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DESIGNING PASSIVE FILTER USING NON-TRADITIONAL TECHNIQUE

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Abstract—Harmonics and its mitigation technique are headache for most of the power engineers for the obvious reasons; its adverse effects on power system. In power system, various techniques exist for mitigation, but most of them are based on the study of harmonic pattern at the site. Beside this, there is no passive filter design for ASDs (Automatic Speed Drives). This paper focuses on filter design technique based on Butterworth filter. It does not need any prior study of harmonics at the site. It is applicable for both VFDs (Variable Frequency Drives) and PCCs (Point of Common Coupling). Butterworth filter provides perfect mitigation technique bringing THD (Total Harmonic Distortion) well fewer than 5%. This paper mostly focuses on mathematical tools of Butterworth filter. But it also provides software analysis of design.

Keywords—Passive Filters, Power System Harmonics, Harmonic Distortion, Butterworth Filter

I. INTRODUCTION

During the last thirty years, much attention has been focused on power system harmonics. This is one of the severe issues affecting power quality, because it affects both the utility company and consumers [1]. Various ideas and techniques have been formulated to reduce harmonics and its effects. However much ignorance still surrounds in the field of harmonic filters as there are flaws in most of the present day filters (both active and passive) [2]. Harmonic filters are basically classified into active and passive based on the technique (concept) and scope of filter.

Active filter: this concept comprises of power electronic devices that generate harmonics with phase shift of 180^0. These filters are relatively new and prove costly as compared to passive. But they have distinct advantages over passive; firstly they do not have any resonating component and also the accuracy of active is more compared to passive. Use of switching devices and other electronic devices restrict the use of active filter to ASDs and PCCs where harmonic distortions are huge [4].Passive filter: this area has been trending for last two decades or so, for the obvious reason cost. Passive filters are inductance, capacitance, and resistance elements configured and tuned to control harmonics. They are used either to shunt the harmonic currents off the line or to block their flow in the system by tuning the components to a fixed resonating frequency. The reason they are cheaper as compared to active is they do not have any electronic components. Frequently used passive filters are

- Single-tuned "notch" filter
- Series passive filters
- Low pass broadband filter
- C filters

All these concepts are frequently and traditionally used at the utility system. Along with the merits passive filters have few demerits as well. One of the unavoidable deficit is the aging of the components, this not only deteriorates the performance of end user equipment but also off tunes the passive design. This aging of components is seen after a long period of time; say after a period of 20-30 years and during this period maintenance is also less as compared to active. Hence for the following reasons passive prove to be reasonable than active.

Passive filters are usually employed at the PCC of industry where it prevents the harmonic components from entering utility and also lowers the demand kVA of industry thus reducing the electricity bill. The passive filters mentioned above cannot be used directly to filter harmonics form VFD. Even if used, the design becomes bulky; also the cost of installation becomes costly as compared to active filter.

This paper encompasses the designing and implementation of "Butterworth filter" technique. Even though this idea is conventionally used in low voltage electronic circuits, it can be equivalently implemented in medium and high voltage circuits using the basic concept of Butterworth filter. The objectives of

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this paper are 1) to provide the concept of Butterworth filter 2) mathematical tools for designing of Butterworth filter and 3) to study practical consideration of each order of the Butterworth filter. The verification of the orders of the Butterworth filter has been done under the guidelines of IEEE-519. Keeping the practical consideration of the order of harmonics, for the study of mitigation technique real time simulation has been carried out.

II. BUTTERWORTH FILTER

A. Concept

Basically it is a signal processing filter designed to have as flat a frequency response as possible in pass band. It is a type of low pass filter which passes all the frequency components which are less than cutoff frequency with minimum attenuation. It is also known as maximally flat magnitude filter. The frequency response (gain) of a general n^{th} order Butterworth filter with a cutoff frequency of 1 radian per second is given by

$$G(\omega) = \sqrt{\frac{1}{1+\omega^{2n}}} \qquad (1)$$

Here ω is the angular frequency in radians per second

n is the order of the filter

Gain plot of the Butterworth filter with the frequency response represented earlier is shown in fig. 1

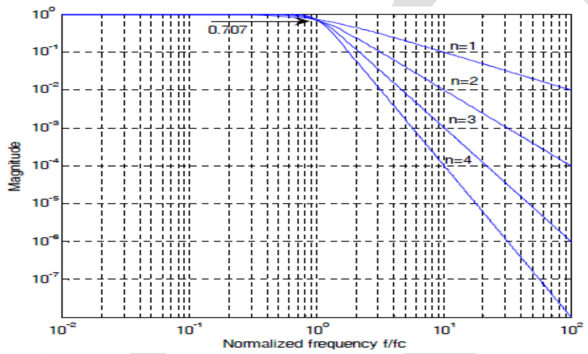

Fig. 1. Gain curve of n^{th} order Butterworth filter

Conceptually a low pass filter allows all signals to pass which are less than cutoff frequency, and those which are higher than cutoff are completely attenuated. But in real world this does not happen, frequency components beyond the cutoff do not get completely attenuated and are rather seen at the input with some magnitude. This can be proved from fig. 1, for a first order system, the curve drops down at a constant slope of -20db/decade. Hence for a harmonic order 5 20% of the magnitude is still seen at the input. The does not bring the THD under limit.

The remedy for this is to increase the order of the system. On increasing the order the slope of the curve after cutoff frequency increases by -20db/decade for every increase in order of the system. For higher orders the curve tends to match the ideal concept. The order "n" stated above is the number of reactive elements in the filter.

B. Mathematical Analysis of Butterworth Filter

The gain G(ω) or the frequency response of an n-order Butterworth filter is given in s domain in terms of the transfer function H(s) using equation (2), which is given as

$$G^2(\omega) = |H(j\omega)|^2 = \frac{G_0^2}{1+\left(\frac{\omega}{\omega_c}\right)^{2n}} \qquad (2)$$

Where

n = order of the filter

ω_c = cutoff frequency

G_0 is the gain when frequency tends to zero

Here all signals or rather all the frequency components below cutoff frequency will be seen with magnitude G_0, while frequencies above it will be suppressed. The extent of suppression depends on value of n. The curve of the above relation is a circle with radius ω_c, and the n poles of the above relation lie on that circle.

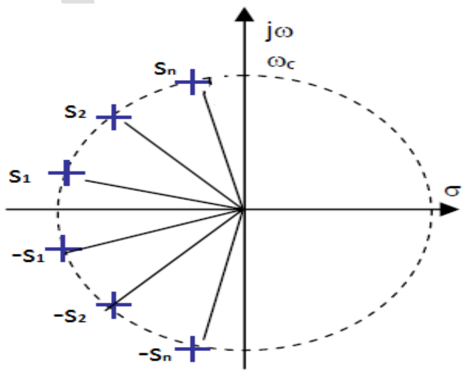

Fig. 2. Poles of Butterworth polynomial

From the above relation on taking s = j ω frequency response in s domain can be computed [5]. The transfer function H(s) is given as

$$H(s) = \frac{G_0}{\prod_{k=1}^{n}(s-s_k)/\omega_c} \qquad (3)$$

The denominator is a Butterworth polynomial in s, where as the term s_k represents the k^{th} pole of the polynomial, and ω_c the cutoff frequency. Here again the poles of the polynomial lie on the circle of radius ω_c, as shown in fig. 2.

III. MATHEMATICAL ANALYSIS OF THIRD ORDER FILTER

A first order Butterworth filter is most simple and cost friendly, as it consist of inductor, capacitor and resistor with inductor in series and both capacitor and resistor in shunt. But

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as studied earlier for proper filtration technique there is need to increase the order of system. Depending on the type of application and budget, the order of the filter can be chosen. Order chosen in this paper is third as an intermediate choice between cost and design effectiveness. The circuit of the third order Butterworth filter is shown in fig. 3.

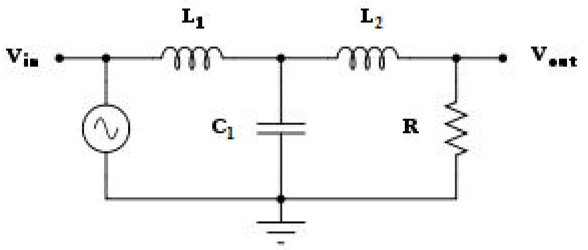


Fig. 3. Circuit of third order Butterworth filter

Here Vin is input sinusoidal voltage where as Vout is the output or the load side non-linear voltage, and the other terms in the fig. have their literal meanings. The transfer function of the circuit is

$$H(s) = \frac{V_{out}(s)}{V_{in}(s)} \quad (4)$$

$$H(s) = \frac{R}{L_1L_2C_1s^3+L_1C_1R\times s^2+(L_1+L_2)\times s+R} \quad (5)$$

Here the transfer function is in s domain; similarly the general Butterworth filter of third order is given as

$$H(s)=\frac{G_0\times\omega_C^3}{s^3-(s_1+s_2+s_3)s^2+(s_1s_2+s_2s_3+s_3s_1)s\text{-}s_1s_2s_3} \quad (6)$$

On equating equations (5) and (6) the values of L_1, L_2, C_1 and R in terms of s_1, s_2 and s_3 can be obtained. Here the values of s_1, s_2 and s_3 can be taken from circular locus of its polynomial, where its radius equals to cutoff frequency in radians per second. The equations of L_1, L_2, C_1 and R are

$$\frac{R}{L_2} = -(s_1+s_2+s_3) \quad (7)$$

$$L_1C_1 = \frac{-(s_1+s_2+s_3)}{G_0\times\omega_c^3} \quad (8)$$

$$\frac{L_1}{L_2} = -1+\frac{(s_1s_2+s_2s_3+s_1s_3)(s_1+s_2+s_3)}{G_0\times\omega_c^3} \quad (9)$$

Here for stability reasons as stated above the values of s_1, s_2 and s_3 lie on left half of s-plane. The other important term in all of the above equations is the value of G_0; it is log of ratio of Vout to Vin at zero frequency or before cutoff frequency, as it is maximally flat response system. Slight variations in the values of filtering elements can be altered by varying the values of G_0. This might help in bringing the values of active and reactive elements within practical limits, but the variation in G_0 should be within prescribed constraint as it affects the voltage variations in the system. Normally the assumed value of G_0 is 1.

IV. DESIGN ANALYSIS OF THIRD ORDER BUTTERWORTH FILTER

Using the design specifications, practical values of have been computed and tested. The testing has been done using p-spice.

A. Selection of Cutoff Frequency

In the system for the power frequency, the most common harmonics are of order five. Hence selection of cutoff frequency is a tough job. Selection of cutoff frequency very near to system frequency increases the values of reactive elements and makes the design bulky, whereas on selecting value very far from power frequency say for near about 150 radians per second or more, the mitigation is not so as desired. The cutoff frequency so taken here is midway between the two constraints. The cutoff frequency in this paper is 95.5 Hz or 600radians per second.

Using this frequency, the poles of Butterworth polynomial can be plotted from the circle of radius equivalent to cutoff frequency. The poles so chosen in this paper are: $s_1=-600$; $s_2=-100+j590$; $s_3=-100-j590$

B. Computation of Values with the Effect of G_0

From fig. 4, using the values of s_1, s_2 and s_3 the values of the reactive elements are

For $G_0 = 1$

$$\frac{L_1}{L_2} = 0.77$$

$$L_1C_1 = 3.7\times10^{-6}$$

$$\frac{R}{L_2} = 800$$

Taking L_2=117mH, the values of other components are L_1=90mH, C_1=41uF and R=94Ω.

For $G_0 = 1.06$

$$\frac{L_1}{L_2} = \frac{2}{3}$$

$$L_1C_1 = 3.49\times10^{-6}$$

$$\frac{R}{L_2} = 800$$

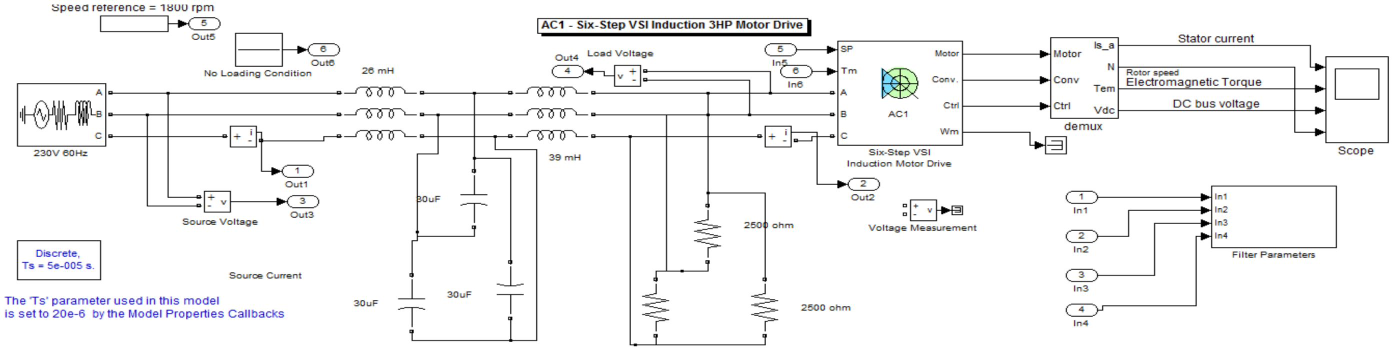


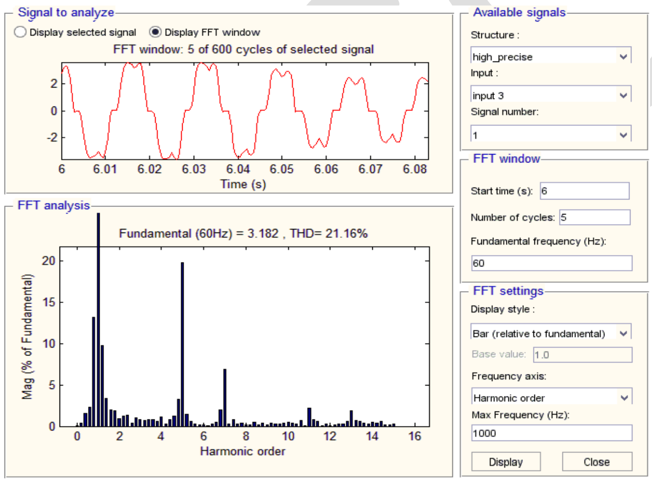
Fig. 4 Circuit simulation of third order Butterworth filter

Taking L_2=117mH, the values of other components are L_1=78mH, C_1=45uF and R=94Ω.

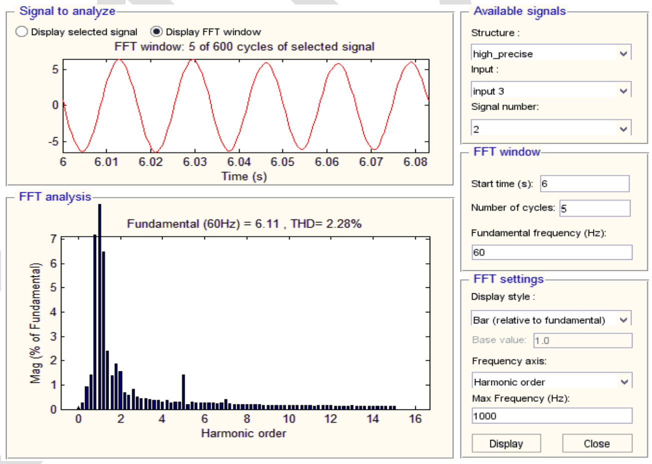
Here it can be observed that slight variation in value of G_0 affects the values of the components considerably; on increasing it there is decrease in the value of inductor but increase in value of condenser. So there is need to choose appropriate value of G_0. Also G_0 is the ratio of voltages which should approximately be equal; hence this factor should also be considered while designing. For rest of the paper all analysis has been done for G_0=1.06.

C. Circuit Analysis

Matlab simulation of the above design has been shown in fig. 4. Here the fundamental frequency taken is 60Hz. Here for the testing of filter is done on VFD as they are the major generators of harmonics. Filtered waveform and THD chart of the simulation is shown in fig. 6.



(a)



(b)

Fig. 5 (a) and (b). MATLAB waveform results.

From fig. 5 (a) it can be observed that the current waveform at the load side is completely distorted where as in fig. 5 (b) one can observe that the overall waveform of the system is completely filtered. This proves that the designed filter blocks higher order frequencies without affecting the fundamental component. From above fig. the THD for (a) is 21.2% where as the THD for (b) is 2.28%. This also verifies that this design brings THD of current lower than 5%.

V. CONCLUSION

Butterworth filter design has been included in this paper for the introduction of an analogous concept in the field of harmonic mitigation techniques. This paper allows implementation of concept which is either ment for digital circuits or for analog system with higher frequency. This paper focuses on improving the field of harmonic filters in power system. It just does not provide mathematical tool for design but also shows testing and verification of prepared design.

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REFERENCES

[1] Nassif, A.B.; Wilsun Xu, "Passive Harmonic Filters for Medium-Voltage Industrial Systems: Practical Considerations and Topology Analysis," Power Symposium, 2007. NAPS '07. 39th North American , vol., no., pp.301,307, Sept. 30 2007-Oct. 2 2007.
[2] Aleem, S.H.E.A.; Zobaa, A.F.; Sung, A.C.M., "On the economical design of multiple-arm passive harmonic filters," Universities Power Engineering Conference (UPEC), 2012 47th International , vol., no., pp.1,6, 4-7 Sept. 2012.
[3] Roger C. Dugan, Mark F. McGranaghan, H. Wayne Beaty, "Electrical Power Systems Quality",
[4] Fujita, H.; Yamasaki, T.; Akagi, H., "A hybrid active filter for damping of harmonic resonance in industrial power systems," Power Electronics Specialists Conference, 1998. PESC 98 Record. 29th Annual IEEE , vol.1, no., pp.209,216 vol.1, 17-22 May 1998.

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