

Mitigation of Harmonics in Power Transmission Network using Filters



K. Neelima, A. Aditya Srikanta Sastry, B. Kshithija, K. Goutam, G. Hima Chandra

Abstract: In the novel times, with the surge in use of power electronics, power quality with system efficiency is playing a symbolic role for the advancement of electric supply. The fundamental purpose of the electric utility is to provide a sinusoidal voltage at constant magnitude throughout the system. This objective is convoluted because of the loads present in the system which produce harmonic currents. Due to these harmonic currents, distorted voltages and currents are carried out which affect the reliability and efficiency of the system in several ways. The sinusoidal waveform produced by electric utilities is distorted due to harmonics and increased use of non-linear loads. The deterioration of the power quality and reliability of the power system is due to the presence of these harmonics in the power system. Hence, we need a proper analytical approach to study, classify and characterize the harmonics present in the system and develop a suitable and effective mitigation method to reduce the harmonics in the power system to standard limits of harmonics prescribed by the IEEE and IEC standards. The study of the level of harmonics present in the system, their causes and effects are known as harmonic analysis or harmonics study. Based on the observations of harmonic analysis we develop mitigation techniques to reduce these harmonics. One such method is the implementation of filters. By implementing harmonic filters, we mitigate the harmonics present in the system by providing a low impedance path. The methodological procedure behind effective design and implementation of filters is achieved by performing load flow analysis to obtain the system data and harmonic analysis to obtain data of harmonics present in the system. Based on the data obtained, the type of filter and the optimal placement of filter is decided to mitigate the harmonics. The mitigation of harmonics can report significant benefits for industries, data centers, etc. in terms of overall installation cost and protection against interruptions and equipment faults in the power system. The overall process of Harmonic analysis and mitigation techniques are performed using Mi-Power software.

Key words: Harmonics, Mi-Power, Mitigation, Non-linear loads, Reliability.

Manuscript received on April 02, 2020.
Revised Manuscript received on April 15, 2020.
Manuscript published on May 30, 2020.

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I. INTRODUCTION

In the present-day technology, the rise of non-linear and time-varying loads effects voltage and current distortions in the system with a rapid increase in reactive power. The satisfactory operation of the system depends on identifying the impacts of interconnections, new loads, new generating stations or new transmission lines before they are installed. As the system impedance is a major parameter to be considered while considering voltage distortions caused by harmonic generating loads and the amount of harmonic current injected, harmonic currents cause further problems such as tripping of circuit breakers, overloading of neutrals and overstressing of power factor correction capacitors, etc [1]. To reduce the harmonics occurred by specific parts such as non-linear loads of the power system, filters are being installed. The simulation has been performed on 8-Bus system and harmonics are introduced considering current distortions due to non-linear loads in the power system network using Mi-Power Software [11][12]. Various parameters such as harmonic factor, characteristic harmonics and non-characteristic harmonics are considered while harmonic specifications are taken into consideration.

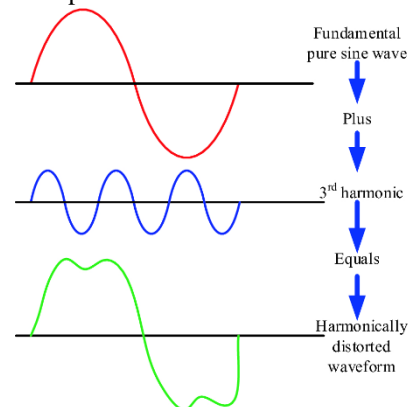


Fig.1. Harmonic Generation

First Load flow analysis is performed which is essential for planning, control and operations of the systems and its future expansion. Different effects such as new loads, interconnections, new transmission lines, new generating stations etc, are to be considered for satisfactory operation of the system before they are being installed. Followed by Load Flow Analysis, Harmonic Analysis is performed. The desired parameters and harmonics at different levels are observed. In this paper, harmonic study is implemented on 5th order harmonic [4][3].

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As harmonics are observed, RMS current sources are used to inject RMS currents at the required buses which represent the non-linear loads and filters are introduced accordingly which thereby brings down the complete system to a stable state within their desired limits.

II. LOAD FLOW ANALYSIS

In an AC power electrical system, Reactive power and Active power flows from generation station to load through network busses and transmission lines which are supplied from the generator at the generation bus. This flow of reactive and active power is called load flow or power flow and the study is known as Load Flow study. The main aim of load flow analysis is to determine active power, reactive power, magnitude and phase angle of voltage flowing in the system under applied load conditions. In load flow analysis, iteration technique is used as the analytic method to solve the load flow problem, which results in nonlinear equations known as load flow equations. The techniques which are conventionally used for load flow analysis are Gauss-Seidel method, Newton Raphson method, Decoupled and Fast-Decoupled method. Equation (1) represents the Newton-Raphson load flow equation where ΔP , ΔQ , $\Delta \delta$, ΔV are the active power, reactive power, voltage phase angle and voltage magnitude respectively. H, M, N, L are the Jacobian matrix elements.

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} H & N \\ M & L \end{bmatrix} \begin{bmatrix} \Delta \delta \\ \frac{\Delta V}{V} \end{bmatrix} \quad (1)$$

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} H & 0 \\ 0 & L \end{bmatrix} \begin{bmatrix} \Delta \delta \\ \frac{\Delta V}{V} \end{bmatrix} \quad (2)$$

Where:

$$\Delta P = H \Delta \delta$$

$$\Delta Q = L \frac{\Delta V}{V}$$

By partially derivating and substituting the values of H and L, the following equations are obtained:

$$\Delta P_i = H \Delta \delta = V_i V_k B'_{ik} \Delta \delta_k \quad (3)$$

$$\Delta Q_i = L \frac{\Delta V}{V} = V_i V_k B''_{ik} \frac{\Delta V}{V} \quad (4)$$

Where V_i is the 'from' bus voltage and V_k is the 'to' bus voltage, B' and B'' are the bus susceptance matrices of order (n-1) and (n-1-m) respectively. In this paper, we are solving the load flow equations using the fast-decoupled method where the convergence pattern is reduced. Hence, fast decoupled method is widely used because it is fast and simple in approach. In this paper, by performing Load Flow Analysis, we will be able to determine the bus voltages and powers at respective buses.

III. HARMONIC ANALYSIS

The four main attributes used to define the power quality of a given power system are voltage, current, frequency and power unbalance. The distortion or unbalance of these attributes are termed as harmonics [2]. In case of supply voltage and current waveforms, it can also be considered as deviation from the ideal sinusoidal waveform. Harmonic analysis or study plays a vital role in understanding and characterizing the extent of harmonic problems [6][10]. The harmonics can be due to non-linear loads like variable speed motors, switching mode power supplies and other equipment's which draw the non-sinusoidal output. The loads which draw non-sinusoidal current when excited by a sinusoidal voltage source of the same frequency are known as nonlinear loads. Harmonic limits [7] are evaluated at the point of common coupling (PCC) between power system load and powerful system utility.

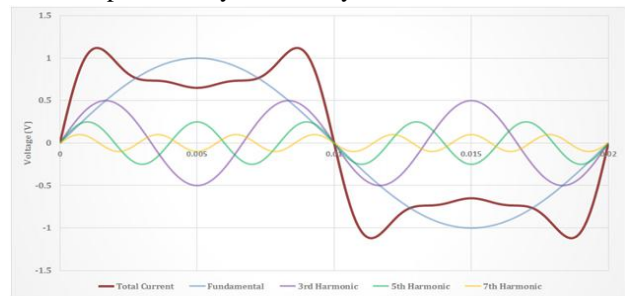


Fig.2. Harmonics in a Power System

Harmonic analysis is performed when finding a solution for an existing harmonic problem such as installation of large capacitor banks on power system or designing a harmonic filter [14]. To reduce these harmonic distortions [8], harmonic mitigation techniques are implemented. One such technique is to install harmonic filters in the power system. In this paper, the mitigation technique we've used to reduce the harmonics is installation of a tuned passive filter [5]. This filter is installed at the buses where the individual harmonic distortion factor is observed to be comparatively high than the other buses and are above standard limits.

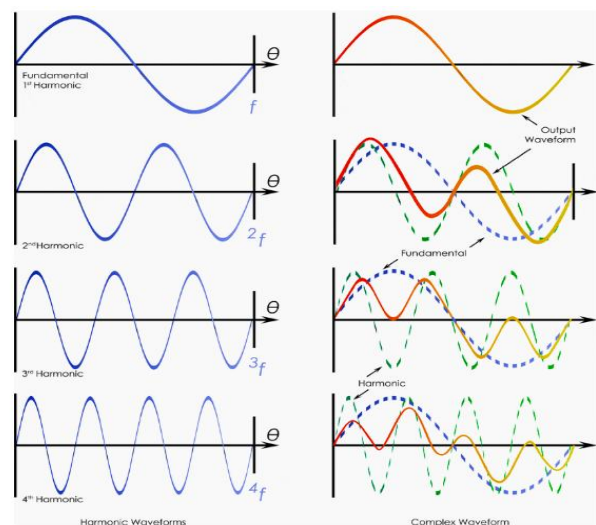


Fig.3. Frequency Harmonic Waveforms

To execute harmonic analysis, first we must perform Fourier analysis. The following are the equations used to perform Fourier analysis:

$$f(t) = \frac{a_0}{2} \sum_{n=1}^{\infty} a_n \cos nt + \sum_{n=1}^{\infty} b_n \sin nt \tag{5}$$

$$f(t) = \frac{a_0}{2} + (a_1 \cos t + b_1 \sin t) + (a_2 \cos 2t + b_2 \sin 2t) + (a_3 \cos 3t + b_3 \sin 3t) + \dots$$

Where,

The term $(a_1 \cos t + b_1 \sin t)$ is known as the fundamental harmonic.

The term $(a_2 \cos 2t + b_2 \sin 2t)$ is called the second harmonic.

The term $(a_3 \cos 3t + b_3 \sin 3t)$ is called the third harmonic, etc.

The limits for Individual Harmonic Distortion (IHD) is given below:

$$IHD_{V,i}^{(h)} (\%) = \frac{|V_i^{(h)}|}{|V_i^1|} \times 100 \leq IHD_V^{MAX} \tag{6}$$

Where $h = h_{th}$ harmonic order

$|V| =$ voltage magnitude at bus 'i'

$IHD^{MAX} =$ Maximum allowable voltage harmonic distortion level

The total harmonic distortion factor is given as:

$$V_{THD} = \frac{\sqrt{\sum_{h=2}^h V_h^2}}{V_1} \tag{7}$$

Where V_1 is the fundamental component

$$\sqrt{3.6238^2 + 3.488^2 + 3.0311^2 + 2.7971^2 + 2.2460^2 + 1.9365^2 + 1.7363^2 + 1.5099^2 + 1.5324^2 + 1.404^2}$$

(These are the values calculated from the graph obtained in this paper.)

$$V_{THD} = \frac{\sqrt{V_2^2 + V_3^2 + V_4^2 + \dots}}{V_1} \tag{8}$$

Where $V_{THD} =$ Voltage Harmonic Distortion Factor

$$V_{THD_4} = \frac{\sqrt{V_5^2 + V_7^2 + V_{11}^2 + \dots + V_{31}^2 + V_{35}^2}}{V_1} \tag{9}$$

(Calculated at bus 4)

IV. METHODOLOGY

The procedure of harmonic analysis depends on the fact whether it is performed on an existing system or a proposed system [13]. In case the harmonic analysis is performed with the help of the basic equation of existing system, the procedure is carried out by measuring the harmonics which is achieved at the plant using harmonic analysers. The complete procedure for executing for load flow [9] and harmonic analysis is implemented using Mi-Power Software

Step 1: Determine the objective of the harmonic study i.e. to determine the harmonics present in a system or to identify the cause and extent of the problem in the currently existing system.

Step 2: In this step, we initialize the process by performing Load Flow Analysis which determines the parameters like active power, reactive power, voltage magnitude and phase angle. We are using Fast Decoupled load flow algorithm to solve the above parameters which are obtained by using (1) and (2) shown above. This is followed by Harmonic Analysis which determines the level of harmonics in the system and also total harmonic distortion factor which is obtained by using (7). The acceptable limits are calculated using (6).

Step 3: Study the data of the existing system i.e. it's working condition, problems and causes.

Step 4: Based on the study performed, a solution such as implementation of filter or other mitigation methods are to be developed. It is also important to check the sensitivity of results. If a filter is implemented to mitigate a problem, the solution is based on the four main attributes of filter design which are fundamental frequency of operation (h), system voltage in kV (v), reactive power requirements of plant (P) and quality factor of the filter (Q). The values of resistance (R), inductance (L), capacitance (C) are calculated using (8), (9), (10), (11).

$$C = \frac{Q_c}{2\pi f V^2} \tag{10}$$

$$X = \frac{1}{2\pi f h C} = \sqrt{\frac{L}{C}} \tag{11}$$

$$L = X^2 C \tag{12}$$

$$R = \frac{2\pi f h L}{Q} \tag{13}$$

Step 5: After a proposed solution is been implemented, study is performed to monitor and verify the operation of the system and their harmonic standards.

V. OBSERVATIONS AND RESULTS

A. Input Data

Table-I: Generator Data

MVA Rating	10
kV Rating	13.8
$X_d = X_q$	0.1
$X_n = X_d = X_q$	0.02857
$X_o = X_d = X_q$	0.02857

Table-II: Series Reactor Data

Bus Code	MVA Rating	kV Rating	Reactance in P.U
1-3	10	13.8	0.00476
3-5	10	13.8	0.0238
5-7	10	13.8	0.02286

Table-III: Bus Data

Bus Number	Bus Name	Nominal Voltage (kV)
1	Bus 1	13.8
2	Bus2	0.48
3	Bus3	13.8
4	Bus4	4.16
5	Bus5	13.8
6	Bus6	4.16
7	Bus7	13.8
8	Bus8	4.16

Table-IV: Transformer Data

Bus Code	MVA Rating	Primary Rating in kV	Secondary Rating in kV	Impedance in P.U	X/R Ratio in P.U
3-4	10	13.8	4.16	0.11	9999
5-6	10	13.8	4.16	0.05	9999
7-8	10	13.8	4.16	0.11	9999

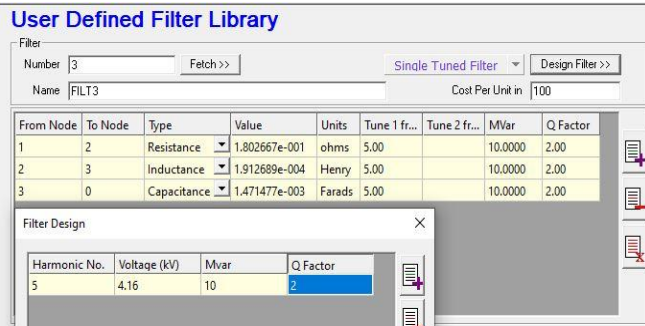


Fig.4. Filter design parameters

B. Output Data obtained from Mi-Power Software

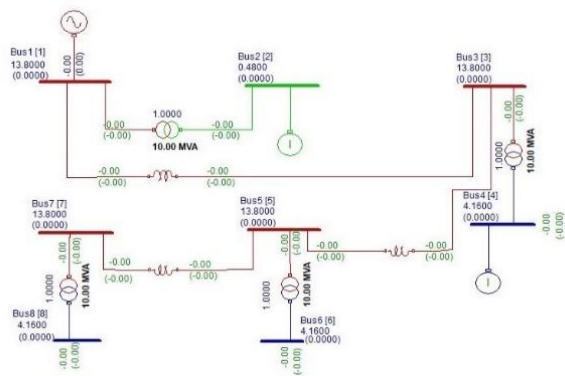


Fig.5. Single Line Diagram without Filters

The above figure displays the single line diagram of an 8-bus system without filters. The different colours of buses resemble the different bus voltages. In this paper, we've used three different bus voltages (13.8kV, 4.16 kV, 0.48 kV). The above diagram consists of four 2-winding Transformers to step-up or step-down the voltage respectively. The two RMS current sources represent the non-linear loads which are the main cause for the harmonics in the system. It also contains three series reactors and one generator connected to the respective buses. For the above system, firstly Load Flow Analysis is performed to determine the active power, reactive power, bus voltages and powers. Later this is followed by performing Harmonic Analysis which determines the Individual and Total Harmonic distortion factors at each bus [8].

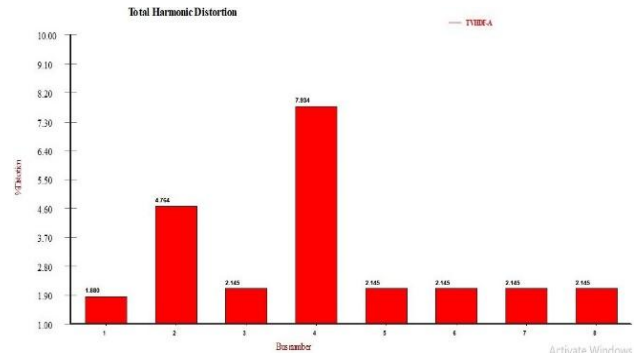


Fig.6. Harmonic Analysis Graph without Filters

The above figure displays the graph for the Total Harmonic Distortion Factor with respect to their bus numbers without filters. From the graph, Harmonic Distortion factors at buses 2 and 4 is high compared to the remaining buses since we've injected RMS current sources at those two buses as our non-linear loads. The Harmonic Distortion factors at the remaining buses are within the standard limits. Thus, to reduce the harmonics at buses 2 and 4, we had to introduce filters at those buses.

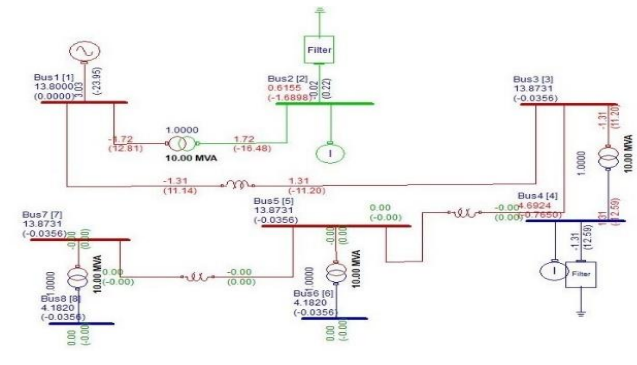


Fig.7. Single line diagram with Filters

The above figure displays the single line diagram of an 8-bus system with filters. We've designed a single-tuned passive filter with the help of Harmonic order (here we are considering for 5th harmonic), voltages at those respective buses, frequency, reactive power values of the system and resistance, inductance and capacitance parameters of those buses. By installing these filters at buses 2 and 4, we can observe the decrease in the level of Harmonics.

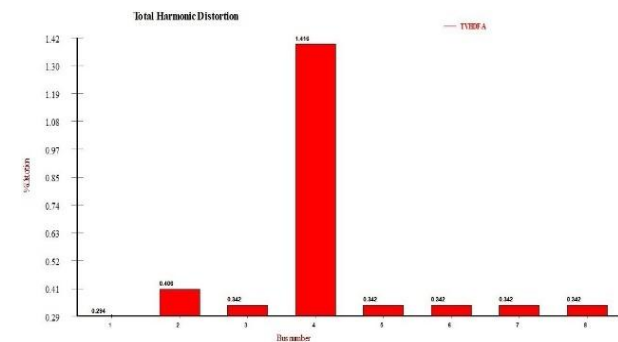


Fig.8. Harmonic Analysis Graph with Filters

The above figure displays the graph for the Total Harmonic Distortion Factor with respect to their bus numbers with filters.

We can observe that the Harmonic Distortion Factor at buses 2 and 4 are reduced to acceptable limits since filters were installed at those buses. It is also seen that the Harmonics at other buses are reduced because the installation of filters will effect the entire system. Hence, the harmonics at all the buses are now within the standard limits.

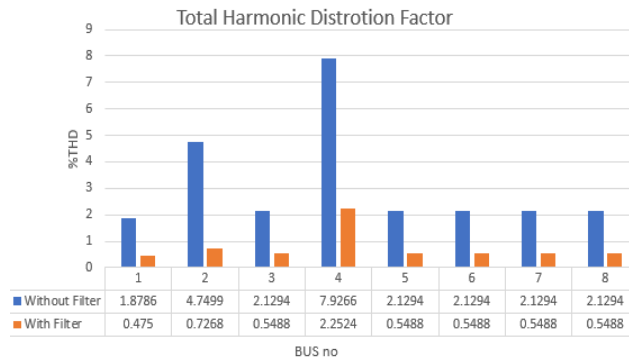


Fig.9. Total Harmonic distortion Factor Graph

The above figure displays the comparison graph of Total Harmonic Distortion Factor with respect to their bus numbers with and without filters.

Table-V: Comparison of harmonics with and without filters

Bus No	Without Filter	With Filter
1	1.8786	0.4750
2	4.7499	0.7268
3	2.1294	0.5488
4	7.9266	2.2524
5	2.1294	0.5488
6	2.1294	0.5488
7	2.1294	0.5488
8	2.1294	0.5488

VI. CONCLUSION

The major aim of the electric utility is to deliver sinusoidal voltage at constant magnitude throughout their system. When considerable harmonic generating loads are introduced to an industrial system, it is a favourable practice to interpret their impact on the power system by implementing mitigation techniques. When alternative loads are connected to the buses, source distributes harmonic currents to the loads. Use of filters can mitigate these harmonic distortions which induces compensating components to the system. The design is done with the help of mathematical modelling of the filter parameter before installation. It is clearly observed from the results and observation in the paper that the level of harmonic is reduced and brought down to acceptable standard limits after installation of filters in a given power system thus improving the reliability and power quality of the system

and reducing the damage caused to the equipment’s connected at the load end such as adjustable speed drives, power electrical switching elements, synchronous machines, and etc. We perform harmonic design analysis of the system at the initial stage of planning before modifying an existing power system or erection of a new power system and obtain simulation results for efficient implementation. Here, the practical and simulation values can be compared after the erection of the power system.

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