



A REVIEW AND CRITIQUE OF ADVANCES IN THE MITIGATION OF HARMONICS

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ARTICLE INFORMATION ABSTRACT

Submitted 18 September, 2021

Revised 20 November, 2023

Accepted 23 February, 2024

Keywords:

Distribution System

Filters

Harmonics

Mitigation

Optimization

Simulation

In electrical power distribution systems, harmonics has always been a major concern as it can adversely affects the performance of the connected loads when tolerable or recommended standard limits are exceeded. There have been consistent and considerable efforts to study the sources, generation and control of harmonics over the years. This paper presents an extensive literature review of the major works on harmonics in the last two and a half decades. The merits and demerits, advantages and limitations of such work were critically reviewed. It was discovered that a lot remains to be done in the optimization of filters especially the hybrid types and that the design of a filter that can simultaneously mitigate low and higher order harmonics has not been thoroughly researched. This paper is intended as a guide for researchers that are interested in solving harmonics problems to identify the gray areas to concentrate and improve on

1.0 Introduction

Harmonics are defined as periodic components of a distinct frequency superimposed on a waveform of a fundamental frequency. Harmonics has been in existence for long; since Steinmetz published a book in 1916 which devoted considerable attention to the study of harmonics in three-phase power systems and also the invention of the very first generators and transistor tubes in the 1930s (Michael, 1999). Since non-linear loads were quite few then, its effects were not easily noted. Between late 1980s and early 1990s, there were tremendous increment in the use of power electronic loads. The increment continues till date leading to creation of more harmonics on electrical power distribution system despite the advantages of power electronic loads in efficiency and controllability. Connection of more electrical loads to such power systems leads to deterioration in power quality (Adesina and Fakolujo, 2015; Rodriguez and Saldanha, 2012; Nicholson, 2006; Holcomb and Briggs, 1994).

Different researchers have reviewed various aspects of harmonics ranging from the sources, generations, to the types and the various forms of mitigation techniques and effects of harmonics current and/or voltages on power distribution network and consumer devices (Czarnecki, 2000; Zamora *et al.*, 2003; Akagi, 2006; Arif *et al.*, 2012; Mujawar *et al.*, 2013; Durdhavale and Ahire, 2016; etc.) Some of such reviews are usually focused towards an integral aspect of harmonics studies. Missing gaps are always existing in each of the works. It is on the basis of this that this paper, from the point of view of power electronics education, intends to educate and identify to a large extent some of the missing gaps in many of the existing works on harmonics. This paper presents a comprehensive holistic review of major works on harmonics done over the last two decades (1998 to 2023).

2. A Survey of Research Efforts on the Nature, Types and Sources of Harmonics

Many authors had researched into the nature, types, sources and methods of preventing, controlling or mitigating harmonics in the last two decades and the efforts still continues till date. Many of these research efforts relating to the nature, types, sources and methods of mitigating harmonics are reviewed in this study.

Middlekauff and Collins Jr. (1998) used simulation method to model an industrial facility with 24KV distribution systems that serves a load which produces harmonics in large quantity. The model was not error free from the phase references, and the orientation of voltage and current transformers which can displace phase angles as well as error due to the type of measuring instrument in use.

The effects of interharmonics generated from induction furnace on a power distribution network was investigated by Dugan and Conrad (1999) using a specific case study. It was concluded that interharmonic frequencies if not properly mitigated can have significant effect on power quality. Many options like adjustment to induction furnace parameters, power supply reconfiguration, use of filters, were proposed as possible solutions. Optimization methods and the use of fast switching devices were left out of the study.

Experimental data were collected by Jalilian *et al.* (2000) to investigate the behavior of a 7.5 kW high efficiency cage induction motor fed by distorted supply. Additional losses in the motor as a result of harmonics were estimated using the weighted-average method. However, a major setback observed in the study is that the derived derating factor (DF) becomes valid and reliable under conditions close to full load. The Maximum Weighted Total Harmonic Distortion (WTHD_{max}) is therefore only a limit in theory.

The importance, essence and significance of controlling harmonics by both the end user and the utility company was the focus of the work by Grady and Santoso (2001). While using the IEEE STD 519-1992 as an excellent background to address both concerns, it was discovered that the issues of acceptable levels of harmonics from nonlinear loads can only be adequately addressed when viable measures are taken from both sides. As good as the work may be, the details of mitigation methods and techniques were not considered.

Dickin *et al.* (2001) investigated harmonics in a major petrochemical facility in Canada. The study investigated the level of harmonics within the plant; compliance with the utility requirements at the point of common coupling (PCC) at 138 kV; and meeting the IEEE STD 519 – 1992; identifying the existence or otherwise of harmonic resonance. The study may be considered to be defective from few perspectives. In real time scenario, some of the assumption made in arriving at conclusions in the study may not hold. The utility harmonic impedance profile was modeled based on the harmonic spectrum provided by the utility. This may be inaccurate. All Adjustable Speed Drives (ASDs) were assumed running at rated load and rated speed for maximum harmonic generation. This is an ideal case that may not hold in reality all the time. The current spectrum for medium-voltage Adjustable Speed Drives (ASDs) was based on measurements taken during factory acceptance tests rather than the typical published values. This is usually not constant. The electric heaters were assumed not to produce any harmonics. This may not be true.

The use of nonlinear control devices and its associated effects in causing harmonics distortion leading to malfunctioning of sensitive devices like metering instruments, on-line process analyzers, measuring devices, were central to the work of Shwehdi *et al.* (2002). A typical petrochemical company in Saudi Arabia was the case study used. However, the study did not conduct an in-depth investigation into the complexity and the dynamic sensitivity of different chemical processes and their electronic and digital controllers which will have effects on current and voltage harmonics in the system.

An in-depth discussion on harmonics in the petrochemical industry was carried out by Nelson (2002). Harmonics caused by saturable magnetic devices like generators and transformers and their controls were covered. Similarly, harmonics from power electronic devices like Variable Speed Drives (VSD) and Uninterruptible Power Supply (UPS) systems were extensively covered. A case study of harmonics in a petrochemical plant was presented. The study, however, did not cover an in-depth investigation of fast varying harmonics as a result of varying the loads connected at the output.

A quantification of the harmonic distortion, the total annual sags and short interruptions of customer classes of the utility of Alexandria based on key indices was reported in Eassa *et al.* (2003). The information in this research was of crucial importance in supporting issues about quality service regulations for customer's satisfaction. Fast switching devices and active filters that can be used in controlling high order harmonics were left out of the study.

An original hypothetical signal was compared to the reconstructed signal using the new Least Mean Square (LMS) algorithm in Manmek *et al.* (2003). The reconstructed signal was the same as the original signal in the steady state (after about 50 msec.). However, the initialization process results in a mismatch in phase information and this is a major limitation to the method.

The load-flow, short-circuit, transient-stability and harmonic studies typically undertaken in petro chemical plants were outlined in Dall *et al.* (2006). The predominant harmonic current sources within the electrical system of an LNG plant are the large variable speed drives for the Liquefied Natural Gas compressors. With increasing Variable Frequency Drive compressor loads, the supply voltage to these drives is also increased. It was established that occurrence of several parallel resonances at or above the 20th harmonic was the major limitation. When harmonic current injections coincide with or are close to the resonances on the system, the resonance is excited and a large component of voltage is produced at the resonant frequency leading to excessive voltage distortion.

Rojin (2006) reviewed the power quality problems and its effects on different apparatuses and methods for the correction. Some power quality enhancement devices such as harmonic filters, isolation transformers were suggested and listed as means of overcoming power quality problems in general. The work was not a detailed investigation of harmonics mitigation techniques and its several associated challenges.

A neural network-based solution for the problem of measuring the actual amount of harmonic current injected into a power network by an individual nonlinear load was researched into by Mazumdar *et al.* (2007). The distinction between load harmonics and supply harmonics were investigated. It was demonstrated that depending on the purity (cleaned or distorted) of the voltage supply to a load, there would always be a difference in the current distortion of the

load. A source modeling scheme was developed and verified in simulation and on the actual field data. As a corrective measure to mitigate the harmonics, the technique projected the condition of the voltage distortion at the Point of Common Coupling in relation to the IEEE 519 standard if the current harmonics in a nonlinear load are decreased. The scheme has the advantages of requiring only waveforms of voltages and currents for its operation and can be applied in both single and three phase systems. There was no investigation as regards the efficiency of optimization methods in controlling harmonics in the research.

New indices to standardize and measure harmonics parameters were proposed by Vlahinic *et al.* (2008). Extensive harmonic measurements of a real distribution system were performed to prove the usefulness of the proposed indices. The total rated distortion (*TRD*) was suggested to simplify and standardize the harmonic current measurements and a second index that represents the increase of the harmonic voltage distortion with *TRD*, the equivalent harmonic impedance Z_{eq} , was proposed as an efficient way of characterizing a particular site. The Z_{eq} was based on the transformer short-circuit impedance, although many other unknown parameters influence its value (the background distortion, the transformer nonlinearity, the diversity between different loads). Both parameters depend on a variety of factors, and their relationship must necessarily vary with the measurement site position. The demerit is that further measurements are needed to explain the observations in more detail. Furthermore, optimization methods were missing in the work.

Bueno *et al.* (2010) investigated instantaneous active and reactive power control on electric traction systems and proposed a compensation scheme to mitigate the harmonic current distortion and reduce the negative sequence under unbalanced operation in steady state. The compensation scheme reduced the system's current Total Harmonic Distortion to less than 20% and reduced the overall unbalance from 97% to 18% for the worst-case scenario. Furthermore, the algorithm developed effectively has a good control on the power factor. It was established that there must be a trade-off between the amount of unbalanced correction and the harmonics reduction. This is a consequence of the finite amount of energy stored by the active filter in its input inductance and the dc-link capacitor. The scheme was validly tested in a railway system and was found reliable. The scheme however did not take optimization methods into consideration. This is a major disadvantage especially when it was established by the work that there is a trade-off between the amount of unbalanced correction and the harmonics reduction. Furthermore, the scheme may be relatively uneconomical.

The sources of power system harmonics and the negative impacts of harmonics were discussed in Xuemei and Yongmei (2012). The study suggested how to strengthen protection measures, by reforming the harmonic source and installing the mitigation equipment to suppress the harmonics. Details exposition of how to make use of software tools to mitigate harmonics were not thoroughly investigated and explored.

Abdelaziz *et al.* (2013) extensively reviewed power system harmonics in the petrochemical industries. The work was a detailed guide for further researches in effects of harmonics, mitigation techniques and distortion allowable limits. An in-depth investigation of fast varying harmonics as a result of varying the loads connected at the output such as the work piece in an induction furnace and an extensive discussion of hybrid optimization methods in mitigating harmonics were missing in the work.

A general study of harmonics in fifty different sites covering heavy current and light current industries using non-linear loads were carried out randomly by Kulkarni and Bharadwaj (2016). An innovative real time harmonic measurement using ADE7880 was implemented. The ADE7880 is a high accuracy, 3-phase electrical energy measurement IC with serial interfaces and three flexible pulse outputs. The ADE7880 device incorporates second-order sigma-delta ($\Sigma\text{-}\Delta$) analog-to-digital converters (ADCs), a digital integrator, reference circuitry, and all of the signal processing required to perform the total (fundamental and harmonic) active, and apparent energy measurements, root mean square (rms) calculations, as well as fundamental - only active and reactive energy measurements. In addition, the ADE7880 computes the root mean square (rms) of harmonics on the phase and neutral currents and on the phase voltages, together with the active, reactive and apparent powers, and the power factor and harmonic distortion on each harmonic for all phases. Total harmonic distortion (THD) is computed for all currents and voltages. A fixed function digital signal processor (DSP) executes this signal processing. The DSP program is stored in the internal ROM memory. The analysis of the harmonics present in the system was carried out using software. Zigbee and GSM technology were used to communicate the data from consumer end to server and smart phone. The large size of the sites and the randomness involved in their selection are major defects that may likely lead to inaccuracies in the data collected and the obtainable results.

The effects of triplen harmonics in the Electricity Company of Ghana (ECG) distribution system was investigated in Eduful and Atanga (2017). The performance of three harmonic suppressors in the control of harmonic emission levels in three ECG's distribution transformer substations were studied. The results of the research proved that the neutral blocking harmonic filters can reduce harmonic current in neutral conductors by 88% and consequently decrease harmonic energy loss by 97%. The estimated annual energy savings from the harmonic reduction for each transformer amounted to 10, 707.86 kWh. Although the harmonic suppressors demonstrated strong ability in the reduction of harmonic energy losses, they were found to increase harmonic voltage distortion levels. This is a major disadvantage with the suppressors as high voltage THDs can lead to erratic behavior of electronic equipment. Methods of optimization were not included in the study.

Satish (2018) carried out an investigation into the nature and analysis of harmonics using Fast Fourier Transform (FFT) to evaluate the Total Harmonic Distortion (THD) of converters with and without filters. MATLAB/SIMULINK was employed for the simulation results. A passive filter was designed to decrease the distortion by shifting the resonance point of the network. The method to design the passive filter and its impact on efficiency and energy usage were outlined. The major demerit of the work is that active and hybrid filters were left out the work.

Ban and Yang (2019) developed the fundamental ideas behind harmonic detection methods including the Fourier transform, short wavelet transform, and wavelet packet transform. Simulation was used to confirm that the proposed methods were effective. Wavelet packet technique was said to increase the detection precision of harmonic signals. The study did not take into account fast switching mechanisms or active filters that can be utilized to reduce high order harmonics.

Vinayagam et al. (2019) conducted a thorough review of harmonics dominance in PV integrated networks. The results of an experimental case study investigating the dominance of harmonics

in a real-time PV integrated micro-grid under varied solar irradiation conditions provide additional support for the findings of the review conducted for various scenarios. The works lacked a thorough description of optimization techniques for harmonics mitigation.

Malekian *et al.* (2020) conducted a study on the validation of harmonic models for power production units utilizing test-bench and on-site data. The focus of the investigation was the power system's renewable energy sources' harmonic emissions. The time variation of harmonics and measurement errors were properly addressed. The proposed model validation process was applied to wind and photovoltaic power production units with various topologies and power classes. The goal of the study was to offer a solid scientific basis for future standards that may take into account the harmonic model validation of power production units. Heavy harmonic industries were missing specific applications in the work.

The work of Urooj *et al.* (2021) concentrated on factors that reduce power quality, accountable for harmonic distortions, and cause inefficiency in power transformers. The suggested Adaptive Neuro-Fuzzy Inference System (ANFIS) offers the best method for harmonic reduction and increases effectiveness all around. The creation of a three-phase power transformer and the effectiveness assessment of the suggested methodology, both carried out in a MATLAB simulation environment, were successful. A thorough study of optimization techniques for harmonic mitigation was also lacking, in addition to specific applications in heavy harmonic industries.

Malik *et al.* (2022) used swarm intelligence-based optimization strength of the cuckoo search method to study a parameter estimation of the power system harmonics. For the performance assessment, various generations and particle sizes for various signal-to-noise ratios were taken into consideration. It was determined that cuckoo search optimization was reliable when assessing various signal-to-noise ratios. Heavy harmonics industries were missing specific applications.

Hu *et al.* (2023) investigated harmonic sources operational procedures, mathematical models, and circuit system. Numerous operational scenarios, including the usual home power load, the scenario for charging electric vehicles, the frequency conversion speed regulating device, the scenario for producing renewable energy, the load on an electric arc furnace, and the load on an electric locomotive, were explored. The papers take a forward-looking approach to harmonic analysis and control in the context of contemporary power systems. The studies lacked a thorough analysis of harmonics mitigation optimization techniques and evaluation of hybrid models.

Srita and Somkun (2023) investigated the implementation process for a current harmonic correction technique of a three-phase grid-connected voltage-source converter (VSC), applied under the grid voltage distortion and frequency variation. To reduce the high-order harmonic current, proportional-integral plus multi-resonant controllers (PIMR) were employed. Harmonics mitigation methods in heavy harmonics producing industries, optimization techniques and specific applications were lacking.

3. Studies on Harmonics Control and Mitigating Techniques

A hybrid reactance one-port compensator was designed to reduce the harmonic distortion in practical single-phase and balanced three-phase distribution systems having different types of nonlinear loads (El-Saadany et al., 1998). The use of iterative method was adopted to study the effect of voltage and current harmonic interactions on a net system distortion. The major drawbacks of the study were that only iterative method was adopted and this did not give room for comparison with other viable methods. The iterative method also made the process to be complicated and time-consuming. High speed switches that may be desirable in controlling high order harmonics was not featured in the study. Frequency domain was equally not considered.

Well over 200 publications on harmonics were reviewed by Singh et al. (1999). Many issues such as components selection, technical considerations, economic feasibilities and their selection for specific applications in respect of active filter (AF) configurations were extensively dealt with. No consideration was however given to optimization of the filters through any technique.

A hybrid active filter that combines a small-rated active filter and a 5th-tuned passive filter for damping of harmonic resonance in industrial power systems was proposed by Fujita et al. (2000). The authors made the hybrid filter acts as an ideal passive filter with infinite quality factor thus improving the damping of the harmonic resonance relative to the passive filter when used alone. Experimental results obtained from a 20 kW laboratory model verify the viability and effectiveness of the proposed filter. Heavy harmonics producing loads, fast switching devices and optimization methods were not taken into consideration.

It was posited by Czarnecki (2000) that resonant harmonic filters can compete favorably and surpass switching compensators in harmonics mitigation. In terms of efficiency and cost, the author rated the former better than the latter. The concept of a harmonic blocking compensator and a fired-pole resonant harmonic filter was developed. However, the use of fast switching devices, software tools and hybrid optimization methods were not addressed in the work.

Rukonuzzaman and Nakaoka (2001) applied an adaptive neural network algorithm for the detection of instantaneous real time harmonics components created from nonlinear loads. An advanced active power filter (APF) was designed to mitigate the harmonics. The disadvantage of learning multiple harmonic components which had an effect on the learning time of the algorithm, leading to a delay in compensation, is a major drawback in the work.

In the work of Abdel-Galil et al. (2001), mitigation of harmonics through active and passive filters, with their various parameters, characteristics and sensitivities, were investigated. The single tuned and the reactance one-port filters were discovered to exhibit low sensitivity to both load variations and elements deviation and were moderately affected by the switching at the utility bus resulting in higher harmonics. The use of software tools and optimization techniques were left out in the work.

Experimental results in the research work of Tey and So (2002) proved the effectiveness of the DSP-controlled series active filter, shunt active filter and Unified Power Quality

Conditioner (UPQC) in mitigating harmonics to a large extent. However, the major drawback is the existence of system instability. The experiment was not subjected to a wide range of load variations.

A method by which the harmonic current in a two-level network-connected inverter can be controlled for use as an active filter in addition to supplying real power, via the intermediate DC link to a motor inverter, was presented by Brogan and Yacamini (2003). The use of a commercially available variable speed drive and modifying its rectifier to be a sinusoidal rectifier was described. Optimization techniques were left out of the study.

Simulation of an active filter for the reduction of the voltage total harmonic distortion created by a steel plant was presented in Zamora *et al.* (2003). The steel plant was simulated considering different levels of load: one, three and six furnaces in operation. The harmonics analysis was limited to the furnaces in the industry. Other sources of harmonics were not considered.

Power system harmonics was postulated as one of the important indices to rate power quality in Manmek *et al.* (2003), Tey and So (2002) and Rukonuzzaman and Nakaoka (2001). Fast Fourier Transform (FFT), application of adaptive filters and neural networks were recommended. Optimization methods were missing in the works.

Three models of active power filters that compensate the harmonics, mitigate the voltage sags and swells, and also correct the power factor in electrical distribution network were formulated in Zamora *et al.* (2003). The simulation results proved that the active power filter models compensate the harmonics, mitigate the voltage sags and swells, and correct the power factor of the system. Fast switching devices, hybrid models, optimization methods were not considered.

The work by Du *et al.* (2004) presented a programmed Pulse Width Modulation (PWM) method to eliminate specific higher order harmonics in multilevel converters. Experimental results confirmed that the technique effectively eliminated the specific harmonics and the output voltage waveforms have less Total Harmonics Distortion (THD) than that from the fundamental frequency switching techniques. The programmed PWM method has the advantage of flexibility between switching frequency and higher order harmonic elimination. However, the high increase in the required switching frequency for the elimination of more harmonics that is higher than the number of levels in a multilevel converter is a disadvantage.

Massoud *et al.* (2004) proposed the adoption of time-based and frequency-based harmonic current extraction techniques after reviewing the use of a converter with unity power factor and the use of a passive or active filter in the mitigation of harmonics in power distribution system. A brief description and classification of each technique were given. The study, however, did not cover an in-depth investigation of fast varying harmonics as a result of varying the loads connected at the output such as the work piece in an induction furnace. A detailed discussion of optimization methods towards mitigating harmonics were missing in the work.

It was clearly stated in Sandoval and Houdek (2005) that there is no single solution or method to the control or mitigation of harmonics that is universally superior and that quite often a hybrid solution usually yields the best results economically and technically after a careful consideration of the end user's objective. The work reviewed the use of typical alternative

three phase harmonic mitigation equipment such as line reactors, Isolation transformers, K-Factor transformers, tuned harmonic filters (fixed capacity or automatic switched multiple banks), IGBT based fast switched harmonic filters, low pass harmonic filters, 12 and 18 pulse rectifiers, phase shifting transformers, and active harmonic filters. The operation of each type of mitigation alternative and the typical results that can be achieved when each type is properly applied were investigated. Despite the detailed investigation, optimization method was still missing in the work.

An excellent comparison between modern active filters and traditional passive filters were made in Akagi (2006). Modern active filters were reported to have multiple functions of harmonic filtering, damping, isolation and termination, reactive-power control for power factor correction and voltage regulation, load balancing, voltage flicker reduction, and or their combinations. The author deals with general pure active filters for power conditioning and specific hybrid active filters for harmonic filtering of three-phase diode rectifiers as well as traditional passive filters. The work was a general review as specific applications in heavy harmonic industries were missing.

An investigation into the generation and control of harmonics in Corus steel production plant in the Dutch town of Ijmuiden was investigated by Hulshorst *et al.* (2006). An innovative solution involving MATLAB/SIMULINK modeling of existing 10KV grid (including harmonics); modeling of the Near Infra-Red (NIR) installation (including harmonics at 0, 4KV) and modeling of the transformers needed to connect the NIR installation (including harmonics at 0, 4KV) to the 10KV grids were developed and analyzed. The results obtained showed that the Total Harmonics Distortion (THD) level can be reduced through the use of a phase-shifting transformer. As good as the solution proffered in the work appears, the phase-shifting transformers are about 10 to 15% higher in costs than the regular transformers, thereby making it uneconomical.

A procedure to calculate optimum controller parameters of Active Power Filters (APFs) was presented by Tlustý and Valoucht (2009). The APFs were implemented into a multi-bus industrial power system for harmonic voltage mitigation. The optimum controller parameters were found by solving the multiple (APF) harmonic problem. It was established that the use of an additional APF at a proper place of the power system may improve the efficiency of an already installed APF, while this place in itself may be even unsuitable for placing the single APF. The method considered the real control strategy as well as APF controller parameters. In practice, the drawback is that the method may not be cost effective.

The subject of harmonic resonance in Industrial electrical network was the focus of El-Sadek *et al.* (2009). A practical case study of the aluminum company at Nag-hammady in Egypt was carried out. The authors were concerned with determination of harmonic resonance and anti-resonance frequencies of large systems containing harmonic sources. Suggested active power filter for damping the harmonic resonance orders or frequencies, for all possible planning and operational conditions faced in practice, was the first goal of the research. Resonances were detected for all expected operational conditions. Harmonic filters were designed, and suggested to be installed, and resonances due to expected switching of those filters were found. Finally, methods of harmonic resonance prevention technique in that company network were

applied and their effectiveness was proved. The use of fast switching devices and the adoption of optimization methods for the control of harmonics were missing in the study.

It was emphasized in Kanerva *et al.* (2010) that designing of medium voltage adjustable speed drive systems (ASD) for safe operation in hazardous areas requires expertise in a number of areas relating to frequency converters, motors, and the way they interact. As the use of different voltage-source inverter (VSI) topologies is increasing in the medium-voltage range, special care has to be taken to limit temperature rise, sparking, and bearing currents as they represent serious problems in oil and gas plants. Temperature rise results from harmonic losses in the motor which are caused by the non-sinusoidal supply from the converter. If not properly mitigated, sparking can occur in both the stators and rotors of converter-fed motors as a result of harmonics and voltage stresses. A procedure was presented on how to validate the entire installation through computer simulation after the ASD has been selected. It was stated that harmonic losses in converter-fed motors can be mitigated at the frequency converter by three main methods. These are the use of: a converter with a higher number of voltage levels, a frequency converter with a higher switching frequency or an output filter. However, the use of a frequency converter with a higher switching frequency increases loss in the frequency converter itself while the use of output filters required may not only be expensive but will also require space and usually result in additional losses. They also increase the complexity of the system and degrade the converter's dynamic performance.

In Saha and Suryavanshi (2010) it was verified that passive filters could be very effective solution for the harmonic mitigation as well as volt ampere reactive (VAR) compensation in offshore oil rigs where large DC drives, usually fed from AC utility services through AC/DC converters are usually in use, which invariably distorts current and voltage waveforms. An effective design procedure of passive filter to mitigate power system harmonics of a typical offshore oil rig was described. It was concluded that the application of properly designed series reactor and passive shunt filters reduces the voltage and current THD levels within the recommended limits of IEEE STD 519-1992. The power factor of the offshore oil rig power system was also improved from 0.78 to 0.97. Parallel resonances were also avoided. Fast switching devices and active filters that can be used in controlling high order harmonics were left out of the study. The methods of optimization were missing in the work.

The importance of analyzing and evaluating the existing harmonic problems in power system and introducing the appropriate solution techniques was stressed by Attial *et al.* (2010). A comprehensive harmonic waveforms analysis through the concept of cancellation and combination was done. Effective technique via the application of phase shifting transformers was introduced. Other alternatives to mitigation of harmonic effects using harmonic filters were given. Electrical Transient Analysis Program (ETAP) computer package was used for a case study to evaluate the merits of each technique. Fast switching devices that can be used in controlling high order harmonics and optimization techniques were left out of the study.

In Pacis *et al.* (2010) compliance with established regulated levels for harmonics through the use of corrective actions such as introduction of active filters was demonstrated by applying simulation technique. The distortion introduced by the installation into the distribution network and the expected reduction when the active filter is in use were studied. Simulation through MATLAB/SIMULINK allows quantifying the harmonic distortion created by the system

and, when a corrective action was introduced, simulation shows the reduction in the distortion. The design of a suitable active filter was also obtained through simulation. The use of simulation tools of MATLAB/SIMULINK, allows reproducing the behavior of the power systems in different situations, analyzing how the system answers in these situations and choosing the solution that better fit with the particular problem without additional costs. Besides, active filters with different rated values can be simulated in order to analyze different reductions of the harmonic distortion. By means of the simulation carried out, the voltage and current harmonic distortions created by an underground traction system and a steel plant were obtained. For very complex system, the simulation time may be very large and this may be a major drawback. Hybrid filters were not considered in the work.

In Kumar (2011), it was established that high order harmonics can be suppressed by employing variants of Butterworth, Chebyshev and Cauer filters. Three phase filter banks were used and connected in parallel. MATLAB/SIMULINK wind farm model was used to generate and analyze the different harmonics magnitude and frequency. The study did not cover the use of fast switching devices that can be used in controlling high order harmonics and the use of optimization methods were missing.

A study on the application of passive filters to mitigate power quality problems caused by induction furnaces was carried out by Arif et al. (2012). Modelling of induction furnaces in ETAP software with real data was carried out and the details of power quality problems caused by the induction furnaces were investigated. Passive filters were designed and implemented and the THD_v and THD_i were within the IEEE limits. Hybrid filter models were left out of the study.

An optimal selective harmonic mitigation method for cascaded H-bridge converter was introduced by Marzoughi and Imaneini (2012). The proposed method uses the least amount of switching frequency, 150 Hz, for individual power switches. The harmonics up to 41st were mitigated to satisfy three voltage harmonic standards EN 50160, CIGRE JWG C4.07 and IEC 61000-3-6 from both individual harmonics and total harmonics distortion (THD) points of view. However, with the limited amount of 150 Hz switching frequency, the method is unsuitable for high frequency electrical system such as induction furnace. Furthermore, another drawback is the introduction of a small filter at the ac side to neutralize the rest of the harmonics.

The design of hybrid active filter to reduce current perturbations produced by power electronics-based devices was done in Memon et al. (2012). The Instantaneous Active and Reactive Power Method (pq) was used to perform the identification of disturbing currents. The Total Harmonic Distortion factor of the source current was analyzed in both time and frequency domains. Simulation results proved that the total distortion of the supply current was decreased from 20.77 to 1.97% which actually met with the IEEE 519 recommended harmonic standard. It was therefore concluded that the hybrid active filter can compensate the harmonic currents effectively and improve power quality. Nevertheless, the research lacks a comparative analysis of the optimization of various types of hybrid filters.

Harmonics mitigation of industrial power system using passive filters was researched into by Memon et al. (2012). A PC-based single tuned and second order high pass passive filters were designed and MATLAB/SIMULINK software was used for simulation purposes with and without the filters installation. The introduction of the filters improved the power factor and reduced

the current harmonics from 20.77% to 4.32%. Lack of specific analysis of harmonics in the context of a heavy current industry such as steel plants and comparative analysis of the hybrid optimization methods are major drawbacks to the work.

A broad categorization of different harmonic mitigation techniques (passive, active, and hybrid) was carried out in Kazem (2013). The Hybrid Harmonic Filter (HHF) was considered to be more attractive in harmonic filtering than the pure filters from both viability and economical points of view, particularly for high-power applications. A general approach to mitigation of harmonics was discussed. Specific analysis of harmonics in the context of a heavy current industry such as steel plants is missing in the study.

A topology for reactive power compensation and harmonic mitigation of distribution system using Shunt Active Power Filter (SAPF) compensator was presented in Mujawar *et al.* (2013). Instantaneous reactive power (IRP) theory for reference current generation, Proportional Integral (PI) controller for DC voltage balancing and Hysteresis current controller (HCC) for gating pulse generation was implemented. Simulations were carried out and Fast Fourier Transform (FFT) analysis were performed on the source and load current which shows that the power factor of source is near unity and harmonic content on source side are well below the harmonic limit imposed by IEEE std. 519-1992. Specific analysis of harmonics in the context of a heavy current industry such as steel plants was missing in the study. Pulse converters and fast switching devices that can be used in controlling high order harmonics and the methods of optimization were not covered in the study.

The development of active power filter (APF) technologies was reviewed in Gupta and Gupta (2013). With a short overview of harmonic distortion difficulties and their impacts on electric power the APF topologies were reviewed taking into consideration the application of the p-q and elongation p-q theorems to mitigate harmonics. A short consideration on the APF-solar photovoltaic system with the shunt APF were considered and proposed. The work did not cover specific applications in heavily harmonics producing industry and a comparative analysis of the hybrid optimization methods was missing.

A selective harmonic elimination (SHE) method to mitigate low order harmonics in single phase nine level, eleven level and thirteen level inverters with different loads were developed by Tamilvani and Valluvan (2014). The different level inverters were realized by cascading H-Bridge in MATLAB/SIMULINK. A pulse wave modulation (PWM) control strategy was applied to the switches at appropriate conducting angles with suitable delays. The Bee algorithm was adopted to optimize the switching angles for improved quality in the output voltage. The lower order harmonics and Total Harmonics Distortion was reduced to about 10%. Despite further tuning of the bee algorithm, the low order harmonics were not fully eliminated, thus there is the need for further improvement.

An overview of different control methods which are applied on Shunt Active Power Filter to achieve harmonics reduction and power factor improvement was presented by Vandana and Tomer (2014). The effectiveness of PI and fuzzy controllers for harmonics mitigation using shunt APF were demonstrated and proven. Using PI controller, the harmonics level dropped to 4.24 % from 29.573 % while the power factor improved from 0.9755 to 0.9906. Using fuzzy logic controller, the THD was 2.49% and the power factor improved from 0.9755 to 0.9952. These satisfied the IEEE Std. 519. However, the use of soft computing techniques such as

Genetic Algorithm, Particle Swarm Optimization and Artificial Neural Network to extract harmonics was missing.

The structure, design and analysis of a 24-pulse ac-dc power auto transformer-based converter that employed a pulse doubling technique for asynchronous motor drive was researched into and presented by Kiran *et al.* (2015). The autotransformer was designed for a 12-pulse converter for effective harmonic reduction. Pulse reinjection technique was used to convert existing system into a multiple pulse converter. With the effect of load variations taken into considerations, low harmonic distortion and approximate unity power factor were obtained. The major drawbacks are that the method is not cost effective, hybrid models were left out and optimization methods were missing.

A multi-objective optimal design of passive and hybrid active power filter based on bacterial foraging optimization algorithm was investigated by Molaei *et al.* (2015). Multi-objective optimization models with relevant constraints for Passive Power Filters (PPF) and Hybrid Active Power Filters (HAPF) set at high voltage levels were formulated for harmonic filtering and reactive power compensation. To solve the multi-objective optimization problems, a bacterial foraging algorithm (BFA) was developed. It was established that the results obtained compared favorably with that of particle swarm optimization (PSO) algorithm. In reality when designing filters, there are many objectives to be considered in determining the optimal solution. Since only three objectives were considered, there is room for improvements. Furthermore, the models developed were not tested in a fast varying and heavy harmonic producing industries such as steel plants with induction furnaces.

A research work titled 'Review of Mitigation Techniques for Power Quality issues in Distributed Generation', that discusses the power quality issues in grid connected Distributed Generation (DG) system and their mitigation techniques was done by Jadhav (2015). The research posited that power quality enhancement and harmonic mitigation is possible using a flexible DG unit. It was established that the DGs reduces greenhouse gas emission and power demand on the main grid but at the same time introduces power quality issues like voltage fluctuation, voltage sags, swells, voltage flicker and unbalance in the distribution system. Various power quality improvement techniques were proposed to maintain the THD within standard limits. The major disadvantage lies in the selection of control techniques that depends on many factors such as response time, accuracy of tracking, complexity, computational burden, robustness and cost of the control system.

Different applications, challenges and trends for traditional active and passive harmonic filters for reduction of harmonic distortion and optimization of the power quality were presented in Motta and Faúndes (2016). The advantages and disadvantages of active versus passive filter technologies were analyzed using real cases from the industry. The authors concluded that nowadays more and more applications require harmonic filtering and not only the classic power factor correction of the past. Besides passive filtering, more and more active filters are required and in many cases hybrid solutions are used where a passive detuned power factor correction (PFC) system is installed for power factor correction, and an active filter is present at the same time for harmonic mitigation and load balancing. The absence of a comparative analysis of the hybrid optimization methods was a major drawback to the work.

An Analysis of Active Power Filter (APF) for Harmonic Mitigation in Distribution System was carried out in Rani *et al.* (2016). PQ theory for controlling APF currents was employed for harmonic mitigation at Point of Common Coupling (PCC) to maintain power quality. The normal system without APF, system with APF with fixed load and also with variable load were considered. Models were developed using MATLAB/SIMULINK. The THD values for source currents were tabulated for different cases. It was proven that the THD is found to be within nominal values when APF was connected to the system with non-linear loads and the results validated an effective application of shunt APF for different load conditions. Specific analysis of harmonics in the context of a heavy current industry is missing in the study and the method may not be cost effective.

Particle Swarm Optimization (PSO) method was adopted in Kumawat *et al.* (2016) to address an optimal allocation of distributed energy resources (DERs) in a highly distorted radial distribution system in order to minimize the power losses and to mitigate harmonics. A backward/forward sweep-based harmonics load flow method was adopted to analyze the total harmonics distortion of Voltage (THDv) value up to the 31st harmonics in a 31-bus distribution network with linear and non-linear loads. The major technical constraints considered are voltage and THDv limit at different buses, line flow capacity and power balance. The Particle Swarm Optimization (PSO) based algorithm was tested for various simulated cases and was found to be robust, reliable and in compliance with IEEE 519-1992 standards. Despite the robustness and reliability of the work, there was no comparative analysis of the PSO method to other well-known optimization methods such as genetic algorithm (GA) in order to establish the superiority of one over the other. The inherent disadvantages of particle swarm optimization (PSO) such as partial optimism (less exact at the regulation of its speed and the direction), inability to work out the problems of non-coordinate or fast changing coordinate system (Bai, 2010) were drawbacks to the study.

Kaiwart and BalaRaju (2016) discusses various harmonic mitigation techniques stating the advantages and disadvantages of each technique. Relevant diagrams and charts were provided to provide useful information. It was concluded that there is no single product or method that provides a universal best solution for harmonics as the best economical and technical solution depends on users' objective, extent or quantity of harmonics distortions, associated costs and benefits. Hybrid method was proffered as the best suitable method. The work was a general characterization of harmonics mitigation techniques. Details of operational principles of the methods, the use of software tools and methods of optimization were missing.

Durdhavale and Ahire (2016) outlined various harmonics detection and measurement techniques stating the advantages and disadvantages of each. A new hybrid optimistic method was introduced and proposed. The system was designed for detection and measurement of harmonics on Advanced RISC Machines (ARM) 7 using FFT algorithm for measuring the total harmonic distortion. Specific analysis of harmonics in the context of a heavy current industry was missing in the study and there was no comparative analysis of the various optimization methods such as genetic algorithm (GA), artificial bee colony (ABC), particle swarm optimization (PSO), etc. to establish further improvements on the new method developed.

A detailed description with classification of the harmonic mitigation techniques based on some distinguish features such as reliability, load influence, total harmonic distortion (THD), cost,

etc. was given by Mahima and Lalwani (2017). The work was a guide towards deciding which harmonic mitigation methods best suit different conditions. Hybrid filters were adjudged to be very efficient and further improvement were proposed through an adoption of new topology. Optimization methods were missing in the study. There was no specific case study to demonstrate the effectiveness or otherwise of the methods.

4. Conclusion

This paper reviewed holistically the work done on various aspects of harmonics by different researchers in the last two and a half decades (1998 - 2023). The areas covered in the study of harmonics, the merits, the demerits and outstanding areas in the works done on harmonics within the specified decades are discussed. In this work, it is discovered that much remains to be done in the area of using different software tools in the optimization of filters, especially the hybrid type models to control harmonics in a power distribution system. Furthermore, the study discovered that the design of filters that can simultaneously mitigate harmonics from heavy, middle or light current devices are largely missing in the efforts made so far on the mitigation of harmonics. In order to expand the frontiers of knowledge in harmonics distortion in contemporary power systems and to create strategies for reducing its detrimental impact on power quality and system stability, the missing gaps such as the design of a filter that will simultaneously cater for harmonics mitigation optimally under different scenario is a necessity. This can of course take several forms as many factors are to be considered. Other researchers that are interested in the field of harmonics may identify these gray areas and fill the missing gaps.

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