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SIMULATION OF HARMONIC FILTERING FOR ELECTRICAL AND ELECTRONIC EQUIPMENT HEALTHY OPERATION

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Abstract— Presence of harmonics in the waveform drawn by electrical and electronic equipment can lead to damage or malfunction. Modern electrical/electronic equipment is made of units that make them draw disproportionate current from the mains. It has the adverse effects of equipment damage and /or system malfunctioning. This paper considers simulation of the filtering of harmonically distorted waveform that may result from non-linear loads drawing disproportionate currents from the supply. Rectangular signal of 5V, 50Hz was input into an active low-pass filter in the domain of the Circuit Maker software. It is discovered that as the order of the filter increased, the shape of the output waveform improved indicating low harmonic contents. To obtain possible optimum level of the desired linear sinusoidal wave, the filtering was increased up to the 14th order. The optimum value was attained at an accuracy of 99.7% that corresponds to a crest factor value of 1.41

Keywords – Accuracy,Crest Factor Error,Filtering ,Harmonics, Healthy Operation, Root Mean Squared Value

I. INTRODUCTION

Harmonic is a composite of multiple waveforms that is produced due to the distortion by non-linear load. Non-linear loads draw current that is not sinusoidal in nature. Each component of the waveforms occurs as an integer multiple of the fundamental frequency of the voltage or current from the mains supply [1]. Thus, harmonic distortion is the degree to which a waveform deviates from its pure sinusoidal values as a result of the summation of all these harmonic elements [2].

A. What Causes Harmonics

The type of load determines whether harmonics will be present or not [2].Linear loads such as resistive heaters, incandescent lamps, and constant speed induction and synchronous motors do not cause harmonics. This is because the current drawn by them is proportional to the voltage and impedance and follows the envelope of the pure sinusoidal voltage waveform.

On the other hand, non-linear loads, such as battery chargers, electronic ballasts, variable frequency drives, and switching mode power supplies, cause the current to vary disproportionately with the voltage during each half cycle. Hence, the current and voltage have waveforms that are non-sinusoidal, containing distortions [3]. Harmonic distortion is the change in the waveform of the supply voltage from the ideal sinusoidal waveform [4].

Fig.1 shows a harmonically distorted waveform that is produced due the presence of third harmonics that occurs at 3 times the fundamental frequency (i.e. 150 Hz).

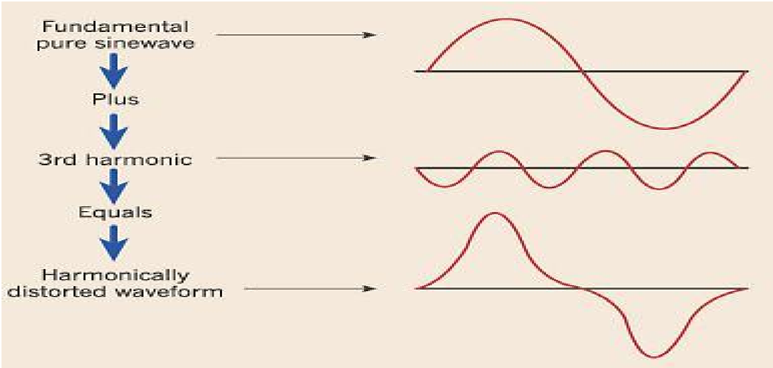

Fig.1: Harmonically distorted waveform from third harmonic and pure sine wave

Virtually all modern electrical and electronic equipment contains a switching mode power supply or involves some form of power control and so is a non-linear load. Linear loads are comparatively rare [5].

B. Effects of harmonics on Electrical Systems

In power installations, it is the *current* harmonics that are of most concern because the harmonics originate as currents and most of the ill effects are due to these currents [5].The effect of harmonics on power system components and loads is an important consideration [6].

The effects of harmonics can be overheating of transformers, cables, motors, generators and capacitors connected to the same power supply with the devices generating the harmonics. Electronic displays and lighting may flicker, circuit breakers can trip, computers may fail and metering can give false readings [7]. This is because our conventional ammeters and voltmeters will not respond accurately.

On three-phase wye systems, current distortion causes higher than expected currents in shared neutrals. This large level of current can easily burn up the neutral creating an open neutral environment. This open neutral creates overvoltage. These voltage conditions easily destroy equipment, particularly power supplies.

II. MEASUREMENT OF HARMONIC DISTORTION

Total Harmonic Distortion (or THD) is used to measure the distortion caused in relation to voltage or current [1] .In terms of current, it is expressed as [8],

$$I_{THD} = \sqrt{\sum_{2}^{\infty} \frac{I_h^2}{I_1^2}}\, x\, 100\%$$

If, for example...

- **I_1**= current at 50 Hz = 250 Amps
- **I_5**= current at 250 Hz = 50 Amps
- **I_7**= current at 350 Hz = 35 Amps

then,

$$I_{THD} = \sqrt{\frac{50^2 + 35^2}{250^2}}\, x\, 100\%$$
$$= 24\ \%$$

The higher the percentage, the more distortion that is present in the mains signal. The summation of all harmonics in a system is known as Total Harmonic Distortion (THD) [2].

The two other measures of distortion are the crest factor and the form factor [9].

Form factor and crest factor can be used to give information about the actual shape of the AC waveform.

A. Crest Factor

The crest factor is the ratio of the peak of a waveform to its RMS value. That is,

$$Crest\ \ factor = \frac{V_{peak}}{V_{rms}}$$

For a linear sinusoidal waveform that electrical and electronic equipment require for their normal operation, the,

$$V_{rms} = \frac{V_{peak}}{\sqrt{2}}$$

Hence, crest factor would be 1.414.

In case of distortion this crest factor value will vary from 1.414 (value for a pure sine wave) if the waveform is distorted. That's because the distortion results in a peak value that's different than that of a pure, undistorted sine wave. Therefore, a “good” sine wave will have a peak value that's close to 1.414 times its true root mean squared value [10].

B. Form Factor

The form factor, or distortion factor, is the ratio of the RMS value of a waveform to the average value of the waveform. This implies that,

$$Form\ Factor = \frac{V_{rms}}{V_{avg}}$$

For a linear sinusoidal waveform that is desired, the

$$V_{rms} = \frac{V_{peak}}{\sqrt{2}}$$ and,

$$V_{avg} = 2\frac{V_{peak}}{\pi}\ is\ the\ average\ value\ of\ the\ output\ voltage$$

Hence, the form factor is 1.11.

The use and calculation of Average, R.M.S, Form factor and Crest Factor can also be used with any type of periodic waveform including triangular, square, saw toothed or any other irregular or complex voltage/current waveform shape.

III.ACCEPTABLE HARMONIC DISTORTION LEVEL

Electrical and electronic equipment have the degree of distortion that will cause damage or malfunction. This is determined by the harmonic voltage that the equipment can tolerate. The malfunction is measured by what is referred to as notch
depth.

The standards address three aspects of harmonics [11]:

(i) The maximum levels of harmonic voltages that are allowed on the supply

(ii) The maximum distorting current that household appliances can draw to ensure that the levels in (i) are met

(iii) The maximum distorting current that industrial installations can draw to ensure that the levels in (i) are met

In the 415 V supply system, the present limits on harmonic voltages is 5% THD.

IV. METHODS OF REDUCING HARMONICS

Research has shown that there are two levels of reducing harmonics: The two approaches of addressing harmonics problems are:

(i) Harmonic mitigation problems and

(ii) Compelling the manufacturers to change the design of electrical loads

The mitigation approaches include what to do to overcome the existing problems. Among these are:

- Oversizing neutrals

- Applying passive or active filters

Compelling the manufacturers to change the design of electrical loads; the measure is meant to limit the consumption of harmonic currents

A. Active Filter

Harmonic filter is built using an array of capacitors, inductors, and resistors that conduct harmonic currents to the ground.

At high frequencies (i.e at frequencies above 1 MHz), filters usually consist of passive components such as inductors, resistors and capacitors .Active filters become important in the lower frequency range (i.e. < 1 MHz). Active filters are circuits that use an operational amplifier (op amp) as the active device in combination with some resistors and capacitors to provide an LRC-like filter performance at low frequencies [12].

V. Methodology: Active Filter

The concept of filtering is used in this study to provide a sinusoidal waveform that electronic equipment will require for linear operation. This is meant to reduce the effects of the distortion due to the presence of harmonics in electronic loads. Circuit Maker software was used to simulate the filtering by an active low-pass filter.The principle is that the distorted signal f(t), that is periodic but non-sinusoidal, can be decomposed into its sinusoidal components using Fourier series given as in equation (1) [13],

$$f(t) = a_0 + \sum_{n=1}^{\infty} (a_n Cos\ n\omega_0 t + b_n Sin\ n\omega_0 t) \quad (1)$$

$$Where,\ \omega_0 = \frac{2\pi}{T},\ T\ is\ the\ fundamental\ period\ of\ the\ signal.$$

a_0 *is the d.c component of the signal and it is given as*

$$a_0 = \frac{1}{T}\int_{-\frac{T}{2}}^{\frac{T}{2}} f(t)dt$$

$$a_n = \int_0^T f(t) Cos\ n\omega_0 t\ dt$$

$$b_n = \int_0^T f(t) Sin\ n\omega_0 t\ dt$$

A 5-V, 50 Hz rectangular wave shown in fig.1 was used to simulate harmonically distorted waveform that could be produced by non-linear loads.

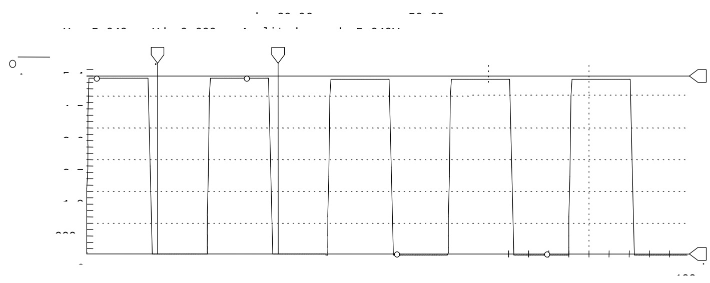

Fig.1: The 5-V, 50-Hz Rectangular Waveform used to simulate the Low-pass Active Filter

The analytic description of fig.1 gives,

$$Period,\ T = 20\ ms$$

$$\omega = \frac{2\pi}{T} = 100\pi$$

$$f(t) = \begin{cases} 5 & 0<t<10\ ms \\ 0 & 10<t<20\ ms \end{cases}$$

$or,$

$$f(t) = \begin{cases} 0 & -10<t<0\ ms \\ 5 & 0<t<10\ ms \end{cases}$$

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Hence,

$$a_0 = 2.5$$
$$a_n = 0 \quad and,$$
$$b_n = \frac{0.05}{n\pi}(1-\cos n\pi)$$
$$= \frac{0.1}{n\pi}, \; for\ n\ is\ odd\ (i.e\ n = 1,3,5,7.......)$$
$$or,$$
$$b_n = 0 \; for\ n\ is\ even\ (i.e\ n = 2,4,6,8.......)$$
$$Therefore,$$
$$f(t) = 2.5 + \frac{0.1}{\pi}(\sin 100\pi t + \frac{\sin 300\pi t}{3} + \frac{\sin 500\pi t}{5} + ...)$$
$$= 2.5 + 0.032(\sin 100\pi t + \frac{\sin 300\pi t}{3} + \frac{\sin 500\pi t}{5} + ...)$$

Hence, active low-pass filter as shown in fig.2 was used to simulate the removal of higher order harmonics at 100Hz, 150 Hz, 200 Hz etc in the waveform in fig.1.

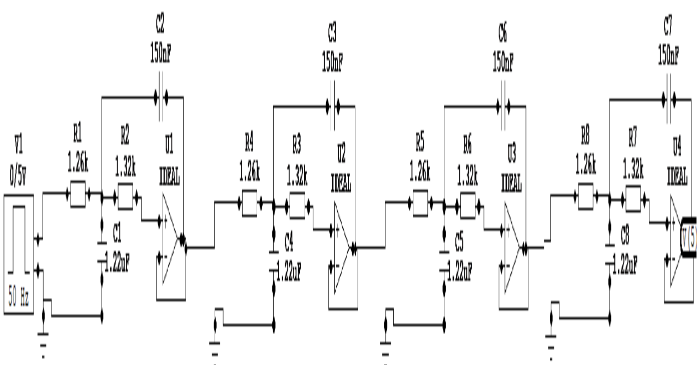

Figure 2: An 8th order active low-pass filter circuit

VI. RESULTS AND DISCUSSION

The simulation was done in each of the stages initially up to 8th order filter stage. Each stage is a second order low-pass filter. It is discovered that the output waveform improved in its closeness to a pure sinusoidal waveform as the order of the filter increased as shown in fig.3, fig.4, fig.5 and fig.6.However,to attain an optimum filtering, the filtering was increased up to 16th order as shown in fig.7, fig.8, fig.9, fig.10 and fig.11.

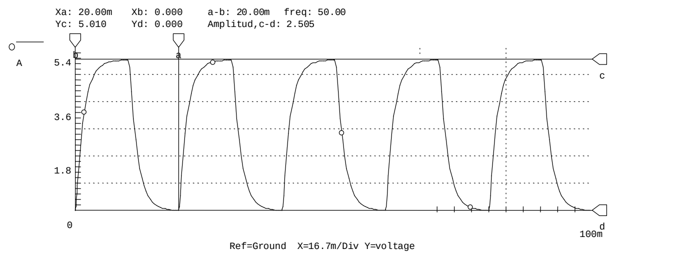

Figure 3: Output waveform of the 2nd order filter

It can be observed that the 50-Hz frequency components have been allowed to pass. It was also discovered that the shape of the waveform is close to that of a sine waveform. However, the amplitude swing tends toward 2.8.Further increase of the order of the filter will make the amplitude swing attain its optimum value of 2.5V.

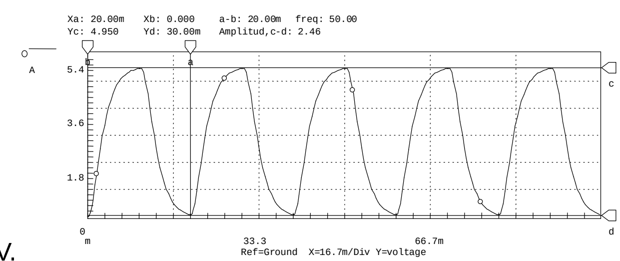

Fig. 4: Output waveform of the 4th order filter

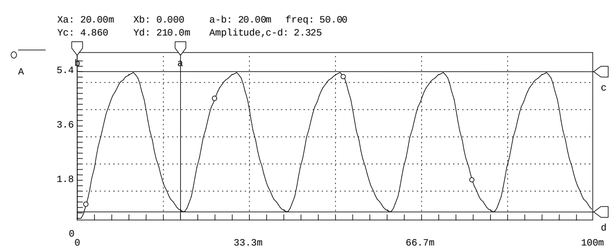

Fig.5: Output waveform of 6th order filter

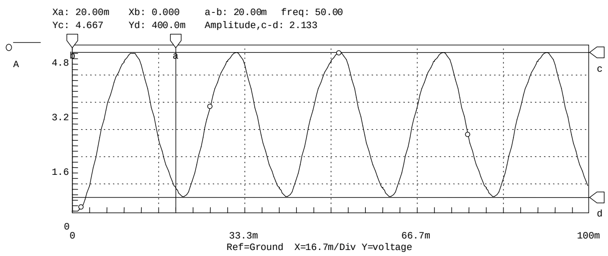

Fig. 6: Output waveform of 8th order filter

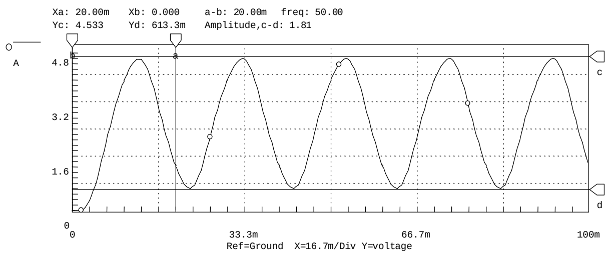

Figure 7: Output waveform of the 10th order filter

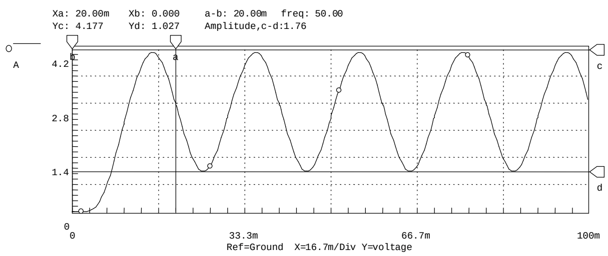

Figure 8: Output waveform of the 12th order filter

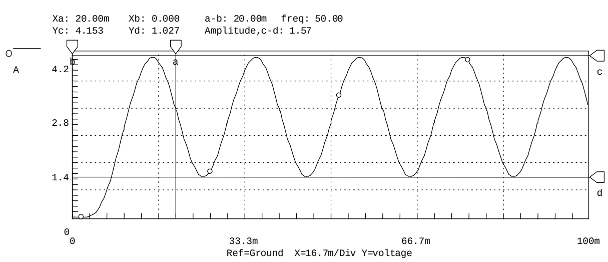

Fig.9: Output waveform of the 14th order filter

Table 1shows the readings obtained in each of order of the partial filter. It is meant to determine the error and accuracy of the 14th order filter in relation to the crest factor.

Table 1: Determination of the accuracy of the 14th order filter

Order of filter	*Measured peak value* (V)	*Measured root mean squared value,* V_{rms} (V)	Crest Factor $\frac{X_1}{X_2}$	Expected Peak Value $V_P = \sqrt{2}\,V_{rms}$	Percentage error
2	2.51	2.076	1.21	2.94	14.49
4	2.46	1.84	1.34	2.60	5.45
6	**2.33**	**1.653**	**1.41**	**2.34**	**0.31**
8	2.13	1.5	1.42	2.12	0.42
10	1.81	1.381	1.31	1.95	7.31
12	1.76	1.29	1.36	1.82	3.51
14	1.57	1.222	1.28	1.73	9.14

In order to determine the error and accuracy of the filtering the expected and the measured peak values were compared as shown in the 6th.

It was discovered that the optimum filtering had been attained at the 6th order stage. The corresponding crest factor value was 1.41.Hence, the accuracy of the filtering was 99.7%.

VIII. CONCLUSION AND RECOMMENDATION

The accuracy of the 14th order filter is 99.7% with a crest factor of 1.41. Filtering removes harmonic contents of distortion that is problematic to electrical and electronic equipment .The equipment requires the use of pure sinusoidal signal for its normal and healthy operation. The pure sinusoidal can be achieved by filtering of the harmonically distorted waveform.

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