Addressing Harmonics in Power Distribution: Effects and Mitigation Techniques

Timsi
Department of Electrical Engineering
Deenbandhu Chhoturam University of Science and Technology, Sonepat, India
22001902002timsi@dcrustm.org

Dr. Naresh Kumar Yadav
Department of Electrical Engineering
Deenbandhu Chhoturam University of Science and Technology, Sonepat, India
nareshyadav.ee@dcrustm.org

***Abstract*— In recent years, non-linear loads have become increasingly prevalent due to their widespread use in power electronics, computers, and variable-speed drives. Linear loads exhibit a proportional relation between voltage and current, the characteristics of linear loads have constant impedance regardless of applied voltage and current whereas Non-linear loads show changing impedance with voltage and current, which leads to a non-linear relation between voltage and current. Non-linear loads are responsible for the distorted waveform that generates harmonic distortion in the distribution system, which can cause various adverse consequences for the Power sector. Load and source, both induce harmonics in the system but the majority of harmonics nowadays are from the load side. Harmonic distortion has now become a common phenomenon in power systems resulting from non-linear loads, such as power electronics devices. Harmonics can cause multiple undesirable effects, including equipment failure, overheating, and voltage instability, leading to power quality issues and system failures. Harmonics can negatively affect the power quality and distribution network's reliability, leading to equipment damage and downtime. Therefore, the incorporation of harmonic mitigation units is essential to minimise the effects of harmonic distortions and ensure the steady & reliable operation of the distribution network. This paper gives a brief overview of harmonics and investigates the sources, effects, and various mitigation techniques for harmonics.**

Keywords*— Single Tuned Filter, Shunt Active Power Filter, Genetic algorithm, Total Harmonic Distortion, Harmonics, Non-linear loads

I. Introduction

Non-linear loads produce non–sinusoidal voltage when supplied with a sinusoidal voltage. Non-linear load leads to distorted sinusoidal current and voltage waveforms. The more the deviation of the waveform from its sinusoidal nature, the more will be the harmonics generated in the system. Harmonics is a significant power quality issue and it is defined as the components of the distorted waveform with the frequencies which are the integer multiples of fundamental frequencies. The frequency of the harmonic order f_h is defined as.

$$f_h = \nu * f_0 \qquad (1)$$

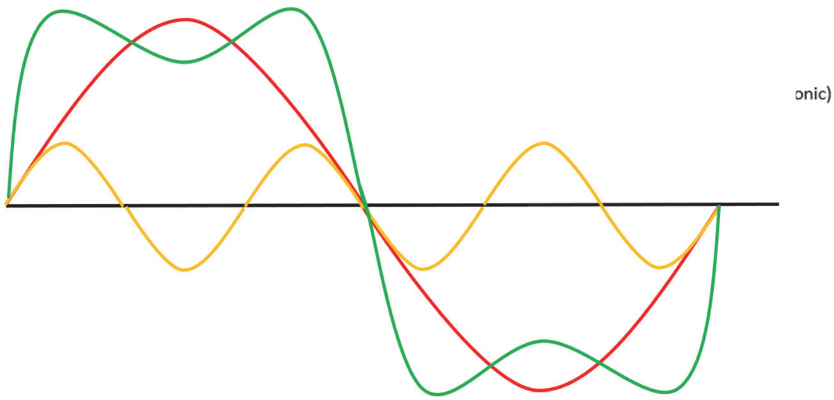
Where,

n = integer,

f_0 = fundamental frequency, (In India, 50 Hz is the fundamental frequency).

For example, with a fundamental frequency of 50 Hz, the 2nd, 3rd and 4th harmonics will occur at 100Hz, 150Hz and 200Hz respectively.

When a waveform is non-sinusoidal but periodic, then that waveform can be communicated in terms of Fourier series by doing Fourier analysis. Fourier analysis is used to analyse and study harmonics. Small order harmonics are more severe as they have a high amplitude whereas large order harmonics are less severe because of their low amplitude. 3rd harmonic is the most dominant harmonic.



[1] Waveform of Harmonics Distortion in Current.

TYPES OF HARMONICS

Based on Signals

- Current Harmonics
- Voltage Harmonics

Based on Order

- Even Harmonics
  Order = 2k, (k ∈ Natural No.)
  (2,4,6,8,...)
- Odd Harmonics
  Order = 2k+1, (k ∈ Natural No.)
  (3,5,7,...)
- Triplen Harmonics
  Order = 3(2k-1), (k ∈ Natural No.)
  (3,9,15,...)
- Non-Triplen Harmonics
  Order = 6k±1(k ∈ Natural No.)
  (5,7,11,13,...)

Based on Phase Sequence

- Positive Sequence
  Order = 3k-2, (k ∈ Natural No.)
  (1,4,7,...)
- Negative Sequence
  Order = 3k-1, (k ∈ Natural No.)
  (2,5,8,11,...)
- Zero Sequence
  Order = 3k, (k ∈ Natural No.)
  (3,6,9,...)

[2] Types of Harmonics

Current harmonics are caused due to non-linear loads. The system's voltage drop becomes distorted because of current harmonics which leads to Voltage harmonics. Therefore, Voltage harmonics in turn arise due to current harmonics. Non-linear load demand non-sinusoidal current even from sinusoidal voltage sources. Therefore, non-linear loads are responsible for harmonics.

So, Sinusoidal Voltage – Harmonic voltage drop = Distorted voltage

II. Literature Review of Related Works

Various researchers have investigated the impacts of harmonics on the distribution system, including the work of Attia, H. A., et al., who found that harmonics can cause voltage distortion and lead to equipment failure in the distribution system, several strategies have been proposed to alleviate the adverse consequences of harmonics, including use of passive & active harmonic filters, proper system design, and load management. The effectiveness of harmonic mitigation techniques has been studied in various research works, including the work of M. Jawad Ghorbani et al., who found that passive filters can effectively mitigate harmonics and improve power quality. Om Prakash Mahela et al. examine the impact of harmonics distortion and other power quality issues on the recharging of electric vehicles.

Ahmed, M. et al. undertake a comparative analysis of two unmistakable filter implementation methodologies, to be specific the Single Tuned Filter (STF) and the Shunt Active Power Filter (SAPF), in the context of an industrial distribution network that is characterized by a significant penetration of renewable energy sources. The researchers suggest a genetic algorithm (GA) based method to identify the ideal location & size of the minimal necessary filtering units which enhance the network's current harmonic scenarios in light of the aftereffects of the examination. Based on the findings, the suggested approach of integrating filtering units exhibited a noteworthy improvement in reducing the overall harmonic distortion (THD) within an industrial power circulation system that has a large proportion of sustainable energy sources.

In another research, Abbas, A. S. et al. analysed the effect of renewable energy sources linked to power electronic devices that exhibit non-linear loads, which can lead to increased harmonic distortion in distribution systems. They introduce a novel approach for simultaneously determining single-tuned harmonic filters' optimal configuration, quantity, and positioning. They have used the Water Cycle Algorithm (WCA) as a multi-objective optimization technique for the filter's optimum allocation. The simulation findings demonstrate the proposed approach's efficacy in ascertaining the optimal configuration, quantity, and positioning of a single-tuned filter within the radial distribution system. The study's discoveries recommend that it's imperative to consider the harmonic spectrum of the DG units during the process of designing the harmonic filters within the system, to avoid any potential escalation of harmonic distortion within the system.

The research conducted by Sabarimuthu, M. et al. pertains to the calculation and analysis of harmonics during the charging of electric vehicles. This study was carried out using a simulation model. The fluke meter is utilized for the purpose of measuring the harmonics that are generated within the charger, while also taking note of the resultant harmonic disturbances. The estimation of the proposed control output involves the computation of voltage and current, while the determination of the Total Harmonic Distortion (THD) value's in light of the examination of the harmonic disturbance graph. The electric vehicle charger's efficiency has been enhanced through the proposal of an appropriate filter to eliminate the aforementioned issues, as indicated by the result analysis. This implementation has been identified as a potential area for future work.

Satish, R.et al. introduced novel HPFA and FPFA techniques for three-phase Software-Defined Networking (SDN) through the utilization of BRANCH_NUM and BUS_NUM matrices. This study examines the effects of the deployment of multiple synchronous-based distributed generation (DG) systems, power electronic-based DG systems, non-linear loads and D-STATCOM. The proposed PFAs employ the compensation-based approach for managing the DGs. The FPFA and HPFA methodologies have been proposed to assess the effects of renewable distributed generation (DG) on various power quality parameters, including fundamental voltage, fundamental power loss, harmonic power loss, Total Harmonic Distortion (THD) & percentage harmonic voltage profile. The integration of synchronous-based renewable distributed generation (DG) has the potential to mitigate total harmonic distortion (THD%); however, the extent of its penetration may be restricted by factors such as the type, location & size of the DGs. The findings of this study prove that the introduction of synchronous-based renewable distributed generation into the power grid can potentially decrease the total harmonic distortion percentage to 5.2442%, in any event, when non-linear loads are available on the grid. Increasing the power rating of synchronous-based renewable distributed generation can further reduce the Total Harmonic Distortion (THD) percentage to below 5%. The network's voltage profile is enhanced by the integration of any form of renewable distributed generation. The power quality of renewable distributed generation (DG) can be constrained by three primary factors: the DGs' location, type, and size. These factors may ultimately restrict the extent to which renewable DG can be integrated into the power system.

The investigation by Faraby, M. D. et al. aimed to assess the effects of the network reconfiguration method on coordinated planning to further develop power quality in radial distribution frameworks. The study reveals the integration of the suggested methodologies yielded a superior outcome in terms of efficacy and efficiency in curbing the propagation of harmonics. The concurrent implementation of H-PSO with capacitor placement, DG placement and network reconfiguration has resulted in an enhanced performance of network reconfiguration. This is achieved by activating all tie switches to limit losses, voltage deviations & $\%THD_v$. The validation of the outcome was carried out using the radial distribution system of IEEE 33-bus. The desired function was derived through the utilization of optimization techniques while adhering to predetermined constraints. This approach was employed to evaluate the efficacy of network reconfiguration techniques. The H-PSO method was utilized to optimize capacitor placement, DG placement and network reconfiguration techniques for scheduling optimization. This combination of approaches resulted in a significant reduction of losses by 110.03 kW or 90.16%, a reduction of $\%THD_v$, values by up to 2.475% or 84.770%, & a reduction of voltage deviation by up to 0.0243 or 92.15%.

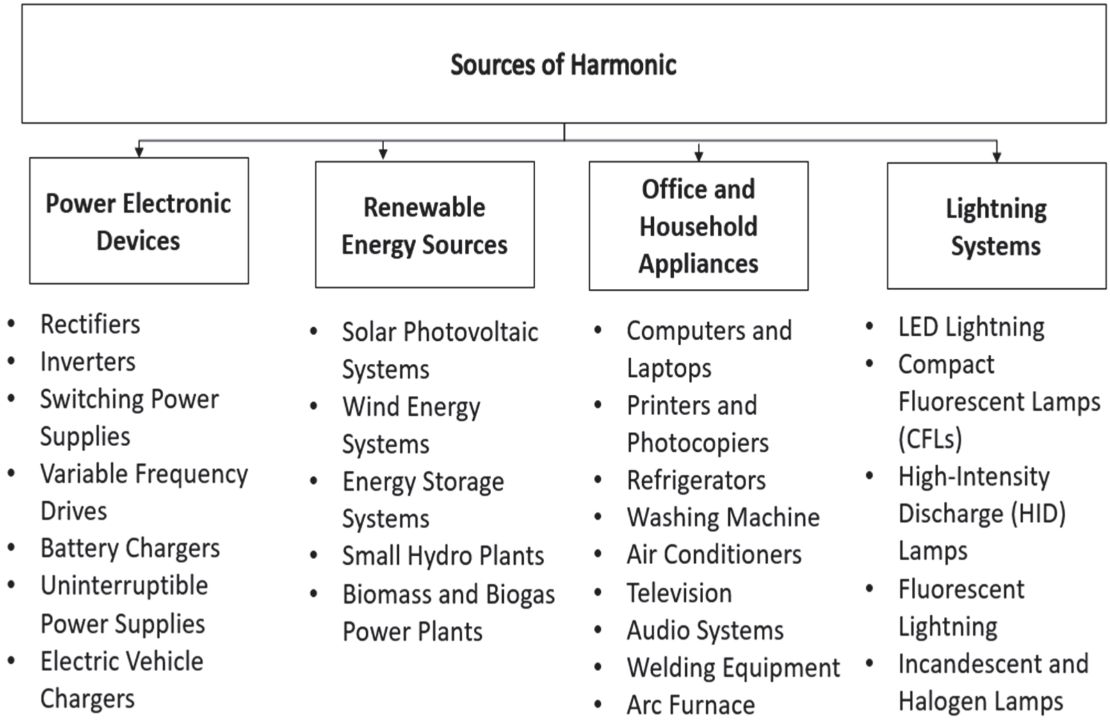
The study by A, S. Vishwanath et al. utilized MATLAB software to simulate and analyse the design and efficacy of STF, DTF, and C-type high-pass filters. The findings of the simulation indicate that the connection of residential appliances to a distribution system leads to the production of a current waveform that is significantly distorted, thereby resulting in the occurrence of harmonic distortion. The issue becomes more complex when the high-level load of the distribution system surpasses the established limit, resulting in amplified losses caused by harmonic pollution. The implementation of DTF proves to be the most advantageous option in comparison to the utilization of two distinct parallel-connected single-tuned passive filters. The findings indicate that the efficacy of the single-tuned and double-tuned filters when combined with a C-Type High pass filter, is comparable. However, the double-tuned filter necessitates smaller dimensions and lower expenses in contrast to the single-tuned filter..

III. UNRAVELLING HARMONICS: DISCOVERING THEIR ORIGIN

Even if sinusoid supply voltage, non-linear loads typically behave in such a way that their current waveform is warped. Most machinery merely generates strange harmonics. Due to differences in source impedance, background voltage distortion, and active power consumption, the current distortion varies for each gadget. The most typical single & three-phase non-linear loads for home & commercial use will be described by Attia, H. A., et al.

Electronic machinery converts AC power to DC power for internal use at various DC voltage proportions when it receives electricity from the low-voltage power supply. These devices include, among others: TVs, printers, video recorders, computers, microwaves, adjustable speed drives, small UPSs, H.F. fluorescent lighting etc.

Higher power applications employ three-phase rectifiers. Diodes, thyristors, or transistors can be used to create a controlled or uncontrolled rectifier. For lower-power applications, a capacitor often makes up the DC link. A smoothing inductor and a capacitor are utilized with larger rectifiers. For controlled transistor rectifiers, an inductor is employed on the line side and a capacitor serves as the DC connection. The power system and industrial applications are where the three-phase group is most frequently used. Adjustable speed drives, large UPSs, HVDC linkages, arc furnaces, traction vehicles and SVCs are a few examples.

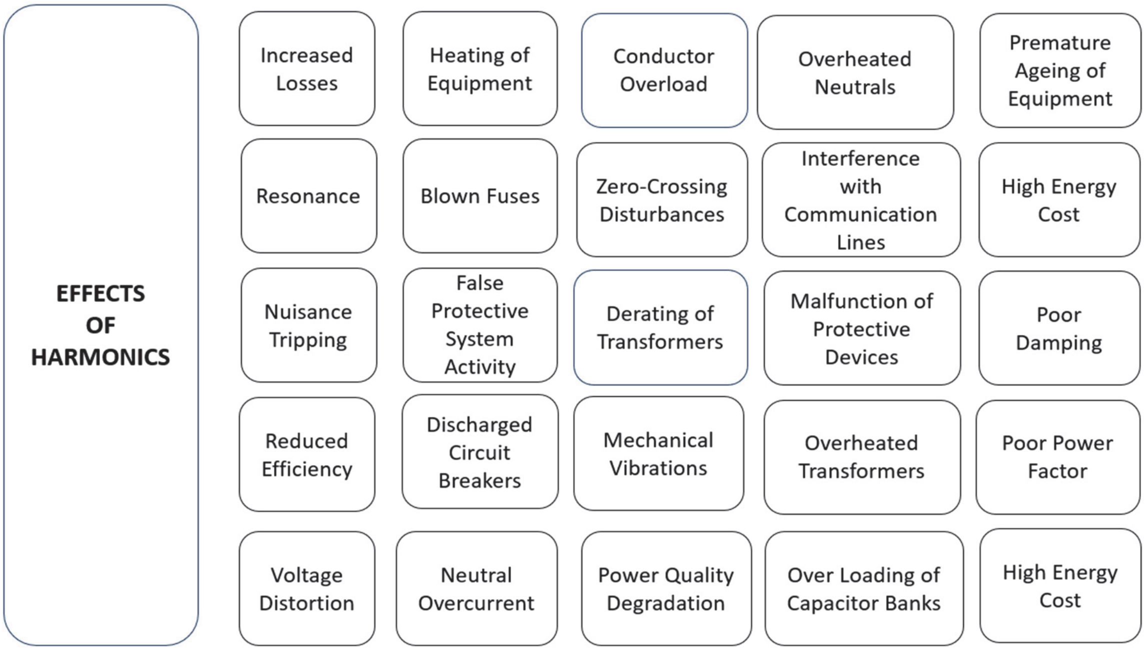


[3] Source of Harmonics

IV. IMPACT OF HARMONICS IN POWER SYSTEM

V.

Throughout recent decades, harmonic distortion has been placed as one of the critical power quality issues. The harmonic effects are burdening the network infrastructure. The essential causes of this issue are the Non-linear loads. Nonlinear loads cause harmonic distortion inside the current & voltage waveform inside the power framework. Harmonics causes various issues. The momentary impacts of harmonics are malfunctions or disappointments of devices because of high harmonic distortion while the longstanding impacts of harmonics are thermal issues & a temperature climb. Higher temperatures of electric systems determine higher misfortunes and abbreviate their life. The impact of harmonics determines increased troubleshooting, losses of production, process restart, equipment damage etc. Then again, harmonics determine premature ageing of the equipment, additional energy losses, lower performance and operating disappointments whenever compared with nominal circumstances. Recognizing & alleviating harmonics is also essential for the smooth combination of sustainable energy into the grid. So, harmonics ought to be addressed straightaway to increase the system's reliability.



[4] Effects of Harmonics

VI. MASTERING HARMONICS: EFFECTIVE STRATEGIES FOR MITIGATING HARMONICS

In this section, different strategies to mitigate harmonics have been discussed.

a) Line Reactors

Line reactors reduce the amplitude of harmonic currents by providing inductive reactance, which opposes the flow of high-frequency harmonic currents. The result is a clean current waveform with fewer harmonic distortions.

b) Isolation Transformers

Isolation Transformers are valuable in mitigating harmonics and improving power quality in the electrical framework. They work by electrically isolating the load from the power source. An Isolation transformer consists of primary and secondary windings that are electrically isolated from each other but magnetically coupled through a core.

c) K-Factor Transformers

The record of the transformer's capacity to supply harmonic content in its load current while staying inside its working temperature limits is named the K-factor. These transformers are designed to handle harmonic-rich environments. The K-factor rating demonstrates the transformer's ability to withstand the heating effects brought by harmonics. K-factor-rated transformers have enhanced cooling and design features to mitigate the effects of harmonics.

d) Passive Filter

Throughout the long term, these Passive Filters have been created for an elevated degree of sophistication. Conventional Passive Filters comprise resistance, capacitance, and inductance elements configured & tuned to manage harmonics. Passive filters work by providing a low-impedance path to the ground for specific harmonic frequencies. When harmonics flow through the filter, they are diverted away from the rest of the electrical system, effectively reducing the harmonics distortion. Double Tuned filters, Single-Tuned filters, Band Pass filters and High Pass filters are some examples of Passive Filters.

e) Active Filter

Active filtering strategies can be applied either as an independent harmonic filter or by coordinating the technology into the rectifier stage of a UPS, drive or other power electronics gear. These Filters use power electronic devices such as IGBTs and MOSFETs, along with sophisticated control algorithms, to inject compensating currents that cancel out the harmonic current in the system. They operate by continuously monitoring the load current, extracting the harmonic components and generating a counteracting current that is injected back into the system. Shunt Active Filter, Series Active Filters & Hybrid Filters are examples of Active Filters.

f) 12-Pulse Rectifier Solution

12 -Pulse rectifier system involves two 6- Pulse rectifier bridges associated in parallel. The bridge's input is provided through a special transformer with phase-shifted secondary windings. The phase shift between the windings creates a condition where the harmonics generated by the two rectifier bridges partially cancel each other out.

g) 18-Pulse Rectifier Solution

18-Pulse Rectifier is an advanced harmonic mitigation technique that provides an even greater reduction of harmonics compared to 6-pulse and 12-pulse rectifiers. Its configuration involves three 6-pulse rectifier bridges, each receiving input from the phase-shifted secondary winding of the specially designed transformer. The phase shifts between the winding result in the cancellation of harmonic components, significantly reducing the harmonic content in the input current.

h) Phase Shifting Transformer

Phase-shifting transformers work by creating phase shifts in the voltage supplied to different rectifier bridges, leading to harmonic cancellation. Phase-shifting transformers have primary winding connected to the power supply and multiple secondary windings which are configured to provide different phase shifts depending on the desired number of pulses in the rectifier system. Each secondary winding supplies voltage to a separate rectifier bridge. The phase-shifted voltages ensure that the harmonic current produced by each rectifier bridge is out of phase with one another.

i) Load Management

Load Management helps in mitigating harmonics in various ways. load management includes power factor correction strategies by using capacitors and synchronous condensers. Load management includes balancing the load distribution which helps minimize the harmonic current that results from unbalanced loads, managing load also helps in reducing responsible peak loads which in turn reduces the stress on electrical equipment. When equipment operates under less stress, it tends to produce fewer harmonics. By ensuring the electrical equipment operates within its optimal range, load management reduces the chances of equipment generating harmonics. Overloaded or underloaded equipment can produce a higher level of harmonics.

VII. CONCLUSIONS

Sources of harmonic distortions that can happen because of the non-linear loads in the power system and related issues were examined momentarily. An overview of the effective strategies to mitigate harmonics was discussed and a literature review of previous works that are associated with the techniques to mitigate harmonics was studied. There is a need for further research on mitigating techniques to minimize the impact of harmonics that occurs due to non-linear loads on the system's power quality, reliability and efficiency.

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