Voltage and Current Waveforms Enhancement using Harmonic Filters

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Abstract

The demand on reactive power in transmission and distribution systems is remarkably increasing especially in areas where extensive utilization of electric furnaces, induction machines, computers, thyristors and florescent lighting fixtures. These have resulted to unbalance in system operation and malfunctions causing distortions to both, voltage and current sinusoidal waveforms by what so known "The Harmonicas".

In this paper, power system components with inductive loads were modeled using computer to monitor the shape of the voltage/current waveforms in the absence of any means of filters. An appropriate filter was designed by the model to limit the distortions and obtain better sine waveforms of the voltage/current variables. The paper outlined the essential design of appropriate filters to dissipate these harmonics to the ground before entering the appliances and cause malfunctions or damage to its insulations.

Keywords: harmonics, distortion, waveforms, filters

1. Introduction

In the last two decades, there has been an explosion of microprocessor based equipments which are known as nonlinear loads. These include computers, variable frequency drives, AC/DC converters, electronic ballasts, hospital endoscope equipment such as X-ray machines and MRI. Harmonics are voltage and current frequencies riding on top of the normal sinusoidal voltage and current waveforms. Nonlinear loads cause some distortion of AC line voltage and current. High harmonic content can disturb or damage the sensitive electronic equipment connected to the same power line or network with frequencies that are integer multiples of the fundamental frequency. It can result in variety of problems such as; system inefficiency, motors/transformers to run hot, audible noise from motor, improper operation of protection devices, high current in neutral conductor, low power factor and increased power system losses. In this paper, a test is carried out on the effect of using filters in limiting the impact of harmonic phenomena using the available powerful application of MATLAB to simulate the system components and the associated filters.

2. Overview:

Power systems have always had harmonics present. In long past history of power system, harmonics were associated with distorted voltage and current wave shapes observed on transmission systems and they did not cause much of problems to industry office buildings as equipment was less sophisticated. Over the recent years, the increasing utilization of electronic devices brought the subject up-front.

Electronic devices are very sensitive to their power quality environment. As the number of electronic devices increased, so did the number of other harmonic-creating devices are also increasing.

Large industries such as steel and aluminum complexes used electricity to power arc furnaces which also distort the waveforms because the current flow is not directly proportional to the voltage. These non-linear loads cause waveforms that are multiples (Harmonics) of the normal frequency sine waves to be superimposed on the base waveform. For instance, the second harmonic is a 100 Hz waveform (2 times 50 Hz), the third is a 150 Hz waveform, and so on. The combination of the sine wave with all the harmonics creates a new, non sinusoidal wave of distortion.

3. Harmonics Distortions

Harmonic frequencies can be *"Even"* or *"Odd"* multiples of the sinusoidal fundamental frequency. A linear electrical load is one, which draws a purely sinusoidal current when connected to a sinusoidal voltage source such as resistors, capacitors and inductors. Traditional devices connected to distribution systems such as transformers, motors and resistive heaters have linear characteristics. Non-linear electrical loads are those which draw a non-sinusoidal current when connected to a sinusoidal voltage source. Fig1 illustrates an example of a periodic distorted waveform which repeats itself 50 times a second.
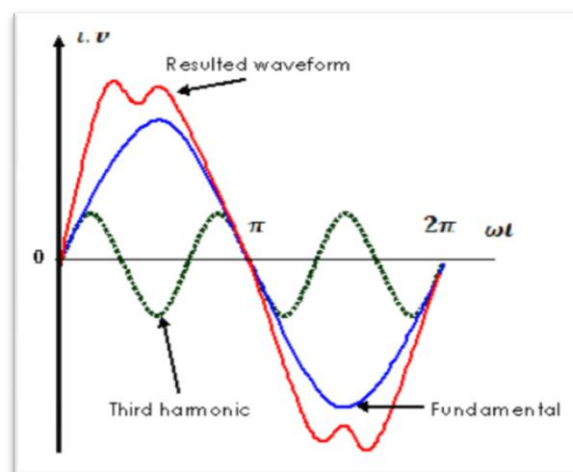

Fig.1: Distorted A.C waveform (Fundamental plus 3rd Harmonic)

When a sinusoidal signal of a single frequency is applied at the input of a nonlinear device or circuit, the resulting output contains frequency
components that are integer multiples of the input signal. These harmonics are generated by the nonlinearity of the circuit and the harmonic distortion is measured by comparing the
magnitudes of the harmonics with the fundamental component (input frequency) of the output.
Consider the input signal to be of the form:

$$x(t) = x_1 \, Cos\varpi_1 t / 2\pi \qquad\qquad 1$$

Where: $f_1 = \varpi_1 t / 2\pi$

x_1 is the amplitude of the input signal

Let the output of the nonlinear circuit be:
$$Y(t) = Y_0 + Y_1 Cos\varpi_1\, t + Y_2 \, Cos\, \varpi_1\, t + Y_3\, Cos\varpi_1\, t + ... \quad 2$$
Where:
Y_0 is the dc component of the output

Y_1 is the amplitude of the fundamental component,

Y_2 & Y_3 are the amplitudes of 2nd and 3rd harmonics.

The 2nd harmonic distortion factor (HD_2), the 3rd harmonic distortion factor (HD_3), and the nth harmonic distortion factor (HD_n) are define as:

$$HD_2 = \frac{[Y_2]}{[Y_1]} \qquad\qquad 3$$

$$HD_3 = \frac{[Y_3]}{[Y_1]} \qquad\qquad 4$$

$$HD_n = \frac{[Y_n]}{[Y_1]} \qquad\qquad 5$$

The total harmonic distortion (*THD*) of a waveform is defined to be the ratio of the rms value of the harmonics to the amplitude of the fundamental component.

$$THD = \frac{\sqrt{Y_2^2 + Y_3^2 + ...\ Y_n^2}}{[Y_1]} \qquad\qquad 6$$

THD can be expressed in terms of the individual harmonic distortion factors as:

$$THD = \sqrt{HD_2^2 + HD_3^2 + ... HD_n^2} \qquad 7$$

4. Harmonic Losses and effect on Rotating Machines

Non-sinusoidal voltages applied to electrical machines may cause overheating. Motors are not normally de-rated so long as the harmonic distortion remains within the 5% normally recommended by the regulations [6]. Above that limit, they will often experience excessive heating problems. On the positive side, motors contribute to the damping of the system harmonic

content by virtue of the relatively high *X/R* ratio of their blocked rotor circuit. Harmonic voltages or currents give rise to additional losses in the stator windings, rotor/stator circuits and rotor/stator laminations. The losses in the
stator and rotor conductors are greater than those associated with the d.c. resistances because of eddy currents and skin effect. Leakage fields set up by harmonic currents in the stator and rotor end-windings produce extra losses. In the case of induction motors with skew rotors, the flux changes in both stator and rotor and high frequency can produce substantial iron loss. The magnitude of these losses depends upon the amount of skew, and the iron-losses characteristics of the laminations.

In considering the harmonic heating losses of synchronous machine rotors, it must be remembered that pairs of stator harmonics produce the same rotor frequency. For example the 5th and 7th harmonics both give induced rotor currents at frequency $6 f_1$. Each of these currents takes the form of an approximately sinusoidal spatial distribution of damper bar currents traveling around the rotor at velocity $6\varpi_1$ but in opposite directions. Thus for a linear system, the average rotor surface loss density around the periphery will be proportional to ($I\,2/5 + I\,2/7$) , however because of their opposing rotations, at some point around the periphery the local surface loss density will be proportional to ($I_5 + I_7$ $)^2$ If the 5th and 7th harmonic currents are of similar magnitude then the maximum local loss density would be about twice the average loss density caused by these two currents.
Extra power loss is probably the most serious effect of harmonics upon AC machines. An approximate assessment of the additional thermal stress of the coils can be achieved with the help of weighted distortion factor adapted to inductance i.e.

$$THD_L = \frac{\sqrt{\sum_{n=2}^{N}\left(\frac{V_n^2}{n^a}\right)}}{V_1}$$

Where: a = 1 to 2
   V_n is the single frequency r.m.s. voltage at harmonic n,

   N is the maximum order of harmonic to be considered, and

   V_1 is the fundamental line to neutral r.m.s. voltage
.

The capability of a machine to cope with extra harmonic currents will depend on the total

additional losses and its effect on the overall machine temperature rise and local overheating (probably in the rotor). Cage-rotor induction motors tolerate higher rotor losses and

temperatures provided that these do not result in unacceptable stator temperatures, whereas

machines with insulated rotor windings may be more limited.

Some guidance as to the probably acceptable levels may be obtained from the fact that the

level of continuous negative-sequence current is limited to about 10% for generators and negative-sequence voltage to about 2% for induction motors. It is therefore, reasonable to expect that if the harmonic content exceeds these negative sequence limits, then problems will start to occur.

5. *Power System Model*

A three phase harmonic filter model is constructed to measure the influence on current and voltage waveforms in a way to reduce the effect of harmonic phenomena. The constructed circuit uses a 12 pulse AC/DC converter as shown in Fig. 2.
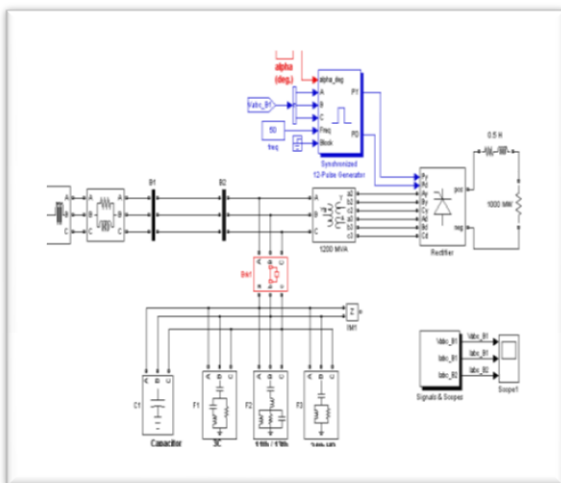

Fig 2: Three-Phase Harmonic Filters Model used on a 12-pulse AC/DC Converter

The *HVDC* rectifier is built up from two 6-pulse thyristor bridges connected in series. The converter is connected to the system with a large 3-ph transformer of 1200-MVA to view the overall effect harmonics in modeled large unites. A 1000-MW resistive load is connected to the DC side through a 0.5 H smoothing reactor. The filters set are made of the following components:

1. One capacitor bank (C1) rated at 150 MVAr modeled by a "Three-Phase Series RLC Load".

2. Three filters mode "Three-Phase Harmonic Filter"

a) One C-type high-pass filter tuned to the 3rd (F1) of 150 MVAr.
b) One double-tuned filter 11/13th (F2) of 150 MVAr.

c) One high-pass filter tuned to the 24th (F3) of 150 MVAr.

The total MVAr rating of the filters set is then 600 MVAr. A three-phase circuit breaker (Bk1) is used to connect the filters set on the AC bus.

The converter is open-loop controlled using the "Synchronized 12-Pulse Generator" with a constant conduction angle alpha of 19 degrees.

A three-phase power supply balanced source is implemented with internal R-L impedance.

The sources connected in star with a neutral connection that can be internally grounded or made accessible. The source can therefore be specified as internal resistance and inductance either directly by entering R and L values

or indirectly by indicating the source inductive short-circuit level and X/R ratio. A three-phase transformer with configurable winding connections is also implemented.

The saturation characteristic was activated in the model as the fluxes are not specified, hence, the initial values are automatically adjusted and the simulation starts in steady state. The leakage inductances and resistance of each winding are given in p.u based on the transformer nominal power Pn and on the nominal voltage of the winding (V1,V2, or V3). An implementation of a universal power converter with selectable topologies and power electronic devices was made. These consist of up to six power switches connected in a bridge configuration. The Universal Bridge block allows simulation of converters using both naturally commutated (or line-commutated) power electronic devices (diodes or thyristors) and forced commutated devices (GTO,IGBT, MOSFET). The Universal Bridge block is considered as the basic block for building up of two-level voltage sourced converters (VSC).

6. *Filters Design*

The Three-Phase Series RLC Load block implements a three-phase balanced load as a series combination of RLC elements. At the specified frequency, the load exhibits constant impedance. The active and reactive powers absorbed by the load are proportional to the square of the applied voltage.

Shunt element three-phase harmonic filters were used in the power system model for decreasing voltage distortion and power factor correction (Fig 3). Nonlinear elements such as power electronic converters generate harmonic currents or harmonic voltages, which are injected into power system. The resulting distorted currents flowing through system impedance produce harmonic voltage distortion. Harmonic filters reduce distortion by diverting harmonic currents in low impedance paths.

Harmonic filters are designed to be capacitive at fundamental frequency, so that they are also
used for producing reactive power required by converters and for power factor correction.
In order to achieve an acceptable distortion, several banks of filters of different types are usually connected in parallel.
The most commonly used filter types are:

(1) Band-pass filters, which are used to filter lowest order harmonics such as 5th, 7th, 11th, 13th, etc.
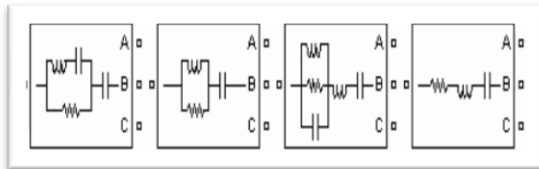

Fig 3: Three-Phase Harmonic Filter

These filters can be tuned at a single frequency (single-tuned filter) or at two frequencies (double-tuned filter).
(2) High-pass filters, which are used to clear high-order harmonics and cover a wide range of frequencies. A special type is the C-type high-pass filters which are used to provide reactive power and avoid parallel resonances. It also allows filtering low order harmonics (such as 3rd), while keeping zero losses at fundamental frequency.
The Three-Phase Harmonic Filter is built of RLC elements. The resistance, inductance, and capacitance values are determined from the filter type and from the following parameters:
- Reactive power at nominal voltage.
- Tuning frequencies.
- Quality factor which is a measure of the sharpness of the tuning frequency that is determined by the resistance value.
The four types of filters that are modeled with the Three-Phase Harmonic Filter block are shown in Fig 4.
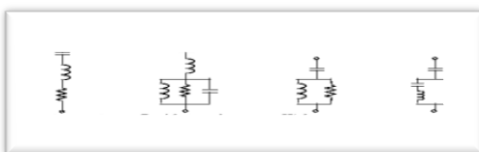

Fig 4: Applicable filter Types

7. Results
The following results were obtained form the simulation. Each with its specific condition of multiple filters switching state:
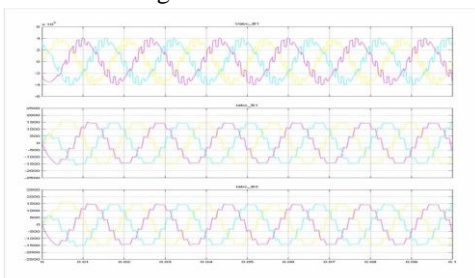

Fig 5: Current and voltage waveforms before Switching-On the filters

In (Figure 5), the constructed model showing a recording of the un-switched multiple of harmonic filters illustrating the voltage and current distortions at points of common coupling. As a result of the nature of load imposed to the system, the figure indicates the impact of such harmonic currents flowing into the system producing harmonic voltages resulting in the presence of great deal of distortion in voltage and current waveforms.
Upon applying the designed specified filters, an appropriate enhanced sinusoidal waveforms were obtained as plotted in (Fig 6).
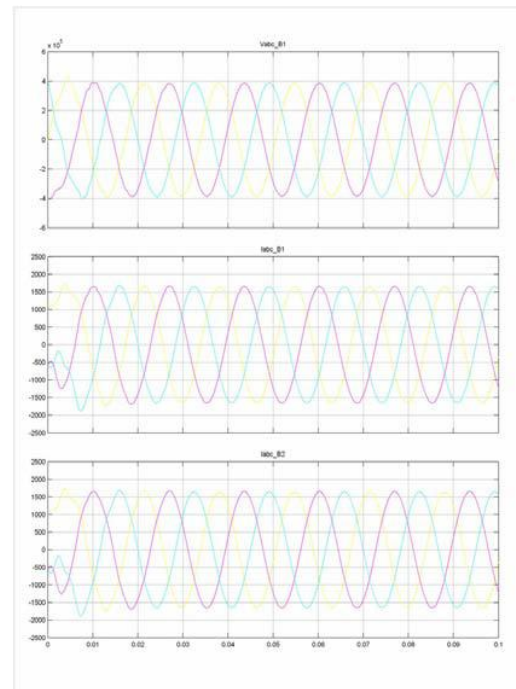

*Fig 6:Typical Improvement of c*urrent and voltage waveforms in the filters Switched-On mode

The results of the waveform shapes in (Figure 6) achieved by applying the multiple designed filters when compared with those waveforms recorded in (Figure 5) and before Switching-On the filters, clearly proves that such filters are beneficial to reduce the harmonic current which enhance the load voltage wave and the line current wave for a satisfactory steady state operation of the entire power system containing such operating characteristics.

8. Conclusions
Harmonics are multiple of the fundamental frequency that continues to exist in our power systems and can distort or degrade the operating characteristics of any protective relays depending on the design features and principles of operation. Continuous operation of power systems with excessive harmonic current can also lead to increased voltage stress and

overheat and can shorten the live cycle of any installed capacitors.

The paper concludes the essential of designing appropriate filters to dissipate and convey such harmonics which result in damage to its insulations. A remarkably, satisfactory results were obtained from the simulation as clearly indicated from the different waveforms illustrated before and after the application of the multiple filters which remarkably reduced the harmonic currents and enhanced the quality of system voltage and current sinusoidal waveforms.

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