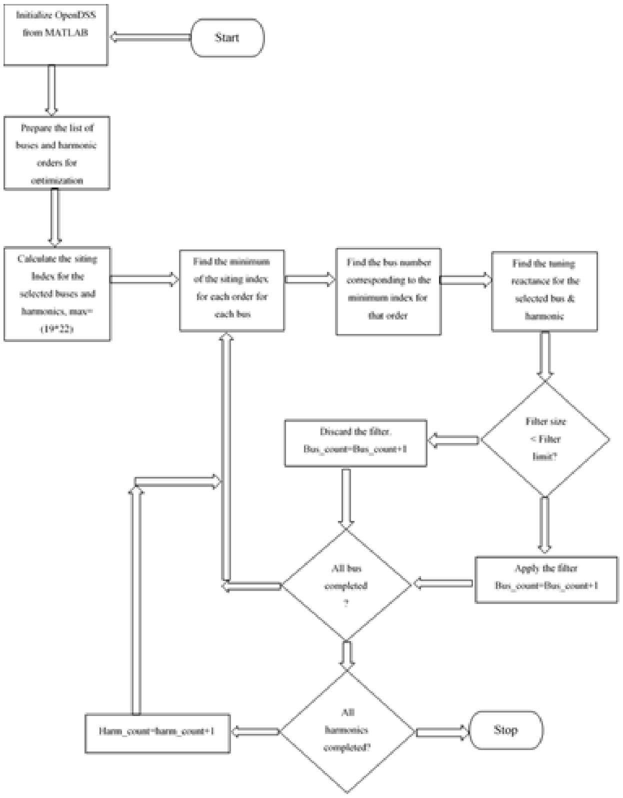

Figure 5: Siting Procedure flowchart

For the placement of filters tuned to the optimal capacitor sizes, the method followed is shown in flowchart in fig 5.

The placement procedure starts by initializing OpenDSS from MATLAB and prepares the list of buses and harmonic orders for optimization. Thereafter, the siting index, as developed previously is calculated for all selected buses and harmonics, and the buses fulfilling the minimum siting index, cut off filter limit and harmonic order is selected for filter application. The process continues until all selected buses and harmonic orders are exhausted.

6. Results

For the 19 bus system under study described above, the optimal capacitor placement analysis is carried out from ETAP, with the goal of improving power factor from 90% to 98% without allowing for over-compensation. The result of optimal capacitor placement analysis is shown by table 1.

Table 1: Optimal and non optimal conductor sizes

Bus No.	kVAR Non Optimum	kVAR Optimum	Bus No.	kVAR Non Optimum	kVAR Optimum
1	160	200			
2	450	700	11	1200	2000
3	150	200	12	75	100
4	200	300	13	50	100
5	350	500	14	200	300
6	400	700	15	450	450
7	800	1300	16	3400	2000
8	150	200	17	200	200
9	50	100	18	200	200
10	75	100	19	700	1000

With the application of optimal sized capacitor, the network voltage profile and power factor improves from the case with non-optimum capacitors and no capacitors. This is shown in figures 6 and 7.

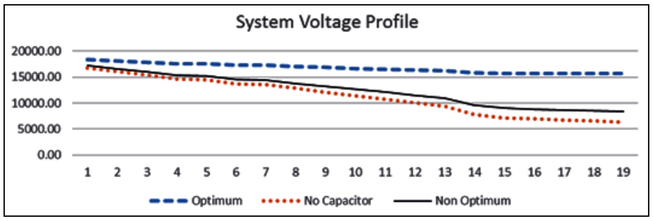

Figure 6: System voltage profile under different condition

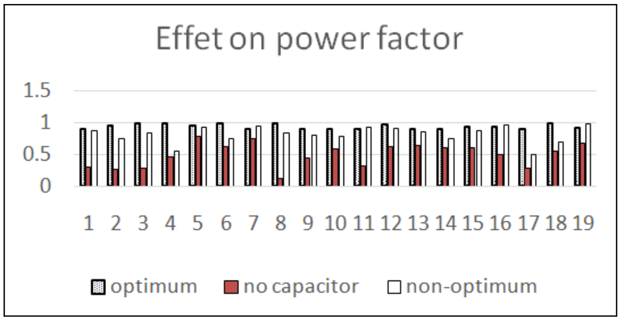

Figure 7: System power factor under different condition

The presence of nonlinear loads and capacitor cause an increase in distortion of the voltage at the capacitor buses and the demand at the point of common coupling. This is shown in figs. 8 & 9.

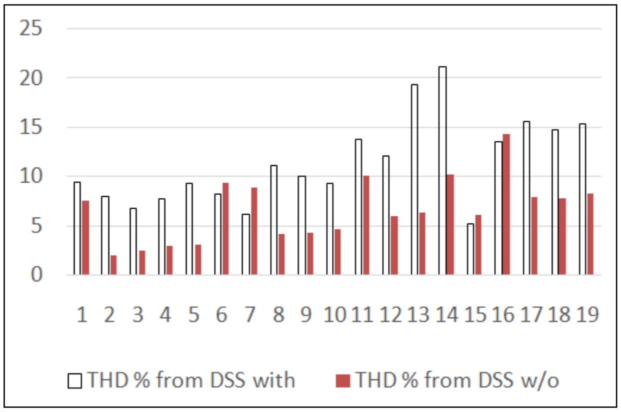

Figure 8: Voltage distortion at different buses with and without capacitors

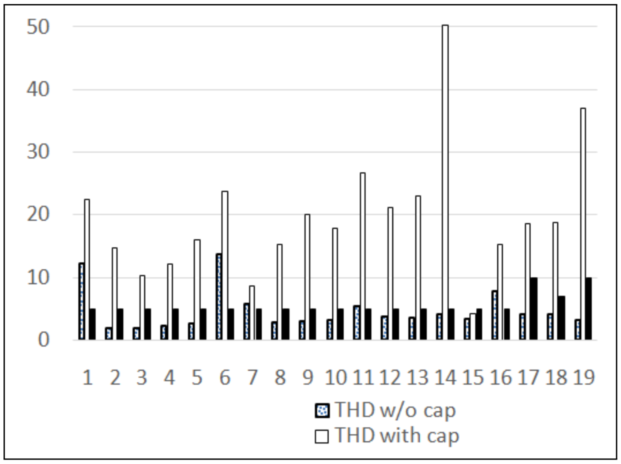

Figure 9: Current distortion at points of common coupling

With the application of siting indices, the tuning order of the filter for each bus are calculated and the order tuned, along with the filter reactance for tuning with the optimal capacitor bank, is as shown in table 2.

Table 2: Tunning reactance for different buses after siting

Bus No.	Harmonic No.	Tuning Reactance, Xl, Ohms	Remarks
1	2,3,5	0.2,0.08,0.03	Multi step bank
2	2,3	0.05,0.025	Multi step bank
3	2	0.2	
4	2	0.133	
5	2	0.08	
6	2,3	0.057,0.026	Multi step bank
7	2,3,5	0.03,0.0136,0.004	Multi step bank
8	3	0.0089	
9	5	0.044	
10	3	0.1788	
11	2	0.02	
12	7	0.033	
13	5	0.064	
14	2,3	0.133,0.059	Multi step bank
15	2,3	0.0889,0.039	Multi step bank
16	2,3,4,6	0.02,0.0089,0.005,0.0022	Multi step bank
17	2	0.2	
18	2	0.2	
19	2,3	0.04,0.01788	Multi step bank

The application of single -tuned passive harmonic filter causes reduction in demand distortion at the various buses. The filter provides a low impedance path for the tuned harmonic allowing it to sink, while providing high impedance for other orders. The result after placement of the passive filter is shown in figure 10.

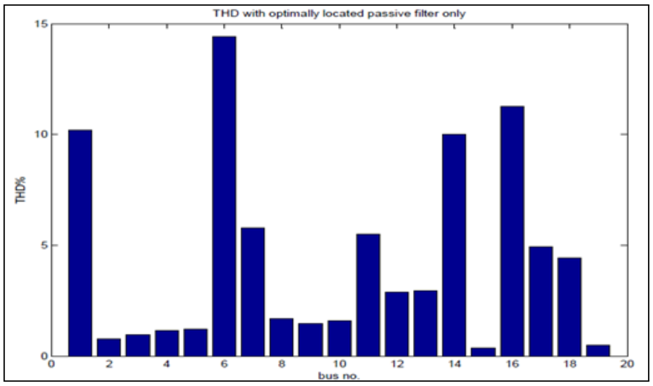

Figure 10: THD of current at different buses after placing passive filter

Further reduction in distortion levels requires the use of active power filter. In iterative software like OpenDSS, the active filter is implemented from MATLAB, with spectrum definitions opposite to that of the local demand.

With the application of active filter, the distortion levels are brought further down, marginally and within limits, as shown in fig 11.

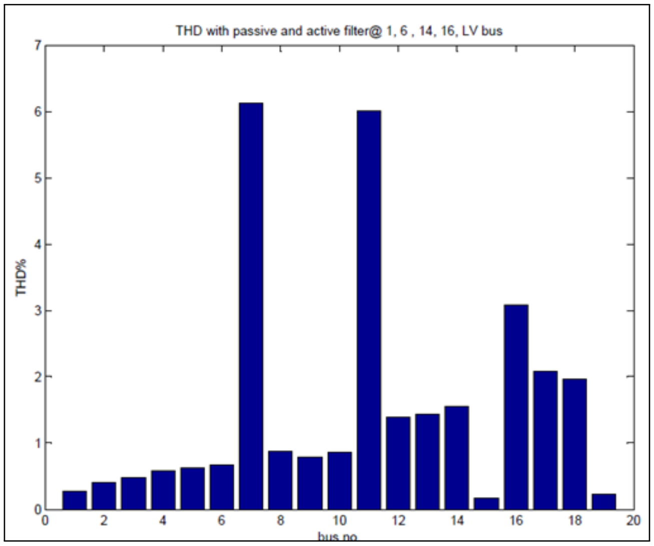

Figure 11: Distortion levels at different buses after placement of both active and passive filters

At the supply source of the utility, the effect of filter placement can be seen more prominently. The placement of hybrid mix of active and passive filters has brought down the distortion levels from 40.28% to 4.018%, with the result of filter placement for various scenarios shown in fig 12.

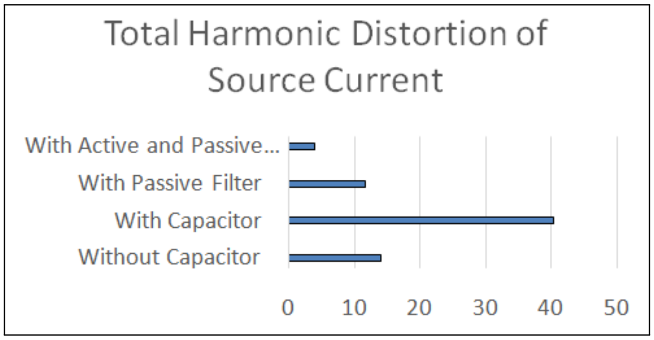

Figure 12: THD of source current under different conditions

7. Conclusions

In industrial distribution networks, capacitors are installed for the purpose of power factor improvement associated with cost benefits from utility. These capacitors, which also aid in improving the voltage profile, aggravate the distortion in the presence of nonlinear loads. In this study, the effectiveness of hybrid filter for harmonic mitigation of an industrial network has been verified by the help of simulation. The capacitors in the network are optimally sized to improve the power factor and then the tuned filters are placed on the network based on the network harmonic sensitivity analysis siting procedure. This process selects the proper bus for controlling the harmonic distortions and tunes the optimally sized capacitors to attenuate the harmonics. Active filters are then placed to bring down the distortion levels further within the prescribed limits.

Following this procedure, the harmonic distortion levels in the industrial distribution network has been brought to 4.018% from 40.28%. Therefore, an optimal hybrid mix of active and passive filters can be used in similar industrial networks to control the problems associated with harmonic distortion. The solution with active filters only is more effective but costlier, while the solution with passive filters alone is less effective but cheaper. Thus a mix of both solutions has the advantages of each.

References

[1] J. C. Das. *Power System Harmonics and Passive Filter Design*. John Wiley & Sons, Inc.,, New Jersey, 2015.

[2] Gary W. Chang, Hung Wang Lu, and Yung Chu Shou. Strategic placement and sizing of passive filters in a power system for controlling voltage distortion. *IEEE Transactions on Power Delivery*, 19(3):1204–1211, 2001.

[3] IEEE tutorial course on harmonics modeling and simulation. Technical report, IEEE Task Force on Harmonics Modeling & Simulation, 1998.

[4] IEEE. *Harmonic Analysis Studies*, pages 265–308. IEEE Recommended Practice for Industrial and Commercial Power System Analysis. IEEE, 1998.

[5] ABB. Technical guide no. 6, guide to harmonics with ac drives. Technical report, ABB, 2015.

[6] Gary W. Chang, Yung Chu Shou, and Lu Wang Hung. Sensitivity-based approach for passive harmonic filter planning in a power system. In *Power Engineering Society Winter Meeting*, 2002.

[7] Roger C. Dugan. The open distribution system simulator reference guide. Technical report, Electric Power Research Institute, 2013.

[8] IEEE. IEEE std 519-1992, IEEE recommended practices and requirements for harmonic control in electrical power systems. Technical report, IEEE, 1993.

[9] W. D. Stevenson and J. J. Grainger. *Power System Analysis*. John Wiley and Sons, 1994.

[10] Wilson Xu. Status and future directions of power system harmonic analysis. In *Power Engineering Society General Meeting*, 2003.