



A NOVEL APPROACH IN THE DESIGN OF OPTIMAL TUNING FREQUENCY OF A SINGLE TUNED HARMONIC FILTER FOR AN ALTERNATOR WITH RECTIFIER LOADS

G.SURESH BABU¹, U.K.CHOUDHURY², G.TULASI RAMDAS³

¹.Associate Professor Dept. Of EEE, CBIT,Hyderabad-75

².AGM,PMM,EMC,BHELcorporate(R&D) Hyderabad

³.Professor,Dept.of EEE & Director (A&P) JNTU, Hyderabad

ABSTRACT

Indian electrical industries supply alternators for rectifier loads, arc furnace loads and thyristor load applications to various customers. In such cases the generator line currents are not sinusoidal but are like trapezoidal which are due to harmonics. They may cause problems for utilities and industrial power system. Single tuned (ST) filter is the most commonly used device for both harmonic suppression and reactive power compensation. The objective of this paper is to obtain the optimal tuning frequency of a single tuned harmonic filter in order to control harmonic current to the allowable value with a minimum filter capacity or a given capacity by scanning the partial resonance ratio and filter resistance within possible range. Computer aided design procedure for ST filters and an associated simulation code for analysis of industrial power system with harmonic filters are illustrated. The reverse order design for multiple filter branches and usage of C#.net software for achieving optimal frequency are added features of this paper.

Keywords- *Filter design; harmonic analysis; single-tuned filter; partial resonant ratio; detuning; optimal tuning frequency.*

I. INTRODUCTION

Non-linear loads in a system will distort the source wave form and consequently tend to generate harmonic currents which will cause interference with communication circuits and other types of equipment. These resonant conditions will cause high levels of harmonic voltage and current distortion. Generally capacitors are used for power factor improvement and also for reactive power compensation which demands for resonant conditions to prevail. Filter detuning strongly affect the filter size and operation performance. Partial resonance is recommended to raise the filtering efficiency of single tuned filter[1] at the worst point in the detuning range.

Advantages of improvement of power factor are

1. Transmission and distribution losses will reduce.
2. Good voltage profile maintenance.
3. By reducing losses, better utilisation of the available power.

By superimposing the harmonic on the fundamental waveform, a composite waveform can be obtained.

The prime source for harmonics are solid state power converters such as rectifiers and SCRs in general and any device which has non-linear V-I characteristics in particular.

Due to the operation of single phase non-linear loads like power supplies for electronic equipment, the third harmonic components are generated in the neutral line. The third harmonic component produced on each phase by these loads gets added in the neutral. In some cases, the neutral current can be significantly larger than the phase currents due to these third harmonic components. The magnitude of non linear loads is increasing in the industrial sector whose contribution to the system is significant. In order to avoid the harmonic resonance problem with one of the load generated harmonics, it is essential to use power capacitors (which are also used for reactive power compensation) as filters.

It is practice to use passive filters in Mega VAR range. An improvement in power factor [6] from 0.85 to 0.9 for a system demand of 100 MVA requires approximately 10MVAR of compensation. Passive filters are being used simultaneously to meet one or more objectives and the requirements of IEEE Std. 519 with

respect to total demand distortion (TDD) at the point of common coupling (PCC).

II . APPROACH OF OPTIMAL TUNING FREQUENCY

The characteristic of non-linear loads in power system, such as electric arc furnace, static power converter and fluorescent lamp with electronic ballast, changes the sinusoidal nature of load current, resulting in the flow of harmonic current in the power supply line and hence the bus voltage distortion.

Harmonics may cause problems for utilities and industrial power system [8]. Single-tuned (ST) filter is the most commonly used device for both harmonic suppression and reactive power compensation [2-4], but filter detuning, which is caused by the variation of system frequency and filter elements, significantly decrease the filter's efficiency and may cause overload in filter. Therefore, it is recommended that the tuning frequency of ST filter is partial from the suppressed harmonic frequency though the selection of right tuning is a complex issue.

References [2 and 3] suggest that a ST filter is tuned to approximately 3% - 10% below the harmonic frequency by experience and trial. The tuning frequency is selected such that the tuned frequency of a ST filter should always be below the harmonic frequency at the maximum detuning, in order to prevent the filter from possible resonance.

II. A. MODELLING OF INDUSTRIAL POWER SYSTEM

A typical industrial power system with nonlinear load and passive harmonic filter is shown in Fig.1. whereas Fig.2 shows its equivalent circuit for harmonic analysis and filter design.

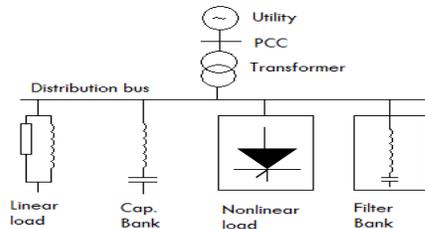


Fig1: Industrial system with Harmonic load and filter

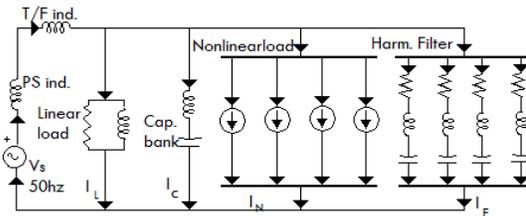


Fig 2: Equivalent circuit for filter design

The supply system is represented as an ideal voltage source in series with the utility source inductance L_U and the transformer inductance L_T , and the system impedance seen from the distribution bus at h^{th} harmonic frequency ω_h is given by

$$Z_{Sh} \approx jX_{Sh} = j\omega_h(L_U + L_T) \quad (1)$$

The linear load and the power factor correction capacitor with a series reactor, is represented by load impedance. The non-linear load is represented as multiple harmonic current sources, and the current is usually derived from actual measurement.

The filter, comprising elements of RLC, is tuned to a harmonic frequency and forms a low impedance path for the harmonic current, hence protecting the supply system against the injection of harmonics. For a h^{th} ST filter, as the inductive and capacitive Impedances are equal at the tuned frequency ω_n ,

$$\omega_n L - 1/(\omega_n C) = 0 \quad (2)$$

The filter impedance has a minimum value and is given by a small resistance. Theoretically, the tuned frequency should identically equal to that of the harmonic the filter intended to mitigate, so as to obtain the highest efficiency.

But in practice, the tuned frequency can not be fixed in the desired point due to detuning. The impedance of the filter with a detuning of δ at h^{th} harmonic frequency of ω_h is given by

$$Z_{Fh} = R + j\omega_h L + 1/(j\omega_h C) \approx R(1+j2\delta q) \quad (3)$$

Where, q is the quality factor of the filter $q = \omega_n L / R$ (4)



Detuning is caused by the system frequency deviation (δ_ω), the tolerance and change in reactor (δ_L) or in capacitor (δ_C) Detuning δ is defined as

$$\delta = (\omega_h - \omega_n) / \omega_n \approx \delta_\omega + (\delta_L + \delta_C) / 2 \quad (5)$$

Typically, the maximum frequency deviation of power supply is less than $\pm 1.0\%$, a tolerance of $\pm 2.0\%$ on reactor and a plus tolerance of 5% on capacitor (no negative tolerance) in industrial environment are Practical[2].

In addition, assume that the capacitance has a variation of $-12\% \sim +1\%$ from its designed value due to temperature changes, aging and capacitor fuse-blowing, the resultant detuning ranges between -8% and $+5\%$. For the specific h^{th} harmonic, the most important effect of linear loads with non-capacitive impedance at this harmonic, including the capacitor with series reactor and the shunt filters whose tuning frequency is below the h^{th} harmonic, is to provide damping, there by reducing the impedance seen by the harmonic current source.

To design a satisfied filter in the worst case, the effect of these loads can be neglected in the h^{th} harmonic filter design. In contrast, the shunt filters, whose tuning frequency is above the h^{th} harmonic, present a capacitive susceptance at the h^{th} harmonic, and therefore increase the h^{th} harmonic current flowing into the supply system due to the parallel resonance with system inductance.

The equivalent capacitive susceptance at h^{th} harmonic frequency of the i^{th} higher order harmonic filter is given by

$$B_i = \frac{\omega^2}{\omega_i^2 - \omega_h^2} \omega_h C_i \quad (6)$$

Where, ω_i and C_i are the tuning frequency and capacitance of the i^{th} harmonic filter respectively. Considering the amplifying effect of those higher order harmonic filters, the lower h^{th} harmonic current injected into the supply line at the installation of h^{th} harmonic filter is given by

$$I_{sh} = \left| \frac{1}{1 + Z_{sh} \cdot Y_F} \right| I_{Nh} \quad (7)$$

$$Y_F = \frac{1}{Z_{Fh}} + j \sum_{i>h} B_i \quad (8)$$

The above formulae imply that filter design should start with the highest order filter and end with the lowest order filter. This reverse-order design procedure makes the filter design complete once and do not need to revise filter's parameters obtained previously.

The design objective of an h^{th} ST filter for an industrial power system is to reduce the h^{th} harmonic current I_{sh} (in percent of maximum demand load current I_L) to an allowable level $I_{sh,max}$, which is recommended by the IEEE standard 519 [8] as shown in Table 1.

III. ADAPTABILITY

Searching the optimal tuning frequency, to have the filter satisfy harmonic control indices with minimum capacity or with a given capacity, features largely in this approach.

I_{sh}/I_L	$I_{sh,max}$					TD D
	$h < 11$	$11 \leq h < 17$	$17 \leq h < 23$	$23 \leq h < 35$	$35 \leq h$	
< 20	4.0%	2.0%	1.5%	0.6%	0.3%	5.0%
20-50	7.0%	3.5%	2.5%	1.0%	0.5%	8.0%
50-100	10.0%	4.5%	4.0%	1.5%	0.7%	12.0%
100-1000	12.0%	5.5%	5.0%	2.0%	1.0%	15.0%
> 1000	15.0%	7.0%	6.0%	2.5%	1.4%	20.0%

Table 1: Maximum harmonic current distortion in percent of I_L

Tuning frequency significantly affects the filter capacity, and usually, it is slightly below the harmonic frequency to guard against the tuned frequency shifting upward due to negative detuning and avoid the associated resonance at the harmonic frequency. Let ω_d denotes the desired tuning frequency of the h^{th}



harmonic filter; the partial resonant ratio ε is defined as

$$\varepsilon = (\omega_h - \omega_d) / \omega_d \quad (9)$$

That is, the filter is tuned to

$$n = h / (1 + \varepsilon) \quad (10)$$

Considering the effect of partial resonance, the filter's integrative detuning can be rewritten as

$$\delta = \varepsilon + \delta_o + (\delta_L + \delta_C) / 2 \quad (11)$$

III A. OPTIMAL TUNING FREQUENCY FOR MINIMUM CAPACITY

A filter with minimum capacity is one that adequately suppresses harmonics at the minimum capacity of filter capacitor, regardless of the reactive power compensation. Filter detuning strongly affects the filter's performance and capacity. A well chosen ε should have the filter satisfy its requirements at the worst point of maximum negative detuning δ_{nm} and positive detuning δ_{pm} . If the partial resonant ratio ε is subject to the following constraint, the filter capacity will be minimized:

$$I_{Sh} |_{\delta = \varepsilon + \delta_{pm}} = I_{Sh} |_{\delta = \varepsilon + \delta_{nm}} = I_{Shmax} \quad (12)$$

In this optimization problem, the system formulations can be generalized for obtaining the optimal values of ε and R by minimizing the error min

$$\{ | I_{Sh} |_{\delta = \varepsilon + \delta_{pm}} - I_{Shmax} | + | I_{Sh} |_{\delta = \varepsilon + \delta_{nm}} - I_{Shmax} | \} \quad (13)$$

$$\varepsilon, R \text{ such that, } \varepsilon \in [-\delta_{pm}, -\delta_{nm}], \quad R \in [0, X_{Sh}]$$

And then the inductance and capacitance can be obtained by

$$L = qR(1 + \varepsilon) / \omega_h \quad (14)$$

$$C = (1 + \varepsilon)^2 / (\omega_h^2 L) \quad (15)$$

III. B. OPTIMAL TUNING FREQUENCY AT GIVEN CAPACITY:

Besides the harmonic mitigation [6], shunt filter is also a reactive power compensator at fundamental frequency.

If the capacitive power from the filters designed previously for the minimum capacity is not enough to meet the load's demand or reactive power, the capacity of one or more harmonic filters needs to be increased. In this case, the filter capacity or capacitance is determined by the reactive power to be compensated, and the resistance and inductance can be described by the following expression:

$$R = (1 + \varepsilon) / (q\omega_h C) \quad (16)$$

$$L = (1 + \varepsilon)^2 / (\omega_h^2 C) \quad (17)$$

Where, ε can be obtained by minimizing of the following error

$$\min_{\varepsilon} \{ | I_{Sh} |_{\delta = \varepsilon + \delta_{pm}} - I_{Sh,max} | \}, \varepsilon \in [-\delta_{pm}, -\delta_{um}] \quad (18)$$

$$\min_{\varepsilon} \{ | I_{Sh} |_{\delta = \varepsilon + \delta_{pm}} - I_{Sh} |_{\delta = \varepsilon + \delta_{nm}} | \}, \varepsilon \in [-\delta_{pm}, -\delta_{nm}] \quad (19)$$

The partial resonant ratio getting from equation (19) will slightly less than that getting from equation (18). Applying equation (18) will make the filter to have a larger safety margin, but applying equation (19) will make the filter more efficient.

IV. SIMULATION RESULTS AND PERFORMANCE EVALUATION

SIMULINK is a software package for modelling, simulating, and analysing dynamical systems. It supports linear and nonlinear systems, modelled in continuous time, sample time, or a hybrid of the two. Systems can also be Multirate, i.e., have different parts that are sampled or updated at different rates. SIMULINK provides a graphical user interface (GUI) for building models as block diagrams, using click-and-drag mouse operations. SIMULINK includes a

comprehensive block library of sinks, sources, linear and nonlinear components and connectors. One can also customize and create his own blocks.

Models are hierarchical, so models are built using both top-down and Bottom up approaches. The system can be viewed at a high-level, by double-clicking on the blocks one can go down through the levels to see increasing levels of model in detail. After defining a model, simulation is done using choice of integration methods, either from the SIMULINK menus or by entering command in MATLAB's command window.

Using scope and powerful-continuous another display blocks, one can see the simulation results while simulation is running. In addition, one can also change parameters and immediately see what happens, for "what if" exploration. Two advantages of SIMULINK are : access to sophisticated routines embedded in MATLAB tool boxes ; and circuit equations are solved much faster than SPICE . Thus SIMULINK requires less CPU run time and memory space. For the performance evaluation of the different control strategies, the Numerical simulation is carried out in SIMULINK.

IV .A. FLOWCHART

According to the optimizing method and the system model mentioned, a PC-based filter design procedure is implemented as shown in Fig.3. Simulation program can be used, before and after the filter design, to analyse the distribution system for the behaviour of harmonic currents and voltages as function of time, and to determine the magnitude of the various harmonic current throughout the system and the voltage distortion at the distribution bus. Simulation is also intended to verify the filter design and check the effectiveness of the filter on different operating conditions, as well as the reduction of the filter effectiveness due to minor harmonics neglected in the process of filter design [7]. Fig. 4& 7 shows a MATLAB-based simulation code for the analysis of industrial power system with harmonic filters. Fig. 5 & 6 depict the frequency response without filter and with 7th harmonic filter for minimum capacity respectively.

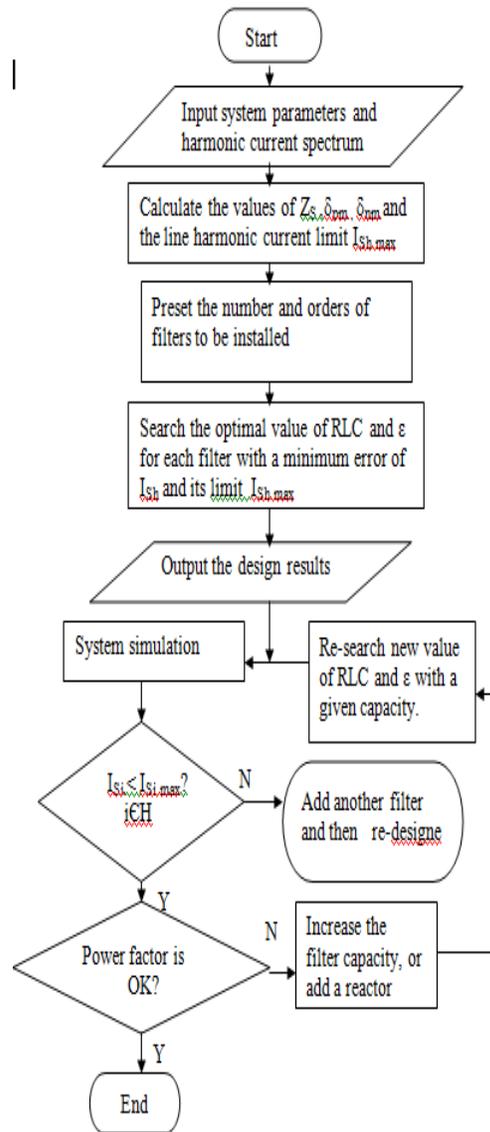


Fig.3 Decision flow chart ST filter design

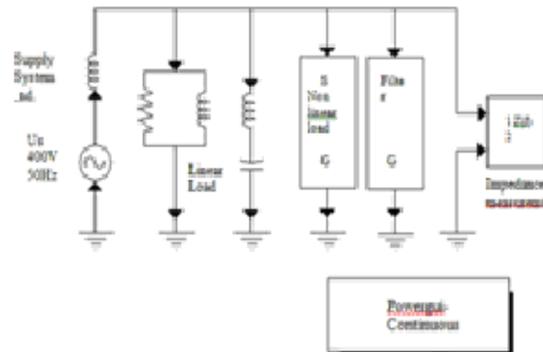


Fig. 4 MATLAB /Simulink based simulation code for an industrial power system with harmonic filters

TABLE 2: Design results for minimum capacity

Filter	n	R	L	C	VAR
5 th	4.63	11.09mΩ	0.2285mH	2064uF	102.6kvar
7 th	6.97	66.04mΩ	0.9026mH	229.96uF	10.4kvar

TABLE 3: Simulation results (% in percent of I_L)

Filter	I _{s5}	I _{s7}	I _{s11}	I _{s13}	THD _i	TDD _i	THD _u	pf
None	23.6%	9.8%	5.6%	3.02%	47.25%	26.44%	5.33%	0.67
7 th	24.4%	6.26%	5.32%	2.89%	48.07%	26.04%	5.08%	0.68
5 th	6.4%	5.8%	3.86%	2.13%	37.97%	9.99%	2.44%	0.9
5 th +7 th	6.49%	4.64%	3.74%	2.07%	34.65%	9.3%	2.27%	0.91

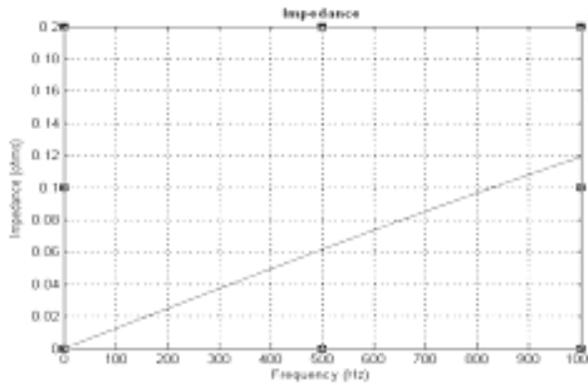


Fig.5. Frequency Response characteristics without filter.

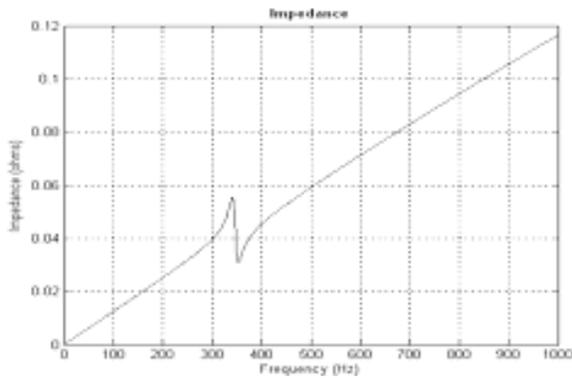


Fig. 6 Frequency response characteristics filter installed (minimum capacity)

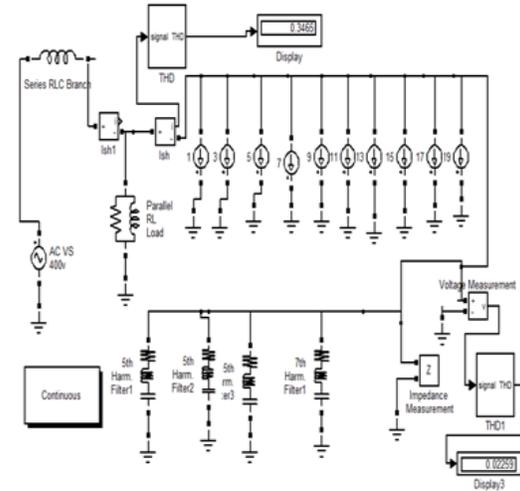


Fig 7 MATLAB/Simulink block diagram for an industrial power system with harmonic Filters for minimum capacity.

IV.B. Application

In order to test the proposed method and the computer code, an industrial distribution system with a sintering furnace powered by a six-pulse phase-controlled converter was used for investigation.

TABLE-4: SYSTEM PARAMETER

Parameter	Value
Max.short circuit capacity at PCC	90 MVA
Transformer capacity rating	1.25 MVA
Transformer impedance in per unit	0.05
Distribution bus voltage rating	400 V
System frequency	50 Hz
Max. demand load /current I _L	1000Kva/1443 A
Power in linear load	400 Kw+j300kVAR
Capacitor bank	0 kVAR
Utility source inductance	0.000012 Henry

Fig.1 shows the single-line diagram of the system, and Table -4 lists the system parameters and Table -5 lists the current spectrum measured in the sintering furnace.

TABLE-5: HARMONIC CURRENTS IN SINTERING FURNACE (IN PERCENT OF I_L)

Order	Current		Phase
	(A)	(%)	
1	808.0	5.6%	-65^0
3	8.9	0.6%	165^0
5	340.2	23.6%	-145^0
7	141.4	9.8%	-95^0
9	0.8	0.1%	135^0
11	80.0	5.6%	-175^0
13	43.6	3.0%	55^0
15	0.8	0.1%	105^0
17	35.6	2.5%	-25^0
19	17.8	1.2%	-155^0

TABLE-6 DESIGN RESULTS FOR GIVEN SYSTEM PARAMETERS

FILTO R	I_{S5}	I_{S7}	I_{S11}	I_{S13}	THD_1	TDD_1	THD_u	PF
None	23.6 %	9.8 %	5.6%	3.0%	47.26 %	26.46 %	5.25 %	0.67
5 th	4.49 %	4.7 %	3.11 %	1.81 %	16.17 %	7.78%	1.92 %	0.993

TABLE-7 SIMULATION RESULTS IN THE FINAL DESIGN

Filter	n	R (mΩ)	L(mH)	C(μF)	KVAR
5 th	4.63	2.303	0.04748	9947	500

It can be obtained from Table- 3 that the ratio of I_{sc}/I_L is 90.

Fig. 5 & 6 depicts that frequency response characteristic without filter and with 7th harmonic filter respectively. Comparing the harmonic currents listed in Table-5 with the maximum allowable value in Table -1, it is evident that the 5th and 11th harmonic currents exceed its limits without filter, and the 7th harmonic current also approaches its limit. So, at least the 5th harmonic filter must be designed.

In order to have the total TDD_i to satisfy its limit of 12%, a 7th harmonic filter may also to be installed.

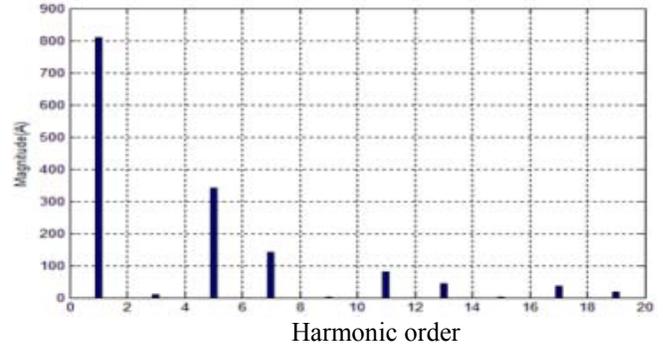


Fig.8 Current Spectrum without filter

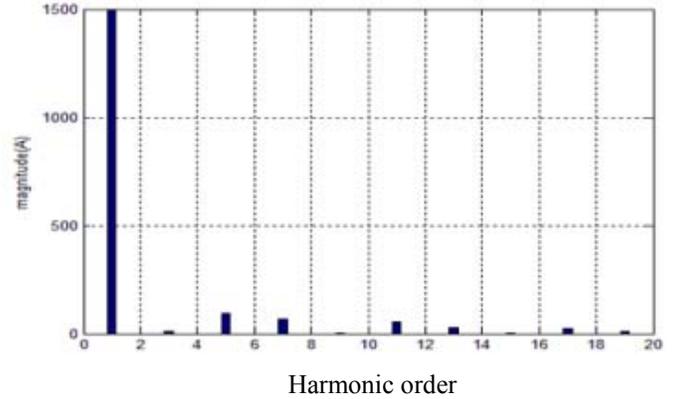


Fig.9 Current Spectrum with 5th+7th harmonic filter. (minimum capacity)

It is evident from the above fig. 8 and fig.9 that the current spectrum for the minimum capacity the magnitude is significant with and without filters.

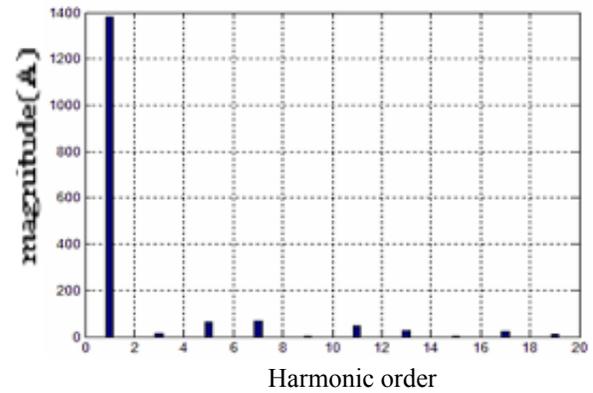


Fig.10 Current Spectrum with 5th harmonic filter (given capacity)

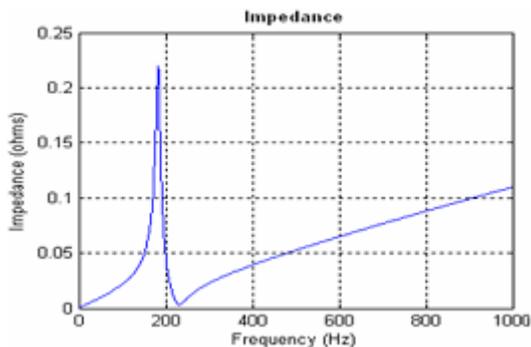


Fig.11 Frequency response characteristics with 5th harmonic filter installed(given capacity)

Fig. 10&11 respectively indicates the current spectrum and frequency response for a given capacity. With a detuning of $-8\% \sim +5\%$, a fixed quality factor of 30, and the maximum allowable harmonic current of 7% the filter design results for minimum capacity are shown in Table -2. Table -3 shows the comparison of the worst value of line harmonic current in percent of I_L , THD_u of bus voltage and Displacement power factor when different filters connected to the industrial power system. Table -3 indicates that all the harmonic control indices are satisfied with operating of the 5th harmonic filter alone or both 5th and 7th filter, Table-3 shows that the 5th harmonic current will be amplified when the 5th filter is out of service but the 7th filter is on line. The 7th filter must not connect to the bus until the 5th filter is in operating

V. CONCLUSIONS

PC-based design procedure of passive harmonic filter is Presented .The filter is intended to control harmonic current in supply line to the allowable value defined by IEEE Std-519 and to improve power factor. The filter parameters are first determined by searching the optimal partial resonant ratio and filter resistance with the objective of minimum capacity, and if necessary then modified by the requirement of reactive power compensation. A simulation program is accompanied to verify the effectiveness of the filter and to check the voltage and currents throughout the system. Simulation results with an industrial system show that the

proposed design methodology is feasible and effective. The same design procedure with certain modification can be extended to filter design for a substation, provided system parameters are known.

REFERENCES

- [1] Xiangqian Tong, Junyi Xue, and Wenjun We, Jie Li“Approach of Optimal Tuning Frequency in Single Tuned Harmonic Filter” IAS 2005, 0-7803-9208- 6/05, IEEE 2005
- [2] J. C. Das, “Passive filters-potentialities and limitations,” IEEE Trans. Ind. Applicat., vol. 40, pp. 232-241, Jan. /Feb. 2004
- [3] D. A. Gonzalez and J. C. McCall, “ Design of filters to reduce harmonic distortion in industrial power systems, ” IEEE Trans. Ind. Applicat, vol. IA-23, pp. 504-511, May/June 1987
- [4] Kun-Ping Lin, Ming-Hoon Lin, and Tung-Ping Lin, “ An Advanced computer code for single-tuned harmonic filter design,” IEEE Trans. Ind.Applicat., vol. 34, pp. 640-648, July/August 1998
- [5] Chi-Ju Wu, Jung-Chen Chiang, and Shih-Shong Yen, et al, “ Investigation and mitigation of harmonic amplification problems caused by single-tuned filters, ” IEEE Trans. Power Delivery, vol. 13, pp. 800-806, July 1998
- [6] M. M. Cameron, “ Trends in power factor correction with harmonic filtering ,” IEEE Trans. Ind. Applicat., vol. 29, pp. 60-65, Jan./Feb. 1993
- [7] Leszek S. Czarnecki , and Herbert L. Ginn, “ Effects of damping on the performance of resonant harmonic filters,” IEEE Trans. Power Delivery, vol. 19, pp. 846-853, April 2004
- [8] IEEE Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems, IEEE Std 519-1992, 1993