Passive Filter for Reducing Harmonic in Adjustable Speed Drives: A Review

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Abstract: Adjustable speed drives (ASD) are used widely in process industries due to better speed regulation, quick response and reduced wear and tear as compared with mechanical alternatives. However, based on topology of ASDs, harmonics injects in the power system and causes distortion of voltage and current waveform and creates some harmful effect to the system. Hence, mitigation techniques are required to limit injection of harmonics in the system. One of the mitigation techniques is the application of passive filter. Installation of passive filter at input of ASDs, reduces harmonics, regulates voltage in steady and dynamic conditions, improves power factor. However, passive filter accompanies problems such as creating resonance to the network which needs to be calculated in harmonic study and resolved during filter sizing. This paper involves procedures for sizing and comparison of different passive filters.

Index Terms* - *Passive filter, Point of common coupling (PCC), Total demand distortion (TDD), Total harmonic distortion (THD), Individual harmonic distortion (IHD).

I. INTRODUCTION

Harmonics are sinusoidal voltage or currents having frequencies that are integral multiples of fundamental frequency at which the system is designed to operate [6]. Power quality includes a broad range of concerns such as sag, swell, imbalances, and fluctuations in voltage, transients, interruptions, harmonics, and power frequency variations.

ASDs feds current harmonics & results in voltage harmonics when flowing through system impedance & affect the power quality of supply. Harmonics are produced by non-linear loads. Generally the grid is filled with 1 phase and 3 phase non-linear loads like rectifiers, converters, static VAR compensators, ASD, arc & induction furnaces, welding machines and power electronics based devices such as SMPS, UPS, & CFL. All these non-linear loads and power electronics based devices produces current distortion causing current harmonics. When these distorted current flows through different impedances available in power system (such as source, transformer, cable) produces voltage drop at that harmonics. Voltage is distorted due to addition of these voltages to the source voltage. Voltage distortion increases as the harmonics current and impedance increases. In order to reduce voltage distortion need to reduce current distortion or lower the impedance of system.

Both harmonic voltage and current can cause following problem [5]

a) Increased losses in equipment & connected cables & lines etc.,
b) Pulsating and reduced torque & vibrations in motors and other rotating equipment,
c) Reduced aging of insulation of electrical equipment due to increased stress,
d) Increased audible noise in static and rotating equipment
e) Mal-functioning of equipment which are sensitive to waveforms
f) Significant amplification of voltage and current due to resonance &
g) Communication interference (proximity effect)

IEEE standard 519-2014, recommended practices and requirements for harmonic control in electric power system, provides guidelines for voltage and current distortion on transmission and distribution network [1, 2]. The purpose is to limit the voltage distortion by limiting the harmonic current injection in to the system injected by individual consumer. Meeting the requirement needs the application of methods of harmonics. There are different methods of reducing harmonics are as follows.

a) Passive filters
b) Active filters
c) Increasing number of pulses of converter
d) Active front end model

Active filter Inject equal and opposite harmonics onto the power system to cancel those generated by other equipment. Benefit of it is having proven very effective in reducing harmonics well below required levels but the high performance inverter needed for the harmonic injection is costly. Power transistors are exposed to situation of the line, so reliability may be a problem. Another method of reducing harmonics is by increasing number of pulses of converter. Hence instead of 6 pulse we can use 12& 18 pulse drive. As number of pulse increases harmonics gets reduced. But increasing number of pulses can be expensive at smaller HP motors. Active front end presents near sinusoidal input current with higher power factor, low frequency current harmonic elimination in static conversion system. However, it involves IGBTs in rectifier instead of diodes and hence, involves high cost. Passive filter consist passive element (R, L &C) & it is cost effective and reliable solution mostly in industry it is preferred. Hence this paper deals with different types of passive filter & designing.

The reminder of this paper is organized as follows: Section II passive harmonic filter. The limit of current & voltage harmonic as per standard 519 is provided in Section III. Section IV describes design of different harmonic passive filter & evaluation of capacitor duty limit. Section V&VI includes comparison &conclusion for this paper.

II. PASSIVE HARMONIC FILTER

Passive filter consists of RLC components. The basic idea behind passive filter is to size L & C in such a way that it creates resonance at unwanted harmonic frequency. The passive filters are classified as series and shunt. Series connected filter creates parallel resonance at tuning frequency which offers very high impedance. Thus filter blocks the harmonics to flow through it. The limitation of series filter is that all the components of the filter are required to be designed for full line current, because of this makes the system very expensive. Mostly used filters are shunt connected to the AC system. It creates series resonance offering negligible impedance at tuning frequency. Hence draws major of portion of harmonics and allow very little portion of the harmonics to flow to the AC system. Component of shunt connected filters are designed for graded insulation level, thus make components cheaper than series connected filters. Shunt connected filters are also called as trap as it absorbs harmonics current at which it is tuned [6]. Shunt filters are classified as single tuned filter (notch filter) & high pass filter

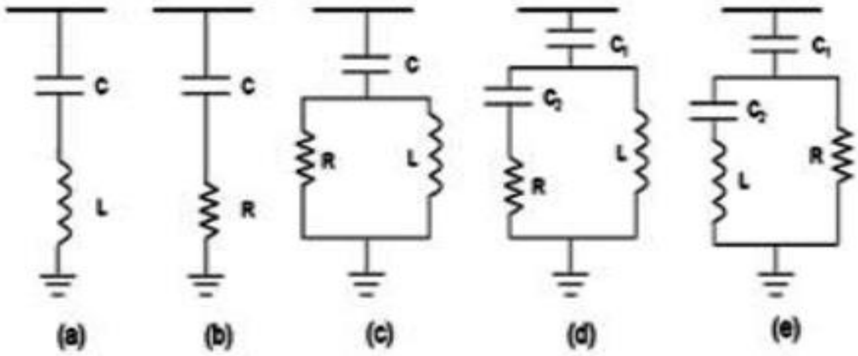

Figure 1 (a) single-tuned (b) first order high pass (c) second order high pass (d) third order high pass (e) c- type

Single tuned filter is aimed at filtering single harmonic frequencies whereas high pass filters effective for range of frequency. High pass filter have again have several variations such as follows-

a) First order high pass,
b) Second order high pass,
c) Third order high pass,
d) C-type filter.

Single tuned filter consist of capacitor in series with inductor. The fundamental idea behind this filter is to size L & C in such a way that it provides negligible or zero branch impedance near a harmonic frequency. Capacitor can also improve the power factor of the system [4]. The advantages of this filter is that it is simple only two components, maintenance required is less, provides maximum attenuation of one harmonic because of high quality factor & limitation is that number of filters required to filter several harmonics as one filter can be used for one harmonic only & more sensitive to variation in the fundamental frequency as well as component values due to high quality factor of the filter which gives low bandwidth. Another limitation is that needs to provide taps on the reactor at site in order to provide accurate tuning which increases cost of the reactor.

First order filter as shown in figure 2 (b) consist of capacitor and resistor. It provides small impedance at high frequency due to capacitor characteristics. Resistance is used to limit the current that flows through capacitor. To provide smaller impedance at high frequency its value needs to be high. This increases cost and size of the filter and could overcompensate the system. Hence performance at low frequency is usually poor [4]. Second order filter consist of capacitor connected in series with the parallel combination of inductor and resistor. The L & C are sized such that it acts single tuned filter below tuning frequency and like to first order at high frequency. The inductive reactance is dominating at low frequencies, bypassing the resistive branch & high at high frequency compared to resistance hence diverting the current to the resistor branch. A notch can be observed at tuning frequency, to get this performance, L & C tuned to the desired harmonic frequency [4].

Third order high pass filter shown in figure 2(c), it behaves like the single tuned filter at low (below tuning) frequency, and acts like first order high pass filter above it. The inductive reactance is small at low frequency diverting the RC branch & large at high frequencies, Hence current flows through R & C_2 branch. The capacitor C_1 & C_2 are tuned to the inductor at the same harmonic frequency. Hence filter provides very low impedance at the tuning frequency, like to the single tuned filter. Filter gets less loss at the fundamental frequency than the second order high pass filter due to addition of capacitor C_2 in series with resistor. Filter shows dipper notch valley due to this tuning scheme than the second order high pass filter [4].Performance of the C-type filter lies in between that of second & third order filter. It consists of capacitor connected in series with the parallel combination of L-C_2 & resistor R as shown in figure 2 (e). The branch consisting L-C_2 tuned to the power frequency. Hence at power frequency this branch provides negligible impedance hence bypassing the resistance branch which reduces power frequency loss. If the frequency increase capacitor C_1 & L becomes resonating hence filter behaves like single tuned filter with damping resistor. At high frequency inductor becomes high so current flows through resistive branch which makes filter similar to first order high pass filter [4].

III. TO FIND OUT LIMIT OF VOLTAGE & CURRENT HARMONICS-STANDARD IEEE 519

Stage 1: To find out level of level ratio of short circuit current in customer-in order to find out the limit of harmonic current and voltage injection in the system needs to consider following steps:

a) Find out capacity of short circuit of system(MVASC)
b) Find out the base impedance (Zbase)
c) Find out the base current(Ibase)
d) Find out source impedance(Zsource)
e) Find out power and customer transformer impedance, Ztrafo & Ztrafo-Cst respectively
f) Find out the line impedance(Zline)
g) Find out short circuit current in the customer(Isc)
h) Find out the installed load customer(IL)
i) Find out the ratio (Isc/IL)

Knowing rated voltage of the system & SCR the limit for current & voltage harmonic can be found from IEEE standard 519. Voltage distortion revised in the standard IEEE 519-2014 given as below. All values should be in percentage of the rated power frequency voltage at PCC. Table 1 applies to voltage harmonics whose frequencies are integer multiple of power frequency

Table1-IEEE 519-2014 harmonic voltage limits

Voltage distortion limits

Bus voltage V at PCC	Individual harmonic (%)	Total harmonic distortion THD (%)
$V \leq 1.0$ kV	5.0	8.0
1 kV $< V \leq 69$ kV	3.0	5.0
69 kV $< V \leq 161$ kV	1.5	2.5
161 kV $< V$	1.0	1.5[a]

[a]High-voltage systems can have up to 2.0% THD where the cause is an HVDC terminal whose effects will have attenuated at points in the network where future users may be connected.

The IEEE 519 Provides harmonic current restrictions for individual customers (table 2). These are intended to limit the insertion of harmonic currents in to the power system so that the resulting voltage distortion will be up to standard for all customers.

Table - 2-IEEE 519 Harmonic current limits

Current distortion limits for systems rated 120 V through 69 kV

Maximum harmonic current distortion in percent of I_L						
Individual harmonic order (odd harmonics)[a, b]						
I_{SC}/I_L	$3 \leq h < 11$	$11 \leq h < 17$	$17 \leq h < 23$	$23 \leq h < 35$	$35 \leq h \leq 50$	TDD
< 20[c]	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

[a]Even harmonics are limited to 25% of the odd harmonic limits above.
[b]Current distortions that result in a dc offset, e.g., half-wave converters, are not allowed.
[c]All power generation equipment is limited to these values of current distortion, regardless of actual I_{sc}/I_L
where
I_{sc} = maximum short-circuit current at PCC
I_L = maximum demand load current (fundamental frequency component) at the PCC under normal load operating conditions

In Table – 2, Point of common coupling (PCC) is the location where harmonic currents are determined most likely by the utility. Probable locations are the metering point or the high side of the customer step down transformer. Maximum demand load current (IL)is given by the average of the monthly maximum demand values for 12 months. Clearly, this must be estimated for new customers or customers who have made changes to their load. Short circuit ratio (SCR-Isc/IL) is the ratio of the short circuit current at the PCC to the maximum demand load current. SCR is high for a strong system with respect to customer size. Higher level of harmonic current generation is approved for higher values of SCR because a single customer has less impact on the system voltage distortion [11].

Stage 2: Find out the individual current & voltage harmonics higher than IEEE standard 519-1992-individual order of current & voltage harmonics compared with IEEE standard 519 & then identify the order of harmonics which are higher than standard.

Stage 3: Find out the maximum value of individual current and voltage harmonic-after finding highest value of individual harmonic, design the filter

IV. DESIGN OF SHUNT PASSIVE FILTER AND EVALUATION OF FILTER DUTY LIMIT

A. DESIGN OF SINGLE TUNE FILTER & EVALUATION OF FILTER DUTY LIMIT-

The most ordinary design of shunt passive filter is single tuned filter. The resonance frequency is given by following equation [6]

$$f_0 = \frac{1}{2\pi\sqrt{LC}} = f_1\sqrt{X_c/X_L}$$

Where,
f_o=resonance frequency
L=inductance of the filter
C=capacitance of the filter
X_L=inductive reactance of the filter
X_C=capacitive reactance of the filter
f_1=Fundamental frequency

Step 1: Decide tuned frequency for filter-tuned frequency for the filter is chosen slightly below harmonics frequency to allow for the tolerance in the filter components & variations in the system impedance. Example for 5th harmonic frequency the filter is tuned to 4.7th.

Step 2: Compute capacitor bank size –passive filter also provides reactive power compensation & can be found as below

$$Q = P \times \{\tan(\cos^{-1} pf_0) - \tan(\cos^{-1} pf_1)$$

Where,
P = active power,
Q = reactive power to be compensated,
Pf_0 = actual power factor,
Pf_1 = power factor to be improved.

The net equivalent filter reactance (capacitive) X_{filt} is calculated by

$$X_{filt} = \frac{kV^2 \times 1000}{kVAR}$$

$$X_{filt} = X_{cap} - X_L$$

For tuning harmonics (h)

$$X_{cap} = h^2 \times X_L$$

Thus desired capacitive reactance can be determined by,

$$X_{cap} = \frac{X_{filt} \times h^2}{h^2 - 1}$$

To achieve this reactance, the capacitor would have to be rated,

$$kVAR = \frac{kV^2 \times 1000}{Xcap}$$

Step 3: To find out filter reactor size-value of filter reactor find out from capacitive reactance as follows,

$$X_L = \frac{X_{cap}}{h^2}$$

$$L = \frac{X_L}{2\pi f}$$

Resistance R of the filter determines quality factor Q_f of the filter & is determine as ratio of inductive or capacitive reactance at resonance to the resistance. Typical values of Q_f ranges between 15-80 for filters used in industrial & commercial application [6].

B. DESIGN OF SECOND ORDER FILTER

The configuration of second order filter is as shown in figure 2(C) it consist of capacitor connected is series with parallel combination of inductor, resistance. Hence it has 3 design equations from that the values of capacitor and inductor can be calculated same way as specified in design of single tuned filter(step 2 & step 3), need to calculate value of damping resistor only & it can be calculated from the quality factor. Quality factor (Q_f) of second order filter is defined as the ratio of resistance to the reactance (inductive/capacitive) of RC parallel circuit at tuned frequency. Quality factor decides bandwidth that determines sharpness at the tuning frequency & is given by

$$Q_f = \frac{R}{\omega_h \times L}$$

Hence value of damping resistor is calculated as

$$R = Q_f \times \omega_h \times L$$

Where,

ω_h- Harmonic angular frequency in rad/sec

C. DESIGN OF C-TYPE FILTER

It consists of main capacitor C_1 connected in series with parallel combination of C_2+L & resistance R. Hence four design equations are presents. The value of main capacitor & inductor can be calculated same way as in single tuned filter. The second capacitor tuned to inductor at power frequency to reduce power frequency loss & is calculated as below,

$$C_1 = \frac{Q}{V^2 \times 2\pi f}$$

$$L = \frac{1}{[(2\pi f_r)^2 * C_1]}$$

$$R = Q_f \times 2\pi f_r \times L$$

$$C_2 = \frac{1}{(V \times 2\pi f)^2 \times L}$$

Where,

Q = reactive power produced by filter at power frequency

V = voltage at which filter is to be installed

f = power frequency

f_r = tuning frequency

Q_f=quality factor of the filter

Once the harmonics study is completed & filter component selection has been made, the capacitor rating relating to voltage, current & kVAR should be checked. All these three ratings need to be satisfied independently according to IEEE STD 18-1992.

V. EVALUATION OF FILTER DUTY LIMIT

Evaluation of filter duty requirements-it involves capacitor bank duties. It includes peak voltage & current &kVAR produced RMS voltage. For limiting these duties IEEE Standard shunt power capacitor is used.

Evaluation of these duties includes three steps, i.e.

a. Calculation for fundamental duties,
b. Harmonics duties, &
c. Peak voltage & RMS current duties and calculation of capacitor loading limits.

Steps are detailed as mentioned in following:

a. Calculation for fundamental duty requirements-the calculation is as follows:

The net reactance of combination of capacitor and reactor at fundamental frequency is,

$$X_{eff} = |X_L - X_C|$$

The calculation of fundamental frequency current for a passive harmonic filter is as follows,

$$I_f(1) = \frac{V_S}{X_{eff}}$$

Where,

V_S=Rated system operating voltage, phase value,

X_C=capacitive reactance at fundamental frequency,

X_L=inductive reactance at fundamental frequency.

Capacitor rated current calculated as follows,

$$I_{nom} = \frac{Q_{CAP}(kVAR)}{\sqrt{3} \times V_{rated}(kV)}$$

Voltage across capacitor at fundamental frequency is,

$$V_c(1) = I_f(1) \times X_C$$

This is the nominal fundamental voltage across the capacitor & it should be less than 110% of the capacitor rated voltage

Per phase reactive power of capacitor at fundamental frequency is given by,

$$kVAR(1) = V_C(1) \times I_f(1)$$

b. Calculation of harmonic duty requirement-the maximum harmonic current is the sum of harmonic current produced by the load and supplied from the utility side.

$$I_{RMS} = if_1{}^2 + if_3^2 + if_5^2 + if_7^2 + \cdots \ldots \ldots \ldots \ldots .)^{1/2}\ A$$

c. RMS current and peak voltage duties and evaluation of capacitor loading limit-peak voltage is calculate by summing the harmonic & fundamental components as given by following equation,

$$V_{cpeak} = [V_c(1)) + V_c(h)]$$

Where,

$$V_c(h) = \sum I(h) \times \frac{X_c}{h}$$

The RMS voltage across the capacitor is

$$V_{CRMS} = [V_C(1)^2 + V_C(h)^2]^{1/2}$$

IEEE 1036-1992 allows for the continuous operation of the capacitor at a voltage 110% above the RMS rated voltage & 120% above the peak of the rated voltage. These margins should be reserved for contingency operation. Consequently, the design for harmonic filter rates the capacitor voltage at 100% of the most severe operating condition. Based on the line to line rated voltage of the harmonics filter capacitor bank, the rated 3 phase kVAR of the capacitor bank is

$$Q_{rated} = \frac{(\sqrt{3} \times V)^2}{X_c}$$

Where,

Q_{rated}- is the 3 phase rating of the capacitor bank

X_c-impedance of the capacitor bank

Evaluation of capacitor rating limits. The duties (peak voltage, RMS voltage, current & kVAR produced) can compare to the IEEE standard limits in table 3

Table - 3 Filter duty limit IEEE Standard 1036-1992

FILTER DUTY LIMITS AS PER IEEE STANDARD 1036 – 1992

Duty	Limit, %
Peak Voltage	120
RMS Voltage	110
Peak Current	180
kVAr	135

VI. COMPARISION

Table - 4Comparison of different types of filter

Criteria	**Single tuned filter**	**Second order filter**	**C-Type filter**
Filtering of harmonics	Single harmonic	single harmonic above certain range	single harmonic and above certain range
No of component	3	3	4
Design Complexity	Simple	Simple	Complex
Losses at power frequency	Less	High	less compare to second order & high compare to single tuned
Quality factor	High (15-80)	Low (0.5-5)	Low (0.5-5)
Sensitive to fundamental frequency & component value variation	High	Low	Low

VII. CONCLUSION

In this paper reviewed different shunt passive filter for reducing harmonics such as single tuned filter, second order high pass filter & C-type filter. The design of each method is presented. And finally comparison conducted on different point such as performance, design complexity and losses.

Though passive filter is having low cost, simplicity, reliability & efficiency it has limitations such as, resonance problem, fixed compensation character, possible overload and poor dynamic behaviour.

REFERENCES

[1] IEEE Standard 519-1992 IEEE Recommended Practice & Requirements for Harmonic control in Electric Power System.
[2] IEEE Standard 519-2014 IEEE Recommended Practice & Requirements for Harmonics Control in Electric Power System.
[3] IEEE Standards 18-1992 for shunt power capacitor
[4] A. B. Nassif, W. Xu, W. Frietas, "An investigation on the selection on filter topologies for passive filter applications", IEEE Transaction on power delivery, vol.24, no.3, July 2009
[5] IEEE standard 399TM-1997 IEEE recommended practices for industrial & commercial power system analysis.
[6] IEEE STD141-1993 IEEE Recommended Practices for Electrical Power Distribution for Industrial Power Plant
[7] Power quality by N Shankaran
[8] Xin Li, WilsunXu, Tianyu Ding, "Damped High Pass Filter-New Filtering Scheme for Multipulse Rectifier System" IEEE transaction on power delivery, vol. 32, no.1, February-2017
[9] ModiPramod s, Joshi S. K..,"An investigation on harmonics and active reactive power of asymmetrical operation of 12 pule converter and mitigation of harmonics"

[10] Mark F. McGranaghan, Dave Mueller, "Designing harmonics filters for adjustable speed drives to comply with new IEEE-519 Harmonics limit " J. C. Das, PE, Passive Filters-potentialities and limitations, IEEE Transaction on industry application, Jan-Feb 2004, 232-241.

[11] Angelo Baggini, hand book of power quality, John Wiley and sons. Lt

[12] Young Sik Cho, Hangu Cha "single tuned passive harmonics filter design considering variances of tuning and quality factor" journal of international council on electrical engineering vol. 1, no. 1, pp. 7-13,2011

[13] Babak Badrzadeh, Kenneth S. Smith and Roddy C. Wilson, "Designing Passive Harmonic Filters for an Aluminum Smelting Plant", IEEE transaction on industry applications, volume 47, NO. 2, March/April 2011